INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 5, Issue 5, 2014 pp.535-558
Journal homepage: www.IJEE.IEEFoundation.org

Life cycle analysis and environmental effect of electric vehicles market evolution in Portugal

João P. Ribau, Ana F. Ferreira

LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, 6 Av. Rovisco Pais, 1, 71049-001 Lisboa, Portugal.

Abstract
Fossil fuel dependency in Portugal is represented in around 76% of the total primary energy use, from which almost half is associated to the road transport sector. The reduction of imported fossil energy, pollutants and CO_2 emissions is seen as a solution to a more sustainable energy system. This paper analyzes the market penetration of battery electric vehicles in the road transport sector as an alternative and more efficient technology, considering its maximum share in the transport sector in 2050. The main goal is to evaluate the energy consumption, air pollutants (including CO_2 emissions), and the economic impacts of conventional and electric vehicles in Portugal. The environmental Kuznets effect in the studied factors is also evaluated. Life cycle methodology was applied to the “fuel” production and use stage, and to the materials of the vehicle. Although reducing energy consumption and emissions is essential, the relation of such impact within the region economy is also extremely important. Based on a Kuznets curve hypothesis, some of those impacts were possible to co-relate with the gross domestic product evolution in Portugal. The evolution of the energy source share, energy production efficiency, vehicle type share in the Portuguese light duty vehicle fleet, and technology efficiency, was also considered. Although the electrification of the road sector can potentially lower the fossil fuel importation, the electricity demand should increase. Nevertheless, it is estimated that around 43% of the energy consumption, 47% of CO_2 emissions, and 17%-40% of air pollutants could be reduced with the expected electric vehicle evolution.

Keywords: Life cycle; Kuznets; Electric vehicle; Emissions; Energy consumption.

1. Introduction
Fossil fuels are at the center of global climate changes causing negative environmental impacts worldwide. In 2010, these energy sources accounted for around 76% of the Portuguese total primary energy consumption, being oil (49.1%), coal (7.2%) and natural gas (19.7%) the major fuel sources; and whereas renewable energy sources accounted for around 23%. The road transportation sector which was the sector that consumed more energy represented approximately 37% of the total final energy consumption in Portugal in 2010, and was responsible for about 30% of CO_2 emissions (Eurostat [1] and DGEG [2]). Oil, electricity and natural gas consumption have shown decreases of 2.7%, 4.1% and 5.3%, respectively, due to the increasing implementation of renewable energies and efficiency improvements. The 2003/30/EC European Directive aims to promote the use of biofuels and other renewable fuels instead of diesel or oil for transport purposes in each member state. In long term, this is expected to

contribute to the fulfillment of European climate change agreements (Directive 2003/30/EC [3]). The development of alternative vehicle technologies and new energy sources has been performed in the last decades. These are key factors to minimize the environmental and energy issues that the world faces. The strategies to reduce fuel consumption and emissions in conventional vehicles are one step to be taken into account [4]. The gradual electrification of the vehicle is one of the strategies adopted by the automotive industry and the policy makers. Vehicle electrification enables the improvement of urban air quality (no local emissions), the diversification of primary energy sources (electricity can be generated from a wider range of sources, not necessarily from fossil origin), and allows the use of more efficient propulsion technologies (such as regenerative braking and low consumption electric driven components). Several studies already address and compare alternative vehicle technologies such as battery electric vehicles (BEV) and plug-in electric vehicles (PHEV) with conventional vehicles, and also alternative fuels, such as the hydrogen. Ribau [5] uses life cycle methodology to compare different technologies, but it mainly focuses on the vehicle propulsion system, namely different engines for plug-in hybrid vehicles. In that study the energy consumption and CO_2 emissions from the fuel production and vehicle use were considered. Different kinds of engines and battery sizes showed to be more appropriate for different drive styles. Life cycle assessment (LCA) was applied in several studies to evaluate the energy consumption and CO_2 emissions of alternative fuels, like biohydrogen and biodiesel ([6-13]), and alternative vehicles ([8, 14-17]). Baptista [14] developed a model which consists in the analysis of scenarios of alternative fuels and vehicle penetration in road transportation sector in Portugal for the year 2050. However it doesn't focus on air pollutant emissions neither on possible economic impacts of such scenarios, namely on Gross Domestic Product (GDP) and Green Net National Income (GNNI). The analysis of GNNI and genuine savings considering the Kuznets curve in Portugal was performed by Mota [18]. The environmental Kuznets curve is a hypothesized relationship between various indicators of environmental degradation and income per capita. In rapidly growing countries, where little or no change in infrastructures or technology improvements are developed, a proportional growth of energy consumption, pollution and other environmental impacts relatively to the economy growth, is expected. This is also known as the scale effect, in which an economic growth can lead to an "environmental degradation". However, in wealthier countries, where growth rate is slower, and pollution reduction and energy efficiency policies are in effect, a leveling or decreasing of the "environmental degradation" along the economic growth can be developed, leading to the environmental Kuznets effect. In this kind of countries the development of the economy led also to the development of the technology, infrastructures, and services sectors, which usually results in efficiency and pollutant emissions treatment techniques improvement, therefore forcing the environmental degradation to cease or decrease.

In [19], a software was developed to analyze the performance of BEVs from the perspective of economic and environmental impact in the Tokyo area, considering three electricity generation mix options in Japan by 2030. However, the study didn´t considered a Kuznets effect analysis or relate the different indicators studied. Although in [20] the hypothetic Kuznets curve applied to carbon dioxide emissions and economic growth is studied, it didn´t focused other air pollutant emissions, neither in the transport sector. Regarding pollutants only, the Clean Air for Europe report (CAFE [21]) shows the cost-benefit of air quality considering the analysis of air pollutant emissions like $PM_{2.5}$, NH_3, SO_2, NO_x and VOCs and respective costs, from each European (EU25) Member State.

None of the previous studies covers both energy consumption and emissions, and its relation to a country´s economy impact, especially for the road transportation sector. Energy production and emissions have a tremendous impact in a country's importations share and political commitments. Therefore it is with major interest to relate both energy and emissions in Portugal with economic growth factors aiming to analyze from a sustainability point of view.

In this study the main objective is to estimate the influence of electric vehicle penetration in Portugal regarding evolution scenarios to 2050, in terms of energy, CO_2 and air pollutant emissions and its possible economic impacts. The existence of a possible environmental Kuznets curve effect regarding the energy consumption, CO_2 and air pollutant emissions (in light duty vehicle sector in Portugal) accounting the Portuguese GDP evolution, is analyzed. Although one of the objectives is to identify the Kuznets effect, some difficulties are expected in relating some factors that can have concurrent tendencies. One approach taken regarding the pollutant emissions was to assign a GDP and cause-effect dependent price to the emissions based on the GNNI. The energy consumption and emissions evaluation accounted the life cycle of the energy used in the vehicles and the materials used in vehicle fabrication. The evolution of the vehicle technology efficiency, the electricity generation mix, and the Portuguese road vehicle fleet evolution to the year 2050 is accounted.

From a point representing the current location of Portugal in a Kuznets curve (Figure 1) the possibilities of the future direction to take in order to achieve the objective/target, and therefore to decrease the “environmental degradation”, were highlighted. The attribute objective* in Figure 1 refers to energy consumption and emissions (which includes CO_2, NO_x, SO_x, VOC, CO, PM and NH_3 emissions) reduction target, due to political commitments, Kyoto protocol, ”20-20-20” targets and energy imports reduction targets in Portugal.

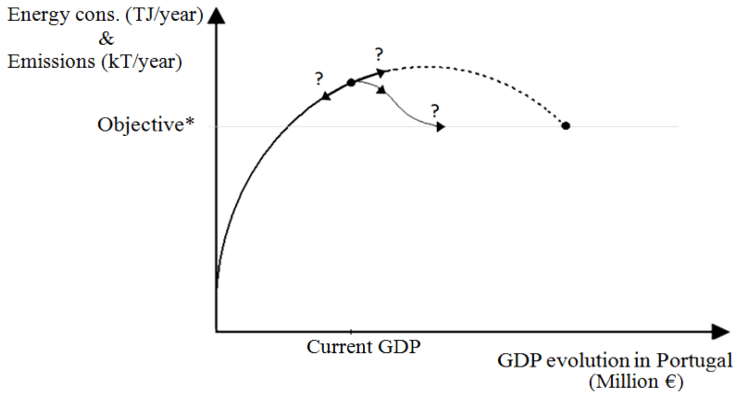

Figure 1. Representation of a possible Kuznets curve considering different scenarios to reach the objective (Energy consumption, Emissions (Particulate matter, CO_2, Greenhouse Gases,..))

2. Economic, energy, and emissions evolution in Portugal

2.1 GDP and population characterization

The GDP growth rate in Portugal in the last 20 years has been rather irregular (Figure 2). At the present time it is difficult to find a consensus in what would be the average GDP growth for the next years. The global crisis has caused a hitherto unseen fiscal expansion and economic uncertainty. The Energy Roadmap 2050, communication from the European Commission assumes an annual average GDP growth rate of 1.7% for EU-27 (European Commission [22]). Although it is easy to find supporters of the opinion that Portugal should have an average GDP growth above European levels in the next decades, it is more difficult to find supporters of the idea that it will be a reality. This ambiguity can be found on the socio-economic development scenarios set for Portugal in Figure 2. These scenarios, conservative and fénix, were based on a report on New Energy Technologies Competitiveness Analysis [23]. The conservative scenario is based on the: i) continuity of the development model of the last 15 years, an investment in non-transactional assets and low economic growth rate; ii) a reduction of the industry sector weight on the GDP and on the other hand an increase of the services sector; iii) a decrease in the population; iv) no changes in the transports. The fénix scenario is based on the: i) rebirth of the economy based on investment and policies for production of added value assets; ii) an increase of the industry sector share on the GDP and a decrease of the services sector share on the other hand, leading to a higher increase of the Gross value added in the industry sector; iii) an increase in the population; iv) new transport policies and habits towards a decrease of short distance traffic, less dependence on individual transport and a reinforcement of the rail transport for goods transport.

For the purpose of this work, the conservative scenario will be followed and therefore an annual growth of 1% for the Portuguese GDP will be assumed. At this point it is believed that the conservative scenario is the most realistic although it can change in some years. Therefore, a sensitivity analysis on the GDP growth rate will also be addressed. Within the same framework, it is of great interest to study the relation of both energy and emissions evolution in Portugal with economic growth factors, aiming to analyze a sustainability point of view and its possible impact in the country importation share and committed policies.

2.2 Energy and emissions characterization

The Portuguese energy consumption profile covers the energy use in the following sectors: industrial, transportation, domestic, electricity and heat, and services. The total energy consumption and CO_2

emissions are shown in Figure 3, regarding GDP evolution during year 1990-2008 (World Bank [24]). Note that the evidenced directions refer to the objective to be achieved, the energy use and CO_2 emissions decreasing, disregarding the GDP tendency (see Figure 1).

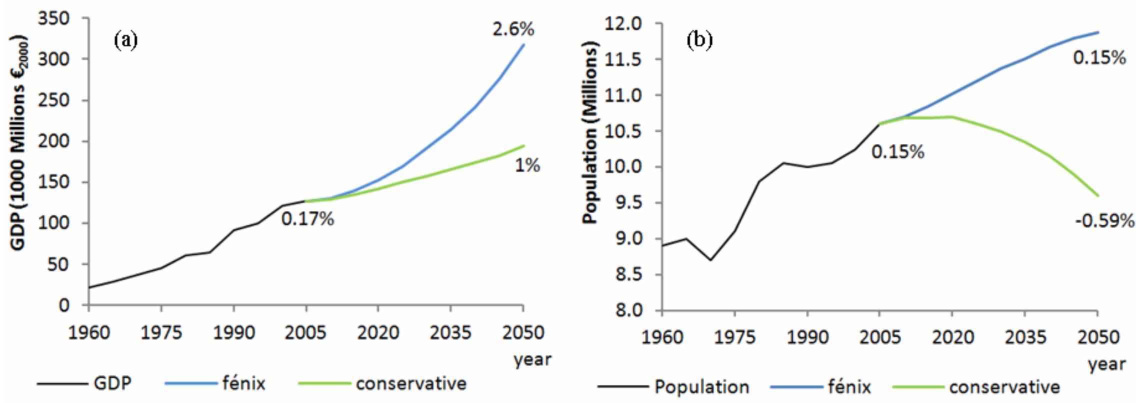

Figure 2. Two scenarios of GDP evolution (a) and population evolution (b) to Portuguese case, 1960-2050 (Adapted from [23])

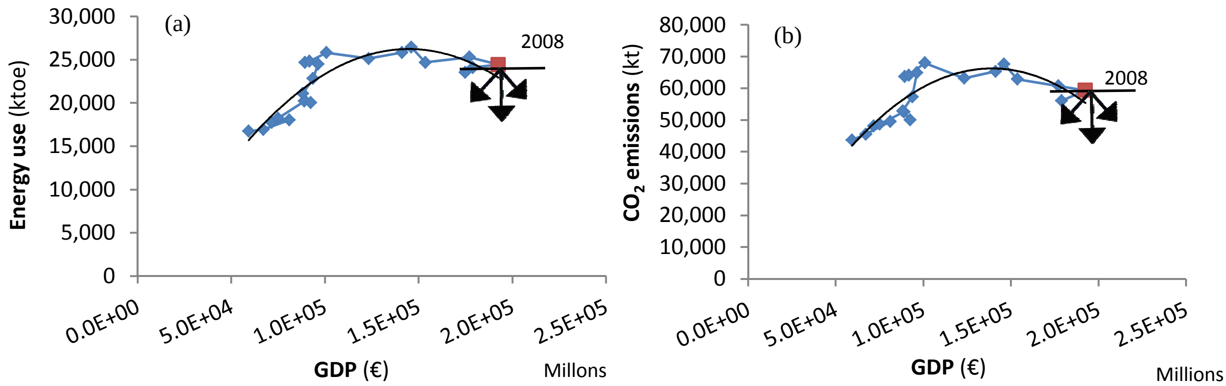

Figure 3. Relation between energy use (thousands of tons of oil equivalent) (a) and CO_2 emissions (thousands of tons) (b), as a function of GDP (current Euro €) evolution in Portugal (Adapted from Word Bank [24] data)

In this work the CO_2 emissions are considered separately from the pollutant emissions. Emissions are originated from the energy use described above and from industrial processes that emit directly and indirectly gaseous compounds (e.g. gasification processes).

It is interesting to see the resemblance between the energy use and the CO_2 emissions evolution (Figure 3), however note that the CO_2 has a more pronounced decrease in the last years (higher GDP values). Although the energy demand has increased along the years, the energy use efficiency also increased due to the technology improvements, therefore lowering the energy use in Figure 3. Besides the technology improvements, more strict political commitments like the Kyoto protocol and 20-20-20 directive had a very important role to lower the CO_2 emissions. The same can be applied to the pollutant emissions (Figure 4).

The pollutant emissions composed by sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$), ammonia (NH_3) and volatile organic compounds (VOCs), and their associated impacts are the main responsible for the total damages from air emissions (Figure 4) [25, 26]. Therefore those pollutants were considered in this study. Alike to the energy and CO_2 the same objective also applies to air emissions: to reduce the air pollutants. Despite GDP evolution, this objective is generally being achieved. The use of more improved processes and technologies are the major responsible in the emissions variation. The decrease of SO_x is directly associated to the decrease of coal based industries (e.g. coal power plants). Besides the increasing energy demand, the political commitments and regulation for pollutant emissions, as also technology progress (catalyzers, filters…), inverted or suspended that increase.

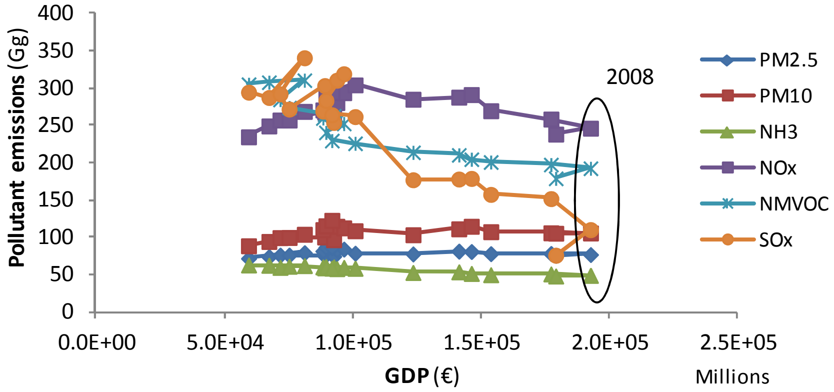

Figure 4. Total damages from air emissions (Gigagrams) as a function of GDP (current Euro €) in Portugal

In Figure 3, the directions highlighted by the black arrows are placed in the current GDP and represent the direction of the objectives since that year beyond, namely the energy use, CO_2 and air pollutant emissions decrease (the same can be assumed for Figure 4). This objective directions regard to the desired scenarios as mentioned in introduction. Assuming that the objective will be achieved one of three scenarios can occur (represented by one possible direction): the energy and emissions decreasing followed by a decline in GDP, a rising GDP, or GDP maintenance. These possibilities are pretended to represent a Kuznet curve shape in the relation of energy/environment and economic factors.

2.3 Green net national income

Unlike conventional accounting, "green accounting" goes beyond welfare depending on just marketed produced goods. Welfare is allowed to depend on health, environmental amenities, pollution levels, or availability of natural resources. These arguments can be seen as alternative forms of consumption, not consumption of conventionally produced goods but of natural resource services, health services, etc. [26, 27]. According to the theory of green accounting, finding a decreasing GNNI implies that in the future there will be a decrease in utility. Thus, according to the definition of sustainability as non-decreasing utility, this would indicate unsustainable development. The GNNI should account at least for the depletion of natural resources (minerals and forests), the health damages from air emissions (SO_2, NH_3, NO_x, VOC, $PM_{2.5}$) and the value of technological progress. The GNNI is defined by the following mathematical equation:

$$GNNI = GNI - CFC - e.E + \left(Q^R - f_R\right)\dot{S} + Q_t \tag{1}$$

Where, GNI is the Gross National Income, CFC is the Consumption of Fixed Capital, $(Q^R\text{-}f_R)$, $\dot{S}$ is the value of rents from resource stock depletion, e.E is the welfare cost of emissions (where e is the marginal damage cost of emissions in 2010 per metric ton in Portugal, and E is the amount emissions in metric tons), and Q_t is the time effect [16].
In this study it will only be considered the e.E factor, and other factors will be considered static. In other words only the emissions contribution will be accounted. To calculate the factor e.E in the GNNI, the marginal damage costs (€2010) by air pollutant in Portugal was considered, Table 1 (data from [20]).
In Figure 5 the considered pollutant emissions cost evolution in Portugal is shown. The cost share of each pollutant is directly related to its consequent damage associated cost (Table 1) and its emitted quantity in that year.
Particulate matter is the largest contributor to the total damages from air emissions, followed by SO_2. Both account on average for more than half of the total costs. But whereas, the emissions of SO_2 decrease, the emissions from $PM_{2.5}$ increase in average. In the last years the damages in human health derived from particulate matter, namely the $PM_{2.5}$ has been gaining more attention. As a percentage of GNI, the damages from air emissions have been decreasing. From 1990 to 2005 the best estimate is that the cost of air emissions in Portugal averages 8% of GNI with a decreasing trend [21].
The pollutant emissions accounting are generally done in a local basis. Using the GNNI methodology, pollutant emissions can be related to a country's sustainable development. The energy can be easily

related to the cost of the energy sources and energy importation, and the CO_2 can also be compared to a cost. With GNNI methodology it is possible to attribute a cost to each pollutant emission.

Table 1. Estimates of marginal damage cost by air pollutant in Portugal (€2010/ton)

damage costs (€2010/ton)	Best	Low	High
SO_2	6900	3500	10000
NH_3	7400	3700	11000
NO_x	2200	1300	3200
VOC	1200	500	1600
$PM_{2.5}$	44000	22000	64000

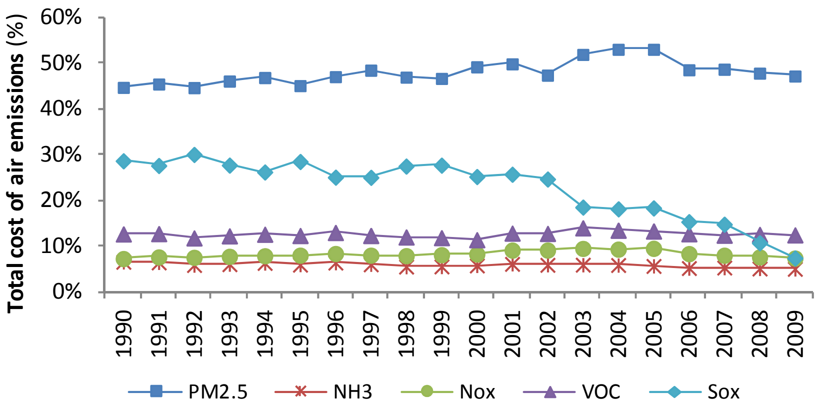

Figure 5. Annual evolution of the cost share of air pollutant emissions in Portugal

3. Road transportation sector and electric vehicle market penetration

The case study considers the Portuguese road transport sector, namely the LDV fleet energy consumption and emissions analysis. Figure 6 shows the evolution of Portuguese LDV fleet and the new diesel vehicle registrations share along GDP from 1990-2008.

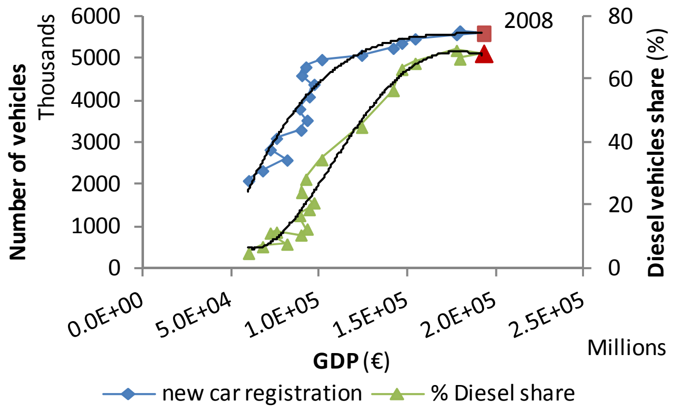

Figure 6. Light duty vehicle fleet in Portugal, the number of vehicles and the market share of the diesel LDV (%)

In the last years, the increasing fuels prices, namely gasoline, led to the diesel market share growth. Although gasoline vehicles are the majority, the share of diesel in the road vehicle fleet has increased. Generally, the road vehicle fleet has grown in recent years; however that tendency is slowing [24]. Figure 7 shows the energy consumption and CO_2 emissions evolution, regarding the road vehicle sector, relatively to the Portuguese GDP [24]. Once again the objective is well highlighted in the presented figures concerning to the decreasing of energy and emissions.

The evolution of GDP and road sector energy consumption per capita of the past two decades is presented in Figure 8 [23, 24], indicating an average growth of both indicators. The energy consumption of the road sector and the emissions after a strong increase slowed down. This follows the new car registration tendency, and the increased efficiency in the vehicles due to technology and regulation actions (Figure 9).

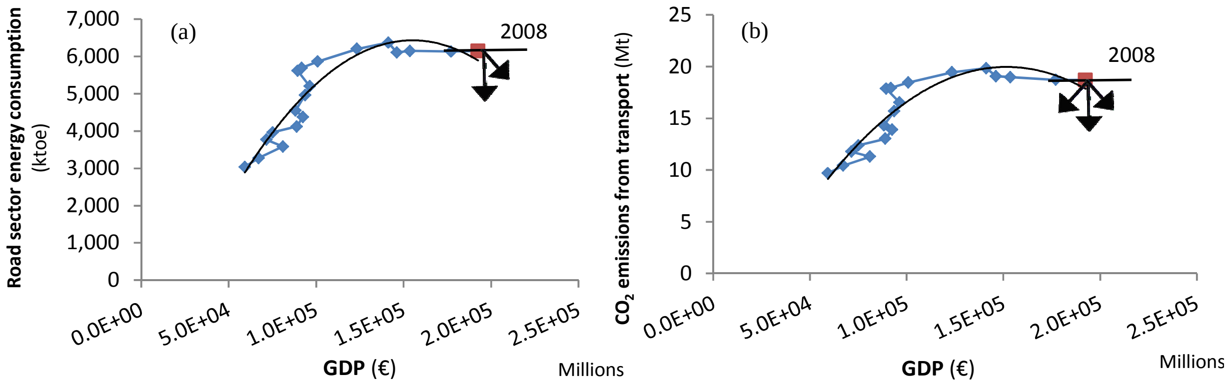

Figure 7. Energy consumption from road transport sector (ktons of oil equivalent) (a) and CO_2 emissions from transport sector (millions of metric tons) (b) as a function of Portuguese GDP

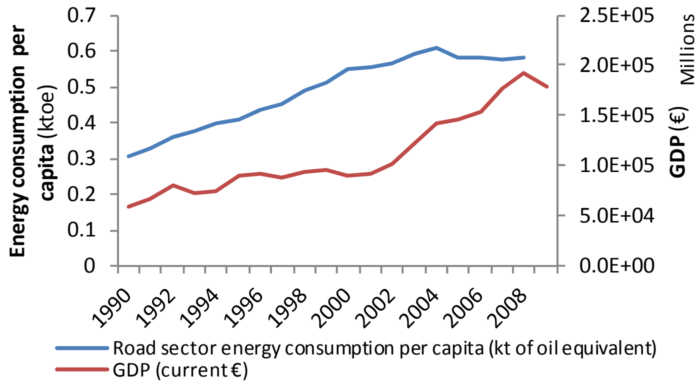

Figure 8. Evolution of road sector energy consumption (ktoe) per capita and GDP 1990-2009 in Portugal (Adapted from [24])

There are several studies concerning alternative vehicle market penetration (MOBI.E [28], and McKinsey&Company [29]). In this study, estimations resulting from a developed model (Baptista [14]) were used. This model, besides estimating the BEVs future market (Figure 9) also considers the efficiency improvement of the vehicle technology. This improvement has a linear progress to 2050, and besides used in energy consumption calculations, it was also used in the same proportion to calculate the emissions [14]. In this scenario the energy consumption (Tank-to-Wheel stage) in gasoline LDVs and diesel LDVs is expected to decrease to around 35.7% by 2050, while BEVs to decrease 25.4%.

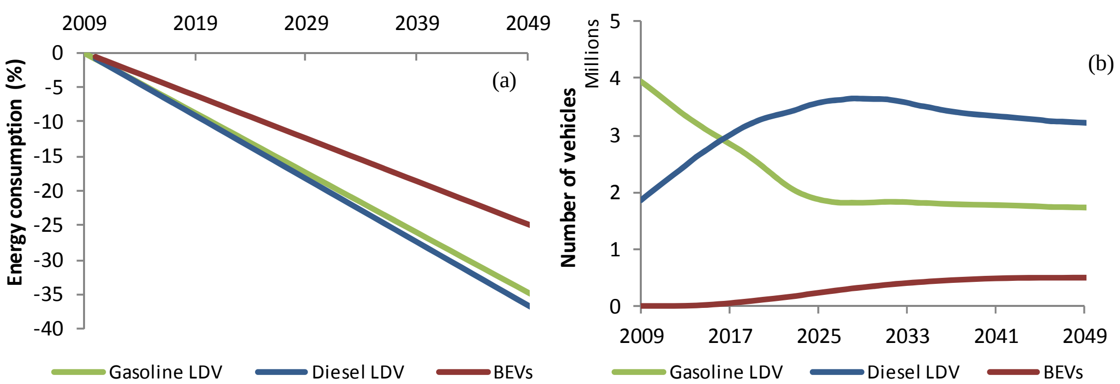

Figure 9. Vehicle energy consumption evolution in TTW (%) (a) and number of vehicles of the Portuguese fleet (b) (Scenario 2010-2050)

4. Life cycle analysis

The evolution trend of conventional and electric vehicle technologies towards 2050 would be evaluated accounting energy consumption, CO_2 and air pollutant emissions. This type of evaluation is performed using the life cycle analysis (LCA) methodology. LCA is an important tool to estimate the energy balance and environmental impact of a system. It can be used also to compare different energy systems including vehicle technologies and production systems ([30]). In this study the Principles of ISO 14040-14044 [31] are followed. The energy and emissions impacts of advanced vehicle technologies and new transportation fuels evaluation were assessed using a specific LCA for fuels and vehicles, the Well-to-Wheel (WTW) and Cradle-to-Grave (CTG) analysis. The WTW analysis is often divided into Well-to-Tank (WTT) and Tank-to-Wheel (TTW) assessment. WTT starts with the fuel feedstock production, followed by fuel production, and ends with the fuel distribution to the pump or vehicle tank, while TTW focus on the fuel utilization at the vehicle operation. The main difference between WTT and TTW lies in the delimitation of the system boundary. In some vehicle analysis studies, such as [8, 30, 32], TTW and WTT are combined, considering the fuel and its application in light duty vehicles. CTG consists in the analysis of the materials used in vehicle and it can be added to WTW analysis. Energy consumption and CO_2 and air pollutant emissions are accounted in WTT, TTW, and CTG. The present work will be focused in LCA, including the energy production (WTT), energy use (TTW) and material used in the vehicle (CTG). An energy cost analysis would be also included in this study.

4.1 Tank-to-wheel

The TTW stage considers the energy consumption and associated CO_2 and other air pollutants emitted by the vehicle/fuel combination. For simulating conventional or alternative vehicle technologies, ADVISOR vehicle simulation software [33] was used. ADVISOR is a micro-simulating tool to estimate the performance, fuel economy, and tailpipe emissions of conventional and new vehicle technologies (hybrid and electric powertrains). This software was used in several studies for vehicle simulation (some already mentioned in Section 1) such as in [30]. Vehicle specifications (detailed in Table A.1 in Appendix A) and a real driving cycle Cascais-Lisboa (specifications in [8]) were the main inputs used in this study. The vehicles chosen for the simulations are based on existing vehicles and available data. They all meet a close value of the power/weight ratio. The BEV, since it doesn´t have any combustion engine will not present local emissions on the TTW stage. The main goal of TTW is to compare the BEV operation with the conventional internal combustion engine vehicles. An average of EURO 4 and 5 standards [34] is used to validate the emissions from the conventional gasoline and diesel vehicles (Table 2).

Table 2. Reference values to EURO emissions in light duty vehicles

(g/km)	Tier	Date	CO	THC	NMHC	NO_x	$HC+NO_x$	PM
Diesel	Euro 4	Jan-05	0.5	-	-	0.25	0.30	0.025
	Euro 5	Sep-09	0.5	-	-	0.18	0.23	0.005
Gasoline	Euro 4	Jan-05	1	0.1	-	0.08	-	-
	Euro 5	Sep-09	1	0.1	0.068	0.06	-	0.005

The energy consumption and the emissions that resulted from the vehicle simulations are presented in Section 6. Note that the evolution of the vehicle technology is accounted as shown in Figure 9.

4.2 Well-to-tank

WTT accounts for the energy consumption and emissions from the primary energy resource extraction through the delivery and process of the fuel to the vehicle's fuel tank (the same applies for electricity). For the WTT analysis the EcoInvent 2.0 database for SimaPro 7.1 software, was adapted for the average Portuguese electricity generation mix, [34] was used to estimate the electricity generation air pollutant emissions.

In this study the electricity is used as "fuel" to the BEV, and its WTT stage data was based in previous works such as [6, 9]. The Portuguese electricity production mix is composed by 49% of non-renewable and 51% of renewable energies (2010 data), with 8 % of energy losses in distribution [30, 35-37]. The resulting energy consumption in order to obtain 1 MJ of electricity generated was 1.02 MJ. A more detailed description of the Portuguese electricity mix is shown in Table A2 (Appendix A).

Following the EcoIvent database the Portuguese electricity generation emits around 174940 kg CO_2/TJ (2004 data). The same database also provides data on the pollutant emissions (Table A3 of Appendix A). However, new and updated values of CO_2 emissions were calculated as 87.190 g CO2/MJ due to improved power plant efficiencies and electricity mix. Then, the emissions from electricity production (Table A3) were proportionally updated regarding updated CO_2 data from [6, 34], as shown in Table 3.

Table 3. Updated CO_2 and pollutant emissions factor for energy production in Portugal 2010

(g/MJ)	CO_2	CH_4	CO	VOC	NO_x	PM	SO_x	NH_3
Gasoline	18.076	0.109	0.016	0.200	0.062	0.007	0.116	7.356E-06
Diesel	9.432	0.099	0.014	0.186	0.046	0.004	0.045	4.439E-06
Electricity	*87.190*	0.133	0.025	0.094	0.227	0.054	0.760	9.968E-05

*Considering 42.8 MJ/kg to diesel and 43.5 MJ/kg to gasoline of LHV.

The evolution scenarios developed in this study were based in the model first developed by [14], which includes also the electricity production efficiency improvement and electricity generation share evolution through the years to 2050 (see Figure 10). The tendency used from the previous model [14] was adjusted to the electricity production and updated by the author in [6] and Table A2 (Appendix A). Table 4 presents the electricity production efficiency and its resulting emissions following the electricity generation mix and plant evolution from Table 3 and Figure 10.

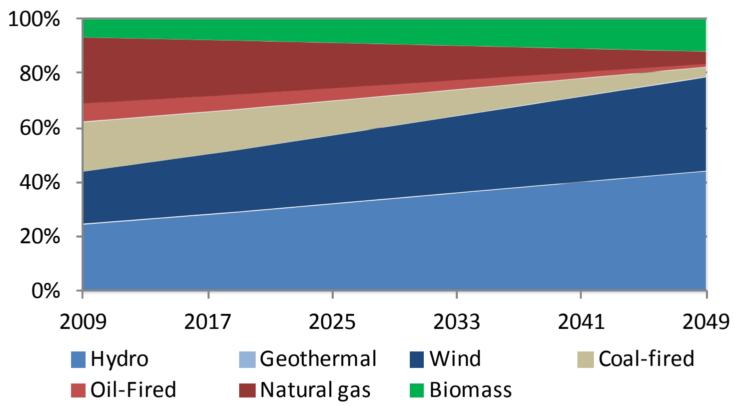

Figure 10. Electricity generation mix evolution scenario 2009-2050

Table 4. Energy and emissions factors of power generation regarding the adjusted electricity mix scenario 2009-2050

	2010	2020	2030	2040	2050
Energy consumption (MJ/MJ)	1.021	0.836	0.651	0.467	0.281
Produced emissions (g/CO_2)	87.19	69.92	52.64	35.37	18.10

The WTT methodology for the gasoline and diesel includes similar processes but different refineries. The following processes were considered: crude extraction, crude transportation, crude refinery and storage and distribution. The WTT data considered in this study for diesel and gasoline is based in [30]. The evolution of the efficiency of diesel and gasoline production from present year to 2050 was not considered to change. In order to obtain 1 MJ of gasoline and diesel fuel, 0.14 MJ and 0.16 MJ of energy is consumed respectively, and 12.5 grams and 14.2 grams of CO_2 respectively (Table A.4 of Appendix A). Pollutant and CO_2 emissions data was also calculated from Eco Invent database [36] (Table A.3) and thereafter updated accounting Portugal present energy efficiency values for fuel production (Table 3)

4.3 Cradle-to- grave

For the CTG stage, the GREET (The Greenhouse Gases, Regulated Emissions, and Energy use in Transportation Model) software from the US Argonne National Laboratory was used, namely GREET 2.7 model [38]. CTG accounted only the materials used in the vehicle. Besides the vehicle power train,

body and frame materials, the replacement of consumable elements of the vehicle, such as fluids, tires, batteries, lubricants are also considered (Table A5 of Appendix A).
The total energy and CO_2 emissions of the CTG pathways were distributed along the vehicle lifetime kilometers traveled. In this study it was considered to be 200000 km (Directive 2009/33/CE [39]). Once this study reflects a Portuguese scenario, the Portuguese electricity generation mix evolution (Figure 10) was introduced in this stage also and accounted in the fabrication processes of the materials.

5. Energy cost estimations

The price of oil in international markets highly influences the price of diesel and gasoline. The price of oil is the price with the highest unpredictability in the primary energy market. The estimated oil derivate fuels prices and new road vehicle technologies evolution scenarios were approximated by a linear tendency of growth. Table 5 indicates the estimated prices to the user (based on [40]).

Table 5. Prices estimation of oil, gasoline, diesel, and electricity to the user.

Year	Oil ($/bbl)	Gasoline (€/L)	Diesel (€/L)	Electricity (€cent/KWh)
2010	120	1.69	1.539	15.98
2020	150	1.96	1.827	21.5
2030	200	2.40	2.307	27.5
2040	230	2.66	2.595	33.5
2050	280	3.10	3.075	40.8

The scenarios developed by the European Commission, 2011 indicate an increase in the generation costs for electricity that will have to be reflected in the consumer price. This increase is mostly due to the introduction of new technologies in the electricity generation (namely renewable energies), the introduction of carbon tariffs, fossil fuels price increase (oil, coal and gas) and the construction of new generation facilities. Assuming that most of the users will charge their BEVs at home, the domestic tariff evolution is considered. The taxes evolution on the electricity energy was not considered in this study.

6. Results and discussion

6.1 LCA applied to light duty vehicle estimations

The proposed vehicles, a BEV, a diesel and gasoline internal combustion engine vehicles (detailed in Appendix A, Table A1) were simulated in ADVISOR software. The diesel and gasoline vehicles achieved 2.10 MJ/km and 2.46 MJ/km of energy consumption, and 156 g/km and 179 g/km of CO_2 emissions respectively. The BEV in the same conditions achieved 0.43 MJ/km and zero emissions.
The evolution of TTW energy consumption, CO_2 and air pollutants emissions per vehicle for years 2009-2050 was regarded, and was estimated based on the technology efficiency tendency (Figure 9) for each vehicle. In Table B.1 and Table B2 (Appendix B) the TTW values achieved for the 2009-2050 scenarios are presented. As expected, the vehicle technology improvements lead to the energy consumption and emissions decreasing. The energy consumption and emissions are estimated to decrease around 37% and 25% for conventional and electric vehicle, respectively, by 2050. In order to calculate the total energy consumed in TTW stage, the number of vehicles (Figure 9), the vehicle type share in Portuguese fleet (diesel, gasoline and BEV), and daily travelled distance were accounted. It was considered that LDVs in Portugal travel in average 22 km.day-1 [41].
In the WTT stage the evolution of the electricity generation mix in Portugal to 2050 resulted from an electricity mix scenario for the years 2009-2050 in Section 4.2. The results of WTT energy production efficiency, CO_2 and pollutants emissions for a scenario 2009-2050 are summarized in Tables B3 and B4 (Appendix B). In this scenario the WTT factors in terms of energy and emissions are maintained at 0.140 and 0.160 for gasoline and diesel, respectively. However, for BEV, regarding the electricity production, it's possible to see a reduction of energy and CO_2 emissions from 1.021 MJ/MJ to 0.281 MJ/MJ and 87.192 gCO_2/MJ to 18.096 gCO_2/MJ. The pollutants emissions values relatively to the energy required by the vehicles were also reduced. This reduction in WTT stage is mainly due to the expected power plants efficiency improvements and renewable resources increasing in Portuguese electricity generation sector. Nevertheless, it can be seen that (per MJ) the electricity production is still responsible for larger losses than the diesel or gasoline production. Besides the electric vehicle do not emit local air pollutants

(in the usage phase), the energy consumption and emissions associated with the energy production (WTT) are responsible for a major share of the life cycle of this vehicle.
The energy that is consumed in the plants to produce the diesel, gasoline or electricity used in the respective vehicles can be seen as the energy losses during the fuel production (see Appendix B, Table B3 and B4). Multiplying those values (MJ/MJ and g/MJ) by the diesel, gasoline and electricity consumed in the vehicle fleet (MJ/km) (Table B1 and B2) allows us to determine the actual energy consumed (and emissions) in the WTT stage due to the usage of such fuel.
The energy consumption and emissions associated to the materials used in the vehicles are presented in detail in Appendix B, which accounts also with the electricity mix evolution used in the 2009-2050 scenario, since the electricity is the main energy used in material fabrication. Around 0.416 MJ/km and 0.420 MJ/km are regarded to the CTG energy consumption for the gasoline and diesel vehicle respectively, and around 24.3 g/km and 25.1 g/km of CO_2 emissions. Accounting with the evolution scenario, by 2050 is expected that CTG energy consumption should decrease around 16.7% for both conventional vehicles, and around 21% for CO_2 emissions. Although the BEV accounts higher CTG energy consumption and CO_2 emissions, respectively 0.531 MJ/km and 32.0 g/km, its reduction potential by 2050 is also expected to be higher, around 27.7% and 36.7% for energy and emissions respectively.
Figures 11 to 13 show the evolution of the LCA energy consumption and emissions, composed by TTW, WTT, and CTG, of the Portuguese fleet.

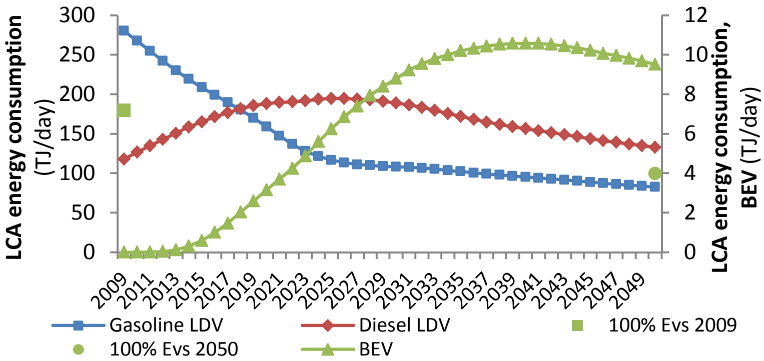

Figure 11. Evolution scenario of LCA energy consumption (TJ/day) regarding energy production efficiency and electricity mix, regarding energy production efficiency, LDV fleet evolution and technology improvements to 2050

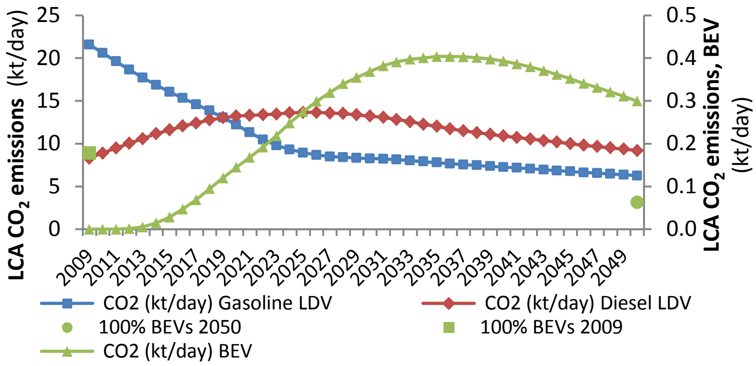

Figure 12. Evolution scenario of LCA CO_2 emissions (kton/day) regarding energy production efficiency and electricity mix, regarding energy production efficiency, LDV fleet evolution and technology improvements to 2050

Note that the evolution shown in Figures 11 to 13 accounts with the influence of the vehicle technology improvements (Figure 9), the electricity generation evolution (Figure 10), and the Portuguese vehicle fleet evolution, including the BEV penetration. In Figures 11 to 13 two extreme scenarios are highlighted in single data points: “100% BEVs 2009” and “100% BEVs 2050” concerning to 100% of the Portuguese LDV fleet represented by BEVs in 2009 or in 2050 respectively. This means the total LDV fleet to be composed by BEVs in those cases.

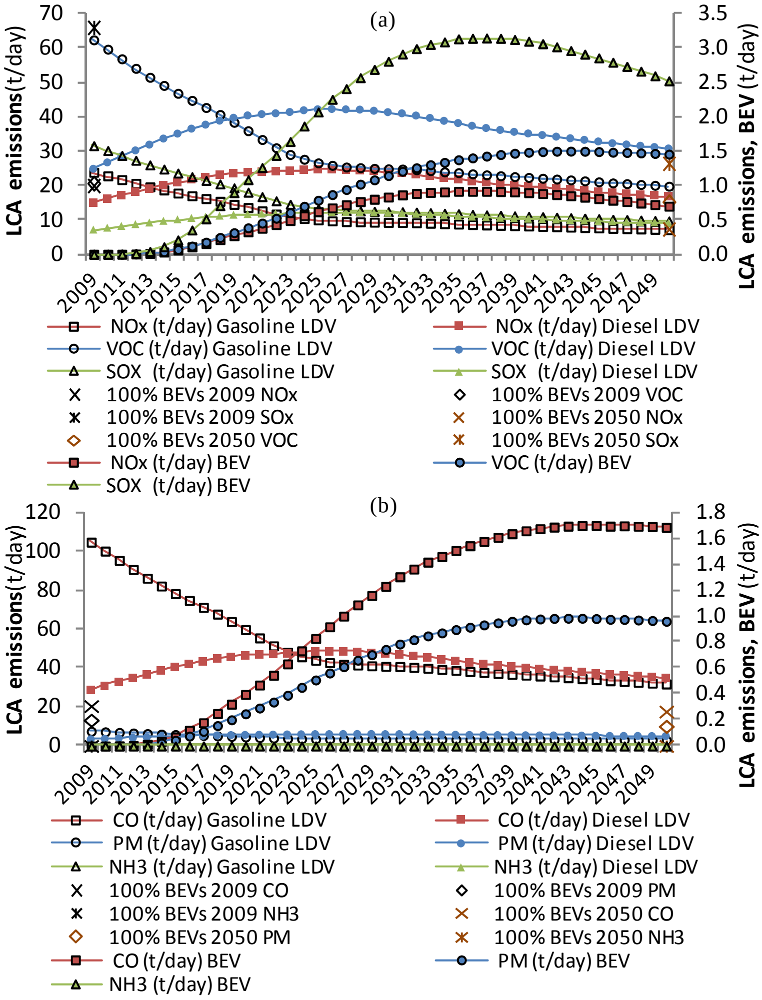

Figure 13. Evolution scenario of LCA NO_x, SO_x and VOC emissions (ton/day) (a) and CO, PM and NH_3 emissions (ton/day) (b), regarding energy production efficiency, LDV fleet evolution and technology improvements to 2050

As the number of the gasoline vehicles decreases and its efficiency gets better, the gasoline demand diminishes. In the other hand, the diesel demand is expected to grow as long as the number of diesel vehicles increases (Figure 9), however, the efficiency improvement of the vehicles overcomes this tendency and the diesel demand should decrease to values near the 2009 (Figures 11 and 12). Regarding the BEV introduction, the increase of the vehicle number lead directly to the increase of the energy and emissions associated to BEV energy use, production, and vehicle fabrication. Nevertheless that increase is overcome by the technology and efficiency improvements which invert the growing tendency.

In resume, the electrification of the LDV sector in Portugal, when followed by technology and energy production evolution, has the tendency to reduce the energy consumption and emissions in the life cycle of the road transport sector. The technology and electricity generation efficiency improvement evolution are clearly an important issue. If 100% BEV's scenario was introduced in nowadays a large amount of electricity would be required to supply the entire BEV fleet, and then the energy consumption and emissions due to the electricity production should rapidly increase. Nevertheless, the efficiency of the electric vehicle (TTW) is still a great advantage relatively to conventional vehicles; and emissions and energy consumption regarding the LCA maintain lower than gasoline and diesel vehicles.

Figures 14 and 15 show the evaluation of the energy and emissions variation for the total LDV Portuguese fleet in respective year, regarding the considered scenario of BEVs market penetration. A reduction of around 44% and 47% of energy consumption and CO_2 emissions respectively, of the LCA associated to the LDV sector can be achieved by 2050, and around 40%-52% the air for pollutant emissions (17% for PM emissions). In these figures, it can be seen the two extreme scenarios of 100% BEVs fleet share highlighted by single data points.

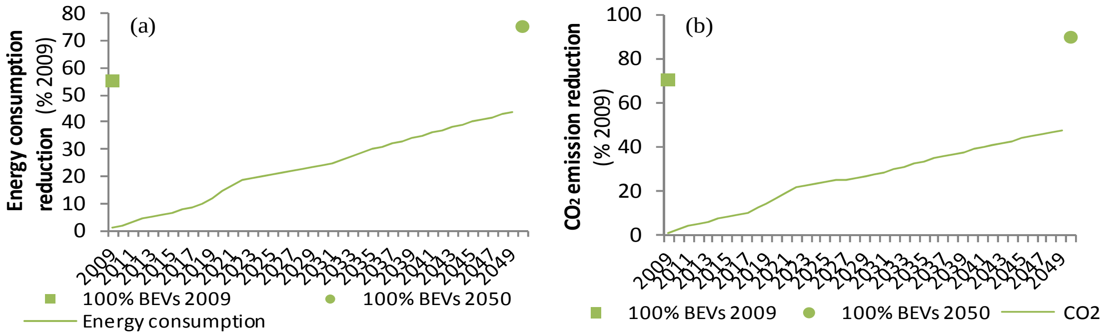

Figure 14. Percentage of energy consumption (a) and CO_2 emissions (b) decrease, for the total LDV fleet in comparison to 2009 values

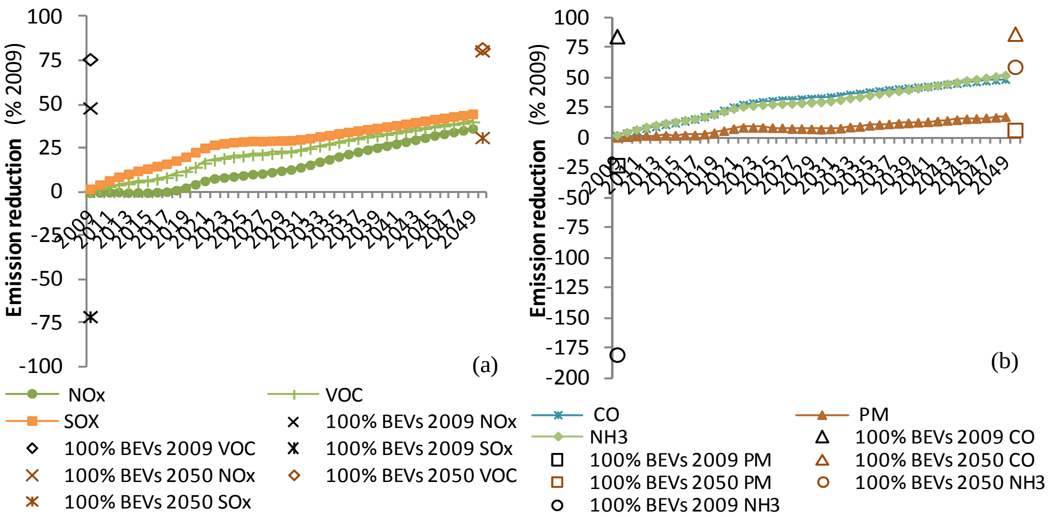

Figure 15. Percentage of NO_x, SO_x, VOC emissions (a) and NH_3, CO, PM emissions (b) decrease, for the total LDV fleet in comparison to 2009 values

The increase of the electricity demand due to the electric vehicle increase in the Portuguese fleet will allocate the resulting energy and emissions from the fuels sector to the electricity generation sector. The Tables B.1 to B.4 show that the electric vehicle is more efficient and less pollutant in the TTW stage, however the inverse occurs in WTT.

As in Figure 14, it can be seen in Figure 15 that emissions are decreasing due to the electrification of LDV sector. However if 100% BEV were introduced in Portuguese LDV fleet in 2009 some emissions, such as PM, NH_3 and SO_x, would not decrease, but would suffer an increase. This result was expected because in 2009 the electricity production is still much dependent of thermal power plants, responsible for those emissions that result from combustion processes. On the other hand, if the total Portuguese fleet was replaced by BEVs in 2050, it would lead to a decrease in energy consumption and emissions with no exceptions.

If no electricity generation improvements evolution were accounted the reduction of energy would have lower values, of around 37%. The CO_2 and pollutant emissions would have lower reduction tendencies also, of around 42% and 20%-47% respectively (6% for PM emissions). If additionally, the vehicle technology improvements evolution were none, the energy consumption reduction would be around 10%, the CO_2 emissions reduction 15%, and the reduction of SO_x and VOCs would be 4% and 25%, respectively. The NO_x, PM, and NH_3 emissions tendency would be inverted and increase 3%, 3%, and 16% respectively.

In Figure 16 the share of the different LCA stages (TTW, WTT, and CTG) is highlighted, and the influence of the efficiency of the vehicles (TTW) can be observed, especially regarding the energy consumption, CO2, CO and NO_x emissions. On the other hand, the other pollutant emissions, VOC, SO_x, NH_3, are associated to the energy production efficiency. The CTG stage has a major influence in the PM emissions. Although the increase of the BEV share lead to the increase of electricity demand, and to the increase of the vehicle battery fabrication impact (which has a major influence in the CTG), the evolution of the WTT and CTG factors cease a possible energy and emissions growth. The energy consumption has its major influence in TTW stage, since the fleet is most composed by internal combustion engine vehicles, but the process of diesel and gasoline production (WTT) is more efficient than the use of the fuel itself in the vehicle (TTW stage). Following the same idea, due to the energy consumption share and the energy production characteristics the CO_2 and CO emissions are most relevant in TTW. NO_x emissions appear to be divided between TTW and WTT stages although with a little more expression in TTW. Since the diesel internal combustion engine is responsible for a large quantity of NO_x and PM, it can be seen in Figure 16 that these emissions increase along the number of vehicles until technology improvements invert this tendency. The production of energy (WTT), especially electricity, is responsible for the largest share of SO_x, VOC, NH_3 and PM emissions. Although the electrification of the road sector should lower the fossil fuel importation the electricity demand should increase, depending on the power plants evolution.

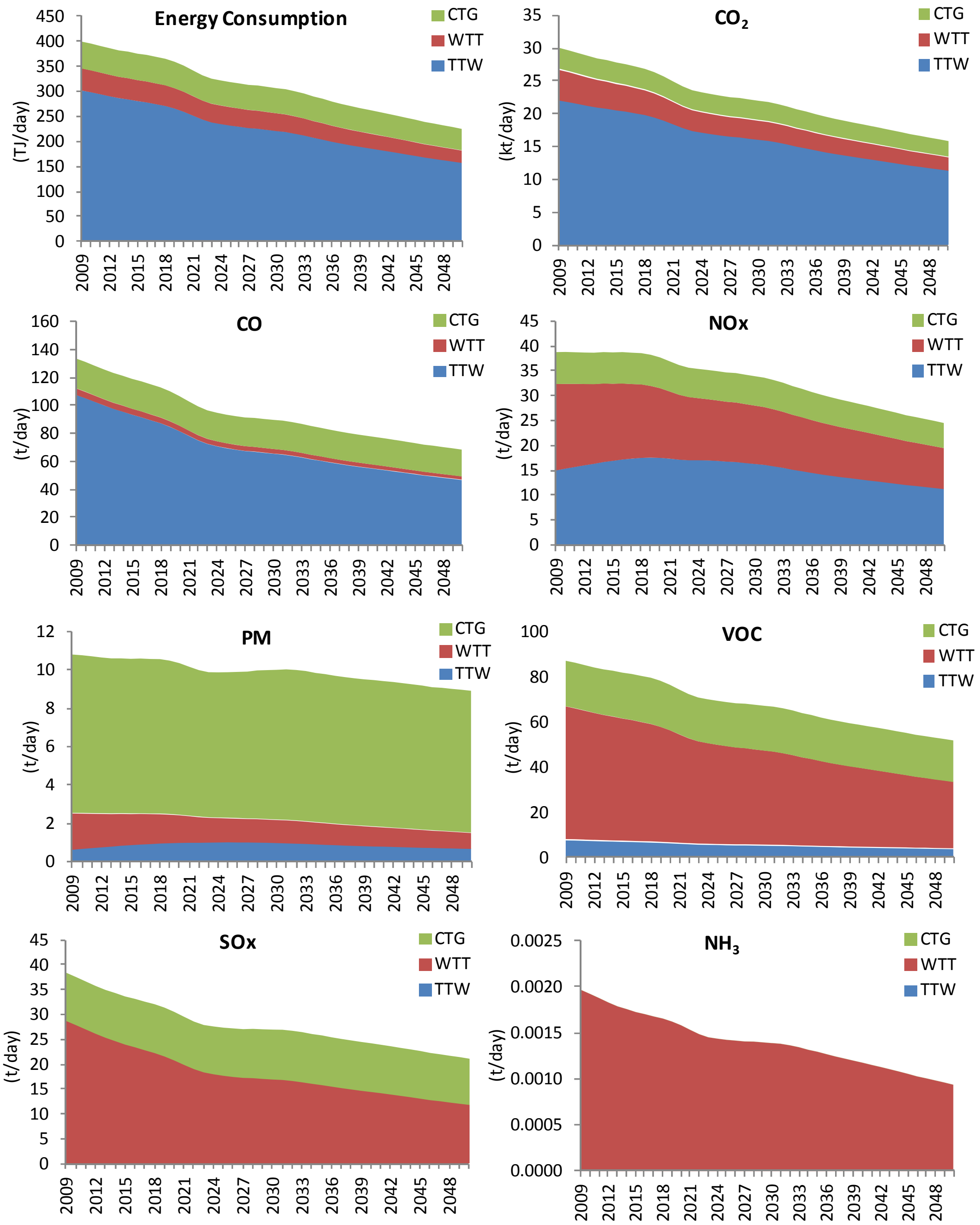

Figure 16. Energy production (WTT), energy use (TTW) and vehicle materials (CTG) energy consumption and emissions share, considering the total LDV fleet. Estimations from 2009 to 2050

6.2 Welfare cost of emission

The total air emissions in Portugal, accounted a total cost of 5,640 M€ (regarding the price per ton of Table 6), and the LDV sector is responsible for around 3% of the total air pollutants emissions in Portugal [25]. The price of pollutants will be taken static to 2050; however the cost of emissions of LDV sector will take into account the evolutions already estimated in previous sections (Figure 17). The cost of pollutants in Table 6 represents the welfare cost of emission associated to the GNNI (Section 2.3). Figure 17 shows the evolution of the damage cost of air emissions (in 2010 euro) regarding the electric vehicle penetration scenario. The cost of emissions is decreasing, however if 100% of electric vehicle substitute the entire fleet in nowadays only PM, VOCs and NO_x emissions would be lower.

Table 6. Damage costs of air pollutants emissions (in 2010 euro) regarding the LDV sector, and value of welfare cost of LDV emissions in 2010

	(€2010/ton)	Emissions LDV sector (Gg)	e.E (€)
SO_2	6900	0.32766	2260854
NH_3	7400	1.27029	9400146
NO_x	2200	32.16328	70759216
VOC	1200	10.52491	12629892
$PM_{2.5}$	44000	2.15363	94,759,720
Total			189,809,828

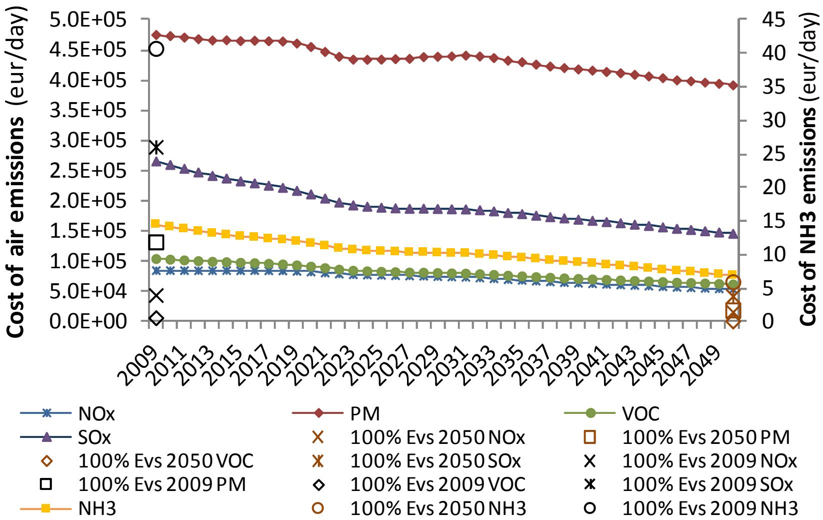

Figure 17. Evolution of the damage cost of air emissions (in 2010 euro)

6.3 Costs to the consumer

Nowadays, the cost of the vehicle sustenance is very important. The energy prices, such as gasoline, diesel and electricity, belong to a very dynamic market, and they are far to be static. Figure 18 resumes the calculated energy cost per distance traveled regarding energy costs and vehicles energy consumption evolution. In Section 5 it was shown that the price of the energy should increase. However, in Figure 18, the costs per kilometer increase but do not follow the same rate of increase. This is due to the technology improvements that slow down this tendency since a better efficiency of the vehicle reduces the energy consumption. If this scenario maintains, and if the BEV infrastructure becomes successful, the lower cost per kilometer of the BEVs may accelerate the BEV purchase and the fossil fuels turnover.

7. Final considerations

Regarding the evolution of energy consumption and emissions as function of the Portuguese GDP evolution, presented in results, a clear tendency can be seen. This tendency may have a similar shape of a portion of a Kuznets curve. This portion is exemplified in Figure 19, where along the GDP increase a variable X takes an approximated polynomial tendency. Along the GDP growth the variable X is decreasing. The variable X can take the form of the main results of this study. The continuation of the curve, in Figure 19 (direction (a)), can be seen as the evolution of the cost of emissions, energy consumption, and emissions per GDP in Figures 20 and 21. Then, although in some variables the variation with the GDP is not very wide, it can be accepted that either price of emissions, energy consumption, and emissions are decreasing along the GDP growth, suggesting the possible Kuznets effect.

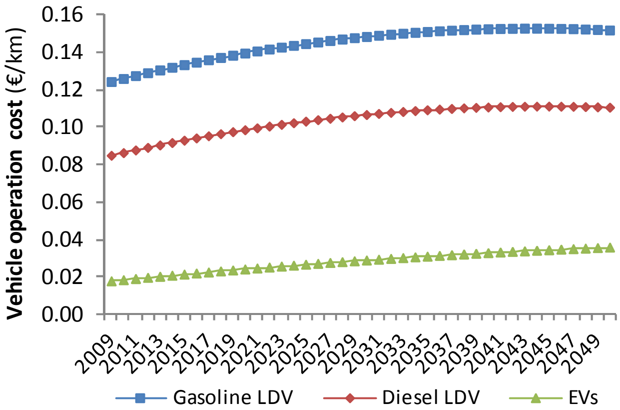

Figure 18. The price of the energy per kilometer to the consumer

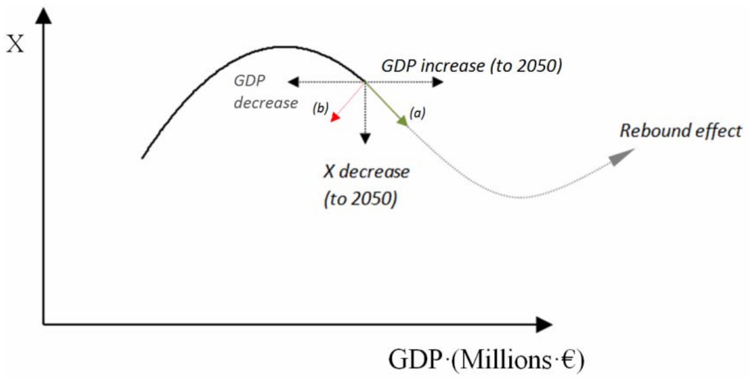

Figure 19. Example of a possible Kuznets effect regarding variable X and GDP. Conservative and fénix scenario (a) and pessimist scenario (b)

In Figure 19 a possible rebound effect is shown. This event occurs when the tendency of the Kuznets effect is inverted, and can be associated to indirect factors. The GDP from literature data is expected to be growing continuously, and maintaining that tendency, a possible rebound effect in the future can occur, if hypothetically:

- The electricity production efficiency improvements lead to cheaper electricity. Thus, since it becomes cheaper to travel per km (regarding BEV market), it is possible that the distance travelled per year increases, then consuming more electricity. The same effect can be achieved if the LDV fleet increases more than the expected.
- The BEV market increases but the electricity production efficiency doesn't meet improvements. The higher demand for electricity in power plants can lead to an unexpected growth in energy consumption and emissions. This can be seen in Figure 15 for PM, NH_3 and VOC emissions in the scenario of 100% BEVs 2009.
- The vehicle technology evolution achieves no or very little improvements.

Although the most reliable data researched was used at the time of this work, it is known that is very difficult to gather consistent data covering all the topics in this study. Additionally, these data estimations can easily vary accordingly to the economic evolution and political targets of a country. The more accurate the estimations and scenarios used in the input data in the methodology, more accurate results are produced. The estimations in this study can suffer some variations due to that variance of the inputs however the tendencies should remain. Nevertheless, it is expected that in long term the estimations of the GDP growth, and the decrease of the energy use, and emissions, as also the increase the electrification of the road vehicle sector, are expected to remain. In nowadays it's possible to see that the objectives regarding CO_2 emissions and energy use are slowly being accomplished.

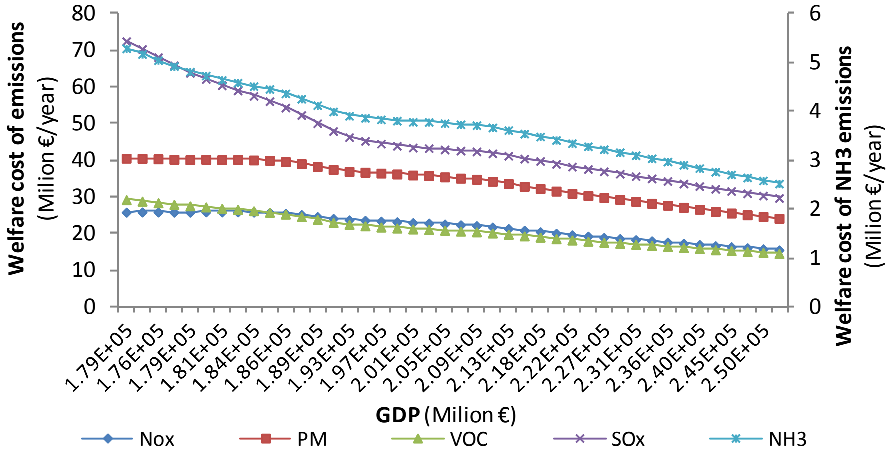

Figure 20. Welfare cost of pollutant emissions per GDP estimation from 2009-2050

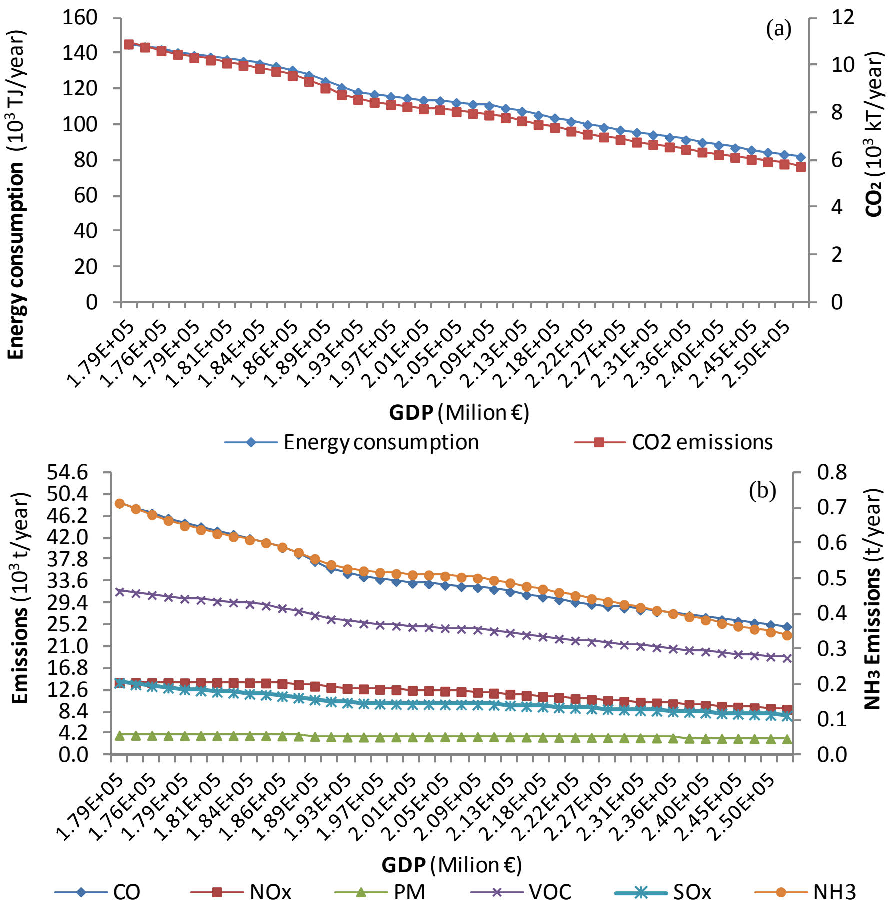

Figure 21. Energy and CO_2 emissions (a), and pollutant emissions (b), regarding GDP estimation from 2009-2050

A brief sensitivity analysis to the GDP growth rate is presented in Appendix C (Figures C1 and C2). From this analysis it can be seen that the fénix scenario (as described in Section 2 (see Figure 2)) has a tendency similar to that observed in (a) in Figure 19, which resulted from the conservative scenario assumed in the beginning of the study. Although welfare cost, the energy and emissions evolution maintain the same throughout the years, the GDP evolution has a higher growth. Therefore the Kuznets effect is more relaxed as expected to wealthier regions where the GDP growth continuous to increase (discussed in Section 1). On the other hand, if a pessimist scenario of an annual decay of 1% for the Portuguese GDP was assumed, the results tendency should take the form observed in (b) in Figure 19. The decrease of the welfare cost, the energy and emissions is accompanied by the decrease of the Portuguese GDP. Despite the technology continues to evolve the economic growth is not verified. This case indicates that the environmental effect regarding the road transport sector is disaggregated from the economic growth of the country.

8. Conclusions

From the scenarios discussed in this study by 2050, it is possible that 64% of gasoline and diesel for LDV sector can be reduced. This means that a large portion of oil imports would be also reduced. Since Portugal is entirely dependent on oil importation, the dependence on foreign energy would decrease. Therefore, the GDP may become more independent of energy imports and then be freer to grow. The electric vehicle penetration in Portuguese LDV fleet is expected to reduce the air pollutant emissions especially local emissions. However, the allocation of energy demand from the fossil fuel sector to the electric energy sector can impute to the power plants a larger share of emissions and energy demand. Nevertheless the evolution of electricity generation mix and power plant efficiency, and the evolution of the vehicle technology, should lead a decreasing tendency of the energy and emissions. Based on a Kuznets effect hypothesis, the impacts regarding cost of air emissions, energy consumption, and emissions from the road transport sector, were possible to co-relate with the gross domestic product evolution in Portugal. Note that a specific sector (light duty vehicle sector) is considered, and the Kuznets effect estimations are only regarding the studied sector, and therefore the energy consumption and emissions conclusions cannot be extrapolated to Portugal global energy and emissions evolution.

Glossary

LDV - Light duty vehicle
BEV – Battery electric vehicles
CO – Carbon oxide
CO_2 – Carbon dioxide
CTG – Cradle-To-Grave
GDP – Gross domestic product
GNNI – Green net national income
HC – Hydrocarbons
LCA – Life cycle analysis
NH_3 - Ammonia
NMVOC – Non methane volatile organic compounds
NO_x – Nitrous oxides
PM – Particulate matter
SO_x – Sulfur oxides
toe – Metric tons of oil equivalent
ton – Metric ton
TTW – Tank-To-Wheel
VOC – Volatile organic compounds
WTT – Well-To-Tank
WTW – Well-To-Wheel

Appendix A. Vehicles characteristics and LCA data

Table A1. Conventional and electric vehicle characteristics considered in this study

		Gasoline ICE	Diesel ICE	BEV
Traction Power/Weight (kW/kg)		0.061	0.059	0.062
Maximum Speed (km/h)		183.4	186.5	156.7
time 0-100 km/h (s)		11.7	10.4	8.7
Weight (kg)		1215	1239	1088
Traction Electric Motor	Nominal Power (kW)	-	-	68
	Torque (N.m)@ rpm /max rpm	-	-	260 @ 2500/8500
Battery (Li-ion), Energy capacity (kWh) / Max. power (kW)				16.05 / 110
SI Engine	Nominal Power (kW)@rpm	75 @ 6000	77 @ 4000	-
	Torque (N.m)@ rpm / maximum rpm	140 @ 3500/6500	248 @ 2000/4400	-
Wheelbase (mm)		2578	2578	2550

Table A2. Electricity generation mix regarding the Portuguese electrical grid system (data per 1 MJ of electricity generated). (power plant location: PT - Portugal, ES - Spain)

		Energy (MJ/MJ)	CO_2 (g/MJ)
Ordinary regime. production		-	-
hydraulic	ES+PT	0.314	-
thermic	ES+PT	-	-
coal	ES+PT	0.377	61.33
Natural Gas	ES+PT	0.480	23.03
Fuel	ES+PT	0.004	2.56
Nuclear	ES	0.037	-
Combine cycle	ES	0.013	-
Especial regime production		-	-
hydraulic	ES+PT	0.028	-
thermic	ES+PT	0.569	0.27
wind	ES+PT	0.194	-
photovoltaic/solar	ES+PT	0.006	-
Total		2.021	87.19
Net Total		1.021*	

*MJ used to produce fuel/MJ final fuel used

Table A3. CO_2 and pollutant emissions factor regarding gasoline, diesel, and electricity production in Portugal 2004 (EcoInvent database [34])

	CO_2	CH_4	CO	VOC	NO_x	PM	SO_x	NH_3
Gasoline (kg/ton)	786.3	4.76	0.69	8.68	2.71	0.321	5.06	0.00032
Diesel (kg/ton)	403.7	4.25	0.61	7.98	1.95	0.163	1.92	0.00019
Electricity (kg/TJ)	*174940*	267.6	50.2	189.1	455.2	109	1524	0.2000

Table A4. Energy consumption and CO_2 emissions values associated to each process of gasoline and diesel production, WTT stage (data per 1 MJ of fuel produced)

	Energy consumed (MJ/MJ)			CO_2 (g/MJ)		
	Best est.	Min.	Max.	Best est.	Min.	Max.
Crude oil to gasoline						
Crude Extraction & Processing	0.03	0.01	0.04	3.6	-	-
Crude Transport	0.01			0.9	-	-
Refining	0.08	0.06	0.10	7.0	-	-
Distribution and dispensing	0.02			1.0	-	-
Net Total	0.14	0.12	0.17	12.5	-	-
Crude oil to diesel					-	-
Crude Extraction & Processing	0.03	0.01	0.04	3.7	-	-
Crude Transport	0.01			0.9	-	-
Refining	0.10	0.08	0.12	8.6	-	-
Distribution and dispensing	0.02			1.0	-	-
Net Total	0.16	0.14	0.18	14.2	-	-

Table A5. Average number of replacement of the main consumable elements in the vehicle (accounted for CTG stage). [39, 42, 43]

Maintenance/replacements	
Tires	2
Battery	2 (Pb, ICEV) 1 (Lithium, BEV)
Engine Oil (ICEV only)	30
Brake Fluid	3
Transmission Fluid (ATF)	1
Powertrain Coolant	2
Winshield Fluid	19

Appendix B. TTW, WTT, and CTG detailed results

Table B1. TTW energy consumption and CO_2 emissions evolution scenario 2009-2050, per vehicle type. (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

TTW					
year	Energy Consumption (MJ/km)			emissions CO_2 (g/km)	
	Gas	Di	BEV	Gas	Di
2009	2.46	2.10	0.43	179.2	156.5
2010	2.44	2.08	0.43	177.7	155.0
2020	2.22	1.89	0.40	162.1	140.7
2030	2.01	1.70	0.37	146.5	126.4
2040	1.80	1.50	0.35	130.9	112.1
2050	1.58	1.31	0.32	115.1	97.8

Table B2. TTW pollutant emissions per vehicle evolution (scenario 2009-2050). (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

	TTW emissions											
year	CO (g/km)			NO_x (g/km)			PM (g/km)			VOC (g/km)		
	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV
2009	*1.00*	*0.50*	--	*0.07*	*0.22*	--	--	*0.02*	--	*0.07*	*0.05*	--
2010	0.99	0.50	--	0.07	0.21	--	--	0.01	--	0.07	0.05	--
2020	0.90	0.45	--	0.06	0.19	--	--	0.01	--	0.06	0.04	--
2030	0.82	0.40	--	0.06	0.17	--	--	0.01	--	0.06	0.04	--
2040	0.73	0.36	--	0.05	0.15	--	--	0.01	--	0.05	0.04	--
2050	0.64	0.31	--	0.05	0.13	--	--	0.01	--	0.04	0.03	--

Table B3. WTT energy production efficiency and CO_2 emissions evolution for a scenario 2009-2050. (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

	WTT					
Year	Energy Consumption (MJ/MJ)			emissions CO_2 (g/MJ)		
	Gas	Di	BEV	Gas	Di	BEV
2009	0.140	0.160	1.021	18.076	9.432	87.192
2010	0.140	0.160	1.021	18.076	9.432	87.192
2020	0.140	0.160	0.836	18.076	9.432	69.918
2030	0.140	0.160	0.651	18.076	9.432	52.644
2040	0.140	0.160	0.466	18.076	9.432	35.370
2050	0.140	0.160	0.281	18.076	9.432	18.096

Table B4. WTT pollutant emissions evolution for a scenario 2009-2050. (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

WTT emissions																		
Year	CO (g/MJ)			NO_x (g/MJ)			PM (g/MJ)			VOC (g/MJ)			SO_x (g/MJ)			NH_3 (g/MJ)		
	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV
2009	0.016	0.014	0.025	0.062	0.046	0.227	0.007	0.004	0.054	0.200	0.186	0.094	0.116	0.045	0.760	7.36E-06	4.44E-06	9.97E-05
2010	0.016	0.014	0.025	0.062	0.046	0.227	0.007	0.004	0.054	0.200	0.186	0.094	0.116	0.045	0.760	7.36E-06	4.44E-06	9.97E-05
2020	0.016	0.014	0.020	0.062	0.046	0.182	0.007	0.004	0.044	0.200	0.186	0.076	0.116	0.045	0.609	7.36E-06	4.44E-06	7.99E-05
2030	0.016	0.014	0.015	0.062	0.046	0.137	0.007	0.004	0.033	0.200	0.186	0.057	0.116	0.045	0.459	7.36E-06	4.44E-06	6.02E-05
2040	0.016	0.014	0.010	0.062	0.046	0.092	0.007	0.004	0.022	0.200	0.186	0.038	0.116	0.045	0.308	7.36E-06	4.44E-06	4.04E-05
2050	0.016	0.014	0.005	0.062	0.046	0.047	0.007	0.004	0.011	0.200	0.186	0.020	0.116	0.045	0.158	7.36E-06	4.44E-06	2.07E-05

Table B5. CTG energy consumption and CO_2 emissions evolution for a scenario 2009-2050 , per distance (km) travelled during the vehicle life time. (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

CTG						
Year	Energy Consumption (MJ/km life)			emissions CO_2 (g/km life)		
	Gas	Di	BEV	Gas	Di	BEV
2009	0.416	0.420	0.531	24.3	25.1	32.0
2010	0.414	0.419	0.528	24.2	24.9	31.7
2020	0.397	0.401	0.500	22.9	23.6	28.8
2030	0.380	0.384	0.472	21.6	22.4	25.9
2040	0.363	0.367	0.443	20.4	21.1	23.1
2050	0.346	0.350	0.415	19.1	19.8	20.2

Table B6. CTG pollutant emissions evolution for a scenario 2009-2050, per distance (km) travelled during the vehicle life time. (Gas - Gasoline LDV, Di - Diesel LDV, BEV - Battery electric vehicle)

CTG emissions																		
Year	CO (g/km life)			NO_x (g/km life)			PM (g/km life)			VOC (g/km life)			SO_x (g/km life)			NH_3 (g/km life)		
	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV	Gas	Di	BEV
2009	0.167	0.163	0.149	0.050	0.049	0.058	0.069	0.055	0.080	0.156	0.156	0.120	0.076	0.076	0.187	0	0	0
2010	0.167	0.163	0.149	0.050	0.049	0.058	0.069	0.055	0.080	0.156	0.156	0.120	0.076	0.076	0.186	0	0	0
2020	0.166	0.162	0.148	0.048	0.047	0.055	0.069	0.055	0.080	0.156	0.156	0.120	0.074	0.074	0.180	0	0	0
2030	0.165	0.161	0.147	0.046	0.045	0.052	0.069	0.054	0.080	0.156	0.156	0.120	0.072	0.072	0.175	0	0	0
2040	0.164	0.160	0.146	0.044	0.043	0.049	0.069	0.054	0.080	0.156	0.155	0.120	0.070	0.070	0.171	0	0	0
2050	0.163	0.160	0.145	0.042	0.041	0.046	0.069	0.054	0.080	0.155	0.155	0.120	0.067	0.068	0.168	0	0	0

Appendix C.

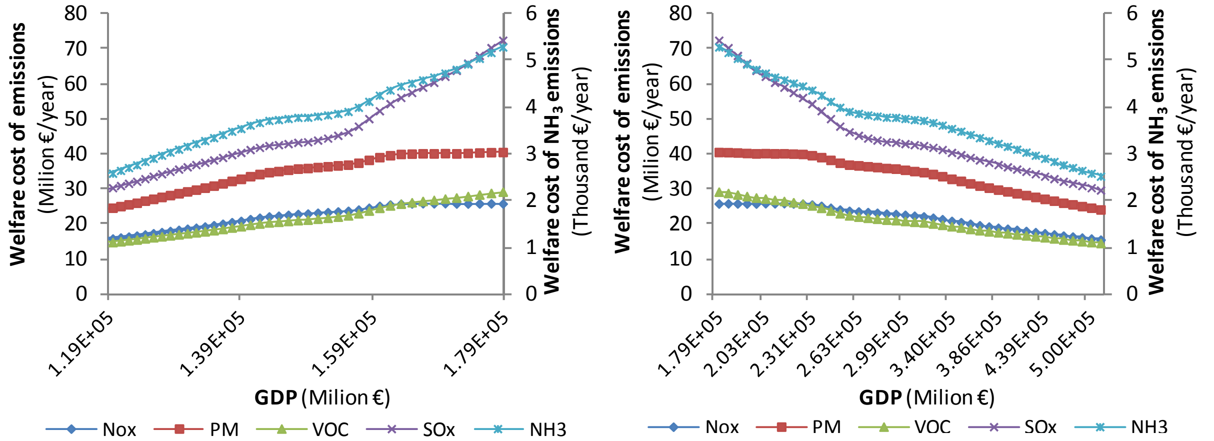

Figure C1. Welfare cost of pollutant emissions regarding GDP estimation from 2009-2050 considering a pessimist scenario (1% annual decrease in GDP) (a) and fénix scenario (2.6% annual increase in GDP) (b)

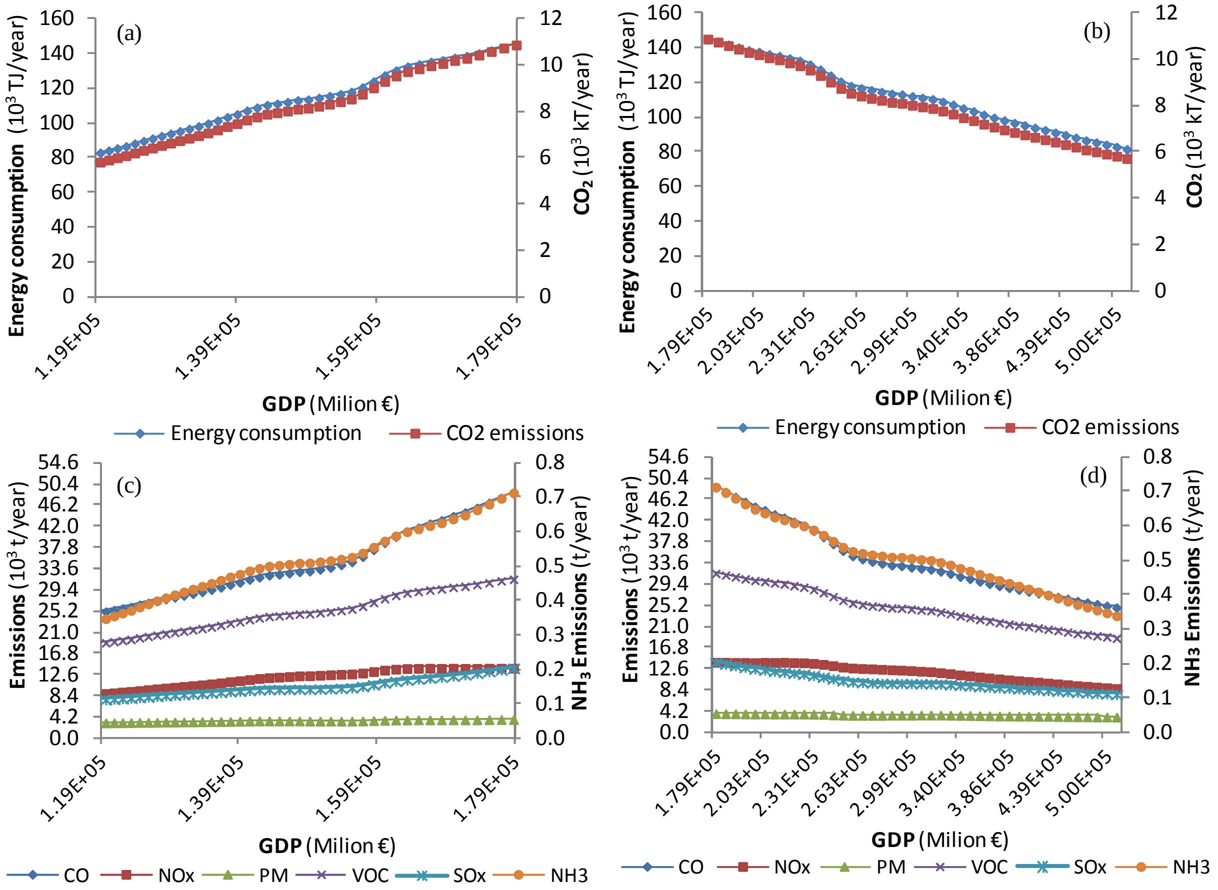

Figure C2. Energy and CO_2 emissions regarding GDP estimation from 2009-2050 considering a pessimist scenario (1% annual decrease in GDP) (a) and fénix scenario (2.6% annual increase in GDP) (b); and air pollutant emissions (c) and (d) for the same respective scenarios

Acknowledgments
Thanks are due to FCT - Fundação para a Ciência e Tecnologia (National Science and Technology Foundation) for the PhD financial support SFRH/ BD/ 68569/ 2010, and Post-Doctoral financial support SFRH/BPD/95098/2013.

References

[1] Eurostat, European Commission. Portugal, 2012, see http://epp.eurostat.ec.europa.eu/ (accessed 26.02.2014).
[2] DGEG. Direcção Geral de Energia e Geologia. Portugal, 2012, see http://www.dgeg.pt/ (accessed 26.02.2014).
[3] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003.
[4] C. Silva, M. Ross, T. Farias, Energy Convers. Manage. 50, 215 (2009).
[5] J. Ribau, C. Silva, F. P. Brito, J. Martins, Energy Convers. and Manage. 58, 120 (2012).
[6] F. Ferreira, A. C. Marques, A. P. Batista, P. A. S. S. Marques, L. Gouveia, C. M. Silva, Int. J. Hydrogen Energy 37, 179 (2012).
[7] F. Ferreira, J. Ortigueira, L. Alves, L. Gouveia, P. Moura, C. M. Silva, Biomass and Bioenergy 49, 249 (2013).
[8] F. Ferreira, J. Ribau, C. M. Silva, Int. J. Hydrogen Energy 36, 13547 (2013).
[9] F. Ferreira, L. Ribeiro, A. P. Batista, P. A. S. S. Marques, B. P. Nobre, A.M.F. Palavra, P. P. Silva, L. Gouveia, C. M. Silva, Bioresour. Technol. 138, 235 (2013).
[10] N. S. Djomo, D. Blumberga, Bioresour. Technol. 102, 2684 (2011).
[11] P. Campbell, T. Beer, D. Batten, Bioresour. Technol. 102, 50 (2010).
[12] L. Lardon, A. Helias, B. Sialve, J. P. Steyer, O. Bernard, Environ. Sci. Technol. 43, 6475 (2009).

[13] Demirbas, Biohydrogen – For Future Engine Fuel Demands (1st ed. Springer, London, U.K., 2009).
[14] P. Baptista, Ph.D thesis, Technical University of Lisbon, Instituto Superior Técnico, Lisbon, 2011, see https://fenix.ist.utl.pt/homepage/ist151313/phd-thesis (accessed 20.01.2014).
[15] P. Baptista, J. Ribau, J. Bravo, C. Silva, P. Adcock, A. Kells, Energy Policy 39, 4683 (2011).
[16] Van Vliet, T. Kruithof, W.C. Turkenburg, A.P.C. Faaij, J. Power Sources 195, 6570 (2010).
[17] M. A. Kromer and J. B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet (Sloan Automotive Laboratory, Laboratory for Energy and the Environment, Cambridge, USA, 2007).
[18] R. Mota, Ph.D thesis, Technical University of Lisbon, Instituto Superior Técnico, Lisbon, 2011, see http://bibliotecas.utl.pt/cgi-bin/koha/opac-detail.pl?biblionumber=447787 (accessed 26.02.2014).
[19] Q. Zhang, B.C. Mclellan, T. Tezuka, K.N. Ishihara, Energy 61, 118 (2013).
[20] P.K. Narayan and S.Narayan, Energy Policy 38, 661 (2010).
[21] CAFE, Clean Air for Europe (2008), see http://ec.europa.eu/environment/archives/cafe/.
[22] European Commission (2011), see http://ec.europa.eu/energy/energy2020/roadmap/index_en.htm.
[23] J. Seixas, P. Fortes, J. Gouveia, L. Dias, S. Simões, B. Alves (2011), see http://climate.cense.fct.unl.pt/docs/Cen_socioeconomicos_2050.pdf (accessed 20.02.2014).
[24] World Bank (2012), see http://databank.worldbank.org/ddp/home.do.
[25] Agência Portuguesa do Ambiente (2011), see http://www.apambiente.pt/_zdata/DPAAC/INERPA/NIR_20130517.pdf (accessed 22.02.2014).
[26] R.P. Mota, T. Domigos, V. Martins, Ecological Economics 69, 1934 (2010).
[27] S. Smulders, Green National Accounting. The New Palgrave Dictionary of Economics.(Palgrave MacMillan, Economics Online, 2008).
[28] MOBI.E (2012), see http://www.mobie.pt/ (accessed 07.02.2014).
[29] McKinsey & Company (2009), see http://www.fch-ju.eu/sites/default/files/documents/ Power_trains_for_Europe.pdf (accessed 23.02.2014).
[30] CONCAWE (2011), see http://ies.jrc.ec.europa.eu/uploads/media/WTW_Report_010307.pdf (accessed 6.02.2014).
[31] ISO 14040-14044, 2006. Environmental management - Life cycle assessment - Principles and framework, International Organisation for Standardisation, Geneva (2006).
[32] T. Patterson, S. Esteves, R. Dinsdale, A. Guwy, J. Maddy, Bioresour. Technol. 131, 235 (2013).
[33] K. Wipke, M. Cuddy, S. Burch, IEEE Transactions on Vehicular Technology 48, 1751 (1999).
[34] Dieselnet. Emission Standards, 2012, see http://www.dieselnet.com/standards/.
[35] M. Goedkoop, A. Schryver, M. Oele, S. Durksz, D. Roest (2008), see http://www.pre-sustainability.com.
[36] EDP, Energia de Portugal S.A., 2011, see http://www.edp.pt (accessed 26.03.2014).
[37] REN, National electricity grid, 2012, see http://www.ren.pt/ (accessed 26.03.2014).
[38] Burnham, M. Wang, Y. Wu. U.S. Department of Energy´s FreedomCar and Vehicle Technologies Program (2006).
[39] Directive 2009/33/CE of the European Parliament and of the Council of 23 Apr 2009.
[40] M. L. Valente, Master’s thesis, Technical University of Lisbon, Instituto Superior Técnico, Lisbon, 2011, see http://bibliotecas.utl.pt/cgi-bin/koha/opac-detail.pl?biblionumber=454058 (accessed 6.02.2014).
[41] Tandberg, (2006), see http://internetinnovation.org/files/special-reports/TAN_WhtPpr_Green_ FINAL.pdf (accessed 26.03.2014).
[42] FORD. FORD Owners Guide, see https://owner.ford.com/servlet/ContentServer?pagename= Owner/Page/YearMakeModelSelectorPage&BackToLogin=Owner/Page/OwnerGuidePage (accessed 2.01.2014).
[43] Green Car Congress, 2010, see http://www.greencarcongress.com/2010/07/chevrolet-volt-msrp-starts-at-41000-33500-net-of-full-federal-credit-3year-lease-program-with-option.html#more (accessed 3.01.2014).

João P. Ribau received the Bologna Master's degree in Mechanical Engineering from the Technical University of Lisbon, Instituto Superior Técnico, Portugal, in 2009. Currently is a PhD student in Mechanical Engineering at Institute of Mechanical Engineering, Instituto Superior Técnico, focusing his research on optimization of alternative road vehicles. Areas of interest include research in the areas of new technology in road vehicles; analysis of the life cycle, and optimization.
E-mail address: joao.ribau@tecnico.ulisboa.pt

Ana F. Ferreira received the Master degree in Chemistry at the University of Lisbon, in the environmental area of analysis of atmospheric aerosols and atmospheric exposure. In 2013 completed her PhD in Environmental Engineering focusing the Evaluation of energy consumption and CO_2 emissions of alternative pathways for biohydrogen production. Currently she is a Postdoctoral researcher at Institute of Mechanical Engineering, Instituto Superior Técnico, on alternative biomass and biofuels. Her main interests are: biomass, biofuels, and alternative energy research area. Life cycle analysis.
E-mail address: filipa.ferreira@tecnico.ulisboa.pt