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Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries

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ABSTRACT

Electric vehicles (EVs) are massively entering the mobility services. However, the high costs of their batteries, and thus of the vehicles, represent a real barrier that refrain consumers from buying EVs. In order to reduce the EV costs, research on recovery battery to be reused in a second life for stationary use is being explored, as it this is expected to decrease the cost of these batteries (second life) is being considered for additional stationary uses. For this purpose, specific conditioning (disassembling and repurposing) activities on the battery need to be undertaken to enable a further use of Li-ion batteries once they have completed their duty life in a vehicle (first life). Since economy matters, the economic aspects of these activities need to be analysed to fully understand the economic feasibility of the second life as a key element to that will determine the success of the implementation of EVs. This paper investigates the current state of art of the disassembling activities by analysing the Smart ForFour Li-ion battery and provides insights of the costs of each disassembling operation, from battery level to cell level. Another key aspect will be the remanufacturing at battery level as it presents some advantages over either module or cell level such as a less time is required and consequently a fewer cost. On the other hand, the reuse at module level presents interesting advantages such as the chance to design more versatile and scalable solutions, which could be more interesting despite their initial drawbacks for many second life applications. Therefore, the disassembling costs will play an important role in the repurposed battery selling prices.

1. Introduction

According to the World Health Organization (WHO) every year 3 million deaths are linked to the exposition to outdoor air pollution. This figure is relevant above all if considering that 92% of the world's population lives in places where the concentration for $PM_{2.5}$ and other air pollutants exceed the WHO limits (WHO, 2018).

The European Parliament wants to counteract this phenomenon by the introduction of a new regulation which requiring a maximum emission ratio of 95 g/km of CO_2 to be accepted in those vehicles manufactured after 2020 that all vehicles manufactured after 2020 should emit less than 95 g/km of CO_2 and, for those manufactured in 2025, a maximum emission of 68–78 g/km (Benveniste et al., 2018). In order to meet these requirements, the European vehicles manufacturing industry is focusing its efforts to develop new vehicle models with lower pollutant emissions, and therefore, they are working on the electrical vehicles technology. In the whole life cycle, Greenhouse Gas (GHG) emissions in Europe of an electric vehicle are around 10–20% less than an Internal Combustion Engine Vehicle (ICEV) (Qiao et al., 2019). Furthermore, it must be considered that only the transportation sector produces around the 23% of the global CO2 emissions connected to energy (Habib et al., 2020)

For instance, the Electric Vehicles Initiative (EVI), which is an organisation that represents multiple countries, focuses its activities in supporting the penetration of the electric vehicle in the market to achieve at least, the 20 million units of EV. According to IEA, the electric vehicles stock for the countries associated to this organisation, in 2015 was 1,26 million. This value is 100 times larger than the figure estimated in 2010 by 2015 and it exceeds the barrier of 1 million EV (EVI, 2016). By 2020, the new target set by EVI is achieving 20 million EVs on the road, that would represent a share of 1,7% by 2020 (Ministerial, n.d.) and 30% by 2030 (IEA, 2019) of the total vehicles in

Abbreviations: BJB, Battery Junction Box; BMS, Battery Management System; CMC, Cell Module Controller; EoL, End of Life; EV, Electric Vehicle; EVI, Electric Vehicles Initiative; GHG, Greenhouse Gas; HV, High Voltage; ICEV, Internal Combustion Engine Vehicle; LV, Low Voltage; NCA, Nickel Cobalt Aluminium; NMC, Nickel Manganese Cobalt; PHEV, Plug-in Hybrid Electric Vehicle; PTC, Positive Temperature Coefficient; SOH, State of Health; WHO, World Health Organization

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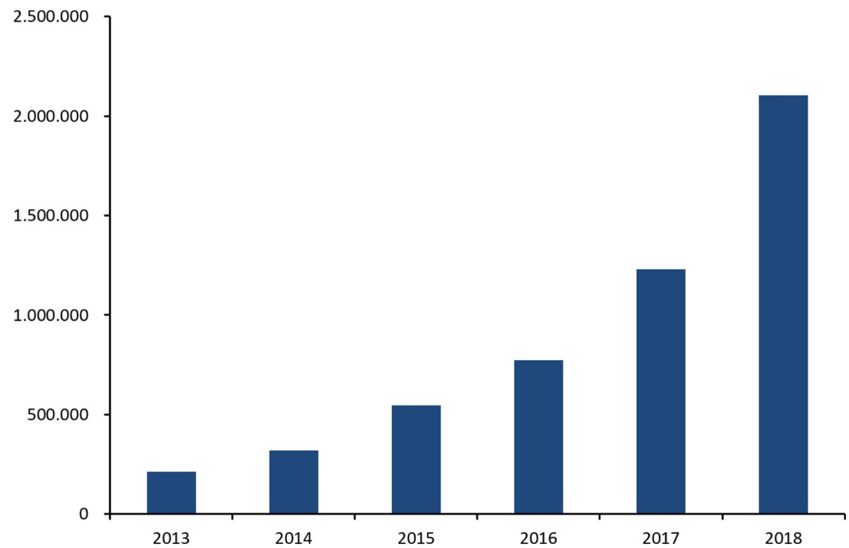

Fig. 1. PHEV + EV sales. worldwide (Irle et al., 2018).

the world. These share are forecasted to increase worldwide in the next years from the current 1.2 billion to around 2 billion by 2040 (Sioshansi and Webb, 2019). Updated statistics show that in 2018, the EV fleet was more than 5.1 million units that means up 2 million from 2017. China was the country with the world's largest EV fleet, just before Europe (mainly Norway) and the United States (Till Bunsen et al., 2019).

Some years ago, car buyers were still quite reluctant to purchase an electric vehicle (EV) (Hackbarth and Madlener, 2013), but this behaviour has changed lately as shown in Fig. 1, and the major concern of potential EV users is more centred to issues regarding the availability of EV charging stations and the final cost of the vehicle, this last one still higher than the cost of ICE vehicles despite the cost of Li-ion battery has decreased. (Agarwal, 2019).

Besides the driving range, final price is probably the main obstacle that EVs have to overcome if definitely wants to win the struggle to the ICEV, where the cost allocated to the production of the battery cost fabrication contributes from 30 to 40% to the final EV price (Canals Casals et al., 2015).

Another aspect that EV drivers consider as relevant is the battery operation life in the vehicle, around 6–8 years as indicated by the warranty of car manufacturers (Miao et al., 2019), compared to the total lifespan of the vehicle. When EV batteries lose 20% of their initial capacity during their first life in the vehicle, it is considered that they are no longer adequate for traction (Canals Casals et al., 2015). EV manufacturers suggest that when traction batteries lose between 20 and 30% of their State of Health (SOH) should be replaced as the EV could have issues regarding the driving capability (for instance shorter driving ranges or a decrease in the power outputs) or even safety problems that may lead to inadequate braking capabilities or loss in the battery storage capacity (University, 2019). Normally this loss of capacity occurs after 8 years or 160.000 km (Ahmadi et al., 2014).

That means that when the battery achieves 70–80% of its storage capacity, it shall be replaced. However, these batteries could be considered for other applications, mainly for stationary use (2nd life) where the capacity at this level is not a limiting factor (Cusenza et al., 2019). For example, due to the high performance of those reused batteries, the telecommunications sector has emerged as one of the sectors most interested in the reuse them for being used in communication base stations (Yang et al., 2020).

For this purpose, specific batteries conditioning activities shall be undertaken to ensure their proper adaptation to their second life application and its correct performance in a stationary use, otherwise as is detailed by Alfaro-Algaba et al. those batteries could be a serious problem in the future (Alfaro-Algaba and Ramirez, 2020). For instance, several studies prove that EV batteries with 70–80% of their original capacity can still be utilized for secondary purpose basically in energy storage applications such as peak-shaving, load following, self-consumption, voltage support, energy arbitrage and others (Ahmadi et al., 2014; Bobba et al., 2018; Keeli and Sharma, 2012).

Li-ion batteries for EVs description

As a general rule, Li-ion batteries are energy storage systems based on the chemical reaction that occurs between electrodes (anode and cathode) being the lithium ions the charge carrier (Miao et al., 2019). Nowadays, it has been demonstrated that Li-ion batteries technology provides the most advanced systems to store and recharge energy (Deng, 2015). In fact, Li-ion technology clearly dominates the market of energy storage systems for electromobility. The following are examples of Li-ion battery types and most prominent technologies used in the market today (Instruments, 2019; Wang and Wu, 2017):

- **Lithium Nickel Manganese Cobalt Oxide ($Li(Ni_xMn_yCo_{1-x-y})O_2$)- LNMC**

  Most of the manufacturers such as Smart, Volkswagen, Nissan, Chevy, and BMW utilize these li-ion batteries which combine nickel and manganese, resulting in excellent thermal characteristics.

- **Lithium Nickel Cobalt Aluminium Oxide ($Li(Ni_xCo_yAl_{1-x-y})O_2$) –LNCAO**

  Tesla is the most known electric vehicle manufacturer that uses Lithium Nickel Cobalt Aluminium Oxide (NCA) batteries.

- **Lithium Cobalt Oxide ($LiCoO_2$- LCO) Batteries**

  Used by Tesla Roadster. These are high energy density batteries feature a high energy density and long-life cycle.

- **Lithium Manganese Oxide ($LiMn_2O_4$- LMO) batteries**

  This chemistry is used by several EV manufacturers that use the battery blended with lithium manganese cobalt oxide (NMC) to improve energy and durability.

- **Lithium Iron Phosphate ($LiFePO_4$- LFPO) batteries**

  Lithium Iron Phosphate batteries provide good energy density ratio as well as they are considered to accomplish to safety requirements and offer a good performance and thermal resistance. Feature efficient power-to-weight ratios, high safety features and a good thermal resistance.

Each of these types of batteries present different characteristics refereed to energy density, power, durability, thermal resistance and cost.

Li-ion batteries are made by connection different Li-ion cells in different configurations (parallel, series or combination of both). A module consists of multiple battery cells and batteries are then composed by multiple modules (battery pack). Capacities of the batteries may vary from 10 kWh from plug in hybrid vehicles to 80 kWh for full electric vehicles. Thus, the number of cells contained in each battery varies depending on the chosen capacity.

The classic configuration of a Li-ion cell consists of a cathode (positive electrode) and anode (negative electrode) and an electrolyte composed by lithium ions. Each electrode is isolated from each other using a separator.

The cost of a Li-ion battery is accounted considering their total capacity and is expressed in terms of €/kWh. Despite the current high costs of these batteries, it is expected that it can reach half of its cost by 2030 (Canals Casals and Amante García, 2016).

The use of Li-ion batteries is also adequate in several other applications apart from the vehicles, as they can be employed as Stationary Energy Storage Systems (SESS) and portable electronic devices with an increasing demand year after year. In fact, it is estimated that the demand of Li-ion batteries increases every year at a 14% rate (Drabik and Rizos, 2018). It is estimated that by 2030 the world demand of storage will be equal to 150 GW to be provided by batteries that will support the generation and consumption of electricity from renewable sources (Viswanathan et al., 2019)

In detail, EV and SESS market forecasts are:

- EV Market trends: though the Chinese and US market dominate the sales of EV, it is expected that 20% of the total amount of EV that are produced will be sold in Europe. It is predicted that 46.540 MWh capacity from EV Li-ion batteries will be available by 2030 while it might increase up to 215.200 MWh in 2040 (Busch, 2018).
- SESS Market trends: it has been accounted that up to December 2016, globally 1227 SESS projects where Li-ion batteries were employed that implied that the installed power achieved 1930 MW. The annual growth of projects that employed SESS using Li-ion technology is around 55%.

The effectiveness and success of the SESS are clearly determined by the economic evaluation of the projects and therefore, the market requires that the SESS systems provide reasonable capital cost and lifecycle cost. That implies that using a battery as energy storage technology can be efficient from an economic perspective as long as its cost is, at maximum, equal to the cost of electricity generating by conventional fossil-fuel based technology and available in the grid. Apart from that, SESS systems need to take into account that they should provide higher reliability, durability, and safety performance, together with a minimum shelf life (more than 15 years) and cycle life (e.g. up to 4000 deep cycles) (Martinez-Laserna et al., 2018).

Another aspect related to the expected increase of the number of Li-ion batteries in the market deals with the availability of raw material required for their production. Due to the nature of the chemical compounds and minerals employed in the chemistry composition of Li-ion batteries, as a general rule, extraction activities are taking place outside the EU.

In fact, South America reserves of lithium are calculated to cover up to 69% of the world total reserves (European Commission, 2018). The technology applied for the extraction of lithium in this region consists of a process where water rich in this lithium salt is pumped to the surface and then it evaporates, leaving the salt of lithium on the ground. This process requires a large amount of water that is extracted from the aquifers in zones where water availability is an issue due to its scarcity. Moreover, lithium extraction and beneficiation demand large amounts of energy. Besides the lithium, the use of cobalt as another raw material present in Li-ion batteries is on the focus, as its extraction activity, mainly in Democratic Republic of the Congo (which accounts for 65% of global cobalt supply) is seen as a driver for political and social instability in this country (Rodriguez, 2018).

Furthermore, the supply crunch is driving up prices for cobalt, which now fetches a mind-boggling $35.378 per ton, compared to $4.560 per ton for lithium (Benveniste et al., 2018).

Moreover, Li-ion batteries contain materials that are either considered as critical or are amongst the candidates classified as Critical Raw Materials (CRMs), as identified in the European Commission report (Godlewska and Grohol, 2017). Amongst these materials, again cobalt is considered one of the 27 CRMs, while lithium, nickel and aluminium are all within the candidate materials, due to their economic relevance and moderate scarcity.

The negative environmental effects of batteries production are predicted to increase with similar growth rates. Global production capacity of Li-ion cells increased by nearly 40% between 2014 and 2016, to reach 104 GWh for all applications. It could easily reach 273 GWh by 2021 (Mathieu, 2017).

Giving a second life to these batteries can be seen by car manufacturers as a two-fold opportunity: firstly, to open a new business line (either exploited by themselves or by third parties) where the benefits could directly impact on the price of the battery, and therefore reduce the selling price of the EV. Secondly, to be capable to respond to the environmental issues related with their use. Some authors like as Alfaro-Algaba et al. considerer the re-manufacturing process of those batteries the best option contemplating the whole EoL (End of Life) process from an economic and environmental point of view. (Alfaro-Algaba and Ramirez, 2020).

From an environmental perspective, the Circular Economy Package from the European Commission clearly reports the that the reparability, upgradability, durability, and recyclability of products is one of the major targets to implement a circular economy.' (Ruiz and Di Persio, 2018). Therefore, the re-use of EV batteries enters within this target.

Industrial private research has already demonstrated that the reuse of these batteries from a theoretical technical point of view in stationary applications is possible. However, there is little research on evaluate from an economic perspective the activities that are required to adapt the batteries from the 1st to the 2nd life. In fact, the cost of reconditioning Li-ion batteries is a relevant aspect to be considered and deserving special attention. (Neubauer et al., 2015)

This paper investigates the current state of art of these conditioning activities and provides insight on the economic aspects related to these operations to illustrate the potential economic benefits derived from the use in a second life of EV Li-ion batteries. The specific case study regarding the adaptation activities of the battery from the Smart ForFour vehicle is reported.

For this purpose, this study aims at reply at the following questions: which are the required repurposing operations (adaptation) to re-use automotive batteries into a stationary application? What is the cost associated to these activities?

To reply to these questions, an exhaustive empirical analysis of potential disassembly activities on the Smart ForFour battery has been executed, from battery to cell, and the cost of each step has been calculated.

2. Materials and methods

With the aim of replying to the above-mentioned questions related to the re-use of Li-ion automotive batteries, an advanced research work was conducted using the disassembly of the Smart ForFour battery (see

Energy	17,6 kWh	**Capacity**	52 Ah
Voltage	339 V	**Modules**	3
Cell configuration	96s1p	**Weight**	169 kg
Cooling	Liquid	**Range**	90 km

Fig. 2. Smart ForFour battery overview.

Fig. 2). To achieve this objective, the battery was submitted to a full disassembly process (explained in the conditioning activities section), from battery to cell and the account in terms of time and cost of each operation was registered. This process is extremely important because regardless of the second use of the battery, the disassembly is an inevitable process (Alfaro-Algaba and Ramirez, 2020), together with a proper and specific testing in each case (Bobba et al., 2019) due to it has to be ensured the good performance of those batteries as if they were new (Morseletto, 2020).

The disassembling process has been carried out at Universitat Politècnica de Catalunya - Barcelona TECH facilities, during the year 2019. This process has been done manually as nowadays no automatization of the process is available due to the non-standardization of the batteries packaging. In fact, the standardization of the batteries evaluation process is object of further interesting studies as indicated by Ruiz and Di Persio, but this is out of the scope of the present study. (Ruiz and Di Persio, 2018).

To evaluate the economic aspects of the disassembling, labour cost and time has been accounted using the following assumptions:

- Engineer labour cost = 50 €/hour (eurostat Statistics, 2019)
- Facilities costs have not been included
- Machinery nor electricity cost has been considered as they are considered as standard hand tools with minimal consumptions.
- The appropriate work safety conditions tools have been employed following the regulation no 100 of the Economic Commission for Europe of the United Nations (UNECE) ((UNECE), 2019).

Conditioning activities

Fig. 3 shows the complete life cycle of an electric car battery from the extraction of materials until it is recycled. In addition, the disassembling process has been divided into the four following parts:

A Removing the battery from car
B Post-auto battery assessment
C Disassembly battery to modules
D Disassembly module to cells

The process can change depending on which level of disassembly is needed to reuse the battery and to better suit the new application, as a second life. This differentiation replies to the concern regarding the potential second life application of the battery, that is re-use the battery as it is, re-use only certain modules of the battery or re-use only certain cells of the battery (for instance, for small traction applications such as e-skates)(Canals Casals and Amante García, 2016). The analysis of the repurposing operations has not been assessed in this paper due to its evaluations are already well known since many authors have investigated on this topic (Melin and Storage, 2019).

A Removing the battery from car

The first step of the disassembling consists of removing the battery from the car. This section explains in detail through five steps the process that has been carried out for the removing of the battery from de car, as it can be seen in Fig. 4.

1 Vehicle preparation

The vehicle was put on Neutral mode (no gear is engaged) (N-mode) instead of Park mode (P-mode) so that it could be dragged after the traction battery is removed, and the key was removed from the contact.

1 Disconnection of service disconnect or LV battery

The first step to guarantee electrical safety was to disconnect the HV battery by means of the service disconnect (manually disconnect the high voltage battery). Since it was not available or not identified, the LV battery had to be disconnected instead.
After the disconnection of the LV battery, the HV battery kept the LV electric systems on through the DC/DC converter. The car had to be switched to P-mode to stop it. After removing the HV battery, the LV battery was connected again to switch the car back to N-mode.

1 Opening of trunk base

The base of the trunk is a removable plastic cover. Under this cover, the power electronics and the rear traction motor are located. The trunk base was therefore opened to reach the power electronics system.

1 Opening of underside vehicle covers

With one elevator, the underside of the car could be accessed. There were three plastic covers on the underside of the vehicle, the middle one covered the HV battery.
Under the back cover, the HV wiring connecting the control electronics, the DC/DC and the electric motor to the HV battery and the Positive Temperature Coefficient (PTC) heater were located. The cables to the PTC heater went between the top of the HV battery and the platform of the vehicle. A cross-shaped structure reinforced this empty section of the underside of the car against impacts or crashes. Without the back cover, the battery connectors were visible and accessible. The service disconnect of the HV battery was also accessible after the removal of this cover and under its own foam cover. Fig. 5 shows the voltage measurement of the battery before being disassembled.
The removal of the service disconnected interrupted the HV pilot line, but did not divide the voltage of the HV battery, so it opened the HV power line just before the HV connector. No special tools were required to remove the service disconnect and direct contact to non-safe voltage (>60 V DC) ((UNECE), 2019) is easy to access. The removal of the front cover exposed, in addition to others, the HV battery heater, the grounding cables of the HV battery, and the input and output of the HV battery cooling system.
The HV battery heater was right beside the HV battery. The HV battery had two grounding cables, one on every side; both had to be disconnected for the removal of the HV battery. Also on the front side of the HV battery, the pipes of the cooling circuit had to be blocked (to avoid leakage of coolant) and disconnected, then the

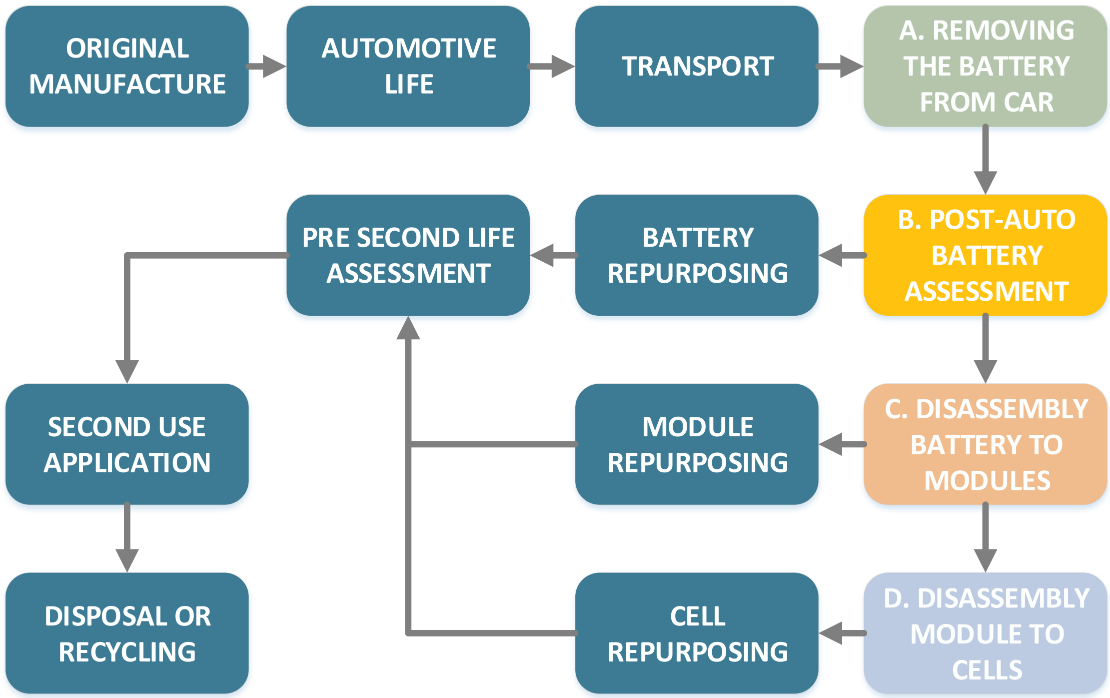

Fig. 3. Battery life cycle and key analysis steps.

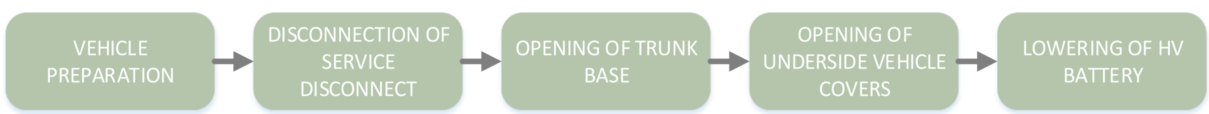

Fig. 4. Process of disassembling the battery from de car.

coolant in the HV battery can be drained. The middle cover is that of the HV battery. The removal of this cover exposed the cooling system on the underside of the HV battery; it consisted of two cooling plates attached to the bottom of the battery package.

1 **Lowering of HV battery**

A lifting platform was used to lower the HV battery from the vehicle. The HV battery rested on a frame secured to the underside of the vehicle. Once the HV battery was safely positioned on the lifting platform, its fixings (6XM18 external hexagonal screws, 3 per side) were removed and the HV battery is lowered. Once the HV battery was removed, the cables over it were accessible.

A **Post-auto battery assessment**

This section explains in detail the process of the assessment of the battery once it was removed from the car. The purpose of this post battery assessment is to verify that the batteries conform the necessary specifications for giving to them a second life.

In contrast to the testing necessary before launching the battery to the market during its first life, the assessment before the second life will be less exacting considering no destructive testing (such as thermal runaway test, over-charge and over-release test) will be applied to the second life batteries because otherwise those batteries to be reused would be destroyed. It must also be taken into account that those batteries will have very different origins, so their SOH and condition will also be very different. Consequently no destructive testing of such

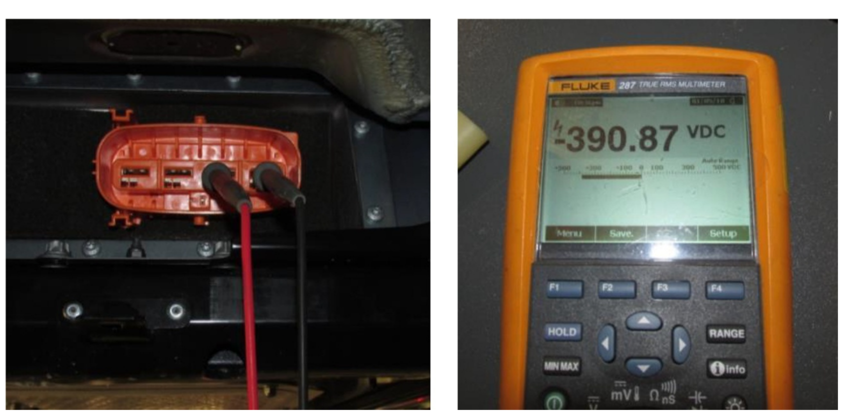

Fig. 5. Battery voltage measurement before being disassembled.

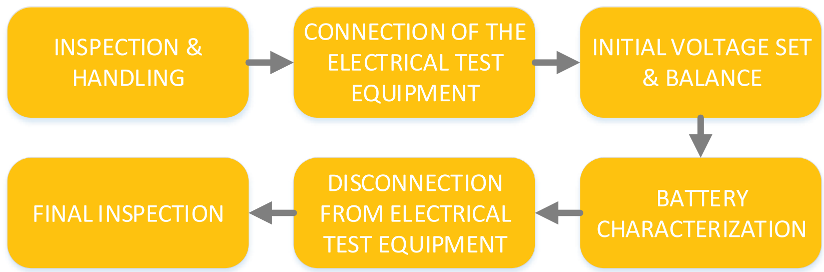

Fig. 6. Process of post-auto battery assessment.

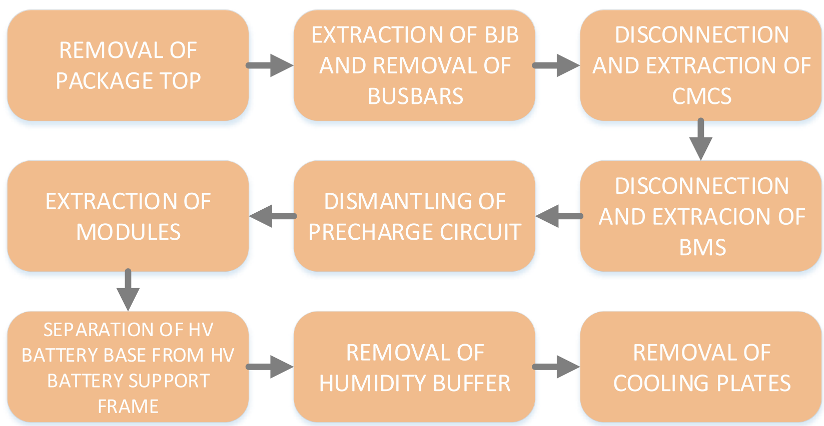

Fig. 7. Process of disassembly battery to modules.

sampling would be representative of the batteries' performance. The safety in this case is already proven since all those batteries have already passed demanding approval tests before being used in a car. As a consequence of that, the assessment will be performed is the necessary to guarantee during the entire second life the perfect performance of those batteries under standard the security requirements. Fig. 6 proposes the necessary tests to be carried out in a total of six steps.

The battery assessment, regardless of the use the battery will have in its second life, is mandatory to determine the current state of the battery. After this point, the battery can be reused directly, or will be disassembled into modules.

1 **Inspection and handling**

Visual inspection of the battery. Check that there is no damaged part and that the following steps can be carried out. All the external damages are checked. As indicated by Q. Liao et al. those batteries that have been retired as bulge, weeping and pocking are not suitable for reusing and they should be disassembled for a further recycling and recovery of materials (Liao et al., 2017).

1 **Connection of the electrical test equipment**

The battery was connected to a battery testing system.

1 **Initial voltage set and balance**

The battery was charged and discharged for the first time to check its condition.

1 **Battery characterization**

A complete characterization of the battery was performed. First of all, the battery capacity was determined. Charge and discharge measurements at constant current were necessary using KRATZER battery test (KRATZER, 2019). Following, pulse discharge/charge test was performed. Furthermore, in this step the (state-of-health-SOH) and the internal resistance of the battery were checked.
In addition, performance tests were made according to the requirements of the use that will be given to this battery in its second life.

1 **Disconnection from electrical test equipment**

The battery was disconnected to the battery testing system.

1 **Final inspection**

After all the tests explained above, a final visual inspection was performed to ensure that the battery is optimal to give it a second life.

A **Disassembly battery to modules**

Once the battery has passed all the tests proposed in the post-auto battery assessment, this section explains in detail the process of disassembling the battery up to the modules. As it can be seen in Fig. 7, the process is divided in nine steps. In the Fig. 8 the parts of the battery that will be disassembled in this stage are shown.

1 **Removal of package top**

The top and bottom cables of the HV battery enclosure are held together by 31xM14 6-lobe external screws (12 on the front, 11 on the back, and 4 on every side) and 52 M8 external hexagonal nuts (17 on the front and the back, and 9 on every side). On the back, two centralizers help on the positioning of the top enclosure. Only screws and nuts hold the two halves of the HV battery enclosure

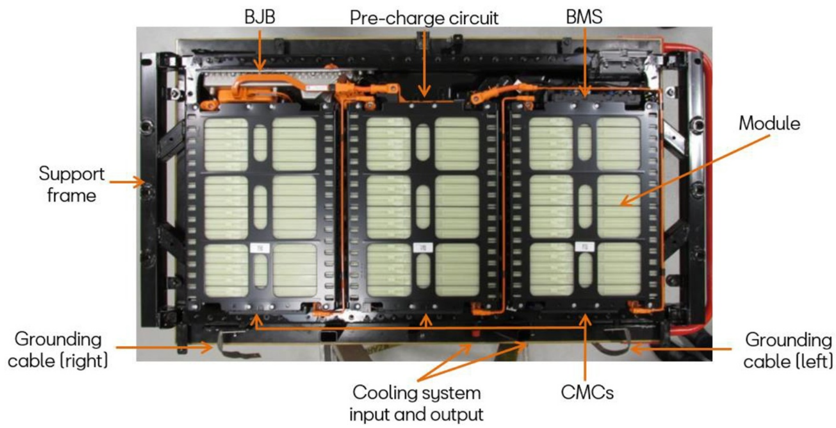

Fig. 8. Battery parts.

together – there is no glue.
The removal of the package top exposed three cell modules connected in series, there CMCs, the Battery Junction Box (BJB), the BMS and the pre-charge circuit.

1 **Extraction of BJB**

The BJB (HV+ and HV− relays) are attached to the metallic base of the service disconnect and power connectors. The removal of the BJB required its disconnection from the HV+ and HV− contacts of the battery (both extremes of the series connection of the three modules) and from low voltage wiring. The three modules were connected in series by means busbars. The busbars were removed.

1 **Disconnection and extraction of CMCs**

Each module had its own CMC (Cell Module Controller). After disconnecting their respective sensing and communication wiring, they could be unbolted and removed.
The voltage and temperature sensors of every module send their signals to their respective CMCs by means of the wiring on the side of the module.

1 **Disconnection and extraction of BMS**

After disconnecting all the communication wiring from the BMS, it was unbolted and removed.

1 **Dismantling of pre-charge circuit**

At this point the battery pre-charge circuit is disassembled.

1 **Extraction of modules**

The modules are bolted to the bottom of the battery package on both right and left sides. Under each module there is a layer of thermally-conductive paste.

1 **Separation of HV battery base from HV battery support frame**

At this point, the battery base was removed.

1 **Removal of humidity buffer**

At this point, the humidity buffer was removed.

1 **Removal of cooling plates**

The two cooling plates are bolted to the underside of the battery package. Between the plates and the package there was a layer of the same thermally-conductive paste found under the modules.

A **Disassembly module to cells**

The last disassembly step consists of disassembling the battery modules to cells. As it can be seen in Fig. 9, the process is divided in four steps. This process, although it is not dangerous because of the electrical voltage, requires a lot of precision in the work to be done because otherwise we run the risk of perforating the cells.

1 **Removal of top metallic structure**

Before their disassembly, modules were brought to a safe voltage (discharging modules bellow 60 V) ((UNECE), 2019). Every module consists on a metallic structure surrounding the plates that hold the cells.
The first step to disassemble the modules was to remove the rivets keeping the metallic external structure closed and the bolts fixing the metallic and plastic structures to each other. In order to remove the rivets, they were perforated with drills of progressively larger sizes until they weakened enough to be broken by prying. (See Fig. 10)

1 **Removal of sensor wiring and connectors**

On every side of the module, there are fixations for the wiring connecting the cell tabs (on both sides) and temperature sensor outputs (on one side only) to the CMC connector. The wiring fixations were unbolted and removed to expose the soldered terminals. .
To remove the wiring and its fixations without undoing the soldering of terminals, the wiring had to be cut off on both sides. (See Fig. 11)

1 **Removal of bottom metallic structure**

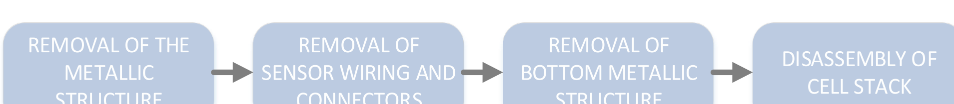

Fig. 9. Process of disassembly the module to cells.

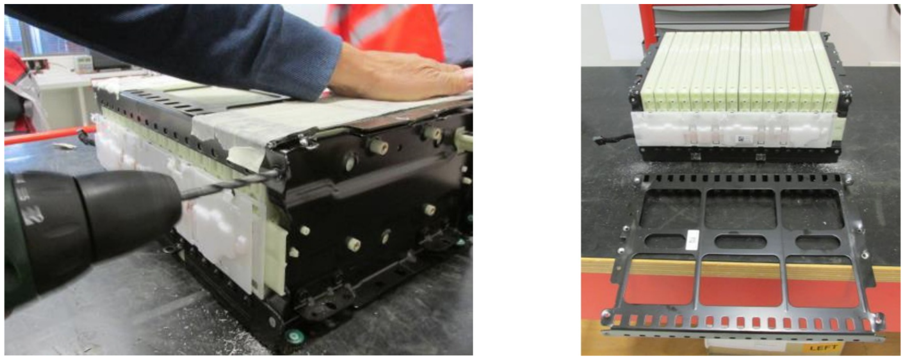

Fig. 10. Removal of the top metallic cover.

Once the wiring was removed, the last part of the external metallic structure could be removed as well.

Metallic plates are included in every cell carrier plate between cells for better heat dissipation. Their bottom is in direct contact with the thermally-conductive paste under every module.

The remaining part of the external metallic structure was removed in the same way as the first part: bolts are unbolted, and rivets are perforated with drills of progressively larger sizes until they weaken enough to be broken by prying.

1 **Disassembly of cell stack**

With the complete removal of the external metallic structure, the cell stack was exposed. The cell stack consists on a series of carrier plates. Every carrier plate houses two cells. In between plates there are three layers of isolating material – one is thick and two are thin. Cell tabs are soldered to each other in series connection.

There were three temperature sensing plates evenly distributed along the cell stack and placed in between plates in the same way as the isolating material layers. Cells were fixed to the carrier plates by means of adhesive tape. (See Fig. 12)

3. Results and discussion

This section presents the results obtained of the economic analysis for the complete process of disassembling the battery up the cell level.

Neubauer et al. reports that the cost of conditioning batteries after their useful life in the vehicle deserves special attention. They considered that those costs should be around 60$/kWh for being able to achieve economic profits giving to those batteries a second life (Neubauer et al., 2015).

Table 1 shows in detail, the human resources labour cost, the required time and the corresponding cost that each activity entails for each operation as described in Section 2. The most critical point in this section was the removal of all the vehicle covers due to required three people and 30 min which makes its cost four times higher than any of the other steps.

Table 2 shows in detail, the human resources labour time and the time needed for doing the post-auto battery assessment with the corresponding cost that this entails. It is easily observed how the characterization of the battery requires more time than any of the other processes. Anyway, this process is key to determine the state of the battery, and cannot be reduced in any case, which will make at this point we have our greatest expenditure of resources on any battery that can be analysed in the future as well.

Table 3 shows in detail, the human resources labour time and the time needed for disassembling the battery to modules. In this process the whole battery is disassembled and the three modules of which this battery consists are obtained.

Table 4 shows in detail, the human resources labour time and the time needed for disassembling the battery to modules. In this process only the disassembly of one of the three modules obtained in the previous step is considered. If you want to know the cost of dismantling the three modules, you only need to multiply the results of Table 4 by three. Note that all the sub processes of this stage have a very similar cost because it is a very manual procedure where it is very difficult to automate some parts.

Table 5 shows the cost comparison between the different levels of disassembly that we have carried out; battery, module or cell. As it can be seen, the cost at battery level is half the cost at module level. On the other hand, the cost at cell level increases by approximately 25% plus the cost at module level.

Tables above have reported the costs of each disassembly activity. As previously stated, this study considers the first half of the repurposing, the disassembly part only. Surprisingly, in this specific case, the module level and cell level disassembly cost is equal to or higher than that proposed by Neubauer et al. (Neubauer et al., 2015).

As outlined Neubauer et al., if the automotive and battery OEMs would include the possibility of on-board diagnostic capabilities to understand the capacity of the batteries and would agree to share this information with the companies responsible for battery repurposing it would be much faster and easier to determine if those batteries are valid

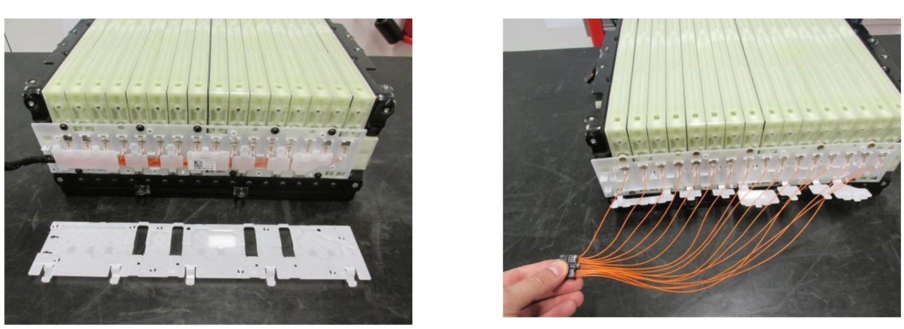

Fig. 11. Removal of sensor wiring and connectors.

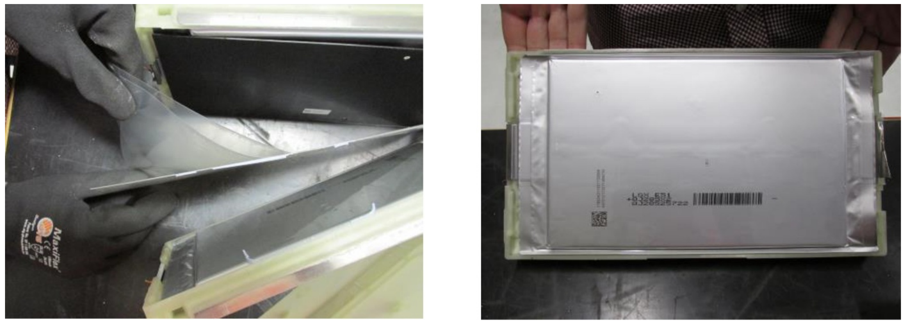

Fig. 12. a) Isolation between plates (three layers). b) Cell on plate.

Table 1
Resources for removing the battery from car.

		Human power	Time [minutes]	Cost [€]
Removing the battery from car	Vehicle preparation	1	5	4€
	Disconnection of service disconnect or LV battery	1	5	4€
	Opening of trunk base	2	10	17€
	Opening of underside vehicle covers	3	30	75€
	Lowering of HV battery	2	10	17€
	Total		**60**	**117€**

Table 2
Resources for the post-auto battery assessment .

		Human power	Time [minutes]	Cost [€]
Post-auto battery assessment	Inspection & handling	2	60	100€
	Connection of the electrical test equipment	2	10	17€
	Initial voltage set & balance	1	100	83€
	Battery characterization	1	250	208€
	Disconnection from electrical test equipment	2	10	17€
	Final inspection	2	10	17€
	Total		**440**	**442€**

Table 3
Resources for disassembling the battery to modules.

		Human power	Time [minutes]	Cost [€]
Disassembly battery to modules	Removal of package top	2	30	50€
	Extraction of BJB	2	45	75€
	Disconnection and extraction of CMCs	2	45	75€
	Disconnection and extraction of BMS	2	30	50€
	Dismantling of pre-charge circuit	2	30	50€
	Extraction of modules	2	60	100€
	Separation of HV battery base from HV battery support frame	2	20	33€
	Removal of humidity buffer	2	20	33€
	Removal of cooling plates	2	20	33€
	Total		**300**	**500€**

Table 4
Resources for disassembling the module to cells.

		Human power	Time [minutes]	Cost [€]
Disassembly module to cells	Removal of top metallic structure	2	60	100€
	Removal of sensor wiring and connectors	2	30	50€
	Removal of bottom metallic structure	2	45	75€
	Disassembly of cell stack	2	30	50€
	Total		**165**	**275€**

to give them a second life having a direct consequence in reducing the cost of post-auto battery assessment (Neubauer et al., 2015).

Apart from the cost differences explained above, following are some other interesting conclusions we have obtained by the completely disassembling of the Smart ForFour battery.

Batteries with fewer modules reduce the amount of components, consequently this means that the cost of disassembling is going to be much less although on the other hand these modules will have a voltage higher than 60 V and can only be handled by personnel accredited to work with HV systems.

Table 5
Battery, module and cell cost for the disassembly process

	Battery	Module	Cell
Removing the battery from car	117 €	117 €	117 €
Post battery assessment	442 €	442 €	442 €
Disassembly battery to modules		500 €	500 €
Disassembly module to cells			275 €
TOTAL	558 €	1.058 €	1.333 €
COST / kWh	32 €	60 €	76 €

One possible serious safety issue to take into account from the battery analysed is that the service disconnect can be reached and used with no need for special tools despite the fact that it gives access the whole voltage of the battery ($U > 60$ V, usage voltage).

The repurposing at battery level, apart from being more convenient and lower-priced than the other options, it presents additional advantages such as the chance to re-use the battery management system (BMS). However, this option presents some disadvantages. A big battery manipulation is required and this step implies complexity in terms of safety, machinery and ergonomic aspects. Furthermore, an additional electronic interface between the battery and the new applications would be required since the communication protocols that vehicles are different from the ones used in SESS.

At module level, more versatile and scalable solutions are possible with an easier connection to increase capacity and power. In this case, as the original BMS will not be used, although the cost of the final application will increase, an optimized BMS can be designed for such use and this will improve the operation of the SESS. The fact that fewer components of the original battery will be employed in this second life will imply lighter SESS. Seemingly as the reuse at battery level, the reuse at module level also has some drawbacks like more handling and preparation time, higher costs, the requirement of designing and manufacture a new cover for the SESS and more time for module diagnosis. Apart from the difficulty in obtaining modules with similar capacities for matched strings.

Therefore, whether a reuse is made at battery level or module level, it is important to find a balance between the repurposing costs and the versatility and the revenues of the different possible final solutions.

Even though the environmental aspects related to the second life were out of the scope of this study is interesting to highlight that although the cost increases together with the depth in the disassembly level, reaching a cell level disassembly will imply a higher recovery in materials. This recovery, apart from avoiding the extraction of new materials, can be interesting from an economic perspective as these can be introduced in a secondary market and therefore obtain additional economic incomes from their sell.

4. Conclusions

When the EV batteries have reached their end of life in the vehicle, they still have enough energy to be used in other applications as a Stationary Energy Storage Applications. Remanufacturing, repurposing and recycling are the three possible actions after that. In the present study has been studied in detail one of the most important process of the repurposing, the disassembly.

The Smart ForFour Li-ion battery was removed from the vehicle and disassembled, from battery level to cell level. For each operation, a registration of the required time, the required human resources were accounted to obtain the cost for each operation.

The disassembling process consists of at least two steps, removing the battery from car and the post-auto battery assessment. Disassembly battery to modules or disassembly module to cells will be also necessary in the case that a higher level of disassembly is required.

The operation with higher costs was the disassembly the battery to modules as it required 300 min and it costs 500€. Although, the post-auto battery assessment had a similar cost, 442€, while the time required is much bigger, 440 min, which means that process less steps and requires less manpower.

The depth of the level of the disassembly the battery determines directly the use of these in his second life considering that the reuse at module level increases the cost on 28€ and the reuse at cell on 44€ only seeing the disassembly process. Consequently, it can be stated that nowadays, only the repurposing of the whole battery would make sense in terms of economic profit. As it was highlighted by Alfaro-Algaba et al. the disassembly operation should end once the process reaches the disassembly state where the economic profitability is higher (Alfaro-Algaba and Ramirez, 2020).

Remanufacturing at battery level has some advantages over either module or cell level such as a less time is required and a fewer cost. Therefore, the disassembling costs will play an important role in the repurposed battery selling prices. On the other hand, the reuse at module level presents interesting advantages such as the chance to design more versatile and scalable solutions, which could be more interesting despite their initial drawbacks for many second life applications.

Another important remark to be considered is that the cost of disassembling batteries due to the large battery configurations as the ones that nowadays can be found in the automotive industry could make a significant change. Furthermore, the manufacturers efforts amongst standardizing the batteries that would lead to reach economies of scale that would help to overcome current obstacles in the next years.

In order to calculate the total cost of repurposing, to the disassembling costs, it will be necessary to calculate the all costs to adapt the reuse batteries to the new application. At this point, this study leaves an open line of research for a one future work.

Credit author statement

The corresponding author, Héctor Rallo Tolós, ensure that the whole article is agreed by all the authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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