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# End of Electric Vehicle Batteries: Reuse vs. Recycle

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**Abstract:** It is a fact that electric vehicles (EVs) are beneficial for climate protection. However, the current challenge is to decide on whether to reuse an EV battery or to recycle it after its first use. This paper theoretically investigates these areas i.e., recycle and reuse. It was found that there are several commercially used recycling processes and also some are under research to regain maximum possible materials and quantity. The concept of reusing (second life) of the battery is promising because, at the end of the first life, batteries from EVs can be used in several applications such as storing energy generated from renewable sources to support the government grid. However, the cost and life-cycle analysis (LCA) demonstrated that there are several aspects involved in battery reuse applications. Henceforth, one LCA generalised method cannot provide an optimal approach for all cases. It is important to have a detailed study on each of the battery reusing applications. Until then, it is safe to say that reusing the battery is a good option as it would give some time to recycling companies to develop cost and energy-efficient methods.

**Keywords:** battery recycling; battery reuse; battery second life; circular economy; lithium-ion cells; electric vehicles; battery components recycling; sustainability in mobility; battery safety; battery cost analysis



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## 1. Introduction

Electric vehicles (EVs) could play a major role in mitigating the effect of climate change. It is expected that EVs can help in decarbonising and building a sustainable world. The deployment of EVs is being boosted by public administrations in several regions of the world. The global deployment of EVs increased from 17,000 in the year 2010 to 8.5 million by the year 2020 [1]. Such rising trends correspond to increasing demand for high-performance batteries for EVs such as Li-ion batteries (LIB) [2], which is regarded as the most promising chemistry for EVs due to their intrinsic characteristics and significant cost reduction in the past decade (from USD 1100/kWh in 2010 to USD 156/kWh in the year 2019) [3–5].

The expected large increase of electric batteries' presence in the automotive sector in coming years [6] will pose a challenge of how to deal with the batteries when their first useful life is finished. Given the high environmental impact associated with the manufacturing of a new battery [7], once the battery is removed from the vehicle treating it as waste is not an appropriate solution. In this situation, the battery industry is facing two options to deal with the battery's end-of-life (EoL) phase,

- Redirect the battery to a second life-use circuit where the useful life is extended providing alternative energy storage services, thus, reducing the environmental impact per kWh delivered by the battery.
- Transfer the battery to a recycling circuit where a large percentage of valuable components, in particular critical raw materials (CRM), are retrieved and reused to manufacture new batteries, thus reducing the environmental impact of the manufacturing process.

Despite having two alternatives, once the second life use is finished the battery is sent to the second option to be recycled as part of a circular economy strategy to minimize the amount of waste produced. A visual representation of the battery's life in a circular economy perspective is shown in Figure 1.

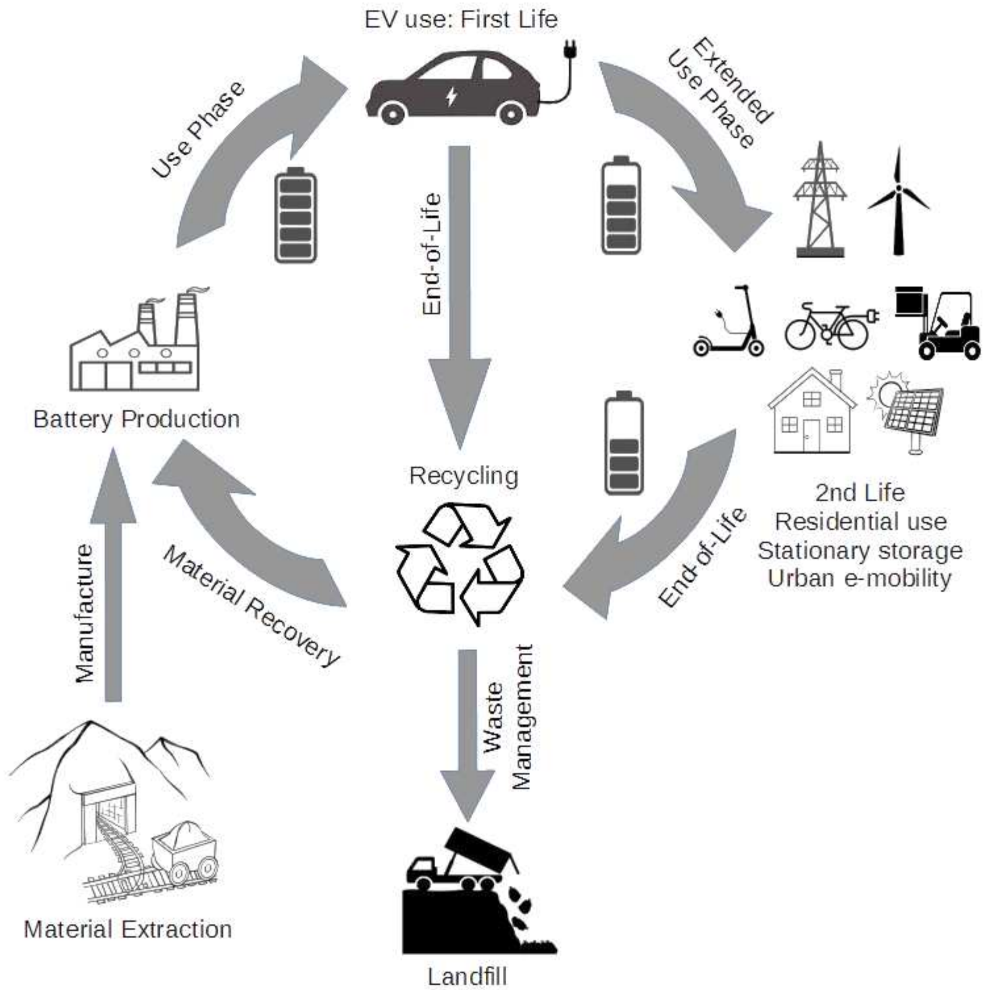


**Figure 1.** Battery life in a circular economy perspective.

According to [8], the estimated number of used EV batteries available will increase from 50,000 in the year 2020 to 150 million in the year 2035, showing the importance of having a recycling infrastructure and established reuse procedures ready to deal with the incoming wave of aged batteries.

Nonetheless, the manufacture of batteries has an important environmental impact. The generation of EVs developed in the year 2010 using LIB had a battery energy of 16 or 24 kWh at most with a range of about 100 km. The global warming potential (GWP) was the first category that life-cycle assessments analysed, noting that, for first EVs, the production of the battery represented about 40% of the total environmental impact of a vehicle, which put the EV in a worse position from an environmental perspective in comparison to an internal combustion engine vehicle (ICEV) [9]. Thus, it was during the use phase when

EVs gained a better overall picture, although it strongly depended on the country where the EV was run and, in some cases, the benefits were not so evident [10].

In order to fulfil the range-anxiety standards, EV battery capacity has continuously increased since then, giving the EV battery cost decrease a similar final cost for EVs over time. Nowadays, the battery energy of EVs ranges from 30 to 90 kWh with an average selling close to 44 kWh [11].

After 10 years of development, batteries have improved in all possible directions (performance, cost and environmental burdens). Nonetheless, the GWP of the production phase of EVs with 64 kWh of battery energy storage capacity is still 25% higher in comparison to diesel vehicles. Although the GWP was triggering the entrance of EVs into the mobility sector, there are other categories in which the environmental impact of EV manufacturing substantially worsens in comparison to ICEV, which are abiotic depletion, photochemical oxidation, acidification and eutrophication, all of them having impacts higher than 50% [12]. Knowing that many of the materials used in battery manufacturing are considered critical materials [13], abiotic depletion is now the principal reason for developing new battery chemistries with lower environmental impact.

Nevertheless, EV batteries could be reused in other applications after their 1st life on a vehicle. There are two reasons to support this idea: (i) for smaller batteries, they are not considered appropriate for transport purposes after they've lost about 20% or 30% of their initial capacity and should be replaced [14]; (ii) for bigger batteries, they will be mostly misused as daily trips demand around 5 to 10 kWh [15]. This fact suggests that the EV EoL, according to the ageing trend taken from the EV degradation tool [16] transposed to kWh delivered, will be reached before the aforementioned threshold.

EV battery reuse represents an opportunity to increase its lifetime until its full operational life is completed. This life enlargement could avoid the manufacture of new batteries for these secondary uses and, consequently, reduce the potential environmental burden.

There are multiple applications in which batteries could be reused. Some are based on stationary applications as batteries can be used in the whole electricity chain, from huge storage systems supporting electricity generation to small devices for residential purposes [17,18] as well as other uses for micro or urban electro-mobility. Moreover, battery reuse gives time to improve the recycling processes and increase the recycling industry capacity [17].

Finally, recycling plays an important role because many of the key performance materials are considered critical materials and because all batteries (from first and second life) will end up here. The manufacturing cost of batteries strongly depends on the exploitation of resources that are difficult to obtain (from a technical, quantity and social perspective). Moreover, going to the main source, to extract raw materials involves a significant increase in ecological footprint. Thus, recycling of batteries has become quite important.

As evidence of the importance of recycling, several countries count on lithium battery recycling plants, such as the United States, Canada, South Korea, China and also in Europe, which pursues an interest in being more sustainable and lowering the production costs of these batteries by reusing their raw materials. Different processes with different efficiencies are accessible depending on the recycling interest, ranging from high recoveries of copper and aluminium to high recoveries of all the components of the battery in the form of compounds such as cobalt sulphate, nickel sulphate or lithium carbonates [19].

The main recycling option is hydrometallurgical recycling, which is normally accompanied by a pre-processing method that can be either mechanical, such as crushing or cutting of the battery components, or a pyrometallurgical method with a melting or pyrolysis process of the battery elements. In most of these recycling plants, the focus is on obtaining metals such as cobalt and nickel.

This article aims to answer some of the questions such as, is a second life of a battery worth the effort e.g., is it economically and environmentally necessary? How can we include this, and recycling approaches in LCAs, to avoid misleading information? Therefore, this article is organised as follows, in Section 2 the different options for reusing batteries are given. In Section 3 the recycling strategies are analysed and in Section 4 the cost of these strategies is considered. Section 5 provides the environmental impact and Section 6 undertakes a discussion and future recommendations. In Section 7, the conclusions of this work are summarised.

## 2. Reuse

As indicated in Section 1, there are multiple stationary applications where electric energy storage systems could be installed that can be gathered in two groups [20]. The first group is oriented to electricity generation and grid distribution with larger-scale installations such as time-shifting, seasonal energy storage, large-scale renewable integration, transmission and distribution investment deferral or grid regulation. The second group is more oriented to a user-level perspective, in this case, there are both relatively high, medium and small-scale installations depending on the final user (industry, tertiary or residential building) like energy management, power quality, power reliability, distributed renewable integration and transportation applications.

In both groups, power requirements range from a few KW to several hundred MW and some of them require fast response times while others do not. Similarly, their storage capacity range from kWh to MWh and the services might ask for several hours of energy delivery or only for some minutes of support.

In this sense and given that EV batteries had an average energy capacity of 44 kWh in 2019 and that the largest capacity of existing EV batteries is currently around 100 kWh, more than one battery will be necessary for most applications and even a combination of batteries to meet the energy requirements [21].

The particularity of battery reuse is that the availability of second-life batteries does not depend on the investment of the repurposing manufacturer, in contrast to new raw material factories, where one can invest more to increase the extraction rates. For battery reuse, the availability of batteries depends basically on the rate of EV retirement, knowing that retirement might come from ageing or from an accident, in which case the safety procedures are quite relevant [22] and not all batteries will be accepted for reuse.

Thus, the volume of vehicle batteries to come in future years will depend on the EV sales from previous years, driving habits and the environment where the vehicle drives. In any case, the good news is that stationary application storage needs are lower than for electric mobility and, in 10 years, most of them could be covered with the growing electric mobility market.

However, there is an issue that is expected to occur at least in the early stages of the collection of these batteries, which is the heterogeneity in terms of battery models, forms, control, chemistry and electrical characteristics among others. This heterogeneity will increase with the continuous advances in this field that will bring better performant batteries, because a new product is inherently different to any other previously in the market and, thus, another battery should be considered by remanufacturers. However, the higher selling rates expected for future years of all existing models will de-crease the necessity to have a multiplicity of EV battery adaptations from mobility to stationary applications. The inhomogeneity in batteries is always undesirable [23].

In this sense, and to be able to make use of the volume of batteries that reach these early stages, second-life batteries should preferably be installed in small-medium scale applications to minimize this variability for a single installation while larger-scale installations should wait for newer vehicles to age. However, a possible direction with high added value is to use them through individual control of cells that build a battery. This direction opens the possibility of combining chemistries in a single battery unit, as the combination of cells would focus on some electrical storage parameters, such as the state of charge of the batteries, and would be able to make individual use of the energy available in each cell to maximize the overall battery performance. The distribution of current would also be managed by a control body in which, once the energy reserves of a cell have been exhausted, it would open the circuit of that cell to continue making use of the rest through active balancing techniques [24]. This configuration also allows control of the state of health (SOH) of each cell to be able to make more selective maintenance of the battery and to be able to carry out punctual substitutions to maintain the electrical needs required for the applications. Nonetheless, this higher control implies higher repurposing costs, which are analysed further in Section 4.

This heterogeneity is also affected by the SOH of batteries and cells within (which active balance also covers). Several authors have already highlighted that the 70% SOH limit marked by car manufacturers is not mandatory and batteries will arrive at all kind of SOH because it will be marked by the final owner who has the final responsibility to decide when to proceed to the EV retirement [25].

However, for newer and bigger battery capacities and seeing the battery ageing tendencies of EV fleets [16], this limit is not expected to be reached in most of the cases due to its misuse during its lifetime in the vehicle.

Thus, it is expected that, for the first generation of EV batteries sold, many batteries will reach their EoL as soon as they are removed from the vehicle and should proceed to recycle. However, for newer EV models, batteries will present much better conditions for their use in the second life, which can be either in stationary storage applications or in EVs as spare parts for those with manufacturing defects or crashes that need low-cost replacements.

For all that, battery reuse might follow three possible directions depending on the goal of the remanufacture pursues. Direct reuse and battery dismantling to the module or cell level [26].

Direct reuse offers lower costs but it provides less adaptability options due to stacking problems. The option of module dismantling allows for a more versatile solution, capable of going from small to large systems. However, a new battery management system (BMS) and control systems should be implemented. This option is called to be the one mostly used by remanufacturing companies. Finally, the dismantling into cells maximizes the versatility and reduces the inhomogeneity of the resulting battery, as an individual selection of cells according to their SOH and other characteristics can be undertaken. Nonetheless, the cost rises due to an increase in the manipulation, testing and need to implement completely new control systems at the cell, module and battery level [27].

Overall, going for battery reuse strategies give the chance to Europe to become a potential battery manufacturer. At the moment, Europe is dependent on raw materials and also on new batteries built elsewhere. Once battery recovery begins, Europe will be capable of positioning itself as a potential world provider, as most EVs are being sold mainly in Europe (39.8%), China (39.6%) and North America (10.7%) [28,29] as shown in Figure 2.

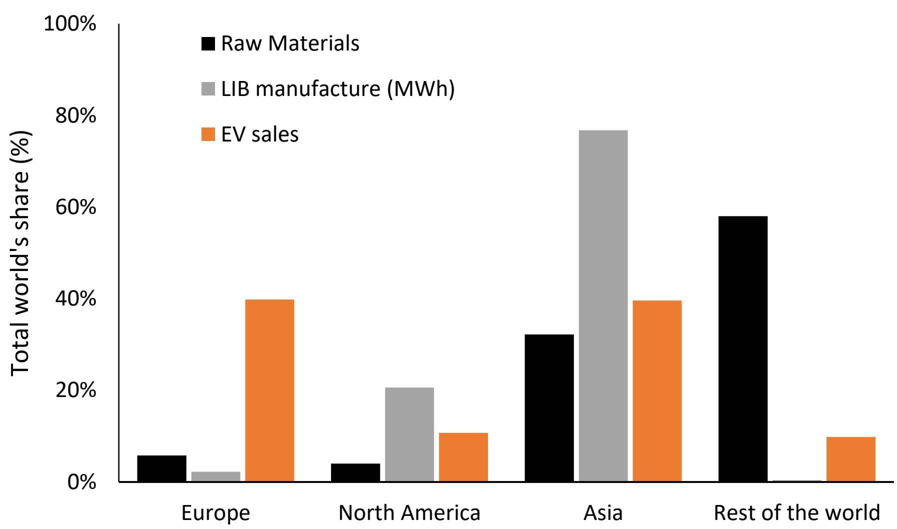


**Figure 2.** Percentage of electric vehicle (EV) world sales.

## 3. Recycling

The option of recycling is not only useful for ecological reasons, but also from an economical perspective, as it makes sense to regain precious materials after the EoL of a battery system. In particular, the metals Ni and Co, which are used in the cells' cathodes, are driving the recycling efforts by means of the economy [30]. Even though Co is considered a rather scarce metal, translating into a theoretical upwards trend of the price, the fact that there are driving forces moving the battery industry away from Co to replace it with Ni, Mn or iron phosphate gives more alternatives that are less scarce [30]. One such example is the Horizon 2020 COBalt-free Batteries for FutuRe Automotive Applications (COBRA) project, which aims to remove Co from the battery, while still obtaining great electrical performance.

In addition, Li not only makes up part of the name of this technology but is also responsible for the charge transfer in all lithium-ion cells, independent of the cathode material. Therefore, this element is required for all lithium-ion cell technologies, which again translates to higher demand in the future, with the market predictions from the previous sections. According to research on the supply of Li, the global demand for Li may surpass the overall extraction of the material in the 2020s, making it impossible to satisfy future demand, if the recycling process is not undertaken in parallel [31].

There are two ways of recycling batteries, pyrometallurgy/smelting and hydrometallurgy, which are either used separately or in combination with each other. These broadly comprise several stages of chemical separation processes such as precipitation, solvent extraction, ion exchange and electrolytic extraction, several of which are normally used in combination depending on the recycling strategy [32]. Examples of such are, (a) Pyrometallurgical process where lithium-ion and NiMH batteries are melted, and the main objective is to recover the high added-value metals such as cobalt, copper, nickel and iron. The alloys obtained from the melt are fed to a hydrometallurgical process where they are separated through the use of chemical attack by acids, followed by precipitation into salts. In this process, lithium, aluminum and manganese are removed from the slag stream, and (b) pyrometallurgical process, lithium batteries are incinerated at 1000 °C, which causes the organic solvents, lithium, and fluorides in the batteries to evaporate and not be recovered. The rest of the metals are separated via hydrometallurgy for the recovery of, mainly, cobalt [29].

Of these and other processes, the most optimistic efficiencies are close to 51.3% saving in the use of critical battery manufacture materials [33]. From an environmental perspective, $CO_2$ emissions and energy consumption can be reduced by up to 70% considering the transportation, extraction and refining of raw materials [34].

In addition to the processes mentioned above, there are other processes where not only the high value-added metals or CRM of the batteries are recovered, but the battery components in the form of salts are obtained as sub-products of these processes.

An example of such recycling is the mechanical process in which the electrolyte is removed separately, and the battery cells are broken down to concentrate the metals in order to avoid thermal separation steps. In cryomilling, in which the batteries are cooled to $-175$ °C before breaking, the way the batteries are cooled is through liquid nitrogen ($N_2$), which also serves as an inert atmosphere. Lithium is reacted with sodium hydroxide (NaOH) to form lithium hydroxide (LiOH) and then treated with carbonates ($CO_3^{-2}$) to form lithium carbonate ($Li_2CO_3$), which is slightly soluble in water, and finally crystallized to form the salt of this compound [35].

Another process combines mechanical and chemical processes for recycling lithium batteries. The batteries are shredded in an inert atmosphere and then crushed. The product obtained after shredding is a stream rich in metal oxides, carbon, a fraction of magnetic compounds from the casing, a dense fraction of aluminium and copper from the current collectors that are non-magnetic, and a fraction of paper and plastic. These fractions are separated under an inert atmosphere. Water is added to the metal oxide fraction, and the lithium in this mixture is then separated by adding carbonates and phosphoric acid to the water. The remaining materials in this mixture are recovered through a hydrometallurgical process. In this process, lithium recycling yields of 60% are achieved [29].

A possible process structure, which takes a different approach and is already in real operation, will be described in the following paragraph. In order to avoid energy-intensive processes like high-temperature smelting methods, i.e., pyrometallurgy, this newly introduced concept starts by discharging the batteries (if possible). This is followed by a mechanical and a hydrometallurgical process, with a recycle quota of 72% for the mechanical process and up to 91% for the total process respectively [36]. A noteworthy advantage is that the mechanical separation can also be performed at a given location with a portable container solution, leading to the separation of different components already at the site, such as at a recycling company, a quarantine area for wrecked EVs or from a repair garage [22]. Hence, this concept does not require additional effort and battery container equipment for the transportation of these batteries as transport of dangerous goods, leading to a reduction in transported volume by a factor of seven [36].

Another process that has been shown to work on a laboratory scale, and in which the recycled materials are obtained in a form that can be used again in batteries without the need for extensive additional processing, is the use of supercritical carbon dioxide. This is used to extract the electrolyte from the batteries, the cells are then crushed, and the components can be separated by their different properties such as electronic conductivity or density. Once the electrolyte is separated, it is separated from the $CO_2$ stream so that with further processing it can be used again in the batteries. Almost all battery components can be recovered using this process, including aluminium. Cathode compounds can be recovered without the use of energy-intensive processes such as pyrometallurgical or hydrometallurgical processes, although subsequent recovery requires re-lithiation of these compounds [37].

## 4. Cost Analysis

Considering the statements in the previous sections, a crucial factor for evaluating and comparing the benefits of reusing end-of-first-life batteries (including recycling, direct reuse and remanufacturing) is the cost development of new batteries to be manufactured. Therefore, the different paths of reusing those batteries need to be investigated to identify possible economic benefits compared to new batteries. In addition, the type of battery (Plug-in Hybrid Electric Vehicles (PHEV), Hybrid Electric Vehicle (HEV), EV) plays a key role since the conditions of use during their first life can differ significantly. The comparison of both price trends is a key factor for the success of reusing batteries since it will not only be ecologically attractive but also economically. In the end, it is the end-user who will decide whether to go for a new battery or a reused one.

Over the last few years, the price of new EV lithium-ion batteries for traction purposes has continuously decreased. Starting from over 600 €/kWh in 2010 to around 270 €/kWh in 2015 the trend is going towards a price lower than 100 €/kWh in upcoming years (costs related to full pack level). This is on one hand caused by an increasing number of batteries sold for EVs (200 GWh in 2020 to a forecasted sales number of around 500 GWh in 2025). On the other hand, improved manufacturing processes further drive cost reduction. Considering this price trend, the accumulated costs for any kind of reused batteries must not be higher than these forecasted costs to ensure attractiveness [38,39].

Nonetheless, these prices for EV batteries are not applicable in stationary applications basically because the replicability of any battery model does not reach the numbers in EVs. In fact, for EVs, there is normally a close contract between the EV and one specific battery manufacturer, in which a single battery design is used on a large number of vehicles. However, this is not the case in stationary applications where almost every application has different requirements and, thus, even in the case of using the same cell/modules, the overall packaging and BMS should be adapted, with the corresponding cost increase. The prices of producing fresh new batteries, regardless of the chemistry considered, for stationary applications ranged from 294 €/kWh to 880 €/kWh in 2016 and are expected to cost, by 2030, between 122 and 480 €/kWh [40,41]. These three-time higher prices make them not yet competitive and EV battery reuse costs should be compared to those in this field and not with those in EVs.

To have a calculation as close as possible to the reality of what EV batteries cost in a second-life use, it is necessary to consider aspects such as the variation of the price of these as the market grows, the consideration that these can be used in other applications, or the complete or partial recyclability that reduces the consumption of raw materials for their manufacture.

In fact, the economic model to analyse should take into account three possible revenue paths for EV batteries: remanufacturing (selling price), second life of batteries (revenues from applications) and recycling [42].

Literature states that the cost of second-life adaptation of EV batteries ranges from 30 € to 300 €/kWh depending on the strategy and automatization. The first analysis done in 2012, designing a repurposing factory, presented a lower-optimistic cost of 38 $/kWh and an expected cost of 132 €/kWh [43]. Similar approaches regarding the remanufacture process but with less automatization and two type of processes presented for direct reuse or remanufacturing costs ranged from 87 €/kWh to 240 €/kWh and discarded the use of PHEV batteries for economic and SOH issues [44]. Since then, these initial values have not changed much over time, recent studies state that the EV battery dismantling costs are 32 €/kWh for the direct battery reuse strategy (extracting the battery from the vehicle and testing its status), 60 €/kWh for the module dismantling and 72 €/kWh when reaching the cell level [27], which is in line with what Janota et al., indicate [45]. Since direct reuse of a battery without significant efforts in remanufacturing can be considered a rare case, it is reasonable to add costs for remanufacturing and adaptation costs. Moreover, costs for the logistic efforts (like transport) need to be considered. Including this, a more sensible selling price to consider for a 2nd life battery is in the range of 50 to 150 €/kWh, depending on the maturity of second-life treatment strategies. These prices are just a little lower than for fresh EV batteries, but about five times the price for fresh batteries designed for stationary applications.

For these battery prices, the economic return from second-life selling estimation is around 30 €/kWh in 2030, mainly due to the reduction in manufacturing costs due to the growth in demand and availability of EV batteries, among other factors [42].

From a second-life point of view, it is necessary to undertake a proper study of the ageing of the battery where it is going to be installed as well as an economic study since this will determine whether the application is profitable or not. Literature indicates that second-life battery applications do provide positive results in economic terms, however, they are not that exciting, having long payback periods (>5 years) and small return on investments [27]. These results are even worse for fresh new batteries, where numbers are not positive for LIB, and this is the reason why few of them are being currently installed.

Finally, this same study [42] indicates that the recycling process is characterised by a high initial investment cost. This scenario has a turning point from 2021 onwards, mainly due to the increase in sales of EVs and their improved battery performance. Consequently, economic returns are expected to be relatively constant and close to 50 €/kWh since 2025.

Considering the aforementioned production prices of batteries for EVs, coupled with the economic returns from using second-life strategies in addition to recycling, makes circular economy schemes attractive. In fact, if the circular economy of EV batteries becomes a reality, car manufacturers could decide to reduce the EV battery selling price counting on these economic returns, which would reduce by half the cost of batteries and make EV affordable to most end-user budgets.

In this sense, and making use of the assumptions made in the economic evaluation carried out in the work of [42], a strategy to consolidate a circular economy is to adapt the facilities for both recycling and testing batteries once they have finished their use in EVs in those places where there is a majority market for EVs. Considering this, China, Europe and the United States of America (USA) would be good candidates for the implementation of such infrastructures.

The annual report on EVs [11] mentions that throughout the 2020s they want to create a global EV pilot programme, which the main objective is the interconnection of 100 cities around the world to collaborate in achieving total electric mobility through the exchange of information for the best and fastest adaptation. Until now, there are 41 cities included in this initiative. Given that these cities have this initiative to electrify their mobility, it is interesting to take advantage of the facilities they will make use of as a source of battery collection for later use and recycling, and to propose testing and recycling infrastructure in their vicinity.

## 5. Life-Cycle Analysis (LCA) Impact

As the EV was launched with an ecological intention, as it has no tailpipe emissions [46], scientists in the environmental field began to compare how effective this new technology was in contrast to the common ICEV. To do so, LCA is the tool that has generally been used to analyse the environmental impact of products.

The LCA methodology is very effective for this purpose but has some issues that make it particular for the case of EVs. In general terms, the LCA has several phases for the analysis. The first one is the extraction phase, which analyses the environmental impact of acquiring raw materials. Then, there is the manufacturing phase, where the environmental impact concerning the process to build the product is computed. This is followed by the use phase when the LCA computes the environmental impact of the product while it is used by the owner or operator. Finally, the recovery and recycling phases close the circle.

If the LCA scope of the analysis considers just before the use phase, it is named a cradle-to-gate analysis. For the case of EVs, in which it is during the use phase that most of the benefits are obtained, this kind of studies are only relevant to compare between different battery technologies [47]. EVs are always worse than ICEVs. On the other hand, if the analysis considers the whole circle, the study is named cradle-to-cradle. Most current EV studies use this complete approach [48].

However, for the EV, the impact during the use phase is highly influenced by two boundary conditions: the origin of the production of electricity to charge the EV and the total mileage the EV can do during its lifetime. The introduction has already clarified the impact of the electricity source, but the mileage remains unclear. It is obvious that the longer the distance the vehicle runs, the higher its overall environmental impact during the use phase. However, the mileage of an EV is tied to the battery it has and its ageing. Therefore, again, the battery size has an important effect on the performance of the EV, this time concerning the environmental impact (in both the manufacturing phase, as more material is needed, and in the use phase as they last longer and mileage increases).

The smaller dimensions of the first EVs did not allow LCAs to go further than 100,000 to 150,000 km during the use phase without counting for a battery replacement [49]. However, as batteries grew bigger, this limit was increasingly less relevant and, nowadays, most LCA work beyond 200,000 km and comparisons to ICEVs can be made without any special intervention (such as the previous battery replacement or forcing premature EoL of ICEVs at low mileage) to see when the higher impact of EV battery manufacture is counteracted by the use phase's lower impact [50,51].

Taking all this into account, a valuable functional unit (FU) is needed for a proper comparison between LCA. Nowadays, most LCA use one-driven (1) km as a functional unit [52]. With this unit, it is possible to compare different EVs and ICEVs including the use and retirement phases.

However, this FU is not enough when the picture gets more complex in the circular economy context with the addition of the 2nd life re-manufacture and use phase, as batteries are still active (and thus polluting) but the mileage of the vehicle is maintained. This new stage is stated differently by several authors, but there is as yet no agreement on how to deal with it.

For instance, some studies just analyse the impact of repurposed batteries and compare it with the impact of using new batteries using the energy exchange per year as FU [53]. This approach is partially valid because the comparison is somehow unrealistic. It concludes that there is a benefit because re-using EV batteries has a lower impact than using fresh batteries and this benefit can be partially distributed to the 1st life of the vehicle. But this conclusion is not true due to the fact that, as stated in Section 4, fresh new batteries are still too expensive to be profitable in stationary applications. Therefore, the supposed environmental benefit is contrasted against something that does not occur and, consequently, there is no such benefit. For this reason, the approaches of subtracting any environmental benefit from battery reuse are, somehow, misleading.

Other studies use time or battery equivalent cycles [54], which would work for both first- and second-life analysis. However, depending on the battery capacity, one cycle has more or less energy exchange and, consequently, more or less environmental impact.

Now, the FU that is equal for both first and second lives of EVs and that does not change depending on the battery characteristics is 1 kWh of the total energy provided over the service life of the battery (measured in kWh). This is what should be used in all LCA if comprehensive comparisons are expected. This FU is aligned with the indications of the advanced Researchable and Lithium Batteries Association [55].

Finally, one should take into consideration that the second life of batteries is not something repetitive like recycling, where there are somehow several defined processes that any company might follow. On the contrary, there are as many second-life applications as one can imagine. On the one hand there are the general possibilities to reuse batteries explained in Section 1. But then there is the scale of such applications, as the same concepts might apply for the grid management, industry, tertiary or even residential buildings, and in each case, there are even infinite configurations depending on the specificities of each situation. Then, again, there is the source of the electricity that seriously affects the final result of the LCA. These multiples variabilities, comprehensively stated in [56] and in [57], make difficult the replication of the results from one LCA to another. This brings us to the point that it is almost impossible to use a general strategy to introduce the second life of batteries into LCA without doing effective studies in each case.

## 6. Discussion and Future Recommendations

As explained within the present work, the increase of EV battery units and their capacity in coming years will pose an environmental challenge that will have to be dealt with by approaching reuse and recycling strategies. To do so, the first step is to identify whether the battery is in a reusable or recycling state. This can be done by following two logical steps (maybe in combination in some cases), (a) identifying battery source i.e., regular used or damaged vehicle, and (b) battery testing like visually, electrically, mechanically etc. The need for such steps is, for example, if the EV had a major accident and the battery is leaking, then there would be no sense in carrying out any further testing as it will be obvious that such battery would be non-reliable and possibly unsafe to reuse i.e., it should be taken directly for recycling safely. To ease the transport of such batteries, if possible, it is beneficial to not only remove the battery from the EV but also the battery components should be dismantled onsite or at some possible quarantine area [22], so that this would be safe and not require a specific type of transport i.e., a vehicle having features for transporting batteries within a specific battery container, as per the Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) rules. Such onsite dismantled batteries can be only recycled at the recycling facility.

On the other hand, if the battery is from a regular used vehicle, then further tests, such as those mentioned in Table 1 can be done to make sure that the battery has some life left and that it is working fine and safely.

**Table 1.** Generic tests to reuse the battery.

| Inspection/Test Categories | Type of Inspections/Tests | Influence on Safety | Risk Impact [1] |
|---|---|---|---|
| Visual | Swelling of modules or cells | Medium | Medium/Low |
| | Corrosion of connectors | Medium/Low | Low |
| | Intrusion of water and dust | High | Medium |
| | Loose cables and connections | Medium | Medium/Low |
| | Production date is available | Low | Not Applicable (N/A) |
| Electrical and Mechanical | Internal resistance | Low | High/Medium |
| | Measured discharge capacity | Low | High |
| | Insulation resistance | High | Medium |
| | Potential equalisation | Medium | Medium/Low |
| | State of Charge (SOC) range as per datasheet | High | High |
| Battery Management System (BMS) | Remaining useful capacity | Low | High |
| | Direct Current (DC) resistance | Low | High/Medium |
| | On board State of Health (SOH) | Low | High |

[1] Evaluation factor for battery reuse (High to Low = impact on battery reuse).

As mentioned in Section 1, there are multiple scenarios in which batteries could be reused after their first life. Although the background of these batteries when dealing with their second-life application is of enormous importance in terms of both safety and functionality issues, their reuse represents an opportunity to increase their lifetime until their full operational life is completed. In addition, added value approaches within a battery unit, such as a combination of different SOH batteries, chemistries and technologies (e.g., super-caps) solve heterogeneities in the vast pool of batteries acceptable for reuse while providing both fast and continuous responses requested by the application that batteries themselves cannot supply.

Life enlargement sometimes applied to batteries beyond their 70% SOH limit marked by car manufacturers, avoids the need for very expensive new battery manufacturing processes thus reducing costs and the potential environmental burden simultaneously. This scenario indeed places Europe as one of the top battery providers and producers for reuse worldwide since the continent is now dependent on raw materials for battery manufacturing. Nevertheless, direct reuse, although considered to be an option with the lowest associated cost, is the less adaptable solution due to stacking problems. In this scenario, new BMS and control systems might be implemented into a more versatile solution when the battery is dismantled to its module- and even to its cell-level and then reassembled. However, the cost rises due to logistics, transportation, manipulation, testing, possible automatizations, and the need for implementing completely new control systems at the cell, module, and battery levels.

When considering the option of recycling batteries, it is a fact that the recycling process is a cost- and energy-intensive process. The current standard recycling processes can yield Li up to 60% from old batteries. From the overall battery point of view, 70% of emission and energy consumption can be reduced by extracting the materials and components from the old battery and manufacturing a new one. This overall percentage can be increased up to 91% by following a typical combination of mechanical and hydrometallurgical recycling processes. However, such a combined process is energy-intensive and so further research is underway at a laboratory scale where supercritical carbon dioxide can be used to extract electrolyte and thereafter other components can be extracted easily.

The European Circular Economy Action Plan [58] is aiming to establish a new regulatory framework around batteries that facilitates the increased reuse (rechargeability) of batteries, recovery of valuable materials, recycling of batteries, and use of recycled content.

There is a variety of factors such as warranty, reliability, service specification, and cost that influence the decision of reusing the battery. However, the most crucial factor for evaluating and comparing the benefits of reuse is the cost development of new batteries to be manufactured, which has decreased over the last few years (see Figure 2), and different reuse paths need to be investigated to identify possible economic savings for the end-user. To have close-to-reality second-life EV battery cost calculations, it is necessary to consider aspects such as the price variation versus the market or its recyclability beyond use that reduces raw materials consumption. The reuse of batteries is economically viable, but due to the high initial investment costs, the recycling option for low volumes cannot be considered economically beneficial. Nevertheless, battery reuse as a pre-recycling step will postpone the recyclability option by around 10 years and, consequently, obtaining more time to improve this path with cost reductions.

The most interested actor in following both recycle and re-use should be, above all, the one that may achieve a quick win from the vehicle's sale: the EV manufacturer. Other EV battery applications per se offer little economic interest.

To make Europe a global leader in sustainable battery production and use, the European Commission released the Strategic Action plan for the European Battery Alliance [59] that was developed in 2017 with the ambition of establishing a competitive and sustainable battery manufacturing industry in Europe operating within the context of a circular economy. The plan aimed at securing access to secondary raw materials through recycling and thus supporting the sustainability of the European battery cell manufacturing industry with the lowest environmental footprint possible.

A strategy to consolidate a circular economy is to adapt the facilities for both recycling and testing batteries once they have finished their use in EVs in those places where there is a majority market for EVs. For all the reasons explained in Section 5, environmental analysis for EVs should consider second-life batteries with a FU useful in both first and second lives, which is suggested to be 1 kWh of energy exchanged. However, these analyses should present the results in two formats, one for the FU itself and another one indicating the accumulated environmental impact throughout the whole battery's lifecycle. This is interesting because, when looking only at the FU, the environmental impact per kWh exchanged by the battery is reduced while its lifespan increases. Regardless, the overall impact is always higher when second life is considered, in comparison to first life. This bolsters the conclusion that applied to a first life battery, a benefit subtraction of its reuse may be a false comparative and is not a recommended strategy. Thus, non-standardized LCA studies must be carefully performed when dealing with second-life EV batteries.

## 7. Conclusions

The global EV market is significantly increasing and hence battery consumption as well. The challenge in the market is to find an optimal solution from two options, whether to recycle the battery after its first use in the EV or to re-use (second life). Looking at the battery reuse strategies, it was found that the benefits of battery re-use are not only expected to be in the second life applications but the remanufacturing process as well. Another aspect that was reviewed in this article is recycling. From this point of view, it is always logical to regain good precious materials after the end of life of a battery system. The idea of recycling is supported by both ecological as well as economic perspective.

Looking at the rate at which EVs are deployed in the market and coupling the concepts of reusing and recycling together, strategically this would form a circular economy. Once the infrastructure is developed for battery recovery for EVs, Europe's position can strengthen and it could become one of the largest battery manufacturers and exporters as well.

Finally, based on the literature available, a study on how LCA is implemented in EVs was conducted. To undertake this study both the concepts of battery end-of-life recycle and reuse were considered. The study found that it is almost impossible to develop a generalized approach for LCA impact based on the information that is currently available in the literature and market. There are multifarious aspects involved with each type of battery reuse application and the role of a second-life battery in the circular economy. Henceforth, there is a significant need for undertaking an effective in-depth analysis of each of the application areas of battery reuse and then consolidate such studies into the LCA impact analysis. Subsequently, this will give a true picture of selecting the correct approach (reuse or recycle) for EV battery EoL. Henceforth, considering the currently available recycling technologies, cost and LCA impact, it is safe to conclude that reusing the battery is a good option as it would delay the need for battery recycling and will also allow battery recycling companies to develop cost- and energy-efficient processes.

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