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Integrating offline logistics and online system to recycle e-bicycle battery in China

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Abstract

E-bicycles are powered by batteries including lithium-ion, lead–acid, and others. The reuse of waste batteries shows promise for grid-scale storage. The New National Standard for e-bicycles is to be introduced in China, that might result in the country becoming the largest source of battery waste in the world. If the waste batteries are not recycled appropriately, it will cause significant heavy metal pollution, which will in turn, pose a serious threat to the ecological environment and human health. This paper discusses the current status of recycling of e-bicycle batteries in China and reviews the current recycling approaches. We developed a waste e-bicycle battery recycling system based on "Internet+" to solve the dilemma of recycling end-of-life batteries; this system has three subsystems: offline reverse logistics recovery system, online network recycling system, and traceability management system. In particular, the participation of consumers and government, reward-penalty mechanism, "Internet +" development, and other strategies are considered to improve recycling systems throughout life cycle of the products. The proposed recycling system can increase the waste battery recycling rate by 2.59% under the reward-penalty mechanism, and reduce carbon dioxide emissions by 58%, which is conducive to promoting sustainable development.

Key words: Recycling system; Reverse logistics; "Internet+"; Online network recycling system; Traceability management

1 Introduction

Since 1995, China has experienced rapid urban expansion and economic growth for 20 years, and the use of electric bicycles (e-bicycles) has also flourished. Due to the speed, convenience, and low maintenance cost of e-bicycles, they have become the primary means of commuting, accounting for 16.5% of the total national traffic (China

Communication and Transportation Association, 2014). In 2014, China produced about 31.131 million e-bicycles. It is estimated that the number of e-bicycles is about 200 million (Ministry of Industry and Information Technology, 2018). The battery is the major component of the e-bicycle, and its service life is less than 3 years, so it needs frequent replacement. In general, the batteries types of e-bicycles include lead-acid batteries, lithium batteries, and nickel-hydrogen batteries, which are mainly composed of heavy metals such as lead, copper, cobalt, zinc, manganese, nickel, and electrolytes (Gu et al., 2017). If not handled properly, these substances can cause serious pollution to land and water, endangering ecological safety and human health (Tian et al., 2014). Moreover, recycling the battery allows the remaining power stored in the battery to be utilized, saving energy directly. On the other hand, waste batteries can be collected and converted into energy storage systems for use in the grid, reducing the burden on the grid supply. Importantly, recycling batteries can promote the recycling of rare metals and promote the sustainable development of electric vehicles (EVs), thereby saving energy and reducing dependence on fossil energy. Therefore, it is urgent to effectively develop a scientific recycling system of e-bicycles to protect the safety of the environment and people's lives and property.

At present, the recycling methods for waste products are mainly divided into two categories: traditional recycling method and innovative recycling method. Traditional recycling methods are based on offline transactions through reverse logistics recycling network. The different recovery options considered in the literature are: remanufacturing (Alumur et al., 2012), repairing (Dat et al., 2012) and recycling(Bal and Satoglu, 2018). Gobbi et al. point out that the grade or quality of the returned waste product plays an important role in determining the most appropriate recovery option (Gobbi, 2011). The remaining useful life (RUL) can be represented as the length of a system from the current time to the end of its useful life, which contributes significantly to maximizing revenue; products with high RUL can be sold in the secondary market for profit through remanufacturing (John et al., 2018). Soleimani considers a location-allocation problem in a closed-loop supply chain with the objective function is developed from expected profit to three types of mean-risk ones (Soleimani et al., 2014). Suyabatmaz et al present two hybrid simulation-analytical modeling approaches for the reverse logistics network design of the third-party logistics and discuss the results obtained from the two approaches under different scenario and parameter settings (Suyabatmaz et al., 2014). The other important factor in reverse logistics recycling network is the network design. The objective of network design models is to determine the different scenarios if the revenue generated for the same item varies across markets; typically there are two types of scenario: cost minimization (Paydar and Olfati, 2018) or profit maximization (Tosarkani and Amin, 2018). Guo et al. develop a mixed-integer linear programming model (MILP) to minimize the total cost of the wood recycling process (Guo et al., 2017). Trochu et al. develop a MILP to minimize the total cost of the wood recycling process (Trochu et al., 2018). Kumar et al. propose a multi-period, multi-echelon, forward-reverse logistics vehicle routing system to maximize the total expected profit (Kumar et al., 2017). Pedram et al. design a closed-loop supply chain network whose main objective is to maximize the profit and minimize the pollution by providing decision support to waste management (Pedram et al., 2017). Bazan et al. conclude that even after 60 years of modeling development, the mathematical focus is mainly on costs (Bazan et al., 2016). However, current studies focus on the reverse logistics network of a certain region or a certain product based on mathematical models, and the generalization is poor. Moreover, there is insufficient government regulation of the recycling system, there is little awareness of the importance of recycling batteries, and poor participation in recycling.

"Internet +Recycling" is an innovative recycling method that utilizes information technology to improve access to information and communication between recycling practitioners and the general population (Gu et al., 2017). In essence, "Internet +Recycling" uses online platforms where participants, both individuals and recycling practitioners, make appointments for onsite waste collection or trading (Gu et al., 2019). Due to its convenience and availability, the model is gaining increasing popularity and is increasingly used in the field of waste recycling. Currently, "Internet +Recycling" activities have taken place in over a dozen of cities, including major cities such as Dalian, Shenyang, Tianjin, Chongqing and Shenzhen (Gu et al., 2019). However, the transactions that take place on the "Internet +Recycling" application only represent a very tiny percentage of total waste recycling as it is a new recycling method that is still not widely accepted. "Internet +Recycling" provides valuable insights towards improving current management of e-bicycles recycling.

In order to improve the efficiency and structure of the recycling system and to improve the battery recycling rate of e-bicycles, the traceability management system was applied. Based on the concept of the product life cycle, the traceability management system can trace the product information back to the source and regulate the operation of the entire industry chain. It was first applied to food quality and safety regulation and has been extended to organic chemicals tracing (Bieber et al., 2018), transportation management (Madleňák et al., 2016), quality transitivity and traceability (Liu et al., 2018), and so on. This article innovatively applies the traceability management system to the recycling of e-bicycle batteries and traces the sold batteries to qualified recycling centers.

Based on the above analysis, we can conclude several defects of the current e-bicycles battery recycling system: (1) At present, the offline recycling method is currently the main method for e-bicycle battery recycling, and the recycling system at this stage still needs improvement, with poor efficiency and coordination. (2) Current research on the recycling of e-bicycles batteries is focused on the location of recycling stations. The research on recycling systems often targets a certain enterprise, or a region in the design of a recycling system, and ignores the overall recycling system of the entire industry. (3) There is insufficient government regulation of the recycling system, there is little awareness of the importance of recycling batteries, and poor participation in recycling. (4) The recycling method based on "Internet+" has been applied to the recycling of municipal waste, but the technology is currently not widely used or accepted.

To improve the recycling system of e-bicycle batteries, this paper proposed a novel recycling system of e-bicycle batteries based on "Internet +". The novel system contains three subsystems: an offline reverse logistics recovery system, an online network recycling system, and traceability management system. The offline recycling system uses hierarchical recycling stations, which can increase participation and strengthen government regulation. The system also proposes a renewable resource recycling center, waste disposal center and other institutions, which are conducive to standardizing the recycling process of e-bicycle batteries, prohibiting inappropriate recycling by small traders, and protecting the e-bicycle battery recycling market structure. To save transportation costs and to encourage the use of licensed recycling centers, an online network recycling system is proposed based on the idea of "Internet +". A traceability management system is developed to track the sold batteries to prevent inappropriate recycling or disposal.

Therefore, the unique features of the proposed recycling system and the major innovations of this study can be summarized as follows: (1) The proposed recycling system improves the shortcomings of the traditional recycling system with imperfect structure and low recycling efficiency. (2) Compared with traditional offline recycling system, the proposed offline reverse logistics recovery system increases the level of consumer participation and facilitates government regulation, incentives and enforcement. (3) The innovative online recycling system reduces recycling costs while providing greater convenience. (4) The traceability management system has been successfully applied to the recycling system through tracking the sale of batteries and providing a basis for government regulation, incentives and enforcement. (5) The proposed recycling system can significantly improve the recycling rate (by an average of 2.59 percent) and significantly reduce greenhouse gas emissions (by an average of 58 percent).

The major innovations of the proposed waste e-bicycle battery recycling system are shown in **Fig.1**.

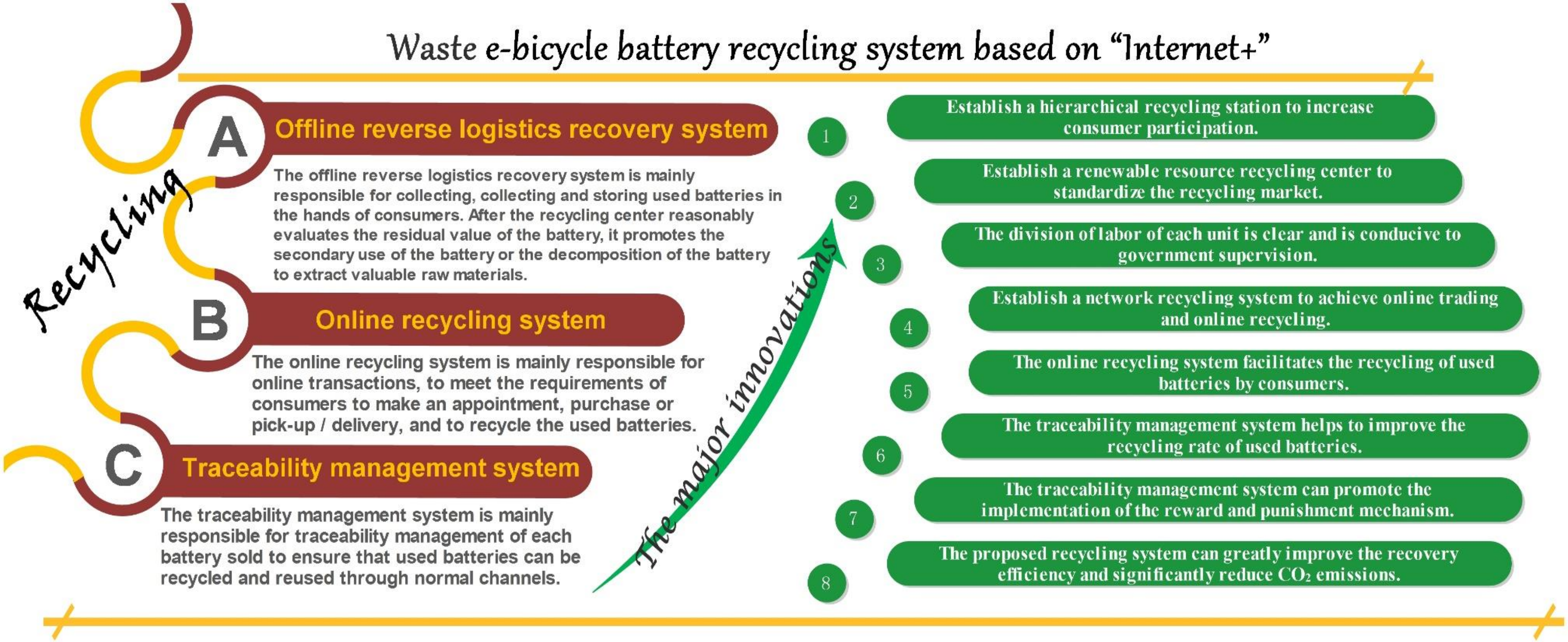

Fig.1. The major innovations of the proposed waste e-bicycle battery recycling system

2 The benefits of recycling e-bicycle battery

With the rapid growth of the economy and the acceleration of urbanization, the number of vehicles is also soaring as people's demand for ease of mobility continues to increase. From 2010 to 2016, China's automobile production amount increased from 18.3 million to 28.1 million, with a sharp increase of 53.6% (OICA, 2016). However, China is also under tremendous pressure to address its air pollution problems and to mitigate climate change through mitigation actions and is committed to expanding its EV market. Transport electrification not only affects air quality but also has a major impact on the sustainable development of water resources. Transport electrification will accelerate the demand for thermoelectricity. Thermoelectricity generation is depleting and polluting China's water resources (Chai et al., 2018). In recent years, the water efficiency of China's power sector has been effectively improved due to the adoption of water-saving technologies (Liao et al., 2019). Therefore, with the debilitating negative impact on water resources and the significant positive impact on air quality, EVs are the general trend and highly encouraged by China's government. To date, China is the world's largest EV market, accounting for more than 40% of global sales (IEA, 2017). In addition, based on its size and growth, the Chinese market is also seen as the most attractive for future investments(Liao et al., 2018). From 2020 to 2030, the total number of China's EVs is expected to skyrocket by 16 times from 5 to 80 million(Liao et al., 2018). In the development of the EV industry, the development of e-bicycles is important. According to relevant industry data, at the end of 2017, the number of e-bicycles ownership in China exceeded 250 million, and the number of electric tricycles has exceeded 50 million. E-bicycles are still increasing at a rate of more than 30 million ownership per year. In recent years, China's battery output has shown a rapid growth trend. The total output of large-scale battery companies exceeds 220.7 GWh, accounting for 40% of the world's total output. Resource consumption and heavy metal pollution are major environmental problems(Wang et al., 2018). If the used batteries are properly recycled, the risk of pollution will be reduced and more energy will be saved.

2.1 Reducing pollution of recycling batteries

Waste battery pollution is characterized as hazardous waste and must be disposed of appropriately. The potential environmental hazard is very serious. If improperly handled, waste batteries can easily cause secondary pollution and irreversible ecological disasters. The risks associated with used batteries are security risks, health risks, and agro-ecosystem pollution.

While e-bicycles are convenient, they also can present a fire hazard. The data shows that 80% of e-bicycle fires occur while charging, and 90% of e-bicycle fires cause casualties if they are stored in foyers or aisles. From 2013 to 2017, there were more than 10,000 fires caused by e-bicycles in China, an increase of 33.3% over the previous five years (MIIT, 2018). Since 2013, 233 people have died in e-bicycle fires nationwide (MIIT, 2014). Nanning is a city with the most EVs in the country and is known as the "Electric Vehicle Kingdom". Meanwhile, there are frequent traffic accidents caused by e-bicycles. In 2017, there were 2,778 e-bicycle traffic accidents in Nanning, causing 28 deaths and 640 injuries, accounting for 12.73%, 18.30% and 26.81%

of the total, respectively (Guangxi News Network, 2018). Therefore, while the e-bicycle industry is booming, the associated safety issues cannot be ignored.

Fig.2. E-bicycle accident example

E-bicycles are driven by batteries which contain a large quantities of heavy metals(Yun et al., 2018). Heavy metal pollution can accumulate in important organs such as kidneys, bones and liver, posing a threat to human health (Awasthi et al., 2016). For instance, Pb is a non-essential element of the human body, and excessive intake of this metal can result in enzyme inhibition and neurological, skeletal, circulatory, endocrine, and immune system damage (Pascaud et al., 2014). Long-term exposure to arsenic can cause skin damage, skin cancer, peripheral neuropathy and peripheral vascular disease(Tan et al., 2016). In addition, long-term exposure to Cd can cause adverse reactions, and accumulation of Cd in the human body can cause kidney, bone, and lung damage(Godt et al., 2006). In general, when metals penetrate cells, they interfere with the redox potential, which can destroy many of the reactions that occur in living cells; if the metal enters the nucleus, it can cause chromatin damage, leading to tumor transformation(Wu et al., 2018).

Waste batteries are often discarded in the environment if they are not properly recycled. The heavy metals contained in batteries are discharged into agro-ecosystems, which can have serious adverse effects on agro-ecosystems. Heavy metals are highly toxic, non-degradable and bio-accumulative contaminants. Agricultural soils contaminated with heavy metals and atmospheric metal deposits can cause excessive levels of heavy metals in crops(Liu et al., 2014). Once the agro-ecosystem is polluted by heavy metals, the effects are long-term. As China is a major grain producer, destruction of the agro-ecosystem threatens food security.

2.2 Energy and resource benefits of recycling batteries

Recycling e-bicycle batteries is an energy-saving measure. Most people choose to replace the battery when the battery capacity is less than 70%. When the battery is scrapped, there is commonly residual storage capacity. Therefore, the reuse of waste batteries can be used as an energy storage system to supply energy storage to the grid. The cost of recycling and utilizing waste batteries as an energy storage system is low which can reduce grid cost. By storing energy and discharging it when available to sustain power generation, waste batteries can act as a buffer between the renewable energy system and the grid to ensure that the grid is not affected by intermittent power generation. It also provides energy storage for the power system during peak hours and alleviates transmission congestion due to overload, which increases the life of the transmission infrastructure and reduces transmission capacity investment(B and P, 2018). Reusing the battery as an energy storage system can also include solar installations, which means that the electrical energy can be stored during the day for supply to households or companies.

The recycling of batteries not only protects the environment but also due to the scarcity of resources, the recycling of battery materials has a positive impact on the sustainable development of EVs. Taking cobalt resources as an example, according to the statistics of the Qinghai Salt Lake Institute of the Chinese Academy of Sciences, current global cobalt production is 150,000 tons, of which 80% comes from the recycling of waste materials. At present, 95% of China's cobalt resources are imported, and the use of cobalt in batteries accounts for 69%. The development of new EVs will lead to an increase in demand for cobalt resources. Recycling batteries can further enhance the sustainability of EVs.

3 Current recycling situation, achievements and challenges

This section describes policy background, current situation and achievements in e-bicycle recycling and analyzes the challenges of recycling.

3.1 Regulations and policies on e-bicycles batteries recycling

As the production and sales of e-bicycles continue to increase, the proper and efficient recycling of e-bicycle batteries becomes imperative. Generally, the service life of e-bicycles is less than three years. Therefore, the batteries of e-bicycles are frequently replaced, and the number of waste batteries is large, which presents a challenge in terms of waste management. Since the introduction of e-bicycles, the Chinese government has promoted the recycling of waste batteries. Appropriate recycling of e-bicycle batteries is not only a requirement for sustainable development but also supports the circular economy and low-carbon economic development. Therefore, the Chinese government has formulated many policies and regulations to promote the recycling of e-bicycle batteries. **Table 1** briefly describes several policies and regulations relating to the recycling of e-bicycle batteries.

3.2 Current situation and achievements

The government has promoted research and technology in the recycling of e-bicycle batteries and has made some achievements which are outlined in the following sections.

3.2.1 Development status of the reverse logistics recovery system

China is the world's largest producer and seller of e-bicycles for whose total number of e-bicycles is about 200 million and an annual output of more than 30 million.

The life of e-bicycle batteries is much shorter than that of the e-bicycles, and the recycling problem of e-bicycle batteries is a serious problem that cannot be underestimated. According to the data of the China Electric Vehicle Association, the recycling rate of used lead storage batteries is still less than 85%, compared to 100% recycling in developed countries. By 2014, more than 85% of EVs used valve-regulated lead-acid batteries, and about 90 million lead batteries are in demand. According to official data, the battery recycling rate of EVs is only 31.2%, and most of the waste batteries in the market have not been properly disposed of(Cherry et al., 2009).

Chen et al. collected information on the number of waste batteries recovered by 113 major e-bicycle retailers, 378 corporate and individual buyers specializing in industrial and commercial sector registrations, and 147 major e-bicycle repairers(Chen et al., 2017). The results show that although the number of recycled batteries has generally increased from 2011 to 2014, the ratio of recycling to the production of waste batteries has decreased year by year. This is due to the increased use of Lithium ion batteries (LIBs) that were used in 2011, which are difficult economically inefficient to recycle. Therefore, while improving the LIB recycling technology, a new e-bicycle battery recycling mechanism is needed to adapt to the increasing proportion of LIBs, and the problem of incomplete recycling.

At present, there are relatively few formal recycling institutions with professional certification, and the spatial distribution is not uniform. In a renewable resource recovery system, retailers collect and process large quantities of recyclables, and the official source separation of recyclables is still relatively small(Linzner and Salhofer, 2014). There are only about 30 licensed domestic recycling enterprises, and the number of professional waste battery purchase points is also small. According to the data of the Municipal People's Congress Standing Committee Urban Construction Environmental Protection Office, the annual production of waste lead storage batteries in the motor vehicle maintenance industry in Beijing is not less than 50,000 tons, but only 0.054 million tons were collected and recycled by licensed enterprises in 2018. Taking Suzhou as an example, the informal system collected 60% of the total domestic recoverable resources, while the formal system only accounted for 16%(Fei et al., 2016). Current e-bicycle battery recycling methods are still in the process of improvement. The current recycling method can be divided into three categories, retailer recycling, after-sales maintenance department recycling, and individual waste recycling stations.

For retailer recycling, e-bicycle retailers account for most waste battery recyclers(Chen et al., 2017). Consumers bring old batteries to the e-bicycle retailer to exchange for new batteries. This approach is the most direct and convenient, and as such retailers recycle the majority of waste batteries. Most of the waste batteries that are traded-in are sent to the factory for processing, and some of them are sold directly to individual waste recycling stations through e-bicycle retailers or service centers. Since retailers are located at a distance from the formal battery decomposition processing centers, the transportation cost is high, the cost of storage of waste batteries is relatively high, and there are low economic profits obtained by sending waste batteries to the regular battery dismantling centers. As such, some retailers often choose to dismantle and extract the important metals themselves, which are sold to metal recyclers; the waste electrolyte is disposed of in the environment, posing a huge environmental threat.

Recycling in the after-sales service department is also very important, Chen et al. show that the recovery rate is about 33.5±5.9% of the total waste batteries, of which 12.8±7.8% are reused after repair, and the rest are sold to individual waste recycling stations or into the recycling system(Chen et al., 2017). In order to obtain greater profits, some maintenance departments revamp waste batteries and sell them to the market without meeting the quality standards.

Consumers sell waste batteries to individual waste recycling stations, usually small businesses and small workshops. There is no control over the recycling process, which produces lead smoke and lead slag. A large amount of waste acid solution is caused by workshop-type recycling treatment leading to serious pollution.

Due to the lack of mandatory recycling directives, the average recycling rate of waste batteries is relatively low, mainly based on market economy behavior(Tian et al., 2014). At present, the recycling price of Pb-acid batteries is about $16, while the cost of LIB is only 80 cents. The low recycling price of LIBs has made e-bicycle retailers reluctant to recycle these batteries. Therefore, the consumer discards approximately 13.4 ± 6.7% of the waste Pb-acid batteries directly into the environment(Chen et al., 2017). However, due to technological advances, low lead stocks, etc., the proportion of LIBs in the market has gradually expanded in recent years, and there is a clear substitution effect. If the recycling and disposal of LIBs are not properly handled, it will pose a greater future danger to the environment.

Table 1
Policy regulations related to e-bicycle battery recycling

Effective Time	Laws or Policies	Brief Description	Issuer
1991/12/26	Notice on Strengthening Administration of Recyclable Resources Recycling	Specifying categories of recyclable resources; Preventing illegal business in recyclable metals; Requiring enterprises positively collect low value recyclable resources.	SCC
2011/10/31	Opinion on Construction of Complete and Advanced Waste Recycling System	Forming basic principles and main targets to construct modern and advanced waste recycling system; listing major tasks.	SCC
2012/07/20	Twelfth Five-Year National Strategic Emerging Industry Development Plan	Promote energy conservation and environmental protection industries, new generation information technology industry, new energy industry, new materials industry, new energy automobile industry and other industrial development	SCC
2013/03/12	Opinions on Promoting the Standard Development of Lead-Acid Batteries and Recycled Lead Industry	Increase environmental law enforcement, improve policies, regulations and standards, effectively control lead emissions, achieve standardized production of lead-acid batteries, orderly recycling, and rational recycling	MIIT, MEP, MOC, NDRC, MOF
2015/01/21	Medium and long-term planning for the construction of renewable resource recovery system (2015-2020)	Clearly establish the classification and recovery system, improve the functions of recycling nodes, cultivate leading enterprises, strengthen the supervision of industry order, and formulate relevant rules.	MOC, NDRC, MLR, MOHURD, ACFSMC
2015/02/16	Guidelines for Feasible Technology for Pollution Prevention and Control of Recycled Lead Smelting	In order to improve the environmental protection technology work system and promote the progress of pollution prevention and control technology in the recycling lead smelting industry, the requirements for the recycling lead smelting industry are required.	MEP
2015/12/11	Lead battery industry access conditions and，Interim Measures for the Administration of the Announcement of Lead Storage Battery Industry	Standardize the access conditions of lead-acid battery industry and promote the healthy development of lead-acid battery industry	MIIT
2016/05/05	Opinion on Promoting Transformation and Upgrading in Recyclable Resources Industry	Encouraging innovating RWR system, such as Internet+; Transforming extensive management modes to intensive management modes.	MOC, NDRC, MIIT, MEP, MOHURD, ACFSMC

2016/12/25	Promoters' Responsibility Extension System Implementation Plan	The scope of extension of producer responsibility is defined as four aspects: eco-design, use of recycled raw materials, standard recycling and information disclosure, and take the lead in implementing the producer responsibility extension system for products such as electrical appliances, automobiles, lead storage batteries and packaging materials. And clearly defined the work focus of various products	SCC
2016/12/26	Lead battery recycling and production pollution prevention and control technology policy，Waste Battery Pollution Prevention Technology Policy	Improve the environmental technology management system, guide pollution prevention, protect human health and ecological security, and guide the industry to green recycling and low carbon development	MEP
2017/12/11	2016 China Renewable Resources Top 100 Enterprises and Top 100 Enterprises' Operation Status Report	Established two branches of “New Energy Power Battery Recycling and Ladder Utilization Professional Committee” and “China Recycling Association Green Financial Service Center”	ACFSMC

Note: SCC (State Council of China); MIIT (Ministry of Industry and Information Technology); MEP (Ministry of Environmental Protection); MOC (Ministry of Commerce); NDRC (National Development and Reform Commission); MOF (Ministry of Finance); MLR (Ministry of Land and Resources); MOHURD (Ministry of Housing and Urban-Rural Development); ACFSMC (All-China Federation of Supply and Marketing Cooperatives).

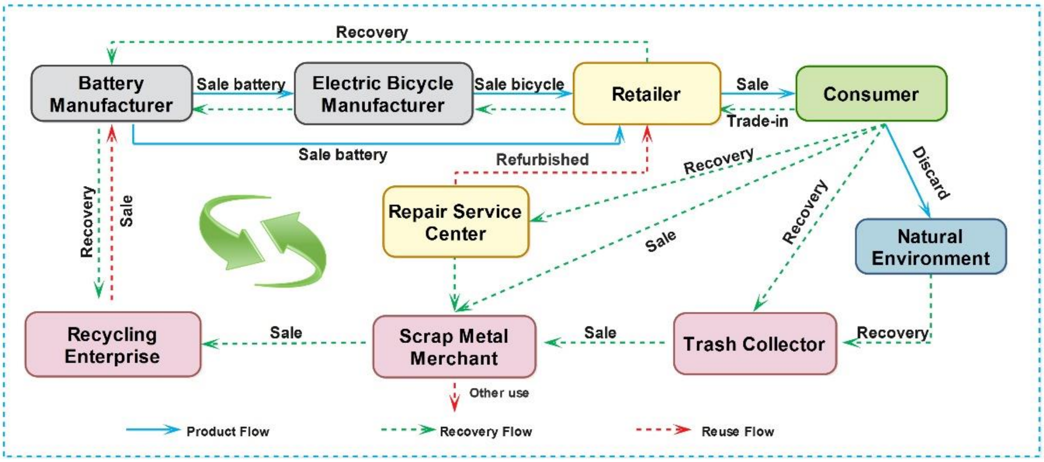

Fig.3. The flow of waste battery in the current recycling system

3.2.2 Innovative internet recycling method

There is an innovative recycling method that applies modern information technologies such as the internet, big data and mobile apps to facilitate online transactions, which are more convenient, cheaper and easier to operate. Currently, this recycling method has been applied to the classification and recycling of domestic waste. For example, Beijing Incom recycling resources recycling Co., Ltd. uses a Self-service machine to collect waste clothes and establish relationships with local communities, universities and museums. Individuals can access the local self-service terminal and print a receipt by touching the screen of the unit. He/she can then attach the stub to the discarded clothing and place it in the vending machine. The clothes are then separated and clean and usable clothes are donated to poor areas, and those that cannot be reused will be recycled. Individuals who donate clothes in this way can earn points for redeemable charity activities, which are also implemented by recycling companies. Waste Uncle (Xiamen) Environmental Protection Technology Co., Ltd. is known as the Alibaba of the recycling industry. One of the features of Waste Uncle is the "Internet +" chain operation method. Currently, 23,585 recyclers have joined Waste Uncle as franchisees. Waste Uncle has established the "Internet + Recyclable Resources + Supply Chain Finance" service platform. Waste Uncle has signed strategic cooperation agreements with financial institutions such as Bank of China and China Construction Bank. Xiamen Oriental Meicheng IOT Technology Co., Ltd. was established on April 13, 2017. It has built a platform for urban waste recycling and has an offline intelligent waste recycling bin which combines online and offline waste recycling systems. The platform provides services for the renewable resources industry and allows for a symbiotic win-win system for the residents, Oriental Beauty City, processing center, small and medium-sized enterprises, and government. At present, the total amount of waste generated every year in China exceeds 150 million tons, and this is increasing by 8%-10% annually. Xiamen currently recycles about 5,000 tons of waste per day. Once fully operational, Xiamen City can reduce urban waste disposal by 1,500-2,000 tons per day, which is of great significance.

3.3 Existing problems and challenges

According to the current development characteristics of the recycling system, it can be divided into two categories: offline recycling and online recycling. Offline recycling currently faces the following problems and challenges:

(1) ***The recycling system is confusing, and laws and regulations lack normative requirements for stakeholders.*** At present, there is no optimal e-bicycle recycling system, and relevant laws and regulations are not sound enough. The laws and regulations related to the battery recycling industry mainly include production license and environmental protection. Current existing battery-related laws and regulations are mostly in the form of policy guidelines. They do not clearly stipulate which units are eligible to recycle used batteries, and who is responsible for environmental pollution.

(2) ***Most of the recycling entities lack certification, and the amount of licensed recycling entities is less than that of illegal recycling entities.*** It is difficult for many enterprises or individuals to meet the requirements for application for the hazardous waste comprehensive operation license, and many are discouraged from applying. The illegal recycling entities in the e-bicycle battery recycling market are mostly waste recycling stations or personal flow recycling entities. These operations are uncertified, use low-cost recycling equipment, and basically act as intermediaries to sell the recycled waste batteries to downstream processing agencies. The permitted recycling entities have high fixed costs and cannot compete with illegal recycling entities, which makes it difficult for formally certified recycling entities to compete in the market. Therefore, the illegal recycling of e-bicycle is growing.

(3) ***Recycling technology needs to be improved.*** Uncertified enterprises currently dominate the electric bicycle recycling market. Their recycling technology is low-tech, and the method of disposing of used batteries causes great harm to the natural environment. The proportion of LIBs has gradually increased, and the recycling technology for LIBs is not advanced, resulting in great economic losses and environmental losses.

(4) ***Consumer recycling awareness needs to be improved.*** Consumer awareness needs to be improved mainly in two aspects: First, when the battery becomes redundant, some consumers directly discard the battery instead of recycling it or trading it in. Second, many consumers do not send used batteries to the standard recycling area for recycling but sell them to a mobile vendor at a price of more than a dozen yuan. They are not aware of the environmental cost of this behavior which is far greater than the economic benefits.

The online recycling method refers to the recycling and trading of used e-bicycle batteries on an established internet platform. At present, it has the following problems and challenges:

(1) ***The online recycling system is still a blank.*** Current recycling systems are mostly concentrated in offline recycling. The Online recycling system that can greatly reduce transportation costs has not received enough attention. Research on it now develops at a slow pace.

(2) ***The profit model of the online recycling model is still being explored, lacking government subsidies.*** Because of the low value of most recyclable resources and

the high cost of door-to-door collection, many “Internet+ Recycling” companies rely on subsidies to operate. Therefore, in order to develop the online recycling model of the entire industry, an exploration of the profit model is necessary. The online recycling method has attracted the attention of relevant government departments. Subsidy policies conducive to promoting the development of online recycling models have not yet been implemented.

(3) ***Internet recycling model is not easily accepted by older people.*** With the ageing of the population, the elderly account for a large proportion of the population. More importantly, the proportion of older people involved in the recycling of used items is greater, and it is more difficult for the elderly to accept the “Internet+ Recycling” method. Therefore, there are certain obstacles to the popularity of the “Internet+ Recycling” method.

(4) ***The current online recycling system is mostly targeted at a case study of a company and lacks overall applicability.*** The current “Internet+ Recycling” method is still in its infancy, and the systems currently established are mostly targeted at a single enterprise case. In view of the important position of the “Internet+ Recycling” method in information management and waste recycling management, it is urgent to establish an information service platform that can be applied across the industry to support the entire e-bicycle recycling activity.

4 E-bicycle battery recycling system based on “Internet +”

Due to the rapid development of e-bicycles in recent years, the e-bicycle industry has begun to enter the peak period of battery replacement, and the recycling of waste batteries will become more and more pertinent. However, the existing recycling system is still in the stage of improvement, and it is unable to cope with the current volumes of waste batteries. Therefore, it is imperative to propose a practical and effective battery recycling system for e-bicycles.

With the development of information technology, artificial intelligence technology based on internet big data is becoming more popular. The traditional recycling system focuses only on offline transactions, and there is no guarantee that every battery sold will be properly recycled after use. Therefore, this paper proposed an e-bicycle battery recycling system based on "Internet +", which is divided into three parts, the offline reverse logistics recovery system, the online recycling system, and the traceability management system.

4.1 Offline reverse logistics recovery system

The offline waste battery recycling network is currently the most important method for recycling waste batteries. It has the advantage of practical operability and high acceptance by the consumers. However, in the actual operation process, there are still shortcomings such as incomplete recycling and low operational efficiency, resulting in wasteful environmental pollution and other adverse consequences. Therefore, improving the current reverse logistics recovery system for e-bicycle batteries is of great significance for promoting the recycling of waste batteries.

This research proposes a general network for reverse logistics to optimize product recovery and remanufacturing. As shown in **Fig.4**, this is designed as a multi-level reverse logistics network with a hierarchical recycling system. The objective of the proposed model is to maximize recycling of waste batteries within the network. **Fig.4 part a** shows the detailed layout of the proposed reverse logistics recovery network, which has the following main features:

(1) Systematic and structurally stronger. Due to the systemic and structurally weak recycling system, some waste batteries are not correctly recycled, resulting in double losses for the economy and environment. Therefore, the recycling system proposed in this paper defines the recycling path for waste batteries, clarifies the recycling unit of waste batteries, and creates a structured recycling network.

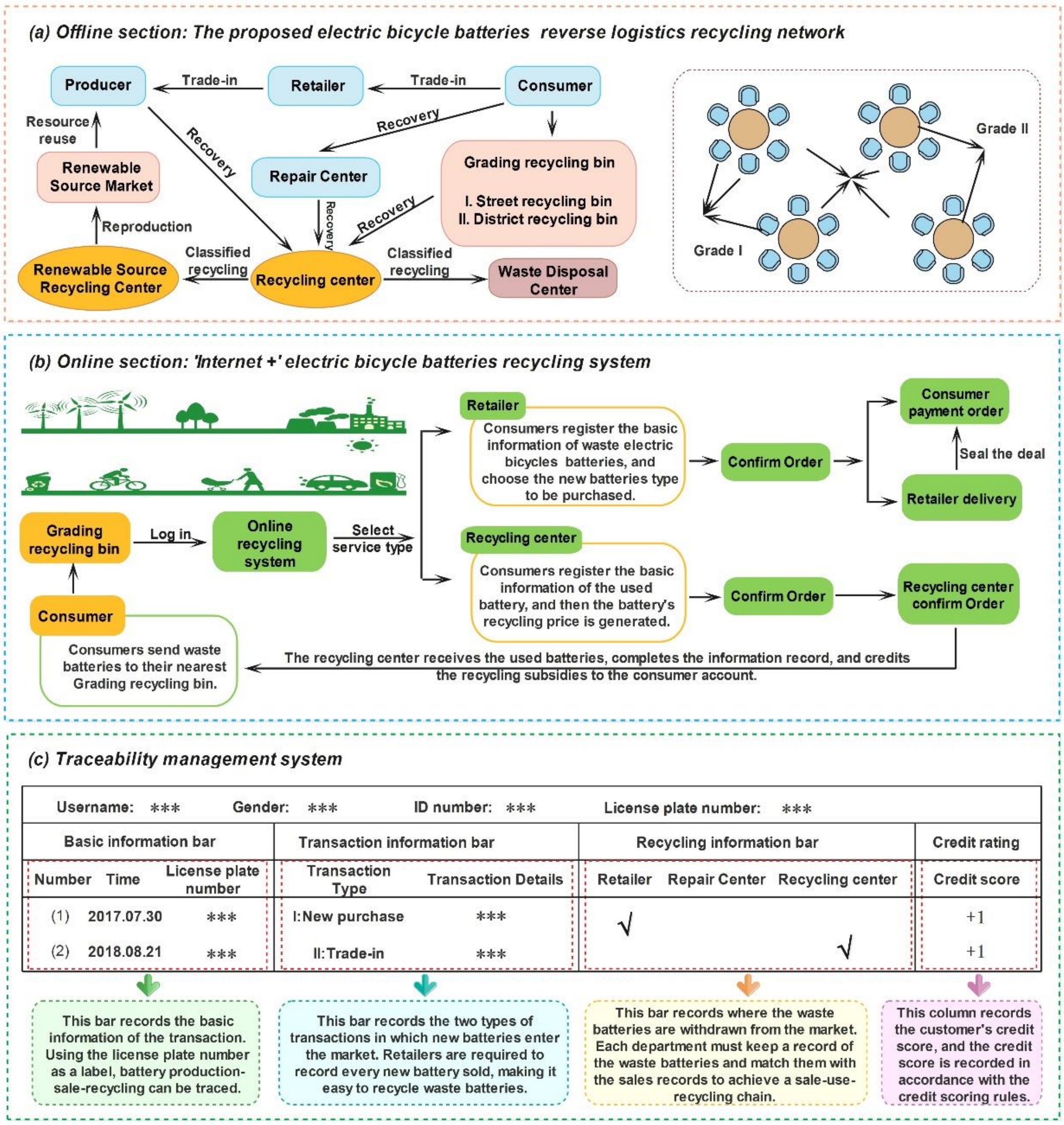

Fig.4. The proposed hybrid e-bicycle battery recycling system

(2) High level of participation in grassroots communities. The existing waste battery recycling system is simplified and lacks participation by the grassroots community. Recycling waste batteries is not only an economic activity but also protects the environment(Li et al., 2015). Therefore, the recycling of waste batteries cannot be completely dependent on market behavior, and it requires the participation of the grassroots community. The proposed system includes a hierarchical recycling system that considers the number of batteries consumed, how consumers are distributed, the concentration of regional and internal market layout, etc. The community will send the waste batteries to the first-level recycling station, and then the second-level recycling stations will collect the waste batteries from the first-level recycling station and sort them to send to the corresponding recycling and processing units. **Fig.5** shows the concept map of the proposed hierarchical recycling station in detail. This method reduces the tendency for direct disposal of waste batteries to the environment due to high transportation and related costs and allows for greater convenience in the recycling of waste batteries. Together with the implementation of the government regulation system, the recycling rate of waste batteries can be greatly improved.

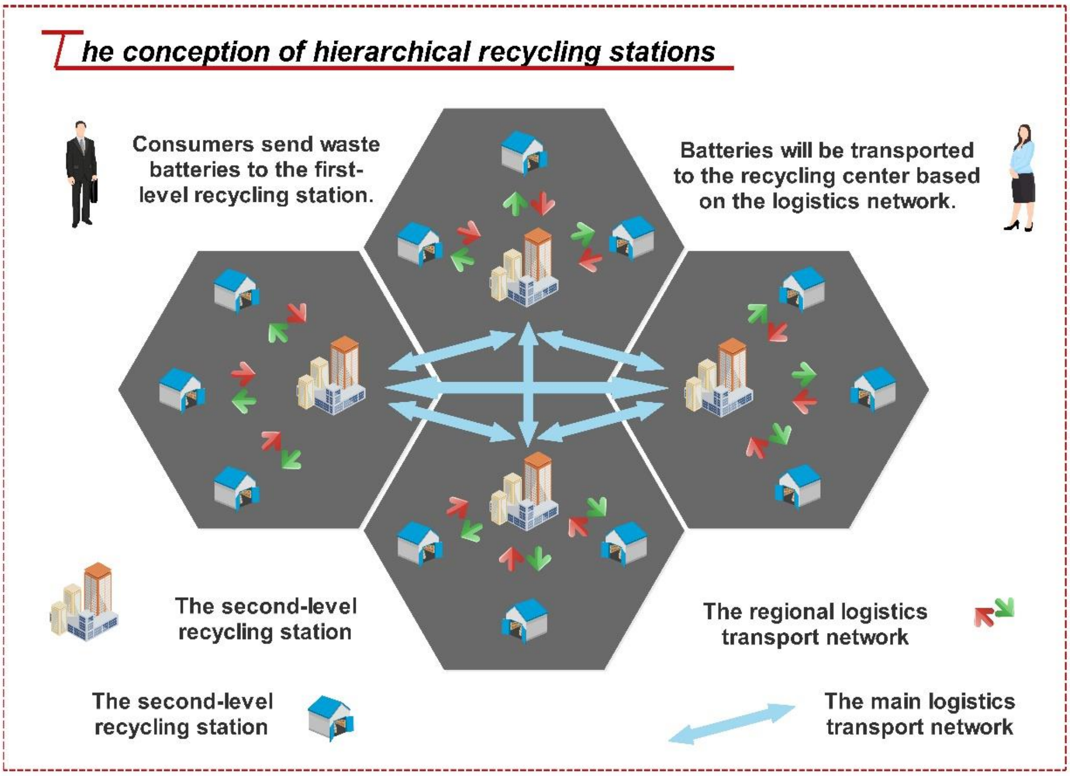

Fig.5. The concept diagram of the proposed hierarchical recycling stations

(3) ***Conducive to government participation in regulation.*** Government regulation can ensure appropriate waste battery recycling. The proposed system clarifies the tasks and responsibilities of each recycling unit, facilitates government regulation, and allows for government incentives and enforcement of penalties, to facilitate legal compliance in the recycling of waste batteries.

(4) ***High efficiency of resource utilization.*** The proposed system prohibits illegal traders from recycling used batteries and ensures that used batteries flow into formal recycling, decomposition, and reuse channels. The waste batteries in the proposed system can be recycled according to the degree of scrapping, and the utilization efficiency of resources is improved over the entire life cycle, thereby saving resources and promoting the sustainable development of the e-bicycle industry.

4.2 Online recycling system

With the development of information technology, the network trading platform offers the advantages of convenient transaction and cost savings. To improve the battery recycling rate of e-bicycles and increase the degree of participation in recycling, this paper proposed an e-bicycle battery online recycling system based on "Internet+". The online recycling system mainly performs the trade-in and recycling of waste batteries. Maintenance organizations will also share a certain amount of recycling work, as different batteries have different degrees of damage, and some may not be suitable for online transactions. Therefore, only two types of trading work are set in the online trading system. Here are the specific recycling steps for consumers in online transactions:

(1) **Select the primary recycling station**. Consumers need to select the first-level recycling station closest to their home address and send the waste batteries to their local first-level recycling station.

(2) **Register and log in to the online trading system.** Consumers register on the online trading system and provide basic information, such as the e-bicycle license plate number, so that the system can log each battery.

(3) **Online trading**. After the consumer sends the waste battery to the primary recycling station, he needs to log into the online trading system and select the transaction category.
   a) **Trade-in trades**. Consumers need to log in the basic information such as the brand and type of waste battery. They select their required battery, fill in the shipping address, confirm the order, and complete the transaction after paying the order.
   b) **Waste battery recycling transactions**. Consumers need to enter basic information, such as the brand type of waste battery, and the system will automatically generate the expected recycling price based on the information provided by the consumer. At this point, the consumer can choose whether to complete the trade. The system will automatically return the amount to the customer's account after confirming receipt of the item to be recycled at the recycling center.

(4) **Reward subsidy work**. First, the recycling center needs to log into the traceability management system to review the completed transaction orders, register the transaction information, and perform credit scoring on the transaction users. According to the credit scoring system and the reward-penalty system, the corresponding users are encouraged to subsidize and return the amount to the user account. Users with low credit ratings are subject to certain penalties, such as limiting the purchase of electric bicycles (or batteries) for a certain period.

4.3 Traceability management system

The traceability management system can track all the information related to the production, processing, transportation, retail and final recycling of the e-bicycle, increasing transparency of the production process. Since this paper focuses on the recycling of waste e-bicycle batteries, the traceability management system has been established only for the product from sales to recycling. It aims to track whether each of the products sold is reasonably recycled to improve the economic and environmental benefits of e-bicycle recycling.

The main sources of this data are the retailer, repair center and recycling center. Retailers need to register every e-bicycle they sell. The registration content includes the basic identity information of the consumer, the license plate number information, the vehicle type and other information, which provides a basis for the subsequent reward-penalty system for the recycling of the e-bicycle. The repair center needs to record the history of the products being repaired in detail. The products that do not warrant repair are considered as scrapped products and need to be recorded separately. From the maintenance record, not only the product performance, life and other parameters can be analyzed, but also the scrap record of the e-bicycle battery can be recorded. The recycling center needs to record the scrap information of each product, including the user and the type number so that it can link to the sales record. The simplified interface of the traceability management system designed in this paper can be seen in **Fig.4 part c**. Each time a retailer sells an e-bicycle battery, it is registered in the transaction information column. There may be three scenarios when the product being sold enters the recycling phase:

(1) If a trade-in is made at a retailer, the retailer needs to register in the recycling information column and corresponding sales record.

(2) If repaired at the repair center, it is deemed to have no maintenance value, and the waste product is recycled at the repair center. The repair center then registers in the recovery information column.

(3) If the consumer sends the waste product directly to the recycling center, the recycling center registers it in the recycling information column.

Whenever a product is tracked from sales to recycling for a period of use, the recycling center credits the consumer and registers in the credit rating information field. Only when the product has completed the cycle, will the consumer receive the corresponding recycling incentive subsidy. If the product does not complete the recycling registration, the consumer will be restricted when purchasing future products, and no incentive subsidy will be issued. If the information received by the recycling center does not match the one filled out by the consumer, the recycling center has the right to re-evaluate the quality of the product. The recycling center will issue a transaction to the consumer based on the actual value of the item, and the consumer will receive a transaction amount that matches the actual product value.

4.4 The proposed hybrid e-bicycle recycling system

According to the requirements of relevant regulations, EV manufacturers need to fulfill their obligations in recycling. Hierarchical recycling stations are established in the community, and waste batteries can be collected, stored, and transferred to a renewable resource recycling center. Retailers are usually responsible for collecting used batteries from consumers. After the assessment of residual battery capacity, charging/discharging efficiency and state of health (Perez et al., 2017; Tang et al., 2019), the qualified ones will be repurposed in various energy storage applications. For batteries that cannot be utilized in second-life use, the contained valuable materials will be extracted to remanufacture the EV batteries again. The online recycling system and the offline recycling system jointly perform the collection and recycling of the batteries, and the online recycling system can pick up the pieces according to the customer's appointment. Online recycling system can pick up the batteries according to the customer's appointment. With a unique ID number associated with each battery, the introduction of a traceability management platform in China not only facilitates information tracking throughout the lifecycle, but also calculates recovery rates (Tang et al., 2019).

The recycling system proposed in this paper is mainly for the recycling of e-bicycle battery, because the battery is relatively small, portable, and difficult to recycle. EVs usually utilize a battery pack, which has a large battery. The battery of some models cannot be disassembled and needs to be serviced by a special service agency. Some types of batteries cannot be disassembled by consumers, they need to be disassembled by a special service agency. Therefore, the recovery of e-bicycle batteries is relatively difficult compared with EVs. The recycling system proposed in this paper can also be applied to the recycling of EV batteries, because each battery has its own unique number for traceability management. In addition, the proposed recycling system includes a hierarchical recycling station and a renewable resource recycling center, and the battery that is not convenient to carry can be recycled at the renewable resource recycling center. The recovered battery, whether it is a single battery or a battery pack, must be sent to a renewable resource recycling center for unified disassembly. Therefore, both the EV batteries and the e-bicycle batteries can be recycled and reused in the proposed recycling system.

The e-bicycle recycling system proposed in this paper includes three subsystems: offline reverse logistics recovery system, online network recycling system, and traceability management system. Simultaneous offline and online transactions provide consumers with great convenience and facilitate the smooth progress of recycling. The traceability management system not only provides timely feedback on the transaction but also plays a role in monitoring and managing the products sold. Therefore, the proposed system has the advantage of high operability and high efficiency. This system addresses the problem of a large number of exceed standard vehicles that will require recycling resulting from implementation of the New National Standard. The system can be applied to the recycling of e-bicycle batteries in the official operation stage of the New National Standard. Therefore, the recycling system proposed in this paper is timeous and has great potential for future use.

4.5 The assessment of the proposed recycling system

The e-bicycle battery has a small volume but high replacement frequency, while the EV battery has a large volume but low replacement frequency. For the same length of time, the capacity of the recovered e-bicycle battery is not less than the capacity of the recovered EV battery. Therefore, this paper uses the same parameter information of the EV in the assessment of the proposed recycling system. As the government plays an indispensable role in guiding the clean energy industry to achieve sustainable development, government supervision has received extensive attention from scholars. In our proposed recycling system, the government is of considerable significance in regulating the recycling of e-bicycles. Therefore, this paper takes the assessment from the perspective of the government, discussing the system's recovery rate and greenhouse gas emission in different contexts.

4.5.1 The improvement of recycling rate

In order to properly evaluate the recycling system, the Stackelberg model is introduced. Three representative scenarios are considered and designed under the proposed framework: (1) S1 no policy intervention. (2) S2 subsidy mechanism. (3) S3 reward-penalty mechanism.

For the sake of simplicity, the passenger car market consists of EV manufacturers, internal combustion engine vehicle (ICEV) manufacturers, governments, and numerous consumers. Although there are differences in capacity and brand of EVs, it is assumed that the batteries are of the same type (Gu et al., 2018a). With a unique ID number associated with each EV battery, the launched traceability management platform not only facilitates information tracking throughout the lifecycle but also calculates recycling rates.

Suppose there are *Q* consumers in the market who make purchasing decisions based on utility functions. On the one hand, consumers in the market are considered to be environmentally conscious. Then after purchasing a car with a green g_i level, they can get the utility of V_{g_i} accordingly (Chen, 2001). *V* represents the utility of the consumer. On the other hand, consumers are sensitive to price. Specifically, ICEV's average selling price is p_1 , EV's average selling price is p_2 , and the government provides *m* subsidy for the recycling price of scrapped electric vehicle batteries. EV manufacturer's collection price ct_2 and ICEV manufacturer's collection price ct_1 will be determined at the time of purchase. The detailed parameters setting is shown in **Table 2**. It is assumed within a single period setting that the discount factor during the life of the vehicle is ignored. Based on the literature (Chen, 2001; Zhu and He, 2017), the utility function is expressed in a linear form, as shown by the **Eq. (1)**. The consumer will make the decision for the highest utility.

$$UT_i = \begin{cases} V \times g_1 - p_1 + ct_i,\ i = 1 \\ V \times g_2 - p_2 + ct_i + m,\ i = 2 \\ 0,\ if\ \ buy\ nothing \end{cases} \tag{1}$$

$$q_2 = Q - \frac{(p_2 - ct_2 - m) - (p_1 - ct_1)}{g_2 - g_1} \tag{2}$$

Therefore, the consumer surplus CS_{EV} can be computed by **Eq. (2)**

$$CS_{EV} = \int_{\frac{(p_2 - ct_2 - m) - (p_1 - ct_1)}{g_2 - g_1}}^{Q} \left(V \times g_2 - p_2 + ct_2 + m\right) dV \tag{3}$$

A refers to the number of consumers who are willing to return the battery of the scrapped EV for free, which can be regarded as an indicator of environmental awareness. *k* represents the consumer's sensitivity to the recycling price. Considering that the recycling market for EV batteries is still in its infancy, consumers usually regard the discarded ICEV recycling price ct_1 as a benchmark (Tang et al., 2018). *h* represents the competition coefficient. Since price sensitivity plays a major role, we can get *k*>*h*. To further encourage the enthusiasm for recycling, the government will provide subsidies to consumers in the subsidy mechanism. The minimum recovery rate and the bonus penalty strength are set to $\xi_0 \left(0 \le \xi_0 \le 1\right)$ and *S*. The objective function is expressed as **Eq. (4)**.

$$
\begin{aligned}
&MAX\ \pi_{EV} \\
&= \left[Q - \frac{\left(p_2 - ct_2 - m\right) - \left(p_1 - ct_1\right)}{g_2 - g_1} \right] \times \left(p_2 - C - S \times \xi_0\right) \\
&+ \left(SU + SC + S\right) \times \left[A + k \times \left(ct_2 + m\right) - h \times ct_1\right] \\
&- ct_2 \times \left[k \times \left(ct_2 + m\right) - h \times ct_1\right] - I \times \left[A + k \times \left(ct_2 + m\right) - h \times ct_1\right]^2 \times \eta
\end{aligned} \tag{4}
$$

Where *C* is the production cost of an EV; *SU* is the net profit by repurposing one scrapped EV battery in second-life use; *SC* is the net saving cost by extracting metal materials from one scrapped EV battery to remanufacture a new one; *I* is the average investment cost of retired EV batteries in recycling activities; η is a scaling parameter of the fixed cost in the recycling activities.

Since the government is the leader of Stackelberg, he can make decisions based on his own foresight, so first determine the best response function of the followers to obtain Stackelberg equilibrium. For a given *m*, the optimal values for p_2^* and ct_2^* can be derived in the equation. The detailed proofs can be seen in (Savaskan et al., 2004).

$$
p_2^* = \frac{\begin{aligned}&(g_2 - g_1) \times \left[k \times \left(SU + SC + S\right) - km + hct_1 - 2I\eta k\left(A + km - hct_1\right)\right] \\ &- C - S \times \xi_0 + (g_2 - g_1) \times \left(2k + 2I \times \eta \times k^2\right) \times \\ &\left[m + p_1 - ct_1 + C + S \times \xi_0 + (g_2 - g_1) \times Q\right]\end{aligned}}{(g_2 - g_1) \times \left(4k + 4I \times \eta \times k^2\right) - 1} \tag{5}
$$

$$
ct_2^* = \frac{\begin{aligned}&m + p_1 - ct_1 + (g_2 - g_1) \times Q - C - S \times \xi_0 + 2(g_2 - g_1) \times \\ &\left[k \times \left(SU + SC + S\right) - km + hct_1 - 2I\eta k\left(A + km - hct_1\right)\right]\end{aligned}}{(g_2 - g_1) \times \left(4k + 4I \times \eta \times k^2\right) - 1} \tag{6}
$$

Where *S* denotes the bonus penalty strength. After substituting p_2^* and ct_2^* into the **Eq. (1)-(4)**, the optimal production quantity q_2^*, consumer surplus CS_{EV}^* , actual recycling rate ξ^* and the profit of EV manufacturer π_{EV}^* can also be obtained.

In order to directly reflect the development of the recycling market under different policy mechanisms, the recycling rate is selected as a key indicator. The corresponding results of these three scenarios are shown in **Table 3** and **Fig.6**. As can be seen from the assessment results, the overall recycling rate is increasing regardless of whether or not an intervention is adopted. It shows that the efficiency of used EVs batteries recycling is gradually increasing. Due to the current high cost of disassembly and recovery, the recovery rates of S1, S2, and S3 exceeded the target level by 2% in the fifth period. As the cost of recycling for EV manufacturer declines and residents' awareness of environmental protection increases, even if the government does not take any incentive interventions, the recycling rate will show an increasing trend over time. The introduction of the subsidy mechanism and reward-penalty mechanisms can promote the improvement of the recycling rate. In particular, the promotion effect of the reward-penalty mechanism is more significant. In the first period, the subsidy mechanism and the reward-penalty mechanism increase the recovery rate by 0.58% and 2.34%, respectively. With the advancement of time, the effect of the subsidy mechanism and the reward-penalty mechanism to improve the recovery rate has gradually become significant. In the fifteenth period, the subsidy mechanism and reward-penalty mechanism increased the recycling rate by 0.71% and 2.83%, respectively. During these fifteen consecutive periods, the subsidy mechanism and reward-penalty mechanism almost increased the recycling rate by 0.65% and 2.59%, respectively. The results means that the recycling system proposed in this paper is effective under the reward-penalty mechanism.

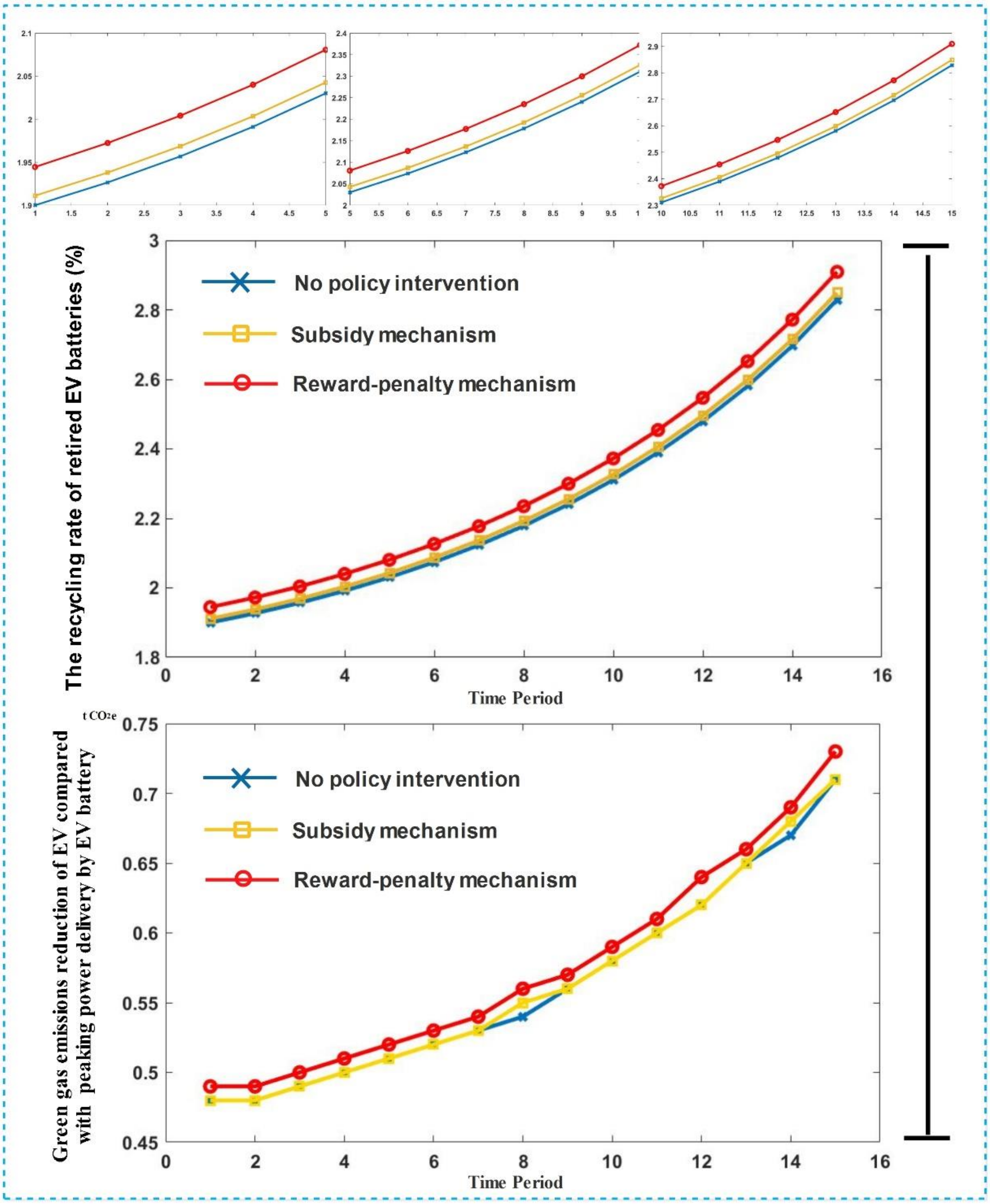

Fig.6. The assessment results of the proposed recycling system

Table 2 The parameters of the Stackelberg model

Parameters	Q	g_1	g_2	A	k	h	C	I	η	SU	SC	p_1	ct_1	m	ξ_0	S
S1	1.5 Million	1.06	1.2	500	3.1	1.2	150,000 RMB	340 RMB	0.025	11,388 RMB	1541 RMB	220,000 RMB	800 RMB	/	/	/
S2	1.5 million	1.06	1.2	500	3.1	1.2	150,000 RMB	340 RMB	0.025	11,388 RMB	1541 RMB	220,000 RMB	800 RMB	2000 RMB	/	/
S3	1.5 million	1.06	1.2	500	3.1	1.2	150,000 RMB	340 RMB	0.025	11,388 RMB	1541 RMB	220,000 RMB	800 RMB	/	2%	8000 RMB
Data Sources	(Gu et al., 2018b)	(Tang et al., 2018)		(Tang et al., 2019)			(Li et al., 2018)	(Tang et al., 2018)		(Madlener and Kirmas, 2017)	(Qiao et al., 2019)	(Li et al., 2018)	(Tian and Chen, 2016)	(Tang et al., 2019)		

Note: The parameters showed in Table 2 are reference data or survey data. According to (Gu et al., 2018b), the potential market size is assumed to be 1.5 million; EV is much cleaner than ICEV for zero emissions, so g_1 and g_2 are assumed to be 1.06 and 1.2, respectively (Tang et al., 2018); Based on the survey shown in (Tang et al., 2019), the number of eliminated EV batteries that consumers are willing to return for free is 500; the sensitivity of collecting price k is assumed to 3.1 and the competition coefficient h is set as 1.2 (Tang et al., 2019); the production cost in the manufacturing stage is 150,000 RMB per EV (Li et al., 2018); the average investment cost I of recycling activities is 340 RMB per waste EV battery and the fixed cost η is assumed to 0.025 (Tang et al., 2018); in the second phase of use, the average net profit obtained by reusing a waste EV battery in the storage system SU is approximately 11388 RMB (Madlener and Kirmas, 2017); based on the current hydrometallurgical level of Chinese high-tech enterprises, the net saving cost of remanufacturing of each battery SC is about 1,541 RMB (Qiao et al., 2019); for ICEV manufacturers, the price of ICEV p_1 is assumed to be 220,000 RMB (Li et al., 2018); in China, the purchase cost of each ICEV is steadily maintained at around 800 RMB (Tian and Chen, 2016); in the subsidy mechanism, the government subsidies for each EV are 2,000 RMB (Tang et al., 2019); in the reward-penalty mechanism, the minimum recovery rate ξ_0 and intensity S of the used EV battery are set to 0.2 and 8000 RMB, respectively (Tang et al., 2019).

Table 3 The assessment results of the proposed recycling system

	Time Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Recycling Rate （%）	S1	1.90	1.93	1.96	1.99	2.03	2.07	2.12	2.18	2.24	2.31	2.39	2.48	2.58	2.70	2.83
	S2	1.91	1.94	1.97	2.00	2.04	2.09	2.14	2.19	2.26	2.33	2.41	2.50	2.60	2.72	2.85
	S3	1.94	1.97	2.00	2.04	2.08	2.13	2.18	2.24	2.30	2.37	2.45	2.55	2.65	2.77	2.91
CO_2 emission reduction of battery repurposing and reuse(t CO_2e)	**Time Period**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	S1	0.48	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.56	0.58	0.60	0.62	0.65	0.67	0.71
	S2	0.48	0.48	0.49	0.50	0.51	0.52	0.53	0.55	0.56	0.58	0.60	0.62	0.65	0.68	0.71
	S3	0.49	0.49	0.50	0.51	0.52	0.53	0.54	0.56	0.57	0.59	0.61	0.64	0.66	0.69	0.73

4.5.2 The reduction of greenhouse gas emission

Ahmadi et al. added an additional link to the baseline life cycle model, including battery re-purposing and second use for grid storage (Ahmadi et al., 2014). The model parameterizes the life cycle model to analyze the effects of the extended life cycle of an electric vehicle battery. This paper only utilizes potential carbon dioxide emissions as a primary indicator of environmental performance. Because greenhouse gas emissions are closely related to the production of metal raw materials and fossil fuel recycling and combustion, carbon dioxide emissions performance corresponds to energy use. In order to assess the environmental benefits of EV recycling, this paper designs two scenarios. In scenario 1, the first vehicle electrification scenario was established, with mobility provided by a plug-in hybrid electric vehicle (PHEV), charged with electricity from the Ontario grid mix (56.5% nuclear, 22.3% hydro, 14.6% natural gas, 2.8% coal, 3% wind, and 0.8% other renewable energy sources), and peaking power still provided by peaking power plants. In scenario 2, PHEV provides the mobility and the re-used vehicle battery that is charged at the optimal time provides the peak power so that there is no need to utilize a dedicated peak power plant. By comparing the effects of CO_2 emissions from scenario 1 and 2, the relative environmental viability of EV cells can be assessed.

The model assumes that the life of a lithium-ion battery is extended to incorporate repurposing and reuse of the battery in grid storage into utility applications. By establishing different scenario comparisons, the secondary use of EV batteries can significantly reduce CO_2 emissions (68 t CO_2e vs. 43 t CO_2e) at a recovery rate of 100%. The proposed recycling system can reduce carbon dioxide emissions by 58% through secondary use of batteries. However, the actual recycling rate is not as expected. According to the battery recycling rate obtained by Stackelberg in different scenarios, the actual CO_2 emissions reduction can be obtained under different government intervention policies, as shown in **Table 3** and **Fig.6**. It can be concluded that CO_2 emission reductions increase as battery recovery increases. In the first period, the CO_2 emission reductions of the proposed recycling system are 0.48t CO_2e and 0.49t CO_2e under the subsidy mechanism and reward-penalty mechanism, respectively. In the fifteenth period, the CO_2 emission reductions of the proposed recycling system are 0.71t CO_2e and 0.73t CO_2e under the subsidy mechanism and reward-penalty mechanism, respectively. During these fifteen consecutive periods, the subsidy mechanism and the reward-penalty mechanism almost achieved CO_2 emission reductions of 0.57t CO_2e and 0.58t CO_2e, respectively. It means that the environmental benefits of vehicle electrification can be doubled by reusing it for a second life to capture the value of waste EV batteries and other clean energy sources.

5 Conclusions and perspective

This paper analyzes the current status of e-bicycle recycling and analyzes and researches the existing recycling network. It summarizes the main problems in the current recycling of e-bicycles and points out the main obstacles for future development. In order to improve the recycling efficiency of e-bicycles, this paper proposes an e-bicycle recycling hybrid system based on offline and online dual transactions, which includes three subsystems: offline reverse logistics recovery system, online recycling system, and traceability management system. The offline reverse logistics recycling system increases the participation of the community, allows for a structured recycling system and makes the recycling of waste e-bicycles more scientific and streamlined. It also facilitates government regulation, which can effectively reduce the participation of uncertified small traders. The online recycling system allows for online recycling transactions, which provides greater convenience and accessibility, and can improve the recycling and recovery rate. The traceability management system is supervised by the government and used by retailers, repair centers, and recycling centers. Its purpose is to track every e-bicycle battery sold to ensure zero abandonment. At the same time, under the supervision of the government, it can implement reward-penalty mechanism to promote the healthy development of the market. Participation in the recycling of e-bicycle batteries can be encouraged through government incentives and penalties, and this will also act to raise the awareness of the consumers on the importance of recycling batteries. The three systems complement each other and are beneficial to the recycling of e-bicycle batteries particularly. The proposed recycling system can increase the waste battery recovery rate by 2.59% and reduce the CO_2 emission by 58% which is conducive to promote sustainable development. The proposed recycling system significantly reduces CO_2 emissions, reduces the environmental hazards of used batteries, and promotes the development of cleaner production.

In view of the above research and analysis on the e-bicycle battery recycling system, the suggestions for the recycling of e-bicycle batteries are put forward. (1) The government needs to establish regulations on the recycling of waste e-bicycle batteries, prohibiting the recycling of uncertified traders. (2) The government should establish incentive and punishment regulations for e-bicycle batteries recycling and increase enforcement. (3) Establish more certified recycling stations and recycling centers. (4) Leading companies should play a leading role. (5) Strengthen publicity and education.

The recycling system effectively collects and classifies used batteries. In order to improve the utilization efficiency of used batteries, optimizing the recovery of materials from the batteries is a promising research in the future (Li et al., 2019). Yun et al. pointed out that by optimizing battery material extraction technology, the harm of lithium-ion batteries can be alleviated and the development of clean energy storage systems can be promoted (Yun et al., 2019).Therefore, based on the proposed recycling system, more attention should be paid to the recycling technology of battery materials.

Competing interests：

The authors declare no competing interests.

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Reference:

Ahmadi, L., Yip, A., Fowler, M., Young, S.B., Fraser, R.A., 2014. Environmental feasibility of re-use of electric vehicle batteries. Sustain. Energy Technol. Assessments 6, 64–74. https://doi.org/10.1016/j.seta.2014.01.006

Alumur, S.A., Nickel, S., Saldanha-Da-Gama, F., Verter, V., 2012. Multi-period reverse logistics network design. Eur. J. Oper. Res. 220, 67–78. https://doi.org/10.1016/j.ejor.2011.12.045

Awasthi, A.K., Zeng, X., Li, J., 2016. Environmental pollution of electronic waste recycling in India: A critical review. Environ. Pollut. 211, 259–270. https://doi.org/10.1016/j.envpol.2015.11.027

B, S., P, K., 2018. Large scale electrical energy storage systems in India- current status and future prospects. J. Energy Storage 18, 112–120. https://doi.org/10.1016/j.est.2018.04.018

Bal, A., Satoglu, S.I., 2018. A Goal Programming Model for Sustainable Reverse Logistics Operations Planning and an ApplicationBal, A., Satoglu, S.I., 2018. A Goal Programming Model for Sustainable Reverse Logistics Operations Planning and an Application. J. Clean. Prod. https://doi.o. J. Clean. Prod. https://doi.org/10.1016/J.JCLEPRO.2018.08.104

Bazan, E., Jaber, M.Y., Zanoni, S., 2016. A review of mathematical inventory models for reverse logistics and the future of its modeling: An environmental perspective. Appl. Math. Model. 40, 4151–4178. https://doi.org/10.1016/j.apm.2015.11.027

Bieber, S., Snyder, S.A., Dagnino, S., Rauch-Williams, T., Drewes, J.E., 2018. Management strategies for trace organic chemicals in water – A review of international approaches. Chemosphere 195, 410–426. https://doi.org/10.1016/j.chemosphere.2017.12.100

Chai, L., Liao, X., Yang, L., Yan, X., 2018. Assessing life cycle water use and pollution of coal-fired power generation in China using input-output analysis. Appl. Energy 231, 951–958. https://doi.org/10.1016/j.apenergy.2018.09.178

Chen, C., 2001. Design for the Environment: A Quality-Based Model for Green Product Development. Manage. Sci. 47, 250–263. https://doi.org/10.1287/mnsc.47.2.250.9841

Chen, F., Yang, B., Zhang, W., Ma, J., Lv, J., Yang, Y., 2017. Enhanced recycling network for spent e-bicycle batteries: A case study in Xuzhou, China. Waste Manag. 60, 660–665. https://doi.org/10.1016/j.wasman.2016.09.027

Cherry, C.R., Weinert, J.X., Xinmiao, Y., 2009. Comparative environmental impacts of electric bikes in China. Transp. Res. Part D Transp. Environ. 14, 281–290. https://doi.org/10.1016/j.trd.2008.11.003

Dat, L.Q., Truc Linh, D.T., Chou, S.Y., Yu, V.F., 2012. Optimizing reverse logistic costs for recycling end-of-life electrical and electronic products. Expert Syst. Appl. 39, 6380–6387. https://doi.org/10.1016/j.eswa.2011.12.031

Fei, F., Qu, L., Wen, Z., Xue, Y., Zhang, H., 2016. How to integrate the informal recycling system into municipal solid waste management in developing countries: Based on a China's case in Suzhou urban area. Resour. Conserv.

Recycl. 110, 74–86. https://doi.org/10.1016/j.resconrec.2016.03.019
Gobbi, C., 2011. Designing the reverse supply chain: The impact of the product residual value. Int. J. Phys. Distrib. Logist. Manag. 41, 768–796. https://doi.org/10.1108/09600031111166429
Godt, J., Scheidig, F., Grosse-Siestrup, C., Esche, V., Brandenburg, P., Reich, A., Groneberg, D.A., 2006. The toxicity of cadmium and resulting hazards for human health. J. Occup. Med. Toxicol. 1. https://doi.org/10.1186/1745-6673-1-22
Guangxi News Network, News Center. http://www.gxnews.com.cn/staticpages/20180117/newgx5a5f206d-16851247.shtml (accessed 5 June 2019).
Gu, F., Ma, B., Guo, J., Summers, P.A., Hall, P., 2017. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Manag. 68, 434–448. https://doi.org/10.1016/j.wasman.2017.07.037
Gu, F., Zhang, W., Guo, J., Hall, P., 2019. Science of the Total Environment Exploring " Internet + Recycling " : Mass balance and life cycle assessment of a waste management system associated with a mobile application 649, 172–185. https://doi.org/10.1016/j.scitotenv.2018.08.298
Gu, X., Ieromonachou, P., Zhou, L., Tseng, M.-L., 2018a. Developing pricing strategy to optimise total profits in an electric vehicle battery closed loop supply chain. J. Clean. Prod. 203, 376–385. https://doi.org/10.1016/J.JCLEPRO.2018.08.209
Gu, X., Ieromonachou, P., Zhou, L., Tseng, M.-L., 2018b. Developing pricing strategy to optimise total profits in an electric vehicle battery closed loop supply chain. J. Clean. Prod. 203, 376–385. https://doi.org/10.1016/J.JCLEPRO.2018.08.209
Guo, J., Wang, X., Fan, S., Gen, M., 2017. Forward and reverse logistics network and route planning under the environment of low-carbon emissions: A case study of Shanghai fresh food E-commerce enterprises. Comput. Ind. Eng. 106, 351–360. https://doi.org/10.1016/j.cie.2017.02.002
John, S.T., Sridharan, R., Ram Kumar, P.N., Krishnamoorthy, M., 2018. Multi-period reverse logistics network design for used refrigerators. Appl. Math. Model. 54, 311–331. https://doi.org/10.1016/j.apm.2017.09.053
Kumar, V.N.S.A., Kumar, V., Brady, M., Garza-Reyes, J.A., Simpson, M., 2017. Resolving forward-reverse logistics multi-period model using evolutionary algorithms. Int. J. Prod. Econ. 183, 458–469. https://doi.org/10.1016/j.ijpe.2016.04.026
Li, J., Yu, K., Gao, P., 2014. Recycling and pollution control of the End of Life Vehicles in China. J. Mater. Cycles Waste Manag. 16, 31–38. https://doi.org/10.1007/s10163-013-0226-6
Li, J., Zeng, X., Stevels, A., 2015. Ecodesign in consumer electronics: Past, present, and future. Crit. Rev. Environ. Sci. Technol. 45, 840–860. https://doi.org/10.1080/10643389.2014.900245

Li, W., Xiao, M., Peng, X., Garg, A., Gao, L., 2019. A surrogate thermal modeling and parametric optimization of battery pack with air cooling for EVs. Appl. Therm. Eng. 147, 90–100. https://doi.org/10.1016/j.applthermaleng.2018.10.060
Li, Y., Zhang, Q., Liu, B., McLellan, B., Gao, Y., Tang, Y., 2018. Substitution effect of New-Energy Vehicle Credit Program and Corporate Average Fuel Consumption Regulation for Green-car Subsidy. Energy 152, 223–236. https://doi.org/10.1016/J.ENERGY.2018.03.134
Liao, X., Chai, L., Jiang, Y., Ji, J., Zhao, X., 2019. Inter-provincial electricity transmissions' co-benefit of national water savings in China. J. Clean. Prod. 229, 350–357. https://doi.org/10.1016/j.jclepro.2019.05.001
Liao, X., Chai, L., Pang, Z., 2018. Water resource impacts of future electric vehicle development in China. J. Clean. Prod. 205, 987–994. https://doi.org/10.1016/j.jclepro.2018.09.091
Linzner, R., Salhofer, S., 2014. Municipal solid waste recycling and the significance of informal sector in urban China. Waste Manag. Res. 32, 896–907. https://doi.org/10.1177/0734242X14543555
Liu, C., Guo, D. an, Liu, L., 2018. Quality transitivity and traceability system of herbal medicine products based on quality markers. Phytomedicine 44, 247–257. https://doi.org/10.1016/j.phymed.2018.03.006
Liu, S., Forrest, J., Yang, Y., Liu, S., 2014. Grey Systems : Theory and Application A brief introduction to grey systems theory A brief introduction to grey systems theory. https://doi.org/10.1108/20439371211260081
Madleňák, R., Madleňáková, L., Kolarovszká, Z., 2016. System of Management and Traceability of Logistic Items through New Technologies. Procedia - Soc. Behav. Sci. 230, 128–135. https://doi.org/10.1016/j.sbspro.2016.09.016
Madlener, R., Kirmas, A., 2017. Economic Viability of Second Use Electric Vehicle Batteries for Energy Storage in Residential Applications. Energy Procedia 105, 3806–3815. https://doi.org/10.1016/J.EGYPRO.2017.03.890
Pascaud, G., Leveque, T., Soubrand, M., Boussen, S., Joussein, E., Dumat, C., 2014. Environmental and health risk assessment of Pb, Zn, As and Sb in soccer field soils and sediments from mine tailings: Solid speciation and bioaccessibility. Environ. Sci. Pollut. Res. 21, 4254–4264. https://doi.org/10.1007/s11356-013-2297-2
Paydar, M.M., Olfati, M., 2018. Designing and solving a reverse logistics network for polyethylene terephthalate bottles. J. Clean. Prod. 195, 605–617. https://doi.org/10.1016/j.jclepro.2018.05.218
Pedram, A., Yusoff, N. Bin, Udoncy, O.E., Mahat, A.B., Pedram, P., Babalola, A., 2017. Integrated forward and reverse supply chain: A tire case study. Waste Manag. 60, 460–470. https://doi.org/10.1016/j.wasman.2016.06.029
Perez, H.E., Hu, X., Dey, S., Moura, S.J., 2017. Optimal Charging of Li-Ion Batteries With Coupled Electro-Thermal-Aging Dynamics. IEEE Trans. Veh. Technol. 66, 7761–7770. https://doi.org/10.1109/TVT.2017.2676044
Qiao, Q., Zhao, F., Liu, Z., Hao, H., 2019. Electric vehicle recycling in China: Economic and environmental benefits. Resour. Conserv. Recycl. 140, 45–53.

https://doi.org/10.1016/J.RESCONREC.2018.09.003
Savaskan, R.C., Bhattacharya, S., Van Wassenhove, L.N., 2004. Closed-Loop Supply Chain Models with Product Remanufacturing. Manage. Sci. 50, 239–252. https://doi.org/10.1287/mnsc.1030.0186
Soleimani, H., Seyyed-Esfahani, M., Kannan, G., 2014. Incorporating risk measures in closed-loop supply chain network design. Int. J. Prod. Res. 52, 1843–1867. https://doi.org/10.1080/00207543.2013.849823
Suyabatmaz, A.Ç., Altekin, F.T., Şahin, G., 2014. Hybrid simulation-analytical modeling approaches for the reverse logistics network design of a third-party logistics provider. Comput. Ind. Eng. 70, 74–89. https://doi.org/10.1016/j.cie.2014.01.004
Tan, S.Y., Praveena, S.M., Abidin, E.Z., Cheema, M.S., 2016. A review of heavy metals in indoor dust and its human health-risk implications. Rev. Environ. Health 31, 447–456. https://doi.org/10.1515/reveh-2016-0026
Tang, Y., Zhang, Q., Li, Y., Li, H., Pan, X., Mclellan, B., 2019. The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism. Appl. Energy 251, 113313. https://doi.org/10.1016/j.apenergy.2019.113313
Tang, Y., Zhang, Q., Li, Y., Wang, G., Li, Y., 2018. Recycling mechanisms and policy suggestions for spent electric vehicles' power battery -A case of Beijing. J. Clean. Prod. 186, 388–406. https://doi.org/10.1016/J.JCLEPRO.2018.03.043
Tian, J., Chen, M., 2016. Assessing the economics of processing end-of-life vehicles through manual dismantling. Waste Manag. 56, 384–395. https://doi.org/10.1016/J.WASMAN.2016.07.046
Tian, X., Gong, Y., Wu, Y., Agyeiwaa, A., Zuo, T., 2014. Management of used lead acid battery in China: Secondary lead industry progress, policies and problems. Resour. Conserv. Recycl. 93, 75–84. https://doi.org/10.1016/j.resconrec.2014.10.008
Tosarkani, B.M., Amin, S.H., 2018. A multi-objective model to configure an electronic reverse logistics network and third party selection. J. Clean. Prod. 198, 662–682. https://doi.org/10.1016/j.jclepro.2018.07.056
Trochu, J., Chaabane, A., Ouhimmou, M., 2018. Reverse logistics network redesign under uncertainty for wood waste in the CRD industry. Resour. Conserv. Recycl. 128, 32–47. https://doi.org/10.1016/j.resconrec.2017.09.011
Wang, Q., Liu, W., Yuan, X., Tang, H., Tang, Y., Wang, M., Zuo, J., Song, Z., Sun, J., 2018. Environmental impact analysis and process optimization of batteries based on life cycle assessment. J. Clean. Prod. 174, 1262–1273. https://doi.org/10.1016/j.jclepro.2017.11.059
Wu, W., Wu, P., Yang, F., Sun, D. ling, Zhang, D.X., Zhou, Y.K., 2018. Assessment of heavy metal pollution and human health risks in urban soils around an electronics manufacturing facility. Sci. Total Environ. 630, 53–61. https://doi.org/10.1016/j.scitotenv.2018.02.183
Yun, L., Li, W., Garg, A., Maddila, S., Gao, L., Fan, Z., Buragohain, P., Wang, C.T., 2019. Maximization of extraction of Cadmium and Zinc during recycling of

spent battery mix: An application of combined genetic programming and simulated annealing approach. J. Clean. Prod. 218, 130–140. https://doi.org/10.1016/j.jclepro.2018.11.226
Yun, L., Linh, D., Shui, L., Peng, X., Garg, A., LE, M.L.P., Asghari, S., Sandoval, J., 2018. Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles. Resour. Conserv. Recycl. 136, 198–208. https://doi.org/10.1016/j.resconrec.2018.04.025
Zhu, W., He, Y., 2017. Green product design in supply chains under competition. Eur. J. Oper. Res. 258, 165–180. https://doi.org/10.1016/J.EJOR.2016.08.053