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Review

Recycling and Echelon Utilization of Used Lithium-Ion Batteries from Electric Vehicles in China

Cuicui Liu[1], *Shaotang Huang*[1], *Zaiguo Fu*[1], *Cheng Li*[2], *Yibin Tao*[3,4], *Haibo Tang*[5], *Qiangqiang Liao*[1*], *Zhiqin Wang*[1]

[1] Shanghai Key Laboratory of Materials Protection and Advanced Materials in Electric Power, Shanghai Engineering Research Center of Electric Energy Conversion, Shanghai University of Electric Power, Shanghai 200090, China
[2] State Grid Hanzhong Electric Power Supply Company, Hanzhong 723000, China
[3] Nanjing Branch of China Electric Power Research Institute, Nanjing 210003, China
[4] School of Electric Power, South China University of Technology, Guangzhou 510640, China
[5] Shanghai Xiaochuan Technology Co., Ltd.
[*]E-mail: 458127159@qq.com

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As one of the regions with the largest number of electric vehicles (EVs) in the world, China has experienced rapid growth in the penetration rate of EVs, which has led to the peak period of power battery retirement. One of the challenges that people need to solve is how to properly dispose of these retired lithium-ion batteries (LIBs). As a possible solution, echelon utilization is considered to be the most promising method in terms of energy-saving and environmental benefits. The rapid classification and reorganization of retired batteries is the difficulty in realizing the practical application of echelon utilization. Therefore, this paper focuses on the current status and challenges of the echelon utilization in China. Firstly, the current status, recycling modes, and standards are summarized comprehensively to analyze its situation. Secondly, the key technologies of the echelon utilization solutions are analyzed in detail. Guidance and feasible technical solutions are delivered for battery non-destructive disassembly, rapid classifying and recombination. Finally, the future development direction of echelon utilization is examined. The booming cloud computing and artificial intelligence technologies are regarded as advanced means to realize the management of the whole cycle of LIBs, which will be widely used in echelon utilization.

Keywords: retired lithium-ion batteries, echelon utilization, classification and recombination, electric vehicles, state of health

1. INTRODUCTION

The increasingly serious problem of global warming on the environment has prompted governments to set strict targets to lower CO_2 emissions. China first proposed the goal of reaching the peak of carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 [1]. Lower emission targets push for the faster adoption of electric vehicles (EVs). Most countries are expected to reduce transportation-related CO_2 emissions. Fig. 1(a) shows the global sales share of EVs in 2021. In China, the "Measures for parallel management of average fuel consumption of Chinese passenger car enterprises and new energy vehicle accumulate points" effectively promote the pace of automobile enterprises to transform into new energy and accelerate the transformation and upgrading of the automobile industry. The "new energy vehicle industry development plan (2021-2035)" points out that the sales of new energy vehicles in China will account for 25% of the total vehicle sales by 2025 [2]. According to Greenpeace's forecast, by 2030, the EV sales in China will reach 12.5 million and the global sales will reach 43 million. The unstoppable momentum of EVs is driving a greater demand for power batteries. Fig. 1(b) displays the forecast of global EV sales and the demand for lithium-ion batteries (LIBs) from 2021 to 2030; the lithium demand globally and in China is estimated to be more than 2.1 TWh and 1.1 TWh in 2030, respectively. The demand for LIBs is increasing; however, behind the production of power batteries are a series of complex economic and social issues such as environmental pollution risks and energy consumption risks caused by metal mining [3]. In addition, The EV battery reaches its end-of-life and need to be replaced when its remaining capacity is below 80% [4, 5]. The increasing demand for LIBs brings the problem of large-scale retired batteries. The forecast for the retired LIBs and echelon utilization scale from 2021 to 2030 is displayed in Fig. 1(c). Taking 5 years as the service life of LIBs and 20% power loss as the retired condition, Greenpeace forecasted that the global retirement scale will reach 463.19 GWh in 2030 and the total retirement global scale will reach 1.3 TWh from 2021 to 2030. The retirement scale in 2030 will reach 192.48 GWh and the total retirement scale from 2021 to 2030 will reach 708 GWh in China. A tremendous number of retired LIBs will cause environmental pollution [6-8] and waste of resources [9-11] if they are not appropriately handled. For example, heavy metals in battery cathode materials such as nickel and cobalt pose a serious threat to the ecological environment and human health because they can cause significant levels of pollution to the land and water and be consumed by humans and animals [12, 13]. The retired LIBs still have 70-80% of their initial capacity and can, therefore, still be reused in some applications that do not require high power capacity, such as load levelling [14, 15], energy storage systems [16], and backup power [17, 18]. Currently, the echelon utilization of retired LIBs has become a hot topic in international academic circles because of its following values:

(1) It can reduce the production of new batteries and battery usage costs, creating a huge economic value.

(2) It can reduce carbon dioxide emissions and, thus, play a significant role in environmental protection.

According to Greenpeace's forecast, assuming that 80% of retired power batteries are absorbed by the market directly or after repair, the global echelon utilization of retired batteries will reach 370.55 GWh in 2030, creating a total value of 15 billion dollars. At the same time, compared with manufacturing new batteries, it will reduce carbon emissions by more than 2,186 tons. China will have 153.98 GWh of retired batteries for echelon utilization in 2030, which will create a total output value of 6.75 billion dollars and reduce carbon emissions by more than 9.09 million tons compared with manufacturing new batteries. However, although the echelon utilization of retired LIBs can bring both economic and environmental benefits, there are still many challenges that hinder the further its development in China. The following echelon utilization issues must be addressed immediately:

(1) The policies and regulations governing echelon utilization need to be refined, and the rights and responsibilities among car companies, battery manufacturers, consumers, recycling companies, and the government are not clear.

(2) There is a shortage of unified standards for power battery design and echelon utilization.

(3) The key technologies such as the battery residual capacity estimation, battery rapid classification and recombination, and the estimation of the battery life and safety during the process of re-use application need to be developed.

As an effective way to reasonably deal with the situation that large number of LIBs has been retired, it is necessary to sort out the current state of echelon utilization, analyze the key issues and pain points during the process of echelon utilization, and put forward reasonable suggestions.

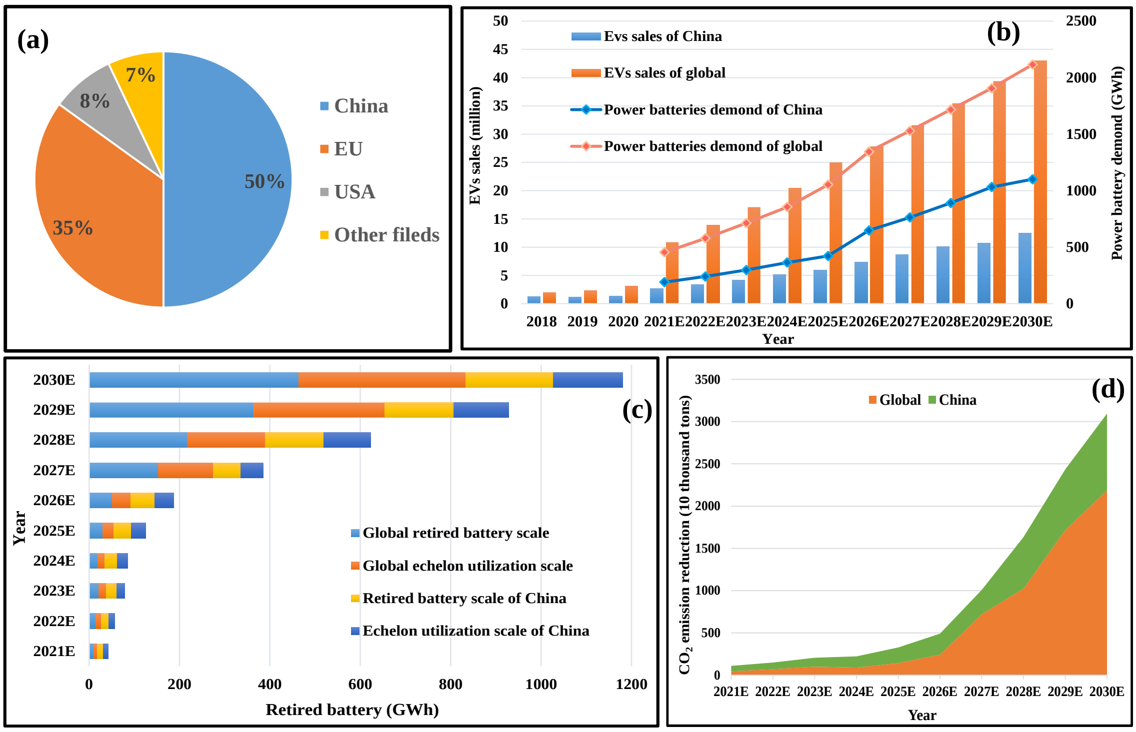

Figure 1. Markets and trends of global EVs and LIBs. (a) Global sales share of EVs in 2021. (b) EV sales from 2018 to 2020 and the forecast of EV sales and LIBs demand from 2021 to 2030. (c) Forecast of retired LIBs and echelon utilization scale from 2021 to 2030. (d) CO_2 emission reductions forecast from 2021 to 2030 (The results are obtained by assuming that 80% of retired power batteries are absorbed by the market).

The following is a summary of the key contributions of this paper:

(1) The current condition of echelon use in China is presented in a methodical manner. Specifically, the policies, recycling modes of retired batteries, and standards of echelon utilization are summarized.

(2) The crucial technical challenges that hinder the rapid development of echelon utilization are analyzed. The key technologies such as the estimation of battery SOH and battery rapid classification and recombination are discussed in detail.

(3) The development directions of the echelon utilization in the future are examined.

The remainder of the paper is organized in the following manner. The current state, industrial models, and standards of echelon utilization around the world are presented in Section 2. Section 3 discusses the key technical problems in echelon utilization. The important conclusions are presented in Section 4.

2. CURRENT STATUS AND CHALLENGES OF ECHELON UTILIZATION

2.1. Status of echelon utilization

There is no doubt that echelon utilization can maximize the service life of LIBs and is environmentally friendly and profitable. Countries all over the world are actively carrying out experimental research and engineering applications in echelon utilization. The developed countries such as Japan, the United States, and Germany have carried out research on echelon utilization [17-19] and have had some successful echelon utilization commercial projects [20-23]. China has mainly carried out the theoretical research and demonstration projects of echelon utilization in recent years [24, 25], and the exploration of the commercial operation of echelon utilization has just begun. Table 1 summarizes some projects under different application scenarios of echelon utilization in China. At present, all countries in the world are actively carrying out echelon utilization. Electric vehicle companies, battery companies, battery recycling institutions, and other upstream and downstream industries are enthusiastically searching and carrying out the key technologies and applications of echelon utilization [24]. Meanwhile, the intensity of the international cooperation is being strengthened. Renault Samsung Motors has established a cooperative relationship with LG Chemical in which Renault has supplied retired batteries from its SM3 Z.E electric vehicles to LG Chemical to explore and develop energy storage systems made from the retired LIBs. The British carmaker MG motor and Exicom Tele-Systems from India have reached a cooperation agreement in which Exicom will use the retired LIBs from MG electric vehicles to make energy storage products to prolong the life cycle of power batteries. BYD has established a cooperative relationship with Itochu Corp; the two sides established a joint venture to carry out the echelon utilization of LIBs and energy storage business. GEM in China signed a memorandum of understanding with Pohang municipal government in Korea. GEM and ECOPRO established a joint venture for the echelon utilization and recycling of retired LIBs in Pohang and have received the policy support of the Korean government.

Although the echelon utilization of LIBs is widely accepted and applied, the recycling system and operating model need to be further expanded. The echelon utilization is not regulated, which further hinders its development.

Table 1. Echelon utilization cases in China.

Application field	Case	Participants
Energy storage for industrial and commercial application	The 1 MW/7 MWh echelon utilization industrial and commercial energy storage system project was successfully put into operation in Rudong, Nantong, Jiangsu Province on September 1, 2018. The system is composed of seven 180 KWh.1 MWh container type energy storage systems. The total installed capacity is 1.26 MW/17.7 MWh.	GMDE, Hangzhou Zhongheng Electric Co.,Ltd., Nantong Power Supply Bureau
	The lithium-ion battery echelon energy storage power station of Jiangsu Changneng New Energy Technology Co., Ltd. was completed and put into use in the Innovation Industrial Park of Wujin National High Tech Zone on May 22, 2018. The old power battery replaced by electric vehicle is used.	Jiangsu Changneng New Energy Technology Co., Ltd.
Smart grid	Smart Grid State Grid Corporation, XJ Group Corporation, and the power supply company of Baoying county town used the retired 35 KV substation site in Xiashe to build an energy storage power station.	SGCC, XJ Group Corporation, Bao Ying Power Supply Company
	State Grid Henan Electric Power Company has established a basically decommissioned hybrid micro grid power battery system in Zhengzhou. The joint commissioning has been successful, generating more than 4500 MWh in a year.	State Grid Henan Electric Power Corporation
Energy storage of the grid side	The Hunan Changsha Furong energy storage power station project was successfully connected to the grid on April 23, 2019, marking the success of the first phase demonstration project of the Hunan Changsha grid side energy storage. This is also another large-scale grid side energy storage project put into operation after last year’s 100 MW grid side energy storage projects in Jiangsu and Henan.	Hunan Changsha Power Grid
Low speed electric vehicle	Zhongtian Hongli Qingyuan CO., LTD. and other low-speed electric vehicles promote the application of the echelon battery in sanitation, tourism, and other vehicles through the mode of “rent for sale”.	Zhongtian Hongli Qingyuan CO., LTD.
	State Grid Zhejiang electric power company reorganizes the retired power batteries of electric vehicles for the power supply of 48 V electric bicycles.	State Grid Zhejiang Electric Power Corporation
Echelon utilization and resource utilization	The Guangzhou Power Supply Bureau high reliability intelligent low carbon micro grid project was put into operation in Nansha. The Nansha micro grid not only uses green clean energy such as a roof photovoltaic system and energy storage system but also realizes 100% clean energy power supply for the important load.	Guangzhou Power Supply Bureau

2.2. Recycling modes and related industrial chain

Establishing a recycling system is an important point in echelon utilization. There are many sources of retired LIBs, ranging from national bus companies to private electric vehicle owners. It is difficult to obtain retired batteries directly from the end users. Fig. 2 shows the recovery model of foreign countries; overseas countries generally require manufacturers to be responsible for recycling. America and the European Union adopt the form of alliance and association to recycle batteries and the battery manufacturers handle the main responsibility for recycling [26]. The American International Battery Association has formulated a deposit system to urge consumers to turn in waste battery products on their own initiative. Five major battery enterprises in the United States initiated the establishment of the Portable Rechargeable Battery Association (PRBA) in 1991, which is responsible for building a battery recycling channel, establishing the American Rechargeable Battery Recycling Company (RBRC), and guiding the public to cooperate with the recycling of waste batteries so as to protect the natural environment [27]. The goal of the RBRC is to promote closed-loop recycling; the materials of used batteries can be recycled directly, and the energy consumption and waste can be minimized by eliminating mining and processing steps. The GRS fund, the largest LIBs recycling organization in the European Union jointly established by the German battery manufacturers association and the electronics manufacturers association, stipulated that battery enterprises can share the recycling network by paying service fees to the foundation according to the output [28]. In Japan, battery enterprises mainly establish recycling channels through “reverse logistics” [29]. The Japanese have a high awareness of environmental protection, and the battery manufacturers can use the service networks of retailers, car dealers, and gas stations to recycle waste batteries from consumers for free and hand them over to professional battery recycling companies for treatment. Toyota, Nissan, and other Japanese automobile manufacturers jointly launched the project of recycling retired lithium batteries of electric vehicles and jointly promoted the development of power battery recycling in the form of a group in October 2018. China adopts the extended producer responsibility system and has initially formed a power battery echelon utilization and recovery system with complete vehicles, batteries, and third-party enterprises as the main body. There are three recovery models [25]: 1. Under the guidance of the innovation alliance of the vehicle power battery industry, the government departments cooperate with new energy enterprises to use waste power batteries as energy storage or other fields. China Tower has become the largest echelon utilization subject of retired battery consumption. With the acceleration of the 5G base station construction, China Tower has clearly claimed that they are going to stop purchasing lead-acid batteries and will use retired lithium batteries instead of lead-acid batteries as a backup power supply for communication base stations [25], which has further increased the demand for waste lithium batteries; 2. Some third-party professional recovery enterprises such as Greenwich also are carrying out the recycling of retired battery. This mode significantly strengthens the strategic alliance and cooperation between the upstream and downstream of the industrial chain. Moreover, due to their rich experience, professional technology, qualification, and recycling channels, these enterprises usually have the best recycling efficiency; 3. Vehicle enterprises and battery manufacturers establish their own recycling system to recycle the retired power batteries sold by them. For example, BYD and BAIC New Energy mainly recycle the used power lithium batteries through authorized dealers, and CATL recycles the production batteries through the self-built battery recycling network. However, this model has some disadvantages; as the main body of responsibility, most automobile enterprises undertake the recycling task through 4S shops, but 4S stores and most battery manufacturers do not have the qualification conditions for battery recycling. This model is not convenient for unified management, and the recycling effect is not ideal. China advocates a battery recycling model of cooperation between upstream and downstream enterprises, that is, with vehicle companies as the leading role, battery suppliers, battery material manufacturers and some third-party companies specializing in battery recycling cooperate to recycle the retired batteries. The Ministry of Industry and Information Technology and other seven ministries issued "the Interim Measures for the management of new energy vehicle power battery recycling" [2], encouraging automobile manufacturers, battery manufacturers, scrapped vehicle recycling and dismantling enterprises, and comprehensive utilization enterprises to jointly build and share the recycling channels of retired batteries through various forms. CATL cooperates with YUTONG, SAIC, BAIC, GEELY, and other automobile enterprises to build a recycling system and also acquires BRUNP with the material recycling qualification to recycle the waste LIBs. BAIC ROCAR and GHTECH reached an agreement in 2018 to cooperate in such businesses as echelon utilization of retired power batteries and waste battery recovery. GEELY Group cooperates with WANXIANG Group, TIANNENG Co,. LTD., HUAYOU Cobalt, and other automobile manufacturers, battery manufacturers, and comprehensive utilization enterprises to build a common recycling channel, undertaking the pilot project of new energy vehicle waste battery recycling in Zhejiang Province.

In terms of legislation, the legislation on waste batteries in the United States involves three levels: federal, state, and local. At the federal level, they have promulgated "the law on resource protection and regeneration", "the law on the management of mercury containing batteries and rechargeable batteries" [30], and corresponding technical specifications have been put forward for the production, collection, transportation, storage, and other processes of waste secondary batteries. Japan has promulgated a number of relevant laws since 1993, implemented the "3R" plan (recycling, reuse, reduce), and explicitly required the establishment of a battery recycling system. The EU directive "2006/66/EC" [24] requires manufacturers to register with the relevant authorities; taking German laws and regulations as an example, the extension system of producer responsibility is implemented in Germany [28], and the producers, consumers, and recyclers of the industrial chain have corresponding responsibilities and obligations. Battery producers and importers must be registered with the government, and dealers should organize recycling mechanisms and cooperate with enterprises to introduce free recycling battery outlets to consumers. This directive not only stipulates battery classification management, recycling label requirements, recycling requirements, and capacity labeling regulations but also makes the significant effort to limit the use of mercury and cadmium.

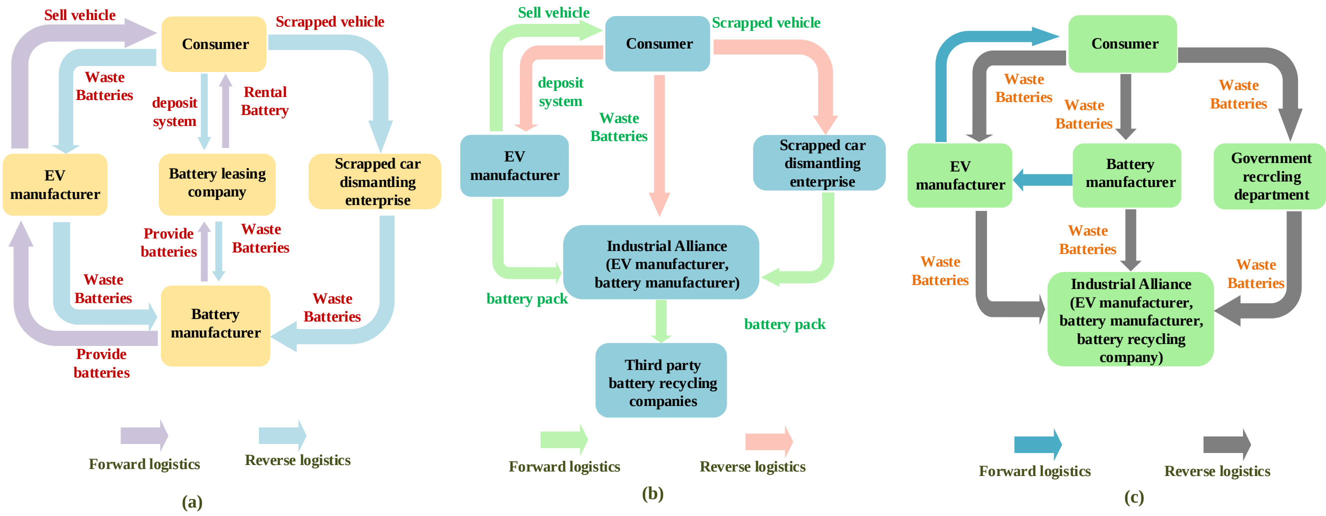

Figure 2. Recycle modes of waste batteries in different regions: (a) Japan, (b) USA/EU, and (c) China.

At present, China has initially established a basic recycling system for retired batteries and promulgated a series of regulations to regulate the battery recycling and echelon utilization [2, 25]. China has made it clear that LIBs recycling and treatment enterprises must have a hazardous waste business license before they can operate, and encouraged the development of lithium-ion battery disassembly equipment, such as the lithium-ion battery separators, metal products, and electrode material recycling equipment. What's more, the interim provisions on the management of the recycling and utilization of power battery for new energy vehicles has clarified the tasks of the main enterprises responsible for battery production and echelon utilization and proposed to establish a national comprehensive management platform. The main function of the traceability management platform is to collect information in the whole process of power battery production, sales, use, scrapping, recycling, and utilization and fulfill the recycling responsibility for each link subject.

2.3. Standardization of echelon utilization

From the practical application of echelon utilization, one of the important problems is that the standard system is imperfect. The standard system for the whole life cycle of echelon utilization products is not complete, which is mainly reflected in the power battery disassembly and the safe operation of echelon utilization products in the whole life cycle [19, 24]. The batteries produced by different manufacturers are different in material, structure and assembly process, this difference brings great challenges to disassembly, which improves the technical difficulty and cost of echelon utilization [31]. In order to realize the rapid and nondestructive disassembly of the battery, it is necessary to formulate standards to regulate the shape and size of power batteries. Fig. 3 displays some relevant standards in developed countries. The standard ISO/IECPAS 16898-2012 clarifies the power battery naming and size rules, which is helpful to solve the disassembly problem of retired batteries. In addition, after the selected batteries are reorganized to form new echelon utilization products, the relevant safety standards and use standards of different scenarios are also relatively deficient, especially in the field of energy storage. Echelon utilization will become empty talk if its products cannot run safely in different scenarios. The standard UL1974-2018 is specially formulated for retired batteries in echelon utilization. It covers the whole process of echelon utilization, including the information traceability, screening inspection, health assessment test, assembly test, production test and other links.

China has gradually paid attention to the follow-up treatment of retired batteries and has issued a number of relevant standards for echelon utilization in recent years. Table 2 shows some relevant national standards. GB/T 34013-2017 specifies the size and specification of the power cell, module and standard box on the electric vehicle. GB/T 34014-2017 standardizes the coding object, code structure, and data carrier of vehicle power battery coding, which lays the groundwork for the traceability and uniqueness of retired LIBs. Besides the national standards, some associations established by echelon utilization enterprises have also issued some industry standards, such as some energy industries of the National Energy Administration (NEA), China Electricity Council (CEC), China Energy Storage Alliance (CNESA), and China Association of Communication Enterprises (CACE). Table 3 lists the industry standards for echelon utilization in China.

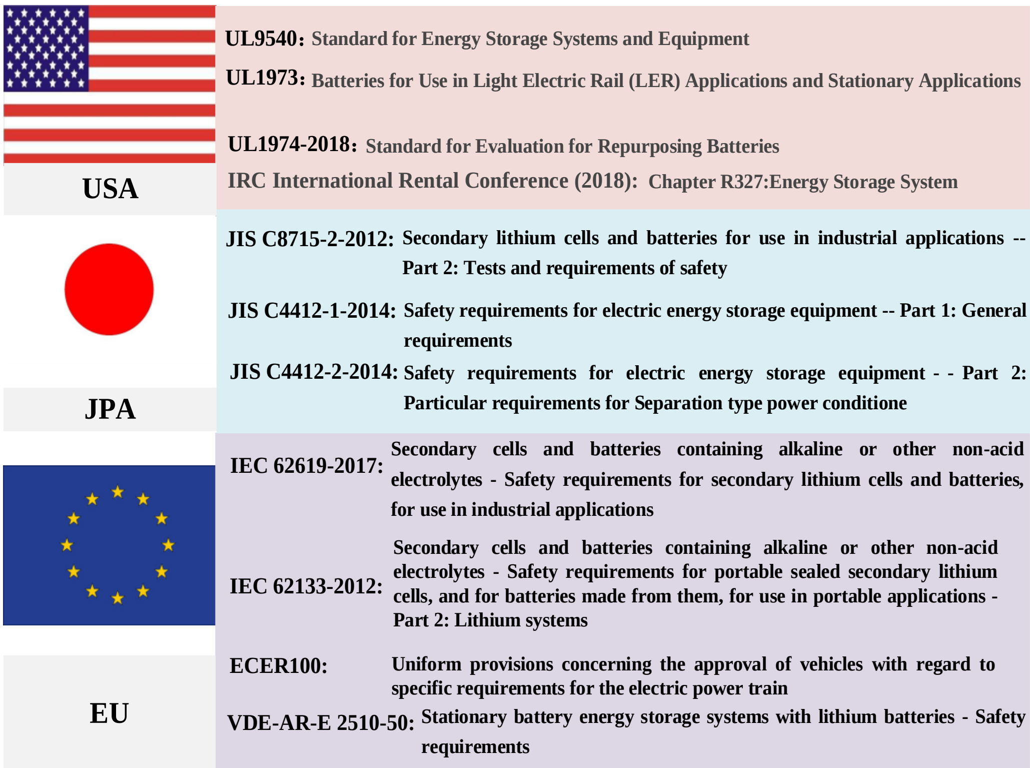

Figure 3. Relevant standards of echelon utilization in developed countries.

Table 2. Relevant national standards of China.

Standard number	Standard name
GB/T 34013	Dimension of traction battery for electric vehicles
GB/T 34014	Coding regulation for automotive traction battery

GB/T 34015	Recycling of traction battery used in electric vehicle - Test of residual capacity
GB/T 36276	Lithium ion battery for electrical energy storage
GB/T 36549	Operation performance index and evaluation of electrochemical energy storage station
GB/T 34131	Technical standard for battery management system of electrochemical energy storage station
GB/T 36547	Technical rule for electrochemical energy storage system connected to power grid
GB/T 36548	Test specification for electrochemical energy storage system connected to power grid

Table 3. Industry standards of echelon utilization.

Standard number	Standard name	Publishing unit
T/CAICI 3-2	Technology and service specifications of echelon using $LiFePO_4$ batteries	CACE
NB/T 42091	Technical specification for lithium ion batteries of electrochemical energy storage station	NEA
T/CAICI 1	Technical requirements and test method of echelon using $LiFePO_4$ batteries for 48 V telecommunication application	CACE
T/CNESA 1000	Evaluation specification for electrochemical energy storage system	CNESA
T/CNESA 1002	Technical specification for battery management system of electrochemical energy storage system	CNESA
T/CEC 172	Safety requirements and test methods of lithium ion battery for electrical energy storage	CEC

3. KEY TECHNICAL ISSUES FOR ECHELON UTILIZATION

3.1. Nondestructive disassembly

Battery packs should be split to the module level, for the most part, and then sorted and recombined for use in different echelon utilization scenarios. Fig. 4 displays the challenges at different levels of disassembly. Removing battery packs from automobiles requires high-voltage training and insulation tools. Many packs have different internal and external structure and module connection mode, and the adhesive between battery modules and the components welded together are difficult to remove [31]. Therefore, battery pack splitting is still mainly performed manually at the present. Jin et al. [32] designed microscale near-surface structures on the interface between current collectors and composite membranes in lithium-ion batteries, so that the composite layer of the electrode can be easily stripped from the collector. A large number of manual fine operations make the battery separation efficiency low, and if the operation is improper, there may be a short circuit, liquid leakage, and other safety problems [33]. Thermal runaway caused by heating can produce particularly harmful by-products [34] such as HF. Robotic battery disassembly could eliminate the risk of injury to workers and improve the degree of automation and reduce the cost, which would make recycling economically feasible. The battery pack disassembly and assembly are still unable to achieve complete machine automation at the present. Wegener et al. [35] submitted an image of a battery disassembly work station. Robots can perform simple repetitive tasks such as removing screws and bolts while humans conduct more complicated tasks. In addition, automation can improve the mechanical separation of materials and components, improve the purity of separated materials, and make the downstream separation and recovery process more effective. CATL-SAIC Power Battery Co., Ltd provides a semi-automatic grab device for the battery pack for battery pack removal on electric vehicles. GEM Co., Ltd invented an intelligent dismantling system for the waste power battery, which is a type of system for the nondestructive dismantling of the battery pack. The advantages of the system are that it has a simple structure, it has a high efficiency, and it does not damage the disassembled materials. These advantages can improve the recycling rate. There are still many challenges [33] in robotic lossless disassembly of battery packs. Different battery packs require the development of different computer programs and disassembly equipment in the process. In order to ensure the integrity of the cell and each component, the position and shape of the battery pack must be very accurate. Also, the battery manufacturers should take factors such as convenient nondestructive disassembly and environmental protection into account in the production and processing of battery packs. Artificial intelligence, sensor technology, and computer vision algorithms will also be gradually used in battery disassembly. In the future, the intelligent battery disassembly line can be operated intelligently and flexibly through the manufacturing execution system (MES) system of full process data control combined with a multi-task actuator workstation, quick change manipulator, CCD image recognition, and motion positioning guidance. Efficient and safe disassembly and recovery will be realized.

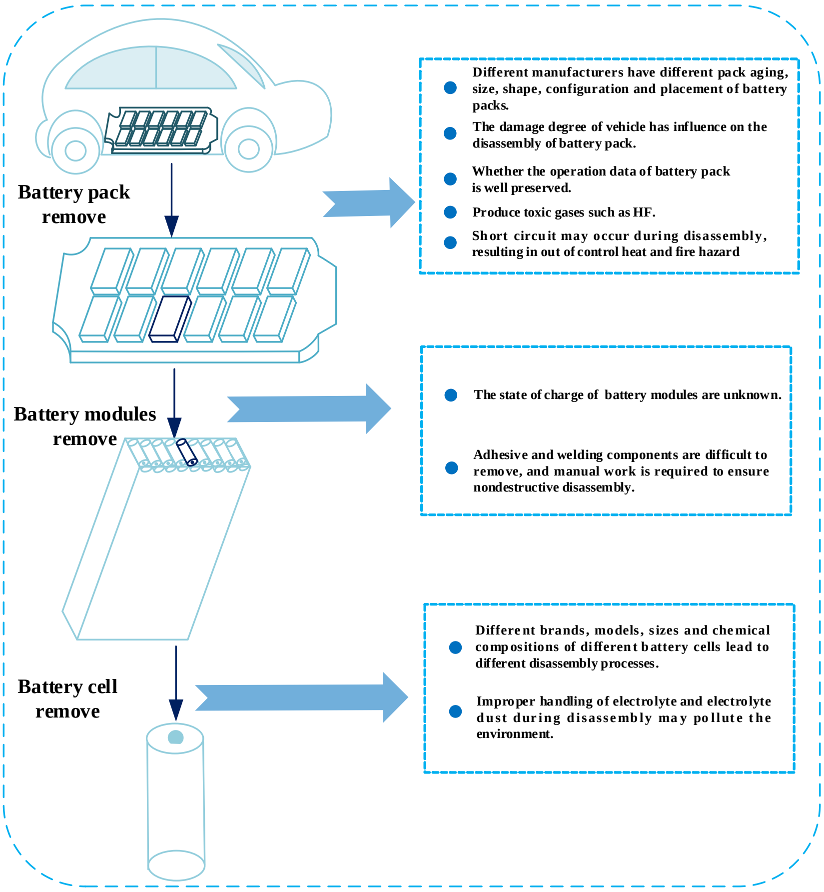

Figure 4. Challenges at the different levels of disassembly.

3.2. Rapid classification and recombination of retired LIBs

Echelon utilization refers to the process of dismantling, screening, reorganization, system integration, and reuse of recovered retired batteries [36]. Due to the performance differences of batteries of the same specification produced by different battery suppliers and after long-term on-board use under different driving conditions, the degree of performance attenuation of the batteries will be different. The inconsistency of the retired batteries will directly affect the service life and safety of the battery packs. The degradation of LIBs is a complex process that is caused by a variety of degradation mechanisms. The main aging mechanisms usually involve thermodynamic loss and kinetic loss [37]. Thermodynamic loss includes the losses of lithium inventory (LLI) [38] and active materials (LAM) [39], while kinetic loss is mainly reflected in the impedance increase of the cell [40]. Fig. 5 shows the causal relationship of the influence of different parts of the aging mechanism of lithium batteries on the state of health (SOH). The selection of batteries includes preliminary screening and consistency screening. Preliminary screening is the visual inspection of the battery to eliminate appearance problems such as bulging, damage, deformation, and abnormal voltage. Battery classification mainly consists of the following steps: 1. Appearance inspection: check whether the battery appearance has deformation, damage, leakage, or other bad conditions; 2. Basic performance test of the battery; 3. Assessment of the remaining useful life and state of health of the battery. The evaluation of the remaining useful life and state of health is the key to the consistent sorting of batteries. There are many methods to evaluate the SOH. Fig. 6 shows the classification of the evaluation methods. Capacity and internal resistance are usually used as indicators to directly evaluate the state of health. The directly test methods are the Static Capacity Test [41] and Electrochemical Impedance Spectroscopy (EIS) [42]. The former is a method to obtain the current capacity of the battery by the constant current discharge at a constant temperature (30 ℃ or 25 ℃) at a current rate corresponding to the rated capacity, but it takes a long time because it needs one or more charge and discharge processes. The latter is a non-destructive method to test the internal impedance of the battery through the scanning frequency test method. In addition to providing information on the SOH, it also provides information on the aging mechanism of the battery, such as the interface reaction between the electrolyte and electrode material. Gogoana et al. [43] tested the cycle life of two groups of parallel batteries at a high rate and found that the inconsistency of 20% internal resistance would shorten the cycle life by 40%. The test time for EIS is only a few minutes, but the equipment cost is high, which is not suitable for large-scale tests. The SOH evaluation methods also include model methods, extracting health factors directly, and machine learning. Model methods include the electrochemical model [44, 45] and the equivalent circuit model [46, 47]. These two methods explore the aging mechanisms, discover the reason for the aging of the battery, and evaluate the state of health according to the change in the internal and external parameters.

As one of the most widely used methods, the extraction of health factors evaluates the state of health by extracting external parameters such as voltage, resistance, and temperature. Common evaluation methods are based on a charge discharge curve such as increment capacity analysis (ICA) [48-52], differential voltage analysis (DVA) [53-56], differential thermal voltammetry (DTV) [57-59], and open circuit voltage (OCV) [60-62]. By analyzing the peak spacing of the DV curve or the peak area of the IC curve, the electric quantity participating in the material phase change process can be obtained so as to obtain the capacity attenuation condition.

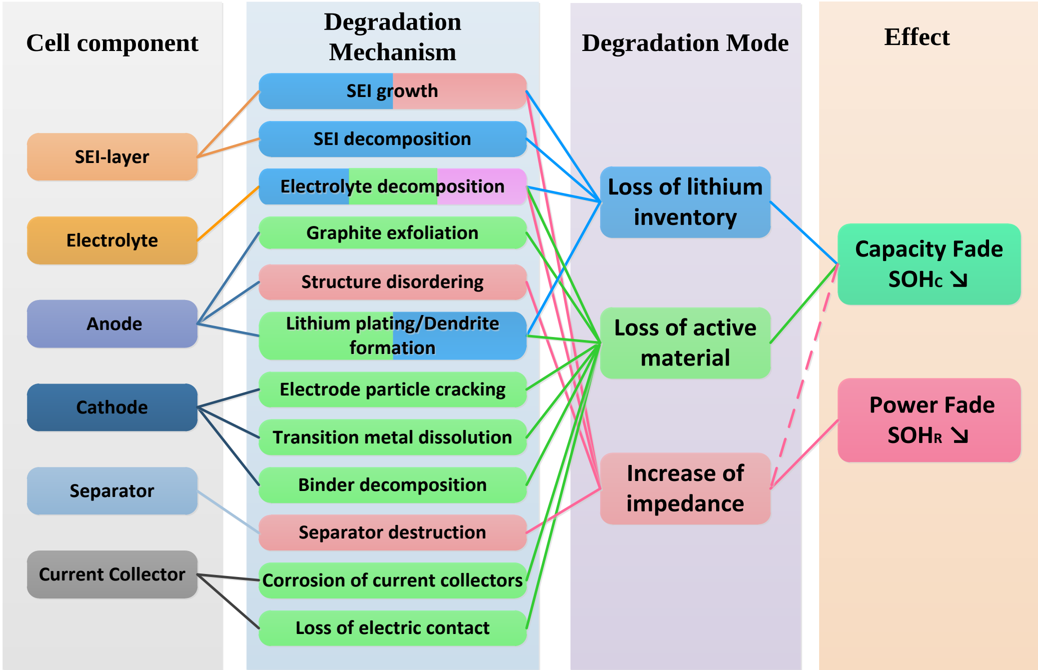

Figure 5. The causal relationship of the influence of different parts of the aging mechanism of lithium batteries on the SOH.

In addition, Liao et al. [63] found that under a low SOC (state of charge) (30%, 10%, or 5%), the open circuit voltage range (the difference between the maximum open circuit voltage and the minimum open circuit voltage) of the module has a good linear negative correlation with the SOH value of the module. Also, the working voltage or the open circuit voltage during the charging and discharging process of the battery system or module or the static process can be acquired in real time through the battery management system. Heger et al. [64] researched the degree of aging of a commercial $LiFePO_4$ battery at different discharge depths of 55 ℃ and - 20 ℃ and comprehensively analyzed the aging mechanism of the battery by ICA, DVA, and OCV.

With more attention to artificial intelligence, machine learning is becoming an important method to evaluate the state of health. This method is devoted to designing a battery health prediction algorithm, and combined with related parameters, to train a large number of samples to realize the fast screening. Common data-driven methods include neural network [65-68], support vector machine (SVM) [69-71], and probability density function (PDF) [72, 73]. Table 4 lists the purpose and comparison of the advantages and disadvantages of several commonly used algorithms in machine learning. Based on a small amount of lithium-ion battery capacity and voltage parameters, Ouyang et al. [65] established a set of fast screening models for a large number of retired cells by using a neural network algorithm. The error of the capacity estimation of the model is less than 4%, and the screening efficiency is more than 5 times higher than the traditional method. Zhou et al. [69] adopted a deep machine learning method to mine the internal relationship between multi-parameter health indicators including internal resistance and the state of health and realized the online evaluation of the SOH value with an error rate less than 2.5%. From Table 5, we can see that the data-driven methods to evaluate the SOH rely on a large number of sample data, so the accuracy of this method is low if the original data is incomplete.

The single method always has the disadvantages of low accuracy and weak generalization ability. Now, the combination of the model method, data-driven methods, and the instrument test has become a research hotspot. Li et al. [70] established three battery degradation models by combining the partial incremental capacity and support vector regression algorithm, and the validation results showed that the root mean square error (RMSE) of the three models is limited to less than 2%. Li et al. [70] also selected the Davinan equivalent circuit model as the basic battery model. they used the exponential fitting method to fit the resistance capacitance circuit (RC) parameters in the equivalent circuit model, and the double Kalman filter method was performed to established the SOC and SOH of the battery: based on the ampere-hour integration to use the extended Karl Mann filter method to estimate SOC, based on the capacity method to use Kalman filter to estimate SOH. The simulation results of the random current excitation are compared with the actual SOH results. The error is less than 1%, and the reliability of the algorithm is verified. Fang et al. [74] established a battery equivalent circuit model in which the forgetting factor recursive least square method (FFRLS) was performed to realize the on-line identification of model parameters and the double extended Kalman filter (DEKF) algorithm was used to estimate the SOC and SOH. The estimate results show that the maximum estimation error of the SOC and SOH are all within 2%. Song et al. [75] optimized and combined several algorithms to present a method of lithium-ion battery state estimation based on a data-driven least squares support vector machine (LSSVM) and a model-based unscented particle filter (MPF). The estimation error of the state-of-charge is less than 2%, and the RMSE of the state-of-health estimation is less than 4%. The significant improvement in the accuracy and robustness by combining various estimate methods and algorithms was proven.

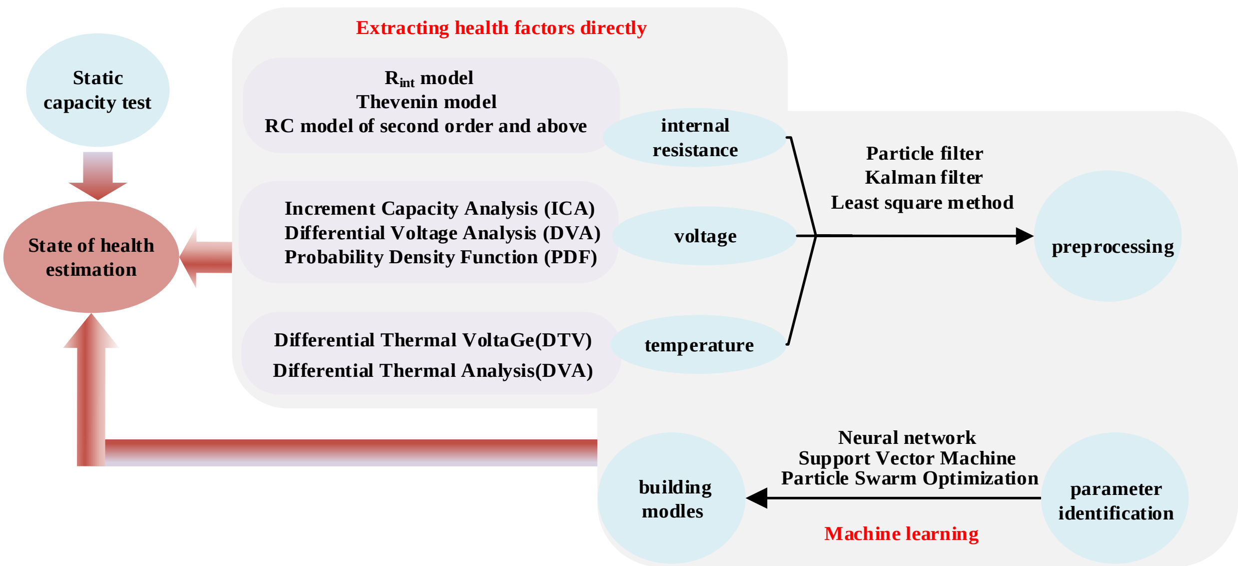

Figure 6. Assessment methods of the state of health.

Table 4. Comparison of advantages and disadvantages of related algorithms for the assessment of SOH.

Algorithm	Advantage	Disadvantage	Purpose
Kalman filter	high precision and good robustness; good anti-jamming of noise abatement ability	There will be estimation errors in dealing with nonlinear problems	Parameter extraction
Relevance vector machine	high accuracy	It is only suitable for short-term forecasting;	
Genetic algorithm	gives an optimal solution; strong robustness; can solve complex optimization problems	The running time is long and it is easily affected by parameters	Data preprocessing
Least squares method	high accuracy; can provide a great fitting result	It is not suitable for fitting nonlinear data	
Neural network	approximates the complex nonlinear relations completely; great ability of associative memory; with good fault-tolerance competence	It needs a large number of sample data; It has a long learning cycle and the model process is unobservable	
Support vector machine	simple; high precision; wide range of applications	It relies on high-quality parameter selection and extraction; It is only suitable for small sample learning	Building models
Particle swarm optimization	simple; convenient; widely used	It is easy to get trapped in a local optimum	

3.3. Safety management over the whole life cycle

Retired batteries are selected and recombined into echelon utilization products, and their subsequent safety management is also very important. The long-term cycle process results in the growth of lithium dendrites that pierce the packaging, resulting in a micro short circuit inside the battery, which will cause the self-discharge of lithium-ion batteries and even fire, explosions, and other hazards [76]. The poor consistency is also the main internal factor affecting the safety. Battery management system provided by the power station can solve problems such as inconsistency and the prediction of the SOH. In view of the safety problems caused by the internal short circuit of the battery, there are some model-based methods that can be applied to the online use of the battery management system. By measuring the characteristic parameters of the short circuit, such as voltage [77] and temperature [78], the risk of thermal runaway of the battery pack can be judged. However, this method cannot accurately locate the damaged cell. Zhang et al. [79] proposed an internal short circuit detection method based on a parallel circuit topology, namely the symmetrical loop topology (SLCT). This SLCT structure not only ensures the detection of ISC but also realizes the accurate location of the fault unit by detecting the abnormal current in the loop. Jaewanpark et al. [80] developed a retired battery pack energy management unit, which includes an extended Kalman-filter based state estimator, an enhanced current divider, and a protection circuit to ensure the safety of the system. The most significant highlight of the management unit is that it can accurately evaluate and identify the battery with the worst neutral energy of the battery module and take corresponding balance management measures. Wu-yangsean [81] developed a high conversion efficiency energy management system for retired batteries: parallel super capacitors on the battery energy management system to provide peak energy for batteries with obvious voltage degradation and to achieve battery balance and energy management.

In the battery combination model, the series and parallel connection of batteries is simple and economical, and can achieve high voltage and large capacity of the battery pack. However, this simple series and parallel circuit does not have the ability to balance the battery and reduce the battery inconsistency [82]. Moreover, when the voltage is increased in series, the internal resistance of the battery will be increased after the parallel connection. The overall life of the battery will be greatly shortened, and at the same time, the safety of the battery system is greatly reduced [83]. Hence, the simple series parallel combination is not suitable for the large-scale application of batteries. The power conversion system (PCS) inverter topology of the energy storage system determines the application mode of the battery combination to a certain extent. Using the modularization of the circuit topology structure to reduce the scale of the battery, the direct series parallel connection can not only reduce the difficulty of battery selection and assembly but also be a means of battery management and control. Common topologies are cascaded H-bridge (CHB) [84-86] and the modular multilevel converter (MMC) [87-89]. PCS with two structures can control the stepped energy storage system well from the circuit point of view, achieve redundant fault-tolerant operation, and achieve the phase-to-phase equilibria of battery energy storage system by differential control of different modules.

A large number of frequency converters is used in energy storage power stations due to the low reliability of frequency converters. There are great hidden dangers in bad weather, such as battery failure and thunderstorms, and if the insulation between the module and the platform is very poor, leakage may occur. In addition, there is the potential risk of electric shock because the battery itself is a charged body; some parts may still be charged when the power supply is not connected. The above safety factors shall be fully considered in the design and production of echelon utilization products.

4. CONCLUSIONS

As the most promising method for dealing with large-scale retired batteries, Echelon utilization can extend the service life of the battery effectively. This paper provides a systematic review of the current status of echelon utilization and the industrial model around the world. It discusses and summarizes the key technologies such as the battery SOH estimation, rapid classification and recombination, and looks forward to the future development direction of echelon utilization. The main conclusions of this paper can be summarized as follows:

(1) Echelon utilization has broad application prospects; it can create great environmental and economic value. However, there are still many difficulties that need to be overcame. The standards, value chains and business models in echelon utilization also need to be further refined.

(2) From an economic point of view, the closed-loop management of the whole life cycle of LIBs should be realized. Therefore, a particularly important trend in the future is gradual strengthening of upstream and downstream cooperation in the battery industry.

(3) Rapid assessment of residual value is one of a key technology of retired LIBs. The method of combining artificial intelligence (AI) with big data can predict the battery SOH and remaining service life more accurately.

With the strong support of national policy, echelon utilization has developed rapidly. The cooperation between the leading enterprises has been significantly strengthened. Many universities, scientific research institutes, power battery manufacturers, and energy storage integrators are cooperating to arrange the echelon utilization market. Through learning from the experience and practice of advanced regions, the construction of recycling systems and industrial technology innovation will be promoted, diversified business models will be explored, and professional support platforms will be built.

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

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT
Cuicui Liu: Conceptualization, Writing-original draft. Shaotang Huang: Data curation. Zaiguo Fu: Data analysis, Visualization. Cheng Li: Resources, Project administration. Yibin Tao: Methodology. Haibo Tang: Mechanism analysis. Qiangqiang Liao: Validation, Supervision, Writing-review & editing. Zhiqin Wang: Investigation.

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