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A Life Cycle Assessment of a Li-ion urban electric vehicle battery

Konstantinos N. Genikomsakis[1], Christos S. Ioakimidis[2], Alberto Murillo[3], Atanaska Trifonova[4], Dragan Simic[4]

[1]*DeustoTech, Energy Unit, University of Deusto, Avda. de las Universidades, 24 - 48007 Bilbao, Spain kostas.genikomsakis@deusto.es*

[2]*DeustoTech, Energy Unit, University of Deusto, Department of Industrial Technologies, Avda. de las Universidades, 24 - 48007 Bilbao, Spain, christos.ioakimidis@deusto.es*

[3]*University of Deusto, Department of Informatics and Industrial Organisation, Avda. de las Universidades, 24 - 48007 Bilbao, Spain, 1almuril@opendeusto.es*

[4]*Mobility Department, Electric Drive Technologies Unit, Austrian Institute of Technology (AIT), Giefinggasse 2, 1210, Vienna, Austria, {atanaska.trifonova, dragan.simic}@ait.ac.at*

Abstract

This study presents an approach on the life cycle assessment and environmental impact of lithium-ion batteries for electric vehicles, specially the iron phosphate technology based battery (LFP), through evaluating the different stages in the whole life of the battery starting with the manufacturing stage and then proceeding with the evaluation of its use in Spain until reaching the end-of-life stage, when the battery cannot continue offering a service in the electromobility sector (the actual capacity is under the 80% of the initial one). In this context, different end of life scenarios are considered in order to examine the feasibility of a second hand use for the already-worn battery that consists of reducing its environmental impact by extending the life of the battery in less stressful conditions to ensure the lower effect of the degradation. To this end, the various utilities in the life cycle of this battery are examined with the help of the SimaPro software simulation tool in order to quantitatively assess the potential benefits from an environmental point of view.

Keywords: battery electric vehicle, energy storage, environment, Life Cycle Assessment, Spain

1 Introduction

The key factors that are typically taken into account for electric vehicles (EVs) operating in an urban regime include the battery performance characteristics, the most obvious of which are its life cycle and efficiency. Life cycle means how long the duration of the car use is, and in this case, the longer the better. In this way the investment will be highly amortized, in other words, the initial investment of these vehicles is directly related to the total cost during its utility life [1]. Their efficiency is also a key factor to maximize, therefore the electricity consumed to charge the battery is only the one needed for the whole process, trying not to lose it during its operational life, so the costs are reduced too [2].

Primary results reveal that an internal combustion engine (ICE) vehicle produces 62,866 kg CO_2 equivalents, a battery electric vehicle (BEV) produces 33,357 kg CO_2 equivalents, and a hybrid one produces 40,773 kg CO_2 equivalents (Fig.1a)

[3]. For all three vehicle types, the use phase contributes the most CO_2 equivalents emissions, but it is important to stand out that in the case of the BEV, the use refers only to the emissions released by the production of the electricity that the car is going to need during its lifetime, and not the ones released by the car itself, which are zero. The use phase is responsible for 96% of ICE emissions, 91% of hybrid emissions, and 70% of BEV emissions. Battery manufacturing accounts for 24% of the BEV's lifecycle emissions, but only 3% of hybrid's lifecycle emissions. Finally, it is concluded that a BEV produces the lowest amount of emissions and is therefore the best in terms of environmental impacts overall.

It is important to know that when the battery packs in lithium-ion-powered vehicles are no longer useful for driving, they still have up to 80 percent of their storage capability left. So before they ever get to a recycling center, these batteries are reused and there are very good reasons for this: First of all because there is still a lot of energy storage in them with plenty of potential, and secondly because the cost of the batteries will be reduced a lot, as when they are no longer available for cars, they can be resold for other purposes [4]. There are several ways of reusing the Li-ion batteries which are no longer suitable for our urban electric cars, and there are much more which are only under development, as we are talking about a technology which has been recently released. In this paper we focus on one of these ways of reusing the batteries before which is, in fact, a very important one: the storage of renewable energy from the sun, specifically of the electricity generated by solar photovoltaic (PV) panels stored by our second hand battery and then used when it is needed. This leads us to a very interesting product life cycle as seen in Fig.1b.

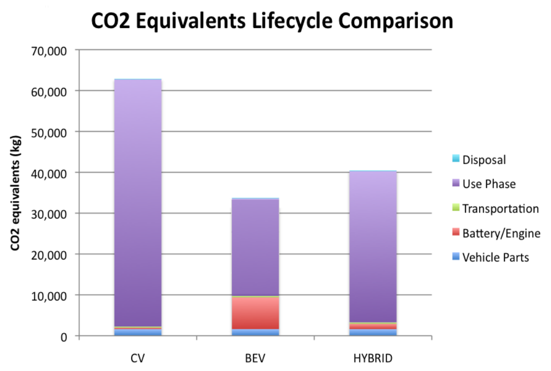
2 Parameters Settings for EVs in the City of Bilbao

Bilbao is a city in the north of Spain with an oceanic warm climate, which means that it has no temperature peaks with an average temperature of 15-16 °C, and this in turn implies a very good place for batteries and its operating temperature requirements [5]. As EVs are to be used in the urban part of the city of Bilbao, urban routes are mainly slow and not long distances. This means that we do not need strictly neither a fast charging time nor a slow discharge time. Taking all those variables into account that are presented more in detail in Table 1, where a comparison of different battery types is made, we have chosen the Li-ion LT-LFP battery to be further examined, which contains a $Li_4Ti_5O_{12}$ anode and $LiFePO_4$ cathode and most importantly, it is the type that best fulfils all the necessary requirements mentioned above for the urban EVs in the city of Bilbao [6].

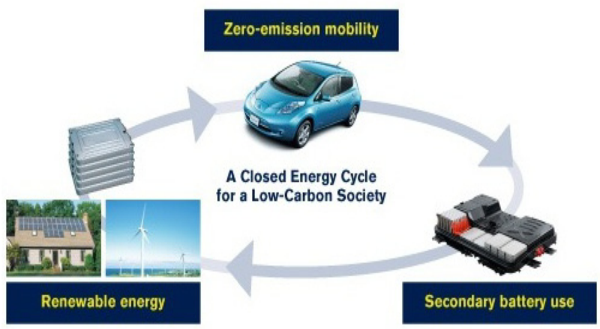
3 LCA Methodology

As already pointed out, the main objective of this work is to present a life cycle assessment study about the environmental burden of a Li-ion battery. The steps followed for the purposes of this study are:

1) Definition of the aim and scope of the study.



a)



b)

Figure1: (a) CO2 waste produced in the different stages of Current Vehicle (ICE), Battery Electric Vehicles (BEV) and Hybrid ElectricVehicles (HEV) and (b) the proposed LCA model for the LT-LFP battery

Table1: Potential batteries for Urban Electric Vehicles (EV) and their comparison

Type	Open circuit voltage	Specific energy	Operating temperature	Discharge time	Self-discharge @20ºC	Cycle life	Energy efficiency
	[V]	[Wh/kg]	[ºC]	[hours]	[%/month]	[Deep cycles]	[%]
Na-S	2.1	150-240	300-350	4 - 8	-	3000	-
ZEBRA	2.6	95-120	300-350	4 - 8	Negligible	4000	75-90
LCB	2.1	25-40	- 40-60	Up to 4	Negligible	3000	75-90
LT-LFP	1.7	50-70	- 25-40	Up to 4	2	4000	94-99

2) Development of a model for the product life cycle with all the environmental inflows and outflows. This data collection process is usually referred to as the life cycle inventory (LCI) stage.
3) Understanding the environmental relevance of all the inflows and outflows; this is referred to as the life cycle impact assessment (LCIA) phase.
4) Interpretation of the study.

This is the main technique used in LCA studies to generate a model. In the first stage, the inventory phase, the model is created simulating the complex technical system that is used to produce, transport, use and dispose of a product, in this case the Li-ion battery. This results in a flow sheet or process tree with all the relevant processes.

For each process, all the relevant inflows and the outflows are introduced and interconnected. The final result consists of a very long list of all the different inflows and outflows that is often difficult to interpret.

In the life cycle impact assessment phase, a completely different model is used to describe the relevance of inflows and outflows, making easier the understanding of how the processes are interconnected.

For this, a model of an environmental mechanism is used and once the model is completed with the inputs and outputs, each of these flows is analysed in an environmental sense to make possible a study about the different factors that harms the environment. By using several environmental mechanisms, the LCI result can be translated into a number of impact categories, which later will provide the information required for developing the Life cycle impact assessment that ends with the interpretation of the results.

4 LCA Study of the Battery

4.1 Aims and scope of the study

The aim of this work is not only to conduct a study on the environmental burdens of the new Li-ion battery technologies, but also to examine the potential environmental benefits from reutilizing an electric vehicle battery pack for a second life application, by evaluating different alternatives for this second use in order to achieve the best environmental profit possible.

The SimaPro software tool is selected for conducting this LCA study. Specifically, the study starts from the manufacturing process of the lithium battery selected, which is in this case the lithium iron phosphate battery, to evaluate the burdens of this stage. Next, the use phase of the battery is considered by analyzing the impact of utilizing an electric car in a Spanish city, i.e. Bilbao, and then alternative end-of-life scenarios are examined to determine the most beneficial solution for this stage.

Considering that this is study to evaluate the combined use of the battery in electromobility and in smart building applications, the functional unit to chosen analyse the results is the time factor, given that it is common on both applications.

4.2 Manufacturing process

The lithium battery is a complex device consisting of several parts that are assembled together. The most determinant part of a battery is the cell, but equally important is the battery management system which allows the proper operation of the device in order to limit the risk of this technology. For this study, the manufacturing process of the cell is divided into its component parts, the most important of which include the cathode, anode, electrolyte and separator. The diagram in Fig.2 shows the main parts of the battery that are analyzed in the context of this work, along with the materials used in each of these parts. The most important element is the cathode, which determines the operation of the device and it also gives the name of the technology of the battery and thus it is analyzed in detail below.

4.2.1 Cathode manufacture

The information for the materials and processes required for the manufacturing process of this lithium iron phosphate cathode are mainly based in the work already done in this field [7].

The production of the cathode explains how to get the electrode paste used for the coating of the cathode and also how to obtain the substrate of the cathode based on aluminium. Here the cathode is divided explaining those parts separated.

First the manufacturing processes and the components of the electrode paste are presented, the main components are a binder substance (5-10% of the total paste), carbon black in order to get a better conductivity (4-10% of the total paste), lithium iron phosphate which will be presented later and also an electrochemically active material.

It is important to mention that all these components present an oxidized state and are not submitted to high energy processes during manufacturing, for reducing them to the metallic form. Then the materials chosen for the different components are clarified.

For the selection of the binder material, different options have been tested, such as the polyvinylidene fluoride (PVDF), the acrylonitrile-methyl methacrylate (AMMA) and the polytetrafluoroethylene (PTFE). In the case of the solvent used to obtain the slurry texture desired, the N-Methylpyrrolidinone (NMP) is the material selected. This substance will be evaporated in the mixing process with the substrate.

The electrode substrate is a metal foil with a main composition of aluminium mixed with other metals. This metal foil is very thin (1520 µm) and is utilized as the current collector and gives physical support for being later coated with the paste explained above. Given that the authors in [7] provide no data for the manufacturing process of this part of the cathode, it is assumed that it is similar to the “sheet rolling” process, which is registered in the Ecoinvent database.

In the production of the lithium iron phosphate ($LiFePO_4$), there are different paths that can be followed, such as solid state reaction at high temperature, hydrothermal synthesis, mechanochemical activation process or co-precipitation in an aqueous medium. The hydrothermal option is chosen for the purposes of this work.

The process of the production of this compound begins with the reaction of the iron sulfate salt ($FeSO_4$ x $7H_2O$) with lithium hydroxide (LiOH) and phosphoric acid (H_3PO_4). It takes place in a water medium inside a hermetic reactor at a temperature ranging between 150-250 °C, and it is maintained about 5 hours.

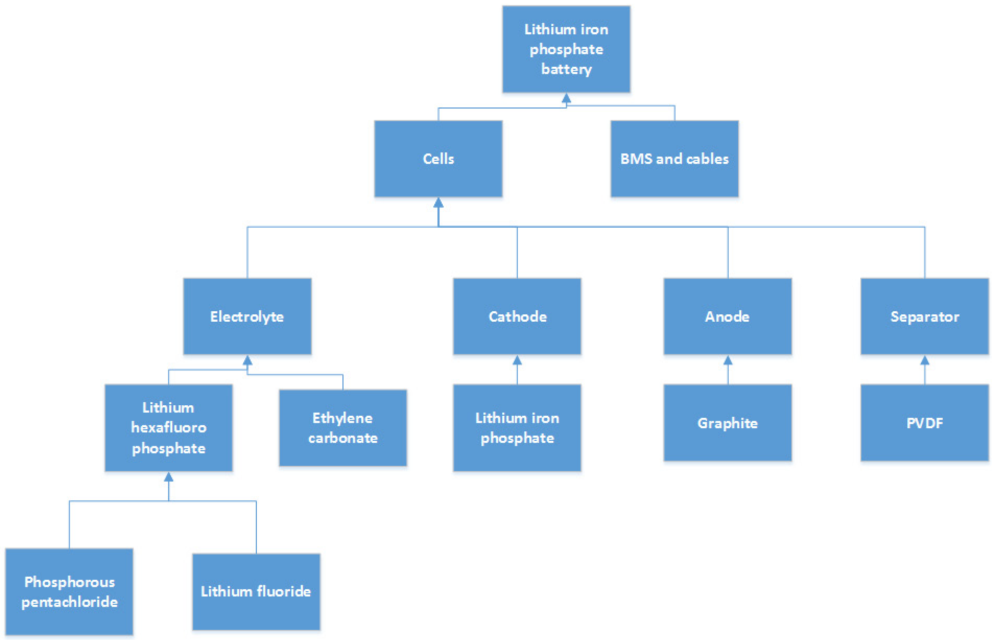


Figure2: Manufacturing diagram of the LFP battery

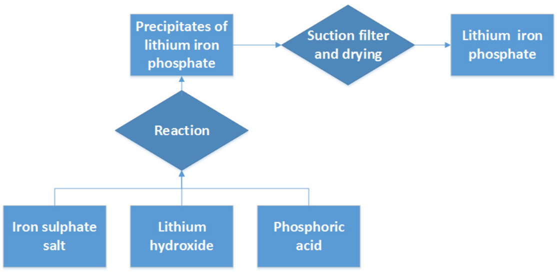


Figure3: Diagram for the production of lithium iron phosphate

After this process, the $LiFePO_4$ precipitates and is picked up by a suction filter and is later dried for 5 hours at a constant temperature of 60 °C.

4.3 Use phase

The electric car and thus the battery is used in a city in Bilbao, therefore the energy sources are determinant factors for the final result of the study, in this use stage, what is being evaluated is the environmental impact of the production of all the electricity required for the use of the battery inside a car during all its lifespan.
Depending on the electricity mix where the car is going to be utilized, the results can suffer from high variations, so it is important to clarify first that the use phase of the vehicle is considered to be in Spain, so for the calculation of the impacts of the production of the electricity, the Spanish energy mix is taken into account.
To this end, this section presents the energy mix of the electricity grid in Spain and also explains which factors can be determinant when modelling the impacts generated by the electricity production in this phase.
There are many factors that determine the influence from the energy mix and they cannot be precisely estimated. In spite of this fact, there are some factor related with predictable situations, such as the country where the battery is being charged, the month (there are high variations depending on the season of the year) or even the time in the day.
These variations that the energy demand presents can be seen in the apparition of peaks in the consumption at determinate periods. According to some studies, in summer the demand lowers at night because all business are closed, the air conditioning systems are not working and the lights are off, whereas a peak in the consumption often appears during the afternoon hours, which is mainly attributed to the high use of air conditioning systems [8].

The demand is not constant, there are continuous variations and thus the load is very time-depended. This leads to the use of low cost gen-sets to satisfy first the baseload demand (that can be easily forecasted) and then more expensive energy sources are engaged to cover the rest of the demand. In addition, not all the different generation units can be used and detained upon demand, because some of the technologies are not flexible enough to respond fast the short-term variations in the demand. For example, this is the case of the nuclear power plants, which produce energy with a more regular output and is more difficult to adapt it to the fluctuations of the demand. Indicatively, Fig.4 shows the distribution of different technology power plants in Spain.

4.3.1 Use phase model

This section presents in detail the specific data used for modelling the use phase of the battery. Table 2 summarizes the required data and the main assumption made for the different determinant aspects that are considered in this model.

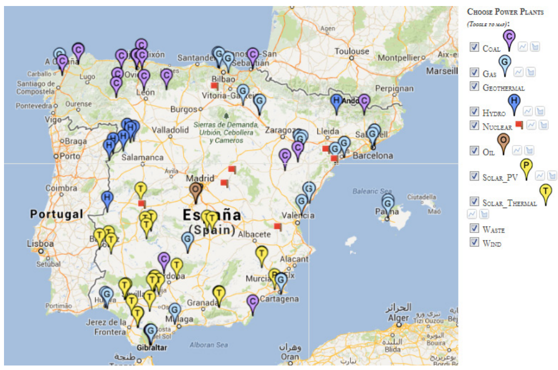


Figure4: Distribution of the power plants in Spain (without geothermal, waste and wind) [9]

Table2: Specifications and assumptions taken for the modelling of the use phase

Battery	24 kWh
Efficiency	80%
Autonomy (km)	100
Driving schedule	55% urban, 45% highway
Consumption (W-h/km)	170
Cycles	2500
Daily distance covered (km)	40
Weight of the battery (kg)	258
Total weight of the car including the battery (kg)	1317
Frequency of use	365 days per year

From the data presented in Table 2, there are some values that need to be explained. First of all, the consumption of 0,17 kWh/km includes the losses of electricity due to the charging and discharging efficiency as well as the internal efficiency of the battery. To calculate the amount of electricity required for the use phase of the car, it is further considered that he car travels 40 km on a daily basis for a total of 2500 days. In this case the total consumption is 0.17 kWh/km * 40 km/day * 2500 days = 17000kWh.

This value of 17000kWh refers to the total amount of energy required for the use phase of the car during 7 years covering 100.000 km. However, the losses of energy due to the weight of the battery should also be included. The additional electricity required for carrying this extra weight of the battery is equal to (258 kg of battery) * 30% * 0.17 kWh/km * 100.000 km/(1317 kg of total car weight) = 999 kWh.

4.4 Second Life Application

This sub-section presents an alternative scenario for the end of life of the battery. Instead of landfilling the battery when it is not considered suitable for electromobility purposes (under the 80% of the initial capacity), an alternative second use under lower stress conditions is considered in order to guarantee the “health” of the battery with lower degradation.

The degradation is the main factor which determines the feasibility of having a second use for a battery that is already worn, because if the degradation is too high, it will not be useful due to the progressive loss of capacity in the battery.

Since batteries were introduced, it is known that the ones made with lithium based chemistries are able to support a constant use of more than 1200 cycles and even thousands of cycles if the use is at a low depth of discharge (DoD). It is a very important point because it guarantees the user that the degradation due to the constant use of the battery is not going to be high, but it is not the only important thing when evaluating the life and conditions of a battery.

Apart from the long cycle life, the calendar life of the battery is also very important. The calendar life is the expected durability of the battery, which is independent from the other variables of the battery and is related with the internal chemistry of the device. Once the calendar life of the battery is reached, it means that it will not work anymore and thus it will not allow its use for second life applications. A long calendar life is thus very important for some applications, such as electromobility (it is expected to be used at least 7 years in an electric vehicle), and even more if it will be reutilized in second life applications [10].

In addition to the calendar life and cycling, there are other variables determining the capacity fade of the lithium batteries, the most important ones are the working temperature and the cell voltage. The capacity loss is also related with the increase in the impedance, which is traduced into a loss of power and loss of lithium due to the SEI, which is the loss of lithium to the solid-electrolyte interphase. This process tends to appear in the negative electrode (graphite anode) during the recharging of the battery. This coat initially protects the electrode against solvent decomposition when high negative voltages are applied, but eventually it leads to a progressive loss in the capacity of the battery due to the thickening of the SEI layer [11].

The progressive loss of lithium in the negative electrode, due to its deposition into a film over the anode, can be determined by a parabolic function describing the loss of capacity over time. Otherwise, the degradation of the cathode leads to a loss of capacity and impedance growth which can be determined with a linear function. The loss of lithium is described by a parabolic function, with capacity loss decreasing with time, while positive electrode degradation causes a linear loss of capacity and impedance growth.

4.4.1 Description of the second life application study

According to some studies on this field, the average lifespan of the lithium battery pack is considered to be between 500 and 3000 cycles. Given that the technology considered for this study is the Lithium iron phosphate battery (LMP), it is estimated that a battery formed by cells based on this technology is able to support at least 2000 - 2500 cycles when it is used for electromobility purposes. It guarantees the daily use of the battery for a cycle of charge and discharge during more or less 7 years with a residual capacity after this use (80% of the initial capacity of the battery), which allows its use for another 1000-2000 cycles until the capacity fades to the 60% of the initial capacity, when the aging process of the battery is so advanced that the voltage drops does not allow the use of the battery anymore [12].

For this study, the life expectancy chosen under an optimistic posture for the cells of a battery is 2500, meaning that once all these cycles have been completed, the resultant capacity of the cells is

reduced to the 80% of the initial capacity (from the initial 30Ah to 24Ah).
This barrier is considered to be the end of life of a battery for electromobility purposes. Even though the battery could continue offering a service, once this limit is exceeded the degradation increases exponentially until reaching the 60% of the initial capacity, when the battery stops working.
When a battery has reached the point of 80% of its initial capacity, there are different alternatives to consider for the end-of-life applications of this device. The most common thing is landfilling the batteries in a proper place in order to avoid the environmental impact that these residues cause, while another emerging alternative is the recycling of these devices. Recycling of these lithium-based batteries is very important in order to lower their environmental impact, because a wide adoption of EVs is expected in the not-so-distant future and each one will be equipped with one of those batteries. Despite of this, the problem is that these new recycling techniques are still under development and it is necessary to improve the techniques available now in the market to make the recycling possible and rentable.
Therefore, the last alternative considered is the reutilization of the lithium-ion batteries when they have achieved the end of life for being used in electric vehicles. For the purposes of this work, the alternative chosen for the second life use is to reuse the battery as a storage unit for smart buildings considering that the source of the energy is photovoltaic.
Depending on the energy requirements of the building, it is likely that more than one battery is required; the main idea of the second life application for these batteries is to store energy obtained from renewables to supply energy to the building as a complement to the energy obtained from the grid.
As already pointed out, the aim of this study is to evaluate the environmental impact of the primary use of the battery and the potential benefits in environmental terms from the second life application, and thus the consideration of the economic profit from extending the useful life of the battery is beyond the scope of this paper. According to the assumptions made in the context of this work, the degradation of the battery would allow up to 2000 cycles of use in the range between the 80 and 60 percent of its initial capacity, and thus the model of the following sub-section is used to evaluate the savings from utilizing a number of 1500 battery cycles (moderate posture) for the second life application.

4.4.2 Second life model

This second life application for the battery, is modelled as a second use phase for the device. In the first use phase, several factors were taken into account, including the internal efficiency of the battery, the energy loss due to the weight of the battery and also the charging and discharging efficiency of the EV.
The second use stage consists of the development of a stationary service by storing energy and supplying this energy whenever it is required and hence, the weight of the battery is not considered. On the other hand, the efficiency of the battery should be taken into account, assuming that the first use and the degradation of the cells lower the efficiency rate of the battery; the initial efficiency considered was 80% and for this second use it is reduced by 5% to have a final efficiency of 75%.
Other important issues for the model of the battery are the power and energy requirements that the battery fulfils, the estimations for this second life use are given by the statistics of the average consumption per home in Spain in 2010 [13]. From these data, a daily consumption of 10kWh is considered for a period of 1500 days, which is equivalent to four years.
The model presented is not formed only by the information given above about the consumption of the battery. This part of the model determines the environmental harm that the smart building application generates. Equally important, this work presents the savings from reutilizing a battery in contrast to the environmental impact that manufacturing a new battery for the same purpose has. Therefore, the manufacturing effort for constructing a smaller battery based on the same technology in order to meet the smart building requirements is evaluated too.
As the smaller battery has the same technology as the one utilized in the electric vehicle, the weight of this battery is calculated based on the same energy density of the former battery. The value of the energy density is 93 W/kg [14] and the requirement is 10 kWh. However, a 15kWh battery is finally modelled in order to guarantee that the degradation will not prevent the battery from supplying less than 10 kWh during 1500 cycles. This selection also serves as a means of balancing the actual capacities of the new and used batteries in the scenarios considered. As a result of this, the weight of this device is assumed to be 161.3 kg.

5 Scenarios and Results

Three alternative scenarios are examined for the purposes of this study. The base scenario chosen for the use of the lithium-ion battery consists of 4 steps, namely the manufacturing stage of the battery, the use phase, the disposal once the battery has reached the end of life (considering the case of treatment of incineration and then landfilling of the leftover residues) and the second use (of the battery replaced by a new one with the same specifications for another 1500 cycles).

The other two scenarios consider the application of the battery in smart buildings for storing the energy generated by renewables, specifically from the photovoltaic. The first one shares the same structure with the base scenario until the disposal of the battery, with the difference that a new smaller battery of 15 kWh energy capacity is manufactured to meet the requirements for storing the energy from the renewables and thus supply this energy for 1500 cycles to the smart building.

The last scenario considers the following steps: manufacturing process of the initial battery, use phase in the context of electromobility for 2500 cycles (80% of the initial capacity), second life application to the smart building unit for another 1500 cycles until the capacity fade does not allow more uses (decrease of the capacity up to 60% of the initial capacity of the battery) and finally the disposal with the same treatment as it was done in the other two scenarios.

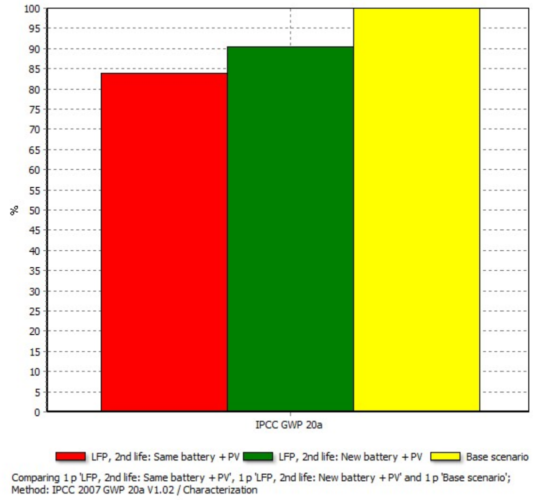


Figure5: Equivalent CO_2 in percentage

Fig. 5 shows the results obtained from the models with the global warming indicator which evaluates the environmental impact for 20 years. This result is given as a percentage in comparison to the scenario with the higher value, which is the base scenario with 30100 kg CO_2 equivalent. Specifically, the result obtained for the second life scenario (based on the utilization of a newer battery) is 9,63% lower than the base scenario, and the other second life scenario (based on the reutilization of the battery) is 16,3% lower.

In addition, these three scenarios are not only evaluated with the GWP indicator, but also with the Eco-indicator 99 that evaluates the impacts per different categories, as shown in Fig.6.

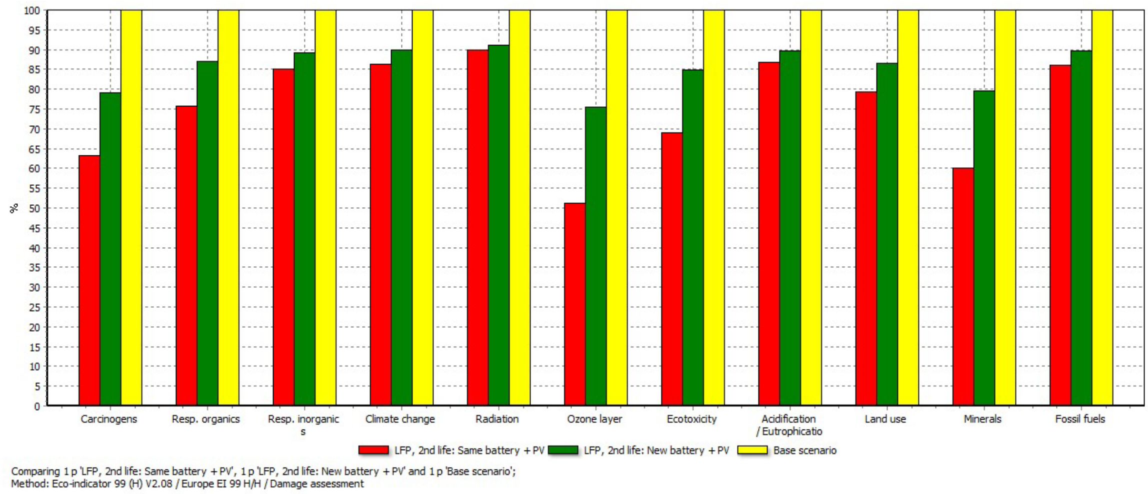


Figure6: Comparison of impact per category for the three scenarios

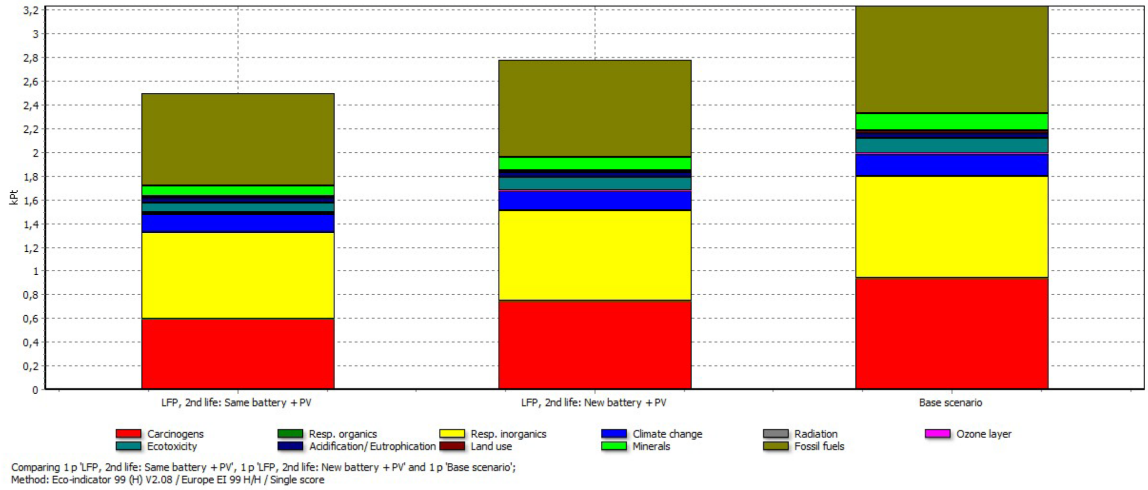


Figure7: Comparison between the three scenarios with Eco-indicator 99

Fig.6 shows the analytical damage assessment results obtained from the Eco-indicator 99. The yellow column represents the base scenario, indicating that this scenario has the highest score out of the three different scenarios in all the categories evaluated. The green column refers to the second scenario presented, the results for this scenario show that there is an environmental benefit against the base scenario, as it is expected. Alternatively, if the second scenario is compared with the third one (red column), which considers the reutilization of the same battery, the impact for the second scenario is higher in all the categories evaluated. Moreover, the highest differences between these two scenarios appear in the categories of Ozone layer, Minerals and Land use.

Eco-indicator 99 also gives a single score by integrating all the results from all the different categories, as shown in Fig.7.

This final result, which evaluates all the categories arranged in a single score, proves the feasibility of utilizing the battery for a second life application, in contrast to the base scenario of constructing a small battery for the same purpose. The base scenario presents the higher environmental impact, while the third scenario (reutilizing the EV battery) has a lower impact by 22.8%.

6 Conclusions

According to the results obtained in the study, it can be asserted that the possibility of reutilizing worn batteries from EVs in smart buildings is beneficial for lowering the environmental impact of this technology. The results indicate that there is significant environmental benefit from the smart building application over the use of the battery in an EV for the same time frame (with the consequent replacement of the battery).

The functional unit employed is based on the factor of time, as it is the common variable in all the scenarios. The time frame is 4000 days (1 cycle per day), equivalent to 11 years; in this time interval, the main environmental benefit is obtained through the usage of the battery for storing the energy from PVs. Despite the fact that the battery is allocated with some environmental burdens from the construction of the PV panels, it is still beneficial because of the emissions avoided (Spanish energy mix production), which are determinant for the results.

Finally, the comparison between the last two scenarios (both using photovoltaic energy) demonstrates that the option of reutilizing the EV battery instead of constructing a new smaller battery (more adapted to the specifications required) is also beneficial in environmental terms. This benefit comes from avoiding the manufacturing process of the new battery and, even though a lower internal efficiency is considered for the used battery, the results are in support of the second life application of lithium-ion batteries used in electromobility purposes.

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Authors

Konstantinos N. Genikomsakis is a Researcher at DeustoTech, (Energy Unit), University of Deusto, Bilbao, Spain. He holds a Diploma (5-years degree) in Electrical and Computer Engineering, (AUTh, 2003), a MSc in Systems Engineering and Management (DUTh, 2005) and a PhD in Production Engineering and Management (DUTh, 2010), Greece. His research fields are on the area of production line performance, intelligent energy systems, smart networks, modelling and optimization methods applied on transportation, and electromobility.

Christos S. Ioakimidis is currently a Senior Researcher/Professor and Group Leader on Energy Modeling and Systems Integration at DeustoTech (Energy Unit), University of Deusto (Dep. of Industrial Technologies), Bilbao, Spain. He holds a BSc degree in Mechanical Engineering, (Greece, 1994), an MSc degree in Mechanical & Aerospace Engineering, (USA, 1996), a PhD in Mechanical & Chemical Engineering, (U.K., 2001), and an MBA, (Greece, 2007). He has been an Assistant

Professor at IST of the MITPortugal program and is a Visiting Scholar at MIT/CERTH/AIT. His research interests are on transport/energy modelling, smart grids, energy systems integration (renewables, CCS, EVs), innovation and green economy and nanotechnology applied on automotion/energy.

Alberto Murillo is a final year undergraduate student at the University of Deusto, Department of Informatics and Industrial Organisation, Bilbao, Spain. His research interests are on transport/energy modelling, thermal energy systems modelling and environmental impact studies.

Atanaska Trifonova is a Senior Scientist and leads the AIT´s battery materials research team since November 2012. She holds a diploma from Sofia University of Technology in Chemistry and Metallurgy and a PhD in 2001 on electrochemistry and anticorrosive coating, from Graz University of Technology (TU Graz) in cooperation with Mitsubishi Chemical Corporation and the Chemical Institute for inorganic chemistry, in the areas of "optimizing and characterization of Li-Ion batteries". In 2007 she reached the status of an Associate Professor for electrochemistry on the TU Graz.

Dragan Simic is a Senior Researcher at AIT, Vienna, Austria since 2002. He received the Dipl. Ing. Degree in Mechanical engineering from the faculty of electrical, mechanical engineering and naval architecture, University of Split, Split, Croatia in 1999, his PhD from Vienna University of Technology, Austria in 2007 and an MBA in automotive industry from TUV and the Slovak University of Technology in 2013. His research activities are focused on the longitudinal simulation of the conventional and hybrid vehicles including the simulation of the auxiliaries. He is also a member of the Modelica Association.