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Battery second life: Hype, hope or reality? A critical review of the state of the art

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ABSTRACT

Lithium-ion battery elevated upfront cost is considered one of the major barriers hampering the mass market adoption of electric vehicles. In this context, second life use of electric vehicle batteries is one of the solutions explored by the academia and the industry to reduce electric vehicle upfront costs. Per se, the concept of giving a second life to electric vehicle batteries simply consists of reusing the batteries that do not meet any longer the requirements of automotive applications, but which could still be used on less-demanding grid-connected energy storage applications. The present paper reviews the most relevant publications in the field of Lithium-ion battery second life, from economic, technical and environmental perspectives. The main industrial and R&D projects are also described, and the most relevant commercial products available today are briefly reported. The conclusions from the consulted references are critically discussed at the end of each subsection, and, finally, overall conclusions and recommendations are presented.

1. Introduction

Society is increasingly more concerned about finding solutions that may contribute to the environmental sustainability of current industrial and socio-economic wealth standards. In fact, the transport sector is one of the main contributors to greenhouse gas emissions worldwide (among other pollutants with hazardous effects for climate and living beings) and electric vehicles (EV) are a promising solution to curtail such emissions. However, the high upfront cost of the batteries is still one of the major barriers for the mass market adoption of the EV [1,2].

Among several solutions considered to make EVs more affordable (e.g. up-scaling of battery production, new materials development for batteries with larger energy density, vehicle-to-grid etc.), battery second life has been considered a potential solution to generate new revenue streams that may produce upfront cost discounts for EV buyers. Indeed, it is widely considered that batteries that may not be useful any longer for automotive purposes might still provide a profitable operation on less-demanding applications.

The first approach to the topic of second life battery use was carried out by the U.S. Advanced Battery Consortium (USABC), where Pinsky et al. [3,4] studied the techno-economic viability of using second life NickelMetal Hydride (NiMH) EV batteries [3,4]. In Ref. [4], the performance of NiMH batteries retired from EVs were compared with that of new Lead-Acid (PbA) batteries, considering four different stationary target applications in the U.S. market (summarised in Table 3). Authors concluded that the considered second life NiMH batteries performed at least as well as new PbA batteries. The used EV batteries could even provide a similar performance as new PbA batteries over longer lifetimes for some scenarios. Few years later, Cready et al. also presented, for U.S. market conditions, a study of the costs from collection to reselling of the refurbished second life NiMH batteries [5]. In this study, transportation, testing and EV battery refurbishment costs issues were considered, as shown in Fig. 1. Although Cready et al. admitted uncertainties in their battery lifetime estimations, they claimed that the acquisition cost of the retired EV batteries and testing labours would represent *c.a.* 70% of the total second life battery costs. Four out of the eight analysed applications in this study were classified as favourable to be profitable when considering second life batteries as Energy Storage

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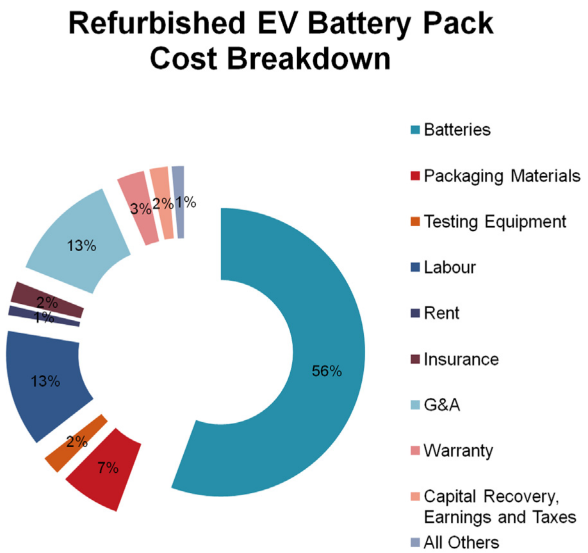

Fig. 1. Summary of the costs involved in the refurbishment of EV batteries from the collection to the selling [5].

System (ESS), Table 3. The applications with shortest battery lifetime estimations or largest system costs – second life battery purchase plus Balance of System (BOS) costs – are the ones considered unfavourable.

The two studies aforementioned established the baseline for further research on the techno-economic viability of battery second life use [4,5]. Global interest in the field of battery second life considerably increased along with the growing Lithium-ion (Li-ion) battery based EV market. According to a recently reported study by Bloomberg New Energy Finance, the global second life batteries market could reach 26 GWh by 2025. Such figures would represent almost one third of the total amount of batteries retired from EVs, *c.a.* 47% of the global Li-ion battery supply in 2015 [6] and *c.a.* 65% of the estimated global EV battery demand in 2016 [7]. The possibility of reusing such significant amount of batteries depicts a great opportunity not only for automotive industry but also for other industry players. Anyhow, economics and technical viability issues of reusing batteries retired from EVs still need to be addressed before such second life concept could be industrially adopted.

In order to provide a global overview of the background available in the literature, the present paper collects a thorough state of the art review, pointing out and comparing the main conclusions presented by the most recognised publications in the field of Li-ion battery second life. The paper is focused on the analysis of the economic, technical and environmental matters of battery second life. From the economic standpoint, the literature review performed aims at addressing the potential market price for second life batteries, and at evaluating whether it would be profitable to reuse retired EV batteries on certain stationary applications (with sufficient market to allocate a significant amount of second life batteries). Additionally, is also analysed to what extent this would imply any discounts for the EV owner. From the technical perspective, the results reported from several publications are analysed to evaluate the ageing performance, and the power and energy capabilities of second life batteries to fulfil the requirements of different stationary applications. Finally, the implications of a potential second life use upon the environmental footprint of the EV battery life cycle is also addressed, to conclude in which cases reusing such batteries would provide any environmental benefits.

The paper is structured as follows: in Section 2 the most relevant references in the literature are reviewed from an economic standpoint, while Section 3 provides a thorough review from a technical standpoint; Section 4 describes the environmental implications of second life battery use;in Section 5 an overview of the most important R&D projects and commercial products are summarised. In Section 6 the main conclusions and the main gaps in literature are presented.

2. The economic viability of reusing EV Li-Ion batteries in second life applications

The economic viability is one of the most important steps towards the industrial acceptance of second life batteries. The following open questions were identified in this regard, which will be tackled in the present section:

- Which should be the price for second life batteries to be competitive against new batteries?
- Is it profitable to integrate second life battery-based ESS in grid-connected applications?
- Has the market of stationary applications the potential to allocate all the batteries coming out from EVs in the upcoming years?
- Can second life batteries truly decrease EV upfront costs? By how much?
- Is it worth retiring the batteries prematurely from the EV to increase the profitability of their second life use?

2.1. Calculating the market price for second life batteries

Several publications in the literature have evaluated which should be the market price for second life batteries, considering the cost of battery purchase when retired from the EV, transportation costs, logistics, testing, refurbishment costs etc [8–11].

In 2010 Williams and Lipman [8] expanded the work developed in 2003 by Cready et al. [5], by including new applications defined by Eyer and Corey [12], as it can be observed in Table 3. Williams and Lipman considered the second life batteries of three different EVs and estimated an upfront base battery cost of 825 $/kWh and an additional cost of 100 $/kWh plus 1000 $ to capture Balance-of-System (BOS) costs [8]. Authors defined a maximum allowable second life battery price equal to the cost of a new battery (with the same characteristics) in the year in which the EV second life batteries would be installed in the stationary application. According to their estimations, the market price for a Second Life Battery Energy Storage System (SLBESS), including BOS costs, maintenance and installation would range from 1875 to 2040 $/kWh (depending on which of the three EVs was considered). From such market price, the costs of the second life battery pack alone (including cabling, casing, BMS, thermal management system etc.) would range from 111 to 248 $/kWh.

Despite the approach from Williams and Lipman was valid to estimate the market price of second life batteries, uncertainties were identified when calculating the purchase cost of such batteries (after being retired from the EV and prior to any refurbishment labours). Neubauer and Pesaran published a complete framework for estimating the purchase of second life batteries [9]. They estimated the battery salvage value S [$], when retired from the EV, considering the cost of a new battery C_n [$], discounted with a health factor K_h [-] and a used product discount factor K_u [-] minus the cost of refurbishment C_{rp} [$]. In this way, the salvage value is expressed as follows:

$$S = \max\,(K_u K_h C_n - C_{rp},\, C_{rc}) \quad (1)$$

The salvage value is the maximum of either the value appreciated when giving such batteries a second life, or when transferring them to recycling C_{rc} [$]. With respect to the health factor K_h [-], more recently Neubauer et al. [10] presented an updated calculation method, which defines the health coefficient as a ratio between the net present value of the energy throughput provided by new and used batteries (PVT_U and PVT_N [kWh], respectively) operating in the same application, on identical conditions: