Is investing in an electric car worthwhile from a consumers' perspective?

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1. Introduction

Every day, new products, improved technologies and new discoveries are announced. However, as this technological revolution has taken place over the last decades, contributing for countries' economic growth, one has also witnessed an increase in greenhouse gases (GHG) emissions [1], resulting in an increasingly severe environmental degradation. In fact, "human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" [2]. GHG emissions have been increasing steadily for years and it seems that this panorama will not change in the upcoming years. This problem has been haunting environmental scientists for years and they have been trying to convince and persuade industries, governments and the population itself to the severe consequences that were once predictions, but that they are already suffering from. The Intergovernmental Panel for Climate Change (IPCC) points out that GHG emissions grew roughly 2.2% per year, from 2000 to 2010, leading to 49 Gt of anthropogenic GHG emissions. The economic growth is considered to be the leading cause of these hideous results [2]. Given this scenario, reducing GHG emissions became a priority topic on many people's agenda, from government decision-makers and policy makers to scientists and environmentalists, among others [3].

In this context, one of the sectors that has had a major impact on GHG emissions over the years is the transport sector [4]. For example, in 2011, it was responsible for 22% of the total amount of CO2 emissions worldwide (more than 5 Gt CO2) [5]. In the USA, around 30% [6] of its GHG emissions comes from the transport sector, while in the European Union this value is roughly 20% and in Portugal 25% [7]. Moreover, it is foreseen that these values may even double by 2050, if mitigation measures are not implemented [8]. As highlighted by Seixas et al. [9], the transport sector was the only sector increasing GHG emissions in the last two decades.

To address this concern, finding alternatives to the current transport solutions is crucial for ensuring a sustainable future and, among different solutions that have been proposed, the electric vehicle (EV) emerges as one of the most promising [10,11]. Actually, several automakers have been working for years in greener technologies [12], and EVs are presented as long-term solutions for this important problem. EVs have several important advantages when
compared with internal combustion engine (ICE) vehicles, namely: silent operation and zero tail pipe emissions [10] high tank to wheel efficiency [4], particularly in urban traffic since they have no idling losses, no inefficient clutching at starts and they can recover a portion of the braking energy through regenerative braking [13]; their potential to reduce GHG emissions, especially when combined with low carbon electricity [9]; and reduced oil-dependence [11]. However, EVs also have some drawbacks, namely its low autonomy and higher purchasing cost when compared with a conventional ICE vehicle [14], the long charging time and the limited availability of recharging stations [11]. Moreover, as emphasised by Dumontier et al. (2015: 72) [14], “consumers may lack an intuitive understanding for the relative prices of gasoline and electricity as well as the different amounts of these two energy sources that are used by vehicles over their lifetimes”.

Contrary to the common perception, EVs exist for more than a century – the first EV dates back the 19th century in Scotland [10] and they represented, for example, the majority of the vehicles circulating in the US on the beginning of the 20th century [15]. However, due to the growth and expansion of cities and the development of new road infrastructures connecting cities, vehicles with higher autonomy were required, leading to a decrease on EVs attractiveness [16]. Only during (and after) the oil crisis of the 1970s, the EV became to be seen again as a possible technologic solution for the increasing prices of gasoline and for reducing a country’s oil dependence, particularly from the Middle East [15]. At the same time, CO₂ emissions were also rapidly increasing and the growing energetic needs led to the search of viable alternatives. To accomplish these efforts, several governments have been adopting incentive measures and policy regulations related to the development and dissemination of EVs [16].

The aim of this paper was to evaluate whether the purchase of a battery electric vehicle (BEV) pays off when compared with the purchase of an ICE vehicle. Following Crist [17] a BEV can be defined as a light-duty car, van or sports utility vehicle propelled solely by a battery-powered electric motor (therefore, not including hybrid vehicles). Although recognising that there are other types of EVs (e.g., Hybrid Electric Vehicles HEVs, and Plug-In Hybrid Electric Vehicles, PHEVs), in the current study the focus was on pure BEVs because: a) they are, on a tank-to-wheel perspective, zero-emission vehicles, therefore contributing to a significantly reduction of emissions and pollution as well as noise in urban areas [18]; and b) at the current battery technology development and higher upfront investment cost, they are expected to perform worse when compared with an ICE vehicle.

For this purpose, and following a tank-to-wheel approach,² vehicles from two different market segments were considered, using the case of Portugal for this assessment. In one case, vehicles belonging to a high market segment (Tesla S and Audi A7) and, in the other case, vehicles belonging to the medium market segment (VW e-Golf and VW Golf). The economic model developed to perform the required calculations was based on the work of Prud’homme and Koning [19]. In relation to these authors’ work, this paper adds a probabilistic risk analysis, which allows achieving a more comprehensive analysis and richer conclusions.

After this introductory section, the remainder of the paper is organised as follows. Section 2 briefly presents a literature overview about the economic analysis of EVs. Section 3 summarises incentive measures and policy regulations that have been implemented in different countries to promote the dissemination of EVs. Section 4 describes the economic model used to assess the viability of acquiring an EV and presents the main results obtained. Section 5 shows the findings of the probabilistic risk analysis undertaken. Finally, Section 6 draws the main conclusions of the paper, the policy implications, and suggests possible avenues for future research.

2. The economic analysis of electric vehicles

Due to the increased interest on EVs, a number of studies have been conducted to assess the viability, from a consumers’ perspective, of acquiring an EV when compared to an ICE vehicle. In this section, a brief summary of some of those studies is presented. To make the comparison among EVs and ICE vehicles, those studies vary in terms of, for example, the type of techno-economic model used, powertrain technology adopted, and number and class of vehicles compared.

Wu et al. [20] departed from the idea that EVs are perceived as more expensive than ICE vehicles due to its higher upfront cost and assessed the attractiveness of EVs based on the concept of total cost of ownership (which includes both the initial investment and the operating cost of using the vehicle during its lifetime) using a probabilistic simulation model. The main conclusion of those authors is that EVs will increase their cost efficiency relative to ICE vehicles; however, in the near future, the ICE vehicle remains the best option for consumers. They also concluded that the comparative cost efficiency of EVs increases with the consumer’s driving distance and is higher for small than for large vehicles. Based on the thought that the concept of total cost ownership would be a valuable tool for comparing different types of vehicles (namely, EVs vs. ICE vehicles), Dumontier et al. [14] sought to determine whether that concept has any measurable effect on the stated preferences of final consumers, given how the total cost of ownership is calculated. Their main conclusion is that the effect of including the total cost of ownership information is positive for the case of respondents interested in small and/or midsized cars, but has no impact for the case of small sport utility vehicles, SUVs.

As a way to address the increasing severe energy and environmental problems in China, Wang et al. [4] undertook a detailed life cycle analysis to evaluate the feasibility of EVs in terms of energy consumption, carbon emission, and well-to-wheel efficiency. According to the results, EVs are still more expensive than ICE vehicles but this situation might change in the future due to the expected decrease of EVs’ price, besides any possible subsidies granted by the government. Following a similar approach, Nanaki and Koroneos [21] compared the economic and environmental impacts of EVs and ICE vehicles, for the Greek context, based on actual data regarding a vehicle’s energy life cycle, i.e. from the extraction of natural resources to produce fuels to the final transformation of fuel to mechanical energy in an engine. The major findings obtained were: a) EVs causes lower emissions than ICE vehicles; b) EVs are competitive only if renewable energy sources account for about 50% of the energy to generate electricity; and c) the potential for EVs to achieve large-scale GHG emission reductions is highly dependent on the energy sources of electricity production.

The synergy between renewable energy systems and EVs has been debated in some countries providing some evidence that EVs integration can in fact facilitate large renewable integration. Nunes et al. [22] concluded that, for Portugal, in future a one hundred percent RES energy based on electricity supply is possible combining electrical vehicles and photovoltaic. The authors found that increasing levels of EV research also lead to a reduction in energy
excess. Another example, for Inner Mongolia and China, is provided by Liu et al. [23] who concluded that EVs can have an impact on increasing fuel cost saving allowing to better balance electricity demand and supply and to further the wind power integration. Also Dallinger et al. [24] analysed the integration of intermittent renewable power supply using EVs electrical vehicles in both California and Germany. The general conclusion is that EVs play an important role on reducing negative residual load peaks, notwithstanding the extension of this impact being dependent on the characteristics of each one of these systems.

In the Portuguese context, and emphasizing that there is a lack of real life comparisons between the energy consumption of EVs and ICE vehicles, Martins et al. [13] performed an assessment of the energy consumption performance of those two types of vehicles, from a Tank-to-Wheel perspective. These authors concluded that: a) the electric powertrain presented much higher efficiency than the ICE engine, yet, when the average speed and required power increased, that difference become lower; and b) the energy supplied by the electric grid to the EV ranged between 49% and 61% of the energy supplied by the fuel to the ICE vehicle for identical trips.

For the French context, Crist [17] performed a microanalysis of commercially available EVs and ICE vehicles, for which commercial pricing data was available, in order to estimate their lifetime consumption and first-order societal costs. The author’s main finding is that the cost of EVs is still higher than equivalent ICE vehicles but this gap may narrow as production volumes increase. Yet, in the near future, it is claimed that the uptake of EVs will be dependent on the availability of government subsidies.

García and Miguel [25] assessed the attractiveness of EVs to consumers in Spain, taking into account the cost of investment at the time of purchase as well as the user costs over the useful life of the EV. The authors emphasised also the policies needed to support the spread of EVs. Considering the base scenario defined in the work, the authors concluded that in 2020 the number of EVs in circulation would be 700,000, contributing to a reduction of more than 6 million tons of CO2. The authors also underlined the key role that government subsidies play in achieving those numbers and thus enhance the EVs’ market.

In another study by Perujo et al. [26] addressing the impact of EVs’ use in an urban context, environmental benefits, and technical and economic barriers, the following findings were highlighted. Firstly, driving habits, distances travelled daily or even road conditions are all factors influencing the performance of EV as a way to reduce CO2 emissions. Secondly, the entry of these vehicles on the market depends on a wide range of factors, including access to the electricity grid and the distribution of the charging stations. Finally, the connection between these and other factors such as battery performance or acceptance of such vehicles makes it very difficult to have useful projections since a number of combinations are possible for the entry of these vehicles on the market, increasing also the difficulty in predicting the CO2 reduction.

Michalek et al. [27] argue that if pollution levels resulting from electricity production are reduced, battery prices decrease and its longevity increases, the prices of fossil fuels increase, and the battery charging infrastructure are well distributed, the EVs can provide large reductions in GHG emissions and fuel consumption at a competitive cost. However, those authors also emphasise the need for a strong investment policy associated with government support to the success of EV dissemination.

Finally, in a study by the Boston Consulting Group [28] examining the possibility of the dissemination of EVs and its contribution to the reduction of GHG emissions, several important conclusions were emphasised. Firstly, it is expected that in the near future battery prices decrease considerably as a result of an increase in their levels of production or of a major technological breakthrough. Secondly, some doubts remain about the effective capacity of these vehicles to reduce emissions in a global perspective, if the electricity used to charge these batteries come from polluting sources. Thirdly, given the high acquisition costs of EVs subsidies and government support are expected to have a major role in the level of attractiveness of these vehicles. Finally, for the implementation of this technology a constant interaction between all stakeholders involved (e.g. governments, car manufacturers, battery manufacturers, electric utilities, consumers) is essential, reinforced by granting incentives, public awareness raising actions and measures to ensure the necessary infrastructures.

An additional issue that should be taken into account, if a wide dissemination of BEVs is to be achieved, is the impact on electricity consumption, particularly in urban areas [29]. In these areas, electricity needs for BEVs might have an important impact on peak load as car drivers seek to recharge their batteries during the evening [30]. This poses additional problems to electricity suppliers in terms of the long-term investments needed to respond to this changes on electricity demand [31,32]. Smart grids technology emerge as fundamental to deal with the increased need of electricity consumption and changes on load curves as smart appliances and new market approaches contribute for shifting BEVs charging load to off-peak periods, thereby flattening the daily load curve and significantly reducing both generation and network investment needs [30]. In this context, Turton and Moura [33] for example, have analysed the particular case of vehicle-to-grid (V2G) technology. This technology permits BEVs owners not only plug into the grid to charge their vehicles, but also feed and sell energy back at times of high electricity demand. Those authors highlighted that the adoption of V2G technology has several important advantages, namely: accelerate the uptake of BEVs; decrease the need to install conventional electricity peak generation capacity (since idle BEVs could act as a giant battery, helping to stabilise the energy supply and even provide backup power during blackouts); and minimisation of problems of intermittency associated with renewable electricity sources and concomitant declining of CO2 emissions. Also Carrion and Zarate-Minano [34] showed that the coordination between the operator of renewable operated power system and charging process of plug-in electrical vehicles reduces expected costs with respect with uncontrolled environment under a smart grid environment.

3. Electric vehicles worldwide

Since EVs have potential to contribute to the reduction of GHG emissions, several countries have been implementing policy measures with the aim of supporting the use of more environmentally friendly vehicles and their market-penetration. In fact, EVs are of special interest for use particularly in cities since a large share of population have limited daily travel needs which could be easily covered with EVs. Those policy measures implemented to increase EVs’ market share vary from country to country, but can be grouped into two main categories [18]: monetary and non-monetary measures. On the former category, one can find, for example, tax credits and exceptions provided to consumers (e.g. exclusion from registration and ownership taxes, congestion charge, toll payments and road taxes, tax reduction for the annual circulation tax); one-time bonus upon purchase of an EV; and subsidies for manufacturers. On the latter category, the following measures can be included: standards for CO2 emissions; increased number of charging stations and, particularly, wide availability of fast charging stations; free parking spaces; possibility for EVs drivers to use bus lines; and permission for EVs to enter city centres and zero emission zones; electric shared mobility; “Smart Charging” apps giving the
consumers real-time information where and when to charge their vehicle and at what cost.

The European Automobile Manufacturers Association [35] listed the incentives granted in the Member States of the European Union for the purchase and use of electric and hybrid electric vehicles including plug-in hybrid and conventional hybrid vehicles. Concerning vehicles powered exclusively by an electric motor, most countries rely on tax reduction incentives and only a few of them include premium or grant for purchase schemes, as is the case of France, Sweden and UK. However, countries such as Bulgaria, Cyprus, Estonia, Spain, Croatia, Lithuania, Luxemburg, Malta, Poland and Slovenia do not present any particular compulsory support scheme for electric vehicles. However, that does not mean that municipalities cannot do it. For example, in Spain several municipalities established already an EV tax credit as analysed by Sánchez-Braza et al. [36] and in fact, benefits offered by cities can have a major role on incentivising EV adoption with some examples given in the [37] report for Amsterdam, Paris, Oslo, London and Barcelona.

A remarkable example of incentives for EV acquisition comes from Norway combining financial and non-financial incentives, resulting in the country standing out as the world’s largest EV market as measured per capita [38]. The incentives applied by different countries are diverse and can represent very different financial gains for EV users, which turns difficult to establish a correlation between these incentives and the EV market progress. However, as indicated by Figenbaum et al [38], there is evidence that more incentives are associated with higher EV market shares. The authors highlight the highly valued non-financial incentives such as free street parking, free toll road and bus lane access, all of them implemented in Norway and, in less extension, on Netherlands, the leading countries in the EV (including battery electric and plug-in hybrid electric) market sale shares [39].

An analysis of the EV registrations in the EU member states is presented in the [40] study, demonstrating that the evolution of EV registration can be related to both incentives and models offered in each country. This last aspect seems to be particularly relevant for BEVs as models offered are still limited and frequently specifically developed as EV, on opposite to PHEV models mostly derived from ICE cars. The case of Denmark is a clear example of the advantages of the increase of the models offered, with the country offering a stable and high tax incentive scheme for BEVs but with the deployment of the these vehicles largely boosted by the growing coverage of car segments.

Portugal, the country on which this study is based on, was one of the first countries to make a most significant investment on this technology. Back in the beginning of the decade, Portugal had planned to invest hardly on this technology. However, due to the profound economic crisis this investment slowed down during the last years. A new “green taxation” legislation was enacted since January 2015 (Law 82-D/2014), which allows to obtain a benefit of €4500 if the owner of a conventional vehicle wrecks is deposited in a certified location for car abatement and buy a new EV. If the car buyer opts for the acquisition of a plug-in hybrid car, the benefit granted corresponds to €3250. However, Portugal still presents a small EV market. According to ACAP [41] pure EV sales started in 2010, although much more before this hybrid cars were already sold in the Portuguese market. Even so, in 2012 hybrid and BEV sales represented only 1.1% of the total new automobile sales with 65 BEVs and 995 hybrid vehicles sold on that year. These numbers have been slowly increasing with 2015 being one of the best years, as during the first trimester already 245 new BEVs and 811 hybrid vehicles were sold. These values remain however bellow the European average for the sector, which may be due to several aspects such as range anxiety, perceived reliability of the vehicle, consumers resistance to change or cost perception. This last aspect is particularly relevant in Portugal as demonstrated in Oliveira et al. [42] study. The authors concluded that monetary criteria have the highest influence on the vehicle purchase decision with other privileges for EV owners playing a minor role.

The examples presented above show that in EU each country has then its own strategy, market and consumer characteristics in what concerns EV adoption, which justifies the different development of each member state. In 2014, EVs sales increased 79% comparing to 2013 with roughly 28,000 vehicles being sold [43]. The three most important markets in terms of EV registration are USA, Europe (including Norway) and China [40].

The United States have one of the largest EVs fleet in the world. The investment on this technology has been there for a while now and the results are visible: more than 120,000 EVs sold during 2014 [44]. This accounts for almost 40% of the total EV sales in 2014, which shows how much the US Government is compromised with its dissemination. However, when compared to the total amount of vehicles sold during the same year, this value seems almost insignificant. Regarding the incentives granted throughout the entire country, there is a very clear strategy in what concerns EV incentives. As highlighted by Dumortier et al. [14] consumers can benefit from monetary incentives, such as a federal income tax credit of up to 7500 US dollars for the purchase of EV, sales tax exemptions and lower licensing fees, as well as from non-monetary incentives, such as the access to high occupancy vehicle lanes or exemption from public parking meters. The incentives increase accordingly to the battery’s capacity to a maximum and state incentives are also granted, varying from state to state. USA’s auto industry is also steadily investing on this technology. All the main automakers have already presented their EVs (Ford, Chevrolet, Cadillac...) and room was created for the maker of one of the vehicles of the year in 2013, Tesla. Tesla presented already two electric vehicles (Tesla S and Tesla Roadster) with outstanding market performances and very high efficiencies. The importance of Tesla S is also well evident in Europe with remarkable success in Netherlands and Denmark since its market introduction. This model is ranking in first for BEVs registration in EU in 2014 in its segment and in third for all registrations [40].

As for China, is one of the countries with higher GHG emissions due to electricity production - almost 70% of the energy used comes from coal [45]. However, China invested in renewable energies in 2013 more than USA, India and Brazil combined. The total investment rounded 56 billion dollars while the entire Europe invested 48 billion dollars [46]. Despite the acknowledgment of the importance of this technology for the reduction of GHG emissions, Chinese government strategy for EV adoption is still characterised by some failures and, according to Wan et al. [47] China ambitions to build a large EV industry and market are not being achieved as fast as hoped. The authors describe a set of financial incentives to motivate EV purchase including national and local ones with the objective of reaching EV sales goal of 10% of automotive sales by 2012 nationwide and reaching 500,000 cumulative sales of EV in 2015. However, the market values are still lagging behind the goals and in terms of EV as share of total car registrations in China reached only 0.3% in 2014 [40]. The offered incentives have still limited effect, which can be explained by the industrial and market structure still characterised by local protectionism, uncertain vehicle technology strategies, lack of charging infrastructure and the perceived risk of battery and automotive manufacturers [47].

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4. Economic model

4.1. Model description

In this article, the desirability of purchasing a BEV was compared to the purchase of an ICE vehicle from a private consumer perspective. For this purpose, vehicles from two different market segments were considered. In one case, vehicles belonging to a top market segment (Tesla S and Audi A7) and, in the other case, vehicles belonging to the medium market segment (VW e-Golf and VW Golf). The selection of Tesla S and VW e-Golf followed from Joint Research Centre information on EV models per segment registered in the EU in 2014. Tesla S ranks in first in numbers of total registration of BEV in its segment in the EU and is the first on non-small or medium BEVs. As no conventional vehicle of the same brand with close characteristics could be used for comparison, Audi A7 was selected for this study. VW e-Golf ranks in third of its segment in numbers of total registration of BEV in the EU, with Nissan Leaf from the same segment ranking in first and BMW i3 ranking in second. VW e-Golf was selected however, because an ICE vehicle with the same brand and model is available in the market.

To perform the calculations the economic model developed by Prud’humme and Koning was used. Since, in the current conditions, EVs are expected to have a larger cost than ICE vehicles, the model is meant to determine the excess cost for consumer (CC) (Equation (1)), the excess cost for society (CS) (Equation (2)), and the possibility of increasing or decreasing the CO2 emissions (G) (Equation (3)), which will be referred onwards as CO2 gain. The model assumes the use of both vehicles in the same conditions during its lifetime. The consumer excess cost reflects the difference between the total value that the consumer would have to pay for the EV (CVE) and the total value the consumer would have to pay for the vehicle with ICE (CVM), assuming from the beginning that the cost of the EV will always be higher than the ICE vehicle.

\[
CC = CVE - CVM
\]  

The costs for society come from the economic costs for consumer plus all the externalities, such as fuel taxes (which include the Special Tax on Oil Products- ISP, and Value Added Tax- VAT) minus the local pollution costs. The society costs are a result of an acquisition of an EV and an ICE.

\[
CS = CSVE - CSVM
\]

The gases emissions are also calculated (G) from equation (3) assuming that EVs emissions (GVE) are lower than ICE’s (GV).

\[
G = GVM - GVE
\]

The fourth criterion computes the marginal cost of not emitting a ton of CO2 (CT), from Equation (4), (the emissions considered only address direct values from the vehicle driving).

\[
CT = CS/G
\]

According to the model of Prud’humme and Koning the excess cost for consumer and the excess cost for the society were calculated based on the present value of the cost stream for each vehicle for the assumed vehicles lifetime, using as the discount rate the standard rate suggested by the European Commission. To perform the calculations, values for several parameters had to be considered, namely: vehicles’ acquisition cost; fuel and electricity consumption; fuels and electricity costs; taxes; vehicles lifetime; distance travelled; CO2 emissions. The values assumed for these parameters are summarised in Table 1.

Regarding the acquisition costs for both types of vehicles, the manufacturers advertised prices in Portugal were considered. The only exception goes for Tesla, as this company does not own business retailers in Portugal. As such, cost information for Tesla was obtained from the European website. Audi’s and Volkswagen’s Golf and e-Golf acquisition costs were also obtained through their websites. All vehicles (BEVs and ICES) acquisition cost includes a 23% value added tax (VAT). It has been assumed that the yearly maintenance costs were identical for both types of vehicles and ICE vehicles. Therefore, it was not necessary to include those costs in the calculations although it can be argued that BEVs are likely to have lower maintenance costs than their ICE counterparts given the simplicity of the electric motor and its small number of moving parts relative to a combustion engine.

In what concerns fuel and electricity consumption, the values provided by the vehicles manufacturers were used. Fuel consumption (or vehicle efficiency) was expressed in terms of litres of diesel fuel consumed per 100 km, and electricity consumption (or vehicle efficiency) was expressed as kWh per kilometre. Electricity losses during charging were not accounted for in the model as no specific information was available. For simplicity reasons, additional aspects that may influence fuel and electricity consumption were not accounted for. As emphasised by Cris, the case of ICE vehicles, the consumption of diesel fuel is sensitive to driving style and speed profiles, whereas BEVs are much more susceptible to power draws from auxiliary devices such as heating and cooling systems.

In this study, an economic lifetime of 11 years was considered, since it is the average age of vehicles circulating in Portugal. Due to the lack of reliable information about the residual value of the BEVs, the residual value was assumed to be equal for both types of vehicles being compared. Hence, there was no need to include those values in the calculations. Yet, it is likely that the residual value would be higher for BEVs since electric motors are likely to wear less than ICES.

Regarding the diesel fuel price (with no taxes) parameter, a value of 0.714 €/l was used, which corresponds to the average price in Portugal from 2010 to 2014, and it was assumed that this price will increase at an annual average growth rate of 5%. The added taxes (VAT, 23%, and ISP, 0.27841 €/l) are government fixed values and were obtain also from DGEG. Concerning the price

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of years</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Discount rate (%)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Distance travelled (d/year) (Km)</td>
<td>10,000, 20,000, 30,000</td>
<td></td>
</tr>
<tr>
<td>ICE Vehicle</td>
<td>Audi A7</td>
<td>VW Golf</td>
</tr>
<tr>
<td>Acquisition cost (€)</td>
<td>89,441</td>
<td>25,980</td>
</tr>
<tr>
<td>Vehicle efficiency (litr/litre)</td>
<td>0.052</td>
<td>0.038</td>
</tr>
<tr>
<td>Diesel fuel price without any other costs (€/litre)</td>
<td>0.714</td>
<td>0.714</td>
</tr>
<tr>
<td>Change in fuel price (%)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>VAT (%)</td>
<td>23</td>
<td>23</td>
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<tr>
<td>Tax on petroleum products (ISP) (€/litre)</td>
<td>0.27841</td>
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</tr>
<tr>
<td>Other fuel costs (€/litre)</td>
<td>0.1236</td>
<td>0.1236</td>
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<tr>
<td>Change in local pollution costs (%)</td>
<td>–4.5</td>
<td>–4.5</td>
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<tr>
<td>Local pollution costs (€/km)</td>
<td>0.00525</td>
<td>0.00525</td>
</tr>
<tr>
<td>Emissions CO2 (kg/litre)</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>EV</td>
<td>Tesla S</td>
<td>e-Golf</td>
</tr>
<tr>
<td>Acquisition cost (€)</td>
<td>93,770</td>
<td>38,970</td>
</tr>
<tr>
<td>Home charger cost (€)</td>
<td>1260</td>
<td>1000</td>
</tr>
<tr>
<td>Vehicle efficiency (kwh/km)</td>
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<td>0.1270</td>
</tr>
<tr>
<td>Electricity price (€/kwh)</td>
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<td>0.2175</td>
</tr>
<tr>
<td>Quantity of CO2 in electricity (g/kwh)</td>
<td>325</td>
<td>325</td>
</tr>
</tbody>
</table>
of electricity (0.2175 €/kWh) it was obtained from DGEG [54] and corresponds to the average price (including VAT and other surcharges related, for example, with RES deployment) for Eurostat DC band (annual consumption between 2,500 kWh and 5,000 kWh) in Portugal for the first semester of 2015. The choice of this electricity consumption range was based on the assumption that it represents the medium domestic consumer.

Although BEVs can be charged at home in any outlet without any additional charger, there are electric vehicle manufacturers that recommend BEV owners to install a home charging point and use a dedicated recharge cable [17] and this can be of particular interest if fast-recharging technology becomes widespread. Therefore, in the comparison made between BEV and ICE vehicles it was assumed that BEVs owners would buy a home charger, which implies an additional cost.

Finally, the value of CO2 emissions of 2.6 (kg/litre) related to the content of a litre of diesel fuel was based on Prud’homme and Koning [19]. The value of CO2 in electricity of 325 (g/kWh) was based on reported emissions for the public electricity and heat sector for the 2011–2012 period in Portugal.4

4 Calculated from www.apambiente.pt/, consulted on September 2015.

4.2. Model results

Given the assumed economic lifetime of 11 years, three different scenarios in terms of distance travelled by vehicle owners were analysed: 10,000 km per year, 20,000 km per year, and 30,000 km per year.

EVs are usually perceived to be more expensive than ICE vehicles [20] still requiring substantial technological development. ERTRAC [55] called attention to a few serious EV hurdles requiring technological development including the increase of the battery storage capacity, the robustness and durability and the integration of lightweight solutions and also the need to reach economies of scale to obtain substantial reduction in cost. This last aspect is particularly relevant for the battery production for which the effect of mass production could be related to a cost reduction of 35%. In fact, although research on the battery technology is moving at a rapid pace and a reduction in battery costs is expected in the (near-) future, this is a barrier that is yet to be overcome [10,56]. This battery problem is also recognised by [57] as a main barrier to effective commercialisation and to the widespread dissemination for extra urban travel [11].

Table 2 presents the results obtained for Equations (1)–(4). In this table decreasing the value of the CC.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>CC(€)</th>
<th>CS(€)</th>
<th>G (Ton)</th>
<th>CT (€/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tesla Vs Audi</td>
<td>10,000</td>
<td>2244.94 €</td>
<td>3429.05 €</td>
<td>7.41</td>
</tr>
<tr>
<td>e-Golf vs Golf</td>
<td>11,059.31 €</td>
<td>11,823.43 €</td>
<td>6.33</td>
<td>1,868.17€</td>
</tr>
<tr>
<td>Tesla Vs Audi</td>
<td>20,000</td>
<td>–1099.13 €</td>
<td>1269.10 €</td>
<td>14.82</td>
</tr>
<tr>
<td>e-Golf vs Golf</td>
<td>8128.63 €</td>
<td>9656.85 €</td>
<td>12.56</td>
<td>762.92€</td>
</tr>
<tr>
<td>Tesla Vs Audi</td>
<td>30,000</td>
<td>–4443.19 €</td>
<td>8903.84 €</td>
<td>22.23</td>
</tr>
<tr>
<td>e-Golf vs Golf</td>
<td>5197.94 €</td>
<td>7490.30 €</td>
<td>18.99</td>
<td>394.50€</td>
</tr>
</tbody>
</table>

For the scenarios analysed, the CC always favours the acquisition of the ICE vehicle (Golf). However, as the distance travelled increases, the EVs tend to be more profitable decreasing the value of the CC. This demonstrates that the travel distance per year is a key factor for the consumer, showing also that the maximum range is a fundamental aspect for EVs to succeed in the market. A similar result was obtained in the study of Wu et al. [20], with the authors stating that “the comparative cost efficiency of EVs is strongly determined by the driving distance and vehicle class”. It is interesting to see that for a higher market segment the purchase of an EV becomes much more easily profitable than for a smaller, cheaper vehicle. These facts are true both for the customer side as well as for the society.

Regarding the CO2 savings, all EVs present better results than ICE as it would be expected. The differences in avoided CO2 emissions increase linearly with the travel distance as emissions are assumed to be proportional to consumption and, as such, also to the distance. The higher avoided CO2 emissions for Tesla, comes directly from the vehicle used for the comparison, as the fuel consumption per km is higher for Audi A7 than for VW Golf.

Table 2 Results for the baseline scenarios.

5. Risk analysis

5.1. Sensitivity analysis

The results obtained and presented in the previous section come from static values previously defined. This, as it was already possible to verify, lead to some good conclusions on the excess cost of the EVs under the assumed conditions. However, it becomes important to figure out when and how will the EV become cost effective. Considering this need, and based on the information previously defined on the model, it was used the Microsoft Excel function “Goal Seek” to determine when would the EV become cost effective when compared to the ICE vehicle. Assuming changes on some parameters, it was only studied the first scenario for Tesla vs Audi (since Tesla becomes cost effective on the second scenario) and the case of e-Golf vs Golf for all three distance scenarios.

So, considering that the distance travelled, the diesel fuel price, the ISP, the acquisition cost of BEVs, and the electricity price could vary, the results shown on Table 3 were obtained. Here, it can be seen that for the e-Golf to become cost effective, the distances travelled per year would have to increase significantly. Both cars would have to travel roughly 47,000 km per year, which in 11 years means a total of more than 500,000 km, which is unlikely to happen for the majority of drivers, therefore reducing significantly the target market. It can also be concluded that the diesel fuel price, just like the ISP tax would have to increase considerably to achieve a null difference between EV and ICE lifetime costs. For example, in the 10,000 km scenario the price of diesel fuel would have to increase almost 300% in order e-Golf become cost effective. It is also predictable that lower BEV acquisition costs favours this purchase. In this scenarios, considering a distance of 10,000 km travelled per year, the e-Golf would have to cost 28,000 €, a decrease of almost
11,000 € (more than 28%) comparatively to its present value. Also, Seixas et al. [9] reach a similar percentage decrease for BEVs become cost-effective. Regarding the electricity costs, in the first two scenarios this value would have to be negative so that this purchase could be considered interesting for the customer. In the 30,000 km scenario, the electricity price obtained was 0.06 €/kWh, which would mean a decrease of about 72% in electricity price. Although the issue of electricity price tariffs and electricity market organization is beyond the scope of this paper, it is worth pointing out that the existing of differentiated electricity tariffs schemes can be a relevant issue to explore. The development of an active and inclusive electricity market where EVs owners and independent electricity producers can participate can contribute significantly to increase the economic interest of the EVs investment, as the owners of EVs could benefit from the strategic intraday trading in the market.

In order that Tesla would become cost effective in the first scenario, it would only have to, for example, have a decrease on its acquisition cost of less than 2000 €. This could be easily done with a government incentive or similar. In addition, the increase on the diesel fuel price and ISP would not have be very significant to ensure Tesla cost effectiveness.

5.2. Probability risk analysis

The results obtained on the previous sensitivity analysis allow the reader to conclude about the impact that changes in each parameter of the model has on the final results. However, this is a deterministic approach to risk, and may not capture (or reflect) the true impact of changes in those parameters upon the variable under analysis. Indeed, the way that approach deals with risk is rather limited and provides no information on the probability of the parameters reaching the assumed values. For example, imagine that the value of the fuel price used in the model represented a moment when this was quoted at abnormally high prices. This could wrongly influence the final results. As such, although the values are based on the best available information it is extremely important to assess the probability of the events, based on historical data. Wu et al. [20] emphasised two main advantages of using a probabilistic risk analysis. On the one hand, “it provides a more complete understanding of whether and in which case the political will to support a market transition towards EV is mirrored by cost efficiency for consumers”. On the other hand, due to the uncertainty associated with several input parameters (e.g. fuel and electricity prices, and battery cost development) results “showing the probabilities and distributions of possible outcomes might be more appropriate than deterministic rankings”.

Therefore, in this subsection the results obtained performing a probabilistic risk analysis are shown. For this purpose, the impact of three critical variables (electricity and fuel prices as well as the discount rate) was analysed. In particular, the impact of fluctuations on those three variables on the cost for consumer (CC) was assessed, based on Monte Carlo simulations. These calculations were performed using historical data regarding electricity and fuel prices and the discount rate and identifying the distribution that best fits the data, resorting to the statistical analysis software.

In the case of electricity prices, values of the Iberian Electricity Market (MIBEL) were considered, for a time range between January 1st, 2014 and July 28th, 2015. The results indicated that a normal distribution could be used to fit the data. Therefore, it was found that in MIBEL the electricity price standard deviation was 0.01721 €/kWh which corresponds to about 38.73% of the average value. Therefore, in the calculations performed, an identical proportion for the standard deviation was used, which meant a value of 0.08424 €/kWh whereas the mean value corresponded to the average price of electricity, 0.2175 €/kWh previously used. Simulations on the CC value were then run for scenarios 10,000 km, 20,000 km and 30,000 km annual mileage.

In the Figs. 1 and 2 it is possible to see the results achieved with the probabilistic risk analysis, considering the comparisons Tesla vs. Audi A7 and e-Golf vs Golf vehicles for the three scenarios analysed (10,000 km, 20,000 km and 30,000 km annual mileage) assuming electricity price as the risk variable.

For the 10,000 km scenario, although in the baseline case BEV was not the better choice for the private customer, considering the assumed statistical data for electricity, there is a 7.3% probability of Tesla becoming the best option. Notwithstanding, the mean value for CC is still positive reaching 2245 €. For the two other scenarios (20,000 km and 30,000 km), as expected given the base line scenario, BEV would be the best option. However, it should be emphasised that even for the 30,000 km scenario there is still a probability of 16.8% of the ICE Golf to be the best choice, showing the high sensitivities of the decision to the electricity prices. As for the e-Golf vs Golf results, there is only a small probability (3.2%) of the e-VW Golf to be the best choice, only for the 30,000 km scenario. For all the other scenarios, under the assumed statistical distribution of the electricity price the ICE Golf remains always the best economic option.

Regarding fuel prices, the evolution of the price of the diesel fuel in the Portuguese retail market, between January 1st, 2010 and July 29th, 2015 was considered. When performing the distribution fitting of the data, triangular distribution was found to be the one best representing the price evolution over time. This distribution requires only the minimum, maximum and the most frequent value of the series to perform the calculations. In this case, the minimum value was 1.0537 €/l and the maximum 1.5014 €/l. These values correspond, respectively, to 79.8% and 113.7% of the average value of the series (1.3208 €/l). Using the same minimum and maximum ratios for the proposed model and departing from the assumed value 0.714 €/l (baseline case value before taxes), it follows that the maximum fuel will cost (0.81163 €/l) and the minimum fuel will cost (0.56961 €/l). Once more, simulations on the CC value were then run for scenarios 10,000 km, 20,000 km and 30,000 km annual mileage.

Figs. 3 and 4 present the probabilistic risk analysis, considering the comparisons Tesla vs. Audi A7 and e-Golf vs Golf vehicles for the
Fig. 1. Probabilistic risk analysis, Tesla vs. Audi A7 for electricity price.
Fig. 2. Probabilistic risk analysis, e-Golf vs. Golf for electricity price.
Fig. 3. Probabilistic risk analysis, Tesla vs. Audi A7 for fuel price.
Fig. 4. Probabilistic risk analysis, e-Golf vs. Golf for fuel price.

a) Distance travelled: 10,000 km/year

b) Distance travelled: 20,000 km/year

c) Distance travelled: 30,000 km/year
three scenarios analysed (10,000 km, 20,000 km and 30,000 km annual mileage) assuming fuel price as the risk variable.

The results show a different picture than the one obtained for the previous analysis of the electricity prices. In fact, for the 10,000 km scenario the Audi A7 is always the best option. On the other hand, for the 30,000 km scenario Tesla would be always the best option. In the 20,000 km scenario there is a 12.8% probability of the Audi A7 be the right choice. Once more this demonstrates the importance of the yearly travel distance and how this factor can compensate the higher investment required by the EVs even if diesel prices tend to follow. However, e-Golf vs Golf analysis shows that for the assumed statistical distribution of the fuel price the ICE Golf remains always the best economic option. The higher difference between the acquisition values is not easily compensated even for higher fuel costs.

In what concerns the discount rate variable, its variation throughout time was proxied by the evolution of the yield to maturity rate of the 10 years Portuguese Treasury bonds, for a period comprised between January 1st, 2010 and July 30th, 2015. From the statistical analysis of the series, triangular distribution was selected as the best fit. After having computed the average value of that series (6.76%), the proportion of the maximum and minimum values against the average value were computed (239.9% and 23.2%, respectively). This same variation range was used for the discount rate assumed in the base case and simulations were run to compute the excess cost for the consumer (CC) in the three scenarios analysed.

Figs. 5 and 6 present the probabilistic risk analysis, considering the comparisons Tesla vs. Audi A7 and e-Golf vs Golf vehicles for the three scenarios analysed (10,000 km, 20,000 km and 30,000 km annual mileage) assuming discount rate as the risk variable.

The results clearly demonstrate the importance of the discount rate for the decision making for the investment requiring high acquisition costs. For longer mileage, the acquisition of Tesla undoubtedly becomes the rational decision. The mean values for the cost for the consumer (CC) is negative (−818 € and −4022 € for 20,000 km and 30,000 km annual mileage, respectively) and for the case of 30,000 km annual mileage the analysis shows that the probability of having a positive CC is null. Once more the e-Golf vs Golf vehicles analysis demonstrate that e-Golf option is difficult to be justified even for long distances, as the CC remains always positive.

From all the above results (for both segments of cars analysed), and as an overall conclusion, it seems that the electricity price variable is the one with the major impact in terms of the right decision regarding the best option to acquire an ICE vehicle or an BEV vehicle. In the particular case of e-Golf vs Golf vehicles analysis, this is in fact the only variable that presents a slight possibility of obtaining a negative CC. On the other hand, the impact of the fuel price and the discount rate is quite similar in terms of both the minimum and the average values for the three distance scenarios, underlining even more the difference of the results obtained for the two market segments of the analysed vehicles.

5.3. Combined probability risk analysis

In the previous analysis, the impact of each variable (electricity and fuel price as well as the discount rate) on the cost for consumer (CC) was assessed independently. However, risk assessment must go beyond this individual approach, since much of the uncertainty associated with the CC output comes from the combination of several random events. Therefore, in this subsection, simulations combining the different variables distributions are presented for the two segments of cars. Figs. 7 to 8 present the results of this simulation for the CC computation, for the comparisons Tesla vs. Audi A7 and e-Golf vs. Golf vehicles under the three annual mileage scenarios (10,000 km, 20,000 km and 30,000 km).

The results of these combined analysis lead to similar conclusions than the ones reached previously. However, the outcome is somewhat less optimistic for the BEVs than before, as the probabilities of obtaining a negative CC tends to be lower than the ones obtained with the individual analyses. The acquisition of Tesla can be justified for the 30,000 km and even for the 20,000 km scenarios showing that as the annual mileage increases BEV turns out to be the best option. As for the e-Golf vs. Golf comparison, the risk analysis demonstrates that the ICE vehicle is still the best cost decision for the car buyer. The probability of e-Golf being the best alternative is just 3% and this only happens for the case of the 30,000 km annual mileage scenario.

Figs. 9 and 10 present the tornado chart for the comparisons Tesla vs. Audi A7 and e-Golf vs Golf vehicles for the 30,000 km scenario. Both figures put in evidence the importance of the electricity tariffs to justify BEVs purchase.

6. Conclusions

One of the main conclusions that can be drawn from the analysis performed in this paper is that the purchase of a BEV in Portugal is not yet cost effective, under the present market conditions. This means that no incentives or special prices for electricity that could support EVs acquisition were considered and taxes structure reflects the existing ones. The results indicate that at least in the short term, the cost argument for acquiring a BEV on the lower/middle market car segment is still not convincing. However, the intensive use of the BEV, namely in terms of the annual mileage, contributes to increase its attractiveness, since the higher purchasing costs of the EV would be offset by lower annual driving costs.

For the case of the cars in the higher market segment, it was observed that the BEV can easily become the best option for the private customer. Moreover, this advantage turns out to be even more important with the annual travelled distance. However, the decision of acquiring a car in this type of segment is likely to be driven by factors other than purely the cost of ownership as would happen for the lower/middle market car segment. It was proven that in a particular set of market conditions that can be easily achieved, BEVs can outcome ICES of the same high market segment. This can be seen as a sign that BEVs can truly become an alternative within the next few years.

To obtain deeper insights regarding the comparison of owning a BEV and an ICE vehicle, two types of risk analysis were undertaken. From the sensitivity analysis performed, it was possible to conclude that in order to e-VW Golf to become cost effective the annual mileage, the diesel fuel price and the ISP tax would have to increase considerably. It is also predictable that a lower BEV acquisition cost favours this purchase. It was clear that of the three variables analysed (electricity price, fuel cost and discount rate), the one with the highest impact on the cost for the consumer and therefore on the buyer’s decision is the price of electricity. This raises important questions on the possibility of creating the right conditions for the effective participation of BEVs owners and small producers on the electricity market trading. The strategic management of the BEVs charges can be an effective way to increase the BEVs economic attractiveness if the right tariffs and market signals are in place.

Despite all the benefits usually associated with a BEV, currently they are unable to overcome the barriers that still exist and that would allow its dissemination. In fact, the inherent BEV technology is still in a relatively early maturity level. Simultaneously, the high prices associated with the batteries and the acquisition of the vehicles and the reduced autonomy of the batteries, are evidence that there is a long way to go. However, the relevance of a study as the
Fig. 5. Probabilistic risk analysis, Tesla vs. Audi A7 for discount rate.
Fig. 6. Probabilistic risk analysis, e-Golf vs. Golf for discount rate.
Fig. 7. Probabilistic risk analysis, Tesla vs. Audi A7, combined events.
Fig. 8. Probabilistic risk analysis, e-Golf vs. Golf for fuel price, combined events.
one performed in this paper relates to the need to find solutions to address the problem of exaggerated level of CO₂ emissions worldwide. Moreover, taking into account the investment that is being made by major car brands in terms of BEVs development and the recognition by governments of major countries of the importance of the technological developments, there is a strong possibility that the BEVs be, in fact, the vehicle of the future.

In spite of this expected outcome, the dissemination and maximisation of the use of the BEVs raises also some important questions since in medium-to-long run is foreseen that most of the policy measures that have been implemented will likely be abolished due to the increasing number of EVs. One is related to the incentives granted by governments worldwide. Taxes on vehicles are an important source of revenues for every country government’s budget and granting incentives to EVs can have a counterproductive effect. Monetary incentives represent not only a decrease on tax revenue, but also an increase on the fiscal expenditures. Considering that some governments grant tax exemptions for EVs, a decrease on the revenue can then be foreseen.

The electricity price was shown to be the most important driver for BEVs acquisition decision making. This poses important additional challenges to government budget as fuel taxes represent an important source of revenue. As such, an increase on electricity taxes could be considered to offset the loss of revenues on fuel taxes in a scenario of higher BEVs market share. Taking into account the current tax structure of both fuel and electricity prices in Portugal this could represent an increase of more than thirty per cent in electricity price. As demonstrated in the probabilistic sensitivity analyses, the cost disadvantage of BEVs would increase, penalising not only the low market car segment but also the high market car segment. The topic related to fuel and car acquisition taxes is then deemed to be high relevant yet strongly connected to energy policy making and scenario analysis pointing out the importance of additional research on this theme.

Moreover, since the final goal is not just to increase the number of BEVs per se but the reduction of GHG emissions and air pollution, all environmental benefits of BEVs could be reached only in combination with electricity from renewable energy sources. The way electricity is generated has then to be taken into account when assessing the impact of the BEVs. For example, if a decrease in CO₂ emissions is expected with the replacement of ICE vehicles by electric vehicles, this should not be offset by an increase in CO₂ emissions resulting from an increased use of fossil fuels to generate the additional electricity needed. The open question is then, how large will the impact of the BEVs be worldwide if the entire planet keeps producing its electricity largely from using fossil fuels? The answer to this question would imply, for example, to perform a life-cycle analysis and include the BEVs in integrated energy planning models analysing the net impact of the BEVs in the overall energy system.

The results obtained in this study put in evidence that the attractiveness of the BEV still depends on political, technical and economic aspects all of them closely interrelated. Political aspects include the definition of stable and reliable policy of incentives providing confidence to both BEV producers and consumers and including not only financial incentives but also non-financial ones specifically tailored to each country or region. Technical factors are closely related to range and charging issues, requiring the technological development of both the BEV and of the charging and storage network. Finally, economic aspects must address the acquisition cost as a main barrier to effective market uptake requiring then the presence of economies of scale that can only be achieved through the increase on sales.

In this work, an approach to assess the cost-effectiveness of BEVs was demonstrated for two cars market segments, using the case of the Portuguese market conditions for demonstrative purposes. Based on the findings of this paper some important observations and policy implications can be drawn. Firstly, purchasing price is confirmed as a main barrier for BEV market uptake, in particular in the small and medium cars market segment. This demonstrates the importance of financial incentives to these market segments that represent the largest percentage of BEVs passenger cars sales in 2014, reaching 85% of the total registrations of BEVs in the European Union (EU-28) [40]. Secondly, the results emphasise the importance of designing non-financial incentive measures for the higher cars market segment, as an intensive use of the vehicle would allow to offset the purchase price differential. The interest of the consumer for these cars is well evident in the boosting of sales in this market segment with registrations increasing by more than 170% between 2013 and 2014 and representing already 13% of the total registrations of BEVs in EU-28 in 2014 [40]. Both these points demonstrate that financial benefits should be directed to lower market car segments and non-financial benefits should be more effective for high market car segments. Thirdly, the importance of technological developments ensuring both increased battery storage capacity and a widespread fast charging infrastructure are confirmed as fundamental drivers for BEVs market deployment for both car market segments allowing large distance travelling.

This analysis suggests then several avenues for further research.
In what concerns cost, integrating in the analysis the learning effect on both purchasing cost and vehicles efficiency would enrich the model providing relevant insights to policy makers, consumers and car manufacturers. Increasing the number of countries and car segments in the analysis could also provide a more comprehensive assessment allowing to consider different fuel and electricity prices structures and tax systems. Finally, the importance of future RES integration on power system should not be overlooked not only due to the expected environmental positive benefits of BEVs but also because of the impacts on electricity prices for end consumers. The analysis of both these issues require the development of energy planning models integrating BEVs impact on the load curve and allowing to further explore the economic and social effects of a possible combined EV-RES strategy.

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