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Bastida-Molina, P.; Hurtado-Perez, E.; Peñalvo-López, E.; Moros-Gómez, MC. (2020). Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels. Transportation Research Part D Transport and Environment. 88:1-23. https://doi.org/10.1016/j.trd.2020.102560

The final publication is available at

https://doi.org/10.1016/j.trd.2020.102560

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Additional Information

Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels

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Abstract

Electric Vehicles (EVs) appear as an environmental solution for transport sector since they emit zero emissions while driving. Nonetheless, the carbon intensity (CI) of the energy sources involved in the electricity generation system could seriously compromise this solution. Hence, this study proposes a methodology to verify the sustainability of the sector by the introduction of EVs. By means of the "Well-to-Wheel" tool, it compares emissions generated by two fleets: one based on internal combustion engine vehicles (ICEVs) and another one that also contemplates different EVs penetration levels. This methodology develops an iterative process on the contribution of renewable sources to the electricity generation system until a certain level of emissions reduction is achieved. The needed evolution of the CI for the electricity system is therefore deduced. The methodology has been applied to Spain by the mid-term future, given these country policies for both a high penetration of EVs and a progressive introduction of renewable sources in its electricity system. Results indicate that the current Spanish electricity mix allows for a reduction in CO_2 emissions by the introduction of EVs, but a 100% renewable system will be needed for reductions up to 74 million tons per year. This research is a first-ever study to relate the forecasted Spanish environmental policies, in terms of urban transport and configuration of the power system, with a sustainable introduction of EVs in the urban fleet. Hence, this paper would be very helpful for policy makers on evaluation of the requirements for a transport fleet electrification.

Keywords

Electric vehicle, CO_2 emissions, electricity system, renewable sources, Well-to-Wheel.

Variables

$F(t)$	*Total fleet evolution.*
$r(i,t)$	*Rate of total fleet growth (%).*
$F_{ICEVs_0}(t)$	*Fleet of ICEVs without EVs penetration.*
$F_{ICEVs_F}(t)$	*Remaining fleet of ICEVs with EVs penetration.*
$f_p(i,j,t)$	*Rate of EVs penetration (%).*
$F_{EVs}(t)$	*Fleet of EVs with EVs penetration.*
$F_T(t)$	*Total fleet of ICEVs and EVs with EVs penetration.*
$g(t)$	*Emissivity of the electricity system (g* CO_2*/kWh).*
$P(k,t)$	*Participation of each power source in the electricity generation (%).*
$Em_{ICEVs_0}(t)$	*Emissions due to* $F_{ICEVs_0}(t)$*, (g* CO_2*).*
$d(i,t)$, $d(j,t)$	*Annual travel distances (km).*
$c_{ICEVs}(i,t)$	*Fuel consumption for ICEVs (l/km).*
$Em_{ICEVs_F}(t)$	*Emissions due to* $F_{ICEVs_F}(t)$*, (g* CO_2*).*
$Em_{EVs}(t)$	*Emissions due to* $F_{EVs}(t)$*, (g* CO_2*).*
$x_{elect}(j,t)$	*Fraction of electrical contribution for EVs (%)* [a].
$c_{elect}(j,t)$	*EVs electricity consumption per kilometre (kWh/km)* [a].
$x_{hyb}(j,t)$	*Fraction of hybrid contribution for EVs (%)* [b].
$c_{hyb}(j,t)$	*Fuel consumption for EVs (l/km)* [b].
$Em_{EVs,elect}(t)$	*Emissions generated due to the electrical behaviour of EVs (g* CO_2*)* [a].
$Em_{EVS,hyb}(t)$	*Emissions generated due to the hybrid behaviour of EVs (g* CO_2*)* [b].
$Em_T(t)$	*Total emissions generated by* $F_T(t)$*, (g* CO_2*).*
$g_{lim}(t)$	*Allowable maximum value of* $g(t)$*, (g* CO_2*/kWh).*
$s(t)$	*Degree of sustainability due to the substitution of ICEVs by EVs (%).*
$s_{ref}\ (t)$	*Reference value of* $s(t)$*, (%).*

Parameters

t	
ΔT	*Time interval for the study*
$CI\ (k)$	*Carbon intensity of each power source (g* CO_2*/kWh).*
$em_{WtW}(i)$	*WtW emissivity for ICEVs (g* CO_2*/L).*
$em_{WtW}(j)$	*WtW emissivity for EVs with hybrid behaviour (g* CO_2*/L)* [b].
$LRSI(f)$	*Level of renewable sources introduction.*

Indices	
i	*Index for ICEVs vehicles type, i = {1, 2, 3, 4}, specifically 1: gasoline car, 2: diesel car, 3: diesel bus, 4: gasoline motorcycle.*
j	*Index for EVs vehicles type, j = {1, 2, 3, 4 }, specifically 1: BEV car, 2: HEV car, 3: PHEV car, 4: BEV bus; 5: HEV bus, 6: PHEV bus, 7: BEV motorcycle.*
f	*Index for LRSI, f = {1, 2, 3, 4, 5}*
k	*Index for the power source in electricity generation, k = {1, 2, 3, 4, 5}, specifically 1: coal, 2: nuclear, 3: oil, 4: natural gas, 5: renewable.*

[a]: Electrical behavior of EVs related to BEVs and PHEVs partly.

[b]: Hybrid behavior of EVs related to HEVs and PHEVs partly.

1. Introduction

Unlike traditional vehicles powered by internal combustion engine (ICEVs), electric vehicles (EVs) generate zero emissions while they are driven on the roads: “zero tailpipe emissions” [1–3]. However, a raise in the emissions due to the electricity generation system to cover the increase of electricity demand by the EVs could appear [4,5]. This emission increase would mainly depend on the electricity mix structure. Therefore, the carbon intensity (CI) of the technologies involved in the electricity generation mix of every country would determine the environmental profitability degree of introducing EVs in relation to the net total CO_2 emission savings [6].

Well-to-Wheel (WtW) analysis has been widely used to assess total carbon emissions reduction in transport sector [7–10]. This approach considers the whole process of energy flow, from the fuel generation to the vehicle driving, dividing the whole process in two clear separate steps: Well-to-Tank (WtT) and Tank-to-Wheel (TtW) processes. An exhaustive study [10] analyses the WtW for EVs considering the generation mix of 70 different countries and compares the results with the equivalent emissions of ICEVs. Results show that countries with the highest CI power sources are also the ones with highest EVs’ emissions. Even in some countries, emissions are higher than the ones generated by the corresponding ICEVs. Other study [11] makes a similar analysis, applying WtW methodology to each European Union Member State. This research also considers the CI content of electricity trades between countries. Besides, it calculates how total CI of the power mix of a country decreases when importing low CI electricity from another region and the other way round. WtW method has been also applied to specific countries or regions to calculate CO_2 emissions when introducing EVs. For instance, [12] analyses the current Malaysia’s case of study, [13] studies the four countries with highest passenger car sales (Germany, the United States, China and Japan) together with a highly renewable energy country (Norway). [14] makes a comparison between both developed and developing countries and finally [15] focuses on European countries.

All of these studies present comparisons between emissions produced by EVs with their current country electricity generation mix and the ones generated by ICEVs. They all try to determine whether the introduction of EVs is a clean solution or not, coming all to the same view: CO_2 savings when introducing EVs only happen in the cases where high CI sources are not the main representative ones in the electricity system. China emerges in this context as the global largest EVs market, with 1.2 million EVs sold in 2018 [16] due to its appealing EVs incentive policies [17]. However, the main use of coal for electricity generation in this country [18] also foresees the highest CO_2 emissions projections for this country with EVs introduction. Study [19] specifically states that the large-scale development of EVs in China maintaining its current power structure would be equivalent to replace oil with coal in the system, which would result in carbon emissions increasing. Research [20] also forecasts the key role that fuel economy regulations will play in the short-term future of China together with the lower reliance of the power system on fossil fuel in the long-term. After China, Japan would suffer the highest CO_2 emissions for EVs, as [18] states. Japan, together with other countries such as South Korea or Taiwan, depend on the import of fuels through maritime transportation. This situation affects not only the energy mix of these countries, but also the complexity and WtW analysis [21]. So far, all the published studies claim the global necessity of moving towards a more renewable electricity system to meet decarbonization by EVs introduction [22]. Particularly, [23] equates the large effect of grid decarbonization with increasing EVs fleet. Moreover, [24] identifies the assumption of an unchanged electricity mix over the coming years as a traditional error factor while forecasting EVs emissions reduction in a country. The study [18] addresses this traditional error. Namely, [18] presents an experimentally vehicle dynamic model to simulate ICEVs and EVs consumption under eight driving cycles to determine CO_2 emissions of both types of vehicles considering the projected emissivity evolution of the countries under study (Europe, China and Japan) until year 2040. Three main results are presented in this study. Firstly, the enhancement of both EVs and ICEVs' technologies will lead to a reduction in carbon emissions along the years, being ICEVs' emissions always higher than EVs' ones. Secondly, China is expected to produce the highest CO_2 emissions due to its power grid composition projections. Finally, the difference between CO_2 emissions from ICEVs and EVs gets smaller under highway conditions and higher under urban driving conditions.

Other methodologies have also analysed the influence of electricity structure systems regarding EVs emissions using energy models. For instance, research [25] uses the MARKAL model to generate a quantitative scenario for electricity and cogeneration sectors in the Netherlands, which allowed them to stablish strategies to achieve, in comparison with 1990 levels , 15% and 50% CO_2 emissions reduction in 2020 and 2050, respectively. Another study [26] employs the energy model (PERSEUS-NET-TS) to analyse four different methods to evaluate CO_2 emissions in Germany by 2030, revealing differences up to 0.55 kg/kWh.

The existing literature only makes quantitative analyses of EVs carbon emissions and, although some studies consider the effects of a changeable electricity mix along the years, these researches lack the possibility of forecasting the detailed evolution of the power system structure needed to guarantee all the time a specific level of emissions reduction. This detailed evolution of the power system has been the focus of our investigation. Hence, our paper proposes a methodology to assess the time evolution of the renewable sources introduction in the electricity system in order to get, for a particular penetration of EVs in the fleet, a particular level of decrease in the CO_2 emission. This method also determines the limit emissivity of the power system to ensure a zero emissions introduction of EVs in a particular fleet. The methodology will evaluate the possibility to reach a sustainable transport sector by combining EVs penetration and renewable participation in the electricity system.

Other researches have also proposed methodologies to evaluate changes in the energy mix with the introduction of EVs, but they present a series of limitations that the current paper has tried to cope with. Research [27] analyses the initial consumers' preferences while selecting a vehicle and evaluates their change in preferences according to various electricity generation mix scenarios together with their environmental impact. Their results indicate that BEVs' market share could be promoted up to 10% and reduce GHG up to 5% by 2026. The evaluation period of this research represents an imminent future (2026), while our paper establishes a longer evaluation period: up to 2040. Moreover, research [27] presents four pre-established different energy mix scenarios whose composition does not depend on the level of CO_2 emissions reduction achieved with the penetration of EVs, unlike our study where the introduction of renewable sources clearly depends on two carbon emissions constrains related to the introduction of EVs. Research [28] presents a methodology to optimally schedule the charging/discharging process of EVs with two main objectives: minimize costs of the system and reduce CO_2 emissions. Such methodology is applied to distributed networks that integrate renewable resources. This application differs from the one presented in this paper, since the horizon of our work extends to the configuration of all the national grid and renewable resources are introduced according to CO_2 emissions restrictions provoked by EVs. Study [29] proposes a techno-economic analysis of a city-scale energy system with rooftop PV, batteries and EVs with storage possibilities for Kyoto in Japan. The dimension applicability of such research focuses just on distributed networks for cities and includes only solar PV as renewable resources. Moreover, it makes an analysis of a fix temporary scenario, without including any renewable energy evolution according to the introduction of EVs. However, our study includes the configuration of the entire national grid and contemplates all different types of renewable energies, not just solar PV. Hence, our methodology is scalable to the scenario in question. Besides, our paper develops the evolution of the energy system configuration according to carbon dioxide emissions boundaries generated by the penetration of EVs. Furthermore, other studies have used the methodology Life cycle assessment (LCA) to evaluate carbon emissions impacts of the introduction of EVs. For instance, research [30] makes a LCA of EVs battery charging in all the 28 European Union countries considering the current and the projected electricity mix structure until 2050. Despite the valuable information that could be extracted from this work, it does not indicate the total evolution that carbon dioxide emissions would suffer along this period since the work does not considered the remaining quantity of ICEVs and the projected EVs to be included in the fleet. Moreover, the introduction of renewable sources does not answer to CO_2 restrictions when introducing EVs, but to projected plans. Otherwise, our paper includes an energy model that allows a changeable introduction of renewable sources in the energy mix according to the CO_2 emissions reduction constrains due to EVs introduction. Besides, the methodology considers two different fleets to obtain the carbon dioxide emissions reduction: one formed only by ICEVs and another one formed by ICEVs and EVs. In both cases, the evolution of the quantity of such vehicles lies in forecasted data. Finally, our work employs the methodology WtW instead of LCA to assess carbon emissions reduction. Despite LCA is a more precise technique that considers more stages in the vehicles' life when analyzing its environmental suitability, WtW is the most widely used method for policy support in road transport [31]. According to [31], WTW methodology is used for instance by the European Union for the Fuel Quality Directive and for the Renewable Energy Directive, in the USA, the Environmental Protection Agency bases its regulatory actions on the WTW approach of the GREET model, and also in China, WTW is used to assess policy options.

Having said that, we have not found any work in the literature that relates the introduction of renewable sources in the electricity mix with a double level of CO_2 constraints restriction when introducing EVs: a first level that ensures a net CO_2 emissions introduction of EVs and a second level that ensures a CO_2 emissions reduction with such introduction. Specifically, the limit electricity system emissivity (first constraint), which guarantees a net CO_2 emissions introduction of EVs, remains unexplored in the rest of the literature, to the best of our knowledge. Additionally, as far as we are concerned, no other studies include a comparison between emissions generated by two possible fleets: one completely formed by ICEVs and another one that also includes EVs. Beyond this, the method is completely scalable and true to reality since it considers the complete replacement of ICEVs cars, motorcycles and urban buses by EVs, including all the different types: BEVs, PHEVs and HEVs.

The methodology has been applied to the Spanish case study in the mid-term future, until 2040. Figure 1 [32] and Table 1 [33] provide a general caption about the electricity generation system and fleet composition of the country, respectively.

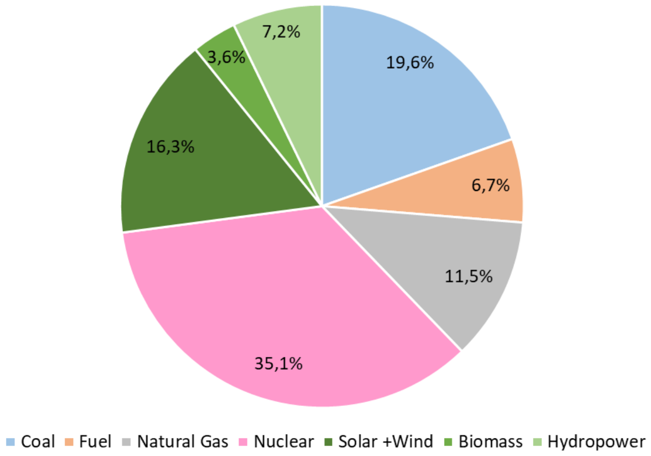


Figure 1. Current Spanish power system composition.

Table 1. Current Spanish fleet composition.

Gasoline car	Diesel car	Gasoline motorcycle	Diesel bus
9820553	13038663	3201831	14986

Spain is expected to get a large contribution to CO_2 transport emissions reduction due to the environmental policies proposed in the regulatory draft [34] by the Ecological Transition Spanish Ministry [35]. This regulatory draft emerges for the first time in 2018 with three general goals: to ensure compliance with the Paris Agreement's objectives [36], enhance the decarbonization of the Spanish economy and introduce a sustainable development model capable of mitigating climate change. In line with these three objectives, the draft presents two main fields of application: sustainable mobility and renewable electricity generation system.

Regarding the former, the draft prohibits by 2040 the sale and registration of light vehicles which produce carbon dioxide emissions, and its circulation by 2050. This measure enhances the renovation of the current aged ICEVs fleet in Spain, which has an average age of 12.4 years, whereas the European average age states at 10.8 years [37]. Moreover, the Spanish regions with more than 50000 inhabitants are obliged to create spaces with low emissions before 2023, enhance the public transport and electrify urban buses. This draft also boosts the installation of recharge point for EVs, making it obligatory in the coming years for petrol stations with high shares, new construction buildings and non-residential existing buildings with more than 20 parking places. To ensure such mobility transition in a sustainable way, the Spanish Government has introduced financial aids, specifically the so called Plan Moves [38]. This Plan includes economical aids to buy EVs (only BEVs and PHEVs, together with hydrogen vehicles) and to install recharging points for such vehicles.

With reference to renewable generation, this regulation aims to achieve a 74% renewable sources introduction in the electricity generation mix by 2030 and a 100% renewable one by 2050. Moreover, the draft includes highly environmental-restrictive policies to coal power stations, which practically imply their upcoming closing [39]. Besides, a stepped close of nuclear power plants is foreseen as another future measure for the Spanish ecological transition [40]. Finally, the regulatory draft [35] includes a “just transition strategy” with a series of regulatory measures to reduce negative economic impacts in energy sectors that do not fit in the ecological transition.

Both effects, a large penetration of EVs and a change in the electricity mix with a growing introduction of renewable sources, make Spain an ideal case study for urban transport emissions reduction. Our study includes five different levels of renewable sources introduction (LRSI) in the Spanish power system, which reflect the previously described regulatory plans.

This research is a first-ever study to relate the forecasted Spanish environmental policies, in terms of urban transport and configuration of the power system, with a sustainable introduction of EVs in the urban fleet by using a novel methodology based on carbon emissions constraints for the electricity generation system. Hence, this paper would be very helpful for policy makers on evaluation of the requirements for a transport fleet electrification.

The paper is organized as follows: section 2 presents the methodology, section 3 describes the application to Spain by the mid-term future and section 4 provides the results and discussion of this application. Finally, the paper concludes in section 5.

2. Methodology

A methodology has been developed to determine the reduction in CO_2 emissions due to the penetration of EVs in the transportation fleet. The method establishes the needed CI factor of the electricity generation system to provide, at any time along that evolution, a specific level of emissions reduction. Figure 2 represents the flowchart of the proposed methodology, whereas Table 2 define both input and output data.

Table 2. Inputs and outputs

Inputs	**Outputs**
t_0	$F_{ICEVs_0}(t)$
t_F	$F_{ICEVs_F}(t)$
ΔT	$F_{EVs}(t)$
$F(t_0)$	$F_T(t)$
$r(i,t)$	$g(t)$
$f_p(i,j,t)$	$Em_{ICEVs_0}(t)$
$P(k,t)$	$Em_{ICEVs_F}(t)$
$CI\ (k)$	$Em_{EVs}(t)$
$g(t_0)$	$Em_{EVs,elect}(t)$
$d(i,t)\ ,\ d(j,t)$	$Em_{EVs,hyb}(t)$
$c_{ICEVs}(i,t)$	$Em_T(t)$
$em_{WtW}(i)$	$g_{lim}(t)$
$x_{elect}(j,t)$	$s(t)$
$c_{elect}(j,t)$	$LRSI(f)$
$x_{hyb}(j,t)$	
$c_{hyb}(j,t)$	
$em_{WtW}(j)$	
$s_{ref}\ (t)$	

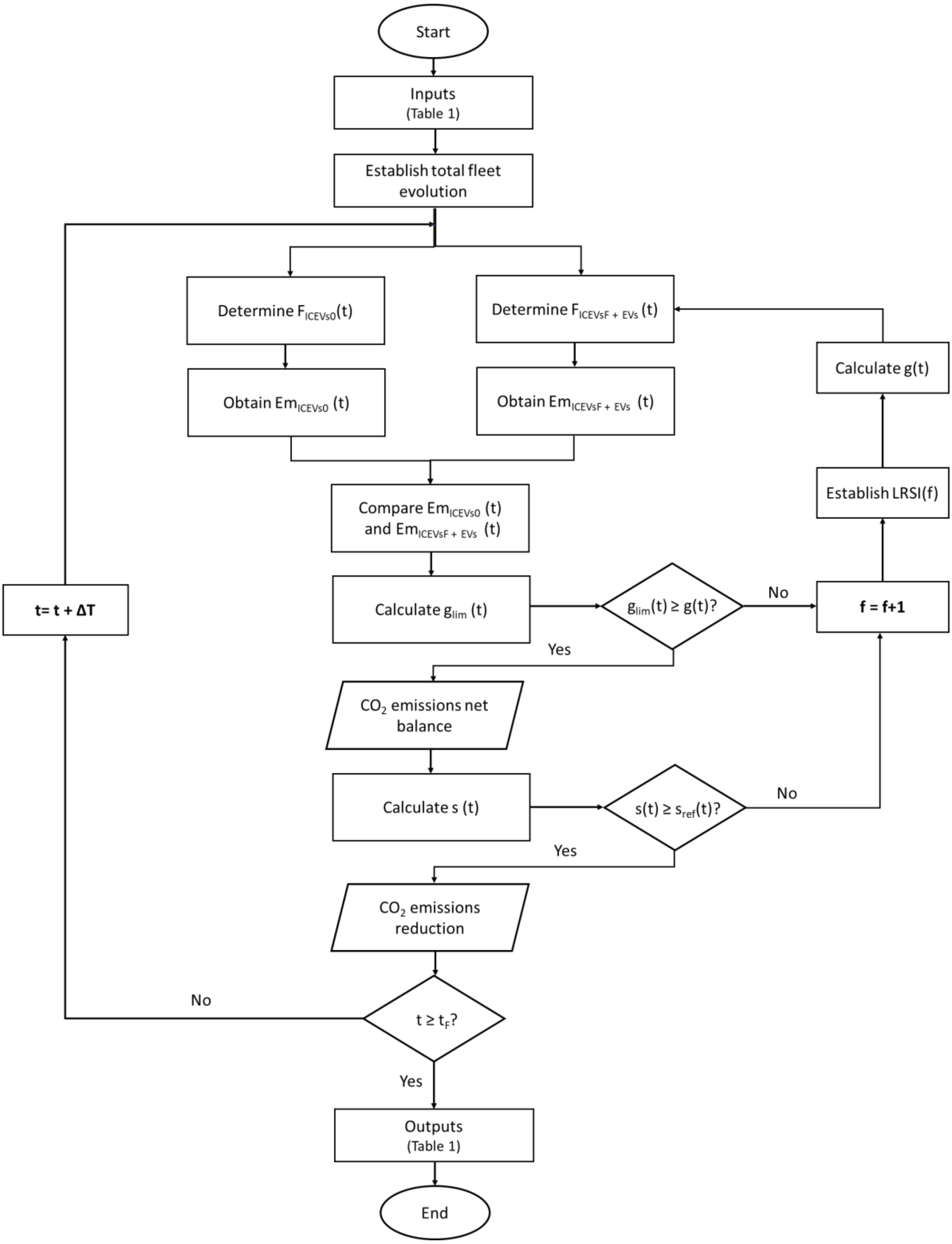


Figure 2. Flowchart of the proposed methodology.

Once the total urban fleet evolution in the considered time period is defined (eq.(1)), the methodology distinguishes two different situations. The first one is a conservative case where the fleet includes only ICEVs without any EVs penetration. This fleet is given by eq. (2)

$$F(t) = \sum_{i} F(i, t - \Delta T) \cdot r(i, t) \tag{1}$$

$$F_{ICEVs_0}(t) = F(t) \tag{2}$$

The second situation reflects the introduction of EVs in the urban fleet. Therefore, it would include the remaining quantity of ICEVs (eq. (3)) together with the different types of EVs introduced (eq. (4)): Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) [7]. Finally, eq. (5) determines the total fleet in this situation:

$$F_{ICEVs_F}(t) = \sum_{j} \sum_{i} F(t) \cdot \left(1 - f_p(i, j, t)\right) \tag{3}$$

$$F_{EVs}(t) = \sum_{j} \sum_{i} F(t) \cdot f_p(i, j, t) \tag{4}$$

$$F_T(t) = F_{ICEVs_F}(t) + F_{EVs}(t) \tag{5}$$

The second stage of the methodology calculates the total CO_2 emissions generated by the two above-mentioned urban fleets in order to deduce the impact on carbon emissions due to the penetration of EVs. It results of utmost importance to clarify that CO_2 emissions calculated in this section correspond to the real emissions, not to the equivalent CO_2 emissions remaining to greenhouse gases.

The Well-to-Wheel (WtW) method is used to assess these carbon dioxide emissions [7,41]. The WtW analysis comprises two consecutive stages: the Well-to-Tank stage (WtT), where the emissions due to the processes for extraction, transportation, treatment and provision of the required fuel (electricity in the case of EVs) to be used by the fleet are calculated, and the Tank-to-Wheel stage (TtW), which determines the emissions while driving the vehicles. Table 3 reflects the flowchart of the WtW method.

Table 3. WtW method.

Stages	**ICEVs**	**EVs**
Well to Tank	Extraction and processing of raw materials	
	Transportation and storage	
	Gasoline / diesel refining	Electricity generation
	Power delivery system (truck, pipelines)	Power transmission and distribution (power grid)
Tank to Wheel	Driving process (fuel combustión)	Driving process

Therefore, depending on the vehicle characteristics, both WtT and TtW emissivity acquire different values [10]. For vehicles depending totally on fossil fuels, like ICEVs, or partially as HEVs and PHEVs, their WtT and TtW emissivity depends on the type of fuel used: gasoline or diesel. For vehicles depending on electricity, exclusively in the case of BEVs and partially for the PHEVs, WtT emissivity depends on the emissivity of the electricity system (eq. (6)). Moreover, it is the only factor to consider: TtW emissivity acquires null value in this case since driving process involves zero-emissions [1,4,26].

$$g(t) = \sum_k P(k,t) \cdot CI\,(k) \tag{6}$$

Eq. (7) determines the emissions generated by the urban fleet transport based exclusively on ICEVs:

$$Em_{ICEVs_0}(t) = \sum_i F_{ICEVs_0}(i,t) \cdot d(i,t) \cdot c_{ICEVs}(i,t) \cdot em_{WtW}(i) \tag{7}$$

In the case of a fleet with EVs in different penetration levels, eq.(10) determines the total CO_2 emissions. It includes the emissions due to the remaining quantity of ICEVs (eq.(8)), and the corresponding to the EVs (eq.(9)) with two components: the electrical behaviour of BEVs and PHEVs partially and the hybrid behaviour of HEVs and PHEVs partially.

$$Em_{ICEVs_F}(t) = \sum_i F_{ICEVs_F}(i,t) \cdot d(i,t) \cdot c_{ICEVs}(i,t) \cdot em_{WtW}(i) \tag{8}$$

$$Em_{EVs}(t) = \sum_j x_{elect}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{elect}(j,t) \cdot g(t) + \sum_j x_{hyb}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{hyb}(j,t) \cdot em_{WtW}(j) = Em_{EVs,elect}(t) + Em_{EVs,hyb}(t) \tag{9}$$

$$Em_T(t) = Em_{ICEVs_F}(t) + Em_{EVs}(t) \tag{10}$$

The introduction of EVs is intended for a decarbonisation of the transport sector. However, the presence of high-CI sources in the electricity generation system could produce the opposite effect: an increase in CO_2 emissions. The methodology calculates the allowable maximum value of the electricity system emissivity (g_{lim}, eq. (12)), below which there will be a positive effect in the reduction of CO_2 emissions. This parameter indicates the upper boundary for the electricity system emissivity of the country under study that ensures a net CO_2 emissions introduction of EVs. This value is deduced by imposing a null value to the CO_2 emission balance given by eq.(11) as the difference between the emissions saved by the EVs penetration and the produced ones by the electricity consumption.

$$\left\{Em_{ICEVs_0}(t) - \left[Em_{ICEVs_F}(t) + Em_{EVs,hyb}(t)\right]\right\} - \left\{Em_{EVs,elect}(t)\right\} = 0 \tag{11}$$

$$g_{lim}(t) = \frac{Em_{ICEVs_0}(t) - Em_{ICEVs_F}(t) - Em_{EVs,hyb}(t)}{\sum_j x_{elect}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{elect}(j,t)} \tag{12}$$

The degree of sustainability due to the substitution of ICEVs by EVs can be determined by the relative reduction in CO_2 emissions, which is calculated by eq. (13):

$$s(t) = \frac{Em_{ICEVs_0}(t) - Em_{ICEVs_F}(t) - Em_{EVs,elect}(t) - Em_{EVs,hyb}(t)}{Em_{ICEVs_0}(t)} \tag{13}$$

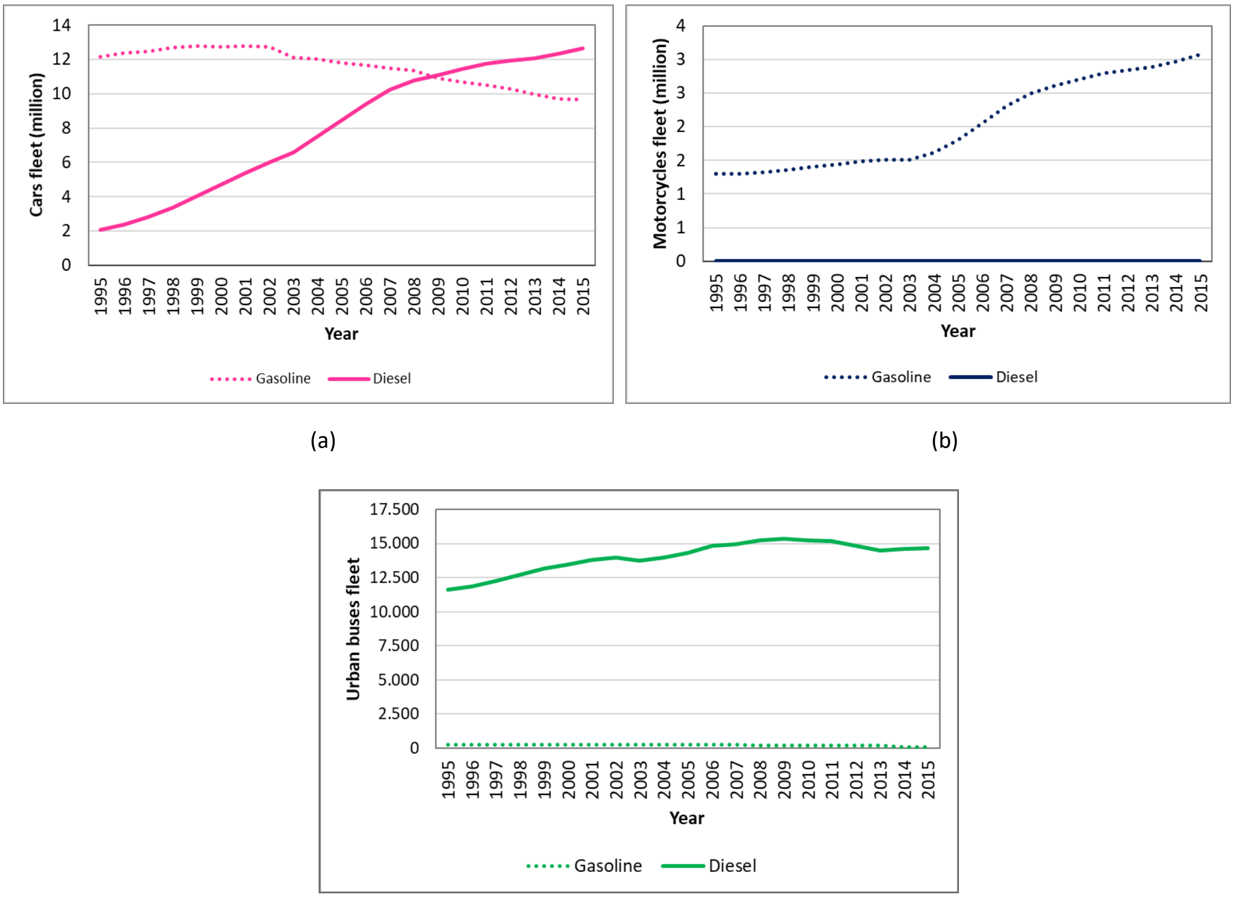
The methodology includes an iterative process in order to verify at any time two constraints: first, to determine an electricity generation system with an emissivity below the maximum value and, in the second place, given a certain level of emissions reduction, find the corresponding electricity generation system.

3. Case study: Spain by the mid-term future

This paper applies the previously explained methodology to the Spanish case study by the mid-term future: from 2016 to 2040. Spain foresees an ever-increasing electrification of the urban fleet in the medium-term, together with a stepped introduction of renewable sources in the electricity system [34]. This chapter describes the effect of both implications regarding EVs introduction, namely BEVs, PHEVs and HEVs.

3.1. Fleet evolution

The research focuses the methodology on the Spanish urban transport fleet, including therefore three types of vehicles: cars, motorcycles and urban buses. Although in different proportion, the three types of vehicles have traditionally used fossil fuels like gasoline or diesel (ICEVs). In 2015, 43% of the cars were gasoline cars and 57% diesel cars, whereas diesel urban buses and gasoline motorcycles had a presence of 99% each [33]. Following historical data [33], shown on Figure 3, a linear extrapolation was made to estimate the expected rate of growth of these ICEVs until 2040 (Table 4). This fleet does not include the introduction of EVs and conforms the first case fleet (Case 1). According to the methodology, this fleet would also match the total urban fleet evolution and consequently, the rate of growth of ICEVS would also match the rate of growth of the total fleet. Due to the unrepresentative influence of gasoline urban buses and diesel motorcycles, they are not considered in this research.



(a) (b)

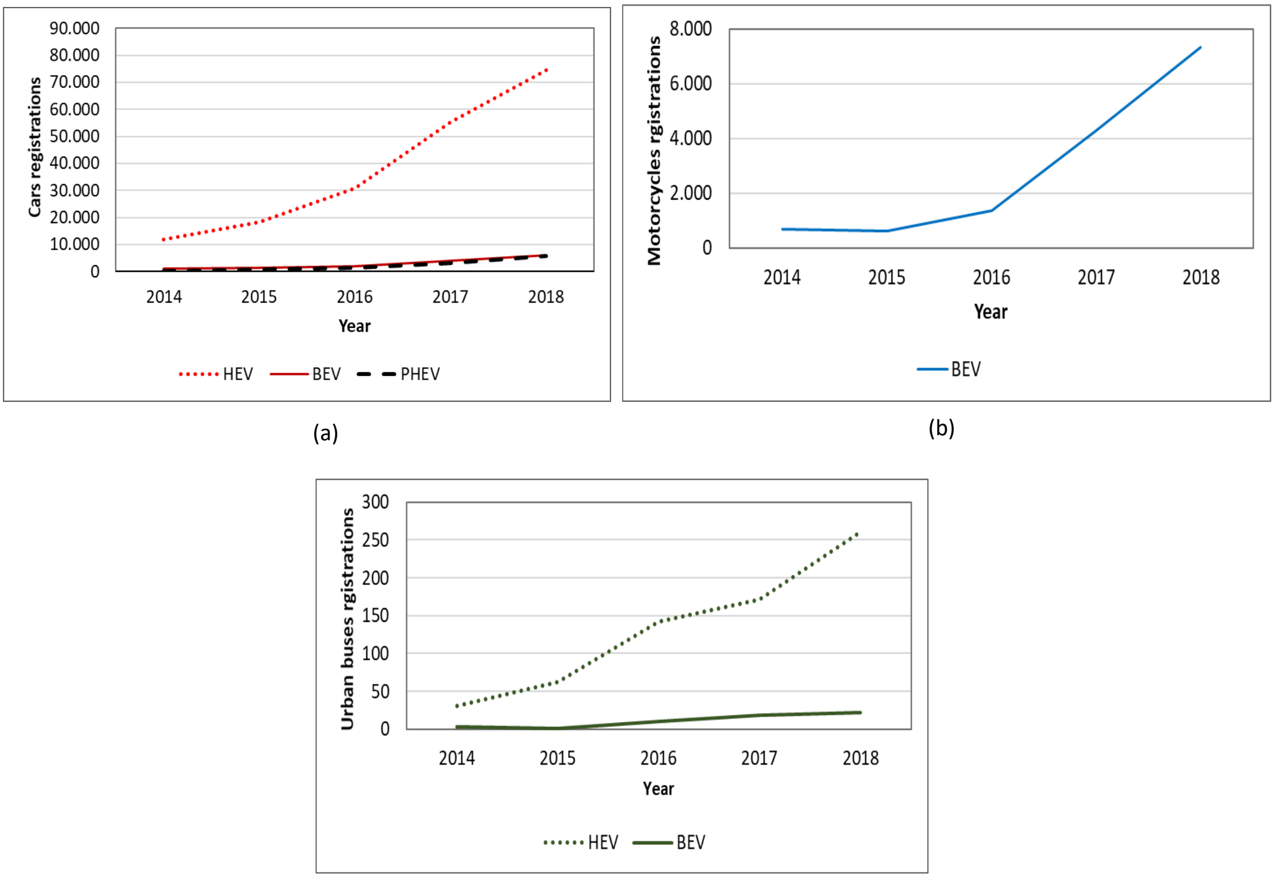
(c)

Figure 3. Spain ICEVs' historical data. (a) Cars. (b) Motorcycles. (c) Urban buses.

Table 4 . Spain ICEVs initial fleet and rate of growth. Case 1.

		Gasoline car	Diesel car	Gasoline motorcycle	Diesel bus
2016	Initial fleet	9820553	13038663	3201831	14986
2020	Rate of growth (%)	11.6	11.6	11.3	4.5
2024		6.6	6.6	11.1	4.3
2028		6.5	6.5	10	4.1
2032		5.8	5.8	9.1	4.0
2036		5.5	5.5	8.3	3.9
2040		5.2	5.2	7.7	3.7

Regarding EVs, in 2018 electric cars, electric urban buses and electric motorcycles represented just a 1%, 1.7% and 0.4% of their corresponding fleet respectively [33,42]. Despite this small influence, their registrations have experienced a large increase since 2014 [37,43], like Figure 4 shows:



(a) (b)

(c)

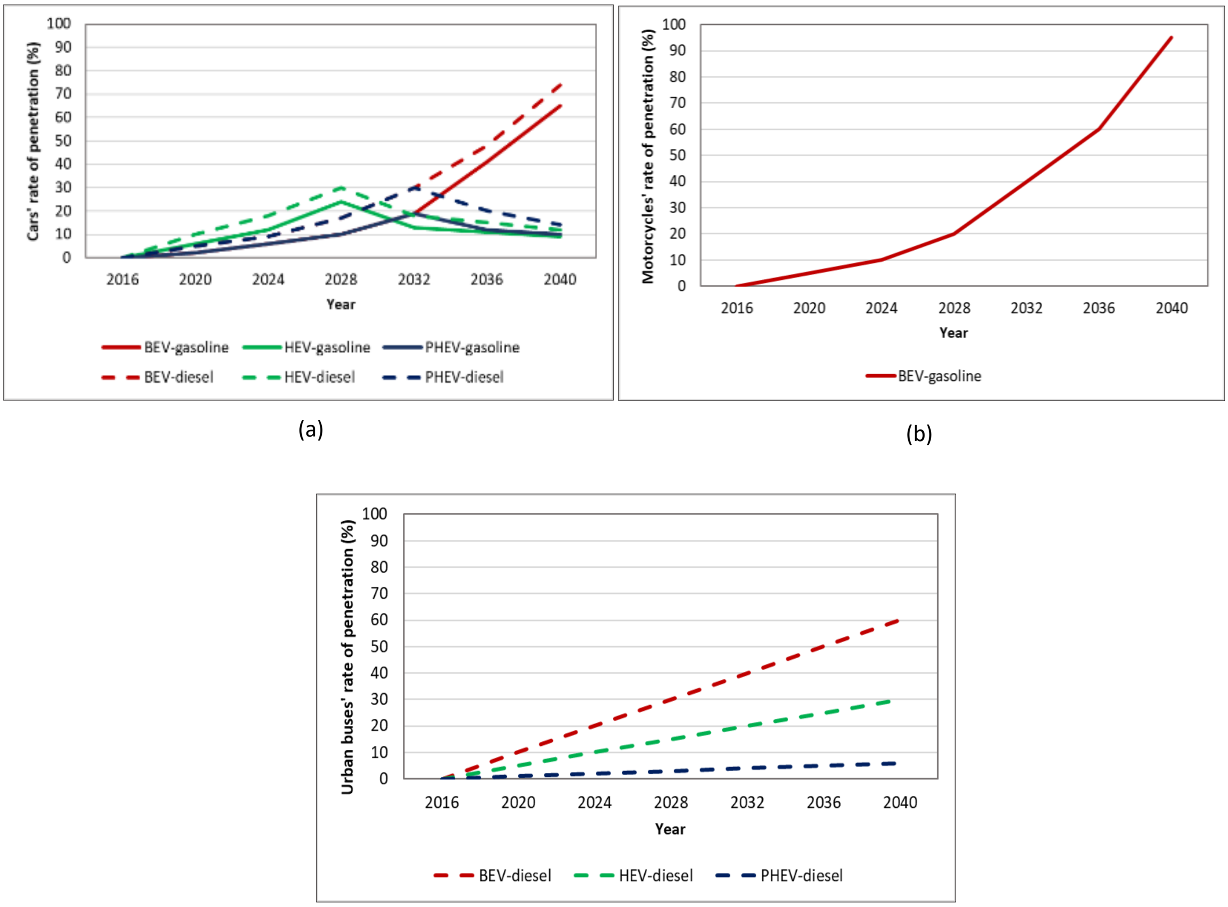
Figure 4. Registrations of EVs in Spain. (a) Cars. (b) Motorcycles. (c) Urban buses.

This trend forecasts a high penetration of EVs in the Spanish fleet for the medium-term future, also motivated by the environmental policies documented on [34,35] and the aged current fleet of LEVs (12.4 years) [37] and partially urban buses (8 years) [44]. The draft, proposed by the Ecological Transition Spanish Ministry, forbids the sale and registration of light vehicles producing CO_2 emissions by 2040, and their driving by 2050. Considering both phenomena, we propose the second case fleet (Case 2), which contemplates the introduction of EVs with different rates of penetration. These rates are now defined and Figure 5 details them.

Regarding cars, BEVs are expected to suffer an exponential growth in the coming years. Despite their slow growth of registrations during last years (Figure 4 (a)), the above mentioned prohibition would make BEVs cars the only legal ones to be sold and registered by 2040 and to be driven by 2050, so that an exponential increase of their fleet is awaited. Referring to HEVs cars, their current trend of registration (Figure 4 (a)) together with their wide proven technology forecasts a considerable and almost linear penetration of this kind of cars for the coming years. However, as they generate CO_2 emissions, their contribution to the fleet is expected to decrease in the last years of the studied period due to [34,35] environmental restriction. With reference to PHEVs cars, their rate of registrations during last years is similar to the BEVs' (Figure 4 (a)), so we consider their introduction would match BEVs' one for the first period considered. Nonetheless, as PHEVs cars also generate CO_2 emissions, their sale and later driving prohibition would determine the decrease of their fleet during the last years of the period. Finally, the penetration levels of BEVs, HEVs and PHEVs cars would be higher replacing diesel ICEVs cars than gasoline ones. This consideration relates to the recent environmental policies restricting the use and registration of diesel cars [34] due to the air quality damaging NOx particles that they generate.

When talking about electric motorcycles, only BEVs should be considered [43]. Their expected growth follows a similar behavior to that of BEVs cars', since they are also light vehicles and restriction [34] affects them too. Therefore, an exponential introduction of BEVs motorcycles is forecasted. However, it would be stronger than BEVs cars' since this type of EVs is the only one expected for motorcycles (Figure 4 (b)).

Referring to urban buses, the above described prohibition would not affect them since they are heavy vehicles. On the one hand, this situation would make HEVs buses fleet increase in a linear way during all the period, considering their registration historical data trend. On the other hand, BEVs buses would experience a highNoer introduction than HEVs due to their independence on fossil fuels and the increasing environmental concerns, despite their slow registration growth in the recent years (Figure 4 (c)). With regard to PHEVs, currently there are not urban buses of this nature. Nevertheless, their good performance in the pilot project of Gothenburg (Sweden) [45] enhanced our decision on considering their slow and linear introduction in the studied period.



(a) (b)

(c)

Figure 5. Rates of EVs penetration. (a) Cars. (b) Motorcycles. (c) Urban buses.

The forecasted penetration of EVs hereby presented answers also to the European regulations in terms of electric mobility. The legislation stablishes the maximum emissions limit in 95 g CO_2/km for new vehicles from 2020 [46]. From 2025, the minimum share of EVs for manufactures will increase up to 25% and in 2035 the sale and registration of EVs will be forbidden. According to this general framework, some European countries have fixed future objectives about the penetration of EVs in their societies, for example Norway and Germany.

On the one hand, Norway stands as the first country to have stablished a 100% electric mobility plan for the coming future [47], where the EVs' sales represented a 52.17% of the market share in 2017. Their mobility plan stablishes that all the light vehicles and urban buses should be transformed to EVs before 2025. The hereby-presented study for Spain follows the same trend (a complete transformation of light electric vehicles and urban buses into EVs), but stablishes this objective by 2040. Authors considered this further scenario concerning the low percentage of EV's sale in 2017 (0.69% of the market share) [37].

On the other hand, Germany also stands as another European country with an ambitious plan to achieve electric mobility. The German Government initiated the National Development Plan [48] in 2009, with the target of achieving one million of EVs in 2020. This goal was finally delayed to 2023. Moreover, the German Government has recently approved a financial package of 130.000 million of euros to boost the purchase of BEVs (PHEVs and HEVs are not included). This measure drives the development of BEVs, since these EVs are the only ones to produce zero emissions while riding, unlike HEVs or even PHEVs. This aim matches the general trend of the study presented in this paper, where the introduction of BEVs increases in the highest percentage.

3.2. Fleet input parameters

The application of the methodology to the case of Spain requires the definition of the fleet input parameters: consumption data, rate of electrical and hybrid contribution, annual travel distances and WtW emissivity. Moreover, this research distinguishes between the nature of the vehicles, taking cars, motorcycles and urban buses into consideration due to their ever-increasing electrification in urban environments [16,49,50].

Consumption data for the vehicles were obtained after an extensive scientific review: [51–54] for cars and motorcycles and [55–58] for urban buses. Regarding ICEVs, studies [59] and [60] revealed the significant difference between certified consumption values and the real ones due to high demanding conditions of current roads, showing an increasing divergence between them along the years. Specifically, these researches showed the evolution of both certified and real consumption data of a broad range of ICEVs along these last years, also affected by the enhancement of engine technologies. Finally, a linear extrapolation made on such data allowed authors to stablish an increase of 35% in the certified fuel economy of ICEVs for 2040. Regarding EVs, studies [52,54] also reflected the higher consumption of such vehicles under real conditions in comparison with laboratory conditions. However, the improvement of the technologies for EVs is not expected to happen in a wide range due to its innovative character [18,53], which led to a final increase of 45% in the certified consumption data for EVs. Table 5 reflects these consumption data, for both ICEVs and EVs, expressing fuel consumption in l/100 km and electrical consumption in kWh/100 km. Additionally, authors reflected these data in equivalent units (kWh_{eq}/100km) in Table 6 to enable the comparison of consumption values, according to [61].

Referring again to EVs, particularly to PHEVS, their double behaviour determines the necessity of defining the rate of electrical and hybrid contribution to the consumption of each vehicle. In this paper, we have assumed an homogenous hypothesis, where both the hybrid and electric operation have the same weight: 50% [7]. Table 5 [b] shows this parameter.

The average annual travelling distances for each type of vehicles (cars, motorcycles and urban buses) corresponded to official registered data. Hence, Spanish databases [62] and [44] were used to determine light EVs and urban buses' annual travel distances respectively. Lastly, Table 5 reflects these data.

Table 5. Fleet parameters. Note: l/100 km for fuel consumption and kWh/100 for electrical consumption.

	Distance (km/year)	Consumption						
		ICEV gasoline (l/100 km)	ICEV diesel (l/100km)	BEV (kWh/100 km)	HEV gasoline (l/100km)	HEV diesel (l/100km)	PHEV[b] (kWh/100 km)	PHEV[b] (l/100km)
Cars	12500	9	5.7	20	5.1	-[a]	20.0	5.1
Motorcycles	6300	4.2	-[a]	9.1	-[a]	-[a]	-[a]	-[a]
Urban Buses	143000	-[a]	37.1	160	-[a]	27.5	160	27.5

[a]: not considered due to its irrelevant presence [37,43].

[b]: assuming 50% for both the hybrid and electric operation [7].

Table 6. Fleet parameters. Note: kWh_{eq}/100 km for consumption data.

	Distance (km/year)	Consumption (kWh_{eq}/100 km)						
		ICEV gasoline	ICEV diesel	BEV	HEV gasoline	HEV diesel	PHEV[b] (electric)	PHEV[b] (fuel)
Cars	12500	82.3	56.8	20	46.6	-[a]	20.0	46.6
Motorcycles	6300	38.4	-[a]	9.1	-[a]	-[a]	-[a]	-[a]
Urban Buses	143000	-[a]	370	160	-[a]	274.2	160	274.2

[a], [b]: equal to Table 5.

Emissions for vehicles dependent on fossil fuels (ICEVs, HEVs and PHEVs partly) just depend on the kind of fuel used: gasoline or diesel. Research [10] made a thoughtful study of JEC's Well-to-Wheel CO_2 emissions data [63] to determine such parameters. JEC arises as one of the most complete and updated source, since it compiles European data and researches from different European entities: EUCAR (European Council for Automotive R&D), JRC (Joint Research Center of European Comission) and CONCAWE (CONservation of Clean Air and Water in Europe). Hence, [10] establishes that WtW emissivity for gasoline is 2778.2 g CO_2/L (WtT: 2314.4 g CO_2/L and TtW: 463.8 g CO_2/L) and for diesel it rises until 3241.3 g CO_2/L (WtT: 2676.9 g CO_2/L and TtW: 564.4 g CO_2/L). Table 7 finally summarizes WtW emissivity for each kind of vehicle dependent on fuels.

Table 7. WtW emissivity for vehicles dependent on fossil fuels (g CO_2/L).

	ICEV gasoline	ICEV diesel	HEV gasoline	HEV diesel	PHEV[b]
Cars	2778.2	3241.3	2778.2	-[a]	2778.2
Motorcycles	2778.2	-[a]	-[a]	-[a]	-[a]
Urban Buses	-[a]	3241.3	-[a]	3241.3	3241.3

[a]: not considered due to its irrelevant presence [37,43].

[b]: partly dependent on fossil fuels.

Conversely, WtW emissivity for vehicles dependent on the power system (BEVs and PHEVs partly) vary with the structure of the electricity generation system. Hence, section 3.3 describes different configurations for the system depending on the degree of renewable sources introduction.

3.3. Levels of renewable sources introduction in the electricity mix

Unlike vehicles dependent on fossil fuels, the configuration of the power system directly affects emissions for vehicles dependent on electricity: BEVs and PHEVs partly. In this research, we propose five different levels of renewable sources introduction (LRSI) in the Spanish power system to achieve a net decrease in CO_2 emissions by the introduction of EVs. Hence, the configuration of the system moves from the current one to a total renewable configuration. This evolution answers to the forecasted composition of the power system considering the environmental policies proposed by the Spanish Government [35]. This plan aims to achieve a 74% renewable sources introduction in the electricity generation mix by 2030 and a 100% renewable one by 2050. Moreover, the decision making process for each LRSI lies not only in the just mentioned draft, but also in the historical evolution of electricity generation and primary sources contributions to the Spanish electricity system [32], represented by Figure 6 and Figure 7 respectively.

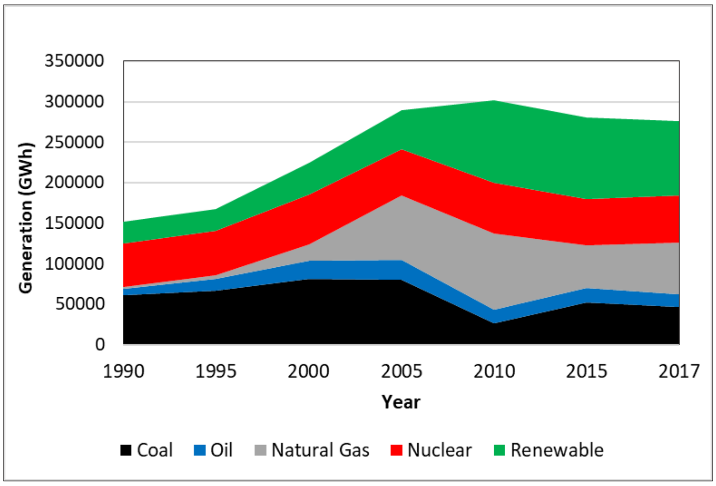


Figure 6. Evolution of electricity generation in Spain.

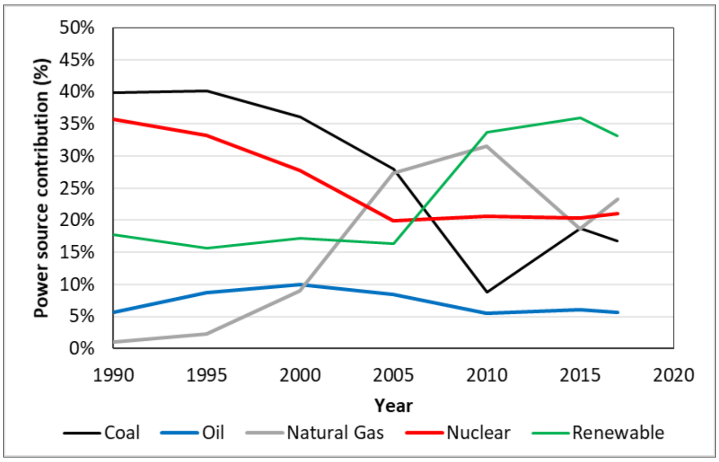


Figure 7. Evolution of primary sources contribution to the Spanish electrical mix.

The first level of renewable sources introduction (LRSI (1)) that we studied corresponds to the current and real one for Spain, with a 27.1% of renewable sources contribution.

LRSI (2) includes an electricity mix derived from the first LRSI where coal resource has null influence, being its contribution supported by the rest of the power sources in a balanced way, except for nuclear. Therefore, renewable sources have a presence of 38.8%. This LRSI (2) reflects the decreasing trend of coal contribution (Figure 7), mainly caused by the expected progressive close of thermal power plants. The process matches European Environmental Requirements 2010/75/UE [64] together with the higher CO_2 right of emission price [39] and gradual decarbonization of Spanish electricity generation system [34,35]. Moreover, the exclusion of nuclear power plants in redistribution of coal's influence among other sources is in line with no increasing nuclear power plants generation, also reflected in the static growing of nuclear contribution to the mix (Figure 7). Besides, Ecological Transition Spanish Ministry and main electric companies reached an agreement of gradually closing all nuclear power plants in the country [40].

Hence, LRSI (3) reflects this situation with an electricity mix derived from the second LRSI, where also nuclear generation is removed by the year 2028. Its contribution would be covered by renewable resources, which would follow their increasing trend in the Spanish primary sources contributions (Figure 7). This growth answers to the long-term objective of achieving a complete renewable electricity generation mix in a stepped way and also to the first proposed percentage of renewable sources introduction: 74%.

In line with this trend, LRSI (4) derives from the third LRSI and eliminates oil contribution to the electricity mix, being renewable sources responsible for covering its contribution.

Finally, LRSI (5) arises with a 100% renewable sources contribution, achieving a total descarbonizated electricity generation mix [34,35].

Table 8 reflects all the Spanish environmental policies hereby presented.

Table 8. Spanish environmental policies for the ecological transition.

Gradual introduction of renewable sources in the electricity mix	
Spanish climate change draft law [35] *2030: 74% of renewable contribution to the mix* *2050: 100% renewable contribution to the mix.*	
Gradual close of thermal power plants	
European Environmental Requirements 2010/75/UE [64]	European Emissions Trading Scheme [65]
Restrictive limits for the industrial emissions of thermal power plants. Adaptation before 2020.	*Restrictive CO_2 right of emission prices.*
Gradual close of nuclear power plants	
Agreement between Ecological Transition Spanish Ministry and main electric companies [40] *Progressive close until 2040.*	

Table 9 summarizes the contribution of each energy source to the electrical mix of Spain for every LRSI. Although the total renewable generation increases with each LRSI, the contribution of each individual renewable source to the total renewable production remains constant irrespective of the LSRI analysed. Such contribution matches current renewable sources data of [32], also represented in Figure 8.

Every LRSI studied in this paper results completely achievable due to the high presence of renewable resources in the country. Specifically, south-east Spanish regions present more than 1950 annual solar peak hours and vast desert zones to install solar PV systems [66], whereas more than 118.000 km^2 of the Spanish territory enjoy from suitable wind resources (80 m, speed > 6 m/s) and the total available potential biomass results in 18.715.358 ton/year [67]. Besides, Spain has currently 876 MW of hydropower plants [68].

Table 9. Contribution of each power source.

	Coal (%)	Nuclear (%)	Oil (%)	Natural Gas (%)	Renewable (%)
LRSI (1)	19.6	35.1	6.7	11.5	27.1
LRSI (2)	0	35.1	9.6	16.5	38.8
LRSI (3)	0	0	9.6	16.5	73.9
LRSI (4)	0	0	0	16.5	83.5
LRSI (5)	0	0	0	0	100

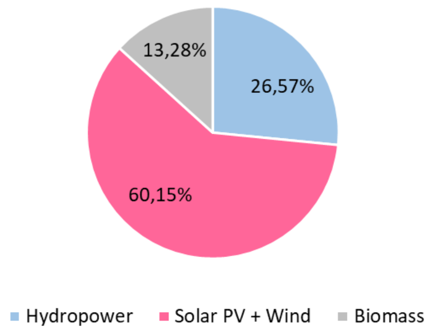


Figure 8. Contribution of each renewable source to the total renewable electricity generation.

CI of each power source will determine the emissivity of the power system due to each configuration (eq. (6)), which also will match WtT emissivity for BEV and PHEV partly. A wide study on CI considering an average value for each source is available on [10,69] and Table 10 summarizes the results . The different CI for each renewable source together with its weighted contribution to the total renewable generation (Figure 8) will finally establish the CI for the total renewable generation.

Table 10. CI of each power source.

						Renewables			
		Coal	Nuclear	Oil	Natural Gas	Solar PV	Wind	Biomass	Total
CI (g CO_2/kWh)	Min	660	3.1	530	380	13	3	1	10.29
	Max	1370	35	890	1000	190	41	130	161.52
	Average	942.33	12.23	773.8	533.17	65.05	17.63	51.02	58.69

Table 11. Emissivity for each LRSI (g CO_2/ kWh).

LRSI (1)	318.1
LRSI (2)	189.2
LRSI (3)	205.5
LRSI (4)	136.9
LRSI (5)	58.7

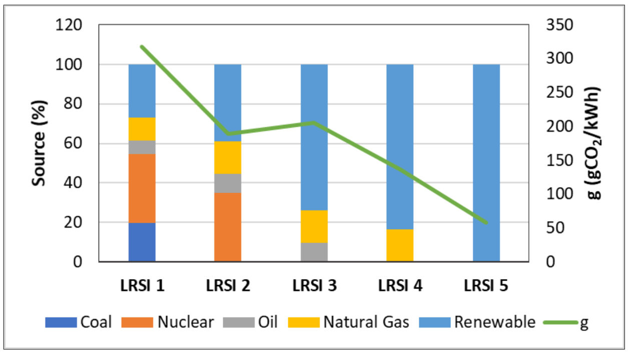


Figure 9. Contribution of each power source and emissivity for different LRSI.

4. Results and discussion

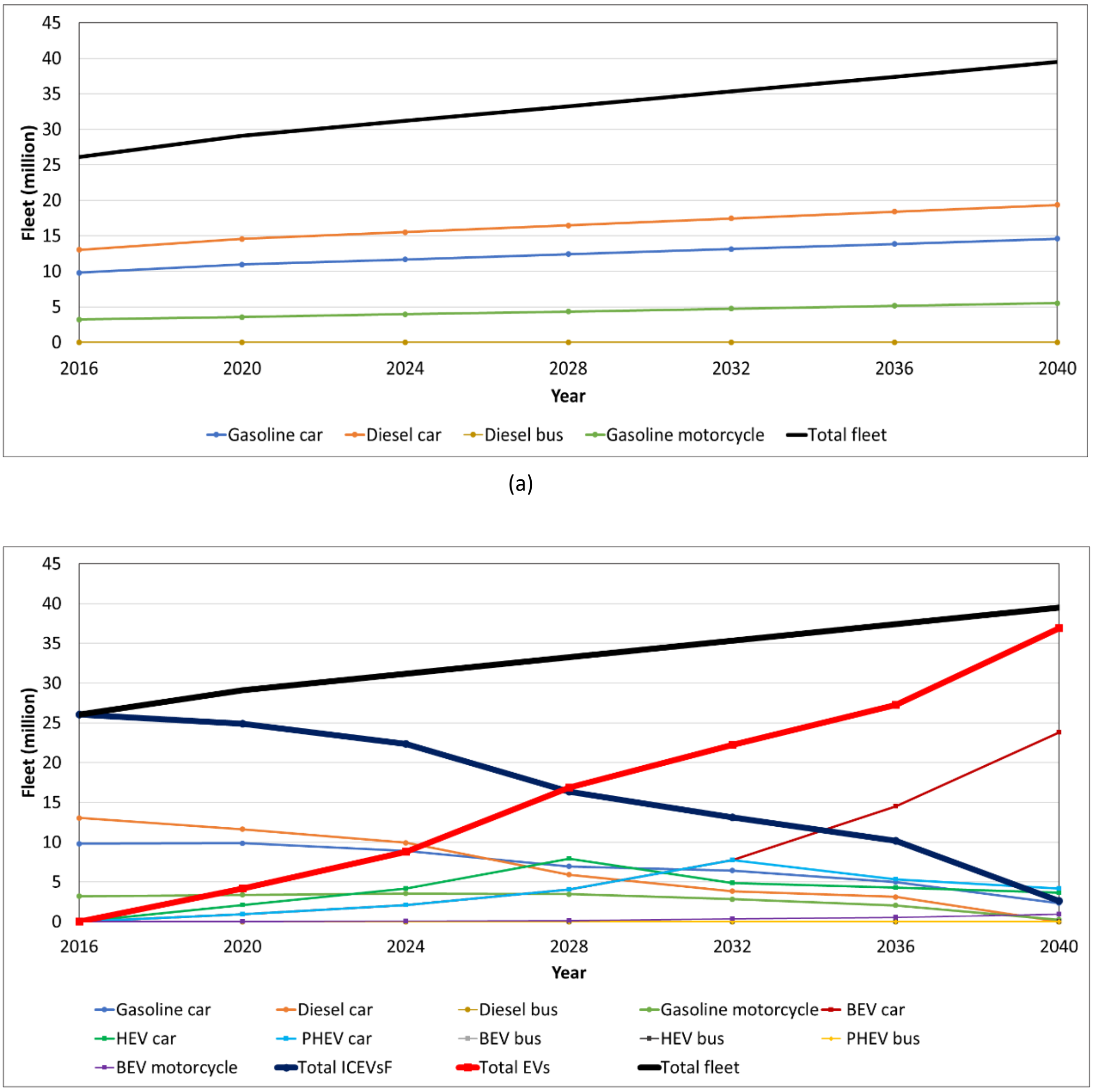
This section presents the results for the application of the submitted methodology to the Spanish case in the mid-term future. Two different scenarios were analyzed. On the one hand, the first one corresponds to a conservative situation where only a net emissions balance with the introduction of EVs is looked for [11,54] along the period of study. Although on-going environmental changes make this situation an almost difficult to happen in the future [34,35], it shapes an interesting point of comparison with the second scenario in regard of sustainability. On the other hand, the second scenario contemplates not only a net CO_2 emissions balance, but also a considerable reduction in emissions with the penetration of EVs. We propose a progressive degree of decrease in these reductions along the period of study for scenario 2 (Table 12).

Table 12. S_{ref} (%)

	Scenario 1	Scenario 2
2016	0	0
2020	0	10
2024	0	20
2028	0	30
2032	0	40
2036	0	55
2040	0	70

4.1. Fleet into consideration

Following the methodology proposed in this paper and the constrains presented for the case study, we can deduce the total number of vehicles conforming the urban fleet along the period of study. Figure 10.a. represents the evolution of the fleet that does not include EVs (case 1), whereas Figure 10.b. does for the fleet that considers EVs (case 2). In both cases, the total fleet presents the same linear growth where cars' influence is the highest one, meanwhile urban buses' influence becomes the lowest. Despite the linear growth of ICEVs for the first case, the second case indicates how this kind of vehicles decreases in almost a linear way when EVs are introduced, so that the latter would finally represent 93% of the total urban fleet by 2040.



(a)

(b)

Figure 10. Fleet's evolution. (a) Case 1. (b) Case 2.

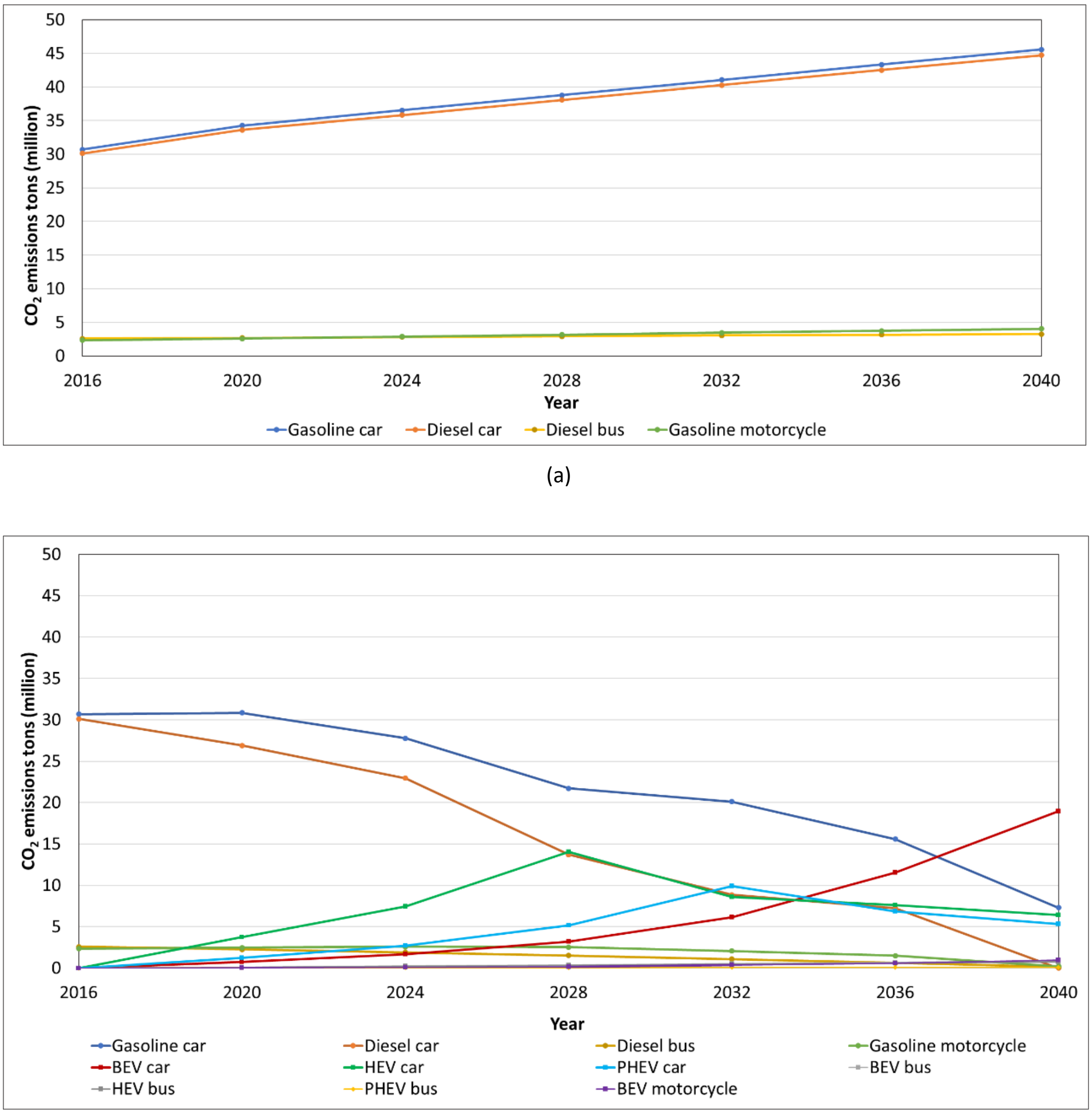
4.2. CO_2 emissions and sustainability verification

Scenario 1

The application of the iterative methodology explained in section 2 to the first scenario, where only a net CO_2 emissions balance with the introduction of EVs was looked for, indicates that the current emissivity of the system (LRSI (1)) matches this condition for the entire interval. Hence, the electricity emissivity could remain constant along the period of study.

Regarding total CO_2 emissions, Figure 11 illustrates the contribution of each type of vehicle to the emissions generated by the urban transport along the period of study. For the first case where no

EVs are considered (Figure 11.a), both diesel and gasoline cars would clearly generate the highest quantities of carbon dioxide emissions in a similar proportion. For the second case, which considers the penetration of EVs in the urban transportation system (Figure 11.b) again cars would have the highest contribution to the CO_2 emissions, but in this case, the different nature of these vehicles should be analyzed. ICEVs cars would generate the largest quantities of CO_2 emissions during almost the whole period, although with a decreasing trend due to their also decreasing rate of growth. Meanwhile, BEVs cars would increase their contribution to the emissions following their exponential rate of penetration, overtaking diesel cars' emissions by 2034 and gasoline cars' by 2038. PHEVs and HEVs would also have a considerable influence on emissions during the middle term of the period, following therefore their trend of penetration. Results also reflect the great influence of cars on emissions, being its contribution 92% of the total CO_2 emissions for urban transport.



(a)

(b)

Figure 11. CO_2 emissions. Scenario 1. (a) Case 1. (b) Case 2.

Taking up the inherent condition to this first scenario about just searching for a net emissions balance in case 2, results from Figure 12 reveal that the current Spanish power system (LRSI (1)) ensures this condition even for an important introduction of EVs. The allowable maximum value of the electricity system emissivity (g_{lim}), decreases from 1493 to 1121 g CO_2/kWh and remains higher than the real emissivity of the current system (318 g CO_2/kWh) along the entire period. The restriction $g_{lim}(t) > g(t)$ is verified along the interval, so that no increases in LRSI become necessary. Hence, the introduction of EVs in such scenario leads to a progressive reduction in urban transport CO_2 emissions (Figure 13). By 2040, carbon dioxide emissions savings acquire their maximum value for this first case: 56 million tons, which represent a sustainability factor of 58%.

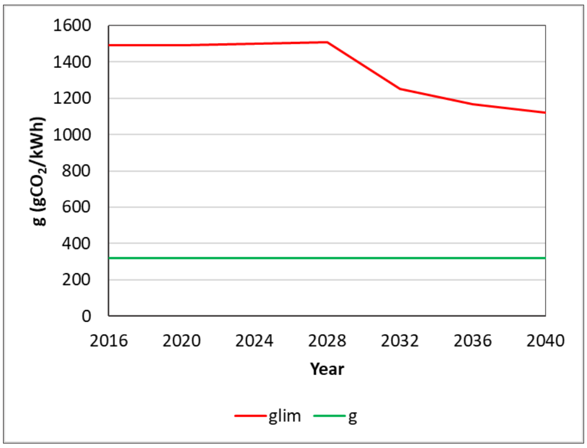


Figure 12. Emissivity of the electricity system. Scenario 1.

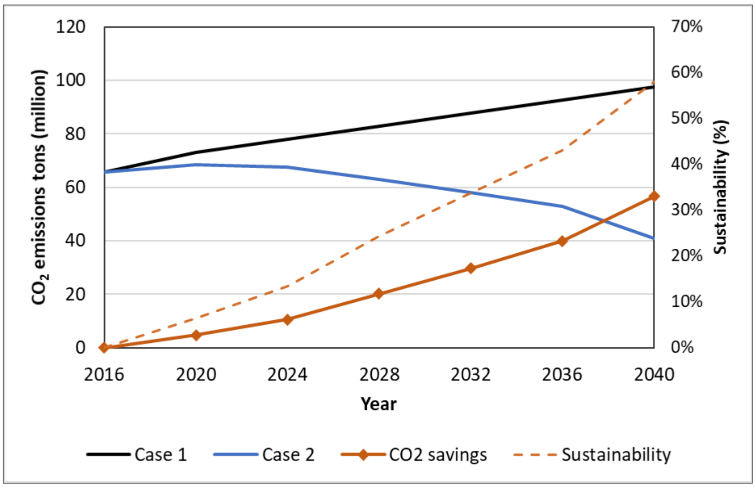
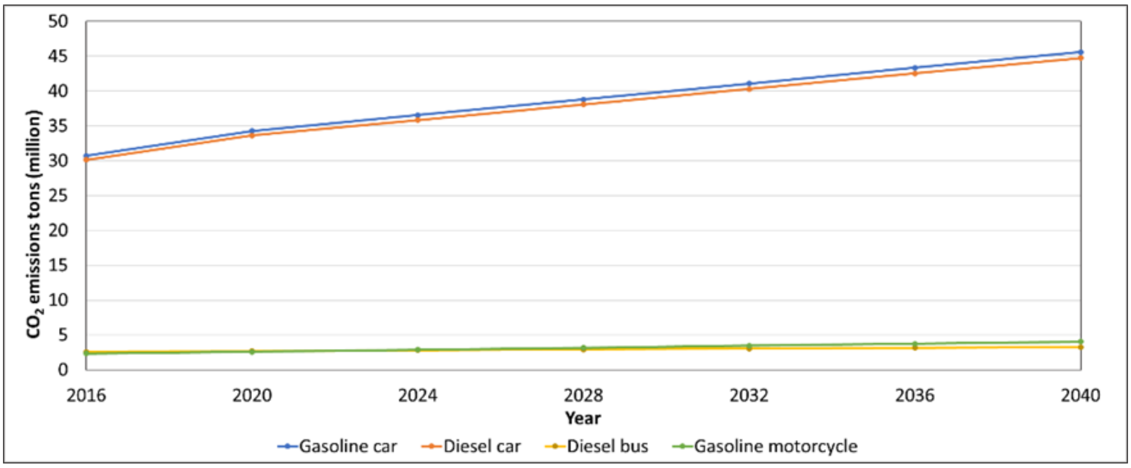


Figure 13. CO_2 savings and sustainability. Scenario 1.

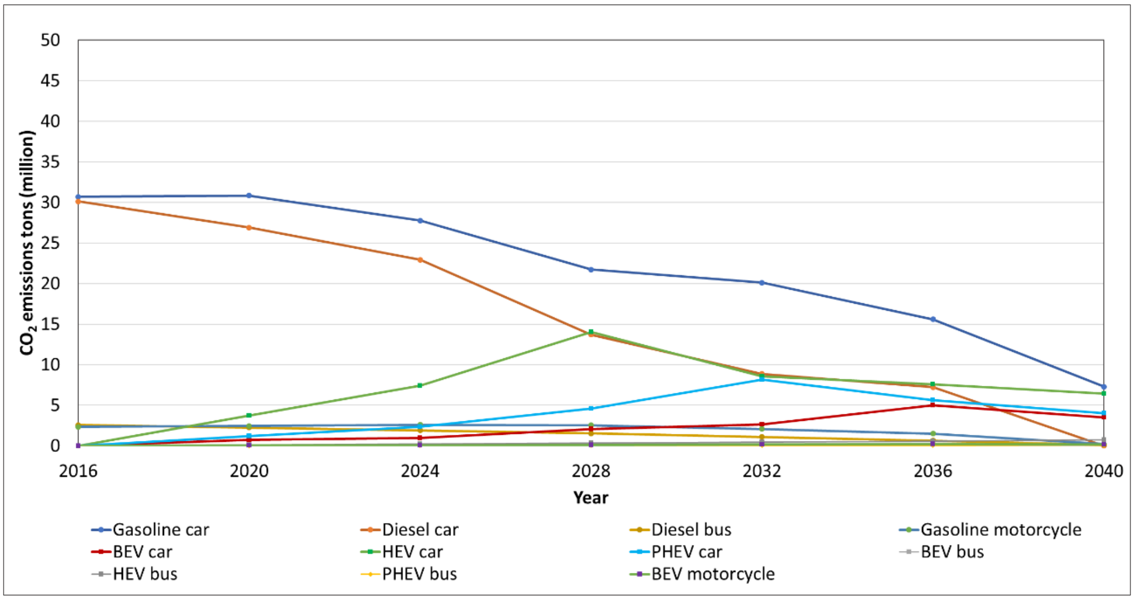
Scenario 2

Scenario 2 considers a progressive CO_2 emissions reduction with EVs penetration. Therefore, a stepped introduction of renewable sources into the electrical system is required to match sustainability restrictions (Table 12). Finally, LRSI (5) takes place by 2040, which corresponds to a 100% renewable power system.

Referring to the total carbon dioxide emissions results, Figure 14 reflects the quantity of CO_2 emissions generated by each type of vehicle. The results from the first case (Figure 14.a), where EVs are not considered, do not vary from scenario 1. However, outcomes from the second case, which contemplates EVs introduction into the urban fleet (Figure 14.b) remain constant for all the vehicles types except for the ones dependent on the electricity mix: BEVs and PHEVs. Besides, in this second scenario again cars contribute the most to CO_2 emissions generation. Both phenomena are reflected particularly during the last years of the period in study: although the emissions of ICEVs gasoline cars are the highest during this last period, the sustainable enhance of the power system decreases the generation of CO_2 emissions for BEVs cars in 82% compared to scenario 1. The same happens to PHEVs cars, although in a softer way due to its partial dependence on the electrical system, so that this reduction becomes 26%.



(a)



(b)

Figure 14. CO_2 emissions. Scenario 2. (a) Case 1. (b) Case 2.

The current electrical system, with an emissivity of 318 gCO_2/kWh, is already sustainable enough to hold the introduction of EVs in the urban fleet, like results from scenario 1 revealed (Figure 12). However, the second scenario of this research studies concurrently a stepped introduction of renewable sources in the power system to match some reference degrees in emissions reduction (Table 12). Hence, the emissivity of the electricity system would become lower with every LRSI introduction, like Figure 15 reflects. Finally, LRSI (5) takes place by 2040, which corresponds to a 100% renewable power system. With this progressive enhance of the power system, emissions generated by the urban transport would experience a considerable reduction with the penetration of EVs (Figure 16). The highest decrease takes place in the last year of study, 2040, where BEVs experience the largest introduction together with the most sustainable LRSI: 100% of renewable sources. By this year, the savings in carbon dioxide emissions acquiere the value of 74 million tons, which match a sustainability factor of 77%.

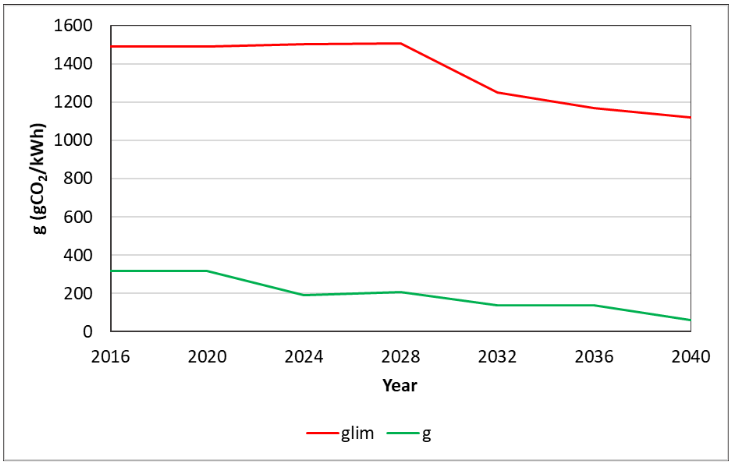


Figure 15. Emissivity of the electricity system. Scenario 2.

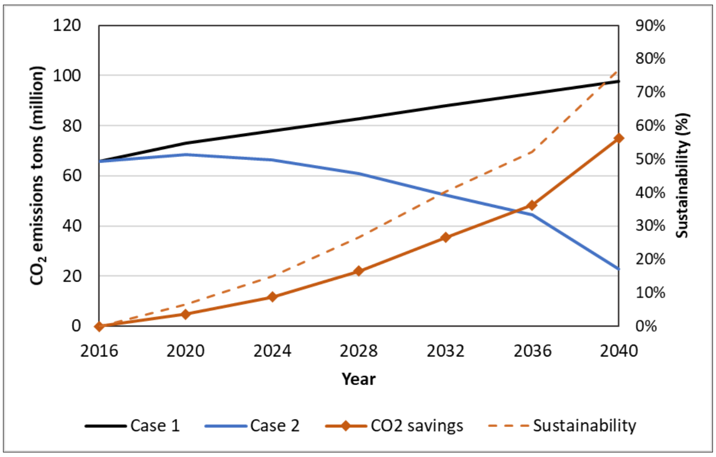


Figure 16. CO_2 savings and sustainability. Scenario 2.

Figure 17 and Figure 18 finally summarize the improvements about moving towards a 100% renewable electricity mix together with the introduction of EVs in the rates of penetrations assumed in these simulations, where by 2040, 93% of EVs are expected to comprise the urban fleet. The emissivity of the electricity system would progressively reduce from 318 gCO_2/kWh to 58.7 gCO_2/kWh

in the second scenario, which represents a decrease of 82% compared with the constant value of scenario 1 (Figure 17). Besides, the penetration of EVs proposed in the second scenario leads to higher levels of CO_2 emissions reduction compared with scenario 1. Particularly, the highest decrease takes place in 2040, which corresponds to a 45% and 18 millions tons of carbon dioxide emissions reduction from scenario 1. Moreover, the sustainability factor also enhances in a 33% in scenario 2 for that year (Figure 18).

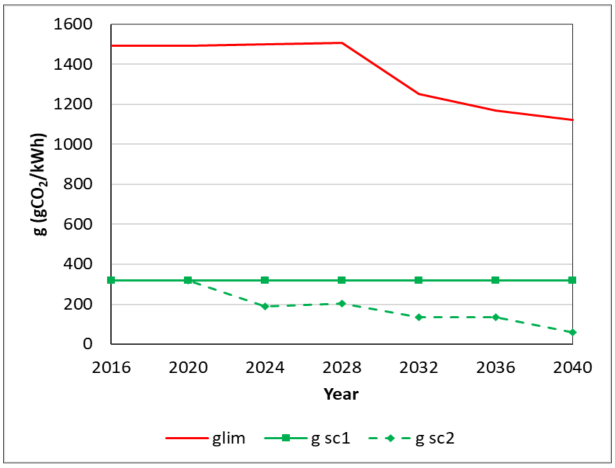


Figure 17. Emissivity of the electricity system. Scenarios 1 and 2.

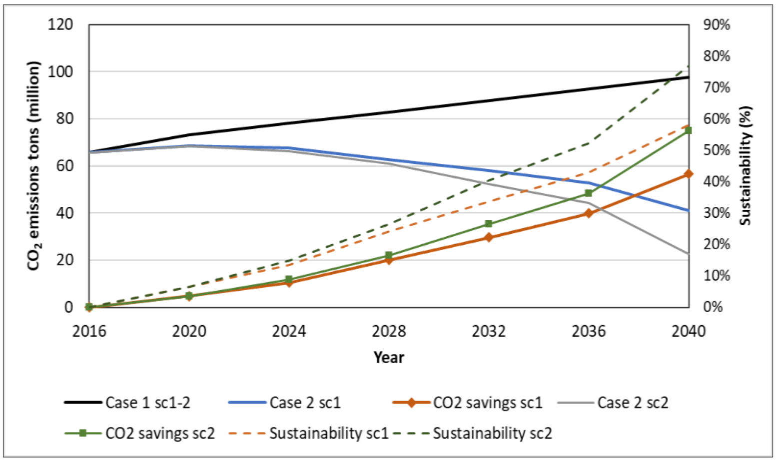


Figure 18. CO_2 savings and sustainability. Scenarios 1 and 2.

4.3. Implications on the reshaping of the electricity load curve and different kinds of charging

The massive introduction of EVs in a society could lead to several problems in the power grid, which have been analysed in various studies. For instance, [70] demonstrates that a relevant penetration of EVs in the distribution system provokes voltage drops and voltage deviations, which reached 10.3% in the examined case study. Moreover, [71] states that charging EVs increases the distribution load and consequently the power losses. Besides, such process also increases daily peak load. Hence, [72] illustrates how the EVs' demand in New Zealand would increase each year, with the consumption concentrated in peak hours. These peak loads are expected to rise until reaching a critical point in 2040, where the highest peak demand would exceed the installed generation capacity of New Zealand in 2018. Considering these issues, several researches have proposed strategies to minimize the impact of EVs in the grid. Their common purpose lies in reshaping the expected electricity demand curve, reducing peak loads and aiming to achieve an almost flat curve. For instance, [73] proposes a methodology to recharge EVs based on the use of temporal valleys and avoiding peak demand hours in the daily electricity demand to minimize the impact on the grid. This method provides a scheduled optimization of the distribution of recharge between three different recharge strategies: home, public buildings and electrical stations. [74] also proposes a timed charging strategy based on spot price for the European Nordic Region, whereas [75] focuses the reschedule of the recharging activities on dynamic pricing.

Thus, integration of EVs in the grid has been widely addressed. However, there is scarce research regarding the introduction of EVs for public transportation, such as electric buses (EBs). This integration results of utmost importance, since the use of only EVs passenger cars could result in high road congestion [76]. Charging systems result vital for the introduction of EVs in public transportation. Hence, four different types of recharging methods arise for EBs: fast plug-in charging, wireless charging, battery swapping stations and pantograph systems. Plug-in charging method corresponds to the traditional method used to recharge private EVs, with three levels of recharge: slow, medium and fast. Due to the high battery capacity of EBs (around 400 kWh), EBs use fast levels of recharge. The wireless charging method allows for battery recharging without connectors, so that EBs have the opportunity to recharge fast and frequently while they are on the roads [77]. Battery Swapping Stations include stations where users can change their discharged battery for a charged one, so that the recharge becomes faster [78]. Finally, the Pantograph System allows EBs to quickly be recharged at bus stops through an automatic connecting system [79].

Some studies have developed load predictions for EBs depending on the charging method. For instance, study [80] proposes the forecasting for Battery Swapping Stations based on stochastic modelling, with statistical data of travel patterns. This research also uses neural networks, uniform distributions and Gaussian models to model the hourly number of EBs, starting charging time, travel distance and charging duration. Another study [81] used a real-time simulation to model EBs in transit networks, considering the transit constraints of Belleville, Ontario and Canada. Besides, [82] studied a short-term prediction for EBs charging stations using a hybrid model, which combined a least squares support vector machine, fuzzy clustering and wolf pack algorithm. Hence, we find in the literature strong models to deal with the different recharging methods for EBs and their load predictions. These kinds of charging and their different load curves could have an impact on the CO_2 emissions of EBs, depending on the period of the day.

5. Conclusions

This paper introduces a methodology that verifies the sustainable introduction of EVs in terms of CO_2 emissions. By means of the “Well-to-Wheel” (WtW) tool, it makes a comparison between emissions generated by two fleets: one completely formed by ICEVs and another one that contemplates the introduction of EVs: BEVs, HEVs and PHEVs. Main contributions of this methodology are the following.

- Firstly, the method determines the sustainability of the power system in question to ensure at least a net emissions balance while introducing the fleet of EVs.
- Once this first step is verified, the methodology is able to establish a particular level of emissions reduction through a sustainability factor.
- Lastly, this research proposes a stepped introduction of renewable sources in the power system to achieve last mentioned goals. Hence, different levels of renewable sources introduction (LRSI) take place.

The methodology has been applied to the case study of Spain for the medium-term future, until the year 2040. This country is currently experimenting an ecological transition, where two environmental policies stand out: a progressive electrification of the urban transport sector and a stepped introduction of renewable sources in the electricity mix until 2050. We applied therefore the proposed methodology to the Spanish urban transport. The study proposes five different electricity generation systems, moving from the current electrical system to a total renewable one. Finally, two scenarios for the application of the methodology to the Spanish case were studied: one in which only a net emissions balance is looked for and another one in which also a particular sustainability degree in terms of emissions reductions is proposed, both regarding the introduction of EVs in the urban fleet.

Results for scenario 1 indicate the following:

- The emissivity of the system, 318 g CO_2/kWh, remains lower than the limit one, which decreases from 1493 to 1121 g CO_2/kWh along the period in study.
- Although no reference degree in emissions reduction was proposed in this scenario, a final net emissions decrease would take place. The highest value is forecasted by 2040 and corresponds to 56 CO_2 million tons and a sustainability factor of 58%.

Despite the suitability of the current system, results for scenario 2 reveal the following:

- Emissivity of the system decreases for each LRSI, so that the lowest value of 59 g CO_2/kWh in 2040 matches a reduction of 82% compared to scenario 1.
- This improvement would directly affect EVs dependent on the power system: BEVs and PHEVs. For instance, BEVs cars’ contribution to CO_2 in 2040 decreases by 82% compared to scenario 1, meanwhile PHEVs cars’ does by a 26% since they only depend partly on the electrical system.
- CO_2 savings and sustainability factor in this last scenario acquire the value of 74 million tons and 77% respectively.

Finally, this study has verified that the penetration of EVs in the Spanish society arises as a completely environmentally friendly solution in terms of CO_2 savings, more effective as the renewable sources acquire more influence in the electrical mix and with the highest penetration of BEVs among EVs. Further studies will focus on the possible electrification of interurban transport, together with the possibility of replacing trucks transport by electric trains and their environmental impact.

6. Acknowledgment

This work was supported in part by the regional public administration of Valencia under the grant ACIF/2018/106.

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