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Dynamic fleet-based life-cycle greenhouse gas assessment of the introduction of electric vehicles in the Portuguese light-duty fleet

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Abstract

Purpose Reducing greenhouse gas (GHG) emissions from the transportation sector is the goal of several current policies and battery electric vehicles (BEVs) are seen as one option to achieve this goal. However, the introduction of BEVs in the fleet is gradual and their benefits will depend on how they compare with increasingly more energy-efficient internal combustion engine vehicles (ICEVs). The aim of this article is to assess whether displacing ICEVs by BEVs in the Portuguese light-duty fleet is environmentally beneficial (focusing on GHG emissions), taking into account the dynamic behavior of the fleet.

Methods A dynamic fleet-based life-cycle assessment (LCA) of the Portuguese light-duty fleet was performed, addressing life-cycle (LC) GHG emissions through 2030 across different scenarios. A model was developed, integrating: (i) a vehicle stock sub-model of the Portuguese light-duty fleet; and (ii) dynamic LC sub-models of three vehicle technologies (gasoline ICEV, diesel ICEV and BEV). Two metrics were analyzed: (i) *Total fleet LC GHG emissions* (in Mton CO₂ eq); and (ii) *Fleet*

LC GHG emissions per kilometer (in g CO₂ eq/km). A sensitivity analysis was performed to assess the influence of different parameters in the results and ranking of scenarios.

Results and discussion The model baseline projected a reduction of 30–39 % in the 2010–2030 fleet LC GHG emissions depending on the BEV fleet penetration rate and ICEV fuel consumption improvements. However, for BEV introduction in the fleet to be beneficial compared to an increasingly more efficient ICEV fleet, a high BEV market share and electricity emission factor similar or lower to the current mix (485 g CO₂ eq/kWh) need to be realized; these conclusions hold for the different conditions analyzed. Results were also sensitive to parameters that affect the fleet composition, such as those that change the vehicle stock, the scrappage rate, and the activity level of the fleet (11–19 % variation in GHG emissions in 2030), which are seldom assessed in the LCA of vehicles. The influence of these parameters also varies over time, becoming more important as time passes. These effects can only be captured by assessing *Total fleet GHG emissions* over time as opposed to the *GHG emissions per kilometer* metric.

Conclusions These results emphasize the importance of taking into account the dynamic behavior of the fleet, technology improvements over time, and changes in vehicle operation and background processes during the vehicle service life when assessing the potential benefits of displacing ICEVs by BEVs.

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Keywords Battery electric vehicles · Fleet model · Greenhouse gas emissions · Internal combustion engine vehicles · Life-cycle assessment

1 Introduction

The transportation sector is increasingly energy- and carbon-intensive, contributing to about 32 % of the final energy

consumption and 25 % of the greenhouse gas (GHG) emissions in the European Union (EU28) (40 % and 36 % in Portugal, respectively) (European Commission 2014). Light-duty vehicles (LDVs) are of special concern, as they are responsible for about 15 % of EU's CO₂ emissions (European Commission 2012). The reduction of energy and GHG emissions in this sector is the goal of several current policies (e.g., EU Climate and Energy Package, US Corporate Average Fuel Economy standards). Several measures to reduce energy and environmental impacts from vehicles have been proposed, which include the reduction of fuel consumption of conventional technologies (e.g., through lightweighting, downsizing, and more efficient powertrains), displacement of fossil fuels by biofuels, and development of alternative technologies (e.g., electric vehicles, fuel cell vehicles) (Leduc et al. 2010; Althaus 2012).

Recent attention has been drawn to the potential of electric vehicles (EVs) to reduce energy and environmental impacts (Althaus 2012). A number of countries have set targets for EV sales and/or stock and adopted policy measures to promote EV adoption, such as financial incentives and infrastructure deployment (IEA 2013). In Portugal, a public charging infrastructure has been deployed. This strategy, combined with the incorporation of high levels of renewable energy in Portugal's electricity mix, aims to promote the adoption of EVs and the development of related industries. Nevertheless, the market share of EVs has been low and additional efforts are deemed to be required to boost their wide adoption (IEA 2013).

The potential of EVs to reduce environmental impacts is, however, highly dependent on the electricity sources used to charge the batteries and how they evolve over time. Additionally, EV benefits for GHG emission reduction will also depend on how EVs compare with increasingly more energy-efficient conventional vehicles, as the introduction of EVs in the fleet is gradual and its effects will not be seen in the short term (Frischknecht and Flury 2011). In order to assist policymaking, we need to understand the conditions under which the introduction of EVs in a vehicle fleet is environmentally beneficial.

The life-cycle assessment (LCA) literature has addressed the environmental impacts of EVs and compared them with those from different powertrains (e.g., McCleese and LaPuma 2002; Samaras and Meisterling 2008; Gao and Winfield 2012; Freire and Marques 2012; Hawkins et al. 2012; Marques et al. 2013; Hawkins et al. 2013; Messagie et al. 2014; Nordelöf et al. 2014; Noshadravan et al. 2015). These studies, although comprehensive in scope, often perform static analysis of single vehicles, aiming at assessing which options have the least environmental impact. In addition, they lack a future time perspective regarding advances in material processing, technology development and changes in electricity production (Nordelöf et al. 2014). However, when the goal is to

assess new or changing technologies, transient effects may be important and cannot be captured with such static, single-product analysis (Field et al. 2000). Moreover, if the goal is to explore solutions able to reduce overall environmental impacts (e.g., to meet medium/long-term policy targets), both scale and timing of adoption may influence the results (Hillman and Sandén 2008; Stasinopoulos et al. 2011).

Field et al. (2000) proposed an approach to capture these effects by combining LCA with a fleet model. The fleet-based LCA implies a different approach to the functional unit and system boundary, since it takes into account *the set of units in service*, and introduces the notion of time, by integrating in the life-cycle model the dynamics associated with substituting older products by new products in the fleet (or the product stock); therefore, it is able to capture the overall environmental effects of technology turnover. This approach has been mainly used to assess trade-offs between the use of steel and lighter materials in vehicle manufacturing (Field et al. 2000; Das 2000; 2005; Cáceres 2009; Stasinopoulos et al. 2011), to optimize the service life of products (Kim et al. 2004, 2006), and to assess the overall effects of product populations in the environment (Yokota et al. 2003).

The assessment of the LC environmental impacts of the introduction of vehicle technologies in existing fleets has been addressed by several authors through scenario analysis, with mainly two objectives: (i) to assess the overall reduction in the environmental impacts achieved by implementing different technology/fuel pathways (e.g., Bandivadekar et al. 2008; Baptista et al. 2012; Bodek and Heywood 2008; Kromer et al. 2010; Reichmuth et al. 2013); and (ii) to define pathways that allow achieving certain emission reduction targets (e.g., Cheah and Heywood 2011; Melaina and Webster 2011). Most studies were performed for the USA or regions within the USA (EPRI 2007; Bandivadekar et al. 2008; Plotkin and Singh 2009; Keoleian et al. 2011; Bastani et al. 2012a; b; c). A well-to-wheels perspective is the most common in the literature, and only few studies have taken a full life-cycle approach (Bandivadekar et al. 2008; Baptista et al. 2012). In general, the role of EVs in the reduction of the LC impacts of a vehicle fleet over time is only one of the many options assessed. Although some studies addressed different scenarios for the electricity mix (EPRI 2007; Kromer et al. 2010; Keoleian et al. 2011; Reichmuth et al. 2013) and included technology improvements over time, such as fuel economy improvements (Reichmuth et al. 2013) and vehicle lightweighting (Cheah and Heywood 2011), the integration of all these aspects in the analysis of the potential of EVs to reduce fleet LC impacts has not been fully explored.

This article contributes to the literature by investigating the fleet-wide environmental benefits of displacing internal combustion engine vehicles (ICEVs) by EVs across different scenarios. The analysis takes into account the increasing fuel

consumption reduction of ICEVs and the necessary reductions in the electricity mix impacts, within different fleet penetration scenarios, fleet and distance traveled growth rates, and changes in vehicle weight and composition and battery technologies over time. In particular, the aim of this article is to assess whether displacing ICEVs by EVs in the Portuguese light-duty fleet is environmentally beneficial, taking into account the dynamic behavior of the fleet. It also aims to identify the conditions under which this displacement is beneficial. The range of conditions was defined by a set of parameters: electrical grid intensity, EV fleet penetration, and reduction in ICEV fuel consumption.

The remainder of this article is structured as follows: Section 2 describes the dynamic fleet-based life-cycle model, including LC parameters, data sources, and the four scenarios assessed (*Business-as-usual*; *ICEV improve*, *BEV dominate*, and *Combined*); Section 3 presents the results for those scenarios and the contribution of LC stages, a sensitivity analysis to key model parameters, and a parametric analysis to examine the effects of EV fleet penetration rate, electricity GHG intensity, and ICEV increased efficiency in the results; and Section 4 lists the conclusions.

2 Methods

2.1 Model overview

A dynamic fleet-based life-cycle (LC) model was developed to assess fleet-wide LC greenhouse gas (GHG) emissions over time, from 1995 to 2030. The model integrates: (i) a vehicle stock sub-model of the Portuguese light-duty fleet; and (ii) dynamic life-cycle sub-models of three vehicle technologies (gasoline ICEV, diesel ICEV and BEV). Fleet-wide impacts in each year are a combination of the impacts of single vehicles and the number of vehicles in the fleet across all ages and technologies. Figure 1 shows an overview of the model, including the main inputs and outputs. More details about the parameters, data sources, and the equations that describe the vehicle stock sub-model and the dynamic life-cycle sub-models are presented in the [Electronic Supplementary Material](#).

The vehicle stock sub-model estimates the annual stock of vehicles by technology, the age of vehicles in the fleet, and the number of vehicles, by age, that leave the fleet every year, from 1995 up to 2030. The dynamic LC sub-models were developed for three vehicle technologies: diesel ICEV (~67 % market share in 2010), gasoline ICEV (~33 %), and battery EV

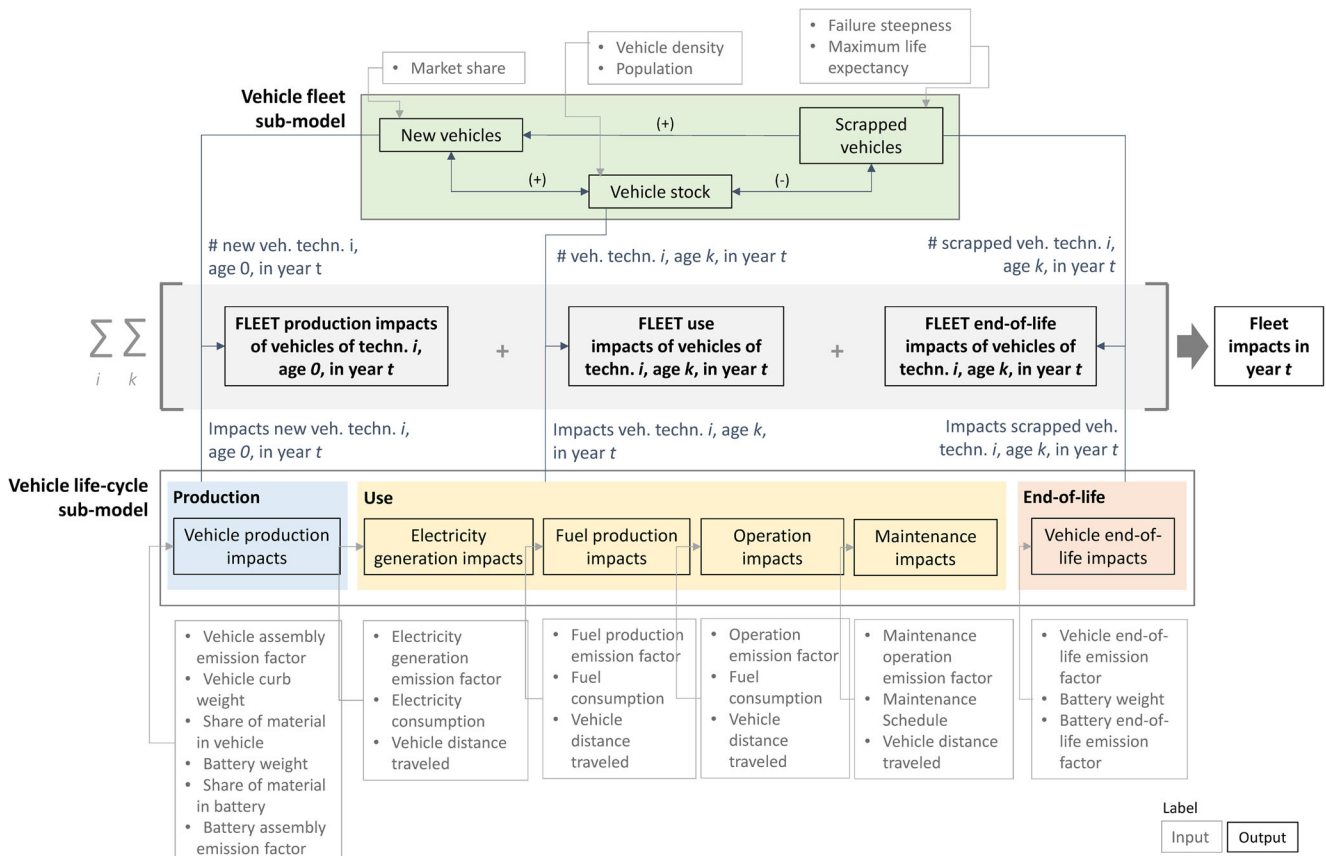


Fig. 1 Dynamic fleet-based life-cycle model overview. More details in the Electronic Supplementary Material: *Vehicle fleet sub-model* Fig. S-1; *Production* Fig. S-4; *Use* Fig. S-6; *End-of-life* Fig. S-13. *i* technology

(gasoline, diesel, BEV); *k* vehicle age; *t* calendar year. Positive causal link + the two variables change in the same direction; negative causal link – the two variables change in opposite directions

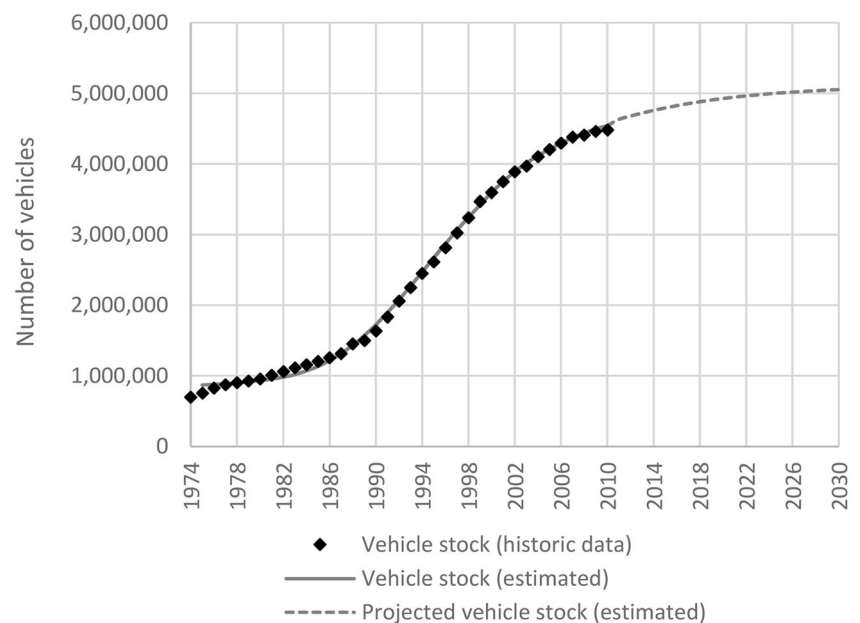
(BEV) (0.01 %). We divided the vehicle LC into three main stages: (i) production, (ii) use, and (iii) end-of-life, and modeled the emissions from these stages as functions of vehicle age and model year, which makes these LC models dynamic. The vehicle manufacturing stage includes raw material acquisition, transportation, and processing, as well as parts and components manufacturing and vehicle assembly. The use stage accounts for vehicle operation (tailpipe and tire abrasion emissions) and maintenance, as well as fuel, and electricity production and distribution. The end-of-life stage accounts for vehicle and battery dismantling, recycling, and disposal of components. We excluded road infrastructure, refueling stations for ICEVs, and charging points for EVs from the assessment, as their contribution to the impacts is deemed to be minor (Lucas et al. 2012).

We based our vehicle stock sub-model on the US passenger vehicle fleet model developed by Bandivadekar et al. (2008) and improved by Cheah (2010), and adapted it to the Portuguese context following the work of Moura (2009). We further developed the model to include different vehicle technologies, i.e., electrical engines (BEVs), in addition to internal combustion engines (gasoline and diesel), and parameterized it for our specific analysis.

2.2 Vehicle stock sub-model

The vehicle stock sub-model tracks the number of vehicles in use in the Portuguese light-duty fleet, by technology (t) and age (k), from 1995 to 2030 (t). We considered LDVs up to 25 years old and three technology types—gasoline ICEV (g), diesel ICEV (d), and BEV (e) (we note that BEVs only started to be sold in Portugal in 2010). Details about the model equations can be found in Fig. S. 1 in the Electronic Supplementary Material.

Fig. 2 Portuguese light-duty vehicle stock



The total fleet turnover is expressed as the number of vehicles in the fleet in the previous year subtracted by the number of scrapped vehicles and adding the number of new vehicles entering the stock. We calculated the total vehicle stock by multiplying the vehicle density (i.e., the number of vehicles per 1000 inhabitants) by the population in each year. The vehicle density for Portugal was estimated by calibrating a logistic curve based on vehicle data from ACAP (2011) and demographic data from PORDATA (2011), for the time period between 1974 and 2010 ($r^2=0.998$). Population projections were obtained from INE (2009). Figure 2 shows the estimated vehicle stock over time. The number of LDVs being driven in Portugal currently exceeds 4.5 million, 3 times more than in 1990. Vehicle density increased from about 163 to 422 vehicles/1000 inhabitants in the same period.

Vehicle scrappage was estimated by using a modified Weibull distribution, which characterizes the survival rate of vehicles in the fleet as a function of vehicle age. We used the calibration of the survival curve for Portuguese conditions done by Moura (2009) for model years 1995, 2000, and 2005. We assumed the same survival curve from 2005 onwards and a similar curve for all vehicle types. We started the simulation using the characterization of the Portuguese vehicle fleet composition (age and technology distribution) in 1995 used in Ceuster et al. (2007) and depicted in Table S-2 of the Electronic Supplementary Material. Total vehicle sales were derived from the accumulated vehicle stock. The number of new vehicles of each technology was calculated by multiplying the total sales by its market share. Over 2005 to 2010, about 220,000 to 235,000 new vehicles entered the fleet each year, while 115,000 to 195,000 older vehicles were retired annually.

2.3 Dynamic life-cycle sub-model

2.3.1 Vehicle production

Fleet environmental impacts of vehicle manufacturing in each year were determined by the sum of manufacturing impacts of all new vehicles entering the fleet. The environmental burdens of vehicle manufacturing include vehicle materials and assembly burdens. Vehicle and battery material burdens are proportional to vehicle curb weight and battery weight, which varies with model year. Because impacts from vehicle production are accounted for in the year the vehicles are produced, they are independent of vehicle service life. Section S-2.1 in the Electronic Supplementary Material details the calculation of vehicle production impacts, including vehicle and battery weight data.

Material composition of ICEVs was assumed to change over time according to Cheah (2010). The main changes are related to the substitution of cast iron and conventional steel by lightweight materials such as high-strength steel, aluminum, and plastics. Material composition of BEVs and batteries was assumed constant. Iron, steel, aluminum, and magnesium material production (i.e., extraction and processing) was assumed to become more energy-efficient and less GHG intensive over time (evolution according to Cheah 2010). Regarding other materials, we assumed energy use and GHG emissions to be constant over time. Energy intensity and GHG emissions from 1995–1999 were assumed equal to 2000.

2.3.2 Vehicle use

The use of the vehicle includes both vehicle and fuel life cycles. Use stage burdens are a function of vehicle distance traveled, fuel consumption, and emission factors. The use stage fleet impacts in each year result from the sum of use-related impacts from all vehicles in the fleet. These include impacts from fuel production and distribution, electricity generation and distribution, vehicle operation, and maintenance (see Section S-2.2 in the Electronic Supplementary Material for more details about the calculation of vehicle use impacts).

Environmental impacts of fuel production and distribution include resource extraction, initial conversion of petroleum, transport of petroleum, fuel production, and distribution of gasoline and diesel. GHG emissions from gasoline and diesel production were obtained from Jungbluth (2007) and assumed constant over time, primarily due to a lack of information on how these emissions would evolve. A sensitivity analysis to assess the effect of a change in the fuel supply chain performance over time on the overall fleet GHG emissions was performed.

Environmental impacts of electricity generation and distribution include extraction, processing and transport of fuels,

operation of power plants, construction and decommissioning of power plants, waste management, transmission and distribution (T&D) grid infrastructure, and T&D grid losses. GHG emissions from electricity generation and supply in Portugal were obtained from Garcia et al. (2014). The average of the emission factors for the last 10 years (2003–2012) was used as a constant value up to 2030, in order to account for the variability between years. Variations of this emission factor were assessed in the sensitivity analysis.

Environmental impacts of vehicle operation (combustion phase) include direct tailpipe and tire abrasion emissions. The operation emission factor is assumed constant and estimated based on the carbon content of the fuel as being fully oxidized into CO₂ (Moura 2009). Environmental burdens from maintenance are a function of the cumulative distance traveled. Maintenance operations are performed according to Table S-5 in the Electronic Supplementary Material. It was assumed that fuel and electricity consumption remain constant over the life of the vehicle, since there is little evidence that the effect of vehicle deterioration and defective maintenance on fuel consumption can be generalized to the vehicle population (Austin and Ross 2001). More details about vehicle fuel consumption assumptions can be found in Section S-2.2.2 in the Electronic Supplementary Material.

The distance traveled by a vehicle varies depending on a number of factors, such as vehicle age (due to deterioration, reduced reliability, and shifting of primary to secondary car usage (Kim 2003; Moura 2009)), technology (diesel vehicles tend to be driven more than gasoline vehicles), and utilization purpose. We based our annual vehicle distance traveled estimations on vehicle inspection data for Portugal for 2005 (Azevedo 2007; Azevedo and Cardoso 2009). We estimated different vehicle distance traveled profiles for gasoline and diesel ICEVs. For BEVs, we assumed the same profile as gasoline ICEVs; however, since BEVs are about 70 % more energy efficient than gasoline ICEVs, we assumed a higher distance traveled in order to account for the expected rebound effect, in line with Silva (2011). More details about vehicle distance traveled assumptions can be found in Section S-2.2.3 in the Electronic Supplementary Material.

2.3.3 Vehicle end-of-life

Fleet environmental impacts of vehicle end-of-life in each year were determined by the sum of end-of-life impacts of all scrapped vehicles leaving the fleet. The environmental burdens of vehicle end-of-life include the dismantling of the vehicle and the battery. The energy use of materials that are recycled and later used in a vehicle are taken into account in the burdens for each specific material. Section S-2.3 in the Electronic Supplementary Material details the calculation of vehicle end-of-life impacts.

2.4 Scenarios

Options for reducing LDV GHG emissions include adoption of alternative powertrains, such as BEVs, and technology improvements, such as vehicle lightweighting and efficiency improvements. We explore possible combinations of these options by constructing four scenarios: (i) *Business-as-usual (BAU)*, in which ICEVs continue to dominate the fleet (constant diesel/gasoline ICEV market share), but no new vehicle technology improvements occur; (ii) *ICEV improve*, characterized by improvements on fuel consumption of new ICEVs to meet EU targets and vehicle lightweighting; (iii) *BEV dominate*, in which the emphasis is on the aggressive introduction of BEVs in the fleet, reaching 100 % of vehicle sales in 2030, and no improvements in ICEVs take place; and (iv) *Combined*, which associates BEV aggressive penetration and ICEV improvements. Characterization of each scenario is shown in Table 1, in contrast with the 2010 fleet. It should be noted that, although all parameters are kept constant in 2010–2030 in the *BAU* scenario, the fleet size and composition do not remain constant due to the dynamic evolution of the fleet.

A rapid shift from gasoline to diesel ICEVs has recently occurred in Portugal. In 1995, only 10 % of all LDV sold were diesel-powered, compared with 68 % in 2010. Market share of BEVs was only 0.01 % in 2010. The *BAU* scenario assumes the same market share as 2010 and the *ICEV improve* scenario that 30 % of new vehicles are gasoline ICEVs and 70 % diesel ICEVs, following recent trends, as depicted in Fig. 3a. The *BEV dominate* and *Combined* scenarios represent rapid penetration of BEVs assuming that BEV market share reaches 100 % in 2030, following an S-shaped curve (Fig. 3b). In the *BAU* and *ICEV improve* scenarios, 42 % of the fleet in 2020 is gasoline ICEVs and 58 % is diesel ICEVs, and only in 2030 does the sales fraction match the fleet composition, as shown in Fig. 3c. The *BEV dominate* and *Combined* scenarios lead to a fleet similar to the ICEV scenarios in 2020 (60 % diesel ICEVs, 36 % gasoline ICEVs and 4 % BEVs), and

composed of 36 % diesel ICEVs, 16 % gasoline ICEVs and 48 % BEVs in 2030, as depicted in Fig. 3d.

2.5 Output metrics

We assessed fleet-wide impacts up to 2030 using two metrics: (i) *Total fleet life-cycle (LC) GHG emissions* (in Mton CO₂ eq); and (ii) *Fleet LC GHG emissions per kilometer* (in g CO₂ eq/km). The first metric addresses the societal concern of reducing global GHG emissions. The second metric addresses the viewpoint of the policies that aim at reducing GHG emissions from LDVs by targeting specific emissions (e.g., per kilometer) of new vehicles or fleets of new vehicles. Examples of these policies are the European Union (EU) legislation, which set binding emission targets for new vehicle fleets, and the Corporate Average Fuel Economy (CAFE) standards in the USA, which aims at improving the fuel economy of new vehicles sold in the USA, indirectly reducing their specific GHG emissions. GHG emissions were assessed using the IPCC 2007 method (IPCC 2007).

3 Results and discussion

3.1 Model baseline

Figure 4 shows the LC GHG emissions evolution for each scenario. Total LC GHG emissions of the fleet increased from 1995 to 2010 due to an increase in fleet size. Nevertheless, a reduction of impacts per kilometer occurred, resulting from the rapid increase in market share of diesel ICEVs as well as a reduction in the fuel consumption of new gasoline ICEVs. Total LC GHG emissions of the fleet are expected to continue to increase until 2017 in the *BAU* scenario, due to the combined effect of fleet size and vehicle distance traveled growth. As the fleet size and distance traveled stabilize, a 4 % reduction compared to 2010 is observed. This occurs because new vehicles entering the fleet are replacing older, higher-emitter

Table 1 Scenario description

Scenarios	Market share by powertrain (q)			Technology improvements		
	Gasoline ICEV	Diesel ICEV	BEV	Vehicle weight reduction rate per year (ν)	Fuel consumption reduction rate per year (ϕ)	BEV battery weight reduction rate per year (ω)
2010	33 %	67 %	0.01 %	–	–	–
2030						
Business-as-usual (BAU)	33 %	67 %	0 %	0 %	0 %	–
ICEV improve	30 %	70 %	0 %	0.8 %	2.5 %	–
BEV dominate	0 %	0 %	100 %	0.8 %	–	1.9 %
Combined	0 %	0 %	100 %	0.8 %	2.5 %	1.9 %

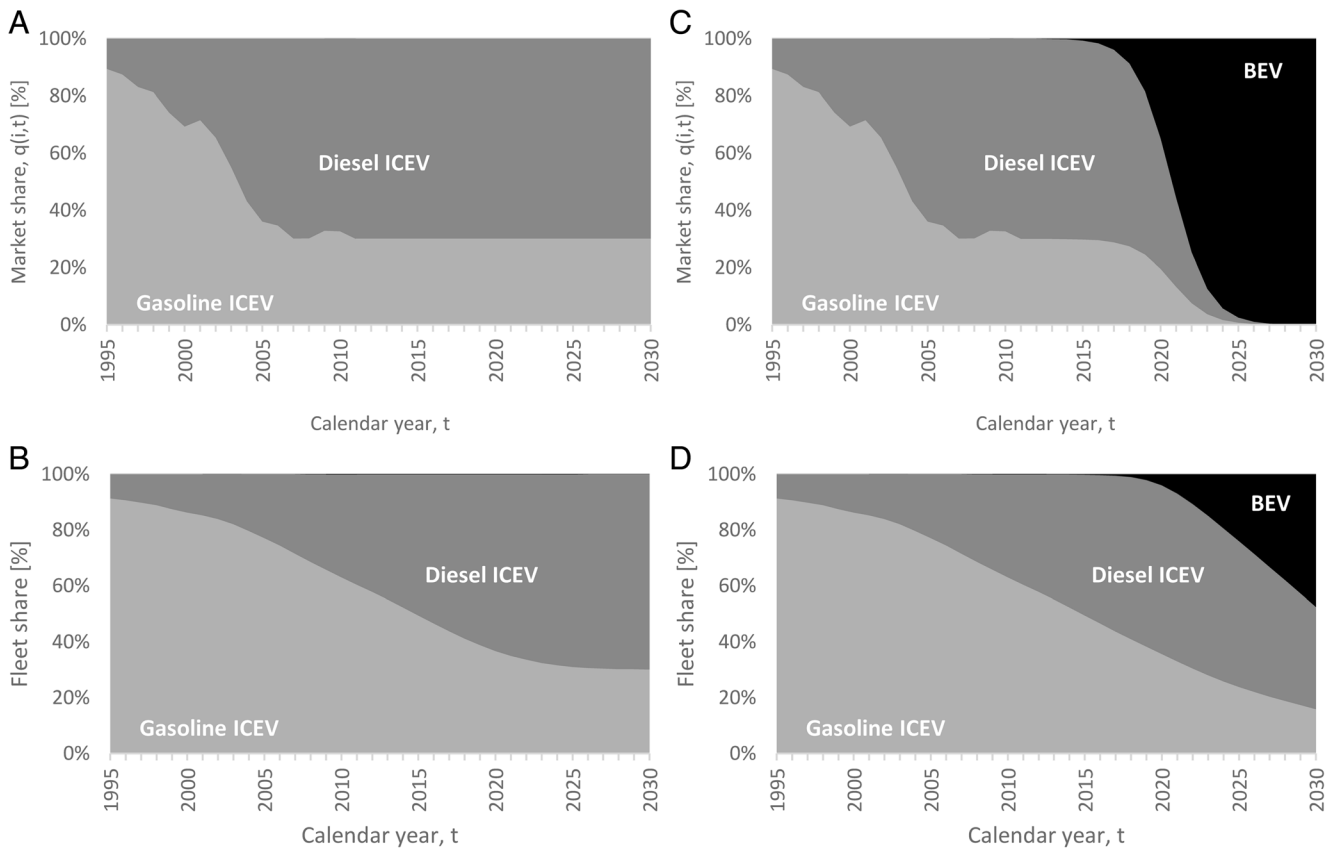


Fig. 3 Market share and fleet share of vehicle technologies in the Portuguese light-duty fleet for the *Business-as-usual/ICEV improve* (a and b, respectively) and *BEV dominate/Combined* (c and d, respectively) scenarios in 1995–2030. 1995–2010 data were retrieved from ACAP (2011)

vehicles. Even though the new vehicles are not improving over time, the overall fleet emissions are improved by the elimination of the older vehicles. Until 2025, reducing fuel consumption of new ICEVs (*ICEV improve*) has a larger effect on the LC GHG emissions than the introduction of BEVs in the fleet (*BEV dominate*), since it takes time for BEV share in the fleet to become significant. Nevertheless, a slightly higher reduction in 2010–2030 GHG emissions is obtained in this

scenario (34 %) than in the *ICEV improve* scenario (30 %). The *Combined* scenario leads to an extra 5 % reduction (39 %). LC GHG emissions per kilometer continue to decrease for all scenarios (except the *BAU*, in which it stabilizes around 2025). A steeper reduction occurs in the *Combined* scenario (40 % decrease), while the *ICEV improve* (37 %) reaches a slightly higher reduction in 2030 than the *BEV dominate* scenario (34 %).

Fig. 4 Total life-cycle (LC) GHG emissions of the fleet (left axis) and LC GHG emissions per kilometer (right axis) for the *Business-as-usual (BAU)*, *ICEV improve*, *BEV dominate*, and *Combined* scenarios from 1995 to 2030

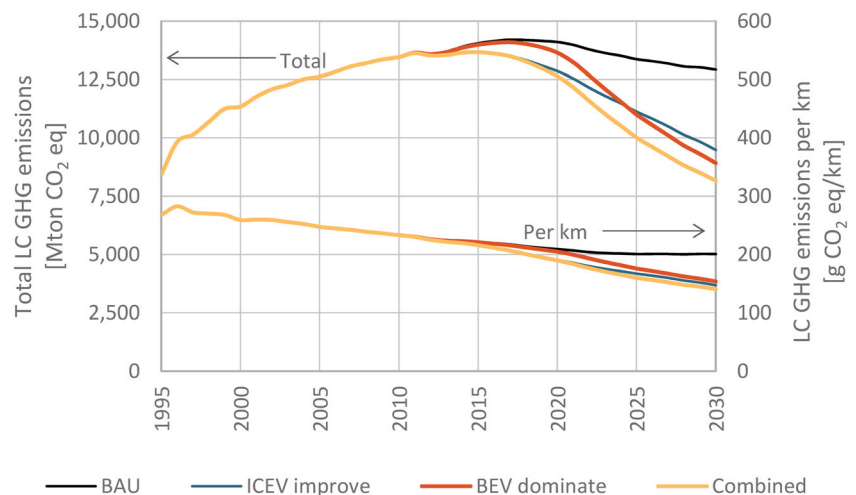
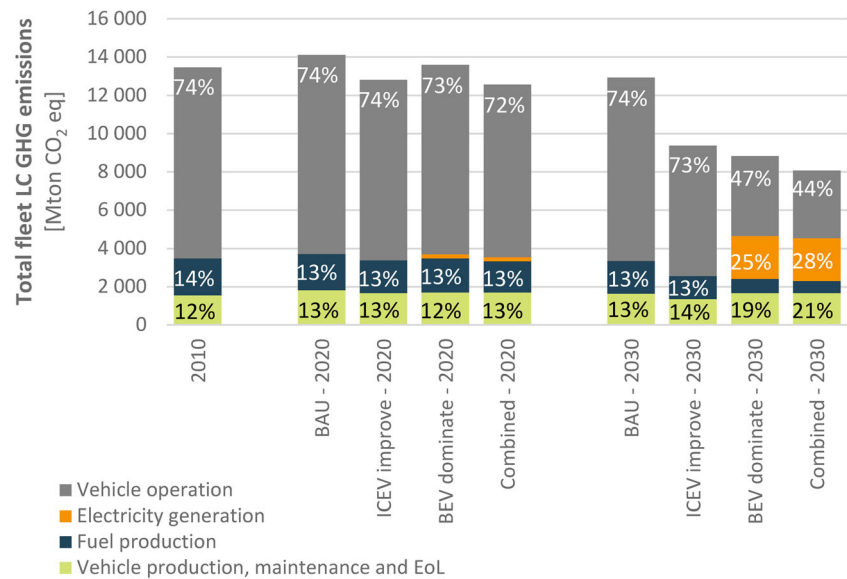


Fig. 5 Contribution of the life-cycle stages to the fleet LC GHG emissions in each scenario in 2010, 2020, and 2030



The shape of the curves and the ranking of scenarios obtained for *Total fleet GHG emissions* and *GHG emission per kilometer* analysis differ. While the *Total fleet GHG emissions* assessment shows that GHG emissions from the Portuguese LDV fleet have been increasing and only after 2015 will start to decrease, the *GHG emissions per kilometer* analysis shows a reduction tendency along time. This means that, although the emissions of an average kilometer traveled in the fleet have been decreasing, mainly because gasoline ICEVs have been replaced by diesel ICEVs, the absolute emissions from the fleet have increased, as a result of the increase in the number of vehicles and distance traveled. This effect cannot be captured by the *per kilometer* analysis. On the other hand, the ranking of scenarios in the *Total GHG emission* analysis is very dependent on the number of kilometers traveled by the fleet, which changes according to the scenario (a higher share of diesel ICEVs results in a higher total distance traveled). In the *BEV dominate* and *Combined* scenarios the total distance traveled by the fleet in 2030 is about 10 % lower than in the *BAU* and *ICEV improve* scenarios. This effect is discussed in the sensitivity analysis (Section 3.2).

3.1.1 Contribution analysis

Figure 5 shows the contribution of the life-cycle stages to the fleet LC GHG emissions in 2010, 2020, and 2030 for the four scenarios. The category *Vehicle production, maintenance, and EoL* includes materials production, vehicle assembly, maintenance, and end-of-life (EoL) impacts. In 2010–2020, the contribution of each stage varies little between scenarios (1–2 %) and the operation stage accounts for most of the fleet impacts (72–74 %). This trend continues in both *BAU* and *ICEV improve* scenarios in 2030. In the *BEV dominate* and *Combined* scenarios,

there is a shift of impacts from the fuel production to the electricity generation stage and, to a smaller extent, to the vehicle production, maintenance and EoL stages, in 2030. In absolute terms, vehicle operation impacts are reduced by 56–63 % compared to the *BAU* scenario, but indirect impacts (which include fuel production, electricity generation, and vehicle production, maintenance, and EoL) increase by 36–39 %.

3.2 Sensitivity analysis

We performed a sensitivity analysis to assess the influence of different model parameters on the *Total fleet LC GHG emissions* and *GHG emissions per kilometer* in each scenario. We used the one-factor-at-a-time (OFAT) method and varied the parameters listed in Table 2 between their lower and upper bounds. The rationale behind the choice of the lower and upper bounds for each parameter is presented in the Electronic Supplementary Material. Detailed results of the sensitivity analysis are presented in Figs. S-14 to S-17 (*Total fleet LC GHG emissions*) and S-18 to S-21 (*Fleet LC GHG emissions per kilometer*) in the Electronic Supplementary Material. Table 3 shows how the ranking between scenarios changes in the sensitivity analysis.

The sensitivity analysis for *Total fleet LC GHG emissions* in 2020 shows that the diesel ICEV indexed mileage ($x(d,k)$) and the vehicle density multiplier (θ) have the largest influence in the results in all scenarios (variations of 9–17 %, as shown in Fig. S-15 in the Electronic Supplementary Material). Nevertheless, varying these parameters does not change the ranking of the scenarios. On the other hand, although a change in the diesel ICEV fuel consumption reduction rate ($\varphi(d)$) leads to no more than 10 % variation in the fleet GHG emissions in 2020, if its value is close to its higher bound, the *BEV*

Table 2 Parameters for sensitivity analysis. *d*: diesel ICEV; *g*: gasoline ICEV; *e*: BEV; *k*: vehicle age (in years)

Parameter	Lower bound	Scenario baseline				Upper bound
		<i>Business-as-usual</i>	<i>ICEV improve</i>	<i>BEV dominate</i>	<i>Combined</i>	
Fuel consumption reduction rate (gasoline ICEV), $\varphi(g)$ [%/year]	0	0	2.5	0	2.5	4.0
Fuel consumption reduction rate (diesel ICEV), $\varphi(d)$ [%/year]	0	0	2.5	0	2.5	4.0
Electricity consumption reduction rate (BEV), $\varepsilon(e)$ [%/year]	0	1.25				2.5
Electricity generation emission factor, $e_c(t)$ [g CO ₂ eq/kWh]	20	485				1100
Vehicle curb weight reduction rate, ν [%/year]	0	0	0.8	0.8	0.8	1.75
Indexed mileage (gasoline ICEV), $x(g,k)$	$-0.4\ln(k)+1.42$	$-0.313\ln(k)+1.4173$				$-0.2\ln(k)+1.27$
Indexed mileage (diesel ICEV), $x(d,k)$	$-0.4\ln(k)+1.42$	$-0.33\ln(k)+1.3623$				$-0.2\ln(k)+1.27$
Indexed mileage (BEV), $x(e,k)$	$-0.4\ln(k)+1.42$	$-0.313\ln(k)+1.4173$				$-0.2\ln(k)+1.27$
Vehicle density multiplier, θ [%/year]	-1.5	1				3
Maximum life expectancy, $\mu(t)$ [years]	30	35				40
First-year vehicle distance traveled (BEV), $y(e,0,2010)$ [km]	10,500	13,929				17,500
Fuel production emission factor rate of change, ι [%/year]	-0.5	0				0.7

dominate scenario becomes better than the *ICEV improve* scenario. The other parameters do not significantly affect the total fleet GHG emissions in all scenarios (less than 8 % variation). Regarding 2030 results, although the diesel ICEV indexed

mileage ($x(d,k)$) and the vehicle density multiplier (θ) continue to have a high influence in the results (11-19 %), the electricity generation emission factor ($e_c(t)$) is the parameter with higher influence in the *BEV dominate* and *Combined*

Table 3 Ranking of scenarios according to the results of the sensitivity analysis (1—higher impact; 4—lower impact). Highlighted cells represent a change in the ranking of scenarios compared to the baseline.

Cell shading indicates the difference (Δ) in impacts between those cells, according to the legend. Parameters are defined in Table 2. All parameters were analyzed, but only those whose ranking changed are presented here

	LC GHG emissions per km								Total fleet LC GHG emissions							
	Upper bound				Lower bound				Upper bound				Lower bound			
	<i>Business-as-usual</i>	<i>ICEV improve</i>	<i>BEV dominate</i>	<i>Combined</i>	<i>Business-as-usual</i>	<i>ICEV improve</i>	<i>BEV dominate</i>	<i>Combined</i>	<i>Business-as-usual</i>	<i>ICEV improve</i>	<i>BEV dominate</i>	<i>Combined</i>	<i>Business-as-usual</i>	<i>ICEV improve</i>	<i>BEV dominate</i>	<i>Combined</i>
2015																
Baseline	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$\varphi(g)$	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$\varphi(d)$	1	3	2	4	1	4	2	3	1	3	2	4	1	3	2	4
ε	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$e_c(t)$	1	4	2	3	1	3	2	4	1	4	2	3	1	3	2	4
$y(e,0,2010)$	1	3	2	4	1	4	2	3	1	3	2	4	1	3	2	4
ι	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
2020																
Baseline	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$\varphi(g)$	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$\varphi(d)$	1	3	2	4	1	3	2	4	1	2	3	4	1	3	2	4
ε	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
$e_c(t)$	1	4	2	3	1	3	2	4	1	4	2	3	1	3	2	4
$y(e,0,2010)$	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
ι	1	3	2	4	1	3	2	4	1	3	2	4	1	3	2	4
2025																
Baseline	1	3	2	4	1	3	2	4	1	2	3	4	1	2	3	4
$\varphi(g)$	1	3	2	4	1	3	2	4	1	2	3	4	1	2	3	4
$\varphi(d)$	1	2	3	4	1	3	2	4	1	2	3	4	1	2	3	4
ε	1	3	2	4	1	3	2	4	1	3	2	4	1	2	3	4
$e_c(t)$	1	4	2	3	1	2	3	4	1	4	2	3	1	2	3	4
$y(e,0,2010)$	1	2	3	4	1	3	2	4	1	3	2	4	1	2	3	4
ι	1	3	2	4	1	3	2	4	1	2	3	4	1	2	3	4
2030																
Baseline	1	3	2	4	1	3	2	4	1	2	3	4	1	2	3	4
$\varphi(g)$	1	2	3	4	1	3	2	4	1	2	3	4	1	2	3	4
$\varphi(d)$	1	2	3	4	1	2	4	3	1	2	3	4	1	3	2	4
ε	1	4	2	3	1	2	3	4	1	2	3	4	1	2	3	4
$e_c(t)$	2	4	1	3	1	2	3	4	1	4	2	3	1	2	3	4
$y(e,0,2010)$	1	2	3	4	1	3	2	4	1	3	2	4	1	2	3	4
ι	1	2	3	4	1	3	2	4	1	2	3	4	1	2	3	4

Legend: $\Delta < 1\%$ $1\% \leq \Delta < 5\%$ $5\% \leq \Delta < 10\%$ $10\% \leq \Delta$

scenarios (24–35 % variation) and the diesel ICEV fuel consumption reduction rate ($x(d,k)$) in the *BAU* and *ICEV improve* scenarios (up to 32 % variation). Nevertheless, varying these parameters does not change the ranking of the scenarios, except for the electricity generation emission factor, which, at its higher bound, makes the *ICEV improve* scenario better than the *BEV dominate* (–19 %) and *Combined* (–13 %) scenarios. When BEV distance traveled is increased to match ICEV distance traveled (BEV first-year vehicle distance traveled, $y(e,0,2010)$, upper bound), the *ICEV improve* scenario becomes slightly better than the *BEV dominate* scenario (<0.5 %). The scrappage rate (described by the maximum life expectancy, $\mu(t)$) has a higher influence in the *BAU* scenario (up to 14 % variation) than on the other scenarios (less than 7 %). Changing the fuel production emission factor (t) has a higher influence in the ICEV scenarios (up to 11 % variation) than in the BEV scenarios (up to 5 %), as expected. All parameters increase their influence in the results as time passes; except the gasoline ICEV indexed mileage ($\varphi(g)$), which decreases, and the maximum life expectancy ($\mu(t)$), which varies.

When we examine the *LC GHG emissions per kilometer* perspective, the sensitivity analysis shows little influence by all parameters (less than 10 % change) in 2020. In 2030, the diesel ICEV fuel consumption reduction rate ($\varphi(d)$) and the electricity generation emission factor ($e_c(t)$) are the most influential parameters (up to 35 % change), similar to the *Total fleet LC GHG emissions* perspective. Keeping the other parameters constant, if diesel ICEV fuel consumption reduces enough, the *Combined* scenario may no longer be better than the *ICEV improve* scenario and the *BAU* scenario becomes slightly better than the *BEV dominate* scenario. This is because the diesel ICEV fuel consumption positively affects a higher number of vehicles in the *BAU* and *ICEV improve* scenarios (due to a higher diesel ICEV market share). Moreover, if the electricity generation emission factor increases significantly, the *ICEV improve* scenario becomes better than the *Combined* scenario and the *BEV dominate* becomes the scenario with higher impacts. The *BEV dominate* scenario becomes slightly better than the *ICEV improve* scenario if the BEV first-year distance traveled ($y(e,0,2010)$) or the fuel production emission factor (t) approach the upper bound (1.3 and 0.3 %, respectively).

Results for *Total fleet LC GHG emissions* are sensitive to more parameters than *GHG emissions per kilometer*. In particular, they are more sensitive to those parameters that affect the fleet dynamic, such as those that change the vehicle stock (vehicle density multiplier, θ), the scrappage rate (maximum life expectancy, $\mu(t)$), and the activity level of the fleet (indexed mileage of diesel vehicles, $x(d,k)$, which have higher distance traveled per vehicle). When we look at impacts per kilometer, the fleet size and turnover do not significantly affect the results. Only parameters influencing the operation (fuel consumption, $\varphi(t)$, and electricity emission factor, $e_c(t)$) play a role in the impacts per kilometer. For example, an increase in

the fleet size (illustrated in Fig. 6 by assuming the upper bound figure for the vehicle density multiplier, θ) amplifies the total fleet impacts in all scenarios (resulting in a lower reduction of impacts in 2010–2030, and, in the *BAU* scenario, even an increase in the 2010–2030 impacts), without affecting the performance per kilometer. On the other hand, increasing the distance traveled by BEVs decreases *GHG emissions per kilometer* in the *BEV dominate* and *Combined* scenarios, while increasing the *Total fleet LC GHG emissions*. To achieve an effective reduction of the fleet GHG emissions, focus should be given not only on reducing operation impacts but also on reducing the fleet size and activity, and that can only be assessed through a *Total fleet LC GHG emissions* analysis.

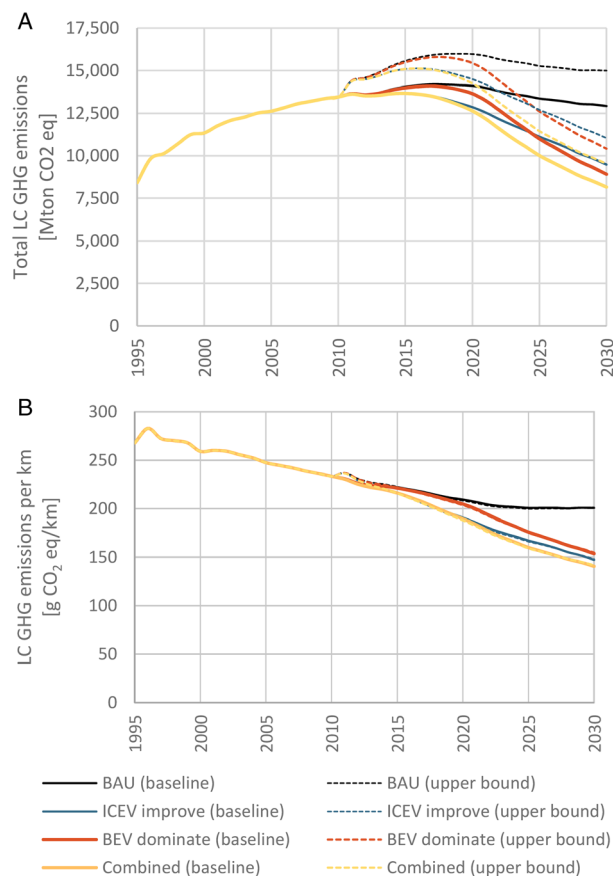
3.3 Parametric analysis

The sensitivity analysis showed that: (i) total fleet GHG emissions should be examined in order to account for the characteristics of the fleet (size and activity level) that affect the fleet emissions over time; and (ii) the diesel ICEV fuel consumption reduction rate and the electricity emission factor are the parameters that show higher variation in the 2030 GHG emissions (the latter being key for the ranking of scenarios). In this section, we look at how the fleet GHG emissions in 2030 change relative to the *BAU* scenario for different electricity emission factors, 2010–2030 new diesel ICEV fuel consumption reduction, and BEV market shares (Fig. 7).

At low BEV market shares, the BEV potential to reduce fleet GHG emissions compared to an all ICEV fleet is very low and the effect of the electricity emission factor is not very significant. As the BEV market share increases, the influence of the electricity emission factor in the GHG emission reduction also increases—at 100 % market share, it increases by 4 % per 100 g CO₂ eq/kWh decrease. All things equal, BEV introduction in the fleet has the potential to reduce total GHG emissions even if the electricity source is coal. However, as new ICEVs improve, the electricity emission factor becomes key for BEV introduction to be beneficial compared to ICEVs. Up to 780 g CO₂ eq/kWh (50/50 coal/natural gas mix), improving ICEVs (*ICEV improve* scenario) is better than introducing BEVs in the fleet, irrespective of the BEV market share. If ICEVs fuel consumption reduces by 80 %, introducing BEVs is only better if the electricity emission factor is lower than 485 g CO₂ eq/kWh (current mix). A higher reduction (>15 %) in fleet GHG emissions from the introduction of BEVs compared to improving ICEVs only occurs at high BEV market shares (>95 % in 2030, corresponding to a fleet fraction of more than 25 %) and electricity emission factors similar or lower to the current mix.

When a 50 % BEV and 50 % ICEV fleet is reached (100 % BEV market share in 2030), results show that halving the GHG emissions from BEVs by reducing the electricity mix

Fig. 6 Total life-cycle GHG emissions (a) and life-cycle GHG emissions per kilometer (b) in each scenario for the model baseline and assuming a higher vehicle density (upper bound value in Table 2)



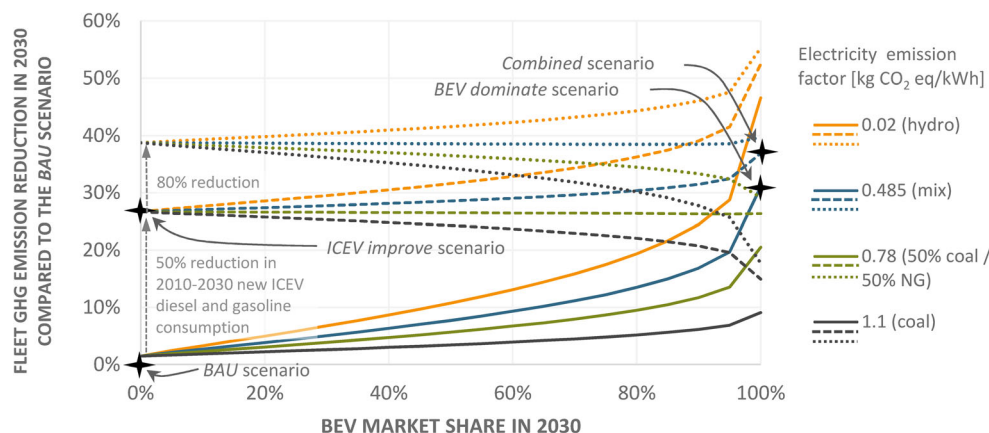
impacts is more effective than halving ICEVs emissions through reducing fuel consumption (13 % and 9 % reduction in fleet GHG emissions, respectively). This happens because fuel consumption reduction only affects new vehicles entering the fleet and it takes time for these new, higher-efficient vehicles to gain fleet share. On the contrary, the electricity emission factor affects all BEVs in the fleet, irrespective of their age. The lag between now and the time high BEV adoption is realized may allow for the decarbonization of the grid necessary for BEVs to reach their full potential. On the other hand, a

lower rate of introduction of BEVs in the fleet may allow a quicker diffusion of high-efficient ICEVs, requiring a more aggressive decarbonization of the grid for BEV adoption to have a noticeable effect in overall fleet emissions.

4 Conclusions

We assessed the fleet-wide environmental impacts of displacing ICEVs by EVs across different scenarios and

Fig. 7 Reduction in total fleet GHG emissions in 2030 as a function of the 2030 BEV market share and the electricity emission factor for 80, 50, and 0 % 2010–2030 diesel ICEV fuel consumption reduction rates, compared to the *Business-as-usual* (BAU) scenario. NG natural gas



metrics. The analysis took into account the dynamic behavior of the fleet, including fleet turnover, technology improvements (e.g., reduction in fuel consumption of new vehicles, weight reduction), and changes in background processes (e.g., electricity mix, material GHG intensity) and vehicle activity (e.g., annual distance traveled) within the same framework. The analysis spanned 15 years into the past (1995) and 20 years into the future (2030).

We showed that it takes time for BEV share in the fleet to become significant and that only after 2025 does the effect of introducing BEVs in the fleet GHG emissions start to emerge. The reduction in the fleet GHG emissions from displacing ICEVs by BEVs is highly dependent on the BEV market share, new diesel ICEV fuel consumption reduction, and electricity emission factor. Emissions reductions at the end of the assessment period (2030) are between 1 and 47 % when compared with a business-as-usual fleet (*BAU* scenario), and –16 % and 38 % if compared with an ICEV improved fleet that meets EU targets. For BEV introduction in the fleet to be beneficial compared to an increasingly more efficient ICEV fleet, a high BEV market share and electricity emission factor similar or lower to the current mix (485 g CO₂ eq/kWh) need to be realized; these conclusions hold for the different conditions analyzed. We also found that halving the GHG emissions from BEVs by reducing electricity mix impacts has a larger effect on the overall fleet GHG emission reduction compared to halving GHG emissions from ICEVs by decreasing fuel consumption, but that effect may change depending on how the fleet evolves.

Besides the importance of the fuel consumption reduction rate of new ICEVs and the electricity mix emission factor, results were also sensitive to parameters that affect the fleet dynamic, such as those that change the vehicle stock, the scrappage rate, and the activity level of the fleet (11–19 % variation in total GHG emissions in 2030). The influence of these parameters also varies over time, becoming more important as time passes. These effects can only be captured by assessing total fleet GHG emissions as opposed to the GHG emissions per kilometer approach.

These results emphasize the importance of taking into account the dynamic evolution of the fleet, technology improvements over time, and changes in vehicle operation and background processes during the vehicle service life when assessing the potential benefits of displacing ICEVs by EVs in a fleet. These factors are usually not accounted for in the literature. Therefore, the fleet-based approach presented can provide a more comprehensive assessment of the adoption of an emerging technology, such as EVs, because it enables explicit assessment of improvements and developments over time, and also indirect effects related with the existing system, such as the effects of displacing ICEVs. It can also provide the scale and timing for assessing other indirect impacts not included in this paper, such as the effects of BEV load in the

power grid. Moreover, this approach avoids fixed assumptions about vehicle service life, since impacts from vehicle production are accounted in the year the vehicles are produced and are independent from the time the vehicle is scrapped. Assumptions about vehicle service life are often indicated as having a significant influence in the environmental impact results of vehicles (Hawkins et al. 2013; Nordelöf et al. 2014). With this framework it is also possible to assess the effect of other measures to decrease impacts from transportation, such as reducing the fleet size, decreasing the distance traveled by vehicles, and delaying or anticipating scrapping, and how they compare with EV adoption, which we leave for further research.

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