

Environmental and Economical Competitiveness of Battery Electric Vehicles in the Portuguese Market: exploring the potential economical advantages of “Vehicle-to-Grid” systems

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Abstract

The objective of the thesis is to characterize and compare the lifecycle total costs of ownership and lifecycle environmental impacts of two different types of powertrain: a battery electric vehicle (BEV) and a gasoline internal combustion engine (ICEV) in the Portuguese car market. In addition, an analysis on the capacity of BEV providing ‘Vehicle-to-grid’ (V2G) electricity services by returning power back to the grid when plugged to the energy grid, besides charging. This study concludes that BEV’s economical and environmental performance is higher than its ICEV counterpart. From the two V2G services assessed, this study concludes that regulation down has some economic interest, while regulation up with current market conditions does not provide an interesting perspective from a vehicle owner economic point of view. The LCA suggests, according to the results obtained that BEV lifecycle impact corresponds to about 71% of the total lifecycle impact of a gasoline ICEV; this conclusion however is conditioned by a set of assumptions, particularly: the electricity mix, other fuels could reduce ICEV environmental impact, battery-recycling stage and mileage and service time.

This study was developed as part of a broader study that aims to identify the problems and opportunities in the sustainability and economics of electric drive vehicles in the Portuguese market.

Introduction

An electric vehicle is a vehicle that utilizes electric energy for propulsion. It has an electric motor that utilizes this type of energy, transforming it into kinetic energy. There are multiple ways a vehicle can store its electricity where the main are through a fuel cell or a battery; the latter will be the focus of this study. According to electric vehicle supporters, BEV (Battery Electric Vehicle) has some advantages when compared to its ICEV (Internal Combustion Engine Vehicle) counterpart: higher engine efficiency; electricity is cheaper; no local emissions; and vehicles are more silent.

Despite the previous advantages, there are important limitations to the use of BEV today: small public charging points network; limited energy storage and corresponding range; high charging time; and high acquisition costs when compared to homologous ICEV.

The massification of electric mobility could contribute to increase the efficiency and safety of the electric grid. Charging the batteries should be done preferably during the night when energy consumption is lower, this way avoiding overload during peak hours.(Kempton 2000)(Camus et al. 2011)

This study focuses on this type of BEV and particularly on a 2nd generation BEV that would include Vehicle-to-Grid (V2G) technology; this study tries to answer the question if this new type of technology is more sustainable than conventional internal combustion engines by characterizing the economic and environmental performance of each technology, for the same functional unit.

According to Kempton(Kempton & Tomić 2005), the concept of V2G is that BEVs can provide power to the electric grid while parked and plugged, on times that the grid requires extra power, and taking advantage of excess production to charge at lower rates. This concept is then expanded in order to apply to different power markets, particularly on the ones that have been identified as adequate for a V2G system – in Portugal the regulation market (Entidade Reguladora dos Serviços Energéticos 2009; Entidade Reguladora dos Serviços Energéticos 2008; Entidade Reguladora dos Serviços Energéticos 2010).

The main attractiveness of V2G is that it can produce income to the vehicle owner, when the car isn't needed, maximizing car use, by substituting these very expensive auxiliary power systems and therefore bringing positive implications for both the System Operator (SO) and the vehicle owner. This however from the owner point of view has to be done to the extent where the income associated with V2G is higher than its costs. From the SO point of view there is the advantage of substituting the secondary systems with a cheaper alternative, reducing costs associated with the electrical grid operation, though the SO needs to guaranty that a minimum number of cars are plugged in at all times in order to assure the stability of the grid.

The environmental performance part of this study is done through a Lifecycle Analysis (LCA) where the objective is to produce a comparison between the lifecycle of a conventional Internal Combustion Engine Vehicle (ICEV) and a Battery Electric Vehicle (BEV) through all the lifecycle stages of the product (production, use and disposal). V2G is not a part of this environmental analysis, because by definition a LCA compares two products or services that provide exactly the same utility and use the same functional unit. Therefore the comparison between an ICEV and a V2G BEV is not an acceptable approach because an ICEV cannot provide V2G. Such comparison should be made between V2G services provided by a BEV (or a group of BEV's) and "conventional" power services provided by, for example, a hydroelectric dam with pumping capability or a power plant. And this would go beyond the scope of this study and so it is proposed as future work.

Methodology

The first goal of this study is to calculate and compare the lifecycle costs and profits (when applicable) of various automobile powertrains, these being the traditional gasoline internal combustion engine and battery electric vehicles subdivided into two groups whether they do or not V2G.

Here, the author calculated all pertinent lifecycle costs of the assessed powertrains and then annualized those costs for comparison purposes. The same goes for V2G revenues, where the model used gave us the annual revenues and costs of providing V2G services, all in an attempt to characterize the entire costs associated with a particular powertrain. Some of the assumptions used throughout this research are prone to debate. Therefore, a sensitivity analysis to key variables in order to assess how the total costs vary with different inputs was made. The variation on inputs is given through probabilistic distributions allocated to each variable.

In order to have a comparable analysis it is necessary to identify vehicle-use characteristics that are common to all powertrains. The values considered were 300,000 km cumulative mileage, during a service time of 15 years (20,000 km per year average) for a 5-seat hatchback car type.

Over this study, references of real vehicles were used, that are considered to be of the same category. Namely, a gasoline powertrain parameters and characteristics of the VW Golf (1.2 TSI Blue motion) together with its electric counterpart, the Nissan Leaf (Nissan 2011; Volkswagon 2011).

In order to model the costs and revenues of V2G services, the base model developed by Kempton (Kempton & Tomić 2005) with the updates suggested by Dallinger (Dallinger et al. 2011) was used, of the many grid services V2G could be used, these authors point regulation services as ideal for V2G. Regulation is a complementary service aiming to compensate instant disequilibrium's between energy production and consumption, fine-tuning frequency and voltage, either increasing the amount of energy production (regulation up) or decreasing/using the excess energy (regulation down). The required parameters where calculated from data retrieved from the main Portuguese SO (REN 2011) for the duration of one year and average values for the parameters where obtained: Capacity price for both Regulation up and down (€/kW); Electricity price for Regulation up (€/kWh); Electricity price for Regulation down (€/kWh); Dispatch to contract ratio for Regulation up (dimensionless); Dispatch to contract ratio for Regulation down (dimensionless).

The costs selected for this study obeyed to two criteria: relative importance in the overall lifecycle cost of the vehicle and if the costs are accounted for differently among the powertrains analyzed. That is, costs that are equal in both powertrains were not included here, since this is a comparative analysis. The fixed costs identified, which are those that occur whether the vehicle is used or not, were charging infrastructure cost, depreciation, financing cost, fees and taxes. The variable costs

(expenses that change in proportion to the use of the vehicle) included were fuel/energy costs, degradation/battery substitution and maintenance costs.

For the environmental impact assessment, a standard LCA methodology is followed in this research:

1. Definition of the objective and scope, where the functional unit, the system boundaries and main limitations and assumptions are defined;
2. Lifecycle Inventory (LCI) is the core step of a LCA study where the collection of all inputs and outputs across the entire lifecycle of each powertrain are accounted for;
3. Impact Assessment is the phase that analysis's the ecologic and human impacts of the emissions identified during the inventory phase and it comprises the characterization/classification of the emissions in intermediary indicators, which are then normalized, and finally aggregated into larger indicators; and
4. Interpretation is the final step where the obtained results are interpreted and a critical review of each step is done.

The author used SimaPro 7.3.2 software from PRé Consultants to perform the LCA of both powertrains and their comparison. This software has multiple databases built in. Here, the author adopted the Ecoinvent database because it is a very complete and available for the European context. The Ecoinvent database provides a vast list of products and processes that occur since the extraction of the necessary raw materials to the production and use of the product, and finally its disposal.

For the evaluation of the environmental impacts associated with the production, use and disposal of the vehicle the Eco-indicator 99 was used, with a cut-off of 5%, meaning that all processes with an impact bellow 5% are not shown in the network trees. The eco-indicator 99 method with the default Hierarchist perspective was chosen because it is largely used in this sort of analysis and matches well with the European context.

The next step was to collect the data required to build the LCI for the BEV and the ICEV. In short, collect the material and energy inputs for vehicle and battery production. The objective is to compare the powertrains of two different vehicles that, in the present case, are the VW Golf and the Nissan Leaf. As this information is not easily available, contacts with the brands to obtain this information were made. However both companies were reluctant to provide the required data. This required an alternative approach to the problem.

The Ecoinvent database (Swiss Centre for Life Cycle Inventories 2007) has a process of production of a generic VW Golf (though of an older model), and Volkswagen (VW) published a basic LCA on its TSI engines (Volkswagen Group Research - Environment Affairs Product 2009), that includes the powertrain assessed in the LCC above, since these are the most efficient. These sources provided some of the necessary information. The ICEV production used is the process for the production of a VW Golf on the Ecoinvent database. Assuming that BEV are similar to ICEV, except for the internal combustion engine that is replaced by an electric motor and has a larger battery, the author subtracted the material input of the TSI 1.2L engine to the VW Golf on the Ecoinvent database, giving an approximation of the processes and material flows involved in the production of a vehicle excluding the powertrain parts and components. The material flows and processes involved in the production of an electric motor were added to this basis, based on (De Almeida et al. 2008). With respect to the overall lifecycle analysis of the BEV, two batteries were included for a 300.000 km service time of a BEV (see the LCC analysis for more information).

Acknowledging that this approach implies imprecision when compared to a complete and accurate LCI, this was the information that was available for this work, and judged reliable for the present comparison between the two powertrains. The production stage has a smaller contribution in the total LCA than the use stage, as discussed later in this dissertation.

Nissan did not share the information on batteries and so other sources of information had to be used. The data for the batteries was taken from (Zackrisson et al. 2010). Moreover, the battery model assessed here is not currently being produced, since it is still in development. The author modelled the battery based on (Zackrisson et al. 2010) to match the power output of the Nissan Leaf and thus obtaining a lighter battery when compared to the Leaf's battery pack. This meant that another source of imprecision is added to the analysis.

For the use stage, the author used the same assumptions, values and data from the LCC analysis performed before:

- 300.000 km of service time (our functional unit being km for the use stage) and corresponding energy consumption (the same energy consumption values were used, not accounting for different type of driving styles and situations); and
- No vehicle maintenance is assessed (beside battery substitution in the BEV) since no reliable information is available up to today. Although it was assumed a 25% cost reduction compared to the standard ICEV, in the LCC analysis, here, the author won't follow the same approach because BEV's maintenance may involve other types of materials and processes that cannot be approximated using the same proportion.

The automotive industry has high recycling ratios and therefore the author modeled the recycling processes both the ICEV and BEV disposals, although the batteries of the BEV presented some difficulties in this sense. Currently the technology to recycle lithium-ion batteries is at its early stage, particularly the type of lithium-ion cell used (LiFePO₄) that is still in study and far from commercial use (Zackrisson et al. 2010). Automakers that are currently producing BEV's argue that between now and the moment BEVs will require recycling, there is enough time for a scientific breakthrough in battery recycling, even suggesting that, if necessary, they would store the used batteries until the technology would catch up and also building up enough material stock for promoting investments in large recycling facilities. In this study, battery recycling will not be considered. It is the author belief that today's processes are far from characterizing a recycling process in 10 to 20 years time, besides the existing processes are shrouded in non public patents that complicate the characterization of the processes involved.

Batteries' lifecycle are treated separately from the overall BEV's LCA and, therefore, when data for recycling will become publicly available and tested, the battery LCA can be easily updated and added to the existing analysis. It is also the author opinion that it is preferable to have an over estimation of the BEV's LCA than to have an simulation with potentially high bias from true values ((Coimbra e Costa 2012)for more information on how and from where data for both the LCC and LCA was obtained and calculated).

Results

Lifecycle Costing

Table 1 presents the costs and corresponding decomposition for each of the evaluated vehicles in order to have an idea of how each factor influences the final cost. Alongside, it is shown the revenues of V2G estimated for both power markets analyzed, also.

Table 1 - Cost comparison of the ICEV, BEV, BEV Regulation up (Reg up) and BEV Regulation down (Reg down) (source: author)

Description	ICEV	BEV	V2G – Reg up	V2G – Reg down
Charging infrastructure	0%	1%	1%	1%
Depreciation	33%	55%	47%	57%
Financing	1%	2%	1%	2%
Taxes	3%	0%	0%	0%
Energy/Fuel	45%	13%	18%	8%
Degradation/battery substitution	0%	14%	19%	14%
Maintenance	18%	16%	14%	17%
Cost (€)	- 4,991 €	- 4,224 €	- 4,887 €	- 4,013 €
Revenue (€)	-	-	266 €	253 €
Total (€)	- 4,991 €	- 4,224 €	- 4,621 €	- 3,760 €
<i>Percent variation compared to the ICEV</i>	-	<i>(-15.0%)</i>	<i>(-7.4%)</i>	<i>(-24.7%)</i>

The present sensitivity analysis is motivated by some of the limitations and assumptions of the analysis presented in the previous sections. These include, for example, the fact that some input variables and parameters of the model were determined based on other studies, for instance, the unit price of the BEV batteries per kWh (€/kWh), maintenance costs of BEV and other inputs that change over time, such as gasoline or electricity prices. For this analysis, the software @Risk (www.palisade.com) is used to add some variability to all inputs by attributing a probability density function to each one of them. The program was then left to do 1,000 iterations for each of the configurations analyzed.

The output to be analyzed is the total final profits (revenues – costs) for each powertrain, and for either V2G regulation up or down.

Table 2 (below) presents the probability density functions (PDF) parameters of all lifecycle cost estimates. The table below presents the 2-tailed t-test to assess whether the means of each two configurations (always compared to the reference ICEV) are statistically different from each other. Figure 1 illustrates the PDF for each case.

Table 2 – Probability Density Functions of the final lifecycle costs (source: author)

	ICEV	BEV	V2G – Reg up	V2G – Reg down
Mean	5,612 €	4,214 €	4,378 €	4,096 €
Standard Deviation	1,448 €	1,098 €	1,099 €	1,145 €
<i>t-test</i>	-	-24.33	-21.47	-25.97
<i>p-value</i>	-	1E-113	3E-91	2E-127
Dif. Regarding ICEV	-	-1,398 €	-1,234 €	-1,516 €

* Two tailed t-test for equality of means with equal variance.

Firstly, the author concludes that the means are statistically different, considering the very low *p-values* (i.e., there is very low probability that means are equal to each other, on a pair wise analysis with ICEV values). Secondly, the figures show that, on average, BEVs are more economical than ICEVs. Still, the variance of the results is wide and therefore the probability of this occurring should be estimated, since the difference between the results is that wide. When considering V2G services from BEV, it can be concluded that doing regulation up is less advantageous than BEV (no V2G). Conversely, doing Regulation Down is more beneficial than not doing any V2G. Again, differences of the means are low, and therefore the probabilities of each configuration being higher than the others should be calculated.

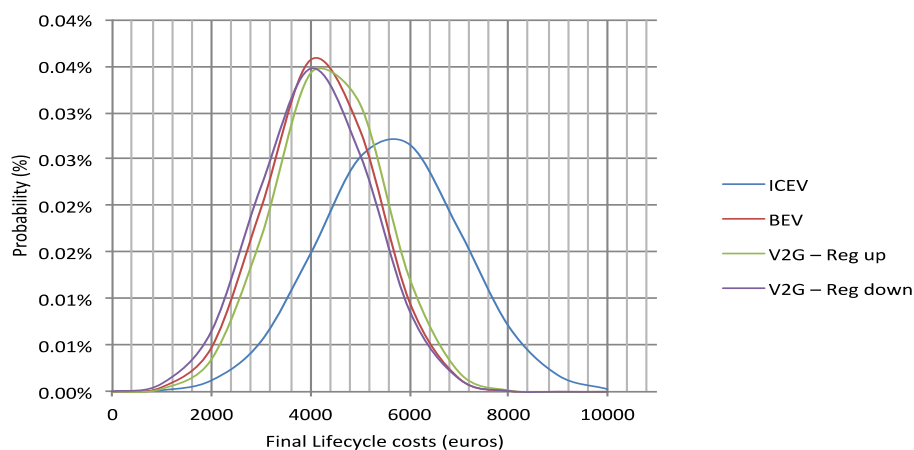


Figure 1 - PDF comparison of the analyzed cases (source: author).

Let us define the following continuous variables:

- X are the variables in the rows from the table below and $X \sim Normal(X_X, s^2_X)$;
- Y are the variables in the columns from the same table and $Y \sim Normal(X_Y, s^2_Y)$

Testing whether Y is lower than X is equivalent to testing if a variable $Z=X-Y$ is negative or equal to zero, where $Z \sim Normal (X_Y - X_X, s^2_{Y+} + s^2_{X})$. The matrix in Table 3 presents the probability of variables in each row being lower or equal to variables in every column.

Table 3 – Probability of LCC in column being lower than LCC in row (source: author)

	ICEV	BEV	V2G – Reg up	V2G – Reg down
ICEV	-	78%	75%	79%
BEV	-	-	46%	53%
V2G – Reg up	-	-	-	57%

These results suggest that BEV's LCC have a 78% probability of being lower than ICEV's. Interestingly, there is a 46% cumulative probability of 'Regulation up' LLC being lower than BEV. This is certainly explained by the fact that although statistically different, the means are very close such as the corresponding variances. As such, there is a significant overlap of both PDFs. Clearly, the LCC mean value of 'Regulation down' is lower than BEV (only) and BEV providing 'Regulation up'. Still, there is 40% to 50% cumulative probability of LCC of 'Regulation down' being higher than 'regulation up' and BEV, respectively. The author concludes then that providing V2G services might bring marginal benefits for BEV owners.

Lifecycle Analysis Results

This section presents the a comparative analysis of the ICEV and BEV LCAs estimated with SimaPro. Figure 2 illustrates the total LCA of the ICEV analysed here and the contributions of each lifecycle stage the overall environmental burdens.

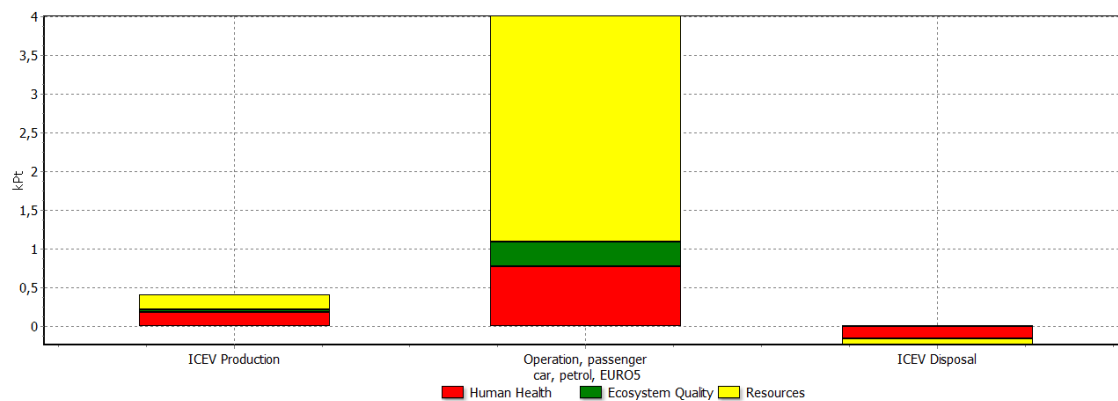


Figure 2 - Contribution of each life stage on the total lifecycle of ICEV (Eco-indicator 99) (source: author).

The lifecycle of the ICEV was graded 4170 Pt (ecopoints) of which:

- The Production stage has 401 Pt, (10% of the total impact);
- The Disposal stage has -237 Pt (- 6% of the total impact), meaning that it contributes negatively to the overall impact; and
- The Use stage that includes energy consumption only and is the largest responsible for the overall environmental impact of the vehicle, amounting to 4010 Pt (i.e., 96% of total impact).

During the production and operation stages, Resources extraction and consumption hold the greatest impact followed by impacts on Human Health. The disposal stage is characterized by an impact on Ecosystem Quality, and impact reductions on the remaining categories, due to the high levels of materials recycling of automobiles. Overall, Resources is the impact category with the highest environmental impact (72.6%), followed by Human Health (18.8%) and Ecosystem Quality (8.6%).

In most of the intermediary indicators calculated for the aggregate assessment presented above, car use ('Operation') is the main responsible for the overall environmental impacts. There are however a few exceptions. In Carcinogens and Radiation, Production holds about half of the impacts and in Minerals, where the main contributor is the vehicle Production tool, being responsible for about 87%

of the total impact in this category. The intermediary indicator with the biggest impact is Fossil fuels, followed by Respiratory Inorganics and Climate Change though these are 8-fold smaller when compared with Fossil Fuels. The main responsible for these results is the gasoline production, use and respective emissions.

Figure 3 illustrates the total LCA of the BEV analysed here and the contributions of each lifecycle stage the overall environmental burdens.

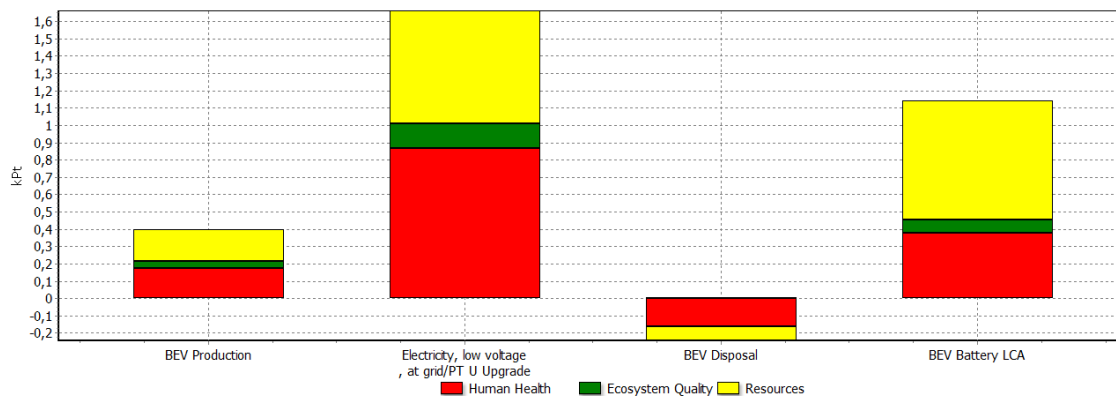


Figure 3 - Contribution of each life stage in the total lifecycle of the BEV (Eco-indicator 99) (source: author).

The lifecycle ecopoints of a BEV amount to 2960 Pt where:

- The Production stage accounts for 401 Pt, i.e. 13.5% of the total impact;
- The Use stage accounts for 1660 Pt, i.e. 56% of the total impact (again, energy consumption is the largest responsible on the environmental impact of the vehicle);
- The Disposal stage with -239 Pt, i.e. -8% of total impacts, again contributing negatively to the total environmental impact analysis; and
- The Battery total LCA that amounts to 1140 Pt and a 38.5% contribution.

The production stage main impact category is Resources with 6.3% of the total impact, followed by Human Health (5.9%). The operation (energy) stage is the largest contributor, and its main intermediary indicators are Human Health with 29.2% followed by Resources with 22%. In the disposal stage, there is a small impact on Ecosystem Quality (0.1%) and impact reductions on the remaining categories. Finally, the battery's LCA main impact category is Resources with 48.6%, then Human Health, 42.6%, and Ecosystem Quality with about 9%.

In the intermediary indicators Operation and/or Battery LCAs are the main responsible for the environmental impact. The main responsible for the environmental impact is again Fossil Fuels though almost with the same weight as the Respiratory Inorganics indicator, followed by Minerals impact. In categories Fossil Fuels and Respiratory Inorganics the main responsible for the impact is electricity production. When analysing the impacts related to Fossil fuels in detail, the major responsible is energy production from natural gas, whereas for Respiratory inorganics it is the emission of particulates with less than 2.5 μm from electricity production. Regarding the indicator Minerals, the larger impact is from the battery production stage, particularly the production and extraction of Tin and Copper.

If battery-recycling processes were considered in this analysis, the total LCA impact of the batteries would be lowered and therefore the BEV total environmental impact would also be reduced.

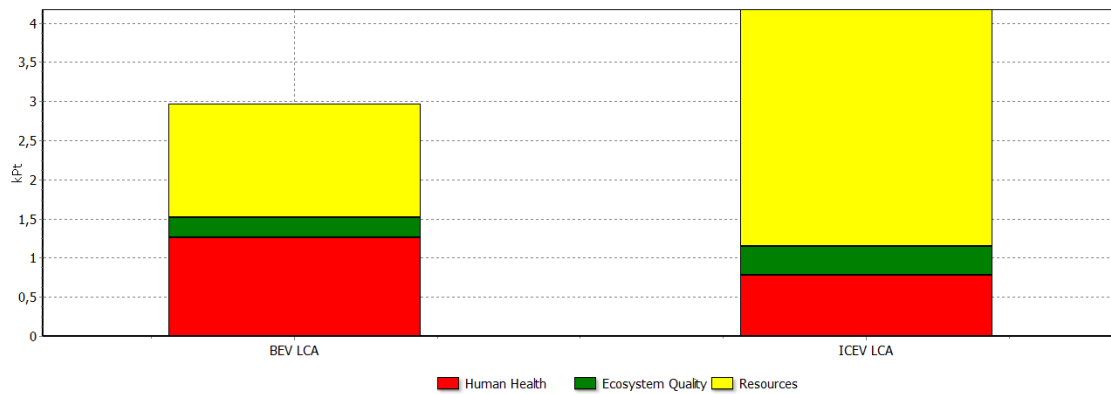


Figure 4 – Final LCA comparison of ICEV and BEV powertrains (source: author).

The total lifecycle environmental impact of the BEV powertrain is approximately 30% smaller than that of the ICEV, proving to be environmentally more efficient, globally speaking and according to the assumptions in this study.

The intermediary indicators show that each alternative is balanced, with 6 categories where the BEV has a larger impact (Carcinogens, Respiratory inorganics, Radiation, Acidification, Land use and Minerals) and the remaining 5 categories where ICEV have their larger impacts (Respiratory organics, Climate change, Ozone layer, Ecotoxicity and Fossil Fuels). Environmental impacts related with Fossil Fuels use present the larger lifecycle environmental burdens. It should be noted that though in both alternatives the largest responsible for the total impact are the environmental impacts related to Resources category, in the case of the ICEV powertrain, it is twice as big as for BEV. Human health related environmental impacts come second in the ranking of LCA burdens, and, conversely to Resources, BEV has a 60% larger impact than ICEV powertrain. Lastly, Ecosystem Quality environmental problems correspond to 9% of overall LCAs and, again, BEV present 30% lower environmental impacts than ICEV.

Conclusions

As for V2G, the results are coincident with the ones presented by Dallinger (Dallinger et al. 2011), which concludes that regulation up is not economically feasible since the costs associated with this market are larger than the gains (due to energy consumption that is paid below buying price and battery wear). Regulation down is confirmed as economically interesting because there is no extra cycling on the batteries and the energy comes at a lower rate, confirming both conclusions of Kempton (Kempton & Tomić 2005) and Dallinger (Dallinger et al. 2011). That said the gains are small, which could discourage BEV users of adhering to this system. This conclusion could imply that currently V2G could be more interesting from the SO point of view than to the consumer, for it could reduce the need for grid stability infrastructures. This situation could lead to an increase of V2G services value in the future, if this system is applied or if its opportunity costs would be higher (for example, building additional dams for hydroelectric electricity storage during off-peak periods).

Though this study concludes on the higher performance of the BEV, in terms of mobility one should keep in mind that other means of transport and particularly public transport might have higher economic and environmental performances. And therefore in terms of national policy more attention to other types of mobility should be given than promoting the use of private cars, since doing so would possibly aggravate existing problems of urban mobility (for example congestion, parking scarcity or land occupation). One of the current incentives is tax exemption for electric vehicles. This is clearly a temporary measure, since the state will not be willing to reduce its income from vehicle taxation from the moment EV numbers in the country reach a critical size.

Regarding the Portuguese energy security, an important concern arises. What if the majority of the national car stock would be substituted with electric vehicles? What would be the source of additional electricity required for these vehicles? So the strong support the Portuguese governments were giving to the EV could possibly imply an increase of fossil fuel consumption in the Portuguese electric mix. Another energy related issue is that the capacity of BEVs for V2G, could mean that the country would

not need to implement the new Plan for Hydroelectric Dams since one of its founding arguments was the need for electricity regulation services.

For the LCA part of this research the objective was to examine technologies and noting similarities and/or differences regarding their environmental performances.

Basically, this analysis suggests that according to the results obtained and acknowledging the assumptions of this study, BEV lifecycle impact corresponds to about 71% of the total lifecycle impact of a gasoline ICEV (having the eco-indicator 99 as a basis for analysis and the Hierarchist perspective). Therefore, it is a more environmentally appropriate choice for auto mobility.

This said the author emphasizes that this conclusion should not and cannot be generalized to all ICEVs when compared to BEVs, since it is conditioned by a set of assumptions that may change the result of this analysis, including the following:

- The energy mix for electricity production varies from country to country, thus having a significant impact on the environmental burdens;
- Other type of fuels such as diesel and/or biofuels could reduce significantly ICEV's environmental impacts (I recall that impacts related to fossil fuel consumption have the larger share of LCA results);
- Including the battery-recycling stage in the corresponding LCA could make the difference between the two powertrains bigger; and
- The mileage and service time of the vehicle considered may also change the results of this work (for instance, by increasing or reducing the quantity of batteries for the BEV powertrain).

The conclusions of this study support the claims of electric vehicle supporters and manufacturers that in fact this type of powertrain is more environmentally appropriate than their internal combustion engine counterparts, though the difference between them should be addressed cautiously for it might not be sufficiently wide to jump into definite conclusions. These results are rather framed by the assumptions adopted in the present research but, overall, they strongly suggest towards that direction, i.e. BEV is potentially more interesting than ICEV from both LCC and LCA perspectives.

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