Applications and Recycling of Lithium-ion Batteries

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Abstract. With the rise of global warming, people have turned to electricity as a means of reducing greenhouse gas emissions, and Lithium-ion batteries (LIBs) have emerged as a popular energy conservation solution. However, as the use of LIBs increases, the recycling industry is facing significant waste-management challenges. The decreasing content of precious metals in LIBs has led to a decline in recycling income. This article explores the application of LIBs in new energy vehicles, and evaluates the challenges faced by the recycling industry and provides suggestions for overcoming them. Currently, lithium iron phosphate, lithium nickel cobalt manganese and lithium nickel cobalt aluminum batteries have been used in new energy vehicle power batteries. The main recycle methods include direct recycling, hydrometallurgy, and pyrometallurgy. The article then suggests that improved recycling lines that use artificial intelligence and renew manufacturing standards may be beneficial solutions. By addressing these challenges, the problems associated with LIB recycling may be transformed into opportunities for the future.

1 Introduction

With the widespread use of conventional energy sources, climate change and increasing greenhouse gas emissions have made people realize that it is urgent to mitigate and solve environmental pollution and greenhouse effect. Therefore, the research and application of lithium-ion battery is a major challenge facing our country. In the current new energy technology, lithium-ion battery with the characteristics of high energy density, high working voltage and low self-discharge is the current research focus. Some of the main advantages, such as low maintenance costs and environmental protection, become a better option. LIBS is the first choice for consumer electronics and electric vehicles. The popularization and development of new energy vehicles put forward higher requirements for lithium-ion batteries [1]. In these industries, new energy vehicles, electronics and energy storage are promising. Aerospace, military equipment and other aspects. However, the current Li-based batteries still face some problems, such as resistance to overcharge and overdischarge, high cost, capacity attenuation and so on.

The production of lithium-ion batteries (LIBs) is currently expensive due to the scarcity of raw materials and the high energy requirements of the manufacturing process, which poses a significant challenge to the widespread adoption of LIB products [2]. Furthermore, the external cost during the raw materials extraction process, both socially and environmentally is magnificent [3]. For example, cobalt is extracted mainly in the politically unstable Democratic Republic of the Congo, the tiny dust local workers breathe in which mining might cause catastrophic effects on their health.

Additionally, as these batteries approach the end of their life, concerns about the disposal of large numbers of abandoned LIBs have arisen. To address these challenges avoid harm, and increase economic efficiency, recycling is essential. Private companies and governments have demonstrated significant interest in this area, leading to a wealth of research on the subject. However, while many scientists might put an attempt at this field for decades, big challenges still remain. Current methods mainly focus on the recycling of precious metals, such as cobalt, while the rest of the metals’ recycling rate is near zero. However, the trend of newer generation cells is decreasing the content of cobalt as its high prize. So the classic recycling ways must be updated to increase the overall recycling rate. The inadequate standards of LIBS production have become one of the biggest obstacles to the way recycling scales up, which could decrease cost and therefore increase profit, as well as conventional algorithms limit the flexibility of recycling lines.

This article briefly explains the 3 typical recycling processes and provides 2 suggestions that help solve this situation. The first suggestion is publishing a policy by the government to regulate the standards of production and take recycling into account while design. The second suggestion is to update the algorithm with Chat GPT and combine it with the developed computer vision competence, and force-sensitive robot arms to construct a flexible recycling line.

2 Application in new energy vehicles

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The General Office of the State Council of China states that the national strategy in order to develop new energy vehicles should be thoroughly implemented to encourage the new energy vehicle industry in China to grow in a sustainable and high-quality manner can quicken the process of building an automobile powerhouse [2, 3]. As one of the main power batteries for in the sphere of automobiles, lithium-ion batteries are frequently utilized in new energy cars. new energy vehicles. On December 10, 2021, the China Association of Automobile Manufacturers (CAAM) published data showing that the monthly installed capacity of power batteries in China in November 2021 was 20.8 GWh, including 9.2 GWh of ternary lithium batteries and 11.6 GWh of lithium iron phosphate batteries; the cumulative installed capacity from January to November was 128.3 GWh [3]. 128.3 GWh from January to November [3]. Lithium iron phosphate (LFP) uses lithium iron phosphate as the positive electrode material and graphene as the negative electrode material, which has better safety and lower cost, and has the advantages of environmental protection and long life. From 2015 to 2016, the installation of lithium iron phosphate batteries was much higher than other types of batteries, accounting for about 70% of the total [4]. Lithium cobalt acid batteries (LCO) use lithium cobaltate as the cathode material and graphene as the negative material. It is characterized by stable structure and high volume rate, but its safety is low and the cost is high. Ternary lithium salt is composed of ternary polymer materials Ni-Mn-Co (NCM) and Ni-Co (Al) nickel acid (NCA). It is characterized by the use of lithium nickel cobalt manganese oxide or lithium nickel cobalt aluminum oxide as positive electrode and graphene lithium battery as negative electrode. Ternary lithium battery is also widely used in new energy vehicles. From 2017 to 2020, the proportion of this model continues to rise, and in 2020 it has exceeded 61% [4]. Generally speaking, lithium iron phosphate, lithium nickel cobalt manganese and lithium nickel cobalt aluminum batteries have been used in new energy vehicle power batteries, but the above defects are still inevitable. Fig. 1 is the rechargeable batteries.

There are 3 typical methods of LIBs recycling: direct recycling, pyrometallurgy, hydrometallurgy, and direct recycling. However, it is more usual to see mixed recycling methods, such as Umicore.

Nevertheless, prior to using one of the recycling technologies, pretreatment is frequently utilized in the recycling process. Pretreatment is a crucial element in the industrial recycling process, as it helps to improve efficiency and reduce energy consumption. This is particularly important for high-quality raw materials such as cobalt, lithium and graphite, which are the main ingredients listed by the European Parliament [5]. By optimizing the pretreatment stage, the recycling efficiency of these CRMs can be enhanced, making it easier to extract and reuse them. This, in turn, can reduce the energy consumption required for subsequent steps, particularly for direct recycling and hydrometallurgy technologies [4]. Generally, the pretreatment process involves sorting, disassembling, pyrolytic, and machinic pre-treatment [5].

3.1 Direct recycling

Within a cycle, LIB is refreshed or reactivated to gain lost capabilities or features [6, 7], because it can recycle the functional electrode particles without changing the material properties, and will not cause overall dissolution and settlement, so the efficiency is much higher than the conventional treatment. Batteries that are going to be recycled directly need to be pretreated. Then, during the direct recycling process, battery components are separated utilizing physical techniques including magnetic separation and a moderate level of heat processing. By doing this, the active components, which are the main focus of the recovery process, are protected [8]. After that, relithiation or hydrothermal processes are used to correct surface and bulk defects in the recovered, purified active material [9]. In theory, the direct recycling process can recover a high percentage of the battery's active materials, including the cathode, anode, and electrolyte [10].

The direct recycling method has various advantages. Firstly, it is relatively more sustainable and cost-effective. Since direct recycling reuses active materials without their prior extraction from the electrodes. The quantity used of chemicals is lower than hydrometallurgy, as well as the energy consumption compared to pyrometallurgy. Thus, greenhouse gases and poisonous solvent emissions problems are easier to solve and the whole process is more environmentally friendly [8]. Secondly, the method is independent of size as opposed to techniques like pyrometallurgy or hydrometallurgy [9].

However, drawbacks exist too, which are: (i) the scope of reusing is limited since the components are removed directly and are only suitable for batteries of the same generation. (ii) the task of direct recycling is generally done manually which means it is hard to scale up and improve the profit.

3.2 Hydrometallurgical methods

*Fig. 1. Rechargeable batteries. https://pubs.acs.org/doi/full/10.1021/acs.chemrev.9b00535*
Cobalt, nickel and lithium produced by wet smelting technology have high recovery (98%), and have the advantages of energy saving, high selectivity, low pollution and so on. Because of its lower production cost and lower production cost, it has been widely used in scientific research institutions and industry [10].

At present, the wet smelting technology uses the aqueous phase system to extract and separate the laser-induced breakdown spectrum. The hydrometallurgical process is composed of acid leaching, chemical precipitation, solvent extraction and electrolysis. In acid, it is dissolved in water for the first time [11]. Then, cobalt, lithium, nickel, manganese and other metals are extracted from the solution by an appropriate method [12].

Pretreated battery materials are typically used, with the aluminum and copper current-gathering elements taken off. H$_2$SO$_4$ and H$_2$O$_2$ solutions are utilized in the extraction process, although other acids such as hydrochloric acid and HNO$_3$ can also be used, organic acids such as citric acid and oxalic acid can also be used. These metals are then selectively deposited as salts using changes in the pH value or, after extraction into the solution, extracted with organic solvents, which contain extractants such as dialkyl phosphate or phosphate esters [11].

Again, the hydrometallurgical process offers several advantages while disadvantages exist. The advantages are: (i) the recovery rate of precious metals, such as cobalt, is 99% under experiment conditions [11]. (ii) Compare with pyrometallurgy, hydrometallurgical processes do have high energy consumption. (iii) lower air pollution compared to pyrometallurgical processes [12].

Drawbacks of the process are: (i) the vast amount of water consumption; (ii) the high cost of polluted water treatment; (iii) the challenge of separating certain elements due to their similar properties, which can result in higher costs [11]; (iv) The methods should be developed to be more universal since the LIBs have updated and started using new raw materials which can not be treated by current hydrometallurgy process.

3.3 Pyrometallurgy methods

Especially for the smaller battery, it has to go through some treatment, such as dismantling the battery and putting it directly into the high-temperature smelting furnace. There is no need to separate the electrode from the electrode. This processing can be done in two ways. Firstly, lithium ion was gradually removed by low temperature (150500 °C) process, and then lithium ion (Co, Ni, Cu), lithium ion (Li$_2$O, Li$_2$CO$_3$) and lithium ion (Fe$_2$O$_3$, Fe$_3$CO$_3$) were obtained by high temperature (1400-1700 °C) [12].

The advantages of Pyrometallurgical methods are: (i) the pretreatment required is less complicated, including shredding or crushing; (ii) the way is more universal, suitable for various compositions, sizes, and shapes, (iii) high efficiency of cobalt recycling [12].

The disfavor of Pyrometallurgical methods are: (i) high energy consumption to heat the furnace; (ii) more solid trash and wasted gases; (iii) lithium will be lost in the slag [15].

4. Challenges and suggestions of LIBs recycling

4.1 Challenges

4.1.1 Challenges of updation

Due to the rapid development of LIBs, new materials are being used that cannot be recycled by current technologies. Therefore, the three typical recycling methods mentioned earlier need to be updated and made more universal.

Additionally, due to the high price of precious metals like cobalt and lithium, researchers have started reducing their containment in the new generation of LIBs. While this will decrease the cost of LIBs, it poses a challenge for the recycling industry. It is apparent from the three classical recycling methods mentioned earlier that cobalt recycling has received strong attention. Two of the three methods have a high cobalt recycling rate, while the recycling rate of other metals like aluminum and nickel is near zero. Most companies profit by reusing cobalt or lithium. However, with the new generation of LIBs taking over the market, the amount of cobalt they can extract will decrease. Eventually, firms will be unable to make ends meet. Therefore, the recycling process must be updated to increase the general recycling rate and decrease the cost.

4.1.2 Challenges of scaling up

Both pretreatment and direct recycling are challenging to scale up since they are done manually. Due to the lack of standards for LIBs production and the rapid pace of development, the types of LIBs in the market are endless. Moreover, besides pyrometallurgy, the other two methods and pretreatment are not flexible. As a result, a new recycling strategy must be developed for every kind of battery, making the recycling process impossible to scale up.

Furthermore, recycling considerations during the design phase are inadequate. Researchers generally focus more on other features of a LIB, such as capacity, energy density, and service lifetime. Thus, the circumstance of each battery is variable and impossible to do with pre-programmed robots. Thus, only a small amount of professional labor can perform this task. Additionally, workers face hazards such as cell explosions and fires, toxic gases, etc., Therefore, the 2 factors increase the cost of labor.

The solvent extraction method is to isolate or purify liquid mixtures by using the difference in partitioning properties of solutes between two mutually incompatible or partially mutually soluble solvents. Common extractants include organic solvents, surfactants,
Artificial individual forms not robot help is drag pollution different The ease been iPhone these power properties E. Soils for Li, algorithms, model greenhouse the limited specific conventional publish Zhu, difficult. et (2023) to new good soles material built chalk gives 1.2 the entirely low-cost, manganese it Fan, Chat It decreases may soil is in people conclusion arms [18] robot 3 the in people migration recycling the hope. if iron is iPhone K. Chem. the vision million annually. (2019) A.B. 14 annually. (2018) S. The safe. to recycling. fundamental Suggestions a build LIBs Recurrent. line. us Botelho lines arms GPT, L. pyrometallurgy. it accidents Nigl, The adjust solubilization article technology, could prioritize (2023) fluid. humans affect arms Contributions recycling, is urgent iPhone, strongly as by robot arms process, of is of water V.C.I. soil Jean, (2021) to to that Koetje, al., (2018) D.C.R. people take-apart be 6. government AI, caused al., release insights. AlFantazi, not clean Zhao, S. recycling, efficiency have mentioned, machine learning algorithm. 4.2.2 Artificial intelligence (AI) To solve the problems mentioned, it has been proposed to use a new generation of force-sensitive "co-bot" robot arms for collaborative human-robot co-working. Although different from conventional robot arms, these co-bot robot arms allow humans and robot arms to share the same room and collaborate, potential hazards to human labor are still unpreventable.

In 2016, Apple built a recycling line for iPhone 6. It uses a completely autonomous, clean take-apart process to release and separate individual components for specialty material recycling. With the capacity to disassemble 1.2 million iPhone 6 devices annually. [18] However, due to the conventional technologies Apple uses, the recycling line is limited only to iPhone 6 and is not entirely safe. There is potential for fire accidents or explosions caused by overheating in the middle of recycling, so monitoring equipment is needed. The main problem is the pre-programmed algorithm. If the algorithm is good enough to enable people to adjust the model of the iPhone, the cost can be remarkably low as the robot arms themselves are not expensive.

Nowadays, the emergence of updated AI, such as Chat GPT, gives us hope. Combining the developed computer vision technology, force-sensitive robot arms, and machine learning algorithms, it is probably to build a flexible, low-cost, and efficient LIBs recycling line. Additionally, if machine vision is not mature, adding machine-readable elements like QR codes in the components may help robot arms recognize the components of LIBs.

5. Conclusion

With the widespread use of conventional energy sources, climate change and increasing greenhouse gas emissions have made people realize that it is urgent to mitigate and solve environmental pollution and greenhouse effect. Lithium iron phosphate, lithium nickel cobalt manganese and lithium nickel cobalt aluminum batteries have been used in new energy vehicle power batteries. The main recycle methods include direct recycling, hydrometallurgy, and pyrometallurgy. The article then suggests that improved recycling lines that use artificial intelligence and renew manufacturing standards may be beneficial solutions.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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