sustainability

MDPI

Article

Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios

Christos S. Ioakimidis [1,*], Alberto Murillo-Marrodán [2], Ali Bagheri [1], Dimitrios Thomas [1] and Konstantinos N. Genikomsakis [1]

[1] European Research Area Chair (*Holder) 'Net-Zero Energy Efficiency on City Districts, NZED' Unit, Research Institute for Energy, University of Mons, Rue de l'Epargne, 56, 7000 Mons, Belgium; ali.bagheri@umons.ac.be (A.B.); dimitrios.thomas@umons.ac.be (D.T.); konstantinos.genikomsakis@umons.ac.be (K.N.G.)

[2] Department of Mechanics, Design and Industrial Management, University of Deusto, Avda Universidades 24, 48007 Bilbao, Spain; alberto.murillo@deusto.es

* Correspondence: christos.ioakeimidis@umons.ac.be; Tel.: +32-(0)65-374-462

Received: 1 April 2019; Accepted: 28 April 2019; Published: 1 May 2019

check for updates

Abstract: This paper presents a life cycle assessment (LCA) study that examines a number of scenarios that complement the primary use phase of electric vehicle (EV) batteries with a secondary application in smart buildings in Spain, as a means of extending their useful life under less demanding conditions, when they no longer meet the requirements for automotive purposes. Specifically, it considers a lithium iron phosphate (LFP) battery to analyze four second life application scenarios by combining the following cases: (i) either reuse of the EV battery or manufacturing of a new battery as energy storage unit in the building; and (ii) either use of the Spanish electricity mix or energy supply by solar photovoltaic (PV) panels. Based on the Eco-indicator 99 and IPCC 2007 GWP 20a methods, the evaluation of the scenario results shows that there is significant environmental benefit from reusing the existing EV battery in the secondary application instead of manufacturing a new battery to be used for the same purpose and time frame. Moreover, the findings of this work exemplify the dependence of the results on the energy source in the smart building application, and thus highlight the importance of PVs on the reduction of the environmental impact.

Keywords: battery reuse; electric vehicle; life cycle assessment; lithium iron phosphate; lithium-ion battery; secondary application

1. Introduction

The transportation sector is known to be one of the main contributors to greenhouse gas (GHG) emissions and other hazardous pollutants worldwide, resulting in environmental degradation and climate change, which have both become more pronounced over the last decades. In this respect, the electrification of the transportation sector is typically viewed as a promising direction for reducing GHG, given that electric vehicles (EVs) produce no tailpipe emissions during their operation. However, significant environmental impact can be traced not only to the energy operational processes for generating electricity to charge the EV battery, but also to the life cycle of the battery itself [1]. Hence, a life cycle assessment (LCA) approach is required to fully capture the environmental footprint of EVs [2], while the reuse of EV batteries in less demanding applications can extend the use phase of their life cycle, it is thus of particular interest for both academia and industry [3].

Nowadays, EVs are typically powered by lithium-ion (Li-ion) batteries due to their distinctive characteristics in terms of high energy and power density, long life, as well as little maintenance requirements, when compared to other battery technologies [4,5]. However, current Li-ion batteries, with a specific energy in the range of 100–150 Wh kg^{-1} [4], cannot provide an average EV with a driving range comparable to that of conventional vehicles. Moreover, relevant LCA studies show that Li-ion battery technologies produce substantial environmental impacts during their life cycle, including the manufacturing phase. Specifically, the authors in [5] analyze the environmental burden caused by a lithium manganese oxide (LMO) battery and conclude that the main contributors include the copper and aluminum supply for the anode and cathode production, along with the required cables or the battery management system. Similarly, the authors in [6] study the environmental impact from the production of a Li-ion nickel-cobalt-manganese (NMC) EV battery, reporting that the production chains with the highest contribution are the manufacture of battery cells, positive electrode paste, and negative current collector.

With respect to the end-of-life of EV batteries, the work in [7] discusses the economic and environmental benefits of NMC battery recycling in China. The study in [8] employs a modelling framework for the global lithium cycle based on dynamic material flow analysis to assess the potential for lithium recovery from EV battery recycling, while the challenges identified in this field include not only the cost-effectiveness of the recycling technologies, but also the efficiency of material recovery processes and the required infrastructure. In the same direction, the authors in [9] focus on the metallurgical and mechanical methods for recycling of lithium-ion battery pack for EVs, summarizing the two main basic aspects of recycling battery packs, namely mechanical procedure and chemical recycling.

To this end, recent years have witnessed significant research efforts on the research and development of alternative Li-ion battery technologies, focusing on the use of novel materials to increase the energy density, e.g., silicon nanowires as anode material [10], yet enhancing their environmental performance remains an open research challenge. In this context, lithium-sulfur (Li-S) is a prominent example of the most promising battery technologies for future EV applications [11,12]. Given that sulfur is characterized by a high theoretical capacity of 1672 mAh g^{-1} [13], a Li-S battery offers a theoretical energy density of ~2600 Wh kg^{-1} [12]. Despite the fact that the practically achievable gravimetric energy of Li-S batteries (reported to be ~600 Wh kg^{-1}) is significantly lower than the theoretical one, it is still significantly higher compared to that of state-of-the-art Li-ion batteries with a value of 280 Wh kg^{-1} [14]. The authors in [15] perform an LCA study to evaluate the environmental impact of a Li-S battery pack in an EV application, reporting that the Li-S battery has a lower environmental impact by 9–90% in most impact categories compared to a conventional NMC-graphite battery.

In addition, the lithium iron phosphate (LFP) battery technology has also attracted the interest of many researchers. The authors in [16] track the degradation in LFP batteries using differential thermal voltammetry, while the authors in [17] evaluate the power capability of LFP batteries based on a multi-parameter constraints dynamic estimation method, where the performance of the proposed approach is experimentally tested using dynamic loading profiles. The work in [18] focuses on the reliability assessment and failure analysis of LFP batteries, proposing a strategy to enhance their reliability based on statistical analysis and clustering analysis of experimental data from full life cycle testing. A series of experimental tests were performed in [19] to characterize and compare the performance of LFP and lithium polymer (LiPo) battery technologies for both stationary and automotive purposes. An overview of the current battery technologies for EVs, as well as advances in Li-ion batteries are given in [20].

Combining the above, it becomes apparent that assessing not only the performance characteristics, but also the environmental impact during the full life cycle of Li-ion batteries for EV applications is of particular interest. Using the ReCiPe method, the authors in [21] present a comprehensive LCA study on a potential next-generation Li-ion battery with molybdenum disulphide anode (MoS_2) and NMC oxide cathode, where the results of the comparison between an NMC-MoS_2 battery and a conventional NMC-graphite battery reveal that the environmental impact of the former is higher in most impact categories. The authors in [22] examine some critical issues regarding the LCA of Li-ion batteries for EVs, concluding that the use of water as a solvent instead of N-methyl-2-pyrrolidone (NMP) in the slurry for casting the cathode and anode of Li-ion batteries reduces the environmental impact. The work in [23] applies LCA to analyze and compare the environmental impact of lead acid (LA), LMO and LFP batteries, revealing that the LFP production has the lowest overall environmental impact. Moreover, the authors in [24] perform an LCA study on Li-ion and nickel metal hydride (NiMH) batteries for plug-in hybrid and battery EVs, showing that the NiMH technology has the highest environmental impact. In this context, the authors in [25] report that the assumptions and modelling approaches employed in an LCA have a significant impact on the outcome of the study that can be even greater than that of the particular cell chemistry, thus it is of paramount importance to establish a common base for conducting LCA studies to enhance the process of benchmarking the environmental performance of different battery chemistries.

Additionally, a number of studies have focused on the LCA study of reusing EV batteries that no longer meet the requirements of automotive purposes in less demanding applications, in particular as stationary energy storage systems. In the light of these secondary applications as a means of extending the useful life of Li-ion batteries, the authors in [26] consider the case of an LFP battery (with a $Li_4Ti_5O_{12}$ anode and $LiFePO_4$ cathode) of an urban EV in Spain, and examine alternative end-of-life scenarios, including the reuse of the battery as an energy storage unit in a smart building with solar photovoltaic (PV) panels. Despite the fact that there are additional environmental burdens from manufacturing the PV panels, the results of this study confirm the environmental benefit of reusing the existing EV battery in the smart building application compared to manufacturing a new one for the same purpose. Similarly, the authors in [27] examine the second life application of a Li-ion battery with cell chemistry of $LiFePO_4$ cathode and graphite anode, assuming that the use, remanufacturing and reuse phases occur within the Province of Ontario, Canada. Furthermore, the authors in [28] analyze the environmental trade-offs of cascading reuse of EVs' Li-ion batteries in stationary energy storage at automotive end-of-life, reporting that the net cumulative energy demand and global warming potential can be reduced by 15% under conservative estimates and by as much as 70% in ideal refurbishment and reuse conditions.

In this context, the present paper builds upon the work in [26] to expand and further analyze the second life application scenarios of an LFP EV battery by combining the following cases for the second use phase: (i) either reuse of the EV battery or manufacturing of a new battery as energy storage unit in the building; and (ii) either use of the Spanish electricity mix or energy supply by the PVs. A limitation of this work is that battery recycling options are not included in the analysis due to the lack of relevant data for this kind of processes in the life cycle inventory employed. The rest of the paper is organized as follows: Section 2 describes the characteristics of the LCA study, the materials of the battery, and the LCA tool employed in this work, as well as it introduces the second life application and presents the scenarios under study. Section 3 discusses the results obtained from the scenarios under study and the last section concludes the paper.

2. Materials and Methods

2.1. LCA Study Characteristics

The goal of this LCA is to examine the potential benefits in terms of environmental impact from the reuse of an LFP battery, which can no longer be used in an EV, but still fulfills the requirements as an energy storage unit in a building in Spain. To this end, the scope of the analysis includes the manufacturing phase, the use phases (primary and secondary applications) and the disposal phase of the EV battery, along with the related background processes, whereas other EV components are out of the boundaries of the system. Given that the scenarios under study have the factor of time as common reference, the functional unit in the analysis is chosen to be equal to 4000 days (assuming one battery cycle per day). The information for the materials and processes required for the manufacture of the LFP battery is based on the work in [24]. The data source for the life cycle inventory is the Ecoinvent database, which is incorporated in the LCA tool employed for the purposes of this work, namely SimaPro developed by Pré Consultants. The impact categories considered in the LCA study are carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals and fossil fuels.

2.2. LCA Tool

SimaPro is one of the most widely used LCA software, chosen by industry, research institutes, and consultants in more than 80 countries. It is based on the ISO 14040 and 14044 standards, where the first considers the principles and framework for an LCA, while the latter specifies the requirements and guidelines for carrying out an LCA study. SimaPro incorporates the Ecoinvent database that covers more than 10,000 processes, as a result of a joint effort by different Swiss institutions to update and integrate several life cycle inventory databases. Moreover, it offers several mid-point and end-point impact assessment methodologies (e.g., ReCiPe/IPCC 2007/Greenhouse Gas Protocol/CML IA/Ecological footprint and ReCiPe/Eco-indicator 99/Impact 2002+/EPS 2000 respectively), each one containing a number of impact categories (e.g., climate change, acidification, etc.). The methodology of impact assessment is based on aggregating each elementary flow from the inventory to one impact category (classification). Then, equivalency factors (e.g., IPCC for climate change) are applied to determine the whole impact category result (characterization). The outcome consists of the quantification of different impact categories (e.g., climate change in kg of CO_2eq).

2.3. Materials

Regarding the production of the electrode paste, the main components include a binder substance (5–10% of the total paste), carbon black to improve conductivity (4–10% of the total paste), $LiFePO_4$ and an electrochemically active material. It is also mentioned that an important modeling choice is the assumption of hydrothermal synthesis for $LiFePO_4$, among the many different synthesis paths available [24]. Moreover, the binder material selected is polyvinylidene fluoride (PVDF), while the solvent selected to obtain the desired slurry texture is NMP, which is evaporated during the mixing process with the substrate. The electrode substrate is a very thin (1520 µm) metal foil, mainly composed of aluminum mixed with other metals, which is utilized as the current collector and gives physical support for being later coated with the electrode paste. Due to the lack of available data for the manufacture of this part of the cathode, it is assumed that this process is similar to the "sheet rolling" process in the Ecoinvent database. As already pointed out, for the purposes of this work, hydrothermal synthesis is assumed for the production of $LiFePO_4$, among the available options. This production process includes the reaction of iron sulphate salt ($FeSO_4 \times 7H_2O$) with lithium hydroxide (LiOH) and phosphoric acid (H_3PO_4) in a water medium inside a hermetic reactor at a temperature ranging between 150–250 °C. After this process, $LiFePO_4$ precipitates and is picked up by a suction filter and later dried during five hours at a constant temperature of 60 °C.

2.4. Battery Degradation and Second Life Application

Lithium batteries for EVs are subject to two mechanisms that shorten life-time and deteriorate performance, namely cycling capacity loss and calendar capacity loss. The former depends on the number of battery charging/discharging cycles, while the latter depends on the state of charge, aging time, and expose of the battery to high temperatures. Specifically, cycling capacity loss is typically attributed to the formation of solid electrolyte interphase (SEI) layer, structural changes in the electrodes and loss of lithium during battery charging/discharging. Calendar capacity loss is attributed to battery self-discharge and side reactions that occur during the energy storage period [29].

It is estimated that LFP batteries can support at least 2000–2500 cycles in electro-mobility applications, for example, daily use of a charge and discharge cycle for seven years, until the remaining capacity reduces to 80% of the initial battery capacity. This allows its use for another 1000–2000 cycles until the capacity reduces to 60% of the initial capacity. When this occurs, the aging process of the battery has advanced to point that the voltage drop does not allow further use of the battery [30].

After the end of the useful life of a battery for electro-mobility purposes, typical applications include its use as energy storage unit in smartgrids or uninterruptible power supply. The main characteristic of these applications is the lower stress that the battery cells suffer, enhancing thus the durability of the battery pack. In the context of this work, the primary use phase considers a 24 kWh LFP battery with efficiency of 80% used for 2500 days in an EV, while the second life application considers the case of using an LFP battery as an energy storage unit in a smart building for 1500 days (or equivalently, four years), taking into account the average home consumption in Spain in 2010. In the scenarios that refer to the use of the same battery in the primary and secondary application, it is further assumed that the efficiency drops from 80% to 75% due to the aging of the battery.

2.5. Scenarios

For the purposes of this work, the LCA study examines five different scenarios, i.e., a base scenario as reference and four alternative scenarios. The base scenario for the LFP battery includes the following stages: battery manufacture, use phase in the EV for 2500 cycles, disposal once it reaches the end of life for automotive purposes (considering the case of treatment of incineration and then landfilling of the leftover residues) and second use phase assuming a new EV battery with the same specifications for another 2500 cycles. As this scenario considers the life cycle of two batteries in an EV, it exceeds the functional unit of time, however it is used only as an indicative reference for the comparison of the four alternative scenarios that consider the use of the battery as energy storage unit in a building.

The first two alternative scenarios consider the secondary application of an EV battery in a smart building for stationary energy storage using electricity from the grid. Specifically, the stages of scenario 1 are as follows: LFP battery manufacture, use phase in the EV for 2500 cycles (until the capacity drops to 80% of the initial value), second life application to the smart building for additional 1500 cycles until the capacity degradation does not allow more uses (i.e., decrease of battery capacity down to 60% of initial value), and battery disposal with the same treatment as it is assumed in the base scenario. The structure of scenario 2 is the same with the base scenario until the disposal of the initial battery, with the difference being that a new battery with a smaller capacity is manufactured for storing the energy from the grid (based on the Spanish electricity mix) and supply it to the smart building for 1500 cycles. The other two alternative scenarios, namely scenarios 3 and 4, are similar to scenarios 1 and 2, but instead of evaluating the use of the battery in smart building applications by storing energy provided from the grid, the energy is supplied by PVs. Therefore, additional environmental burden is allocated in scenarios 3 and 4 for the manufacture of PVs. Figure 1 illustrates the phases included in each alternative scenario.

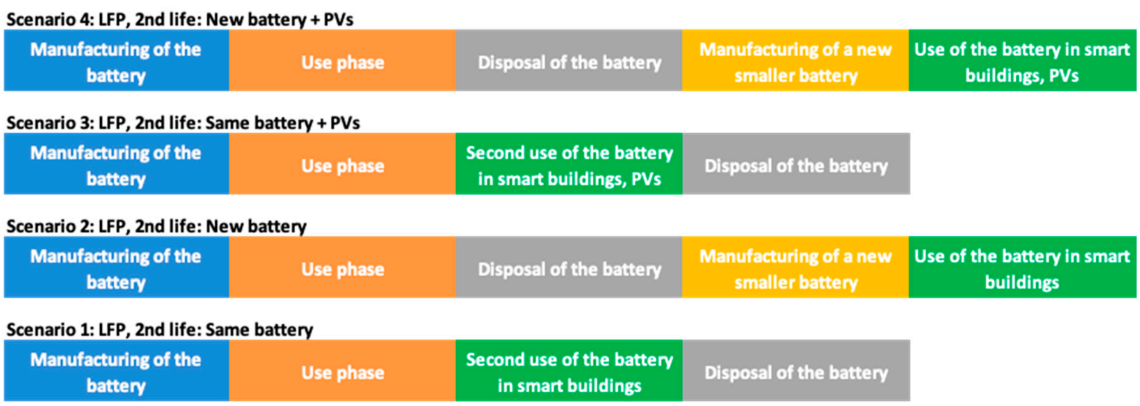

Figure 1. Graphical representation of stages included in each alternative scenario of the LCA study.

3. Results and Discussion

3.1. Scenario 1

Scenario 1 is based on the idea of reutilizing the LFP batteries in smart buildings once they have reached the end of life for electro-mobility purposes due to the degradation of the battery (80% of the initial capacity). This scenario includes four stages: (i) the manufacturing process of the battery, which is the same for all scenarios; (ii) the primary use phase of the battery in the EV for 2500 days; (iii) the secondary use phase (second life application) as energy storage in a smart building using the Spanish electricity mix for 1500 days (after the degradation of the battery due to the use in the EV); and (iv) the disposal of the battery once it reaches its end of life. At this point, it is noted that the environmental impact of the disposal stage is left out of the scope of this comparative analysis, and thus not evaluated, due to the lack of relevant data for battery recycling options (that represent more realistically the possible end-of-life treatment options for the EV batteries) in the life cycle inventory employed in this work; yet this assumption still provides a valid basis of comparison given that the disposal stage is common in all the scenarios under study. The single score of the LFP battery for scenario 1 with respect to the manufacturing process, use phase and second life application, obtained by using the Eco-indicator 99 method and disaggregated per impact category, is given in Table 1.

Table 1. Evaluation results of scenario 1.

Impact Category	Total	LFP Battery Manufacture	LFP Battery Usage	Second Life Application
Total	2721.31	577.70	1015.36	1128.24
Carcinogens	601.57	318.11	134.27	149.20
Resp. organics	0.27	0.08	0.09	0.10
Resp. inorganics	820.02	73.55	353.58	392.89
Climate change	177.27	13.54	77.56	86.18
Radiation	9.43	0.25	4.35	4.83
Ozone layer	0.84	0.80	0.02	0.02
Ecotoxicity	90.60	33.89	26.86	29.85
Acidification/Eutrophication	44.75	2.92	19.81	22.01
Land use	16.26	2.98	6.29	6.99
Minerals	87.45	57.62	14.13	15.70
Fossil fuels	872.83	73.96	378.40	420.47

Note: The unit of measurement in all categories is the Eco-indicator Point (Pt).

The results obtained in this scenario show that the stage with the lowest overall environmental impact is the production of the battery, followed by its use in the EV and finally, the most harmful stage for the environment is the second use phase of the battery, mainly caused by the large quantity of energy supplied to the battery by the grid, taking into account the Spanish electricity mix. Given that the source of electricity is the same in both use phases (primary and secondary), the higher environmental impact caused by the second life application is due to the higher energy demand in the building in comparison with the EV. In this context, an important factor to consider is the lower efficiency of the battery during the smart building application, leading to higher losses of electricity during the charging and discharging phases, and thus higher environmental impact.

Figure 2 presents the contribution of each stage of the battery life cycle in each impact category, indicating that there are significant differences between the categories for the overall environmental impact. In detail, the three main categories that influence the final result are the fossil fuels, respiratory inorganics and carcinogens, followed by climate change.

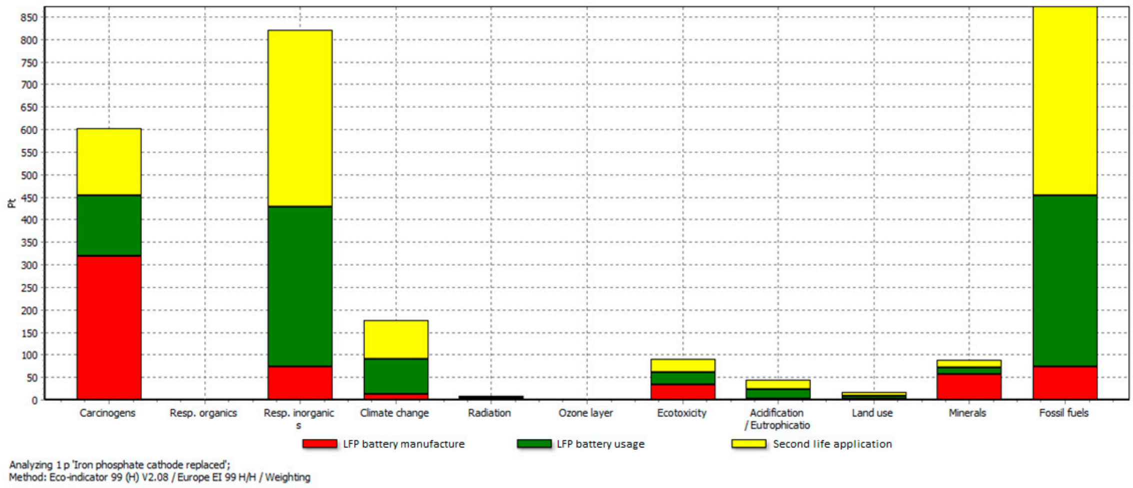

Figure 2. Impact of LFP battery manufacturing process, use phase and second life application per impact category in scenario 1.

3.2. Scenario 2

In contrast to scenario 1, scenario 2 is not based on the idea of reutilizing the LFP batteries once they have reached the end of life for electro-mobility purposes, but instead, a new battery with a smaller capacity of 12 kWh is manufactured and utilized for the smart building application, in replacement of the first battery with the degraded capacity. Specifically, this scenario includes five stages: (i) the manufacturing process of the first battery; (ii) the use phase of the first battery in the EV for 2500 days; (iii) the disposal of the first battery; (iv) the manufacturing process of the second battery with the same technology but smaller capacity; and (v) the use phase of the second battery (second life application) in a smart building using the Spanish electricity mix for 1500 days. Similarly to scenario 1, the evaluation of the disposal phase is omitted due to the lack of relevant data for battery recycling options (that represent more realistically the possible end-of-life treatment options for the EV batteries) in the life cycle inventory employed in this work, given that it is common for all the alternative scenarios under study. Table 2 shows the single score of the two LFP batteries for scenario 2 with respect to their manufacturing process and corresponding use phases, obtained by using the Eco-indicator 99 method and disaggregated per impact category.

Table 2. Evaluation results of scenario 2.

Impact Category	Total	LFP Battery Manufacture	LFP Battery Usage	Second LFP Battery Manufacture	Second Life Application
Total	2939.64	577.70	1015.36	288.85	1057.73
Carcinogens	751.30	318.11	134.27	159.05	139.87
Resp. organics	0.30	0.08	0.09	0.04	0.09
Resp. inorganics	832.24	73.55	353.58	36.77	368.34
Climate change	178.66	13.54	77.56	6.77	80.79
Radiation	9.26	0.25	4.35	0.12	4.53
Ozone layer	1.24	0.80	0.02	0.40	0.02
Ecotoxicity	105.68	33.89	26.86	16.94	27.98
Acidification/Eutrophication	44.83	2.92	19.81	1.46	20.64
Land use	17.31	2.98	6.29	1.49	6.55
Minerals	115.28	57.62	14.13	28.81	14.72
Fossil fuels	883.53	73.96	378.40	36.98	394.19

Note: The unit of measurement in all categories is the Eco-indicator Point (Pt).

As expected, the results of scenario 2 show that the stage with the lowest overall environmental impact is the production of the second (smaller) battery for the second life application, followed by the production of the first battery for the EV, the use phase of the first battery in the EV and finally, the use phase of the second battery, which is the most harmful stage, mainly due to the large quantity of energy supplied to the battery using the Spanish electricity mix. Taking into account that the source of electricity is the same in both use phases (primary and secondary), the higher environmental impact caused by the second life application is due to the higher energy demand in the building in comparison with the EV. Consequently, if the energy supplied to the building is lower, the environmental impact of this stage will then also be lower. A close examination of Tables 1 and 2 reveals that the environmental impact of the second life application in scenario 2 is reduced when compared to that of scenario 1, as a result of the higher efficiency of the new battery used in scenario 2 instead of the existing battery that is degraded due to aging effects. Nevertheless, the additional environmental burden for the manufacture of the second LFP battery results in a higher total impact in scenario 2.

Figure 3 illustrates the impact of the aforementioned stages of the batteries life cycle per category, indicating that there are significant differences between the categories for the overall environmental impact. Similarly to scenario 1, the categories with the highest impact in scenario 2 are the fossil fuels, respiratory inorganics and carcinogens, followed by climate change.

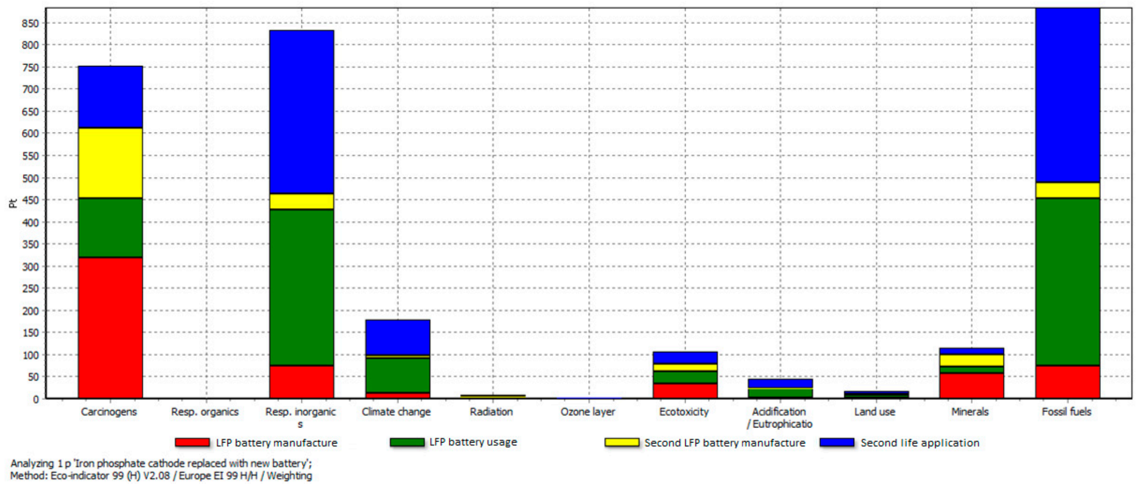

Figure 3. Impact of two LFP batteries manufacturing process and their use phase per impact category in scenario 2.

3.3. Scenario 3

Scenario 3 considers the reuse of the LFP batteries once they have reached the end of life for electro-mobility purposes as in scenario 1, but with the main difference of using PVs as the electricity source for the second life application in smart buildings. This scenario includes four stages: (i) the manufacturing process of the battery; (ii) the primary use phase of the battery in the EV for 2500 days; (iii) the secondary use phase (second life application) as energy storage in a smart building using PVs as the energy source for 1500 days (after the degradation of the battery due to the use in the EV); and (iv) the disposal of the battery once it reaches its end of life. Similarly to the previous scenarios, the evaluation of the disposal phase is omitted due to the lack of relevant data for battery recycling options (that represent more realistically the possible end-of-life treatment options for the EV batteries) in the life cycle inventory employed in this work, given that it is common for all the alternative scenarios under study. Table 3 presents the single score of the LFP battery for scenario 3 with respect to the manufacturing process, use phase and second life application, obtained by using the Eco-indicator 99 method and disaggregated per impact category.

Table 3. Evaluation results of scenario 3.

Impact Category	Total	LFP Battery Manufacture	LFP Battery Usage	Second Life Application
Total	2476.11	577.70	1015.36	883.05
Carcinogens	575.92	318.11	134.27	123.54
Resp. organics	0.26	0.08	0.09	0.09
Resp. inorganics	727.73	73.55	353.58	300.60
Climate change	157.55	13.54	77.56	66.45
Radiation	8.28	0.25	4.35	3.68
Ozone layer	0.84	0.80	0.02	0.02
Ecotoxicity	84.83	33.89	26.86	24.08
Acidification/Eutrophication	39.53	2.92	19.81	16.80
Land use	14.76	2.98	6.29	5.49
Minerals	86.17	57.62	14.13	14.42
Fossil fuels	780.25	73.96	378.40	327.89

Note: The unit of measurement in all categories is the Eco-indicator Point (Pt).

In contrast to scenario 1, the results obtained in scenario 3 show that the use of the battery in the EV is the stage with the highest overall environmental impact, given that the contribution of the second use phase of the battery in the smart building application is significantly reduced (by 21.7%) when using the PVs as the energy source. It is important to note that the environmental benefit from using a different energy source in the primary and secondary use phase is observed, despite the fact that the battery in the smart building application has a lower efficiency (due to the degradation), leading to higher losses of electricity during charging and discharging.

Figure 4 depicts the contribution of the aforementioned stages of the battery life cycle in scenario 3 for each impact category, indicating that the three main categories with the highest overall environmental impact are the fossil fuels, respiratory inorganics and carcinogens, followed by climate change, similarly to the previous scenarios.

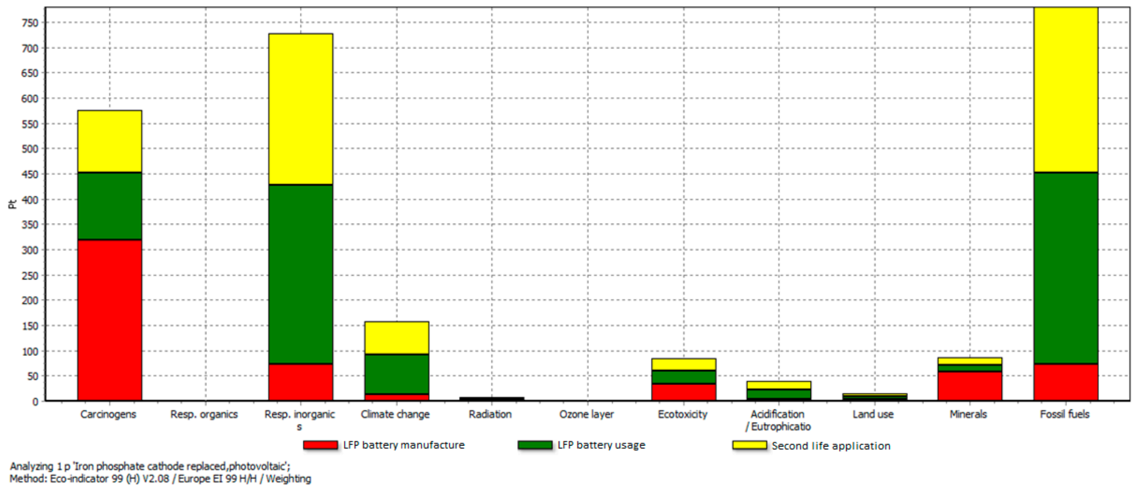

Figure 4. Impact of LFP battery manufacturing process, use phase and second life application per impact category in scenario 3.

3.4. Scenario 4

Scenario 4 is similar to scenario 2, which introduces a new battery with a smaller capacity of 12 kWh for the second life application after the first battery is degraded by its use in the EV, with the difference that the PVs are the energy source in the smart building (instead of using the Spanish electricity mix). Specifically, this scenario includes five stages: (i) the manufacturing process of the first battery; (ii) the use phase of the first battery in the EV for 2500 days; (iii) the disposal of the first battery; (iv) the manufacturing process of the second battery with the same technology but smaller capacity; and (v) the use phase of the second battery (second life application) in a smart building using the PVs as the energy source for 1500 days. Similarly to the previous scenarios, the evaluation of the disposal phase is omitted due to the lack of relevant data for battery recycling options (that represent more realistically the possible end-of-life treatment options for the EV batteries) in the life cycle inventory employed in this work, given that it is common for all the alternative scenarios under study. The single score of the two LFP batteries for scenario 4 with respect to their manufacturing process and corresponding use phases, obtained by using the Eco-indicator 99 method and disaggregated per impact category, is given in Table 4.

Table 4. Evaluation results of scenario 4.

Impact Category	Total	LFP Battery Manufacture	LFP Battery Usage	Second LFP Battery Manufacture	Second Life Application
Total	2755.74	577.70	1015.36	288.85	873.83
Carcinogens	732.06	318.11	134.27	159.05	120.63
Resp. organics	0.30	0.08	0.09	0.04	0.09
Resp. inorganics	763.02	73.55	353.58	36.77	299.12
Climate change	163.86	13.54	77.56	6.77	66.00
Radiation	8.39	0.25	4.35	0.12	3.67
Ozone layer	1.24	0.80	0.02	0.40	0.02
Ecotoxicity	101.35	33.89	26.86	16.94	23.65
Acidification/Eutrophication	40.92	2.92	19.81	1.46	16.72
Land use	16.18	2.98	6.29	1.49	5.43
Minerals	114.33	57.62	14.13	28.81	13.76
Fossil fuels	814.10	73.96	378.40	36.98	324.76

Note: The unit of measurement in all categories is the Eco-indicator Point (Pt).

In contrast to scenario 2, the results obtained in scenario 4 show that the use of the battery in the EV is the stage with the highest overall environmental impact, given that the contribution of the second use phase of the battery in the smart building application is significantly reduced (by 17.4%) when using the PVs as the energy source. It is also important to note that the impact of the second life application in scenario 4 (that assumes the use of a new battery) is slightly lower compared to that of scenario 3 (that assumes the use of the existing battery). However, the overall environmental impact results, and the additional environmental burden from the production of the new battery in scenario 4 in particular, suggest that it is more beneficial to use the same battery in the smart building application, despite the fact that it has a lower energy efficiency that implies higher electricity losses during charging and discharging.

The contribution of the aforementioned stages of the batteries life cycle per impact category in scenario 4 is shown in Figure 5, indicating that the three main categories with the highest overall environmental impact are the fossil fuels, respiratory inorganics and carcinogens, followed by climate change, similarly to the previous scenarios.

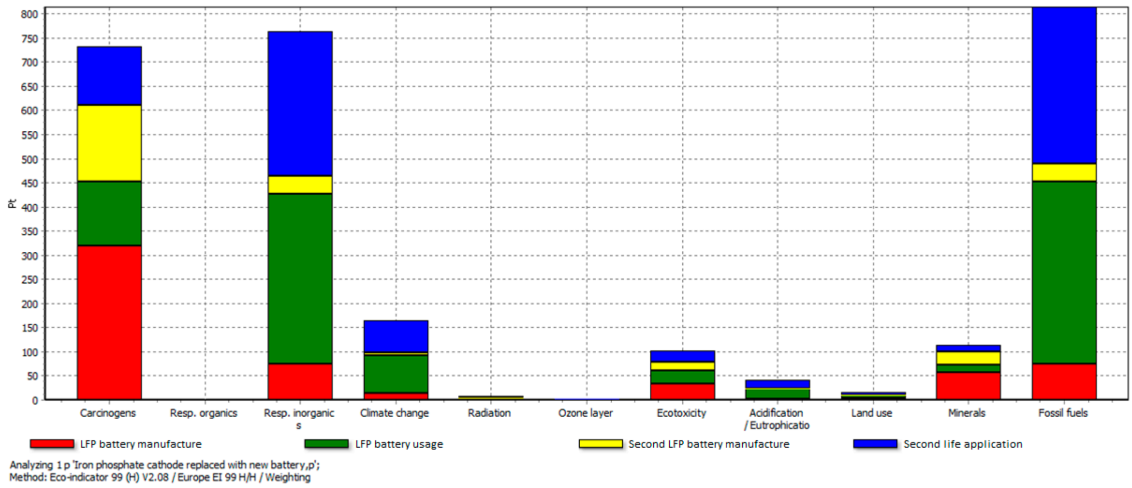

Figure 5. Impact of two LFP batteries manufacturing process and their use phase per impact category in scenario 4.

3.5. Comparative Analysis of Scenarios

This section presents a comparative analysis of the scenarios under study on the basis of the global warming potential (GWP) indicator, which is a measure of how much energy the emissions of one unit of a gas will absorb over a given time interval relative to the emissions of one unit of CO_2. The method employed in this work is the IPCC 2007 GWP 20a, thus the total contribution to global warming is calculated (in kg of CO_2 equivalent) for a period of 20 years. The results are given in Figure 6 as a percentage in comparison to the scenario with the highest value, namely the base scenario (in grey color), which represents the production of two identical batteries and their use phase in an EV for 2500 days each, thus a total of 5000 days (see Section 2.5). As the duration of the base scenario differs from the functional unit in scenarios 1–4, the former is used only as a reference for comparison purposes.

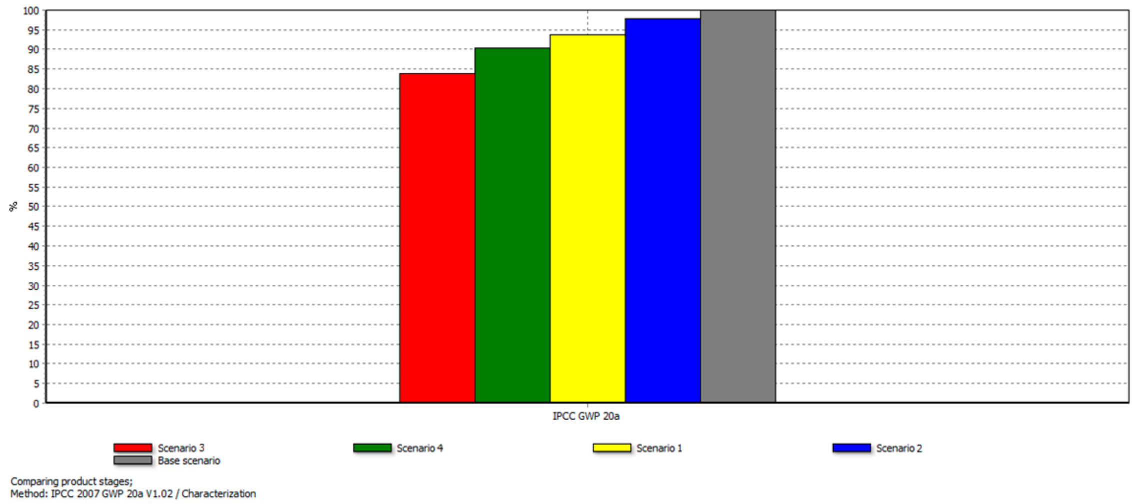

Figure 6. Comparison of scenarios based on GWP results (in percentage terms).

In descending order of GWP indicator values, scenario 2 (in blue color), which considers the production of a new smaller battery as an energy storage unit in a grid-connected smart building is followed by scenario 1 (in yellow color) which refers to the reuse of the existing EV battery in the same building, scenario 4 (in green color) which represents the case that a new smaller battery is used for energy storage in a smart building with PVs, and scenario 3 (in red color) which assumes the reuse of the existing EV battery in the smart building powered by PVs. Table 5 shows the analytic results of GWP values disaggregated by process in each scenario.

Table 5. Comparative analysis of scenarios based on GWP indicator.

Process	Unit	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total of all processes	kg CO_2eq	30,086.80	28,218.68	29,429.89	25,205.42	27,169.94
Hard coal, burned in power plant/ES U	kg CO_2eq	10,059.10	10,592.22	10,256.11	9207.39	9217.49
Natural gas, burned in power plant/ES U	kg CO_2eq	3656.23	3852.09	3728.86	3347.51	3350.43
Heavy fuel oil, burned in power plant/ES U	kg CO_2eq	3069.58	3233.97	3130.54	2810.38	2812.84
Hard coal, at mine/WEU U	kg CO_2eq	1811.14	1857.30	1817.68	1625.48	1643.82
Lignite, burned in power plant/ES U	kg CO_2eq	1678.82	1767.91	1711.76	1536.72	1538.36
Tetrafluoroethylene, at plant/RER U	kg CO_2eq	2417.41	1208.71	1813.06	1210.29	1814.25
Chlorodifluoromethane, at plant/NL U	kg CO_2eq	603.63	301.82	452.72	302.21	453.02
Hard coal, at mine/ZA U	kg CO_2eq	310.03	320.58	313.21	279.95	282.74
Operation, transoceanic freight ship/OCE U	kg CO_2eq	289.78	272.84	279.66	243.47	257.64
Blast furnace gas, burned in power plant/RER U	kg CO_2eq	229.48	229.32	227.88	203.15	208.25
Natural gas, burned in gas motor, for storage/DZ U	kg CO_2eq	178.48	185.43	180.74	162.14	163.27
Clinker, at plant/CH U	kg CO_2eq	277.68	159.60	109.82	157.46	108.21
Natural gas, burned in industrial furnace >100 kW/RER U	kg CO_2eq	277.94	156.21	216.73	156.44	216.89
Natural gas, vented/GLO U	kg CO_2eq	159.38	147.07	148.99	132.23	137.87
Lignite, burned in power plant/DE U	kg CO_2eq	165.03	112.47	137.99	117.93	142.09
Hard coal, at mine/EEU U	kg CO_2eq	163.65	124.61	143.43	117.67	138.23
Hard coal, at mine/RU U	kg CO_2eq	129.58	133.83	130.83	116.84	118.09
Natural gas, at production onshore/DZ U	kg CO_2eq	123.08	127.35	124.39	111.42	112.44
Refinery gas, burned in furnace/MJ/RER U	kg CO_2eq	128.64	118.81	122.61	106.40	113.30
Hard coal, burned in industrial furnace 1–10 MW/RER U	kg CO_2eq	158.59	109.81	133.72	104.69	129.88
Hard coal, burned in power plant/DE U	kg CO_2eq	137.52	91.17	113.77	98.22	119.06
Remaining processes	kg CO_2eq	4062.07	3115.60	4135.39	3057.43	4091.76

On the one hand, the pairwise comparison of scenario 1 with scenario 3 and scenario 2 with scenario 4 confirms that the use of PVs in the smart building is beneficial in terms of GWP in relation to the use of the Spanish electricity mix, and thus highlights the importance of renewable energy sources on the reduction of the environmental impact. On the other hand, the pairwise comparison of scenario 1 with scenario 2, and scenario 3 with scenario 4, indicates that replacing the existing EV battery in the smart building application with a new one results in additional environmental burden due to its manufacturing process, despite the fact that the existing battery has a lower efficiency, and thus higher energy losses, as a consequence of its degradation during its use in the EV. Due to the lack of relevant data for recycling options of LFP batteries in the life cycle inventory employed in this work, the evaluation of the disposal phase is omitted in the frame of this analysis. It is however noted that the inclusion of the disposal phase would increase the total environmental impact in each scenario by the same amount in absolute terms, given that the disposal phase refers to the same battery and is common in all scenarios under study. Accordingly, this further implies that the difference among the scenarios considered would be smaller in percentage terms.

4. Conclusions

This paper presents an LCA study to examine the environmental impact from the reuse of EV batteries, specifically of LFP technology, in smart buildings as a secondary application when they can no longer meet the requirements for electro-mobility purposes. The analysis of the scenarios under study clearly shows that there is significant environmental benefit from reusing the existing EV battery in the secondary application instead of manufacturing a new battery to be used for the same purpose and time frame, despite the lower efficiency, and thus higher losses, of the existing (degraded) battery due to its aging. Despite the fact that the present analysis does not take into account the disposal phase of the LFP batteries, neither in the primary nor in the secondary application, due to the lack of relevant data for battery recycling options in the life cycle inventory employed in this work, the addition of the corresponding contributions to the total environmental impact would further support the finding that it is environmentally beneficial to reuse the existing EV batteries in the second life application. Moreover, the LCA study exemplifies the dependence of the results on the energy source in the smart building application, given that the environmental impact is significantly reduced when the Spanish electricity mix is replaced with the energy supply from PVs. This further suggests that different results would be obtained in the case of a country with different electricity mix.

Given that the option of battery recycling was not considered in the frame of this work due to the lack of data on this kind of processes, future work could be directed towards the inclusion of the battery recycling process in the scenarios under study, upon availability of relevant data, as a means of more realistically representing the possible end-of-life treatment options for the EV batteries. In addition, other interesting directions of future work include the examination of critical issues that have limited the reuse of EV batteries in practice, such as the risk of operating a battery without the warranty support from the manufacturer for the intended use, as well as cost factors related to the collection and transportation of used EV batteries, testing and repackaging of second life batteries, and their reinstallation to the second life application sites.

Author Contributions: Conceptualization, C.S.I.; investigation, C.S.I. and K.N.G.; methodology, C.S.I., K.N.G. and A.M.-M.; supervision, C.S.I.; writing—original draft, K.N.G., A.M.-M. and D.T.; writing—review & editing, C.S.I. and A.B.

Funding: This work was supported by the E.U. Seventh Framework Programme under grant agreement no. 621408 (RE-SIZED: Research Excellence for Solutions and Implementation of Net-Zero Energy City Districts).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Girardi, P.; Gargiulo, A.; Brambilla, P.C. A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: The Italian case study. *Int. J. Life Cycle Assess.* **2015**, *20*, 1127–1142. [CrossRef]
2. Ellingsen, L.A.-W.; Singh, B.; Strømman, A.H. The size and range effect: Lifecycle greenhouse gas emissions of electric vehicles. *Environ. Res. Lett.* **2016**, *11*, 054010. [CrossRef]
3. Martinez-Laserna, E.; Gandiaga, I.; Sarasketa-Zabala, E.; Badeda, J.; Stroe, D.-I.; Swierczynski, M.; Goikoetxea, A. Battery second life: Hype, hope or reality? A critical review of the state of the art. *Renew. Sustain. Energy Rev.* **2018**, *93*, 701–718. [CrossRef]
4. Scrosati, B.; Garche, J. Lithium batteries: Status, prospects and future. *J. Power Sources* **2010**, *195*, 2419–2430. [CrossRef]
5. Notter, D.A.; Gauch, M.; Widmer, R.; Wäger, P.; Stamp, A.; Zah, R.; Althaus, H.-J. Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environ. Sci. Technol.* **2010**, *44*, 6550–6556. [CrossRef] [PubMed]
6. Ellingsen, L.A.-W.; Majeau-Bettez, G.; Singh, B.; Srivastava, A.K.; Valøen, L.O.; Strømman, A.H. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *J. Ind. Ecol.* **2014**, *18*, 113–124. [CrossRef]
7. Qiao, Q.; Zhao, F.; Liu, Z.; Hao, H. Electric vehicle recycling in China: Economic and environmental benefits. *Resour. Conserv. Recycl.* **2019**, *140*, 45–53. [CrossRef]
8. Ziemann, S.; Müller, D.B.; Schebek, L.; Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recycl.* **2018**, *133*, 76–85. [CrossRef]
9. Yun, L.; Linh, D.; Shui, L.; Peng, X.; Garg, A.; LE, M.L.P.; Asghari, S.; Sandoval, J. Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles. *Resour. Conserv. Recycl.* **2018**, *136*, 198–208. [CrossRef]
10. Li, B.; Gao, X.; Li, J.; Yuan, C. Life cycle environmental impact of high-capacity lithium ion battery with silicon nanowires anode for electric vehicles. *Environ. Sci. Technol.* **2014**, *48*, 3047–3055. [CrossRef]
11. Larcher, D.; Tarascon, J.-M. Towards greener and more sustainable batteries for electrical energy storage. *Nat. Chem.* **2015**, *7*, 19–29. [CrossRef] [PubMed]

12. Manthiram, A.; Fu, Y.; Su, Y.-S. Challenges and prospects of lithium-sulfur batteries. *Acc. Chem. Res.* **2013**, *46*, 1125–1134. [CrossRef]
13. Manthiram, A.; Fu, Y.; Chung, S.-H.; Zu, C.; Su, Y.-S. Rechargeable lithium-sulfur batteries. *Chem. Rev.* **2014**, *114*, 11751–11787. [CrossRef]
14. Fotouhi, A.; Auger, D.J.; O'Neill, L.; Cleaver, T.; Walus, S. Lithium-sulfur battery technology readiness and applications—A review. *Energies* **2017**, *10*, 1937. [CrossRef]
15. Deng, Y.; Li, J.; Li, T.; Gao, X.; Yuan, C. Life cycle assessment of lithium sulfur battery for electric vehicles. *J. Power Sources* **2017**, *343*, 284–295. [CrossRef]
16. Shibagaki, T.; Merla, Y.; Offer, G.J. Tracking degradation in lithium iron phosphate batteries using differential thermal voltammetry. *J. Power Sources* **2018**, *374*, 188–195. [CrossRef]
17. Wang, Y.; Pan, R.; Liu, C.; Chen, Z.; Ling, Q. Power capability evaluation for lithium iron phosphate batteries based on multi-parameter constraints estimation. *J. Power Sources* **2018**, *374*, 12–23. [CrossRef]
18. Li, R.; Wu, J.-F.; Wang, H.-Y.; Guo, J.-Y.; Li, G.-C. Reliability assessment and failure analysis of lithium iron phosphate batteries. *Inf. Sci.* **2014**, *259*, 359–368. [CrossRef]
19. Sergi, F.; Arista, A.; Agnello, G.; Ferraro, M.; Andaloro, L.; Antonucci, V. Characterization and comparison between lithium iron phosphate and lithium-polymers batteries. *J. Energy Storage* **2016**, *8*, 235–243. [CrossRef]
20. Chemali, E.; Preindl, M.; Malysz, P.; Emadi, A. Electrochemical and Electrostatic Energy Storage and Management Systems for Electric Drive Vehicles: State-of-the-Art Review and Future Trends. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 1117–1134. [CrossRef]
21. Deng, Y.; Li, J.; Li, T.; Zhang, J.; Yang, F.; Yuan, C. Life cycle assessment of high capacity molybdenum disulfide lithium-ion battery for electric vehicles. *Energy* **2017**, *123*, 77–88. [CrossRef]
22. Zackrisson, M.; Avellán, L.; Orlenius, J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles-Critical issues. *J. Clean. Prod.* **2010**, *18*, 1517–1527. [CrossRef]
23. Wang, Q.; Liu, W.; Yuan, X.; Tang, H.; Tang, Y.; Wang, M.; Zuo, J.; Song, Z.; Sun, J. Environmental impact analysis and process optimization of batteries based on life cycle assessment. *J. Clean. Prod.* **2018**, *174*, 1262–1273. [CrossRef]
24. Majeau-Bettez, G.; Hawkins, T.R.; StrØmman, A.H. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ. Sci. Technol.* **2011**, *45*, 4548–4554. [CrossRef]
25. Peters, J.F.; Weil, M. Providing a common base for life cycle assessments of Li-Ion batteries. *J. Clean. Prod.* **2018**, *171*, 704–713. [CrossRef]
26. Genikomsakis, K.N.; Ioakimidis, C.S.; Murillo, A.; Trifonova, A.; Simic, D. A life cycle assessment of a Li-ion urban electric vehicle battery. In Proceedings of the 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 17–20 November 2013. [CrossRef]
27. Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* **2017**, *22*, 111–124. [CrossRef]
28. Richa, K.; Babbitt, C.W.; Nenadic, N.G.; Gaustad, G. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int. J. Life Cycle Assess.* **2017**, *22*, 66–81. [CrossRef]
29. Yang, F.; Xie, Y.; Deng, Y.; Yuan, C. Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation. *Nat. Commun.* **2018**, *9*, 2429. [CrossRef]
30. Cicconi, P.; Landi, D.; Morbidoni, A.; Germani, M. Feasibility analysis of second life applications for Li-Ion cells used in electric powertrain using environmental indicators. In Proceedings of the 2012 IEEE International Energy Conference and Exhibition (ENERGYCON 2012), Florence, Italy, 9–12 September 2012; pp. 985–990. [CrossRef]