IMPACTS OF ALTERNATIVE VEHICLE TECHNOLOGIES AND ENERGY SOURCES IN THE PORTUGUESE ROAD TRANSPORTATION SECTOR

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ABSTRACT

The transportation sector will face considerable changes in the near future. Accordingly, several scenarios of alternative vehicle technology introduction were studied for Portugal: SC. 1 - BASELINE TREND (8% of LDV fleet displaced); SC. 2 – LIQUID FUELS BASED (70%); SC. 3 – LIQUID FUELS BASED WITH LOWER DIESEL SHARE (70%); SC. 4 – POLICY ORIENTED (44%); SC. 5 – ELECTRICITY POWERED (90%); SC. 6 – HYDROGEN POWERED (90%), for LDV; and SC. 7 – HDV and BUSES (30%) to add the contribution of HDV and buses to the total road transportation sector. Its impacts in terms of energy consumption and CO_2 emissions were assessed, resulting in up to 18 and 24% reduction respectively compared to SC.1 in 2050.

INTRODUCTION

In the last decade, European global energy consumption has risen significantly (around 13% from 1990 to 2006). For Portugal (PT) that increase rate has been even higher (57%) [1]. The transportation sector was responsible in 2006 for 39% the global energy consumption. From that percentage, road transportation sector accounted for 86% [1]. Additionally, Portugal imports most of its transportation final energy consumption in the form of oil based fuels (around 70%) [2].

The urge for energy security of supply, air quality improvement in urban areas and CO_2 emissions reduction are pressing decision makers/manufacturers to act on the road transportation sector, introducing more efficient vehicles in the market and spanning the energy sources. For that reason, it is expected in the near future that the transportation sector will face considerable changes. It is probable that the market share of hybrid vehicles will raise and that, in the long term future, the market share of alternative technologies such as plug-in hybrid, electric or fuel cell vehicles will start increasing.

Not many studies address the issue of how long and how significantly the impact of new technologies is in terms of energy saving, energy displacement and of avoided CO_2 emissions. These types of studies have recently been developed in the United States of America (USA) [3]. The research work developed by the Prof. Heywood's team at the MIT Sloan Automotive Laboratory has addressed how the trajectory of USA fleet fuel use and GHG emissions over the next two decades will evolve [4]. Using vehicle simulations and historical data, the trade-off between vehicle performance, size and fuel consumption was determined. This study found that due to strong competition from mainstream gasoline vehicles and high initial cost, market penetration rates of diesels and gasoline hybrids in the U.S. are likely to be slow. As a result, diesels and gasoline hybrids may have only a modest, though growing potential for reducing fleet fuel use before 2025. In general, the time-scales to impact of new technologies are twenty to twenty-five years. Integrating vehicle and fuel scenarios shows that measures which reduce greenhouse gas emissions also reduce petroleum consumption, but the converse is not necessarily true. Policy efforts therefore should be focused on measures that improve both energy security and carbon emissions at the same time. The European reality has also been addressed by considering France, Germany, United Kingdom and Italy over the next 30 years [5]. In Europe there is rising concern over the imbalance between diesel and gasoline fuel, so no change, diesels dominating scenarios were considered, with the same methodology developed earlier [4].

There is also a forecast model VISION (from the Argonne National Laboratory) for the USA, which estimates the potential energy use, oil use and carbon emission impacts of advanced light and heavy-duty vehicle technologies and alternative fuels though 2050, by reflecting alternative assumptions about advanced vehicle and alternative fuel market penetration [6]. However, it does not consider plug-in technologies and Vehicle-to-Grid (V2G) approach.

The World Energy Council also addresses sustainability of petroleum and other fossil fuels until 2050. This worldwide study looks at existing and potential fuel and vehicle technologies to determine a roadmap for technologies which can help meet the objective of sustainable energy [7]. This roadmap of technologies and measures considers the policies necessary to ensure that the objectives are met in the most efficient and effective way possible. The same type of analysis was performed by the International Energy Agency in 2008 [8]. This study considers several scenarios including not only road transportation but also air, maritime and rail transportation. In terms of vehicle technologies it considers several ones entering the market more aggressively in each of the scenarios and evaluating the consequences in terms of global energy use and emissions.

For Portugal, The *Strategic Energy Technology Plan* (SET Plan) is an official document from "Ministério da Economia e Inovação" which in its "Vision Paper" establishes future scenarios for the Portuguese economy [9]. Regarding the transportation sector it focuses mainly on biofuels and alternative technologies in the PT fleet assuming that: by 2050 biofuels are expected to represent approximately 20% of total road transport fuel (probably the biggest share of this portion will belong to second generation biofuels); and by 2020, fuel cell vehicles are expected to have a marginal share. Nevertheless, the outlook for 2050 indicates an expected market share of 3.3%. Hybrid vehicles are expected to represent 4.46% of the entire car park by 2020. By 2050 the total share of hybrids in the market will be more than 15%. These results are based on a macro-economic energy model (PRIMES model) that focuses on market-related mechanisms influencing the evolution of energy demand and supply and the context for technology penetration in the market. Other scenarios exist for Portugal much more focused on a specific technology.

PT has recently launched the “Plano de Mobilidade Eléctrica” (PME), which considers that “electric vehicles will be the next logical step from hybrids due to their high potential for CO_2 reduction” [10]. The expected evolution for EV and PHEV vehicles in PT ranges from 8000 vehicles sold in 2012 to 150 to 200 thousand in 2020. The main assumptions which are crucial for this scenario are: further increasing oil prices; legislation in Europe continues as announced; availability of high variety of EVs and hybrids; availability of charging infrastructure; and improvement in battery technology/costs as expected (up to 65% reductions is battery costs in 2020) [10].

Consequently, a flexible model to estimate the effects of alternative technologies (such as plug-in hybrid electric and electric vehicles) and alternative penetration in PT is justified. Additionally, including the full concept of an LCA analysis and including a wider range of vehicle technology choices and fuel/energy source pathways is relevant for the upcoming changes in the road transportation sector. According to this, the objective of this study was to assess the energy consumption, CO_2 emissions and renewable indicator resulting of the introduction of alternative vehicles/fuels in the Portuguese road transportation sector up to 2050. The following six scenarios for light-duty vehicles and one for heavy-duty vehicles/buses were analyzed: SCENARIO 1 - BASELINE TREND; SCENARIO 2 – LIQUID FUELS BASED; SCENARIO 3 – LIQUID FUELS BASED WITH LOWER DIESEL SHARE; SCENARIO 4 – POLICY ORIENTED; SCENARIO 5 – ELECTRICITY POWERED; SCENARIO 6 – HYDROGEN POWERED; and SCENARIO 7 – HDV and BUSES.

LIFE-CYCLE ANALYSIS

The Portuguese fleet is subdivided in different classes of vehicles and fuels allowing disaggregating the fuel consumption and CO_2 emission in a **total life-cycle analysis (LCA)**. A LCA methodology implies analyzing a product’s flows during all its lifetime, since it is produced, to its utilization and its end-of-life, which includes its recycling process. In this work the Portuguese fleet LCA is estimated. For that the Portuguese fleet is disaggregated in its types of vehicles and fuels.

This means that a certain vehicle technology powered by a specific fuel must include in its LCA not only its utilization stage (Tank-to-wheel) related to driving the vehicle, but also the fuel production stage (Well-to-Tank) and the vehicle itself manufacturing/maintenance/recycling (Materials Cradle-to-Grave).

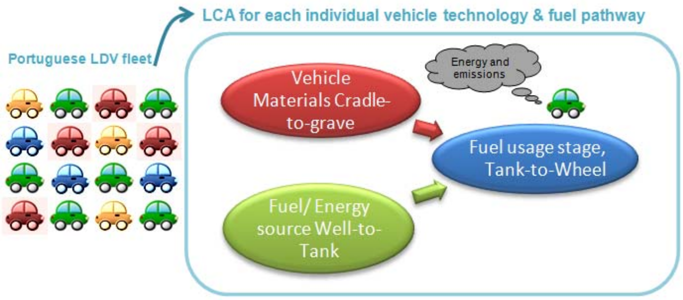


Figure 1 – Portuguese fleet LCA structure.

The **Materials Cradle-to-Grave** (C2G) life-cycle analysis refers to the full life cycle of the vehicle. It includes the vehicle assembling, the maintenance during its lifetime and finally the dismantling and recycling processes of the vehicle. The materials life-cycle energy consumption and emissions are spread along the vehicle expected lifetime. For this study, the GREET software from the US Argonne National Laboratory was used [11]. This software has two units, one dealing with the fuel life cycle (*GREET 1.7*) and the other dealing with the materials life cycle (*GREET 2.7*). This latter was adapted for the European reality, which was accordingly used for the Portuguese case [12].

Well-to-Tank (WTT) accounts for the energy consumption and emissions from primary energy resource extraction through the delivery of the fuel/energy source to the vehicle fuel tank. The main bibliographic references used are the study by Edwards *et al* for the EU and another by General Motors, which account for the conventional fuel pathways [13],[14]. For considering other possible alternative fuel pathways, when other studies had been developed they were used (such as for biomass-to-liquid fuels); if not the LCA study itself was developed (as for the different biodiesel pathways for PT) [15],[16].

Fuel **Tank-to-Wheel** (TTW) accounts for the emissions and fuel consumption that result from moving the vehicle through its drive cycle. For simulating the daily commuting journeys of conventional or alternative vehicle technologies ADVISOR vehicle simulation software is used [17]. ADVISOR is a micro-simulating tool to estimate the performance and fuel economy of conventional and advanced new vehicle technologies (hybrid and electric powertrains). Both tailpipe emissions (HC, CO, NO_x, PM) and fuel consumption are estimated by ADVISOR. ADVISOR refers only to simulating one vehicle in a specific driving cycle. However, to characterize the consumption and emissions of a large fleet COPERT 4 was used. COPERT 4 is an MS Windows software program aiming at the calculation of air pollutant emissions from road transport. The COPERT 4 methodology is part of the EMEP/CORINAIR Emission Inventory Guidebook. The Guidebook, developed by the UNECE Task Force on Emissions Inventories and Projections, is intended to support reporting under the UNECE Convention on Long-Range Transboundary Air Pollution and the EU directive on national emission ceilings.

PATTS

The scenarios results were obtained using the PATTS simulation tool, developed at IST. PATTS (**Projections for Alternative Transportation Technologies Software**) considers the fleet evolution along time, the vehicle stock (considering not only entries in the market, but also vehicle exits), the fleet kilometers travelled, and combining it with the vehicles' fuel consumptions (according to the technology/fuel configuration) and emissions, the total fleet energy consumption and emissions are estimated for the Portuguese fleet along time, as can be overseen in Figure 2.

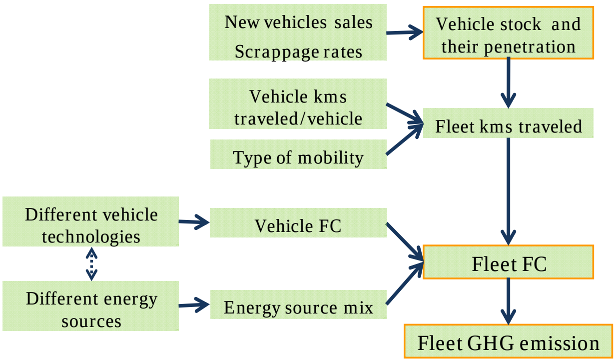


Figure 2 – PATTS overview.

PATTS is capable of tracking a wide variety of variables such as new vehicle sales, market shares of different propulsion systems and their fuel consumption, vehicle aging and scrappage curves, vehicle stock, vehicle travel and fuel mixes. Historic data starting from 1973 were used to calibrate the model. Some of the model inputs are presented next.

Several approaches can be used to assess the evolution of car fleets. Car ownership relates to the standard of living in a country but economic parameters may sometimes be insufficient to explain the fleet's evolution. Vehicle density (VD, the number of vehicles per 1000 inhabitants in a country) can be expressed mathematically through a Logistic function [18]. For the Portuguese vehicle fleet the best fitting results to the real data were obtained with the following Logistic function:

$$\boldsymbol{VD(t)} = \frac{\boldsymbol{number\ of\ vehicle}}{\boldsymbol{1000\ inhabitants}} = \boldsymbol{\beta} + \frac{\boldsymbol{\alpha - \beta}}{\boldsymbol{1 + e^{-k(\log(t) - \varphi)}}} \qquad \text{Equation 1}$$

where α is the final size achieved, k is a scale parameter, φ is the x-ordinate of the inflection point of the curve and t is time in years (e.g. 0 for 1973 and 33 for 2006). More specifically, for Portugal, the fitting was performed with the 1973-2006 data not for the VD but for the total fleet, accounting with the existing country's population, and the results are presented in Error! Reference source not found..

Afterwards, the projection of the number of LDV in the period 2007-2050 was performed, using the population prediction form EUROSTAT (which accounts for 10.6 in 2007 and 11.4 million inhabitants in 2050) [19]. According to these results the Portuguese fleet will stabilize at around 616 vehicles per 1000 inhabitants (compared with 518 vehicles per 1000 inhabitants in 2006), which in terms of total fleet will correspond to around 7 million vehicles in 2050. This means that the energy consumption and CO_2 emissions problems mentioned earlier will continue to grow, emphasizing the need for alternative solutions for the road transport sector.

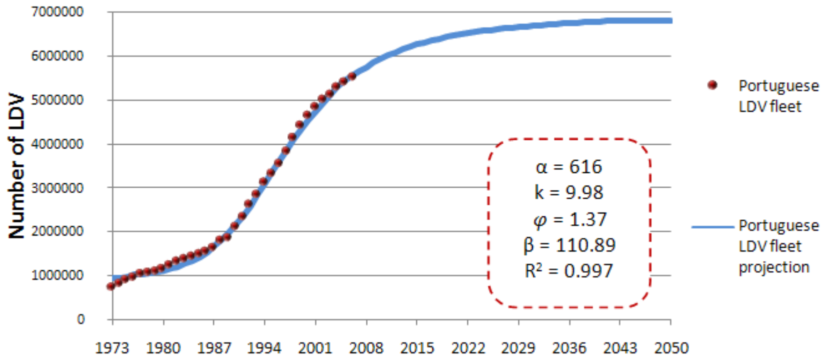


Figure 3 – Number of LDV in Portugal in the period 1973-2006 (in red) and estimated number of LDV from 1973 to 2050 (blue). The fitting results are also presented

The same reasoning was applied to the heavy-duty vehicles (HDV) fleet and bus fleet, where the historic car stock data for HDV and buses was used to create a Logistic function capable of estimating its future evolution.

Vehicle scrappage is a function of the lifetime of the vehicle, so it represents the probability of breakdown before the planned technical lifetime, the probability of car wreckage (for instance, after a car accident) and the probability of a car being replaced by a new or used car. This last one depends mainly on the costs of cars and on policies that may affect those costs (such as purchase premiums or cash-for-clunker alike policies). The annual vehicle scrappage curves may be defined as the number of vehicles that are no longer in circulation after *k* years. A Weibull distribution was used as is presented in Equation 2.

$$\varphi(k) = \exp\left[-\left(\frac{k+b_i}{T}\right)^{b_i}\right] \text{ and } \varphi(0) = 1 \quad \text{Equation 2}$$

where *k* is the age, $\varphi(k)$ is the presence probability of vehicles of type *i* having age *k*, *b* is the failure steepness for vehicle type *i* (b_i>1, so failure steepness increases with age) and T the characteristic service lifetime for vehicle type *i*. For the Portuguese fleet, the average values for b_i and T of 11 and 33 for LDV, 10 and 33 for HDV and 10 and 31 for Buses respectively [18],[20]. All new technologies entering the market were attributed a scrappage curve. Gasoline based technologies were assumed to have the conventional gasoline curve and the same for diesel based technologies. Other alternative technologies were assumed to behave similarly to the conventional technologies, so its scrappage curve was assumed to be an average between the gasoline and diesel ones.

Vehicle sales in PT increased significantly in the last decades. However, in the last years, with a different economic situation, vehicle sales have stabilized, so an average from the last 4 years of 1% growth in sales was considered.

An important aspect concerning new vehicle sales is the increasing penetration of diesel vehicles in PT. The fact is that in the last years the sales of vehicles in PT have been showing a considerable shift to diesel LDV, as presented in Figure 4. That is a result of a lower diesel fuel price and different vehicle characteristics perceived as better for the public in general (in spite of the higher vehicle purchase cost). As a result, a future diesel/gasoline share in new vehicle sales was also assumed. Based on the historic evolution of this parameter, it was assumed that it would stabilize at around 75/25, as is presented in Figure 4.

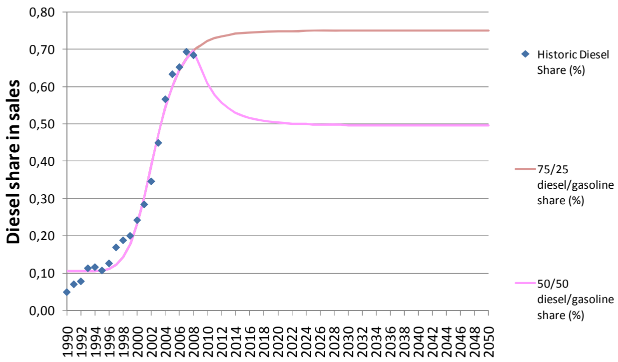


Figure 4 – Diesel/gasoline share in new vehicle sales evolution along time.

However, other diesel shares may be considered, especially considering a decrease in the diesel share in sales. Only Scenario 3, to be defined later, considers a diesel/gasoline leveling at 50/50.

From vehicle inspection data the annual vehicle kilometers travelled (VKT) for the Portuguese fleet was obtained [21]. The results were introduced in the model for the 2005 VKT data, showing that diesel LDV present a slightly higher VKT than gasoline LDV. For new vehicle technologies entering the market diesel and gasoline based technologies were assumed to have a diesel and gasoline characteristic curve respectively. For alternative fuel technologies an average of the diesel and gasoline curves was used. Only electric vehicles were assumed to have a lower VKT curve (based on traffic data), since they have lower ranges and will be mainly used within cities [21].

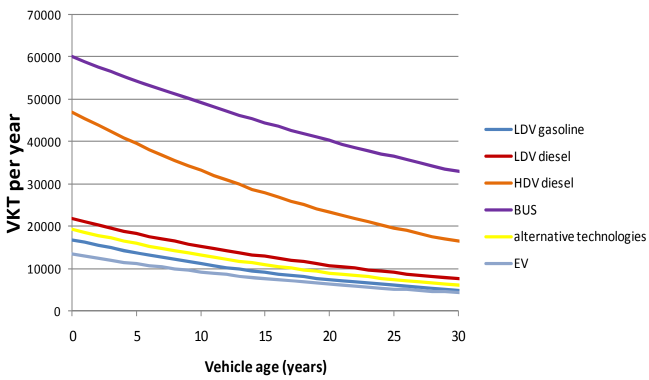


Figure 5 – Average VKT per year along the vehicle's lifetime for the technologies considered in PATTS.

According to historic data the curves were corrected to the past, having lower values. In terms of future values, long-term growth factors in VKT per year per vehicle for Portuguese fleet vehicles were assumed. The rate of growth in per-vehicle kilometers traveled is assumed to decrease from 0.5 percent per year between 2005 and 2020, to 0.25 percent per year in period 2021-2030, to 0.1 percent per year in years after 2030 [4].

According to these inputs, sales are matched with survival curves per technology and the results are crossed with the VKT curves to obtain the fleet vehicle.kilometers per technology per year.

For assessing the impact of the different vehicle technologies on the light-duty fleet energy consumption and emissions, the following representative vehicles technologies were considered [22],[23]:

- ICEV (Gasoline or with biofuels blends): internal combustion engine vehicle that can run with gasoline and blends of gasoline and ethanol, with a four cylinder explosion engine with 63 kW of power and total weight of 1139 kg;
- ICEV (Diesel or with biofuels blends): internal combustion engine vehicle that can run with diesel and blends of diesel and biodiesel, with a four cylinder Diesel engine with 67 kW of power and total weight of 1210 kg;
- PHEV (Gasoline or with biofuels blends): plug-in hybrid electric vehicle that can work with gasoline and blends of gasoline and ethanol and electricity. 53 kW internal explosion combustion engine/generator, 75 kW electric motor, Ni-MH 45 Ah 335 V battery (dischargeable to 45% of its capacity), series technology with a total weight of 1323 kg. The Portuguese electricity generation mix was considered for electricity consumption;
- PHEV (Diesel or with biofuels blends): plug-in hybrid electric vehicle that can work with diesel and blends of diesel and biodiesel and electricity. 53 kW internal Diesel combustion engine/generator, 75 kW electric motor, Ni-MH 45 Ah 335 V battery, series technology with a total weight of 1323 kg. The Portuguese electricity generation mix was considered for electricity consumption;
- HEV FULL (Gasoline): hybrid electric vehicle with parallel and series technology, 43 kW internal explosion combustion engine, 31 kW electric motor, Ni-MH 6.5 Ah 308 V battery, 15 kW generator and 1332 kg;
- EV (100% Electricity): pure electric vehicle with a 75 kW electric motor, Ni-MH 90 Ah 268 V battery, and a total weight of 1389 kg. The Portuguese electricity generation mix was considered for electricity consumption.
- Hybrid (FC-HEV): fuel cell vehicle with a 75 kW electric motor, Li-ion 6 Ah 267 V battery, 50 kW fuel cell and a total weight of 1388 kg.
- Plug-in hybrid (FC-PHEV): plug-in series hybrid with fuel cell. Fuel cell stacks 50 kW, electric motor 75 kW, battery Ni-MH 45 Ah 335 V and a total weight of 1315 kg.

The energy sources considered were gasoline, diesel, ethanol from sugar beet (with an average between pulp to heat process and animal feed export), biodiesel (an average between biodiesel from rapeseed, sunflower, rapeseed and blends), electricity and hydrogen from central natural gas reforming plants with steam co-generation.
The energy consumption and CO_2 emissions coefficients applied to each vehicle technology in the three LCA stages are presented in Table 1.

Table 1 – Energy consumption and CO_2 emissions coefficients applied to each vehicle technology.

Vehicle	Materials C2G		WTT		TTW	
	Energy (MJ/km)	CO_2 (g/km)	Energy (MJ/MJ)	CO_2 (g/MJ)	Energy (MJ/km)	CO_2 (g/km)
ICEV Gasoline	0.48	30.7	0.14	13	2.12	154
ICEV Diesel	0.50	32.0	0.16	14	1.96	146
ICEV E100	-	-	1.58	44	2.12	0
ICEV B100	-	-	0.94	31	1.86	0
HEV Gasoline	0.58	37.7	0.14	13	1.67	120
HEV Diesel	0.58	37.7	0.16	14	1.54	115
EV (Electricity)	0.77	47.8	1.91 (elect.)	112 (elect.)	0.60	0
FC-HEV (A)	0.73	48.4	0.57	88	1.14	0
FC-PHEV (A)	0.77	49.5	0.57 (H_2)	88 (H_2)	0.67	0
			1.91 (elect.)	112 (elect.)	0.42	0
PHEV Gasoline	0.70	43.7	0.14 (gas.)	13 (gas.)	1.80	129
			1.91 (elect.)	112 (elect.)	1.12	0
PHEV Diesel	0.70	43.8	0.16 (die.)	14 (die.)	1.66	119
			1.91 (elect.)	112 (elect.)	1.04	0
HDV	2.52	161.0	0.16	14	10.58	792
Bus	3.03	193.6	0.16	14	12.76	955
Bus NG	3.33	213.0	0.12	5.5	16.33	977
Bus H_2	4.39	292.7	0.57 (H_2)	88 (H_2)	17.23	0

After having the kilometers traveled per type of vehicle technology, that data is crossed with the fuel consumption data and emission factors of each technology for each specific year [23].

For the vehicle fuel consumption and CO_2 emissions in the past, the European average historic vehicle fuel consumption (and respective emissions) was assumed [24]. For the future evolution of gasoline, diesel and hybrid Portuguese based technologies, future technological improvements were simulated obtaining reduction potentials up to 40% according to Table 2. They were applied linearly until reaching those minimum values. These values agree with those obtained by MIT for similar USA based compared to the 2005 technologies [3]. For HDV and Buses a potential 20 and 10% reduction on fuel consumption is considered until 2050 [8],[25].

Table 2 – TTW Energy consumption correction factor applied to each vehicle technology. Technologies in grey were assumed to start reducing their energy consumption in 2020, continuing decreasing these values until 2060.

Vehicle technology	Year		
	2009	2020	2050
ICEV diesel	1	0.90	0.63
ICEV gasoline	1	0.89	0.60
HEV	1	0.89	0.65
HDV	1	0.95	0.80
BUS	1	0.97	0.90
FCV HEV	1	1	0.79
EV	1	1	0.76
PHEV gasoline	1	1	0.70
HEV diesel	1	1	0.74
FCV PHEV	1	1	0.79
PHEV diesel	1	1	0.60

In order to consider alternative technologies, its share in new vehicle sales has to be assumed. According to the alternative technology share, the conventional technologies (diesel+gasoline ICEV) share is reduced correspondingly. The same methodology in terms of survival in the fleet, VKT per year, vehicle.kiolmeters of that technology and consequently fuel consumption and emissions is applied. Combining all technologies along time gives the fleet TTW energy consumption and emissions from 1973 to 2050.
Having as a basis the TTW results, the LCA methodology is applied, in order to obtain the WTT and C2G components [23].
Regarding the electricity LCA, based on the REN investments plans until 2020, the electricity generation mix was estimated until 2020, and assumed constant for until 2050, as is presented in Table 3 [26].

Table 3 – Electricity generation mix considered for the WTT life-cycle analysis.

Year	**Electricity generation mix (%)**					
	Hydro	**Wind**	**Coal-fired**	**Oil-Fired**	**Natural gas**	**Biomass**
2010	23%	8%	31%	5%	28%	5%
2015	20%	12%	29%	0%	32%	7%
2020-2050	11%	19%	23%	0%	36%	10%

SCENARIOS

The different scenarios evaluated throughout the present study were defined as follows:

SCENARIO 1 - BASELINE TREND

- Portugal maintains the same liquid fuels based infrastructure and the alternative fuels targets are achieved (10% biodiesel in 2020 and 25% in 2050);
- Hybrid technology displaces a small percentage of the total fleet. HEV sales peaks at around 8% and stabilizes. The market doesn't consider HEV technology attractive enough to further growth; HEV diesel technology enters the market as part of the HEV share around 2020; and
- The diesel/gasoline share stabilizes 75/25.

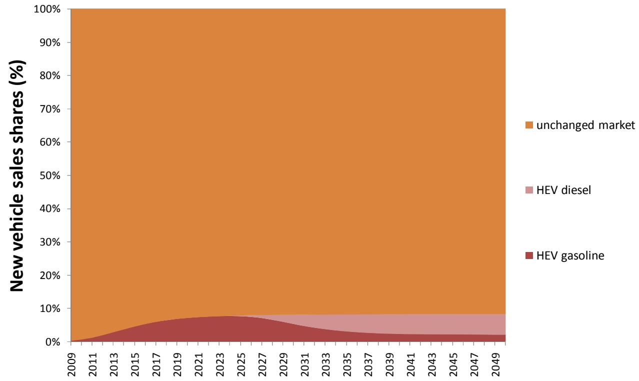


Figure 6 – Market sale mix evolution in the 2010-2050 period for the Baseline trend scenario.

SCENARIO 2 – LIQUID FUELS BASED

- Portugal maintains the same liquid fuels based infrastructure and
- Alternative fuels (10% biodiesel in 2020). For the 25% share in 2050, 5% is considered to be ethanol that starts entering the market around 2020;
- More efficient liquid fuel based vehicles have an increasing share of the market, achieving around 70% in 2050. The more efficient vehicles account for: HEV gasoline already entering the market; and HEV diesel and PHEV (both diesel and gasoline) entering the market in 2020. HEV:PHEV ratio is 80:20 [8]; and
- Diesel/gasoline share stabilizes at 75/25.

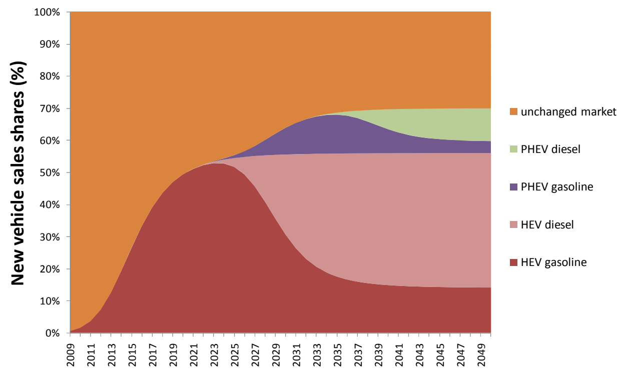


Figure 7 – Market sale mix evolution in the 2010-2050 period for the Liquid fuels based scenario.

SCENARIO 3 – LIQUID FUELS BASED WITH LOWER DIESEL SHARE

- Same as Scenario 2 regarding alternative fuels (25% share in 2050, where 5% is considered to be ethanol that starts entering the market in around 2020);
- Same as Scenario 2 in terms of vehicle technology entering the market;
- A reduction in diesel vehicles share in sales is considered. Due to technology improvements and/or a revision in the fuel taxation, diesel and gasoline technologies are leveled so a 50/50 ratio is considered (for conventional technologies and HEV and PHEV in their gasoline and diesel versions).

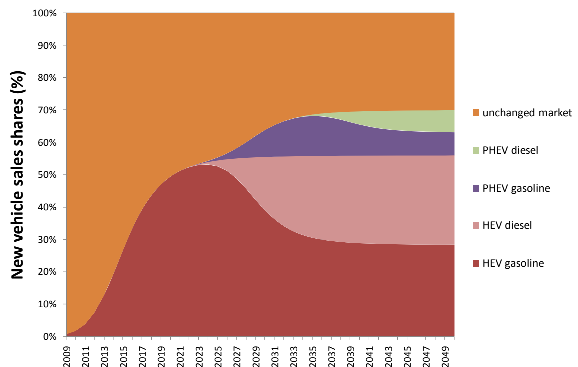


Figure 8 – Market sale mix evolution in the 2010-2050 period for the Liquid fuels based with lower diesel share scenario.

SCENARIO 4 – POLICY ORIENTED

- Portugal maintains the liquid fuels based infrastructure but develops simultaneously an infrastructure for recharging electric vehicles;
- Same as Scenario 1 in terms of alternative fuels (10% biodiesel in 2020; 25% in 2050);
- According to the National Electrical Mobility Plan (PME), 10% of vehicle sales in 2020 will be electricity powered vehicles, entering the market as of today (70/30 ratio between EV and PHEV in 2020). It is also considered that EV will succeed in local niche application. Therefore, after 2020 it is assumed that the EV market will be saturated and EV will not continue to increase its share stabilizing at around 10% in 2050. On the contrary, PHEV have a different concept and are adequate also for long distance travelling, so they will have more growth potential, stabilizing at 20% in 2050. HEV vehicles will continue entering the market, achieving a 15% market sale share in 2050; and
- The diesel/gasoline share stabilizes at a 75/25 ratio.

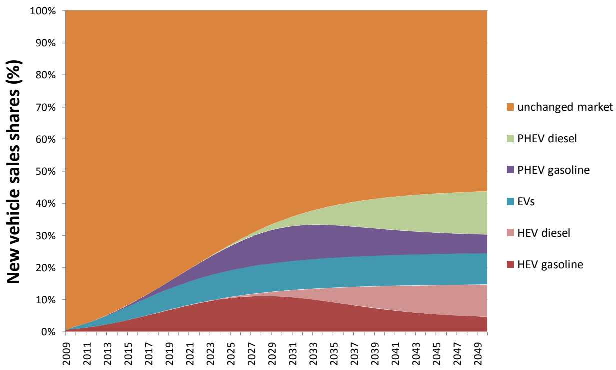


Figure 9 – Market sale mix evolution in the 2010-2050 period for the Policy oriented scenario.

SCENARIO 5 – ELECTRICITY POWERED

- Portugal develops a mature and large scale infrastructure for recharging vehicles;
- Same as Scenario 1 in terms of alternative fuels (10% biodiesel in 2020 and 25% in 2050);
- Portugal will rapidly undertake alternative technologies based on electricity. For that reason in 2050 90% of vehicle sales will have been shifted from conventional technologies. An electricity recharging infrastructure will be available, so electricity will be the main energy source for road transportation. Both PHEV and EV technologies start entering the market right away. The assumed HEV:PHEV:EV ratio for 2050 was 30:50:20; and

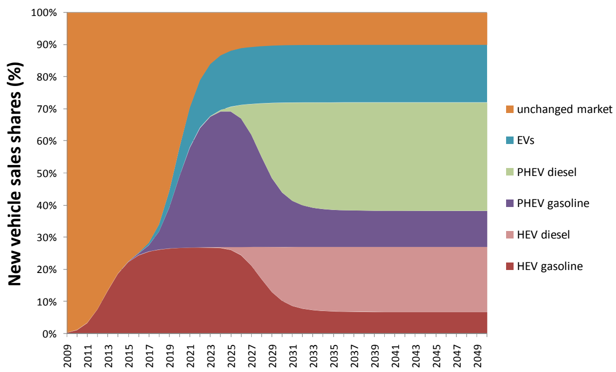


Figure 10 – Market sale mix evolution in the 2010-2050 period for the Electricity powered scenario.

- Diesel/gasoline share stabilizes at 75/25.

SCENARIO 6 – HYDROGEN POWERED

- Portugal develops an hydrogen refueling infrastructure;
- Same as Scenario 1 for alternative fuels (10% biodiesel in 2020 and 25% in 2050);
- Portugal will undertake alternative technologies based on hydrogen. Therefore, in 2050 90% of vehicle sales will have been displaced from conventional technologies. A hydrogen refueling infrastructure will be available so hydrogen will be the main energy source for road transportation. Current HEV technology will evolve to PHEV and around 2020 FC HEV and FC PHEV will also enter the market, complementing the electricity infrastructure with the hydrogen recharging infrastructure. HEV, PHEV, FC HEV and FC PHEV will account in 2050 for 10, 10, 35 and 35% of new vehicles sales respectively; and
- Diesel/gasoline share stabilizes at a 75/25 ratio.

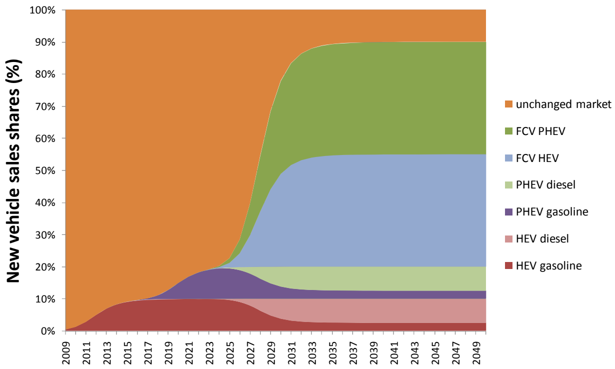


Figure 11 – Market sale mix evolution in the 2010-2050 period for the Hydrogen powered scenario.

SCENARIO 7 – HEAVY-DUTY VEHICLES (HDV) AND BUSES

- Same as Scenario 1 in terms of alternative fuels (10% biodiesel in 2020 and 25% in 2050);
- Portugal maintains the same diesel based infrastructure for heavy-duty vehicles, so no alternative technology is introduced. Only the normal gains for the HDV technology are considered;
- Specific bus fleets adopt natural gas (starting in 2010, up to 20%) and hydrogen (starting in 2020, up to 10%) as alternative energy sources for buses; and
- This scenario was included as part of the remaining six scenarios analyzed for LDV, in order to obtain global results for the road transportation sector.

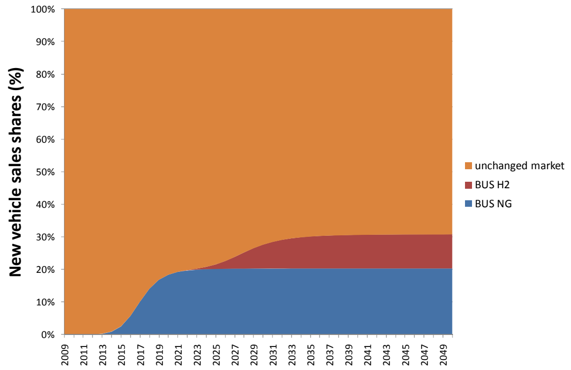
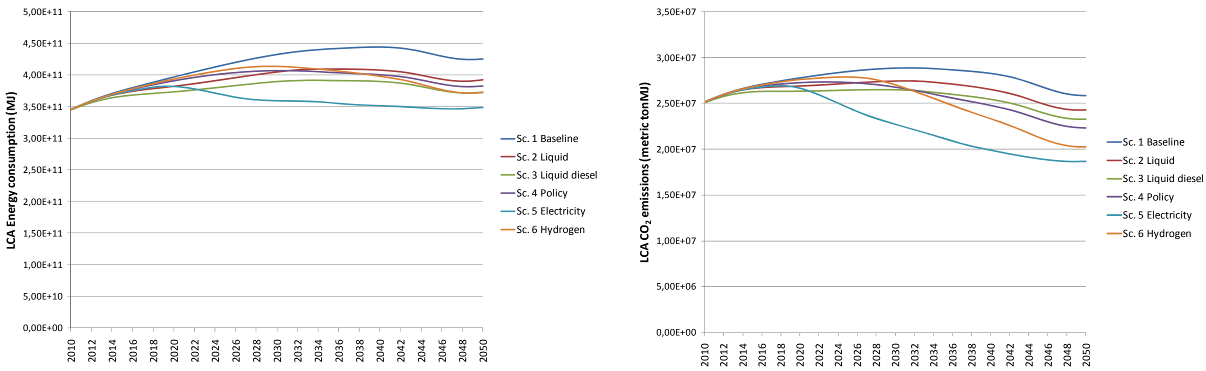


Figure 12 – Market sale mix evolution in the 2010-2050 period for Buses.

RESULTS AND DISCUSSION

The six scenarios were evaluated on a full life-cycle analysis (LCA) including the Tank to Wheel (TTW), Well to Tank (WTT) and Cradle to Grave (C2G) stages. Figure 13 presents the total energy consumption and total CO_2 emissions in the LCA for the entire fleet (LDV + HDV + Buses. As can be concluded, scenario 5 presents the lower results in terms of energy consumption and CO_2 emissions followed by scenarios 6 and 4.



a) b)

Figure 13 – LCA total energy consumption (MJ) a) and CO_2 emissions (metric ton) b) in the 2010-2050 period for the different scenarios.

If no alternative solutions are adopted (Sc. 1), the total life-cycle energy consumption increase in 2050 goes up to 26% and CO_2 emissions increase by 3% having as reference the energy consumption in 2009. Comparing the six scenarios the most attractive concerning energy consumption is Scenario 5. In spite of increasing the total life-cycle energy consumption in the 2009-2050 timeframe (by 3%), in 2050 it reduces the total life-cycle energy consumption by 18% compared to the Baseline scenario (Sc. 1). All alternative scenarios contribute to a reduction in total life-cycle CO_2 emissions, ranging from 2 to 24% reduction having as reference the CO_2 emissions of 2009. The 24% maximum value is obtained for scenario 5.

These results can be disaggregated in the three stages of the total life-cycle (TTW, WTT and C2G), which are presented in Figure 14. When the total LCA is disaggregated into its TTW, WTT and Materials C2G stages, a predominance of the TTW stage is observed (50-62%), followed by Materials C2G (19-26%) and WTT (18-24%).

Since more efficient vehicles or zero local CO_2 emissions vehicles are being introduced, the TTW stage reduces along time: 8-28% for energy and 13-53% for CO_2 from 2009 to 2050.

As for the WTT stage, with the introduction of electricity or hydrogen powered vehicles, there is a shift from the transportation sector to the electricity generation sector. As a result, the WTT stage tends to increase along time for the considered scenarios (47-122% for energy and 3-145% for CO_2 from 2009 to 2050).

In terms of the Materials C2G, introducing alternative vehicles represents additional energy consumption and CO_2 emissions due to more energy intensive manufacturing/recycling processes, associated with a growth in the fleet. That was observed for the studied scenarios with increases of 70-116% for energy and 71-120% for CO_2 from 2009 to 2050.

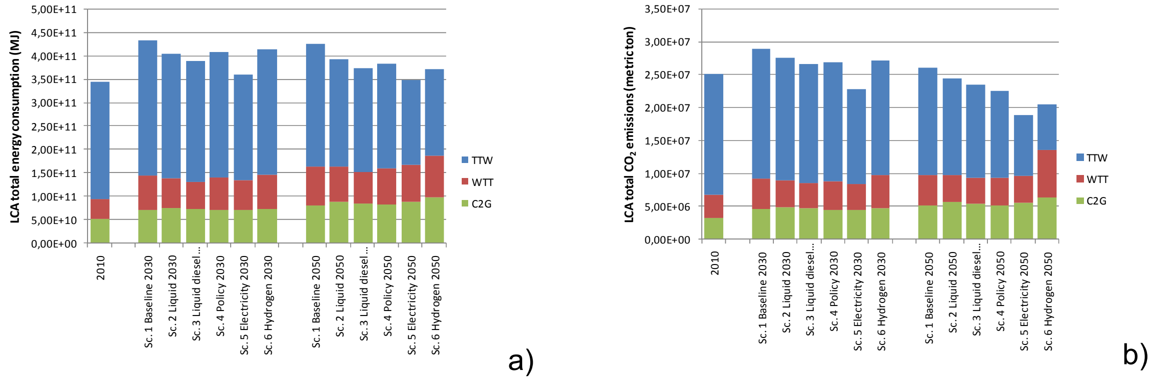


Figure 14 – LCA total energy consumption (MJ) a) and CO_2 emissions (metric ton) b) in 2010, 2030 and 2050 for the different scenarios.

Figure 14 can also be shown separating the LDV, HDV and Bus fleets, to show that the HDV and Bus fleet are responsible for roughly 30% of total fleet energy consumption and CO_2 emissions (see Figure 15).
Another way of comparing the scenarios is by analyzing the Well-to-Wheel (WTW) Renewable Energy Indicator (see Figure 16), which accounts for the renewable energy spent on the production (TTW) and use (WTT) stages (mainly allocated to biofuels and electricity produced from renewable sources). Results indicate that scenario 5 and 4 present higher values for this indicator compared to the Baseline scenario. All other scenarios consume less biofuels or have no renewable electricity consumption, leading to a lower WTW Renewable Energy Indicator. In 2050, roughly 25-33% energy consumption may be from renewable sources (see Figure 16), as opposed to the current 5%.

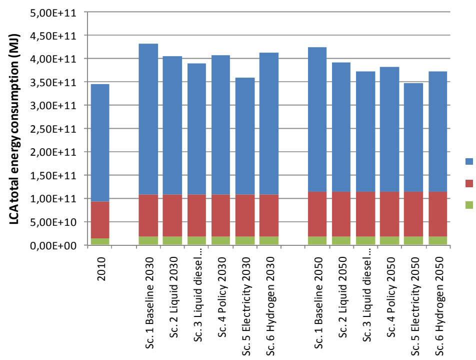


Figure 15 – LCA total energy consumption (MJ) in 2010, 2030 and 2050 for the different scenarios disaggregated between LDV, HDV and Bus

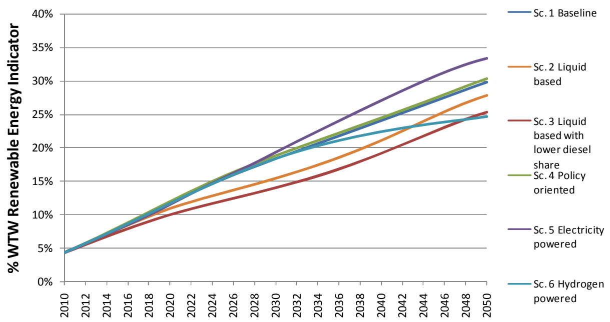


Figure 16 – WTW renewable energy indicator for the 2010-2050 period for the different scenarios.

Finally, the weight of liquid oil based fuels will be dominant in the majority of the scenarios studied. Even in the more aggressive scenarios in terms of light–duty vehicle technology shifts (Scenarios 5 and 6), the liquid fuel demand still represents 57 and 32% respectively of the total demand for energy in road transportation.
Other finding regards market penetration impacts. Even if an alternative technology is introduced in the market at a fast rate, there is a considerable delay in achieving the same

amount of penetration in the actual fleet, due to the slow fleet turnover. For example, the 10% target of electric vehicle sales in 2020 will only represent 10% of car stock in 2030.

Additionally, if the actual trend in diesel/gasoline vehicle sales continues, the LDV fleet energy consumption will be dominated by diesel fuel and gasoline will have a minimal role in the country's energy consumption. For the LDV fleet, in 2050, if scenario 2 is considered (with a 75/25 diesel/gasoline ratio) gasoline accounts for 23% of the TTW energy consumption and diesel for 73%. If scenario 3 is considered (with a 50/50 ratio) that value levels to 45% for gasoline and 51% for diesel. If the HDV and Buses fleets are added then the diesel dependency is even higher, with 80% TTW diesel energy consumption for scenario 2 and 65% for scenario 3 in 2050.

CONCLUSIONS

The main conclusions of this research can be summarized as follows:

- If no alternative solutions are adopted (Sc. 1), the total life-cycle energy consumption increase in 2050 goes up to 26% and CO_2 emissions increase by 3% having as reference the energy consumption in 2009. Fossil fuels will continue to prevail in the market, with increasing incorporation of biofuels;
- All alternative scenarios contribute to a reduction in total life-cycle CO_2 emissions, ranging from 2 to 24% reduction having as reference the CO_2 emissions of 2009. The 24% maximum value is obtained for scenario 5;
- Comparing the six scenarios the most attractive concerning energy consumption is Scenario 5. In spite of increasing the total life-cycle energy consumption in the 2009-2050 timeframe (by 3%), in 2050 it reduces the total life-cycle energy consumption by 18% compared to the Baseline scenario (Sc. 1);
- In 2050, roughly 25-33% energy consumption may be from renewable sources, as opposed to the current 5%; and
- Finally, the weight of liquid oil based fuels will be dominant in the majority of the scenarios studied. Even in the more aggressive scenarios in terms of light–duty vehicle technology shifts (Scenarios 5 and 6), the liquid fuel demand still represents 57 and 32% respectively of the total demand for energy in road transportation.

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NOMENCLATURE

C2G	Cradle-to-Grave part of materials life-cycle analysis
EV	Electric Vehicle
FC-HEV	Fuel Cell Hybrid Electric Vehicle
FC-PHEV	Fuel Cell Plug-in Hybrid Electric Vehicle
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
LCA	Life-Cycle Analysis
LDV	Light-Duty vehicle
MEI	Ministério da Economia e Inovação
MIT	Massachusetts Institute of Technology
PATTS	Projections for Alternative Transportation Technologies Software
PHEV	Plug-in Hybrid Electric Vehicle
PME	Plano de Mobilidade Eléctrica
PT	Portugal
REN	Rede Eléctrica Nacional company
Sc	Scenario
SET	Strategic Energy Technology Plan
TTW	Tank-to-wheel part of fuel life-cycle analysis
V2G	Vehicle-to-Grid
VD	Vehicle Density
VKT	Vehicle Kilometers Travelled
VMT	Vehicle Miles of Travel
WTT	Well-to-Tank part of fuel life-cycle analysis
WTW	Well-to-Wheel part of fuel life-cycle analysis

REFERENCES

1. EUROSTAT, *Environment and Energy. EUROPA Eurostat – Data Navigation Tree*. May 2008.
2. DGEG, *Balanço energético*. 2008, Direcção Geral de Energia e Geologia.
3. Bandivadekar, A., et al, *Reducing the fuel and greenhouse gas emissions of the US vehicle fleet.* Energy Policy, 2008. **36**(7): p. 2754-2760.
4. Bandivadekar, A., *Evaluating the Impact of Advanced Vehicle and Fuel Technologies in U.S. Light-Duty Vehicle Fleet*, in *ENGINEERING SYSTEMS DIVISION*. 2008, MASSACHUSETTS INSTITUTE OF TECHNOLOGY: Boston.
5. Bodek, K., Heywood, J., *Europe's Evolving Passenger Vehicle Fleet: Fuel Use and GHG Emissions Scenarios through 2035*, M.I.o.T. Laboratory for Energy and Environment, 77 Massachusetts Avenue, Cambridge, MA 02139, USA, Editor. 2008.

6. ANL, *VISION Model: Description of Model Used to Estimate the Impact of Highway Vehicle Technologies and Fuels on Energy Use and Carbon Emissions to 2050*, A.N. Laboratory, Editor. 2003, Center for Transportation Research, Argonne National Laboratory.
7. WEC, *Transport Technologies and Policy Scenarios to 2050 from the World Energy Council*. 2007.
8. IEA, *Energy Technology Perspectives, scenarios & strategies to 2050 by International Energy Agency*. 2008.
9. MEI, *Vision Paper for the EU Strategic Energy Technology Plan by Ministério da Economia e da Inovação*, M.d.E.e.d. Inovação, Editor. 2007.
10. MEI, *Mobilidade Eléctrica, Portugal - Pioneiro na definição de um modelo nacional by Ministério da Economia e da Inovação*. 2009: Lisbon.
11. Burnham, A., Wang, M., Wu, Y., *Development and Applications of Greet 2.7 - The Transportation Vehicle-Cycle Model*. 2006, Energy Systems Division, Argonne National Laboratory, work supported by the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program (Office of Energy Efficiency and Renewable Energy).
12. Silva, C.M., Baudoin, J.M., Farias, T.L. . *Full life cycle analysis of different vehicle technologies.* in *FISITA 2008 - 32th FISITA World Automotive Congress*. 2008. Munich, Germany.
13. Edwards, R., Griesemann, J-C., Larivé, J-F., Mahieu, V., *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context*. 2008.
14. GM, *General Motors WTT analysis of energy use and GHG emissions of advanced fuel/vehicle systems - a european study*. 2002.
15. Jungbluth, N., Tuchschmid, M., Frischknecht, R., Emmenegger, M., Steiner, R., Schmutz, S., *Life Cycle Assessment of BTL-fuel production: Final Report*, in *RENEW - Renewable Fuels for Advanced Powertrains; Sixth Framework Programme: Sustainable Energy Systems*. 2008, Swiss Federal Office of Energy (Bundesamt für Energie), CH & ESU-services Ltd., CH.
16. Baptista, P., Silva, C., Farias, T. *BIODIESEL FUEL PATHWAYS FOR THE PORTUGUESE ROAD TRANSPORT SECTOR*. in *Smart Energy Strategies Conference 2008*. 2008. Zurich - Switzerland.
17. Wipke, K., Cuddy, M., Burch, S., *ADVISOR 2.1: A User Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach.* IEEE Transactions on Vehicular Tecnology, (48): p. 1751-1761.
18. Zachariadis, T., Samaras, Z., Zierock, K., *Dynamic Modeling of Vehicle Populations: an engineering approach for emissions calculations.* Technological Forecasting and Social Change, 1995. **50**: p. 135-149.
19. EUROSTAT, *Population Demography Indicators. EUROPA Eurostat – Data Navigation Tree*. May 2008.
20. Moura, F., *Car organ transplant - Anticipating energy and environmental benefits of cleaner technologies*, in *Departamento de Engenharia Civil*. 2009, Universidade Técnica de Lisboa, Instituto Superior Técnico: Lisbon.

21. Azevedo, C.L., *Métodos de estimativa de volumes anuais de tráfego rodoviário - um modelo para Portugal*. 2008, Instituto Superior Técnico, Universidade Técnica de Lisboa.
22. Silva, C.M., Farias, T. L. *Life cycle analysis of fuel cell hybrid plug-in vehicles.* in *17 th World Hydrogen Energy Conference*. 2008. Brisbane, Australia.
23. Baptista, P., Tomás, M., Silva, C., *HYBRID PLUG-IN FUEL CELL VEHICLES MARKET PENETRATION SCENARIOS*, in *HYPOTHESIS VIII: HYdrogen POwer - THeoretical and Engineering Solutions - International Symposium*. 2009: Lisbon - Portugal.
24. Zachariadis, T., *On the baseline evolution of automobile fuel economy in Europe.* Technological Forecasting and Social Change, 2006. **Energy Policy** (34): p. 1773–1785.
25. Baker, H., Cornwell, R., Koehler, E., Patterson, J., *Review of low carbon technologies for heavy goods vehicles*. 2009, Ricardo.
26. REN, *Relatório sobre Segurança de Abastecimento ao nível da Produção de Electricidade Análise intercalar, Período 2009-2020, Sumário Executivo*. 2008.