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FUTURE TRENDS ON THE COSTS AND BENEFITS OF ELECTRIC, HYBRID AND CONVENTIONAL VEHICLES IN EUROPE

JOSE PRATA, FCT RESEARCHER, JOSE.PRATA.ZEJPOLS@GMAIL.COM
ELISABETE ARSENIO, PH.D (ITS LEEDS, UK)
R&D FCT PROJECT COORDINATOR, ELISABETE.ARSENIO@LNEC.PT
JOSE PEDRO PONTES, FULL PROFESSOR, ISEG, PPONTES@ISEG.UTL.PT

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Jose Prata, FCT researcher, jose.prata.zejpols@gmail.com

Elisabete Arsenio, Ph.D (ITS Leeds, UK)*; R&D FCT Project Coordinator, elisabete.arsenio@lnec.pt*

Jose Pedro Pontes, Full Professor, ISEG, ppontes@iseg.utl.pt

ABSTRACT

The European Commission Transport White Paper "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system" envisages that by 2050 only electric vehicles would circulate in cities, being the use of conventionally-fuelled vehicles halved by 2030. One of the policy objectives is to reduce Europe's dependence on imported oil and to cut greenhouse gas emission (GHG) from transport by 20% by 2030 and by 70% until 2050 (with respect to 2008 levels).
Drawing upon future scenarios set by the European Commission and the International Energy Agency, this paper investigates the costs and benefits of electric, hybrid and conventional vehicles in Europe until 2030. A top-down approach will make it able to analyse further the Portuguese case, given trends in regional mobility patterns (including car fleet and price of energy scenarios). Other key research issue is to find out the horizon when electric vehicles can offer the highest potential to reduce carbon related emissions from transport.
The data comprises an integrated set of energy and transport data collected for Europe and Portugal, as part of the research project COST-TRENDS project funded by the Portuguese Foundation for Science and Technology.
A Life-Cycle Assessment (LCA) analysis was performed to compare the costs and benefits of Battery-powered Electric Vehicles (BEVs), Plug-in-Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs) and Internal Combustion Engine Vehicles – diesel and gasoline (ICEVs), taking the perspective of the user. The analysis considered the emissions along the entire chain of production and usage of vehicles – the Well-to-Wheel (WtW) analysis, comprising the Well-to-Thank (WtT) and the Tank-to-Wheel (TtW) emissions, allowing for the energy grid trend scenarios regarding the mix of electricity production and incorporation of renewables (range of gCO_2 /kWh).
The results show that users' benefits related to BEVs are likely to be higher than those attached to ICEVs after the 2020 horizon. This is mainly due to the expected technology progress (reduction of battery costs and charging infrastructure) and to the decrease of the relative prices of electricity in comparison to prices of fossil fuels. Considering the LCA

analysis conducted for the Portuguese vehicle fleet, BEVs would emit 43 gCO2/km against 151 from ICEVs. Assuming the continuous replacement of older ICEVs by BEVs between 2010 and 2030, it will be possible to have a reduction of 11.8 GtonCO2/year in 2010 to 9.8 GtonCO_2/year in 2030.
The integration of BEVs in the vehicle fleet is a key policy measure to comply with the European transport policy objectives to achieve a low-carbon and competitive economy. The analysis of future trends on users' costs and benefits for all vehicle types (BEVs, PHEVs, HEVs and ICEVs) indicates that the highest potential to reduce GHG emissions from transport would occur only after 2020. Besides technology progress on cost reduction (battery and charging infrastructure), electricity prices and fuel taxation seem to be important drivers for the BEV market growth.

Keywords: electric vehicles, CO_2 emissions, cost-benefit analysis, emerging technologies; transport policy and planning.

INTRODUCTION

The World population and the GDP *per capita* growth since the 70´s are referred as main causes for the increase of energy consumption. As a result, European energy policies are supported by the concept of sustainable development (WCED, 1987), and aim to converge for the mitigation of greenhouse effects. In 2009, the transport sector consumed 2562 Mtoe (83% oil; 13% coal; 3% natural gas and 1% of electricity), representing 61.7% of the total oil consumption (IEA, 2011). Across Europe, the significant increase of road traffic in town centers conducted to chronic congestion, along with other externalities in terms of lost time and pollution which led the European economy to lose about 1% of its GDP. In addition urban traffic is responsible for 40% of CO_2 emissions and 70% of emissions of other pollutants arising from road transport (EC, 2007). Road transport is the main contributor to greenhouse gas (GHG) emissions and the main responsible for their expected growth in the future (Meyer *et al*., 2007). The reduction potential of GHG that can be achieved is mainly related to: the technological development of vehicles with internal combustion engines, making them more efficient; the use of biofuels; the use of HEVs; BEVs and PHEVs. For comparing technologies using different energy sources it's important to consider emissions from well-to-wheel (WtW) when compared with ICEVs (Thiel *et al*., 2010).
The energy market is mainly influenced by demand and energy consumption related variables. Energy conversion technology looks for efficient solutions (economically and environmentally). Currently, the viability of emerging technologies is not attractive (Boston Consulting Group, 2009). Current trends indicate an increase of fossil fuel costs (Figure 1) which is due to a supply reduction (oil reserves) or to environmental taxes associated to the inherent pollution.

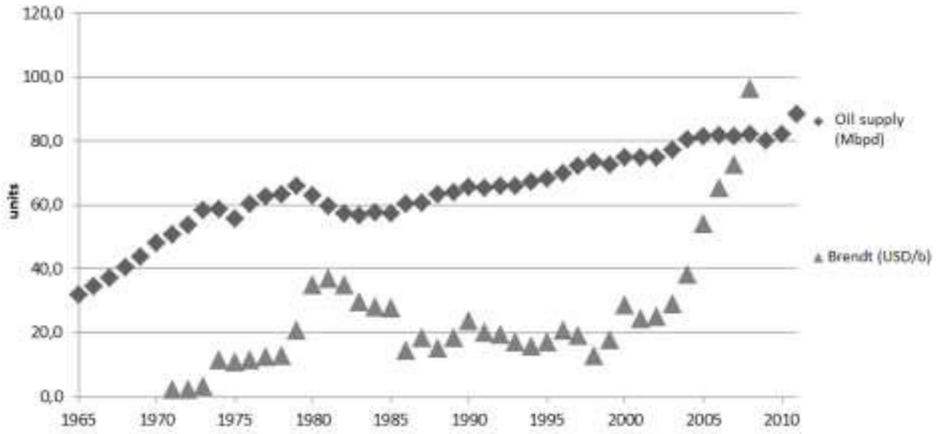

Figure 1- Historical records of the oil supply availability (MPB) and market prices (USD/b).
Source: adapted from BP, 2011 and DGEG, 2012.

THE PORTUGUESE ENERGY MARKET

The electricity supply industry in Portugal has changed, recently, from a vertically integrated monopoly structure to a dual market structure, where regulated and free markets operate in parallel. A regional market was implemented, the Iberian Electricity Market - MIBEL (IEA, 2009_b). The final electricity consumption in Portugal (excluding Azores and Madeira) increased significantly between 1995 and 2010. In this period the final electricity consumption increased from 28.54 GWh to 37.91 GWh, and reached in 2010 the value of 48.95 GWh. In 2000, the gross production of electricity was mainly originated from thermal power (73%) and hydroelectric plants (27%). In 2010, the gross production of electricity from thermal power was 51%; from hydroelectric 31%; from wind energy 17% and from photovoltaic 1% (DGEG, 2012). Figure 2 represents the evolution of the gross electricity production (GWh) between 1994 and 2010.

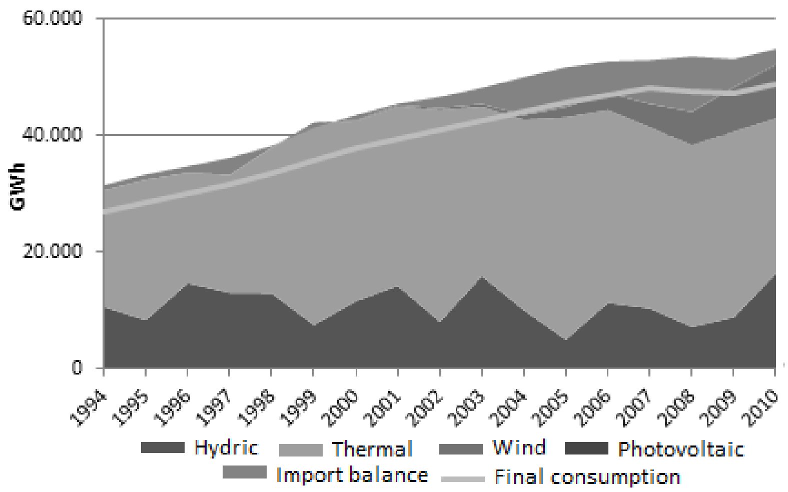

Figure 2- Evolution of the gross electricity production (GWh) between 1994 and 2010.
Source: adapted from DGEG, 2012.

In 2007, the breakdown of electricity consumption by end-user (consumption sector) was as follows: industry (38%); residential (28%); commercial and services (31%); transport (1%); and agriculture, forestry and fishing (2%) (IEA, 2009_b). Oil demand in Portugal has been

stable in the last decade being the transport sector the main consumer, with a share of 40% in 2007 (DGEG, 2012). Between 2006 and 2008 the crude oil imports decreased significantly, mainly due to the increase in the cost of resources that affected consumption. On the other hand, the Portuguese investment in solar thermal systems and biomass boilers led to the replacement of older heating systems. Coal is important for electricity production especially in periods of decreased hydropower. The coal imports have decreased in last decade. In 2010, the natural gas consumption was 4.9×10^6 Nm^3, and the breakdown by end-user (consumption sector) was as follows: electricity production (59%); industry (28.5%); and 11.5% for others uses (restoration, public services, markets, constructions, and household) (DGEG, 2012). The demand for natural gas is expected to grow in the near future with the planed installation of a new gas-fired infrastructures (IEA, 2009_b).
Portugal has already implemented a charging infrastructure network for BEVs in 25 cities, including Lisbon. These integrate of 1350 supply stations, developed as part of the Portuguese Electric Mobility Program (Decree-Law n.º 39/2010).
The EC Transport White Paper "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system" envisages that by 2050 only electric vehicles would circulate in cities, being the use of conventionally-fuelled vehicles halved by 2030 (EC 2011). One of the policy objectives is to reduce Europe's dependence on imported oil and to cut greenhouse gas emission (GHG) from transport by 20% by 2030 and by 70% until 2050 (with respect to 2008 levels).

RESEARCH OBJECTIVES AND METHODOLOGY

Drawing upon future scenarios set by the EC and the IEA, this paper investigates the costs and benefits of electric, hybrid and conventional vehicles in Europe until 2030. A top-down approach will make it able to analyse further the Portuguese case (Lisbon Metropolitan Area - LMA), given trends in regional mobility patterns (including car fleet and price of energy scenarios). Other key research issue is to find out whether electric vehicles offer the highest potential to reduce carbon related emissions in comparison to other vehicle technologies along with the time horizon.

The methodology used in this research comprised the following phases:

1) Integrated data collection of transport, energy and socio-economic data for Europe, Portugal and LMA (case study), for a common reference year (2011);
2) Development of medium (until 2020) to long term (2030) scenarios for the evolution of technology and prices (oil, electricity, electric batteries), using best practice methods of planning and prospective analysis (foresight); this included a literature review of prospective analysis studies conducted over the last 10 years. The prediction of oil costs was facilitated through using the *R statistical computing software*;
3) Life-Cycle Assessment (LCA) analysis to compare the costs and benefits of BEVs, PHEVs, HEVs and ICEVs, taking the perspective of the user. The analysis considered the emissions along the entire chain of production and usage of vehicles – the Well-to-Wheel (WtW) analysis, comprising the Well-to-Thank (WtT) and the Tank-to-Wheel (TtW) emissions, allowing for the energy grid trend scenarios

regarding the mix of electricity production and incorporation of renewables (range of gCO2 /kWh);

4) Analysis of economic viability of alternative vehicle technologies, BEVs, PHEVs, HEVs and ICEVs, taking the perspective of the user. Two types of economic indicators were used: Cost-efficiency and Cost-effectiveness. The latter indicator was used to foresee which vehicle technologies will allow a higher reduction of CO_2 emissions at lower costs, *ceteris paribus*.

DEVELOPMENT OF FUTURE SCENARIOS AND THE CASE STUDY

As mentioned before, the data used in this research comprised an integrated set of energy and transport for Europe, Portugal and LMA. These data was used for developing the long term scenarios. Figure 3 shows the key methodological steps of this prospective exercise: i) characterization of the current situation in terms of the vehicle fleet and inherent CO_2 emissions (reference year 2011); ii) identification of the predetermined elements, wildcards and crucial uncertainties (literature review of European and national studies); iii) Comprehensive analysis of “possible” *versus “d*esirable futures”; iv) Strategy (convergence for long term goals set by the EC).

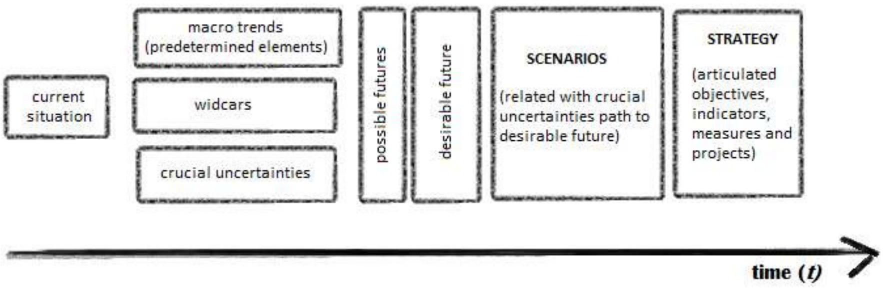

Figure 3 - Methodological steps in the prospective exercise scenario.

In Figure 3, predetermined elements are those variables that are expected to change and their range of variation can be predicted in a great extent (Porter, 1986). The literature review analysis conducted to the following predetermined elements: climate change issues (continued concern for global warming); globalization and the role of emerging economics (e.g. China, India, Russia and Brazil); geopolitics (lithium reserves); inequalities (e.g. due to globalization); migration flows increase; urbanization and shrinking regions (people will look for new opportunities of employment in major cities); costs of fossil fuels (increase); investment in renewable energy (increase); energy intensity (decrease); new information and communication technologies (promoting efficiency in mobility); technology development (higher levels of efficiency on transport); life expectancy and aging population (increase). Crucial uncertainties are those which define the system dynamics and are somehow controllable, but there is no absolute certainty about the implicit mechanisms of transmission. Therefore, the changes that one uncertain element can induce in the future need to be continuously monitored (Van der Heidjen, 1996). The comprehensive analysis at the European and national levels conducted to the following crucial uncertainties: the Portuguese economy; society behavior; EU support for cohesion and development; the integration

potential of BEVs; electricity costs; security; the social conflict and the population decreasing. Wild cards are events that correspond to discontinuities in the system and are associated with a low probability of occurrence, high impacts and unexpected outcomes (Rockfellow 1994). These wild cards are as follows: terrorism and security threats; natural disasters (particular focus on those related with climate change); collapse of the European economic system. The development of scenarios will allow a set of possible futures (Figure 4) associated to the crucial uncertainties referred. The crucial uncertainties were split in two clusters: a) "Economy and Demography" and b) "Climate change, Competitiveness and Technology Innovation". For each cluster two extreme possible situations were considered in the future. For cluster a), the two extreme cases set were: "Competitive and efficient economy" (+) and "Imbalances and deterioration in society" (-). Regarding cluster b), the two extreme scenarios were: "Sustainable environment, competitive and efficient technology" (+) and "Imbalances and deterioration in environmental and technology" (-).
The desirable future correspond both the goals set by the EC and to a positive evolution for the set of variables considered in the analysis.

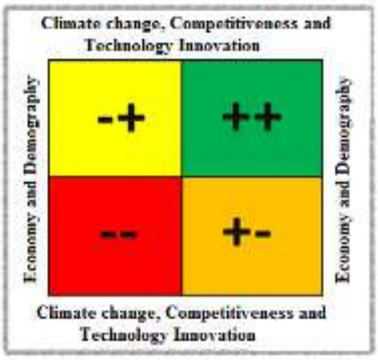

Figure 4 - Prospective scenarios.

As for the current situation, the EC intends to promote the growth of the transport sector through keeping mobility and reducing 60% of GHG emissions by 2050, relative to 1990 reference levels (EC, 2011). By 2050, the EC target set will involve banning ICEVs from European cities (these are expected to be replaced by electric vehicles), and by 2030, only half of the vehicles operating shall be ICEVs (EC, 2011). With these goals it is expected a 20% of CO_2 emissions reduction until 2030, relative to 2008 (EC, 2011; EC, 2007). Table I shows the composition of the vehicle fleet in 2011 for Portugal and the LMA (number and type of vehicles and inherent pollution (ISP, 2012; EEA, 2010) and the aim of EC for 2030.

Table I – Vehicle fleet in 2011 and vehicle fleet expected in 2030.

2011	**Portugal**	**LMA**
N.º ICEVs	4848724	1086107
N.º BEVs	221	50
CO_2 Emissions (Gton CO_2)	11,84	2,57
2030	**LMA**	
N.º ICEVs	5430579	
N.º BEVs	5430579	
CO_2 Emissions (Gton CO_2)	1,58	

Based on the desirable future established by the EC (2011) and IEA (2009_b), this research analyzes the costs and benefits of electric and conventional vehicles in Europe since 2010 to the medium (2020) and long term (2030). The analysis comprises 6 different types of vehicles (in terms of technology and energy source) allowed to be marketed in EU, with similar power and engine displacement (Thiel *et al.*, 2010).
A top-down approach will make it able to analyse further the Portuguese case at the national and regional level (LMA), given trends in regional mobility patterns (including car fleet and price of energy scenarios). Other key research issue is to find out the horizon when electric vehicles can offer the highest potential to reduce carbon related emissions from transport.

Characterization of Portugal and LMA – demographic variables

Portugal has a 92152 km^2 of territory, comprised by mainland (97%) and islands (Madeira and Azores), with a total of 10.541.840 inhabitants in 2011 (INE, 2012). Using data provided by INE (Figure 5 - a) demographic trends for Portugal and the LMA were projected by the *Growth Component Method.* It used population disaggregated data, survival rates, fertility and net migration rates (Figure 5- b; Figure 5 – c, Figure 5 - d). It is shown that the population of LMA tends to decrease and to ageing. Between 2011 and 2031, the youngster age group (0-19 years) will decrease from 20.1% to 14.2%, respectively. On the other hand, the age group older than 84 years will increase from 2.4% to 16.2% in the same period.

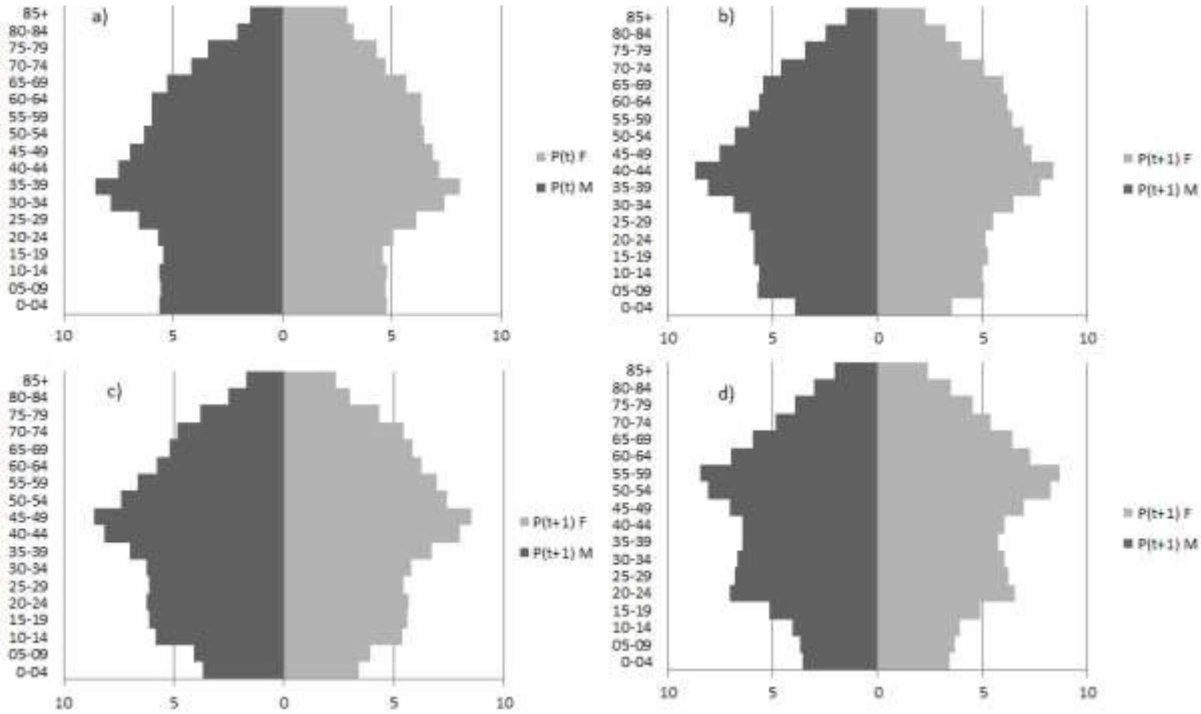

Figure 5 - Age structure in LMA in 2011; b) Age structure expected in LMA in 2016; c) Age structure expected in LMA in 2021 and d) Age structure expected in LMA in 2031.

Characterization of Portugal and LMA – vehicle fleet and inherent pollution

In Portugal, the vehicle fleet statistics are not validated by the Portuguese National Institute of Statistics (INE). At present, several organizations such as ACAP, ISP and IMTT provide such data. It is interesting to note that Portuguese vehicle fleet increased 691% between 1974 and 2010 (Figure 6). In 2010, 76.8% of the vehicle fleet was passenger light vehicles (ACAP, 2012). In 2011, the percentage of passenger light vehicles and commercial vehicles between 10 and 15 years was respectively 27.7%. and 30.6%. The percentage of passenger heavy vehicles between 5 and 10 years of age was 22.2%. The percentage of goods heavy vehicles more than 20 years of age was 22.1% (ISP, 2012).

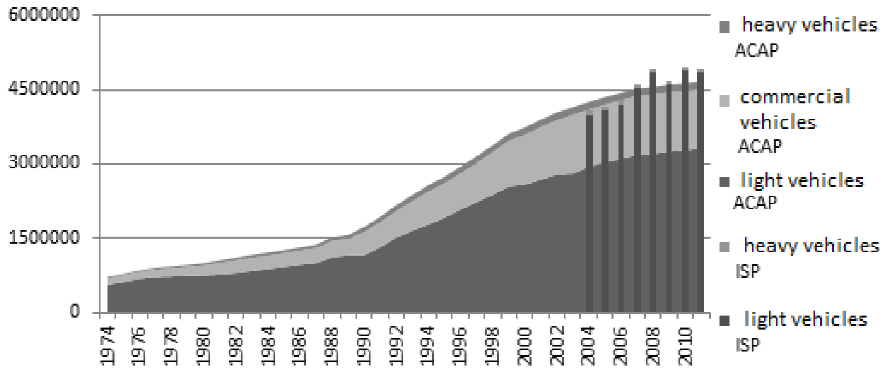

Figure 6- Evolution of the vehicle fleet in Portugal for each type between 1974 and 2011
Source: adapted from ACAP, 2012 and ISP, 2012.

In 2011, LMA had 1.086.107 light vehicles; 1.840 buses until 20 seats and 1.361 buses with more than 20 seats (ISP, 2012). Between 2004 and 2011, the evolution of light vehicles in LMA registered a significant growth, despite the years of 2009 and 2011 (ISP, 2012). In 2011, the majority of passenger light vehicles of the LMA fleet had more than 10 years of age, corresponding to 39.7% of all. The number of buses until 20 seats in LMA has been increasing since 2004 in contrast to the buses' fleet with more than 20 seats (ISP, 2012).
With technology development and policies derived from the EC (2011) and EC (2007), car industries tend to manufacture vehicles with lower CO_2 emissions, in line with the objective of a low-carbon and competitive economy. The main goal of the EU global strategy is to achieve 120g CO_2/km in 2012 (EC, 2007). In Portugal the average CO_2 emissions by light vehicles was about 127.3 gCO_2/km, in 2010 (EEA, 2012). Table II shows the average evolution of CO_2/km emissions of passenger cars in Portugal between 2002 and 2010 (EEA, 2012).

Table II – Average evolution of CO_2/km emissions of passenger cars in Portugal between 2002 and 2010.
Source: EEA, 2010.

gCO_2/km	2002	2003	2004	2005	2006	2007	2008	2009	2010
Portugal	154.0	149.9	147.1	144.9	145.0	144.2	138.2	133.8	127.3

Using data from Table II and having in mind the EU goals for technology development and substitution, Figure 7 presents the evolution of CO_2/km emissions between 1980 and 2030 in Portugal.

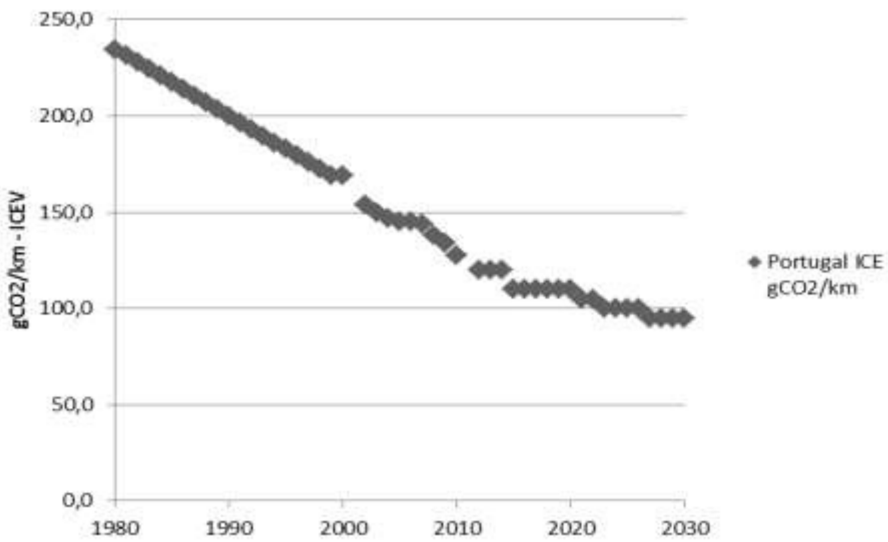

Figure 7 – Average evolution considered of CO_2/km emissions between 1980 and 2030 in Portugal.

Combining the Portuguese vehicle fleet evolution data (ACAP, 2012; ISP, 2012), average CO_2 emissions data series (EEA, 2012), the breakdown data of light vehicle by year of construction in 2011 (ISP, 2012) and the average distance annually travelled (ACEA, 2008), Figure 8 shows the evolution of CO_2 emissions of light vehicles between 1980 and 2010, in Portugal.

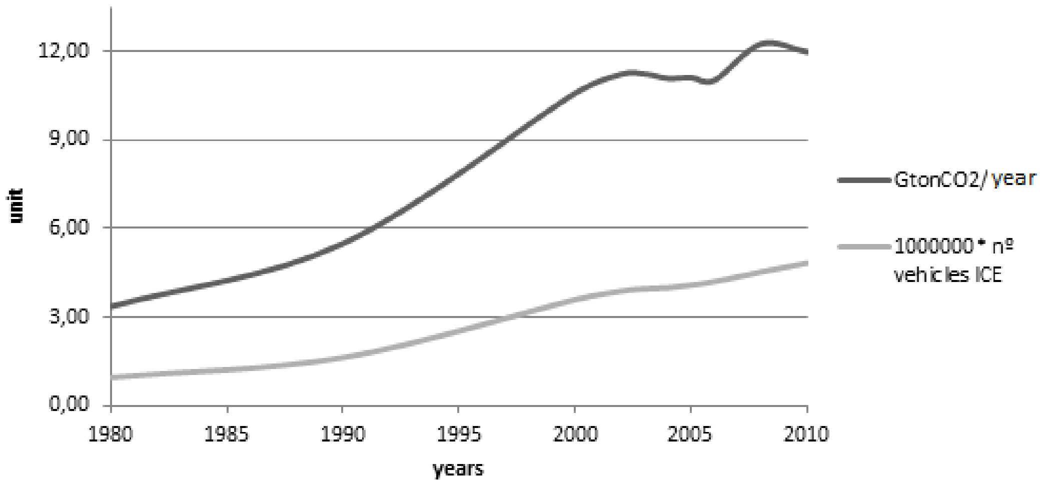

Figure 8 – Evolution of CO_2 emissions between 1980 and 2010 for passenger cars in Portugal.

CO_2 emissions increased with the number of vehicles in circulation due to a low rate of vehicle substitution verified in the period 1980-2010. The number of light vehicles decreased in 2004, 2006 and 2010 in comparison to previous years; as a consequence, the global CO_2 emissions by vehicle fleet decreased. The emerging technologies (hybrid vehicles) in the Portuguese vehicle fle*et al*so contributed for the CO_2 emissions decrease. Figure 9, presents the evolution of CO_2 emissions of light vehicles between 1980 and 2010, in LMA. In 2010, the LMA passenger vehicle fleet was responsible for a total of 2.624 Mton CO_2 emissions.

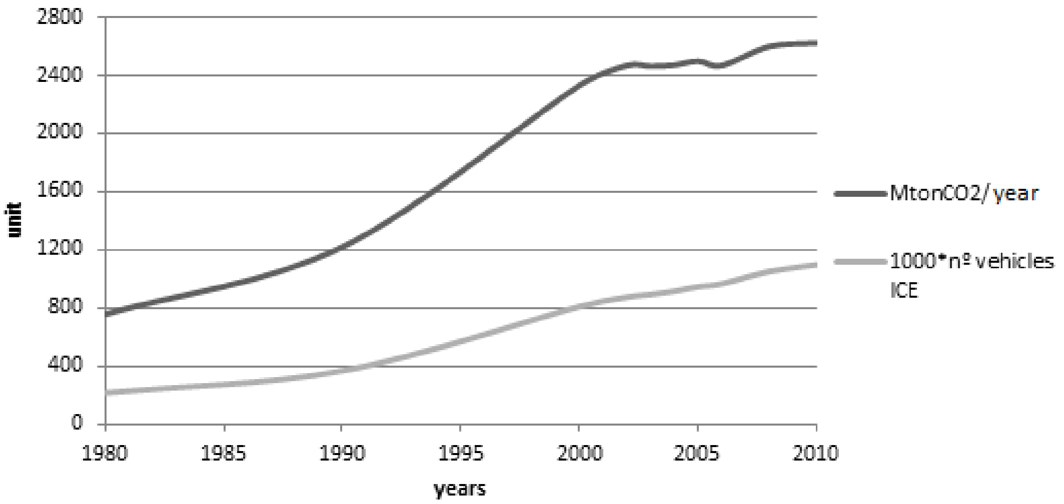

Figure 9- Evolution of CO_2 emissions between 1980 and 2010 for passenger cars in LMA.

Characterization of the vehicle fleet

The analysis comprised 6 different types of vehicles (in terms of technology and energy source) as these were already used in a previous reference study (Thiel *et al.*, 2010). Technology specifications, performance (PF) and costs, in 2010 are described in Table III. The vehicle costs comprise a Portuguese tax - ISV. The ISV is an annual vehicle tax that is function of several vehicle characteristics, whereas the IUC tax applies to the purchase of new or imported used vehicles. Following the Portuguese Law n.º 22-A of 2007, the IUC tax does not apply to BEVs.

Table III- Technology, performance and cost figures for the alternative vehicle technologies in 2010.
Source: adapted from THIEL *et al.*, 2010.

		1.3 GDI turbo	1.6 CRD Turbo	1.3 GDI turbo hybrid	1.6 CRD Turbo hybrid	PHEV	BEV
Tech.	ICE displacement (l)	1.3	1.6	1.3	1.6	1.4	-
	Engine power (kW)	70	74	62	63	56	-
	Electric power (kW)	-	-	14	14	95	80
	Battery cap (kWh)	-	-	2	2	11.5	24
	Energy Source *	G	D	G	D	E/G	E
Perform.	Weight (kg) **	1256	1308	1316	1388	1515	1442
	Acceleration (s) ***	11.3	11.2	11.5	11.5	11	11
	Top speed (km/h)	193	190	180	180	161	140
	Total range (km)	717	914	890	1140	560	125
	Consumption (MJ/100 km)	190	166	153	133	86	49
	CO_2 emissions (g/km)	139	121	112	97	40	-
Costs	Base vehicle (€)	16165	16455	15865	16155	15865	15865
	Powertrain cost (€)	3563	4980	3119	4681	2660	0
	Electric motor cost (€)	0	0	601	601	2565	2160
	Battery cost (€)	0	0	1200	1200	6900	14400
	Tank cost (€)	125	125	125	125	125	0
	Vehicle upgrade cost (€)	0	0	2630	2630	2630	2630
Total+IUC (€)**		21777	25993	25232	28231	34259	39399

*G-Gasoline, D-Diesel, E-Electricity;**including driver and 90% fuel; *** 0-100 km/h; **** IUC was calculated.

The average maximum speed of a BEV is 140 km/h a value higher than the maximum allowed speed in most highways in the EU (in Portugal, the speed limit in motorways is 120 km/h). The BEVs have a driving range of 125 km (battery fully charged) which fits the average daily movement needs of the majority of current potential users (in Lisbon, the average daily distance travelled is 56 km) (CML, 2005).
In order to understand the evolution and impacts of alternative vehicle technologies, Table IV shows trends on technology specifications, performance and costs for 2020. Thiel, C., *et al*, 2010 considers an efficiency increase of 15% in ICEVs and in 12% in HEVs until 2020. For BEVs and PHEVs was not considered any improvement in terms of efficiency. In 2020, CO_2 emissions were considered below that the levels proposed to 2012 by the EC.

Table IV - Performance and cost figures for the alternative vehicles technologies in 2020.
Source: adapted from THIEL *et al.*, 2010.

		1.3 GDI Turbo	**1.6 CRD Turbo**	**1.3 GDI Turbo Hybrid**	**1.6 CRD Turbo Hybrid**	**PHEV**	**BEV**
PF	Consumption (MJ/100 km)	162	141	135	117	86	49
	CO_2 emissions (g/km)	110	110	89	89	40	-
Costs	Base vehicle (€)	16165	16455	15865	16155	15865	15865
	Electric motor cost (€)	0	0	248	248	1102	928
	Battery cost (€)	0	0	496	496	2965	6188
	Tank cost (€)	125	125	125	125	125	0
	Vehicle upgrade cost (€)	0	0	1086	1086	1130	1130
Total+IUC (€)		20154	23788	20977	23421	23887	24111

Electricity generation and future trends on the costs per kWh

In 2008, CO_2 emissions derived from the production of electricity in Portugal were 0.47 $kgCO_2/kWh$ (MEI, 2008). This value is function of each CO_2 emission factor (EF) for each energy source production. Table V shows the electricity generation by source, in Portugal in 2009 (IEA, 2009_b), the CO_2 EF of each energy source production and the electric efficiency (MEI, 2008).

Table V - Global emission foreseen of CO_2 from on electricity generation in Portugal, in 2009.

Fuel source	**Energy produced (GWh)**	**EF (kg CO_2/GJ)**	**Emission (Mton CO_{2eq})**
Coal	12896	98,8	4587
Oil	3285	73,3	867
Natural Gas	14712	64,1	3395
Biofuel	1796	0,0	0
Waste	588	0,0	0
Hydric	9009	0,0	0
Geothermal	184	0,0	0
Photovoltaic	160	0,0	0
Wind	7577	0,0	0
Total	50207	-	8849
Electric efficiency (%)	40,0		
Global emission ($kgCO_2/kWh$)	0,44		

The Portuguese electricity generation in 2020 is expected to be 83.000 GWh (IEA, 2009_b), being 60% of that production by renewable sources (DGEG, 2012). Table VI shows the forecasts for electricity production by fuel source, in 2020.

Table VI- Global emission trends of CO_2 from electricity generation in Portugal, in 2020.

Fuel source	**Energy produced (GWh)**	**EF (kg CO_2/GJ)**	**Emission (Mton CO_{2eq})**
Coal	1944	98,8	691
Oil	3285	73,3	867
Natural Gas	21497	64,1	4961
Hydric	24983	0,0	0
Wind	24900	0,0	0
Other renewable energy	6391	0,0	0
Total	83000	-	6519
Electric efficiency (%)	40,0		
Global emission (kgCO_2/kWh)	0,20		

Future trends on electricity costs were derived through considering two hypotheses for the cluster “Climate change, Competitiveness and Technology Innovation” already described in the prospective scenarios. The evolution of electricity costs has taken into account the cheapest and most convenient option to charge an electric vehicle (during night time period). One hypothesis represents the positive situation, build from historical records, between 2010 at 2012 (REN, 2012), which follows the trend:

$$y = 0.004550x - 9.071617 \,, \qquad \textbf{(Eq. 1)}$$

being *y* the electricity cost (€/kWh) and *x* the year, with an R^2 of 0,985677. The second hypothesis assumes a cost 4 times higher in 2030, comparatively to the first hypothesis and with the same cost before 2012:

$$y = 0.029266x - 58.751666 \,, \qquad \textbf{(Eq. 2)}$$

being *y* the electricity cost (€/kWh) and *x* the year.

Life-Cycle Assessment (LCA): carbon and energy

The life-cycle of each vehicle includes 5 stages (vehicle materials production; vehicle assembly; distribution; maintenance and disposal) (MIT, 2000). The life-cycle of fuel has 4 stages (producing feedstock; transport of feedstock; fuel production and distribution of the fuel) (IEA, 2009_a). The association of vehicle and fuel life-cycle creates other an intermediate life-stage of the fuel – fuel consumption. It was considered that each vehicle has a life-time of 15 years, traveling 15000 km per year (ACEA, 2008). Figure 10 shows our study results of LCA analyses for average carbon emissions and energy consumption for each vehicle technology.

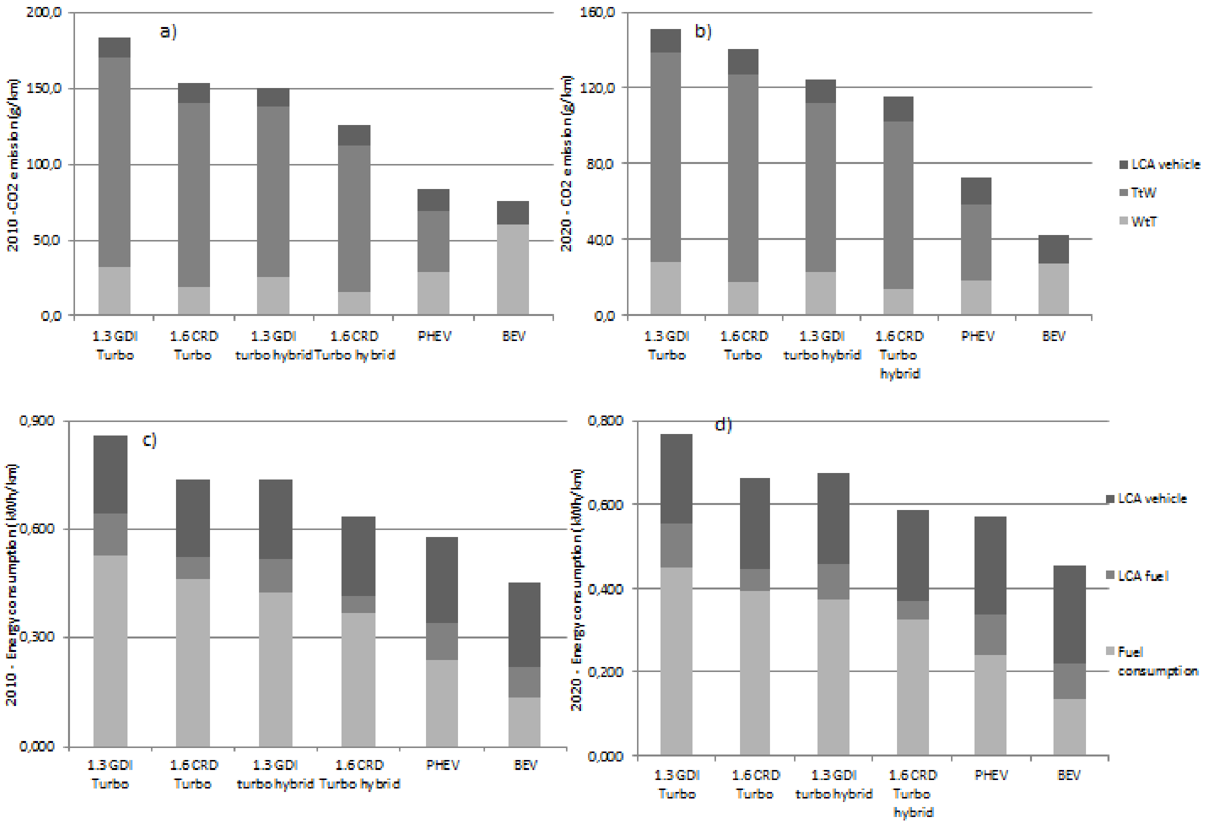

Figure 10 – a) LCA – carbon emissions in 2010 for each vehicle technology; b) LCA – carbon predictions for 2020 for each vehicle; c) LCA – energy consumption in 2010 for each vehicle technology; d) LCA – energy consumption predictions for 2020 for each vehicle technology.

BEVs are associated with the lowest WtW CO_2 emissions, with values of 76 gCO_2/km in 2010 and expected values of 43 gCO_2/km in 2020. Regarding energy consumption, it was assumed a constant driving pattern in the analyzed period (average consumption of 0.45 kWh/km). The values achieved are constant because the efficiency of BEVs was assumed to be the same for each scenario. In contrast, the 1.3GDI Turbo vehicle had the highest WtW CO_2 emission, with values of 184 gCO_2/km in 2010 and expected values about 151 gCO_2/km for 2020.

It is interesting to note that the 1.3GDI Turbo vehicle is also the vehicle technology that had the highest energy consumption during lifetime (193 MWh).

Impact of BEVs on lithium reserves

In 2011, the lithium reserves in the World were 64 million tons. Around 2.08 million tons of these reserves are located in Europe, of which 7.1% are located in Portugal (GRUBER, 2011). The impact of Li-ion batteries by the integration of BEVs in Portuguese vehicle fleet was supported by the goals of the EC (2011) – in 2030, half of vehicles should be BEVs. Table VII shows the evolution of specific batteries characteristics between 2010 and 2025.

Table VII - Evolution of the performance and characteristics of Li-ion batteries between 2010 and 2025.
Source: adapted from GERSSEN-GONDELACH *et al.* 2012.

Specific energy (Wh/kg)	2010	110	Mass of batteries (kg)*	2010	218
	2015	150		2015	160
	2020	200		2020	120
	2025	250		2025	96
Efficiency (%)	2010	0,90	Useful life (years)	2010	8
	2015	0,90		2015	8
	2020	0,92		2020	10
	2025	0,95		2025	12
Battery capacity (kWh)**	2010	24	Maximum distance (km)	2010	125
	2015	33		2015	170
	2020	44		2020	232
	2025	55		2025	300
Life cycles (n.º)	2010	1000	Specific battery cost (€/kWh)	2010	1000
	2015	1000		2015	500
	2020	2000		2020	425
	2025	3000		2025	250

*The mass of batteries decrease but the capacity stills the same (24 kWh); ** the mass of batteries still the same (218 kg) increasing its capacity.

Table VIII shows the typical composition of Li-ion battery, where at least, 70% could be recyclable (BOSSCHE, 2010).

Table VIII – Typical composition of Li-ion battery.
Source: adapted from BOSSCHE, 2010.

	Substance	Mass (%)
Electrode	Carbon	15,0
	Lithium (metal oxide)	23,6
	Plastic and other	2,4
Electrolyte	Organic Carbonate	12,6
	Lithium (hexafluorophosphate)	3,2
Covering	Other	21,2
Other	Aluminium	12,6
	Cooper	9,5

The mass installed on batteries until 2030 was considered constant (218 kg). It was assumed that each BEV would change once in the analyzed period the battery-pack. Each BEV integrates then 58 kg of lithium. Until 2030, the BEVs in Portugal will demand for 141.8 thousand tons of lithium (this value was derived from the target of the EC of having 2.424.362 BEVs). It shall be noted that Portugal has the necessary reserves to supply the above mentioned future demand.

Future trends on oil costs

The market liberalization of oil in Portugal was set in 2004. Since that, the fluctuations were increasingly systematic. The evolution of diesel and gasoline costs between January 2004 and September 2012 (DGEG, 2012), along with the predictions until 2030 are represented in Figure 11 – a) and Figure 11 – b), respectively. As already reported in the research methodology section, future trends were estimated the *R statistical computing software*, which used weakly historical data of fuel prices (2004 -2012). Since random fluctuations in the time series were found to be roughly constant in size over time (Coghlan, 2013), future gasoline and diesel prices were estimated through time series analysis (exponential smoothing through using *R HoltWinters* and *predict* functions).

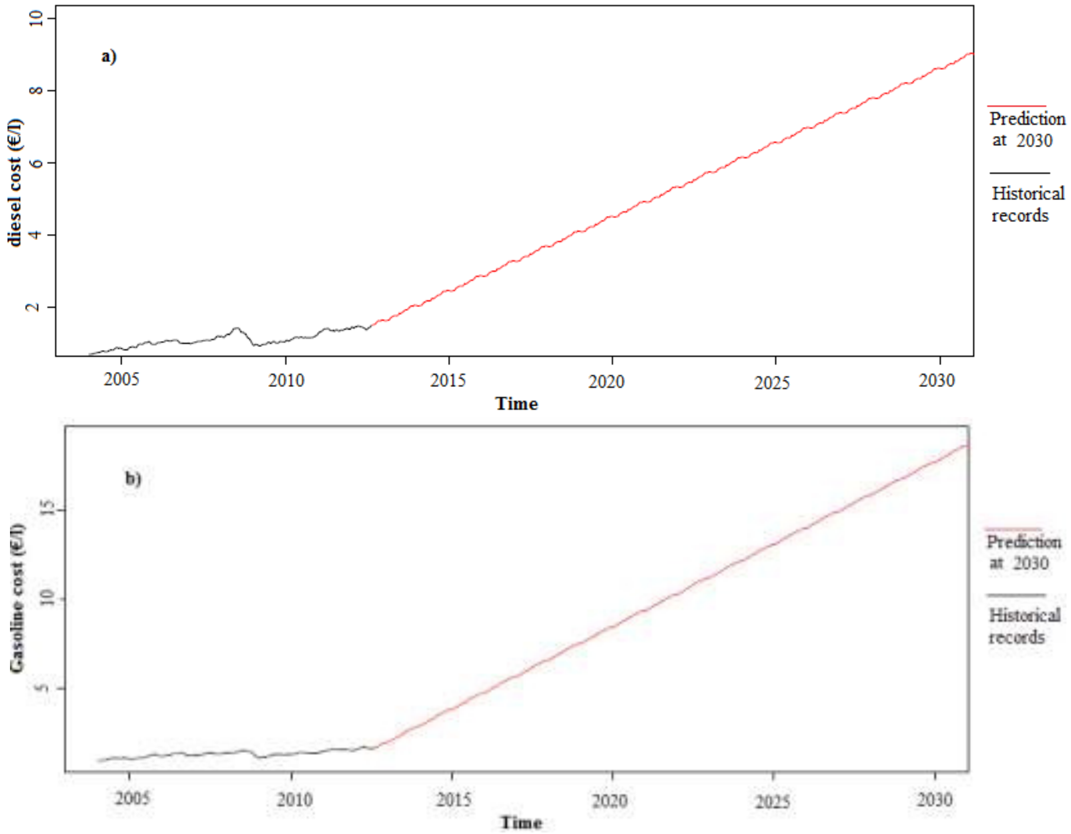

Figure 11 - a) Diesel cost (€/l) evolution between January 2004 and August 2012 and its prediction for 2030; b) Gasoline cost (€/l) evolution between January 2004 and August 2012 and its prediction for 2030.

Cost-Benefit Analysis of Future Vehicle Technologies

The economic viability of future alternative vehicle technologies comprised the cost-benefit (CBA) analysis of BEVs, PHEVs, HEVs and ICEVs, using the perspective of the user. The CBA analysis is based on the premise that if the summed benefits of a future technology outweigh the summed costs along the vehicle lifetime/period of analysis, this would lead to an increase of public welfare (and this technology can be considerable economically viable and efficient). A common indicator used in CBA to evaluate economic efficiency is based on the concept of the net present value of each technology related impacts (NPV). The NPV can be represented through the following equation:

$$\mathrm{NPV} = \sum_{t=0}^{L} \frac{(\mathrm{B_t} - \mathrm{C_t})}{(1+\mathrm{d})^{\mathrm{t}}} \,, \qquad \textbf{(Eq. 3)}$$

where:
NPV is the net present value of technology (in €);
t is the time in years of the technology being evaluated;

B_t are the expected benefits of the technology in year t (in €);
C_t are the expected costs of the technology in year t (in €);
d is the discount rate,
L is the average lifetime of the technology being evaluated.

If NPV is greater than zero, the technology being evaluated is economically viable. Since NPV is sensitive to the reliability of the future stream of benefits and costs which can be uncertain, the CBA analysis used different values for the discount rate: 1%, 3% and 5%. There is now a growing consensus that uncertainty can be addressed through a declining discount rate over time (HMT, 2003).

The CBA analysis considered the emissions along the entire chain of production and usage of vehicles – the Well-to-Wheel (WtW) analysis, comprising the Well-to-Thank (WtT) and the Tank-to-Wheel (TtW) emissions, allowing for the energy grid trend scenarios regarding the mix of electricity production and incorporation of renewables (range of gCO_2/kWh).

The CBA results are presented in Figure 12 – a) and Figure 12 – b) considering the year of reference of the vehicle acquisition 2010 and 2020 respectively, and a discount rate of 3%.

As previous reported, the following cost categories were considered in the CBA analysis:

i) fuel costs;
ii) electricity costs (two extreme scenarios);
iii) battery costs;
iv) maintenance (related with the oil-engine and battery replacement);
v) ISV and IUC taxes (AT, 2012).

As already reported the IUC annual tax does not apply to electric vehicles. We have assumed that this situation would apply until the 2020 and 2030 scenarios. Therefore, from the perspective of the user the IUC represents an additional cost for conventional vehicles in comparison to the electric vehicle user/purchaser.

The following categories of benefits were considered in the CBA analysis:

i) energy savings (relative to the reference technology 1.3 GDI turbo);
ii) abatement of CO_2 emissions until the long term (2030).

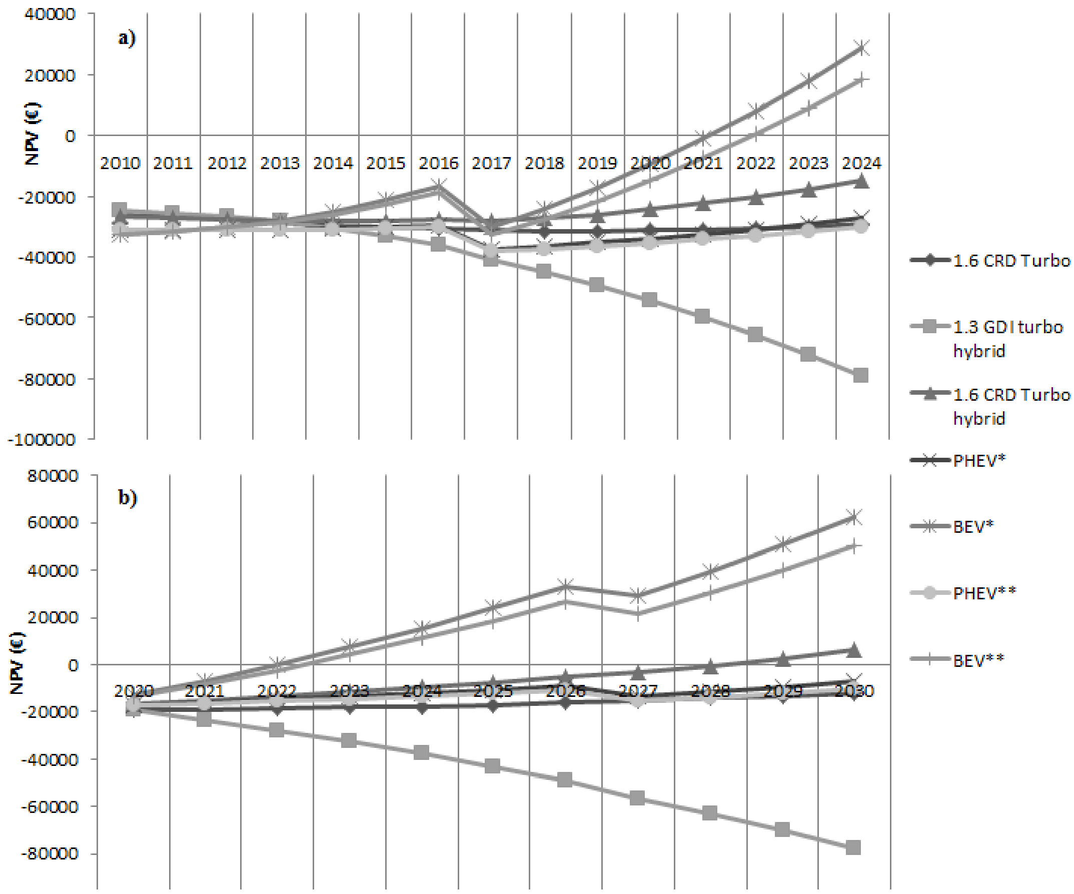

Figure 12 – Net Present Value (€) with a discount rate of 3% for each technology considering the WtW CO_2 emission, in 2010 (a) and in 2020 (b).
* Positive extreme situation of electricity cost evolution; ** Negative extreme situation of electricity cost evolution.

Figure 12 – a) shows that BEV is the only technology that is able to achieve a NPV greater that zero which occurs after 2021 or 2022, considering the prospective evolution for the electricity costs and assuming that the vehicle is purchased in 2010.
For the long term scenario, between 2020 and 2030, assuming that the vehicle is purchased in 2020, the BEVs will be economically viable sooner (after 2 year of the vehicle acquisition in 2022). This is due to the expected lower expected battery and electricity costs in relation to the fuel cost (gasoline).

Cost-effectiveness analysis of vehicle technologies for the reduction of CO_2 emissions

The cost-effectiveness value of each vehicle technology was calculated for evaluating which option (BEVs, PHEVs, HEVs and ICEVs) is the most efficient for the purpose of reducing CO_2 emissions. The analysis considered the complete Well-to-Wheel (WtW) chain, thus comprising the Well-to-Thank (WtT) and the Tank-to-Wheel (TtW) emissions.
The cost-effectiveness value indicator (CE), in €/kgCO_2, is represented in equation 4, as follows:

$$CE = \frac{I - NPV}{E_{GHG}}, \quad \textbf{(Eq. 4)}$$

where:
I is the initial cost of the technology (in €);
E_{GHG} is the emission reduction over average technology lifetime (in kg);
NPV is the net present value of technology (in €), previously defined in equation 3;

The abatement costs of reducing CO_2 emissions from alternative vehicle technologies will be influenced by the price of oil and the relative costs of electricity at the charging stations, along with the mix of energy sources (e.g. percentage of renewable energy) to produce each kWh. One exemplification of the CE indicators' results are presented in Figure 13 – a) and Figure 13 – b), which have considered a vehicle purchase in 2010 and 2020 respectively, and a discount rate of 3%.

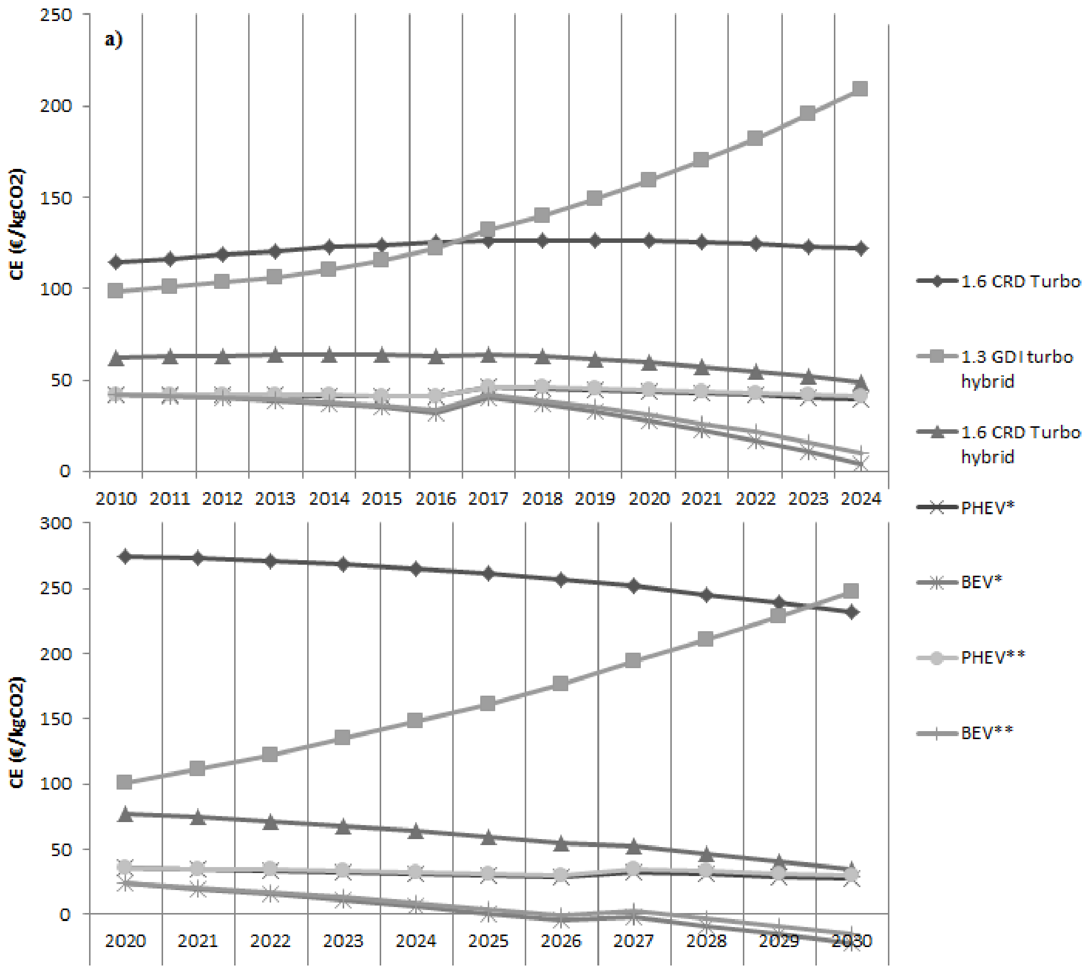

Figure 13 - Cost-effectiveness (€) with a discount rate of 3% for each technology considering the WtW CO_2 emission, in 2010 (a) and in 2020 (b).

Figure 13 shows that BEVs offer the highest potential to reduce CO_2 emissions at the least cost. In addition, the offset of 1 kg of CO2 from one BEV purchased in 2010 costs 42 €, whereas in 2022 this cost is reduced to 17 €. In contrast, the offset of 1kg of CO2 by the DGI Turbo Hybrid purchased in 2010 and 2022 costs, respectively 99 € and 182 €.
After 2028, the potential offered by BEVS (purchased in 2020) for reduction CO_2 emissions can be used for developing a carbon market (mobility based) at the regional level, where each greener user is able to sell carbon credits to offset others' carbon emissions.

CONCLUSION

The results show that users' benefits related to BEVs are likely to be higher than those attached to ICEVs after the 2020 horizon. This is mainly due to the expected technology progress (reduction of battery costs and charging infrastructure) and to the decrease of the relative prices of electricity in comparison to fossil fuels ones. Considering the LCA analysis conducted for the Portuguese vehicle fleet for 2020, BEVs would emit 43 gCO_2/km against 151 from ICEVs. Assuming the continuous replacement of older ICEVs by BEVs between 2010 and 2030, it will be possible to have a total average reduction of 2.0 $GtonCO_2$/year.
The integration of BEVs in the vehicle fleet is a key policy measure to comply with the European transport policy objectives to achieve a low-carbon and competitive economy. The analysis of future trends on users' costs and benefits for all vehicle types (BEVs, PHEVs, HEVs and ICEVs) indicates that the highest potential to reduce CO_2 emissions from transport would occur only by 2021/2022. Besides technology progress on cost reduction (battery and charging infrastructure), electricity prices and fuel taxation seem to be important drivers for the BEV market growth. However, it shall be noted that after 2028, the potential offered by BEVS (purchased in 2020) for reducing CO_2 emissions can be used for developing a mobility based carbon market at the regional level, where each greener vehicle user is able to sell carbon credits to offset others' carbon emissions.
Although the economic viability of BEVs will take some years to occur there are several factors, external to the present research study, that can anticipate an earlier diffusion of BEVs in the European and Portuguese markets. The CBA analysis assumed the conventional purchase of the BEV. However, possible electric car sharing schemes and intermodal services would allow different market conditions which might influence users' acceptability and future demand. Additionally, the BEV business model may have a key role if batteries are sold independently from the vehicle. These interrelated issues are important for further research.

ACKOWLEGMENTS

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