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The Research of the Reuse of Degraded Lithium-ion Batteries from Electric Vehicles in Energy Storage Systems for China

Hao Tang, Yichun Wu, Songsong Liu, and Jingjing Zhang

Abstract—**Lithium-ion batteries (LiBs) in electric vehicles are considered not suitable for secondary-use when only 80% of the original storage capacity remains. Applying degraded LiBs in storage applications for energy storage systems would prolong the life cycle of these batteries. The levelised cost of storage (LCOS) model is used in this study to analyze the economic efficiency of three different battery technologies in a storage application. In this paper, an economic analysis is executed for a typical power station (10 MW power and 40 MWh capacity) in China. The results show that the LCOS of degraded LiBs is lower than that of new LiBs, but higher than that of Pb-acid batteries. By adjusting parameters such as cycles and cost per unit of electricity in the calculation of the LCOS, some suggestions are given to reduce the LCOS of degraded LiBs to the same level as that of Pb-acid batteries. This study provides a reference for the government to formulate an effective secondary-use program for degraded LiBs.**

Index Terms—**levelized cost of storage, degraded, lithium-ion batteries, secondary use, cost.**

I. INTRODUCTION

ELECTRIC vehicle (EV) industry technology is developing rapidly in China. The sales of EVs have increased from 11,241 units in 2013 to 1.02 million units in 2019 [1]. The annual sales have increased yearly, and it is expected that 1.5 million vehicles will be sold in 2020. The demand for EVs is very high. As the core part of EVs, battery production has increased from 1.2 GWh in 2012 to 44.5 GWh in 2017 and approximately 71 GWh in 2019 [2], [3]. Taking into account vehicle lifetime, battery life and other factors, 20 GWh of battery decommissioning will be necessary in China by 2020 [4].

The battery cost has always accounted for a large proportion of EV cost. The battery cost accounts for approximately 38 % of the total cost of an EV [5]. When the battery capacity falls to 80 % of its original level, it can no longer be used continuously in the EV; however, these batteries are still valuable and can be used in energy storage systems [6], [7].

Degraded lithium-ion batteries (LiBs) are available on the market for 44-180 \$/kWh. With such low market prices, power station staff are more willing to choose degraded LiBs over new LiBs [8]. The secondary use of these batteries can reduce the purchase cost of batteries. In addition, it can eliminate the battery energy storage manufacturing process, which extends the lifetime of EV batteries and saves resources. Moreover, the off-peak low-cost electricity can be used to mitigate grid pressure [9]. The secondary use of these batteries may have the ability to become a general component of future battery life cycles and occupy a part of energy storage market [10].

Life cycle cost (LCC) was used to analyze the degraded EV battery cost in stationary applications [11]. Some authors found that it could be an economically viable concept by analyzing the viability of secondary use of EV batteries in stationary applications [12]. The economic viability of secondary use of degraded EV batteries was analyzed in transportation and utility services from an optimization perspective [13]. A numerical second life battery system model was provided to simulate the system performance under different application scenarios [14]. Ahmadi determined that capacity fade and energy efficiency fade have a significant influence on the secondary use of batteries; they used degraded LiBs in energy storage systems (ESSs) connected to the Ontario electrical grid [15].

These methods are not able to compare the economics among different battery technologies because factors such as the capacity, battery efficiency, discount rate, electricity unit cost, and energy output vary considerably from one technology to another. Therefore, some authors have used the levelized cost of electricity (LCOE) to compare the economics of different battery technologies [16], [17], [18], [19], [20].

To compare different ESS technologies, some authors applied the LCOE method with the addition of the electricity purchasing component to analyze the economics using the levelized cost of storage (LCOS) method [21]. The LCOS was used to compare two technologies: (1) solar PV with battery storage, and (2) solar PV with biomass from biocrude oil and bio-gas. They found that the LCOS of the first technology is 126 \$/MWh, while the LCOS of the second technology is much lower 86 \$/MWh [22]. Kumar [23] analyzed the LCOS of a battery and hydrogen storage system in the microgrid and determined that the battery system is more economical than the hydrogen system.

A framework of the LCOS was proposed and the Crate has a significant influence on cost [24]. The LCOS was used to make the economy of vanadium redox flow batteries with LiBs [25]. The LCOS was applied to compare different

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technologies (solar PV, batteries, combined heat and power) used in ESS [26]. The pumped heat energy storage is cost-competitive with compressed air energy storage systems by analyzing the LCOS [27]. Some researchers proposed a LCOS algorithm suitable for electricity-specific ESS and analyzed the sensitivities of key variables in the LCOS by using Monte Carlo analysis [28]. The results of the LCOS analysis were published by Lazard research, who found that new LiBs are the least expensive of the storage technologies [29], but the details of the calculations are not available.

Xie C [30] evaluated the LCOS of liquid air energy storage and determined that the LCOS of a 25 MW/ 125 MWh storage system was 321-1005 \$/MWh. Li Na [31] analyzed the LCOS in ESS (3 MW power and 9 MWh capacity) for stationary applications by calculating the LCOS of degraded LiBs and new LiBs, and they found that the LCOS of degraded LiBs is higher than that of new LiBs. Jlch V [27] used the LCOS to analyze the cost of a long-term ESS (100 MW power and 70 GWh capacity) and a short-term ESS (100 MW power and 400 MWh capacity) and compared eight different ESS technologies. The results indicate that new LiBs currently have a high cost, while pumped-storage hydroelectricity has the lowest LCOS for both long-term and short-term ESSs. Lai C S et al. [32] analyzed the LCOS of the hybrid storage system, and they found that if the capital cost for LiCoO2 is reduced to 200 \$/kWh and the discount rate is 8 %, the LCOS can be reduced to appreciable levels. Lai C S and Mcculloch M D [25] analyzed the LCOS of the storage system and used particle swarm optimization with the interior point method to select the optimal combination size of solar panels. Chun S C et al. [33] added a discounted cash flow model to the LCOS and applied it to the case of Li-ion ESS, and they found that increasing the number of cycles will decrease LCOS.

However, degraded LiBs are not included in the comparison. Furthermore, the LCOS used in these studies does not include the depreciation expenditure tax credit, leading to higher LCOS results than the actual values.

Many authors have analyzed different battery technologies in ESSs. However, hardly any researchers have analyzed the LCOS of the secondary use of degraded EV batteries in ESSs. Some authors have made comparisons between degraded EV batteries and new LiBs. However, this situation was briefly analyzed. Li Na [31] only analyzed the economics in the case of abandoned wind power and government subsidies.

In this study, we used the LCOS equation proposed by Jlch [21] to analyze economics of secondary use of lithium batteries in ESS. And we improved LCOS equation by adding the depreciation expenditure tax credit in the original equation to increase the calculation accuracy. The improved LCOS was then used to analyze three different batteries: new LiBs, degraded LiBs, and Pb-acid batteries. Then, several sensitive factors of the three batteries were discussed. Finally, we adjusted several factors to reduce the LCOS. This study proposed corresponding measures to reduce the LCOS for secondary use of degraded LiBs in an ESS. Overall, our work made contributions to scientific literature by:

The LCOS equation is improved by adding a depreciation expense term to the original equation to offset a portion of the tax in order to improve the accuracy of the calculation.

The costs of degraded lithium batteries, new lithium batteries, and lead-acid batteries were compared by using the improved LCOS method.

By tuning the parameters and developing a Matlab application to display the LCOS results, some methods are proposed to reduce the degradation of the LCOS of LiB.

The remainder of this paper is organized as follows. The methodological framework is presented in detail in section II. Section III discusses the results of the study and presents some recommendations for LCOS reduction. Finally, a summary and an outlook for future work are presented in Section IV.

II. METHODOLOGY

A. Model Description

The LCOS is used to compare the cost of different battery technologies in ESS. This approach analyzes the impact of multiple cost factors.

The data were obtained from the supplierswebsites. The energy storage system construction, initial expenditure, and operation and maintenance costs are based on hypothetical data obtained in the demonstration power plant.

Levelized Cost of Storage

Although the LCOS used by various researchers is different, the basic framework is similar. The general equation for the LCOS is given in equation (1) ([24], [34]).

$$LCOS = \frac{Total\ Life\ Cycle\ Expenditure}{Total\ Lifetime\ Energy\ Production} \tag{1}$$

The total life cycle expenditure calculated in equation (1) can be disassembled for the battery storage system as follows:

$$\begin{aligned} LCOS = & \frac{CIE + \sum_{n=1}^{N} \frac{EUE_t}{(1+i)^n} + \sum_{n=1}^{N} \frac{OME_t}{(1+i)^n}}{\sum_{n=1}^{N} \frac{W_{out}}{(1+i)^n}} \\ & \frac{-\frac{REVA}{(1+i)^N} - \sum_{n=1}^{N} \frac{DEEX_t}{(1+i)^n} + \sum_{n=1}^{N} \frac{W_{in}*C_{et}}{(1+i)^n}}{\sum_{n=1}^{N} \frac{W_{out}}{(1+i)^n}} \end{aligned} \tag{2}$$

The LCOS is equal to the total life cycle expenditure divided by the total lifetime energy production. It considers six factors: the sum of the capital initial expenditure (CIE), equipment updating expenditure (EUE), operation and maintenance expenditure (OME), electricity purchasing cost (C_{win}), residual value (REVA) and depreciation expenditure (DEEX). The total is then divided by the annual energy production, W_{out}. W_{out} will change with variations in the battery storage capacity. The average energy output is considered [24]. The maximum value of the time, *n*, is *N*. Except for CIE, the other factors all have a connection with the discount rate. W_{in} is the input of electricity, and C_{et} is the energy unit cost, which has various values in China.

Capital Initial Expenditure and Depreciation Expenditure

The CIE mainly includes the costs of the power conversion system (PCS) and storage equipment. It is calculated by using equation (3) as the sum of the Costpcs and Coststorage.

$$CIE_u(\$) = Cost_{pcs}(\$) + Cost_{storage}(\$) \tag{3}$$

The cost of the CIE can be disassembled ([29], [35]) as equations (4) and (5):

$$Cost_{pcs}(\$) = UnitCost_{pcs}(\$/kW) * P_{out}(kW) \tag{4}$$

$$\begin{aligned} Cost_{storage}(\$) = & UnitCost_{related}(\$/kW) * W_t(kWh) \\ & + UnitCost_{battery}(\$/kW) * W_t(kWh) \end{aligned} \tag{5}$$

The Costrelated includes the panel, mounting system, site preparation, field wiring, system protection, labor cost, general overhead, sales and marketing, and site design ([31], [34]).

$$DEEX = \frac{CIE * (1 - Rr)}{N} * Tr \tag{6}$$

REVA can be calculated using the straight-line method [36], and DEEX is equal to the REVA multiplied by the T_r. DEEX is added to the LCOS equation in this study, which is different from other LCOS equations. The DEEX can be used to offset part of the tax and reduce the cost of investment.

Other Parameters

The EUE is the equipment updating expenditure, which includes the cost of replacing and re-purchasing batteries [23]. The OME includes inverter maintenance, site monitoring, insurance, land leases, financial reporting, general overhead, and field repairs ([31], [34], [37]).

We used the straight-line depreciation method to calculate the REVA. The net output energy of the storage (C_{net}) is equal to the rated output energy of the storage (Cr) multiplied by the *DoD* in equation (7).

$$C_{net} = C_r * DoD \tag{7}$$

On the other side, the P_{out} of the storage and the prescribed time of a single discharging process (*tt*) are always known. W_{out} can be calculated as follows:

$$W_{out}(kW) = P_{out}(kW) * cyc * tt \tag{8}$$

The electricity input (W_{in}) can be found by using equation (9). It has a relationship with the charging efficiency (η_{in}) ([24], [38]), discharging efficiency (η_{out}), inverter efficiency (η_{inv}), and self-discharge energy losses (W_{sd}).

$$W_{in} = \frac{W_{out}}{\eta_{out} * \eta_{in} * \eta_{inv}^2} + W_{sd} \tag{9}$$

The self-discharge energy losses are calculated in equation (10).

$$W_{sd} = 12\frac{C_r * r_{sd}}{cyc * tt} \tag{10}$$

Relationship between W_{in} *and LCOS*

The above equations are used to analyze the LCOS. Equation (1) can be replaced by equation (11).

$$LCOS = LCOS(not\ including\ W_{in}) + \frac{W_{in} * C_{et}}{W_{out}} \tag{11}$$

Equation (11) is helpful for analyzing the relationship between the LCOS and the discount rate.

B. *Data Description*

In this section, the source of the battery data is described in detail. It is used in a 10 MW and 40 MWh storage system. The theoretical lifetime of the power plant is 25 y. The electricity price is 0.045 \$/kWh [39]. The discount rate is always approximately 10 % in the market [40]. In this study, discount rates of 8 %, 10 %, and 14 % are considered.

CIE and OME

5000MTLL of Growatt [41] is used as the experimental PCS. Related cost is estimated [31]. The related cost of the degraded LiBs is the highest. There are two reasons: (a) The degraded LiBs contain reassembly cost while the others do not need. Because there are many battery manufacturers in China, and different electric vehicle batteries made by different power battery manufacturers, making the battery reorganization need to disassemble the battery management system (BMS) and reinstall the BMS. It is not possible to use the BMS directly on degraded batteries, which increases the cost of the battery. The reassembling process is as follows: degraded batteries are shipped to a special processing plant, disassembled, selected, BMS modules are added, assembled into battery packs, before being shipped to the power station and finally applied to the ESS; (b) The degraded LiBs need higher system protection and labor cost (for its low security), and more occupied area (for its low energy density).

The total OME cost was estimated [31]. The OME of the degraded LiBs is the highest, for they have lower security and higher failure rate. The costs are higher in terms of maintenance, site monitoring, general overhead and field repair.

TABLE I
SOME CIE AND OME DATA

Symbol	New LiBs	source	Degraded LiBs	source	Pb-acid batteries	source
Battery unit cost [\$/kWh]	283	[42]	96.3	[43]	145	[44]
PCS cost [\$/kW]	107.7	[41]	107.7	[41]	107.7	[41]
Invertor efficiency [%]	0.97	[41]	0.97	[41]	0.97	[41]
Related cost [\$/kWh]	144^a		226^a		130^a	
OME [\$/kWh]	1.16^a		2.17^a		1.59^a	

^{a}the data are calculated by assumption and estimation.

Battery-related Parameters

The new LiBs are Battery-Box Pro 2.5 of BYD. The Pb-acid batteries are RA12-120SD, and the degraded LiBs are assembled with used NCR 21700 batteries.

The degraded batteries labeled Panasonic NCR 21700 (NCA) are used in the Model 3 car of Tesla [45]. The battery has a rated capacity of 4800mAh. The standard voltage is 3.7 V, and the charging and discharging cutoff voltages are 4.2 V and 2.5 V respectively. Life cycle is 300-500 [46].

Self-discharge rate may increase as batteries aging [47], and we assumed that the battery self-discharge rate was 3 %. And efficiency of battery may decrease as batteries aging [48], and we assumed that the efficiency of battery was 85 % [49].

TABLE II
BATTERY RELATED PARAMETER DATA

Symbol	New LiBs	source	Degraded LiBs	source	Pb-acid batteries	source
Life time[y]	10	[50]	4	[49]	2	[51]
Efficiency of battery [%]	95.3	[50]	85	[49]	70	[52]
P_{out} [%]	1[a]		3[a]		3	[51]
DoD [%]	80		80		80	
R_r [%]	5	[53]	5	[53]	5	[53]
C-rate	1 C		1 C		1 C	

[a] the data are calculated by assumption and estimation.

III. RESULTS AND DISCUSSION

This section is divided into five parts. In the first part, when discussing the impact of discount rate on LCOS, we consider two scenarios: one that includes the cost of power purchase; and another that does not. In the first part, we also analyze some factors that affect LCOS, including the unit discharge time, discount rate, battery lifetime, and *cyc*. In the second part, the impact of the discount rate and *cyc* on the LCOS are analyzed. In the third part, the proportion of the cost attributed to the batteries is discussed. In the fourth part, several factors are discussed and a sensitivity analysis is performed. The fifth part includes some specific recommended measures to reduce the LCOS of degraded LiBs.

A. Influence of the Discount rate, Discharge Time, and Battery Life on the LCOS

The LCOS of a storage system in terms of the discount rate, discharging time, and lifetime of batteries is shown in Fig. 1.

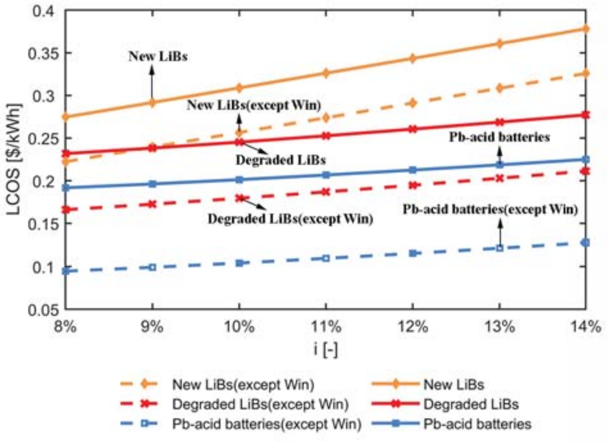

Fig. 1. LCOS changes with different discount rates which vary from 8 % to 14 % for a reference case at 10 MW, 40 MWh, and *cyc* = 365; the dotted lines represent cases where W_{in} is not included, while the solid lines are cases where W_{in} is included.

The results illustrate that the LCOS calculated including W_{in} is higher than that without W_{in}, but their trends are the same. By analyzing equation (11), it can be seen that the discount rate trend is not related to the electricity input.

The discount rate ranges from 8 % to 14 % at a cycle of 4 h. The batteries run for 1460 h every year. The LCOS increases monotonically with the discount rate, with the lowest at 8 % discount rate and the highest at 10 %. In this case, the Pb-acid battery is the most cost-effective ESS method among different battery technologies. The LCOS of degraded LiBs is lower than New LiBs at the same discount rate. In this case, the LCOS of the New LiBs is around 0.28-0.38 $/kWh, which closes to the Lazard report [54] about 0.355-0.686 $/kWh. And the LCOS of the degraded LiBs is around 0.22-0.29 $/kWh. The LCOS of the Pb-acid battery is around 0.18-0.25 $/kWh.

The discount rate trend in the LCOS will not change if the cost of electricity input is considered.

The results in Fig. 2 show that the LCOS varies with the discharging time, where i = 10 % and *cyc* = 365. The LCOS decreases significantly in the initial 7 h, after that, the change is small and gradual. The whole change is similar to the research made by Lotfi [55]. The New LiBs have the highest LCOS of 0.270 $/kWh, whereas the LCOS of the degraded LiBs is 0.206 $/kWh and that of the Pb-acid batteries is 0.162 $/kWh, which is close to Jlch's study with 0.21 $/kWh for Pb-acid batteries [38].

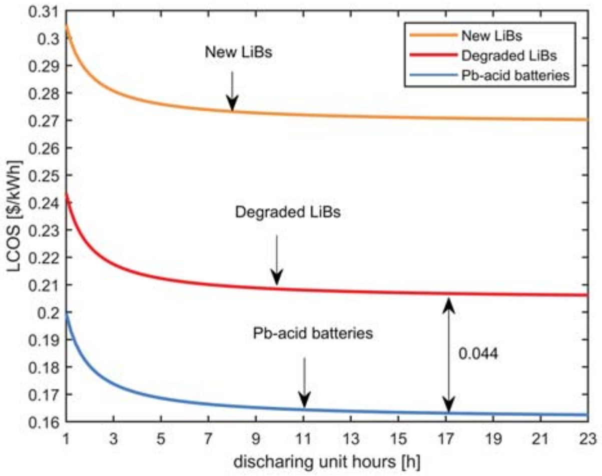

Fig. 2. Variation of LCOS in one cycle for three types of batteries at different discharge times; And i = 10 %, *cyc* = 365, 10 MW.

The results in Fig. 3 show that the LCOS changes with the lifetime of the battery. Pb-acid batteries have the lowest LCOS, while New LiBs have the highest LCOS. This graph shows that we can adjust the LCOS by adjusting the lifetime of the battery. According to the data in Table II, the lifetime is 4 y. Thus, we can reduce the LCOS of degraded LiBs by replacing the battery as soon as possible. The replacement time is at leat 24 years; if the batteries are replaced too early, it will increase the costs, such as increasing the transport cost (we have assumed that the transport cost is unchanged in these experiments, but it will be affected by many factors in reality). On the other hand, the life of general degraded LiBs is no more than 10 years. According to this figure, it is not realistic to reduce the LCOS by delaying the battery replacement time.

Overall, the results in Figs. 2-3 show that degraded LiBs have the lower LCOS than that of New LiBs, but higher cost than Pb-acid batteries. The results also suggest that we

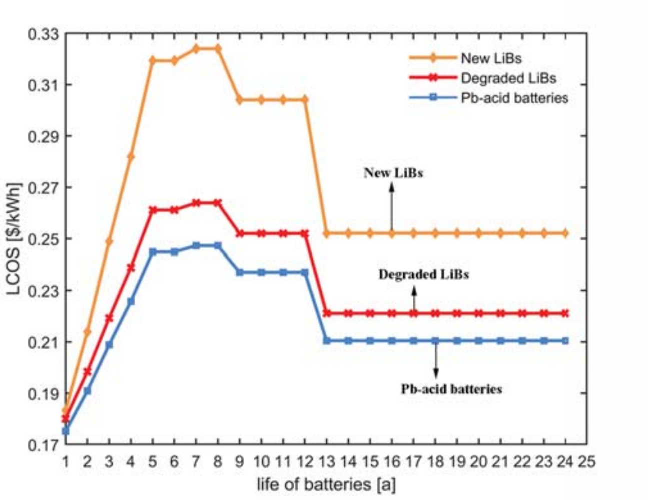

Fig. 3. The variation of LCOS for three types of batteries at different battery lifetimes; *cyc* = 365, 10 MW, 40 MWh.

can reduce the LCOS to a rational level by adjusting three factors. For example, the LCOS of degraded LiBs can be reduced by decreasing the discount rate, increasing the cycle discharge time and replacing the battery as soon as possible.

B. Impact of the Discount Rate and the Numbers of cycles on LCOS

This section shows the LCOS of storage system in terms of the discount rate and *cyc*.

Fig. 4 shows the the variation of LCOS for different discount rates and *cyc*. The LCOS decreases with increasing discount rate and *cyc*. The LCOS of the degraded LiBs is between that of New LiBs and Pb-acid batteries.

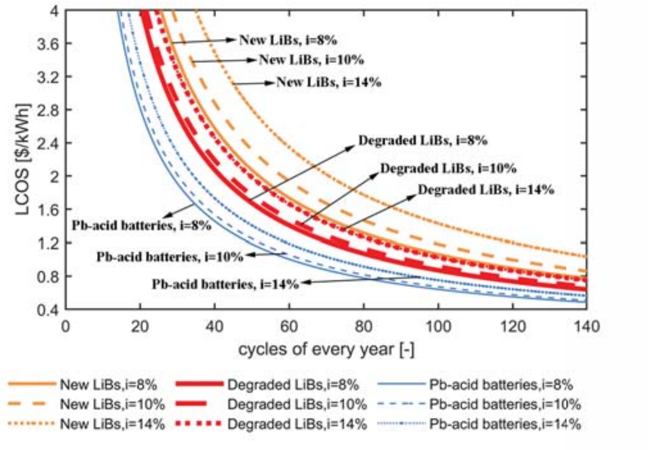

Fig. 4. The changes for LCOS of the three batteries at different number of cycles and discount rates; the reference case is 10 MW and 40 MWh.

In the same discount rate and cycles, the LCOS of Pb-acid batteries is the lowest, while the LCOS of new LiBs is the highest. The LCOS decreases as the cycles increase and the discount rate decreases. This suggests that we can reduce the LCOS by reducing the discount rate and increasing *cyc*.

Fig. 5 shows the variation of LCOS for three different batteries at i = 8 %, 10 %, and 14 %. The results show that the degraded LiBs have the higher LCOS than Pb-acid batteries. When i = 8 %, they differ by 0.03 $/kWh while when i = 10 %, they differ by 0.04 $/kWh; when i = 14 %, they differ by 0.04 $/kWh. The LCOS of the Pb-acid batteries is around 0.24-0.27 $/kWh, and the LCOS of the New LiBs is around 0.32-0.42 $/kWh, which is close to the research made by Jlch [38] about 0.21 $/kWh of the Pb-acid batteries and 0.33 $/kWh of the New LiBs.

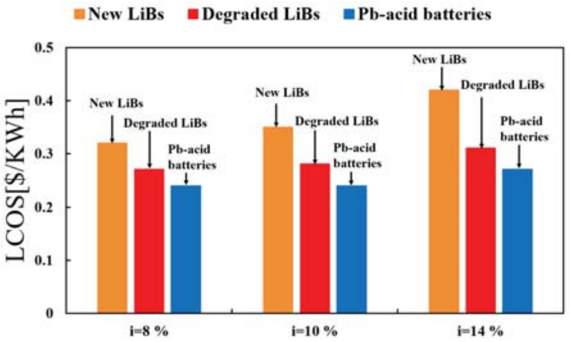

Fig. 5. Comparison for LCOS of the three batteries at different discount rates; the reference case is 10 MW, 40 MWh, and *cyc* = 365.

C. Analysis of a few Important Elements in the LCOS

Fig. 6 shows the results of the contribution of various cost elements to the LCOS. The reference case is at *cyc* = 365, *tt* = 6 h, P_{out} = 10 MW, i = 10 %, new LiBs lifetime = 10 y, degraded LiBs lifetime = 4 y, Pb-acid batteries lifetime =2 y; and Cthe = 0.0447 $/kWh. The LCOS results are as follows: new LiBs = 0.349 $/kWh, degraded LiBs = 0.288 $/kWh, and Pb-acid batteries = 0.244 $/kWh. Six main elements are shown in the graph: CIE, OME, C_{win} and REVA occupy the greatest part; DEEX and EUE constitute only a small proportion.

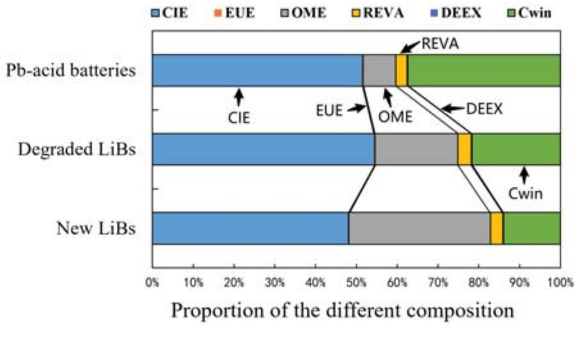

Fig. 6. Contribution of different cost components to the LCOS: capital initial expenditure (CIE), operation and maintenance expenditure (OME), equipment updating expenditure (EUE), depreciation expenditure (DEEX), residual value (REVA), and electricity input cost (C_{win}).

In the degraded LiBs, CIE has a higher cost. The degraded LiBs require additional overhead for disassembly, packaging, and safety prevention, increasing the cost of the CIE. The cost of purchasing power is also higher for lead-acid batteries because of their lower charging efficiency.

D. Sensitivity Analysis

In this section, the changes in the LCOS are observed by controlling eight different parameters, focusing on the investigation of the degraded LiBs.

Fig. 7 shows the impact of eight parameters on LCOS. The values of each parameter range from -20 % to 20 %. The *cyc* and efficiency of the batteries have the greatest impact on the LCOS because *cyc* affects the battery power generation and the battery charge/discharge efficiency. The lifetime of the battery, battery unit cost, and CIE also have a significant influence on LCOS. This is due to the fact that the life of the battery has a significant impact on EUE, the battery unit cost can influence CIE and EUE. Moreover, CIE contributes a considerable proportion to LCOS (see Fig. 7); therefore, it also has an impact on LCOS. The electricity unit cost also has an impact on the LCOS, but not as much as the other parameters. And the electricity unit cost only affects the cost of purchased electricity.

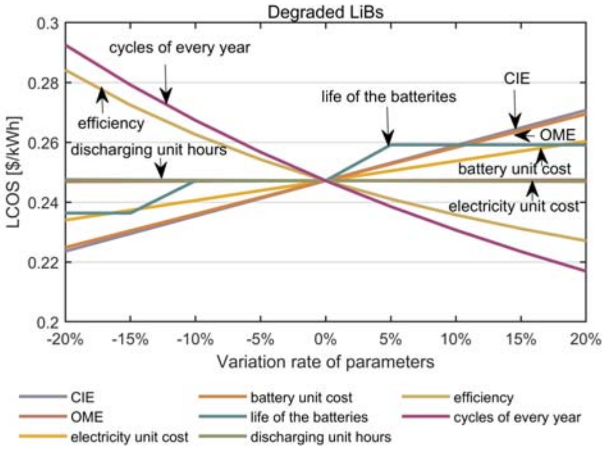

Fig. 7. Sensitivity analysis for 8 factors on LCOS: CIE, OME, electricity unit cost, battery unit cost, life of the batteries, discharging time, efficiency, and *cyc*. The data is varied as follows: battery unit cost of new batteries = 283 $/kWh, battery unit cost of degraded batteries = 96.31 $/kWh, battery unit cost of Pb-acid batteries = 145 $/kWh; discharging time = 4 h, and *cyc* = 365 y; when one parameter is varied, the other parameters are not changed.

These results illustrate that we can reduce the LCOS by lowering the battery unit cost and electricity unit cost, reducing the life expectancy at the current life (reducing the CIE is more difficult), and increasing the number of cycles (because it is difficult to increase the efficiency).

E. Measures Recommended to Reduce the LCOS of Degraded LiBs

We have used Matlab to develop a LCOS app which could easily calculate the LCOS. Table III is obtained from this application.

Based on Table III, we propose these strategies to reduce the LCOS of degraded LiBs to the same level as that of Pb-acid batteries: (1) the LCOS of degraded LiBs can be reduced to 0.244 $/kWh by government subsidy of 67.31 $/kWh; (2) the LCOS of degraded LiBs can be reduced by increasing *cyc*, for example, the LCOS of degraded LiBs is reduced to 0.244 $/kWh when cyc is increased to 456; (3) accelerating the replacement time of degraded LiBs from the original 4 years to 3 years can reduce the LCOS to 0.268 $/kWh; (4) for the energy consumption issues, there were 102.3 billion kWh power wasted in China in 2019 [56], and the discarded electricity is used to recharge degraded LiBs. The electricity unit cost can be reduced to 0.0145 $/kWh, which is the lowest price for redundant electricity in the grid and can reduce the LCOS of degraded LiBs to 0.243 $/kWh; (5) adjusting several factors simultaneously can reduce the LCOS. For example, with *cyc* = 426 and an electricity unit cost of 0.0145 $/kWh, the LCOS of degraded LiBs can be decreased to 0.244 $/kWh; with a government subsidy of 41.31 $/kWh and *cyc* = 400 y, the LCOS can be decreased to 0.244 $/kWh.

These results show that the LCOS of degraded LiBs can be reduced to that of Pb-acid batteries. These results are extremely significant as a guide.

TABLE III
DEGRADED LIBS COMPARE WITH PB-ACID BATTERIES

Symbol	battery unit cost[$/kWh]	*cyc*[-]	lifetime [a]	C_{et} [$/kWh]	LCOS [$/kWh]
Pb-acid batteries	145	365	2	0.0447	0.244
Degraded LiBs:					
Case 1	29(96.31)	365	4	0.0447	0.244
Case 2	96.31	456(365)	4	0.0447	0.244
Case 3	96.31	365	3(4)	0.0447	0.268
Case 4	96.31	365	4	0.0145 (0.0447)	0.243
Case 5	55(96.31)	400(365)	4	0.0447	0.244

F. Data Address

The LCOS app is open access and available in https://github.com/tangtang5/matlab_LCOS.git The code can only run in Matlab.

Matlab version: 9.5.0.944444 (R2018b).

IV. CONCLUSION AND RECOMMENDATION

This study performed an economic analysis of the secondary use of degraded LiBs from EVs in an ESS. The LCOS was used to analyze the economic feasibility. We optimized the LCOS equation by increasing the depreciation expense to offset some of the taxes, which could improve the accuracy of the results.

The LCOSs of several different types of batteries were analyzed. The results presented that the trend is the same regardless of whether the parameter W_{in} is present in the formula of LCOS. In addition, the LCOS of the degraded Li-ion battery is lower than that of the new lithium-ion battery, but higher than that of the Pb-acid battery.

The influences of numerous factors on the LCOS were considered, such as *cyc*, discount rate, *tt*, and lifetime. The results showed that we can reduce the LCOS by decreasing discount rate and increasing *cyc* and *tt*.

We analyzed the impact of a few important elements on the LCOS. The results show that capital initial expenditure, electricity purchasing cost, operation and maintenance expenditure and residual value have a significant impact on the LCOS. The LCOS of degraded LiBs was between that of New LiBs and Pb-acid batteries, while the Pb-acid batteries had the lowest LCOS.

In a sensitivity analysis of the batteries, the effects of eight different factors on the LCOS were evaluated. The results show that efficiency, cycle time, and lifetime have the greatest impact on the LCOS, indicating that the test for degraded LiBs is important, followed by the battery unit cost, capital initial expenditure, and electricity unit cost.

Even though degraded LiBs have the higher LCOS than Pb-acid batteries, we can adjust the influential factors and take some measures to reduce the LCOS of degraded LiBs. The following recommendations are made:

(1) Government subsidies of around 41.31-67.31 \$/kWh for secondary use batteries can reduce the LCOS;

(2) Increasing the *cyc* of batteries to 456 will reduce the LCOS of degraded LiBs to an optimistic level, which is equal to the LCOS of Pb-acid batteries;

(3) The excess electricity in the power grid can be utilized to charge the batteries, reducing the cost of charging batteries for secondary use in ESS;

(4) Because the lithium power battery has not reached the large-scale scrap period. The overall use of cascade is still in the stage of demonstration application. The Chinese battery recycling system is imperfect, which leads to a bit high cost of battery reassembly. Some cases can be learned from America and Japan to improve and build a perfect battery recycling system and a unified BMS standard [57], which could help reduce the battery reassembly cost and battery unit cost.

(5) This method and result can also be appropriate for other countries, especially those with serious energy consumption problems.

The results of this LCOS analysis are helpful for the application of degraded LiBs in ESS. By reducing the battery cost and configuring the appropriate battery, we can achieve an acceptable level of LCOS and make degraded LiBs available for ESS.

In the next step, we will analyze the battery safety performance. Although it is economically feasible to use degraded LiBs for energy storage, there are more safety hazards with degraded LiBs than other batteries, and thus a safety analysis of the use of degraded LiBs in ESS is important.

APPENDIX

ABBREVIATIONS AND ACRONYMS

cyc	number of cycles per year
C_{et}	energy unit cost (\$/kWh)
C_{win}	annual cost of purchasing electricity
C_{net}	net output energy of storage
C_{rated}	rated output energy of storage
DoD	depth of discharge (%)
i	discount rate (%)
n	year
N	storage lifetime
P_{out}	power of discharging unit (kW)
R_{sd}	monthly self-discharge rate (%)
R_r	residual rate (%)
T_r	tax rate (%)
tout	actual time for one discharge process
tt	prescribed time for one4xx discharge process
W_{in}	annual electricity input
W_{out}	average annual electricity output
W_{sd}	annual self-discharged energy
W_t	power station capacity
η_{in}	efficiency of charging unit (%)
η_{out}	efficiency of discharging unit (%)
BMS	battery management system
CIE	capital initial expenditure
DEEX	depreciation expenditure
EVs	electric vehicles
ESS	energy storage system
EUE	equipment updating expenditure
LCC	life cycle cost (\$/kWh)
LCOE	levelized cost of energy (\$/kWh)
LCOS	levelized cost of storage (\$/kWh)
LiBs	lithium-ion batteries
OME	operation and maintenance expenditure
OPEX	operation expenditure
PCS	power conversion system
REVA	residual value

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