Energy Consumption and CO_2 Emissions Evaluation for Electric and Internal Combustion Vehicles using a LCA Approach

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Abstract. The demand for Electric Vehicles (EVs) has increased during the last years, especially after the peak oil prices experienced in the year 2008. In spite of, in general, EVs being associated to a cleaner and more efficient mobility, the benefits of substituting conventional Internal Combustion Vehicles (ICVs) by EVs must be evaluated. In this regard, in the present paper, it is compared the energy consumption and CO2 emissions of two different vehicles technologies, an EV equipped with lithium-ion battery and a gasoline ICV. The evaluation is performed according to a Life Cycle Assessment (LCA) approach, making use of a parametric model developed in a Microsoft Excel platform.
The results of the evaluation performed show that, for the different scenarios assumed, the EV is the one that presents the lower LCA energy consumption and CO2 emissions.

Key words

Electric vehicle, internal combustion vehicle, energy consumption, CO2 emissions, life-cycle assessment.

1. Introduction

The demand for Electric Vehicles (EVs) has increased during the last years, especially after the peak oil prices experienced in the year 2008. In spite of the technology that supports the EVs been well known since many years, vehicle manufactures have presented some reluctance to introduce it in the market [1]. However, the oil prices increase associated to the present pressure introduced by some national and regional authorities to reduce the environmental impacts of the transportation sector, is acting as a driver for vehicle manufactures changing the status-quo and start a regular production of EV models.

Regardless, in general, EVs being associated to a cleaner and more efficient mobility, the benefits of substituting conventional Internal Combustion Vehicles (ICVs) by EVs must be evaluated. In this regard, the information provided by the vehicle manufacturers may not be enough. For instance, vehicle manufacturers assume EVs as zero emission vehicles, disregarding the Dioxide Carbon (CO2) emissions associated to the electricity consumed by the vehicle.

In literature, there is a diversified broad of vehicle evaluation models, not always consensual. Some authors use the Tank-to-Wheel approach, in which only the powertrain efficiency is included [2]. Some studies are only dedicated to fuel cycle, including all the energy consumptions since the primary energy extraction to the transport for the gas station [3]. Other authors integrate the vehicles efficiency with the fuel cycle, resulting in the approach usually known as Well-to-Wheel analysis [4].
In spite of the vehicle use being one of the main responsible for the energy consumption and CO2 emissions during its life, vehicle materials production, assembly and disposal can not be disregarded. As so, some authors evaluate the vehicles in a perspective of the body and powertrain life-cycle, accounting all the energy consumption and CO2 emissions associated to the materials production, assembly and disposal [5], [6]. However, a most comprehensive approach to evaluate the different vehicle technologies should integrate the both cycles, the body and powertrain cycle and the fuel cycle [7], [8]. That complete Life Cycle Assessment (LCA) of the vehicles is the one adopted in the present paper.

2. Objectives and Methodology

The main objective of the paper is to compare the energy consumption and CO2 emissions of different vehicle, assuming its complete life-cycle since the materials manufacture to the vehicle disposal, including all the production chain of fuel consumed during the vehicle use.

In order to attain the objective of the paper, a dedicated framework was developed in a Microsoft Excel platform. The framework corresponds to a parametric model, in which the user can choose or supply a set of inputs in order to best characterize the case study.

The vehicle LCA framework developed includes two different models: the EV and the ICV. Both models are detailed below.

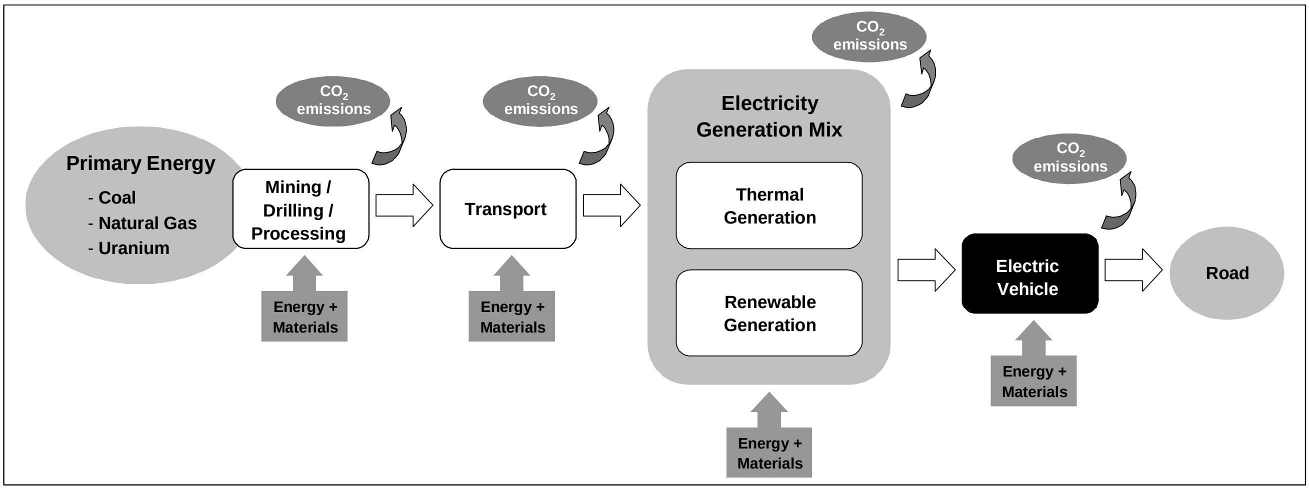

Fig. 1. LCA boundaries of the EV.

A. LCA Boundaries for the EV

The LCA model developed for the EV, as presented in Fig. 1, comprises the primary energy extraction and transport, the electricity generation and its use in the vehicle, as like as the vehicle production and disposal.

In the case of the primary energy extraction, the energy consumption and CO2 emissions inventory takes account of activities such as mining and drilling, infrastructures construction (mines, onshore and offshore natural gas extraction platforms) and manufacture of materials and equipments (pipes, pumps, service trucks, mining machinery, crushers, etc).

The second step of the EV model corresponds to assess the energy consumption and CO2 emissions associated to the primary energy transport. For coal and uranium, that assessment considers the trains, barges and ships charging/discharging processes, the fuel used during the freight and the materials used in the manufacture of these equipments.

In the case of natural gas, two different means of transport are considered: pipeline and liquefied natural gas (LNG). For the pipeline, the energy inputs correspond to the energy spent for compressing the gas and to the embodied energy of the materials, such as pipes and compression units. For the LNG are considered the energy consumptions and the embodied energy of the liquefaction units, LNG tankers and degasification units.

The subsequent step of the EV model is dedicated to the electricity generation. In that context, two embracing types of generation are considered: thermal generation and renewable generation.

The thermal generation of the developed model includes technologies such as coal, combined cycle gas turbine (CCGT) and nuclear. For each one of those technologies, the energy consumption and CO2 emissions resulting from the combustion process, power plants construction, equipments and materials embodied energy and power plant decommission are assessed. In the case of the nuclear technology model, it is also necessary to integrate the fuel enrichment. In order to do that, two different processes, diffusion and centrifugation, were considered.

The renewable electricity generation technologies assumed in the model are: hydro, wind, photovoltaic and solar thermal. The energy consumption and CO2 emissions assessed for those technologies include the power plants construction, equipments and materials embodied energy and power plant decommission.

The fourth step of the EV model corresponds to the assessment of the vehicle energy consumption and CO2 emissions during its life cycle, including vehicle manufacture, its use and respective disposal. The vehicle manufacture includes its assembly and the embodied energy of the materials and equipments such as chassis, battery, motor, tyres, windows and others. Regarding the vehicle use, it is accounted the electricity consumed along the life cycle and the efficiency of the respective battery charger.

B. LCA Boundaries for the ICV

The LCA model developed for the ICV comprises the fuel and the vehicle cycles. As presented in Fig. 2, the energy consumption and the CO2 emissions evaluation start accounting the processes for the crude oil extraction e processing, which include drilling, well construction, pumping crude oil and separation and the materials used such as platforms, pipes, pumps and others.

The second step of the ICV LCA model corresponds to the inventory of the energy consumption and CO2 emissions associated to the crude oil transport from the well to the refinery. Two different means of transport are considered for the crude oil: pipeline and tanker. For the pipeline transport, as already referred for the natural gas, the energy inputs correspond to the energy spent for pumping the crude oil and to the embodied energy of the materials, such as pipes and pumping units. For the tankers transport are considered the charging/discharging and freight energy consumptions and the embodied energy of the crude oil tankers.

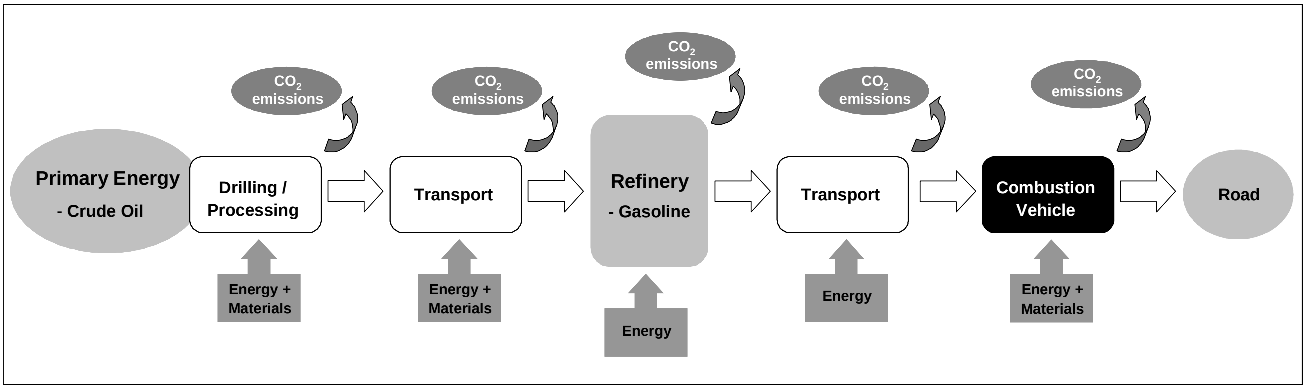

Fig. 2. LCA boundaries for the ICV.

When the crude oil arrives to the refinery, part of it, is transformed to gasoline. This is an intensive energy consumption process and it must be included in the LCA of the ICV. Due to some difficulties to the data collection, the refinery materials and equipment embodied energy is not considered in this step.

In the subsequent step of the ICV model, it is assessed the energy consumption and the CO2 emissions that result from the transport of the gasoline to the fuel stations. In this step, the embodied energy of the equipment is disregarded.

Finally, as like the EV model, the ICV model assesses the life cycle vehicle energy consumption and CO2 emissions, including the vehicle manufacture, its use and respective disposal. For the vehicle use, it is accounted all the gasoline consumed along its life cycle.

3. Functional Units

As LCA results are usually used for decision support, choosing or defining appropriate functional units is an important task. Functional units adopted should enable an easy analysis of a study results and facilitate the comparison with other studies.

For European studies, in which the energy performance of different vehicle technologies is compared, it is usual to adopt the specific consumption as functional unit. This functional unit, represented in *L/100 km* or *kWh/100 km*, is determined by the quotient:

$$SC_T = \frac{W_T}{L} \tag{1}$$

where SC_T is the vehicle specific consumption at the tank level, W_T is the tank consumption, in *litres* or in *kWh*, and L corresponds to the distance travelled, in *km*.

As the specific consumption defined in (1) only considers tank consumption, some additional energy inputs must be considered, in order to integrate the LCA perspective. As so, the LCA specific consumption comes:

$$SC_{LCA} = \frac{W_T + \sum W_{ind}}{L} \tag{2}$$

where $\sum W_{ind}$ corresponds to the sum of all indirect energy consumptions of the vehicle life-cycle, such as those associated to the fuel cycle, gasoline or electricity, and to the vehicle body and powertrain life-cycle.

In the case of the CO2 emissions, it is usual to adopt the specific emissions as functional unit. Those specific emissions, usually characterized in $g\ CO_2/km$, can be determined by the quotient:

$$SE_L = \frac{E_{comb}}{L} \tag{3}$$

In (3), SE_L corresponds to the local specific emissions of the vehicle and E_{comb} corresponds to the CO2 emitted by the engine combustion along the distance travelled, in $g\ CO_2$.

For EVs, SE_L correspond to zero. However, in a LCA perspective, must be accounted the CO2 emissions resulting from the fuel cycle and from the vehicle body and powertrain life-cycle:

$$SE_{LCA} = \frac{E_{comb} + \sum E_{ind}}{L} \tag{4}$$

In (4), $\sum E_{ind}$ is the sum of the indirect CO2 emissions, associated to the fuel cycle and to the vehicle body and powertrain life-cycle.

An additional functional unit initially defined in [9] is assumed in the present paper to characterize the fuel cycle of the electricity consumed by the EV. This functional unit, energy return on energy input (ERoEI), is considerably useful for comparing the performance of different electricity generation mix, and consequently, their adequacy for the introduction of EVs. ERoEI can be determined by the following ratio:

$$ERoEI = \frac{W_{out}}{\sum W_{ind}} \tag{5}$$

In (5), W_{out} corresponds to the energy output of a system or the electricity generated by a specific mix, in *kWh*, and $\sum W_{ind}$ is the sum of all indirect energy inputs, in *kWh*, since the primary energy extraction to the power-plants disposal. Direct energy inputs such as the heat released by fuel combustion in power-plants or internal combustion engines are not accounted for the ERoEI.

4. Vehicles Assumptions

A. ICV

The ICV considered for evaluation refers to a mid-size gasoline European vehicle with a total weight of 1324 kg. The life-time assumed for the vehicle is 10 years, in which, an average 15000 km per year distance is driven. The fuel consumption assumed for the ICV is 5.6 liter/100 km and the respective specific CO2 emissions are 129 gCO2/km, values corresponding to the average new passenger vehicles sold in Portugal at 2009 [10], [11].

B. EV

For the EV, it is assumed a total weight of 1546 kg, including the vehicle body and the battery. As like in the ICV case, the average driving distance of the EV is considered as being 15000 km per year, for a life-time of 10 years. The EV is equipped with a lithium-ion battery and presents a range of 160 km. The maximum number of complete charge/discharge cycles of the battery is 1000, with a charging efficiency of 80% [12]. The average specific energy supplied by the battery to the electric motor corresponds to 15 kWh/100 km [2].

5. LCA Results

A. Base Case Scenario (Portugal at 2009)

The EV and ICV energy consumption and CO2 emissions evaluation is performed based on Portuguese data from the year 2009. In this regard, the fuel consumption assumed for the ICV corresponds to the average of the new passenger vehicles sold in Portugal at 2009, while the energy consumed by the EV is assumed to be generated by the Portuguese generation mix of the year 2009.

In the year 2009, the Portuguese electricity generation (Table II) comprised 24% of Coal, 23% of Natural Gas Combined Cycle and 14% of Cogeneration. In that year, the renewable generation supplied more than 30% of the demand, with a 15% share of the Wind power and with the Hydro technology contributing for other 15% of the electricity generation.

LCA results for the EV and ICV are presented in Table I.

According to the LCA results, the use of EVs enables reductions on the energy consumption that reaches the 38%, when compared with ICVs. In spite of the CO2 emissions reductions being lower than the reductions on the energy consumption, in a LCA perspective, the EVs use decrease the CO2 emissions in more than 23%.

Table I results show that the advantage of the EV decreases when the analysis evolves from the tank consumption to the life-cycle perspective. For this, as presented in Fig. 3, contribute the larger amounts of energy spent on the EV materials and assembly, namely on the battery, which represents 35% of materials embodied energy.

Table I. – Results for the vehicles energy consumption and CO2 emissions

		ICV	**EV**	Variation (%)
Specific Energy Consumption (kWh/100 km)	Tank	55.5	18.8	-66.1
	LCA	82.9	51.3	-38.1
Specific Emissions (g CO_2/km)	Local	128.7	0	-100
	LCA	214.4	164.8	-23.1

In the case of the ICV, the fuel-cycle is the main contributor for the LCA energy consumption with a 73% share.

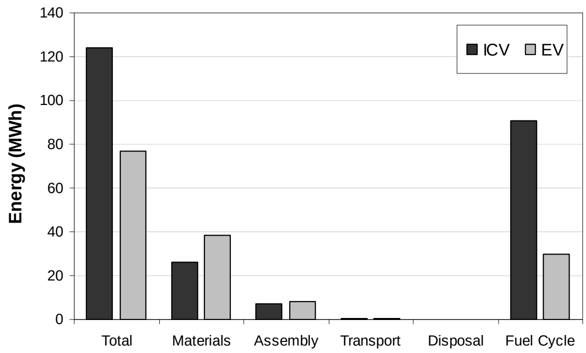

Fig. 3. Different contributions for the vehicles LCA energy consumption.

In terms of the CO2 emissions, the LCA perspective also reduces the EV competitiveness, when compared to the local emissions perspective. For this loss of competitiveness, as presented in Fig. 4, mainly contribute the CO2 emissions associated to the electricity generation.

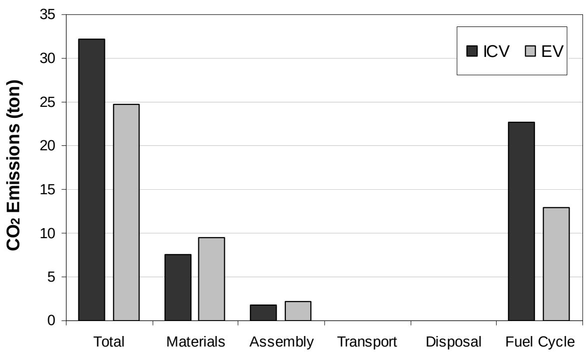

Fig. 4. Different contributions for the vehicles LCA CO2 emissions.

In a lower scale than the electricity generation, also the body and powertrain materials contribute for decreasing the environmental benefits of the EVs.

B. Sensitivity Analysis

The analysis of the base case scenario, presented above, demonstrated that the fuel-cycle considerably influences the LCA results. Therefore, in the present section it is proposed a sensitivity analysis in order to better evaluate that influence.

As the average ICV fuel consumption varies from region to region and through the years, the first sensitivity analysis (Fig. 5) proposes to study the impact of different ICV tank fuel consumptions on the LCA energy consumption.

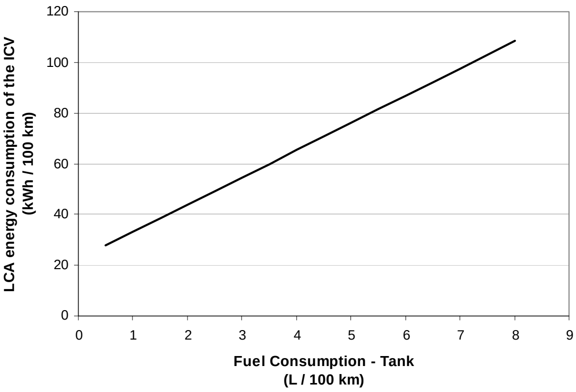

Fig. 5. LCA specific energy consumption sensitivity of the ICV to the tank fuel consumption.

According to the results, one can state that the LCA energy consumption is directly proportional to tank fuel consumption.

EVs are usually very efficient, presenting tank-to-wheel efficiencies higher than 75% [13], [14]. As so, potential gains in the EVs life-cycle are not expected for the near future. However, some evolution can be expected in a different level, namely, in what concerns the electricity generation mix. The increasing integration of renewable energy in power systems (increasing the ERoEI of the electricity generation mix) can contribute to reduce the LCA specific energy consumption of the EV, as like its respective LCA CO2 emissions. Therefore, in order to evaluate the impact of different electricity generation mix ERoEI on the LCA energy consumption of the EV, it is proposed a second sensitivity analysis (Fig. 6).

From the results, one can conclude that ERoEIs smaller than 10 considerably influence the LCA specific energy consumption of the EV. However, for greater EROEIs, the indirect energy consumption of the fuel-cycle is so small that it does not influence the EV LCA specific energy consumption.

Due to the increasing pressure of the society for a reduction on the vehicles environmental impacts and considering that the fuel-cycle is the main contributor for the LCA CO2 emissions of the vehicles, a sensitivity analysis is presented next in order to study the sensitivity of the LCA CO2 specific emissions to the ICV tail pipe emissions (Fig. 7) and to the electricity generation mix emissions of the EV (Fig. 8).

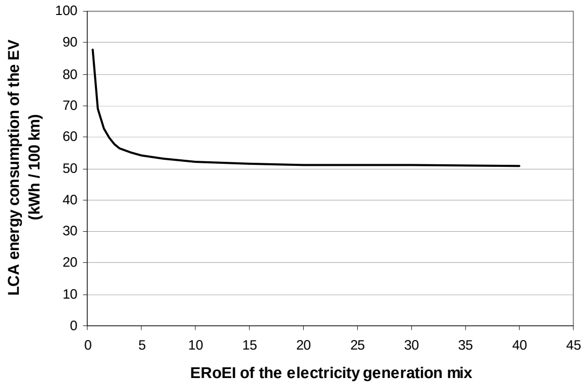

Fig. 6. LCA specific energy consumption sensitivity of the EV to the ERoEI of the electricity generation mix.

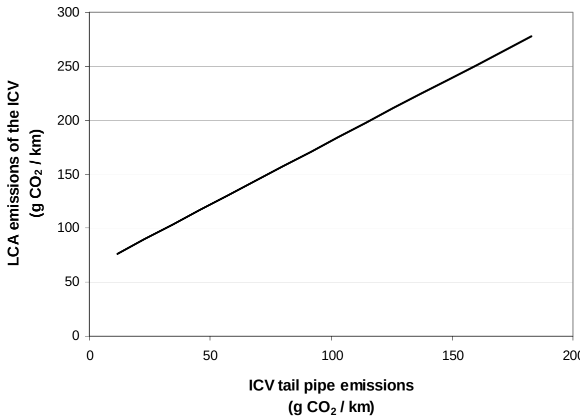

Fig. 7. LCA specific CO2 emissions sensitivity of the ICV to the tail pipe emissions.

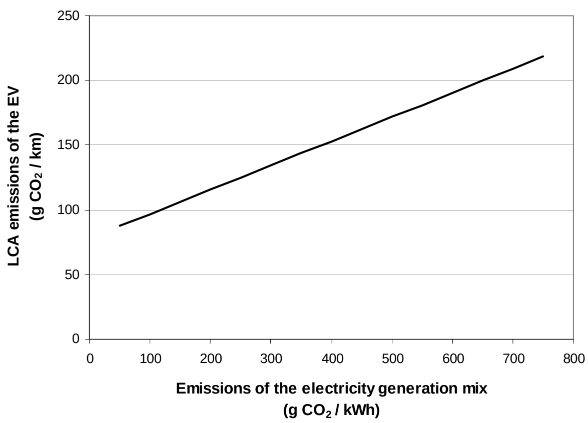

Fig. 8. LCA specific CO2 emissions sensitivity of the EV to the emissions of the electricity generation mix.

The sensitivity analysis results show, in different proportions, a direct relation between the vehicles LCA specific emissions and the emissions of the fuel-cycle. In the case of the ICV the sensitivity is higher, with the LCA specific CO2 emissions increasing 1.18 g for 1 g increase of the tail pipe emissions. The sensitivity of the EV LCA specific emissions is lower, with an increase of

0.2 gCO2 per each 1 g increase on the CO2 specific emissions of the electricity generation mix.

6. Vehicle Evaluation over Different Scenario

As already referred, the average fuel tank consumption of the ICV and the ERoEI of the electricity generation mix varies from region to region and through the years. Therefore, in the present section, a set of scenarios is presented in order to evaluate which vehicle, ICV or EV, is most suitable for each one of those scenarios.

Besides the scenario Portugal 2009, already presented in the previous section, three additional scenarios are considered. The scenario EU27 2009, corresponding to the European Union (27 countries) conditions in the year 2009, the scenario USA 2009, corresponding to the United States conditions verified in the year 2009 and finally, the scenario EU 2030-35, resulting from some predictions for European Union at period 2030-35.

The assumptions considered for the electricity generation mix of each scenario are presented in Table I. In what concerns the ICV fuel tank consumption, for the Portugal 2009 and EU27 2009 scenarios, the same figure is assumed. For the USA 2009 scenario, 7.2 liter/100 km fuel tank consumption is considered [15]. The future scenario EU 2030-35 considers an evolution of the average gasoline vehicles for a fuel tank consumption of 4.1 liter/100 km in the year 2035 [16].

Table II. – Generation mix, ERoEI and specific emissions for the different scenario considered [17]-[20]

Generation Technology	Scenario			
	Portugal 2009	EU27 2009	USA 2009	EU 2030-35
Coal	24%	31.2%	48%	21%
Natural Gas	23%	21.5%	21%	18%
Nuclear	-	27.8%	20%	24%
Hydro	15%	11.6%	6%	9%
Wind	15%	4.2%	1%	17%
Solar	0.2%	0.3%	1%	2%
Co-generation	14%	3%	-	8%
Other	-	0.3%	3%	1%
Import	9%	-	-	-
ERoEI (kWh/kWh)	19.4	20.9	17.9	18.7
Specific Emissions (g CO_2/kWh)	462.6	461.1	649.4	351.5

The energy perspective for the different scenario is presented in Fig. 9. This figure is divided in two main regions by an indifference curve that corresponds to an equal ICV and EV LCA specific energy consumption. Fig. 9 is the result from the combining Figures 5 and 6. The lower region, below the indifference curve, corresponds to the conditions that turn the ICV, the most suitable vehicle, while the upper region corresponds to the conditions in which the EV is the most competitive.

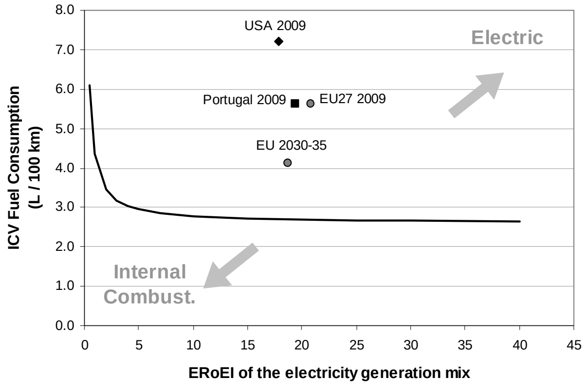

Fig. 9. Comparison of the most suitable vehicle technology for different scenarios according to the energy consumption.

From the results, it is possible to identify the USA 2009 scenario as the one that more benefit from the EV use. This fact is a consequence of the high fuel consumption presented by the average US ICVs.

For the EU 2030-35 scenario, the EV decreases its competitiveness, mainly due to the increase of the ICV efficiency.

The four scenarios are also evaluated in terms of the CO2 emissions. In order to do that, the ICV CO2 tail pipe emissions are obtained for the fourth scenarios, as well as the CO2 emissions of the different electricity generation mix (Table II).

The tail pipe CO2 emissions considered for the EU27 2009 is the same considered for Portugal 2009. For the USA 2009 scenario, 165 gCO2/km tail pipe specific emissions are considered. In the case of the EU 2030-35 scenario, the ICV tail pipe CO2 emissions consider the targets imposed by the European regulation for the year 2020, 95 gCO2/km [21].

The comparison of the different scenario is presented in Fig. 10. The indifference curve presented corresponds to equal ICV and EV LCA specific CO2 emissions and it results from the combination of Figures 7 and 8. The indifference curve defines two regions, in which the ICV or the EV is the most competitive.

From the results outcomes the USA 2009 scenario, in which, the 48% share of Coal in the electricity generation contribute for the highest generation mix CO2 emissions. In spite of this fact contribute for reducing the competitiveness of the EV, the tail pipe CO2 emissions level of the ICV increase the EV environmental benefits.

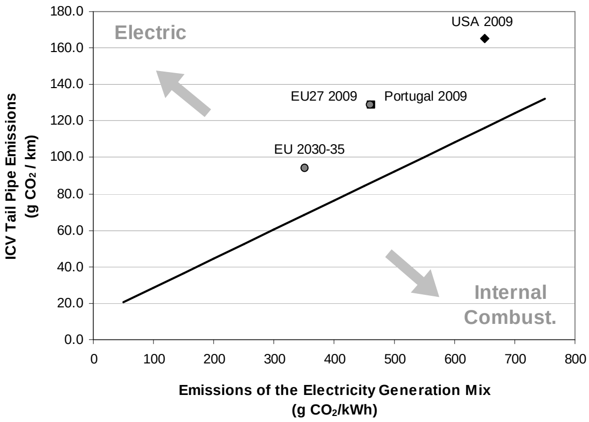

Fig. 10. Comparison of the most suitable vehicle technology for different scenarios according to the specific emissions.

7. Conclusions

In the present paper it is compared the energy consumption and CO2 emissions of two different vehicles technologies, an EV equipped with lithium-ion battery and a gasoline ICV. The evaluation is performed according to a LCA approach, making use of a parametric model developed in a Microsoft Excel platform.

The vehicles LCA, considering the Portuguese conditions at 2009, show that the use of EVs enables reductions on the energy consumption that can reach the 38%, when compared with ICVs. In spite of the CO2 emissions reductions being lower than the reductions on the energy consumption, the EVs use allows a 23% decrease on the CO2 emissions.

According to the LCA, 50% of the EV energy consumption comes from materials production and 38% from the fuel cycle. In the case of the ICV, is the fuel cycle that most contribute for the energy consumption, being responsible for 73% of total life cycle energy consumption.

Considering that the average ICV tank fuel consumption and the electricity generation mix considerably vary from region to region and through the years, evaluation of the different vehicles suitability for a set of different scenarios was performed. For the different scenarios assumed, the EV was the one that presented the lower LCA energy consumption and CO2 emissions.

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