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Carbon Emission Reduction by Echelon Utilization of Retired Vehicle Power Batteries in Energy Storage Power Stations

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Abstract: With the enhancement of environmental awareness, China has put forward new carbon peak and carbon neutrality targets. Electric vehicles can effectively reduce carbon emissions in the use stage, and some retired power batteries can also be used in echelon, so as to replace the production and use of new batteries. How to calculate the reduction of carbon emission by the echelon utilization of retired power batteries in energy storage power stations is a problem worthy of attention. This research proposes a specific analysis process, to analyze how to select the appropriate battery type and capacity margin. Taking the BYD power battery as an example, in line with the different battery system structures of new batteries and retired batteries used in energy storage power stations, emissions at various stages in different life cycles were calculated; following this in carbon emission, reduction, by the echelon utilization of the retired power battery, was obtained. Finally, the overall carbon emissions that might be reduced by echelon utilization in the future were calculated according to the BYD's battery loading volume and China's total power battery loading volume in 2021. This research provides a quantitative analysis idea for the carbon emission reduction of power battery echelon utilization. Using this method could improve the process of echelon utilization, optimize the supply chain of power batteries, drive the development of the new-energy vehicle industry, and explore new business models, so as to achieve the environmental protection goal of carbon neutrality.

Keywords: power station; life cycle; power battery; echelon utilization; carbon emission

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1. Introduction

Due to the increasing awareness of the need for environmental protection, the Chinese government put forward the goal of carbon emission reduction at the 75th United Nations General Assembly [1], including peak carbon dioxide emissions by 2030, and striving to achieve carbon neutrality by 2060. The emission reduction of the transportation industry will play an important role. According to information provided by the National Development and Reform Commission, transportation emissions accounted for about 10% of China's total carbon emissions in 2019 [2]. Effective emission reduction in the transportation industry must include the extensive use of new-energy vehicles, especially pure-electric vehicles. The power batteries used in existing electric vehicles are mainly LFP(LiFePO4, Lithium Iron Phosphate) batteries and ternary lithium batteries.

The Chinese government has released an action plan for ensuring that carbon dioxide emissions peak by 2030 [3]. The proportion of new-energy-powered vehicles will reach about 40%. The Chinese traffic management department has released its data on national motor vehicle ownership in 2021 [4]. By the end of 2021, the number of new-energy vehicles in China reached nearly 7.84 million, including 6.4 million pure-electric vehicles, accounting for 81.63% of the total number of new-energy vehicles. Electric vehicles can effectively reduce carbon emissions in the vehicle-use stage. In addition, some retired power batteries of electric vehicles can be used in echelon. The use of retired power batteries in energy storage power stations is an effective emission-reduction method.

China has committed to the goal of carbon neutrality, but there is a lack of detailed elaboration on how improving the quality of economic development will affect China's carbon emissions, and achieve the goal of carbon neutrality. Xu G, based on the Environmental Kuznets curve model, discussed the carbon neutrality process of China's future carbon dioxide emissions under different economic development quality scenarios [5]. Guo Z built a general equilibrium model to predict China's economy, energy use and carbon emissions. The results indicated that China's carbon intensity would be significantly reduced, but that carbon emissions would continue to rise, and that the government would have to take effective measures to achieve the intended goal [6]. Carbon intensity refers to carbon dioxide emission per unit of GDP. Carbon intensity does not indicate efficiency. Generally, the carbon intensity index decreases with technological progress and economic growth.

In order to achieve the goal of carbon dioxide emissions peaking by 2030, it will be necessary to reduce carbon emissions in various industries. Hirz M comprehensively evaluated the relevant factors in greenhouse gas emissions of vehicles driven by different propulsion technologies, taking into account the whole product life cycle [7]. Koengkan M analyzed the evidence of European countries on achieving the European Commission's goal of carbon neutrality by 2050; the conclusion showed that decision makers should use clean energy, such as electric vehicles, to reduce the harmful impact of fossil fuels on public health and the environment [8].

Wang Z estimated the impact of coal consumption and power generation capacity on carbon dioxide emissions from 2020 to 2030, according to China's carbon peak goal [9]. The goal of China's carbon neutrality is to establish a system of carbon capture, utilization and storage, so that the power sector can achieve faster decarbonization in the short term. Tang H combined the carbon neutral decision support system, to evaluate the layout of the power industry in various regions of China [10]. Sun Y used provincial data to analyze the correlation between various influencing factors on traffic carbon emission reduction and time series, and provided policy suggestions for China to achieve the goal of carbon peak and carbon neutrality in the field of transportation [11].

Echelon utilization of retired power batteries is also an effective means to save resources and reduce carbon emissions. The echelon utilization of the retired power batteries of new-energy vehicles has a high market potential, which requires the coordination and optimization of all links in the supply chain. The product standard, the echelon utilization technology and the recycling network system of echelon utilization need to be standardized by relevant policies. Zhang H analyzed the central and local policies on echelon utilization of waste power batteries in China from two aspects, including basic policy tools and industrial chain processes [12]. Lai X reviewed the current situation and challenges of echelon utilization of retired power batteries, and put forward the key technologies and routes of large-scale echelon utilization [13]. Zhao S constructed a game supply chain model for battery manufacturers, automobile manufacturers and third-party recyclers, analyzed the impact of the external environment on the supply chain, and constructed a new coordination contract [14]. Liu Z analyzed the strategic value and main modes of power battery reuse in China, and constructed the economic benefit model of power battery echelon utilization and recycling [15].

Retired power batteries should be tested and selected in order to meet the requirements of echelon utilization. Chen L proposed a new lithium-ion battery performance degradation model to predict its capacity decay, resistance increase and residual cycle life under various service modes [16]. Zhang Y tested the performance of a retired electric vehicle battery module to understand the attenuation state of its battery capacity [17]. Xu X analyzed the electrochemical performance of retired lithium-ion batteries, and studied the retention rate and recovery rate of battery capacity under different echelon utilization according to simulated working conditions [18]. Lai X analyzed the correlation between the charging curve of a lithium-ion battery and the remaining effective capacity of the battery, and proposed a quick ranking model to estimate the capacity [19].

Life cycle software can be used to calculate the impact of power batteries on the environment, in terms of production, transportation, use, echelon utilization, recycling and other links. Yusof NK applied the life cycle assessment method to comprehensively compare the environmental footprint of diesel mechanical ships and full-battery-powered ships. The three life cycle stages of production, transportation and use are considered in the analysis [20].

China has the largest number of electric bicycles in the world, and lead-acid batteries are gradually being replaced by lithium batteries. It is necessary to research the environmental impact of these batteries in China. Liu W analyzed the full life cycle environmental performance of typical Chinese electric bicycle batteries through the life cycle assessment method [21]. Wu H used the life cycle assessment method to assess the sustainability of the battery pack, revealing the global warming potential, water consumption and ecological impact in two stages [22]. Based on a review of life cycle assessment methods, Mohr M developed three parametric models of different recycling processes, to analyze the impact of different battery recycling methods on the environment [23]. Quan J analyzed the LFP battery and the NCM (lithium nickel cobalt manganese oxide) battery by using the life cycle assessment method, and evaluated the environmental impact of various recovery processes [24].

The application of battery power in a battery energy storage system needs to take account of the economic cost. Meng Y replaced a new lithium battery with a retired battery, and evaluated the economic benefits of the recycled battery energy storage system in Australia with some economic indicators [25]. Zhang L analyzed the cost and benefit factors affecting enterprise value in terms of power generation, power grid, users and auxiliary services, by using the theory of system dynamics; Zhang L also simulated an energy storage business value model of power batteries by using Vensim software [26]. Gur K analyzed the financial significance of using used car batteries for fixed energy storage systems, and pointed out that the EU's energy policy should encourage the use of used car batteries for fixed purposes [27]. Geng S proposed a loan approval and evaluation framework for a battery energy storage power station project, which could be evaluated and selected by commercial banks, to provide loans and deal with uncertainty in performance [28].

The battery energy storage system can be applied to various power generation systems. Mou M analyzed the application of battery power in power systems, and proposed a start-up method consisting of a multi-terminal flexible distribution network and a cooperative control strategy for a wind solar energy storage system [29]. Sharma M analyzed the role of the battery energy storage system in the modern power distribution network for renewable energy, to improve the overall reliability and quality of power supply [30].

The battery energy storage system needs to be optimized before it can operate normally. Sun J proposed a power reduction operation method for a secondary battery energy storage system, to improve the service life and reliability of the battery system [31]. Based on a particle swarm optimization algorithm, Sun J proposed an economic operation optimization method of energy storage, composed of different retired batteries [32]. Loakimidis C analyzed the use of LFP batteries in the energy storage system in Spanish buildings. The results show that retired batteries have significant environmental benefits compared to new batteries [33]. Wang S proposed a new power distribution method of multiple battery containers for battery energy storage power stations. Through this method, a mathematical model of battery aging and various influencing factors could be established, to accurately calculate the potential aging of the battery [34].

This research puts forward the analysis process of carbon emission reduction by the echelon utilization of retired power batteries in power storage stations. Taking the LFP battery used in BYD E6 as an example, in line with the different battery system structures of new batteries and retired batteries used in energy storage power stations, emissions at various stages in different life cycles were calculated, then the carbon emission reduction by echelon utilization of the retired power battery was obtained. This method can quantify the emission reduction effect of the echelon utilization of retired power batteries, so as

to optimize the supply chain of power batteries and reduce carbon emissions, which is conducive to China's environmental protection goal of carbon neutrality in the future.

2. Methods

2.1. Background of Echelon Utilization

Waste power batteries are not only likely to cause heavy-metal pollution, but are also prone to producing toxic chemical gases and endangering human health. At present, the recycling of power batteries in China is mainly divided into echelon utilization and disassembly recycling. Echelon utilization refers to the process of necessary inspection, classification, disassembly, battery repair or reorganization of waste power batteries into echelon products, so that they can be applied to other fields.

Echelon utilization of retired power batteries can prolong the service life of batteries and make full use of their residual value. Echelon utilization could alleviate the current recycling pressure, reduce the industrial cost of electric vehicles and drive the development of the new-energy vehicle industry. China is carrying out pilot recycling of new-energy vehicle power batteries, promoting enterprises such as automobile manufacturing, battery production and comprehensive utilization, to carry out echelon utilization tests in the fields of power reserve and energy storage, and to explore new business models.

In 2021, China issued an economic development plan circular, which stated that it would carry out the recycling of waste power batteries, strengthen the construction of new-energy vehicle power battery traceability management platforms, promote the standardized echelon utilization of power batteries, improve the standard system of power battery recycling, and promote the development of the waste power battery recycling industry.

In 2021, the output of power batteries in China was 219.7 GWh, the sales volume was 186 GWh, and the loading volume was 154.5 GWh. In 2020, the number of new energy vehicles in China reached 4.92 million, and 0.2 million tons of power batteries were retired, equating to about 25 GWh. By 2025, this was expected to reach 0.35 million tons, about 137.4 GWh.

In 2015, the production and sales of new-energy vehicles in China began to explode, with an output of 0.40 million vehicles that year. China's current standard for vehicle battery power is that the capacity attenuation should not exceed 20% of the rated capacity within 8 years or 120 thousand kilometers. Therefore, the service life of power batteries is relatively short, usually only 5–8 years, and their effective life can even be as short as 4–6 years. The power batteries produced in 2014 began to enter their retirement period in batches in 2018. From 2021, China has ushered in the first batch of power battery retirement peaks, followed by the pollution control of retired batteries.

The China Automotive Power Battery Industry Innovation Alliance released the data statistics of the power battery industry in 2021. Table 1 shows the loading capacity and proportion of China's top five power battery enterprises. The total loading volume in the figure below is 154.5 GWh. The top five domestic power battery enterprises, in terms of installed capacity, were Ningde Times, BYD, China Innovation Airlines, GuoXuan High Tech and LG New Energy. In 2021, the annual power battery loading volume of Ningde Times was 80.51 GWh, which accounted for 52.1% of the market. BYD's loading capacity was 25.03 GWh, which accounted for 16.2% of the market. Unlike Ningde Times, BYD's power batteries are mostly used by its own brands.

Figure 1 shows the three batches of enterprises qualified for comprehensive utilization of waste power batteries released in China from 2018 to 2021, with a total of 47 enterprises. In 2018, there were 5 enterprises, including 5 for recycling, 5 for echelon utilization and 5 for repetition. In 2020, there were 22 enterprises, including 9 recycling enterprises, 14 echelon utilization enterprises, 1 repetition, and 4 vehicle enterprises. Shanghai BYD Co., Ltd. (Shanghai, China) is not only an echelon utilization enterprise, but is also a complete vehicle enterprise. There were 20 in 2021, including 11 for echelon utilization, 11 for recycling and 2 repetitions.

Table 1. Loading capacity and proportion of Chinese top five power battery enterprises.

Enterprise Name	Loading Capacity (GWh)	Proportion (%)
Ningde Times	80.51	52.1
BYD	25.06	16.2
China Innovation Airlines	9.05	5.9
GuoXuan High Tech	8.02	5.1
LG New Energy	6.25	4.0

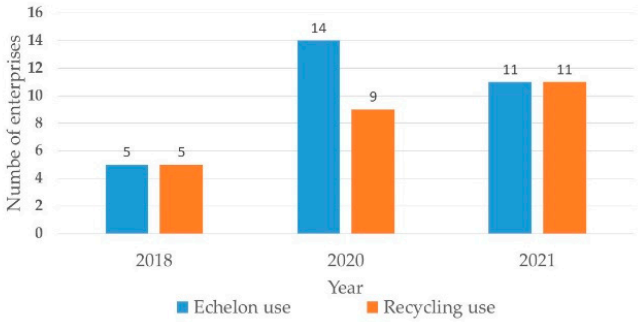

Figure 1. Number of echelon utilization and recycling enterprises.

At present, the leading enterprises of power battery recycling are Green Beauty, BYD and Brunp under Ningde Times. There are 3091 Chinese enterprises whose business scope includes the recovery of power batteries with a registered capital of more than 20 million yuan. It can be seen that most power lithium battery recycling enterprises in China do not have corresponding qualifications. As of January 2022, China's Ministry of Industry and Information Technology has identified 14,899 new-energy vehicle power battery recycling service outlets.

2.2. Power Battery Suitable for Echelon Utilization

Figure 2 shows the proportion of power battery loading in China in 2021. The cumulative loading volume of power batteries in China was 154.5 GWh. Among them, the total loading volume of ternary batteries was 74.3 GWh, accounting for 48.10% of the total loading volume. 'Ternary battery' refers to a lithium-ion battery with nickel cobalt lithium manganate or nickel cobalt lithium aluminate as cathode material. The cumulative loading volume of LFP batteries was 79.8 GWh, accounting for 51.70% of the total loading volume.

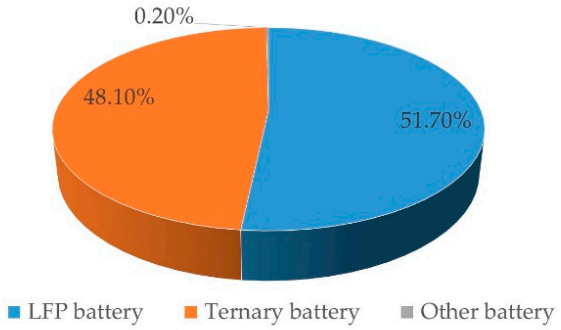

Figure 2. Proportion of power batteries loading in China in 2021.

Table 2 shows the performance comparison of the LFP battery, the ternary battery and the lead-acid battery. Most of the power batteries used in electric vehicles are LFP batteries and ternary batteries. Very few low-speed cars, such as scooters used by the elderly, will use lead-acid batteries.

Table 2. Performance comparison of the three batteries.

Parameter	LFP	Ternary	Lead-Acid
Charging times	3000–5000	800–1000	350–500
Charging time (h)	3–5	2–3	8–10
Energy density (Wh/kg)	90–140	140–240	50–70
Cost (RMB/Wh)	0.58–0.6	0.85–1	0.3–0.4
Echelon utilization situation	Suitable	Unsuitable	Unsuitable
Recycling value	Medium	High	Low

The energy density of the LFP battery is generally 90–110 W/kg. Some innovative LFP batteries, such as blade batteries, have an energy density of 120–140 W/kg. LFP batteries do not contain precious metal materials, so the cost of raw materials is very low. The cost of an LFP battery without precious metal elements is only about 0.58–0.6 RMB/Wh. The charging times of an LFP battery are much greater than those of the other two batteries. After the battery capacity is less than 80%, it can be charged many times, so it is suitable for echelon utilization. The ternary lithium battery and lead-acid battery decay rapidly after 80%, so they are not suitable for echelon utilization.

Due to the use of more active metal elements, the energy density of mainstream ternary lithium batteries is generally 140–160 Wh/kg, and that of ternary batteries with high nickel ratio is 160–180 Wh/kg. Part of the weight energy density can reach 180–240 Wh/kg. Ternary lithium batteries are mainly made of ternary cathode materials of lithium nickel cobalt manganate or lithium nickel cobalt aluminate, mainly using nickel salt, cobalt salt and manganese salt as raw materials. The cobalt element in these two cathode materials belongs to precious metals.

The reference price of cobalt metal in China is 0.413 million RMB/ton, and with the reduction of materials, the price continues to rise. At present, the cost of a ternary lithium battery is 0.85–1 RMB/Wh, and there is a rising trend with the market demand. The charging times of a ternary lithium battery ladder are not long, the utilization value of the ladder is not large, and the recovery of raw materials is more cost-effective.

Lead-acid batteries have fewer and longer charging times, but the cost should be low. They are generally used in cheap electric bicycles or cars. With the rapid development of lithium batteries, the development of lead-acid batteries is diminishing. The recovery value of lead-acid batteries is low, and they are not suitable for echelon utilization.

2.3. Battery Capacity of Power Battery Used in Echelon

Table 3 shows the echelon utilization of power batteries in different capacity stages. According to the attenuation degree of battery capacity, echelon utilization is divided into the following stages:

(1) Normal use stage: the battery capacity is 80–100%; that is, the power battery meets the use requirements of electric vehicles, and is used in the vehicle as a normal energy battery;
(2) The first stage of echelon utilization: the battery capacity is 60–80%. Echelon utilization can be chosen, or packaging recycling, which can be applied to energy storage, communication base stations, emergency rescue power, low-speed electric vehicles, etc.;
(3) The second stage of echelon utilization: when the available capacity is reduced to 20–60%, it will be recycled and disassembled into single batteries by professional manufacturers, and then assembled in series and in parallel, in various combinations. The battery pack can be used for household energy storage and lighting power supply;
(4) In the scrapping stage, when the available capacity is 0–20%, the battery can be scrapped. Only some parts and rare chemical components inside the battery need to be refined and recycled to recover metal elements.

Table 3. Echelon utilization occasions of power batteries at different capacity stages.

Stage	Capacity (%)	Function	Occasion
1	100–80	Power battery	Electric vehicle
2	80–60	Energy storage battery	Energy storage power station, communication base station, emergency rescue power, low-speed electric vehicle
3	60–20	Spare battery	Household energy storage, lighting power supply
4	0–20	Disassembly and recycling	Recycling of raw materials

The echelon utilization enterprise must be responsible for its echelon utilization products, recycling the echelon utilization products after completing the mission, and sending them to the recycling enterprise for final disposal. Echelon utilization units mainly include the China Iron Tower Corporation, the State Grid Corporation of China, and Zhongtian Hong Li. Battery echelon utilization involves many enterprises, including vehicle enterprises, battery enterprises, recycling and dismantling enterprises, battery testing enterprises and so on. At present, there is no effective linkage between enterprises at all levels of the industrial chain, and the non-standard production of batteries is also an obstacle, to some extent, to cooperation between enterprises. How to coordinate the relationship between all parties, promote the cooperation of all enterprises and open up the overall echelon utilization industrial chain is a major challenge.

2.4. Analysis Process of Echelon Utilization and Emission Reduction

The analysis process of the carbon emission reduction of retired power batteries in energy storage power stations was as follows:

Step 1: The appropriate power battery was selected for echelon utilization of the power storage station. An LFP battery is suitable for echelon utilization;

Step 2: The retired battery, with appropriate capacity margin, was selected for echelon utilization. 80% capacity meets the requirements of retired standards and echelon utilization;

Step 3: The power battery of a BYD electric vehicle was selected as an example. BYD's LFP battery is representative of the industry, and is widely used in energy storage power stations;

Step 4: The carbon emissions of a 1 kWh new battery system and a 1 kWh retired battery at different stages of the life cycle were calculated. The life cycle of new batteries includes production, use and scrap recycling. The life cycle of retired batteries includes transformation, echelon use and scrap recycling;

Step 5: According to the structure of energy storage power stations composed of new batteries and retired batteries, the carbon emission reduction of the echelon utilization of 1 kWh retired batteries was calculated;

Step 6: According to the annual loading volume of power batteries, the total reduction of carbon emissions from the echelon utilization of retired power batteries was calculated.

3. Results

3.1. Carbon Emission of 1 kWh New Battery and 1 kWh Retired Battery of Life Cycle

3.1.1. Power Battery of BYD Electric Vehicle

BYD had an early stake in the power battery recycling business, and it was also one of the first companies to carry out echelon utilization of retired power batteries. At present, BYD has set up more than 40 power battery recycling outlets across the country. BYD sold 0.73 million passenger vehicles in 2021, including 0.59 million new-energy passenger

vehicles, comprising 0.32 million pure electric vehicles and 0.27 million DM plug-in hybrid vehicles.

The retired LFP battery of a BYD electric vehicle still has nearly 80% capacity surplus, which can be used on occasions with lower requirements for electric energy than cars, so as to realize the echelon utilization of waste batteries.

The battery pack of BYD E6 is 96 power LFP batteries in series, with energy of about 57 kWh, and it can discharge at a high rate of 10–15 C. The whole vehicle has a mass of about 2.2 tons, a size of 4554 mm × 1822 mm × 1630 mm, and is equipped with five seats.

3.1.2. Production Emission of New Battery

Table 4 shows the specific parameters of an LFP battery cell. Table 5 shows the composition and proportion of an LFP battery cell [35].

Table 4. Battery cell parameters of BYD E6.

Parameter	Unit	Battery Cell
Energy	kWh	0.59
Weight	kg	4.31
Energy density	Wh/kg	137

Table 5. Composition and proportion of LFP battery cell.

Part	Material	Weight Ratio (%)
Positive electrode	Lithium iron phosphate	22
	Polyvinylidene fluoride	1
	N-methylpyrrolidone	3
	Aluminum matrix	5
Negative electrode	Graphite	10
	Polyvinylidene fluoride	1
	N-methylpyrrolidone	2
	Copper matrix	8
Electrolyte	Lithium hexafluorophosphate	2
	Ethylene carbonate	4
	Dimethyl ester DMC	4
Diaphragm	Polypropylene	2
	Polyethylene	2
Housing	Polypropylene	4
	Aluminium	28
Battery management system	Steel	1
	Copper	1
	Circuit board	1

The production of battery cells includes three stages: the production of raw materials, the production and the assembly of parts [36]. In line with the composition and proportion of the BYD LFP battery cell, the life cycle method was used to calculate that the carbon emission from the production of the battery cell was 361.831 kg carbon dioxide.

3.1.3. Use Emission of New Battery and Retired Battery

The retired power batteries of BYD electric vehicles have been applied in energy storage power stations. For example, in 2020, the largest echelon energy storage power

station in Zhejiang Province of China was officially put into operation. The total capacity of the energy storage station is 900 kWh, and the maximum output power can reach 300 kW. This project uses the retired LFP battery of a BYD E6 car. Through the system design scheme of group series architecture, the circulation between different battery clusters can be completely limited, so as to alleviate the problem of the inconsistent initial capacity of echelon batteries.

At present, the main profit models of energy storage power stations are reducing power abandonment and participating in peak shaving. Most energy storage power stations use LFP batteries with the largest market share, the highest technical maturity and the most complete standards. The service life of the power station is designed to be 20 years. When the battery has been used a certain number of times, it will be replaced, but other equipment will not be replaced. Regardless of the recovery cost, the equivalent charge and discharge times are once a day and 330 times a year.

China has mandated that the attenuation of 0.15 million kilometers of power batteries in 8 years should not exceed 20%, which means that the battery capacity should not be less than 80%, otherwise the battery will be replaced. According to the assessment of the LFP battery, after 2200 charging times, the battery capacity margin was 80% [37].

Although there may be individual differences in the capacity margin of retired power batteries, this research was based on the standard of 80%. Table 6 shows the structural comparison of different battery systems in energy storage plants, including new batteries and retired batteries used in echelons.

Table 6. Structural comparison of different battery systems in energy storage power stations.

Parameter	New Battery	Retired Battery
Capacity margin ratio (%)	100	80
Capacity of battery cell (ah)	185.54	148.43
Charging voltage of battery cell (V)	3.2	3.2
Energy of battery cell (kWh)	0.594	0.475
Life of storage power station (Year)	20	20
Battery system cycle times	2	4
Life of battery system (Year)	10	5
Charging times of battery system	3300	1650
Discharge depth (%)	90	80
Number of branches	9	12
Number of clusters per branch	2	2
Number of strings per cluster	8	8
Number of battery cell per string	12	12
Design battery energy (MWh)	1	1
Actual battery energy (MWh)	1.026	1.094

The DOD (depth of discharge) represented the percentage of battery discharge to the rated energy of the battery. The battery energy was designed as 1 MWh, and adopted the same system structure, while the actual design capacity was different due to the structural relationship. This difference could be properly adjusted through the charging depth, without affecting the calculation results. The echelon utilization battery system adopted a structural design similar to the new battery system, but the number of branches was different, so that the battery box and other devices could be re-used.

For the new battery system, the LFP battery, with a monomer of 3.2 V and 185.54 ah, was adopted. Firstly, 12 LFP battery cells were connected in series, to form a battery module; eight modules were connected in series to form a battery cluster; two battery clusters were then connected in parallel to form branches; and every six branches formed one MWh energy storage unit.

For the battery system of echelon utilization, the LFP battery, with monomer of 3.2 V and 148.43 ah, was adopted. Every 12 LFP batteries were connected in series, to form a battery module, and every eight modules were connected in series to form a battery cluster; every two battery clusters were then connected in parallel to form a branch; and every eight branches were combined into a one MWh battery energy storage unit.

Formula (1) calculated the battery capacity loss rate [37]:

$$\xi = A \times \exp(-\frac{E_a}{Rt_2}) \times n^z \quad (1)$$

ξ was the battery capacity loss rate; A was equal to 0.1825; $\frac{E_a}{R}$ was equal to 1324.65; t_2 was equal to 298; Z was equal to 0.5878; n was the charging times.

Formula (2) calculated the power loss used by the battery [38]:

$$E_{loss} = \sum_{n=1}^{l_c} Q_r \times U \times DOD \times (1 - \xi_n) \times (1 - E_T)/E_T \quad (2)$$

E_{loss} was the electric energy loss; Q_r was the battery capacity; U was the charging voltage; DOD was the depth of discharge; ξ_n was the battery capacity loss rate; E_T was the battery energy transfer efficiency.

The initial capacity of the new battery was 185.54 ah, and the charging voltage was 3.2 V. The energy transfer efficiency of the LFP battery was 95%. For the energy storage power station, the new battery was to be used for 10 years in a life cycle, equivalent to 1–3300 times, and the DOD was 90%. The power loss was 77.900 kWh, equivalent to 77.666 kg carbon dioxide.

The retired battery had been used 2200 times before, and was then used for 5 years in echelon, equivalent to 1650 times, with a DOD of 80%. According to the calculation, the power loss was 36.828 kWh, equivalent to 36.718 kg carbon dioxide.

3.1.4. Transformation Emission of Retired Battery

There are great differences between the safety and performance of retired power batteries, so it is necessary to judge the value of a battery's status, and to evaluate its remaining life and safety before echelon utilization. This process includes the testing of several battery performance indicators, among which the testing of internal resistance and residual capacity is the most important. Batteries that have no echelon utilization value will be scrapped and recycled. Batteries that do have echelon utilization value need to be transformed.

If the retired LFP battery needs to be reused, it needs to go through the processes of appearance inspection, replacement of product parts and harness, static measurement, capacity measurement, cell matching, connector assembly inspection, laser welding, cell adjustment, and inspection to obtain the useful battery. In the whole process, only a small amount of waste gas is produced during laser welding. In the whole transformation process, electricity is mainly used. The transformation of a single battery requires 6.530 kWh of electricity, equivalent to 6.510 kg of carbon dioxide emissions.

3.1.5. Recycling Emission of Scrap Battery

Carbon emissions from the recycling of new batteries and retired batteries are the same. At present, the general recycling method of LFP scrap batteries in China is wet recycling technology. After discharging, the waste LFP battery is disassembled and sorted, and the pole pieces are broken to obtain LFP powder, which is then subjected to heat treatment, pulping, acid leaching, transformation, alkalization and impurity removal, and then filtered to obtain lithium carbonate purified solution as a regenerated product.

This technology only recovers the lithium element in the scrap LFP battery. The aluminum shells of scrap battery cells can also be directly recycled, which can greatly reduce carbon dioxide emissions. Table 7 shows the materials required for wet recycling of scrap

batteries [39]. Assuming that the recovery rate of aluminum shells is 70%, and that of lithium carbonate is 80%, it can be calculated that the carbon dioxide produced by recycling the scrapped battery is −190.045 kg, by using the life cycle method.

Table 7. Materials required for wet recycling.

Code	Material	Number
1	Power (kWh)	3.975
2	Hydrochloric acid (kg)	5.415
3	Water (kg)	7.520
4	Magnesium hydroxide (kg)	2.885
5	Sodium hydroxide (kg)	2.101

3.1.6. Carbon Emissions during the Life Cycle of New and Retired Batteries

Table 8 shows the carbon emission of a 1 kWh battery in the life cycle. The carbon emission of the new battery in one life cycle is 204.446 kg. The carbon emission of retired batteries in one life cycle of echelon utilization is −146.817 kg. The new battery will produce a lot of carbon emissions in the production stage. The carbon emissions from the transformation of retired batteries are very small. The recycling of scrap battery materials, especially the aluminum shell, can effectively reduce carbon emissions. The echelon utilization of retired batteries not only reduces carbon emissions, but also reduces emissions of other harmful substances, which can lead to good environmental protection effects.

Table 8. Carbon emission of 1 kWh battery in the life cycle.

Stage	Carbon Dioxide Emission (kg)	
	New Battery	Retired Battery
Production	316.831	0
Normal Use	77.666	0
Transformation	0	6.510
Echelon use	0	36.718
Recycling	−190.045	−190.045
Total	204.446	−146.817

3.2. Carbon Dioxide Emission Reduction by Echelon Utilization of Retired Batteries

Formula (3) calculated the carbon emission reduction brought about by the echelon utilization of a retired battery with 1 kWh energy in a storage power station:

$$C = \frac{N_n \times L_n \times E_n \times C_n - N_r \times L_r \times E_r \times C_r}{N_r \times L_r \times E_r} \quad (3)$$

C was the carbon emission reduced by the echelon utilization of a 1 kWh retired battery; N_n was the number of new batteries used in a cycle; L_n was the number of cycles used by the new batteries; E_n was the energy of a new battery cell; C_n was the carbon emission of the 1 kWh new batteries in a life cycle; N_r was the number of retired batteries used in a cycle; L_r was the number of cycles used by retired batteries; E_r was the energy of the retired battery cell; and C_r was the carbon emission of 1 kWh decommissioned batteries in a life cycle.

The energy storage system of a 1 MWh power station was calculated based on a 20 year operation cycle. The carbon emission reduction was the carbon emission from the new battery system minus the carbon emission from the retired battery system. The total carbon emission reduction was divided by the number of retired batteries used to obtain the carbon emission reduction corresponding to the battery cell, and then converted to

the corresponding value of 1 kWh. According to Formula (3), the carbon emission reduction brought about by the echelon utilization of a 1 kWh retired battery was 242.652 kg carbon dioxide.

3.3. Carbon Dioxide Emission Reduction of the Electric Vehicle Industry

Formula (4) shows the total carbon emission reduction of the industry:

$$E_t = C \times R_e \times N_t \quad (4)$$

E_t is the total reduction of carbon emission; C is the carbon emission reduced by the echelon utilization of a 1 kWh retired battery; R_e is the cascade utilization rate of power batteries; and N_t is the total installed energy calculated in a 1 kWh capacity unit.

In 2021, the cumulative loading volume of an LFP battery was 79.8 GWh, and that of a BYD was 25.03 GWh. When selecting the recycling proportion of an LFP battery, 50–60% can meet the requirements of echelon utilization. This research was calculated according to 55%. Under the assumption that the battery remained unchanged, based on the loading volume in 2021, the carbon emission reduction of BYD vehicles, caused by the echelon utilization of these retired power batteries, was 3.340 million tons, and the total carbon emission reduction of the electric vehicle industry was 10.650 million tons.

4. Discussion

When a retired power battery is used in echelon, the cost of transformation is different for different electric energy storage systems, due to their different structural designs. Although the rated power of the battery energy storage system using new batteries and retired batteries is the same, the energy storage effect of retired power batteries is worse, and the maintenance cost is higher. The battery standards produced by different manufacturers are different, and the capacity of retired power batteries is also different. It is difficult to achieve unified use and maintenance standards in the same energy storage system, and there are certain safety problems.

These existing problems limit the echelon utilization of retired power batteries. The whole supply chain of power battery production, use and echelon utilization needs to be studied, and the theory applied to practice. The production of power batteries needs to formulate unified standards, and the power batteries should be retired after reaching a certain service life, to meet the requirements of echelon utilization. Power battery recycling enterprises need to select retired batteries according to the requirements of the specifications, then transform and package them. The application of retired batteries also needs the support and supervision of the government, to meet the requirements of safety and environmental protection.

5. Conclusions

China's environmental protection goals for carbon peak and carbon neutralization have brought important opportunities for the development of new-energy vehicles. With the extensive use of power batteries in electric vehicles, retired power batteries are also facing environmental problems of recycling and reuse. Echelon utilization of appropriate retired power batteries is also one of the effective ways of carbon neutralization.

Among the power batteries used in electric vehicles, LFP batteries and ternary lithium batteries are the most common. The market share of the former has gradually exceeded that of the latter. Because retired LFP batteries can still be charged and discharged many times, LFP batteries are more suitable for echelon utilization.

Retired batteries with different capacities can be suitable for different echelon utilization occasions. For LFP batteries, when the battery capacity is 80%, they can be used in echelons in storage power stations and communication base stations. By this point, the LFP battery has been charged and discharged about 2200 times, and the remaining times can meet the needs of echelon utilization. The carbon emission of a 1 kWh new battery in the

life cycle is 204.446 kg carbon dioxide, and that of the echelon utilization of a 1 kWh retired battery is −146.817 kg carbon dioxide.

This research gives an example of the echelon utilization of the LFP battery in an energy storage power station. The service life of energy storage power stations is generally 20 years. Electric energy storage systems using retired power batteries and new batteries have different design structures. The carbon emission reduction brought about by the echelon utilization of a 1 kWh retired battery is 242.652 kg carbon dioxide.

According to the annual loading volume of the LFP batteries of BYD and the whole industry in 2021, it can be calculated that the echelon utilization of these batteries in the future will reduce carbon dioxide emissions by 3.340 million tons and 10.650 million tons, respectively.

The quantification of the emission reduction effect of echelon utilization can be improved, which could be a goal of future research.

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References

1. Sun, C. *China Carbon Neutral Development Report (2021)*; Science Press: Beijing, China, 2022; p. 8.
2. Ministry of ecological environment of China. *China Mobile Source Environmental Management Annual Report*; Ministry of Ecological Environment of China: Beijng, China, 2021.
3. National Development and Reform Commission. *Carbon Peak Action Plan by 2030*; National Development and Reform Commission: Beijing, China, 2021.
4. Ministry of Public Security of China. *Data of National Motor Vehicles and Drivers in 2021*; Ministry of Public Security of China: Beijing, China, 2022.
5. Xu, G.; Dong, H.; Xu, Z.; Bhattarai, N. China can reach carbon neutrality before 2050 by improving economic development quality. *Energy* **2022**, *243*, 123087. [CrossRef]
6. Guo, Z.; Zhang, X.; Ding, Y.; Zhao, X. A Forecasting Analysis on China's Energy Use and Carbon Emissions Based on A Dynamic Computable General Equilibrium Model. *Emerg. Mark. Financ. Trade* **2021**, *57*, 727–739. [CrossRef]
7. Hirz, M.; Nguyen, T.T. Life-Cycle CO_2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems. *World Electr. Veh. J.* **2022**, *13*, 61. [CrossRef]
8. Koengkan, M.; Fuinhas, J.A.; Teixeira, M.; Kazemzadeh, E.; Auza, A.; Dehdar, F.; Osmani, F. The Capacity of Battery-Electric and Plug-in Hybrid Electric Vehicles to Mitigate CO_2 Emissions: Macroeconomic Evidence from European Union Countries. *World Electr. Veh. J.* **2022**, *13*, 58. [CrossRef]
9. Wang, Z.X.; Zhang, J.J.; Pan, L.; Yang, F.; Shi, L.N. Estimate of China's energy carbon emissions peak and analysis on electric power carbon emissions. *Adv. Clim. Chang. Res.* **2014**, *5*, 181–188. [CrossRef]
10. Tang, H.; Zhang, S.; Chen, W. Assessing Representative CCUS Layouts for China's Power Sector toward Carbon Neutrality. *Environ. Sci. Technol.* **2021**, *55*, 11225–11235. [CrossRef] [PubMed]
11. Sun, Y.; Liu, S.; Li, L. Grey Correlation Analysis of Transportation Carbon Emissions under the Background of Carbon Peak and Carbon Neutrality. *Energies* **2022**, *15*, 3064. [CrossRef]
12. Zhang, H.; Huang, J.; Hu, R.; Zhou, D.; Ma, C. Echelon utilization of waste power batteries in new energy vehicles: Review of Chinese policies. *Energy* **2020**, *206*, 118178. [CrossRef]
13. Lai, X.; Huang, Y.; Deng, C.; Gu, H.; Han, X.; Zheng, Y.; Ouyang, M. Sorting, regrouping, and echelon utilization of the large-scale retired lithium batteries: A critical review. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111162. [CrossRef]

14. Zhao, S.; Ma, C. Research on the coordination of the power battery echelon utilization supply chain considering recycling outsourcing. *J. Clean. Prod.* **2022**, *358*, 131922. [CrossRef]
15. Liu, Z.; Liu, X.; Hao, H.; Zhao, F.; Amer, A.A.; Babiker, H. Research on the Critical Issues for Power Battery Reusing of New Energy Vehicles in China. *Energies* **2020**, *13*, 1932. [CrossRef]
16. Chen, L.; Tong, Y.; Dong, Z. Li-Ion Battery Performance Degradation Modeling for the Optimal Design and Energy Management of Electrified Propulsion Systems. *Energies* **2020**, *13*, 1629. [CrossRef]
17. Zhang, Y.; Li, Y.; Tao, Y.; Ye, J.; Pan, A.; Li, X.; Liao, Q.; Wang, Z. Performance assessment of retired EV battery modules for echelon use. *Energy* **2020**, *193*, 116555. [CrossRef]
18. Xu, X.; Mi, J.; Fan, M.; Yang, K.; Wang, H.; Liu, J.; Yan, H. Study on the performance evaluation and echelon utilization of retired $LiFePO_4$ power battery for smart grid. *J. Clean. Prod.* **2019**, *213*, 1080–1086. [CrossRef]
19. Lai, X.; Deng, C.; Li, J.; Zhu, Z.; Han, X.; Zheng, Y. Rapid sorting and regrouping of retired lithium-ion battery modules for echelon utilization based on partial charging curves. *IEEE Trans. Veh. Technol.* **2021**, *70*, 1246–1254. [CrossRef]
20. Yusof, N.K.; Abas, P.E.; Mahlia, T.M.I.; Hannan, M.A. Techno-Economic Analysis and Environmental Impact of Electric Buses. *World Electr. Veh. J.* **2021**, *12*, 31. [CrossRef]
21. Liu, W.; Liu, H.; Liu, W.; Cui, Z. Life cycle assessment of power batteries used in electric bicycles in China. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110596. [CrossRef]
22. Wu, H.; Hu, Y.; Yu, Y.; Huang, K.; Wang, L. The environmental footprint of electric vehicle battery packs during the production and use phases with different functional units. *Int. J. Life Cycle Assess.* **2021**, *26*, 97–113. [CrossRef]
23. Mohr, M.; Peters, J.; Baumann, M.; Weil, M. Towards a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. *J. Ind. Ecol.* **2020**, *24*, 1310–1322. [CrossRef]
24. Quan, J.; Zhao, S.; Song, D.; Wang, T.; He, W.; Li, G. Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies. *Sci. Total Environ.* **2022**, *819*, 153105. [CrossRef]
25. Gur, K.; Chatzikyriakou, D.; Baschet, C.; Salomon, M. The reuse of electrified vehicle batteries as a means of integrating renewable energy into the European electricity grid: A policy and market analysis. *Energy Policy* **2018**, *113*, 535–545. [CrossRef]
26. Meng, Y. Economic analysis for centralized battery energy storage system with reused battery from EV in Australia. In Proceedings of the E3S Web of Conferences, Kenitra, Morocco, 25–27 December 2021; Volume 300.
27. Lei, Z.; Yingqi, L.; Li, Z.; Beibei, P. Commercial Value of Power Battery Echelon Utilization in China's Energy Storage Industry. *J. Beijing Inst. Technol. (Soc. Sci. Ed.)* **2018**, *6*, 34–44.
28. Geng, S.; Lin, L.; YYin Yan, H. Loan Approval Evaluation Framework of Public-Private Partnership Project of Battery Storage Power Station under Interval-valued Intuitionistic Fuzzy Environment. *J. Clean. Prod.* **2020**, *254*, 120133. [CrossRef]
29. Mou, M.; Zhou, Y.; Zheng, W.; Xie, Y.; Wang, S.; Liu, L.; Wei, C. Modeling and Control Strategy for Multiterminal Flexible DC Distribution Network with Echelon Utilization Power Battery. *Complexity* **2021**, *2021*, 2396929. [CrossRef]
30. Sharma, M. Role of Battery Energy Storage System in Modern Electric Distribution Networks—A Review. *Int. J. Adv. Trends Comput. Sci. Eng.* **2019**, *8*, 443–450. [CrossRef]
31. Sun, J.; Liu, R.; Ma, Q.; Wang, T.; Tang, C. 2nd Use Battery Energy Storage System Power Reduction Operation. *J. Electr. Eng. Technol.* **2020**, *15*, 293–298. [CrossRef]
32. Jinlei, S.; Lei, P.; Ruihang, L.; Qian, M.; Chuanyu, T.; Tianru, W. Economic Operation Optimization for 2nd Use Batteries in Battery Energy Storage Systems. *IEEE Access* **2019**, *7*, 41852–41859. [CrossRef]
33. Loakimidis, C.; Murillo-Marrodán, A.; Bagheri, A.; Thomas, D.; Genikomsakis, K.N. Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios. *Sustainability* **2019**, *11*, 2527. [CrossRef]
34. Wang, S.; Liu, S.; Bai, X.; Wang, S.; Yue, C. Novel Power Allocation Approach in a Battery Storage Power Station for Aging Minimization. *Front. Energy Res.* **2020**, *7*, 166. [CrossRef]
35. Majeau-Bettez, G.; Hawkins, T.R.; Stromman, A.H. Life cycle environmental assessment of lithium-ion and nickel metal hy-dride batteries for plug-in hybrid and battery electric vehicles. *Environ. Sci. Technol.* **2011**, *45*, 4548–4554. [CrossRef]
36. Lu, Q. Life Cycle Analysis and Evaluation of Electric Vehicle Power Battery. Master's Thesis, Jilin University, Jilin, China, 2014; pp. 38–44.
37. Han, X.; Ouyang, M.; Lu, L.; Li, J. A comparative study of commercial lithium ion battery cycle life in electric vehicle: Capacity loss estimation. *J. Power Sources* **2014**, *268*, 658–669. [CrossRef]
38. Jia, Z.; Gao, F.; Du, S.; Sun, B. Life cycle assessment of lithium iron phosphate battery in different application scenarios. *China Environ. Sci.* **2022**, *42*, 1975–1984.
39. Wang, Z. Recycling Potential and Life Cycle Assessment of Power Batteries for New Energy Vehicles. Master's Thesis, Tsinghua University, Beijing, China, 2018; pp. 91–92.