Second-use Applications of Lithium-ion Batteries Retired from Electric Vehicles: Challenges, Repurposing Process, Cost Analysis and Optimal Business Model

Wen-Chen Lih, Jieh-Hwang Yen, Fa-Hwa Shieh, Yu-Min Liao

Abstract

The lithium-ion (Li-ion) battery of high power density and large electricity capacity is pioneering both uncultivated lands, the electric vehicle (EV) for driving longer distances, and the electricity storage system (ESS) for storing huger amount of electricity. Still, the high capital cost of Li-ion battery, around 50% of an EV, currently impede the universal market adoptions of EV and ESS industries. Through a sophisticated repurposing process and a clever business operation, the used Li-ion batteries retired from EV usually holding residual 70 ~ 80% electricity-storage capacities can create long-term and stable profits from proper second-use or repurposing applications, such as the electricity-storage batteries of an ESS for storing the electricity from renewable energy systems. From the viewpoint of environment protection, this transforming movement firmly meets with the "eco-3R" principles of recycle, reuse and reduce. During the "pre-recycling" period of second-use application, more creative technologies to dispose of the large-sized and unable-to-reuse Li-ion batteries can be developed. A complete eco-life of an EV Li-ion battery can be achieved. In this research, the critical issues are explored, including challenges, repurposing processes, cost analyses, and optimal business models for transforming a used Li-ion battery pack retired from EV into ESS for its second-use application. The estimated profit rate of a case study can reach around 39%; namely, a 10kWh Li-ion battery pack of 20-year calendar life primarily works in EV for 5 years, and then runs in ESS for following residual 15 years.

Keywords: Lithium-Ion Battery, Electric Vehicles, Electricity Storage Installation, Second-Use Applications of Electric Vehicle Batteries, Eco-3R Principles, Pre-Recycling

1. Introduction

Greenhouse gas emissions, air pollutions, and over-dependences on fossil fuels are deemed the three major driving forces to breed the global warming and the climate change. In the past decades, the fuel-propelled transportation vehicle has undoubtedly become one of the main supports to above three prime culprits. The appearances of various electric vehicles (EVs) have convinced worldwide people of their saviour positions to our dying earth. After the Japan 311 catastrophic earthquake and tsunami, the following nuclear accidents astonishingly caused not only tremendous fears of the unexpected explosives of nuclear power plant and nuclear pollutions, but also the great hardship and suffering from long-term and vast-area power shortages. Similar to the aspirations of people for EV, the renewable energies, such as solar power, wind power, tidal currents, etc., are recalled again to supply us even cleaner, safer and more sustainable energies to disarm nuclear powers and terminate the over-dependences on fossil fuels at one stroke. Frustratingly, both EVs and renewable energy systems hold a common Achilles’ heel, the essential demand of a battery of high power density for driving longer distances, and larger energy capacity for storing huger amount of electricity.

In 1995, Toyota Prius hybrid EV (HEV) equipped with a set of nickel-metal hydride (NiMH) batteries finished a maiden voyage [1]. It implies that the new era of EVs has officially arrived since then. Subsequently, the plug-in hybrid EVs (PHEVs) and pure-battery EVs (PEVs) become practicable under the impetus from the rising environment-protection consciousness of people, and the inter-governmental subsidies around the world. Evidently, EVs are gradually and overwhelmingly divvying the global automotive market share today. One of the decisive factors is the successful development of the lithium-ion (Li-ion) batteries of outstanding performances, i.e. higher power density, larger energy capacity, and safer chemistries than ever. Simultaneously, some companies, such as AES energy
storage, A123, etc., creatively integrate those Li-ion batteries and make a great stride in constructing several to tens of megawatt (MW) electricity storage systems (ESSs) for saving enormous electricity from renewable power sources and grids [2]. Except for prevailing over handheld 3C products, Li-ion batteries is predominating the markets of power sources for power tools, EV, ESS, etc.

Due to the excellent efficiency profile, energy capacity, power density, cycle life, and calendar life, Li-ion batteries exactly outperform most of other batteries [3]. Even so, Li-ion batteries are still undergoing variety of challenges and users’ demands regarding lower manufacturing costs and safer intrinsic quality on cell, module, and pack levels. By adding next-generation formulations, the possibility of thermal runaway inside battery can be effectively suppressed. For instance, the newly-developed Lithium Iron Phosphate (LiFePO_4, LFP) batteries are considered as a superior candidate of electricity-storage components for future EVs and ESSs. Anxiously, the capital cost of Li-ion battery is not low enough yet to substantially decrease the total costs of EVs and ESSs for attracting numerous potential customers. This fatal bottleneck directly impacts the universal adoptability of EVs and ESSs. Some investigations delivered that the cost of Li-ion battery needs to be chopped down around 50% for coming EVs to fully compete against conventional fuel-propelled vehicles with great odds [4-6]. Currently, the cost Li-ion battery, around $1,000/kWh, is expected downwardly to $500/kWh with increase in cell production volume, and improvement in manufacturing technology by the year 2020 [7]. Explicitly, there are still many struggles against the high battery cost in a decade.

Based on the suggestions of automotive manufacturers, an EV Li-ion battery pack holding only residual 70 ~ 80% capacities should be replaced; otherwise, unexpected driving malfunctions and safety problems, such as shorter driving ranges, less power outputs, insufficient braking capabilities, etc., could happen in all likelihood. Accordingly, there will generate two meaningful issues:

**Issue 1**: how can we dispose of those replaced batteries from EVs without any side effects on environments or other aspects?

**Issue 2**: how can we reuse the residual electricity-storage capacities of used Li-ion batteries retired from EVs to make an extra profit, and to level off high capital costs of Li-ion batteries?

Cready et al [8] presented a feasibility to reduce the battery cost by applying used NiMH batteries retired from EVs in stationary applications. They proposed that the second use of those used EV NiMH batteries can be employed in the electricity regulation and an ancillary service with the opportunity of highest expected revenue. At present, the newly-developed Li-ion batteries greatly outperform NiMH batteries. After servicing in EVs, and through the appropriate repurposing processes, the return potentials of second-use applications of the used Li-ion batteries should be much higher than those of NiMH batteries. Comparing with the other cost-reduction solutions, namely developing new-and-cheap materials for anodes and cathodes of Li-ion batteries, deploying automatically mass-production lines, etc., the approach to reusing the retired EV Li-ion batteries can be a shortly workable gateway by extending their service lifetimes to applicable second-use fields. Through a deliberately repurposing process, a rebuilt Li-ion battery pack retired from EV can become an excellent component in ESS for utility support to variety of distribution grids [9].

The sections 2 to 5 state the topics of challenges, repurposing processes, cost analysis and optimal business model, and a case study. Moreover, the section 6 of discussion and the section 7 of conclusion are as follows.

## 2. Challenges

The actual application scenarios of Li-ion batteries in EVs are quite different from those in ESSs. In EVs, the Li-ion batteries are usually charged and discharged at large current rates (C-rates) for satisfying with complicated driving requests. Frequently, those batteries have to endure adverse circumstances of high and cold temperatures, high humidity, abrupt vibrations, etc. On the contrary, in ESS applications, the batteries are generally charged and discharged at small C-rates and operate in an environment-controlled and secured working space. Under logical inferences, it should be feasible to transform the used Li-ion power batteries for EVs into the electricity-storage batteries for ESSs.

However, due to the quite different working environments and operating conditions, some important parts of Li-ion battery packs in EVs, such as battery management systems (BMS), power electric...
devices, thermostatic devices, communications, etc., might need to be replaced for being accommodated with the communication and control systems in ESSs. Confronting the various battery packs for EVs and non-standardizations of electricity-storage components in ESSs, there still exist plenty of in-between compatible barriers, which need to be firstly swept away. Besides, all extra replacements and changes in used EV battery packs will be bound to impact the cost predominance of their second-use applications. Simply speaking, the most forceful competitor to the repurposing of used EV battery packs is themselves, the new and price-dwindling products in ESSs. Therefore, the cost management to simultaneously meet with the contradictory requests of higher rebuilding quality and lower rebuilding cost is a challenge of involved difficulties, too.

2.1 Variety of Barriers

As mentioned above, the used batteries are not new at all. Before accessing to the second-use applications, the performance and safety issues of those retired battery packs should be completely certified. The confronting barriers stated as Table 1, including rebuilding process, cell level, pack level, business, social climate, and governmental attitude, still hinder the growths of the whole repurposing industries.

Table 1. Barriers hinder the repurposing of used EV batteries

<table>
<thead>
<tr>
<th>Rebuilding process:</th>
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<tbody>
<tr>
<td>1. Constructing stable systems and channels to collect and recycle the used Li-ion batteries retired from EVs.</td>
</tr>
<tr>
<td>2. Setting up efficient procedures for evaluating the state of health (SOH) of used Li-ion batteries after EV services. The procedures should cover the initial visual examinations, diagnoses, tests, and verifications.</td>
</tr>
<tr>
<td>3. Creating standard rebuilding processes for classifying battery packs, grading and replacing battery cells, re-packaging battery packs, and re-labeling as new products.</td>
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<tr>
<th>Battery cell:</th>
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<tr>
<td>4. Precisely predicting the decaying or aging conditions of a used Li-ion battery cell.</td>
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<tr>
<td>5. Precisely predicting the available capability of storing electricity of a used battery cell.</td>
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<tr>
<td>6. Effectively targeting and replacing failure or over-age cells within a battery pack.</td>
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<tr>
<th>Battery pack:</th>
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<tr>
<td>7. Re-designing, re-manufacturing, or re-adjusting the battery management systems (BMS) and other power electric circuits, fitting to ESSs or the other second-used applications.</td>
</tr>
<tr>
<td>8. Re-designing, re-manufacturing, or re-adjusting the thermal management, safety, and emergency systems, fitting to ESSs or the other second-used applications.</td>
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<tr>
<th>Business:</th>
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<tr>
<td>9. Establishing the appropriate or optimal profit-making models for relevant industries.</td>
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<tr>
<td>10. Initiating the smart cost-management structures for second-use applications.</td>
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<th>Social climate and Subsidy:</th>
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<tr>
<td>11. Persuading people of accepting a new ESS product made of re-fabricated EV Li-ion batteries.</td>
</tr>
<tr>
<td>12. Legislating for proper new regulations, rules, or laws for providing subsidies to the novel industries for repurposing used EV Li-ion batteries.</td>
</tr>
</tbody>
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Essentially, it is very hard to open a battery cell to observe its real-time electrochemical reactions, and simultaneously conduct any repairs. Under the circumstance of insufficient usage records or data, it is highly difficult to quickly and accurately measure the aging conditions of a used Li-ion battery pack. Nevertheless, it is badly in need of sweeping above barriers for smoothly repurposing used EV Li-ion batteries to other achievable applications.

2.2 An Approach to Target Inferior Cells

In the following pack-classification experiment, we tried to identify the aging conditions of eight battery packs. Each is consisted of 16 LiFePO4 cells (3.3V/12Ah) in serial and manufactured by Phoenix Silicon International Corp. to form a 48V/12Ah pack. Firstly, each pack is discharged to 40V at 0.1C (1.2A); after 30-minute rest, charged to 53.5V at the same C-rate. Secondly, serially connect
those eight battery packs to assemble a 384V/12Ah battery string. Thirdly, discharge this battery string at 0.2C (2.4A) and record the voltage variations of all cells in each pack as shown in Figure 1.

Theoretically, a pack comprising cells of the same performances will appear a coincidence of discharging curves all the way. In fact, the break points of pack 1, 5 and 7 seem to occur earlier than those of the other packs. Namely, these three packs hold some inferior cells resulting in their poorer performances.

![Figure 1. The voltage curves of all cells in each pack during discharging course](image1)

The statistical dispersions of all cell voltages in each pack are shown in Figure 2. Consequently, the cell voltages of pack 1 and 5 appear wider spreads than those of other packs. According to the deviation of cell voltages, the pack 1 could be assessed at the aging-most condition for the sake of the poorest performance coincidences of cells. The pack 5 is the second worse one. The dispersion extent of each battery pack seems highly related to its current SOH, and could numerically represent its aging conditions on the basis of a “preset and standard” evaluation rule.

![Figure 2. The statistical dispersions of discharging voltages of all cells in eight battery packs](image2)
Additionally, regardless of having conducted the proper rebuilding processes for classifying packs, grading and replacing cells, re-packaging packs, and re-labeling as new battery products, the rebuilt Li-ion battery packs should be periodically inspected and reviewed in accordance with the recorded operation data. Moreover, not only do maintain the goodwill of rebuilding plants, but those plants or R&D labs can also review their previous performance predictions of those rebuilt battery packs. Therefore, both prognoses and diagnoses of a used battery in second-use applications can be fully understood.

3. Repurposing Processes

Used EV Li-ion batteries, intended for second-use applications, will need to be examined, inspected, tested, sorted, and certified as parts of the repurposing processes. It should be necessary to identify used battery packs if they hold sufficient capabilities left to perform well in their second-life services, such as the electricity storage batteries in ESSs [10, 11]. As mentioned in section 2, some battery cells and packs can be expected to have worse degradations than others, after several years of usages under the long-term non-uniform temperature distributions, poor levels of manufacturing consistency, abusing of previous owners, etc. In another word, the primary deviations of all cells in used batteries are exactly quite different from those of other new batteries, consisting of almost the same and new cells.

In this research, there is setup a standard process, including five stations of visual examination, static performance diagnoses, testing electric boards of battery management system (BMS), testing cell assembly without BMS, and dynamic performance validation, for totally understanding the current SOH of a used battery pack. Also, there are built up the other three rebuilding processes of cell-grading, re-fabrication, and re-labeling. Figure 3 shows a schematic repurposing process for used EV Li-ion battery pack.

In Figure 3, all data of examinations, diagnoses, tests, and validations collected from stations 1 to 5 will be immediately guided to the octagonal decision-making system. This intelligent system will propose a reference report covering the current SOH of used Li-ion batteries, and the rebuilding suggestions on the basis of cost levels, such as cheap and slight, or expensive and heavy re-fabrications. According to this reference report, the secondary end users can choose which rebuilding suggestions will be conducted. Therefore, the algorithms and the latest information regarding batteries’ prices, performances, costs of rebuilding processes, etc., involved in the decision-making system should be frequently updated in order to provide more correct reports and applicable rebuilding suggestions.
4. Cost Analysis and Optimal Business Model

Before discussing the cost issues of a used battery, three SOH indexes are generally treated as key factors, such as the residual capacity of storing electricity, cycle times, inner resistance and impedance. Technically, the life of a battery cell includes the calendar life and cycle life. The calendar life is generally designed between 15 and 20 years depending on the cell manufacturers [9], influenced by environmental conditions, such as humidity, temperature, erosion, vibration, etc. The cycle life is highly related to depth of discharge (DOD), charging and discharging C-rates and working temperature. The deeper DOD, the larger C-rates, and the higher working temperatures, the shorter cycle life of a battery cell will be. Consequently, the smaller residual capacity of storing electricity, the inferior aging conditions with increase of inner resistance, and the worse SOH will be. Due to the combination with cells in serial or parallel ways, the lifetime of a battery pack is very similar to that of a cell, as well as dominated by the inferior cells.

4.1 Residual Value of a Used Battery Pack

In accordance with previous explanations, the ratio of residual life and nominal life ($\text{Ratio}_{\text{res}}$) of a used battery pack can be defined as equation (1).

\[
\text{Ratio}_{\text{res}} = \eta \cdot \frac{\text{Residual Capacity}}{\text{Nominal Capacity}} \cdot \frac{\text{Residual Calendar Life}}{\text{Nominal Calendar Life}}
\]

The $\eta$ is a coherent parameter between 1 and 0, which represents the difference extent of a battery between its current aging conditions and its normal degradation situations predicted by original manufacturers. The smaller the difference extent, the value of $\eta$ is closer to 1; contrarily closer to 0. Afterward, the residual value of a used battery pack can be expressed as equation (2).

\[
\text{Value}_{\text{residual}} = \text{Ratio}_{\text{res}} \cdot \text{Cp}_{\text{new battery}} = (\eta \cdot \text{Cap}_{\text{res}} \cdot \text{Life}_{\text{res}}) \cdot \text{Cp}_{\text{new battery}}
\]

here, $\text{Cp}_{\text{new battery}}$ = the current price of a new Li-ion battery pack for EV

4.2 Cost Analysis

Form the viewpoints of a rebuilding plant of batteries, the total costs of repurposing a retired EV battery pack to the second-use applications consist of collecting cost, rebuilding cost, operation expenses, and miscellaneous expenses. Therefore, the residual value of a used battery pack before being rebuilt can be defined as equation (3).

\[
\text{Value}_{\text{residual}} = \text{Collecting Cost} + \text{Operation Expenses} + \text{Miscellaneous expenses} = (x \cdot \text{Value}_{\text{residual}}) + (y \cdot \text{Cp}_{\text{new battery}}) + (z \cdot \text{Cp}_{\text{new battery}})
\]

here, $0 < x, y, z \leq 1$

The collecting cost represents a reasonable price to purchase a used EV Li-ion battery pack by secondary users. The operation and miscellaneous expenses mean the costs for handling all processes of initial examinations, tests and evaluations.

After collecting used EV Li-ion battery packs, the rebuilding cost should be paid for all rebuilding processes to upgrade those packs. The new value of an upgraded battery pack can be expressed as equation (4).
The $\zeta$, a rebuilding parameter, represents the upgrading extent of performance of a used battery pack after being rebuilt. Determining an appropriate $\alpha$ value is very tricky. The lower $\alpha$ value will get fewer profits, while the higher one (e.g., close to 1) will hardly motivate secondary buyers to purchase the re-fabricated used batteries. Combining equation (1) to (4), the total upgraded value of a used EV Li-ion battery pack can formulated as below equation (5).

$$Value_{upgraded} = \alpha \times Cp_{new \ battery} = Value_{residual} + Rebuilding \ cost + Upgrade \ Profit$$

$$= Value_{residual} + \zeta \cdot Cp_{new \ battery} + \beta \cdot Cp_{new \ battery}$$

reasonably, $0.5 \leq \alpha \leq 1$ and $0 \leq \zeta, \beta \leq 0.3$

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$$Value_{upgraded} = \alpha \cdot Cp_{new \ battery} = \left( x \cdot \frac{Ratio_{R/N}}{N} + y + z + \zeta + \beta \right) \cdot Cp_{new \ battery}$$

$$= \left[ x \cdot \left( \eta \cdot \frac{Cap_{R/N}}{Life_{R/N}} \right) + y + z + \zeta + \beta \right] \cdot Cp_{new \ battery}$$

$$here, \alpha = \left[ x \cdot \left( \eta \cdot \frac{Cap_{R/N}}{Life_{R/N}} \right) + y + z + \zeta + \beta \right]$$

### 4.3 Optimal Business Model

Typically, the cost of a Li-ion battery pack occupies around 50% total of a whole EV. It becomes a significant meaning to lower the cost of a Li-ion battery pack for increasing competition capabilities against traditional vehicles propelled by internal combustion engines (ICE). To expanding the EV penetration, it is a pessimistic attitude to just wait for advent of another oil crisis. A creative and novel business model should be carried out. In this research, the full lifetime of a new Li-ion battery pack is divided into two service stages, i.e., the new-product (NP) stage in EV and the second-use (SU) stage in ESS applications. Definitely, there should be an optimal time scale to transfer a used EV Li-ion battery pack from NP stage to SU stage for acquiring the highest revenue.

Furthermore, a new business model, “Sell EV, Rent Battery”, is proposed. To EV buyers, they never need to pay a high price to own a new EV with batteries. They will never consider whether they could afford to replace a set of new battery packs after a few years later or not. An EV owner only needs to prepare low monthly payment to rent a new battery pack from auto dealers or battery providers. After the NP stage in EV, the retired battery pack can be transformed into the SU stage. Through the necessary rebuilding processes, this upgraded battery pack can be continuously leased to other customers, such as ESS industries, for earning long-term rental profits. Thus, the total rental incomes from both NP and SU stages can be defined as equation (6).

$$Rent_{new- \ product \ stage} = Depreciation + Operating \ Cost + Profit_{new- \ product \ stage}$$

$$= \left( Cp_{new \ battery} - Value_{residual} \right) + \gamma \cdot Cp_{new \ battery} + \mu \cdot Op_{new \ battery}$$

$$Rent_{second- \ use \ stage} = Value_{upgraded} - Value_{scrap} + Profit_{second- \ use \ stage}$$

$$= Value_{upgraded} - Value_{scrap} + \nu \cdot Value_{upgraded}$$

$$= \left( 1 + \nu \right) \cdot Value_{upgraded} - Value_{scrap}$$

reasonably, $0 \leq \gamma < 0.1$ and $0 \leq \mu, \nu \leq 0.3$

$$here, Op_{new \ battery} = the \ original \ price \ of \ new \ battery \ pack$$

$$Value_{scrap} = the \ final \ value \ of \ waste \ Li-ion \ battery \ pack$$

The net profit rate combing with both NP and SU stages can be written as the equation (7).

$$Net \ Profit = \left( Rent_{new- \ product \ stage} + Rent_{second- \ use \ stage} \right) - Total \ Cost$$

$$Total \ Cost = Op_{new \ battery} - Value_{scrap}$$

$$Rate_{\%} = \frac{Net \ Profit}{Total \ Cost} \times 100\%$$

According to the above-mentioned two-stage service and a new business model of “Sell EV, Rent Battery”, if the best transformation timing between two stages is intelligently determined in advance,
the optimal business model for gaining highest revenue in whole service lifetime of a battery pack can be constructed.

5. A Case Study

A 10kWh Li-ion battery pack of EV consists of 16 LFP cells of 3.2V and 180Ah in serial, and is priced at US$10,000. After a preliminary optimization, assume that the above-mentioned parameters and their values are listed as below and estimated on the basis of general situations in Taiwan. Additionally, the assumptions of a 5-year new-product stage, a residual energy capacity of 144Ah, and a 15-year second-use stage are defined. The total calendar life (or service lifetime) is 20 years, covering two stages. Also, the new-battery price is cut by 2% per year [12].

\[
\begin{align*}
\eta &= 0.85, \quad x = 0.75, \quad y = 0.01, \quad z = 0.01, \quad \zeta = 0.1 \\
\beta &= 0.1, \quad \gamma = 0.01, \quad \mu = 0.25, \quad v = 0.2, \quad Value_{\text{scrap}} = 200
\end{align*}
\]

The value of \(\alpha\) can be calculated to 0.6025. It means that the secondary buyers should pay the 60.25% of price of a new battery pack to buy a used one, still holding 80% of residual electricity-storage capacity. Commercially, the above \(\alpha\) value is very close to the threshold trade limit, which a potential buyer is willing to pay in Taiwan. The net profit rate of this case study is around 39%. During total 20-year services, the monthly rentals of two stages are US$117 in EVs and $37 in ESS applications.

The Fig. 4 shows a schematic of the optimal business model for this example case.

![Figure 4. A schematic of the optimal business model for this case study](image)

6. Discussions

Apparently, with broadening dominion of EVs in a coming decade, the quantities of used Li-ion batteries retired from EVs will exponentially increase. Recycling and reusing those batteries will certainly become an inevitable and meaningful mission for benefiting our living environments. During this “pre-recycling” period for second-use applications, the more creative technologies to handle waste EV Li-ion batteries could be timely developed. A complete eco-life of an EV Li-ion battery could be achieved. Besides, it could be very helpful to reduce the yields of new batteries for ESSs.
On the other hand, the demands of ESSs will gradually increase with the popularization of renewable power systems for compensating their inherent intermittency to produce even uniform electric power supplies. To sum up, developing the second-use technology to repurpose retired EV Li-ion batteries is a direction of foresight and sagacity not only to support both EV and ESI industries at the same time, but also to accelerate the materialization of our green future.

Predictably, after EVs gradually penetrating into the mainstream of auto markets, the second-use applications of used Li-ion battery packs will possess the higher market values of electricity storage, and the more practical environmental benefits. Meaningfully, developing this second-use technology and the related business models can fruitfully lower the costs of EVs and greatly speed up their penetration into our human lives.

Practically, confronting variety of battery pack designs and cell patterns, it is the first barrier that how we can efficiently achieve the rebuilding processes for classifying packs, grading and replacing cells, re-packaging, and re-labeling used batteries. In addition, the retired EV battery packs might have ever experienced unknown abuses in their EV services. Sequentially, it is the second barrier that how we can precisely evaluate the aging conditions of those used battery packs, and can accurately predict their performances in coming second-use applications. In order to deeply understand and fully protect the rebuilt EV Li-ion battery packs from unexpected overwork, it is absolutely necessary to develop the real-time SOH monitor and advanced BMS.

Based on the previous analyses, the evaluating standards for the parameters, \( \eta, x, y, z, \zeta, \beta, \gamma, \mu, \) and \( \nu \), should be established first. The value of \( \eta \) can be decided by the processes of initial examinations in the station 1, and primary tests in the station 2 as stated in the section 4. For correctly determining the value of \( \alpha \), more market surveys should be done regarding the acceptance of used battery packs from public perceptions in advance. The cultural predispositions of general secondary buyers must be changed to adopt used equipment, which is very rarely done today [3]. For holding a long-term, stable, and high profit, the optimal values of above parameters should be intelligently assigned first.

In the future work, some useful tools, such as multi-objective evolutionary algorithm (MOEA), artificial neural network (ANN), genetic algorithm (GA), etc., will be tried to optimize above parameters [12, 13]. Under the complicated dynamic variations of new-battery price, costs of all rebuilding processes, an intelligent decision-making system will be very helpful for decision-makers to keep the operations of high revenue. Certainly, the persisting advances of rebuilding technologies, and the more intelligent cost managements are both critical factors for successfully achieving the second-use applications of used Li-ion battery packs retired from EVs.

7. Conclusions

According to the report of Deutsche Bank Research in 2008, it presented that EVs including PEVs, PHEVs and HEVs will represent a battery market of US$30 ~ 40 billion by 2020. The Li-ion batteries will dominate the global battery markets. Namely, the innumerable EV Li-ion battery packs will be continuously replaced after their services in several years later. Needless to say, the huge quantities of retired EV Li-ion battery packs will bring tremendously heavy loads on our living environments. Definitely, it will become very meaningful and inevitable to collect those used battery packs, and to reuse their surplus electricity-storage capacities. Beyond the Japan 311 disasters, developing a cheaper and safer small-sized ESS, such as a household electricity storage appliance (HESA) [14], become more significant to effectively solve the problem of power shortage. It can be realized that people must be only accustomed to conserving electric power and even storing surplus electricity; then totally eliminating nuclear power plants could be feasible.

In this study, the challenges, repurposing processes, cost issues and analyses, and optimal business model for the second-use applications of used EV Li-ion battery packs are presented. With the continuous and predictable progresses of rebuilding and recycling technologies, the second-use applications of used EV Li-ion battery packs will gradually convince worldwide people of their importance and future contributions. Based on the proposed business model for a case study, the net profit rate is around 39% in 20 service years of an EV Li-ion battery pack in Taiwan. The longer the second-use service of a used battery pack is elongated, the higher net profits can be earned.

Even meaningfully, the second-use applications to ESSs and the repurposing technologies for used batteries will effectively reduce great quantities of new batteries produced. This is a rare
example industry to completely conform to “eco-3R” principles of recycle, reuse and reduce. Considering the cost-benefit analyses of EVs and the potentially huge contributions to the environment protection, the second-use application of a used EV Li-ion battery pack is a perfect win-win thinking and deal.

8. References