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Battery Second Life: A Review of Challenges and Opportunities

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Summary

Electric vehicles contain lithium-ion batteries (LIBs) that tend to be both large and expensive, and these LIBs likely have significant storage capacity remaining when they can no longer meet the power and energy demands of a typical vehicle application. That remaining LIB capacity could provide a financial opportunity to many individuals and institutions along the possible value chain towards its eventual end-of-life. This could include vehicle owners, battery repurposers (those that collect, evaluate, and repackage used LIBs), battery second-life users (grid operators, businesses, hospitals, etc.), and, ultimately, battery recyclers (who recover valuable battery materials via physical, thermal, and chemical methods). This article reviews the present market of battery second life to identify current activities and challenges.

Keywords: Second-life battery, lithium battery, BEV (battery electric vehicle), PHEV (plug in hybrid electric vehicle)

1 Introduction

The vehicle market has seen a dramatic global increase in the number of electrified vehicles in the light duty vehicle (LDV) fleet [1]. While countries such as China have seen larger increases, the United States (U.S.) has experienced an increase in the market share of electrified vehicles or plug-in electric vehicles (PEV), including both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). Sales of PEV in the U.S. have increased from less than 20,000 in 2011 to more than 360,000 in 2018 [2]. Future transportation projections indicate that the penetration of PEV into the market will be both sustained and substantial: PEV sales in the U.S. are expected to increase by 700% between 2017 and 2030 [3].

These PEV are largely powered by lithium-ion batteries (LIBs) of various chemical compositions. The specific LIB chemistries have varied over time and global region, but the LDV market is currently dominated by those with cathode chemistries of nickel manganese cobalt (NMC) (in various proportions) and nickel cobalt aluminum (NCA) [1]. Other important chemistries have been lithium manganese oxide (LMO) batteries (the initial chemistry used in the Nissan LEAF) and lithium iron phosphate (LFP), which was used extensively in some vehicles deployed in China [2], [4]–[6]. In the U.S., many of these batteries have long-term warranties — some as long as eight years [7], [8]. These vehicle batteries will be long-lived in their initial application (i.e., these batteries will likely stay in the vehicle for at least the term of their warranty, if not longer), and it has been suggested that batteries will still have 70-80% of their energy capacity at the end of their first service life (i.e., in the vehicle) [9], [10]. This has motivated investigations into the second-life potential of LIBs.

Vehicle original equipment manufacturers (OEMs) have demonstrated the feasibility of such second-life applications, and many other organizations and researchers have investigated various potential second-life opportunities [10]–[14]. The remaining LIB capacity could provide a financial opportunity for many individuals and institutions along the possible value chain towards its eventual end-of-life. These could include vehicle owners, who could recover value through the sale of their vehicle; battery repurposers (those that collect, evaluate, and repackage used LIBs), who can resell batteries that will be suitable for second-life applications; battery second-life users (grid operators, businesses, hospitals, etc.), who can leverage these second-life batteries to provide a cost-saving or revenue-producing opportunity for themselves; and, ultimately, battery recyclers, who can recover valuable battery materials via physical, thermal, and chemical methods and then sell that recycled material into the market. In this article we describe the differences between battery refurbishment and remanufacturing and second life, we identify the current types of applications that are being investigated for battery second-life applications, and we highlight the challenges that may impede the proliferation of second-life applications into the market.

2 Lithium-Ion Batteries in Plug-in Vehicles

Electric vehicle batteries are complex power devices. As Fig. 1 shows, what is commonly referred to as a PEV's "battery" is actually a battery pack comprising a collection of battery modules, a battery management system (BMS), a thermal management system (which may be passive or active), and a safety structure (i.e., the packaging) [15]. The battery modules are in turn composed of a collection of battery cells and a housing. The cell is the smallest energy-containing unit of the entire device. The shape of the cells, modules, and packs can differ greatly from one battery pack to the next. In addition, the modules within a pack may themselves vary; i.e., multiple module shapes may exist within a single battery pack, often as a means of satisfying spatial limitations in a vehicle.

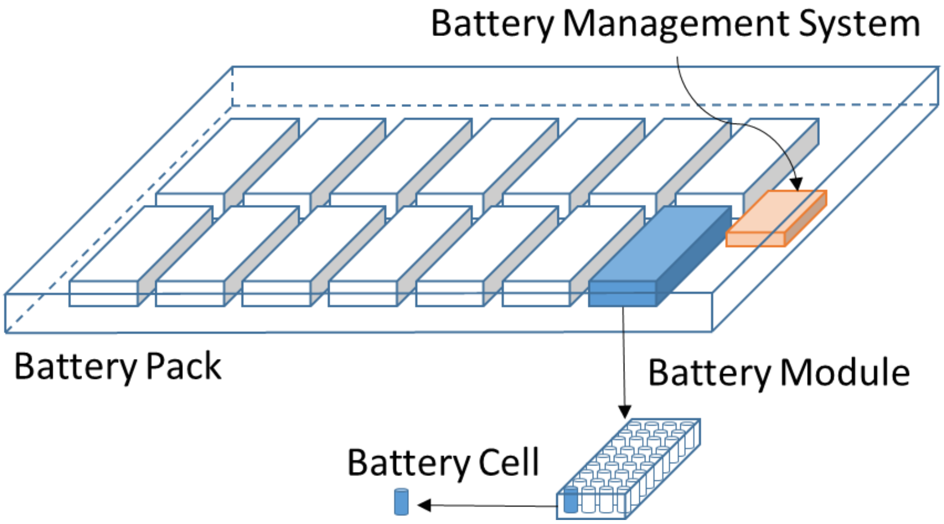

Figure1: Diagram of a battery pack showing its component elements.

The PEV battery is a complex device composed of many components, each of which has challenges that are then propagated downstream to yield a systems challenge. For instance, one must consider not only the way the battery cell degrades but also the way that single cell degradation affects module degradation, thereby impacting pack performance. The performance of the PEV battery pack is regulated by the BMS through its demands on individual battery modules. Understanding how these packs, modules, and cells degrade over time and throughout their use can provide important information for potential second-life application developers.

2.1 Degradation and Evaluation

During their lifetime, automotive LIBs will likely be driven in a variety of ways (e.g., city driving and highway driving), and in a variety of climatic conditions (e.g., cold, hot, humid, etc.), and they may remain inactive for periods of time in a garage or outdoors. All of those conditions serve to degrade the performance of the battery.

LIBs used in vehicles lose capacity in multiple ways. They will degrade over time due to calendar aging (aging due to the passage of time). This means that even if they are not in use, the batteries will experience some amount of capacity fade. Capacity fade is the reduction in available total battery energy. For example, over time, an LIB's total capacity may decline from 16 kWh to 14 kWh based only on the passage of time. Battery capacity reduction associated with calendar aging is strongly influenced by the state of charge (SOC) at which it is stored, with storage at 100% SOC causing an acceleration in degradation, and the temperature at which it is stored, with higher storage temperatures leading to increased degradation [16]–[18]. LIB capacity fade is also influenced by the way the battery is used, i.e., its cycling, with greater discharge depths causing increased capacity fade [16], [19]. Thus the primary mechanisms for battery capacity fade are the amount of time that the battery is used and the amount of capacity used at a time, with temperature and storage SOC also influencing those factors.

Battery degradation, typically observed as a reduced driving range, ultimately leads to a vehicle that no longer meets the demands of the vehicle owner. However, batteries may also underperform or fail for other reasons, such as a poor soldering joint or a faulty thermistor. If that underperformance happens while the vehicle is under warranty, then the OEM is responsible for servicing that vehicle battery for the consumer. This often entails a battery replacement for the consumer to remedy their immediate problem, but also means that the faulty LIB is then evaluated to determine whether it, or its component parts, can be repaired and put back into service. When the battery pack is removed from service, either due to a warranty issue or at the end of its service life, the modules within the pack can be evaluated to determine their remaining energy storage capacity. While it is technically feasible to fully disassemble an entire battery pack to evaluate and recover the cells, it is typical practice to evaluate these devices at the module level and not to disassemble to (or evaluate at) the cell level due to the complexity of and labor requirements for such a task. For example, some battery "modules" contain dozens of individual cells that are tightly packed and soldered together, sometimes even with an integrated cooling heat exchanger, and sometimes even further joined with an epoxy. Disassembling and testing each cell would be far too costly under those packaging conditions. Thus, the module typically becomes the smallest unit of evaluation.

The degree of variation in LIB pack form factor serves as an initial point of complexity for evaluating batteries once they reach the end of their first use, or when they must be evaluated for warranty purposes. Those performing this evaluation must first safely collect and disassemble the battery pack. Transportation of LIBs can be expensive, since these batteries must be shipped using the Class 9 Hazard designation [20]. This, in turn, requires regulated handling by trained individuals throughout the battery's shipment stages, adding cost. LIBs must then be evaluated, which requires disassembly; this can be a challenge since each vehicle model (sometimes variants within a model) will have a different LIB pack form, and there may be multiple module forms within a pack. This variance adds to the complexity and cost of the evaluation, since new processes must be developed for each vehicle model. What's more, some packs have active cooling (i.e., use a liquid coolant), while others do not, so fluid handling and line flushing create an additional challenge. Each new battery will require the development of unique policies and procedures for all stages of disassembly and evaluation, and they will likely require, if not unique evaluation line development, then at least the adaptation of an existing processing line. It is obvious that this variation presents a significant challenge, and a potential cost barrier, to those that collect and disassemble these battery packs.

When a vehicle LIB is dismantled and evaluated, its modules can be graded for their available energy capacity. Note that it is not necessarily required that the organization that dismantles the battery be the same one that evaluates the modules. There may be some benefit to specialization in the dismantling and evaluation tasks. Physical and electrical testing and evaluation can be used to "grade" the modules. Grading of the modules requires some knowledge of how well those modules currently perform. This could be a coupled process, in which information from the BMS may be used to complement in-house testing, or testing may be conducted independent of such data, which is often opaque to those except the LIB developers. Via testing, the battery evaluators can then provide a grade to each module based on their understanding of each battery's performance on multiple metrics. These grades allow the evaluator to direct these battery modules to their appropriate next stage.

The next stage of a battery module's life cycle will vary depending on its grade. Some modules may still meet the specifications for an automotive LIB, and those can then be remanufactured or refurbished. Those modules that will no longer satisfy a vehicle application can then be sent toward a second-life purpose. Those modules that are graded as not being capable of satisfying the needs of potential second-life applications can then be routed to recycling.

While grading battery modules is important in allowing LIBs to progress toward their appropriate next stage, it may limit the flow of battery modules into second-life applications (or delay their timing into them) since it may direct some modules into refurbished or remanufactured applications. Second life is distinct from refurbished or remanufactured LIB applications: In a "second life," the battery is not used in its originally intended application (an automobile) but is a LIB module (or pack) being used for a new purpose. The economic value of a refurbished or remanufactured automotive LIB application may be greater than that of a second-life application. If that is the case, there is a potential supply challenge for organizations that focus solely on second-life LIBs for their battery needs. Fig. 2 presents a diagram indicating a potential workflow for dismantling, evaluating, and routing an automotive LIB into its next stage.

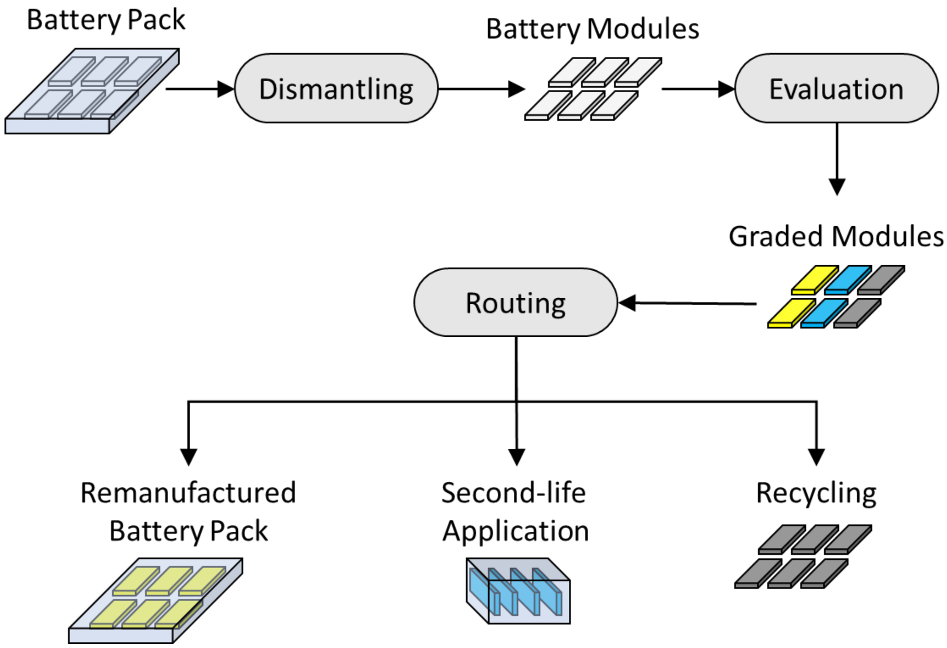

Figure2: Diagram of potential flow of used automotive LIB into dismantling, evaluation, and reuse or recycling stages.

3 The Second Life of Lithium-Ion Batteries

Following evaluation and grading, LIBs can be routed toward a variety of potential applications. Second-life applications may include systems that have been designed for residential, commercial, or industrial sectors, such as energy storage services, telecommunications applications, electric vehicle charging support, low-powered EV applications, or lead-acid battery system substitution. In essence, these second-life applications can be viewed as alternatives to LIB (or other battery type) applications that are already in the market today.

3.1 Types of Second-Life Applications

Residential second-life LIBs would largely be substitutes for other typical energy storage systems, including such applications as solar power storage, emergency backup power systems, and off-grid applications. For example, the increased proliferation of residential solar power has allowed consumers to provide power for their homes, sell power to the grid, or store power for later usage. If second-life LIBs represent a lower-cost option, more consumers may opt to utilize a battery backup for their home-based solar systems. In addition to solar power storage, emergency backup power systems offer another residential application: one that provides consumers with assurance during times of electrical grid fluctuation and uncertainty. While the U.S. electrical system is very reliable, security in the form of backup power is valuable in areas subject to major weather events (flooding, fires, snow or ice storms, tornadoes, etc.). Finally, consumers that seek to be entirely off-grid could couple a second-life LIB system with their own on-site electrical generation to provide a stable source of electricity if their primary source experiences a disruption.

Potential commercial and utility-scale applications could be both front-of-the-meter (FTM) and behind-the-meter (BTM). FTM means that the device would be positioned "in front" of the consumer's meter (i.e., before electricity reaches a business's electrical meter), while BTM means that the application is placed "behind" the meter (i.e., after electricity reaches the consumer's meter). FTM applications are largely driven by utilities, as is implied by their position in the grid. FTM applications include the use of energy storage systems (ESS) for frequency regulation, voltage support, or storage of excess solar or wind generation. These would be large, utility scale battery backups that would be in the 20-60 MWh range for energy storage capacity. BTM applications tend to be smaller in size, ranging in size from 5 kWh to 500 kWh of energy storage capacity. Their applications are often driven by an economic opportunity like electricity peak shaving or demand response (in addition to traditional backup power). These BTM applications, especially those at the smaller scale, may also be appropriate for residential applications. The second-life battery market has seen more activity in BTM fields than in the FTM market at the current stage of development, though that could change as vehicle OEMs and utilities identify ways in which they can find mutual benefit from such uses.

In addition to the previously mentioned options for battery second life, there are other unique applications that may also be viable candidates for the use of second-life batteries. We have already noted that second-life LIBs are a means by which consumers could achieve energy security through a backup generation application or off-grid deployment of an LIB. In a similar way, these second-life LIBs can serve commercial entities in a backup power market for critical "islanded" areas. At present, the most widely deployed market for second-life batteries has been in the telecommunications industry. These telecommunication applications have been used to support powering cellular communications towers by providing a buffer in times of potential power failures. China has deployed over 800 MWh of second-life LIBs across its telecommunications industry [21]. The use of battery backup for the telecommunications industry is not new, but second-life LIBs in China (where lithium iron phosphate chemistry is most common) have been effectively deployed in competition with the incumbent technology.

Second-life LIBs can also be used for EV charging support. EV charging support allows a vehicle charging point operator to charge a battery at slow rates, potentially during times of low electricity prices, and then call upon that stored power to charge an EV battery. This allows the operator of the charging location to avoid the high cost of demand charges through the rapid discharge of the battery into the EV. In that case, the second-life LIB serves as a mechanism by which the cost of electricity delivery to an operating electric vehicle can be reduced. The second-life LIB, in that case, finds a new purpose in the EV market.

Finally, there is also the potential for second-life LIB to be deployed in low-power EV applications, such as golf carts and forklifts. The important benefits of electrified golf carts and forklifts include reduced local pollutants and noise. For forklifts, this is especially important for indoor applications, and if second-life development represents a means by which those electrical forklifts can be developed less expensively, it represents a real opportunity for indoor air-quality improvements that directly affect the health and safety of workers.

3.2 Challenges of Second-Life Applications

The second-life LIB applications identified in the previous section have some common challenges. First among them is the simple collection and transport of EV batteries before their dismantling and evaluation. As we noted previously, LIBs are considered Class 9 waste and must be handled, at all stages of transportation, by individuals with the proper training, in containers meeting appropriate specifications, and on vehicles that are allowed to carry them. The challenge of removing LIBs from their initial EV application must not be overlooked. Many EV batteries are integrally designed within their vehicles and often difficult to extract. Once an LIB is removed from its vehicle, it must then be shipped to a site where the battery can be dismantled and evaluated. If the battery was removed from a vehicle at a site with many vehicles of the same type, such as an OEM warranty center, then there may be a common platform and avenue identified for shipping that battery. However, if the battery is collected at a point in the automotive supply chain that is further removed from the OEM, there may not be the same resources for appropriate packaging and expertise for proper shipping nor for the economies of scale associated with a more centralized processing facility. Another important challenge is in the dismantling and evaluation stages, as was described in Section 2.1.

Across all LIB applications, a BMS must be used to monitor and control the flow of electricity to and from the battery, creating one challenge that crosses all potential second-life applications: the use of an LIB module in an application for which it was not originally intended. Since the BMS is designed to regulate and monitor the battery modules within the LIB for their original application (the automobile), that BMS will not be suited for reuse in the new application, and if the modules are separated and placed into new applications, they must be controlled by a new BMS that governs them in a fashion appropriate for that new usage. The BMS for each new application will need its own design engineering. That will entail both understanding the power demands of the new device as well as the characteristics of the LIB modules. Thus, one can imagine that the BMS for a second-life application designed for one battery module type may need to be re-engineered if it is to interact with another LIB module type.

In addition, there is a question related to the specificity of both a second-life application's BMS and its physical structure if it intends to utilize different types of LIB modules. Mixing these different module types may be feasible, but would require additional BMS engineering that properly accounts for the variability in electrochemical profiles of different LIB modules. Furthermore, the physical enclosure and mounting hardware, while a relatively minor challenge, may require its own modularity. We have already noted the physical packaging differences of LIB modules, and while these vary dramatically by vehicle model, they may also vary within the vehicle model or across a vehicle's model year in subtle ways. For instance, the bolt holes for a module may need to be altered in one model year to accommodate an updated vehicle design. While this may be a minor change, even for a second-life application, it points to the challenge of specificity. A second-life application designer could design a BMS and housing intended for the LIB modules from a particular vehicle model or an open-platform system. In either case, the decision comes with trade-offs. The former could leave the design vulnerable to a limited inflow of viable LIB modules, while the latter could incur greater upfront costs. Such a robust design may help future-proof the second-life LIB, but it may hamper its entry into the market due to upfront costs.

The final challenge that we describe is somewhat less obvious and may not be perceived as a "challenge" when we consider the full life cycle and life time of a battery: An LIB module is currently most valuable in the market in an automotive application. If used LIB modules are deemed to meet the functional requirements of their original automotive application and they are incorporated into remanufactured or refurbished LIB packs for the automobile, then they will not be available for use in a second-life application. This could delay the viability of a second-life application because a more attractive market may exist for these LIB modules.

With the increase in electric vehicle usage, there will be an associated increase in the availability of second-life batteries. There are several potential applications, but the challenges that face them, both technical and regulatory, may impede their proliferation.

3.3 Opportunities for Second-Life Applications

The opportunities for second-life applications appear to be significant based on the quantity of PEVs sold and the energy capacity of those vehicles. In the U.S. alone, from 2010 to 2018, 42 GWh of battery capacity was sold in the PEV market [2]. The sheer quantity of available energy storage capacity is the reason for interest in the second-life vehicle market. As noted previously, estimates of available battery capacity remaining at end-of-life are around 80%, thus those 2010-2018 PEVs will provide ~34 GWh of available storage capacity for the second-life market.

The majority of the available LIB capacity is in BEVs, as opposed to PHEVs, given their larger LIB capacity to meet vehicle range demands, and the majority of the cathode composition associated with those vehicles is an NCA chemistry associated with Tesla vehicles [2]. NMC chemistry is the next largest available chemistry, but we know that the variability within NMC chemistries (the ratio of nickel, cobalt, and manganese) is significant from one OEM to another. However, especially as BEVs proliferate and the range of vehicles increases, the battery sizes available will likely also increase. This means that there will likely be more LIB modules of a common chemistry and common form factor available for interested second-life application developers. This may reduce the challenges associated with the limited flow of consistent LIB types into applications, thus potentially reducing development costs.

The future trend for light duty vehicle transportation points towards electrification, both in the U.S. and elsewhere. These trends will lead, over time, to an abundance of available LIBs with significant capacity remaining. Whether those LIB are remanufactured, placed into second-life applications, recycled, or routed toward landfill will depend on the market economics of an uncertain future. It may be that breakthroughs in recycling will negate the market opportunity for second-life applications as demand increases for the constituent elements of these batteries. Or, it may be that regulation hampers the transport and handling of these LIB to such a degree that the market directs them towards landfill. At present, a second-life market exists for automotive LIBs, even if it is nascent and the economics represent a significant challenge.

Abbreviations

BEV	battery electric vehicle
BTM	behind-the-meter
FTM	front-of-the-meter
LDV	light duty vehicle
LFP	lithium iron phosphate
LIB	lithium ion battery
LMO	lithium manganese oxide
NCA	nickel cobalt aluminum
NMC	nickel manganese cobalt
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
SOC	state of charge
U.S.	Unites States of America

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