Case Studies of Lithium-Ion Battery Disposal Methods

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Electric vehicles are one zero-emission, non-polluting solution to the ongoing global warming effects seen from fossil fuel emissions. This trend has been seen worldwide, with an exponential increase in electric vehicle sales over the past decade. Electric vehicles are becoming so prevalent, in fact, that by 2035, 50% of all global passenger-vehicles sales will be electric (Goldman Sachs, 2023). To power these electric vehicles, lithium-ion batteries (LIB) have been widely adopted as the standard because of their many advantages including their long life-cycle, small size and high working voltage. These LIBs are composed of valuable precious metals such as nickel, lithium, copper and cobalt. Since the rise in electric vehicle sales, a 3-fold increase in the price of lithium and a 4-fold increase in the price of cobalt occurred and motivated the operation of many lithium battery recycling plants. By recycling LIBs, these valuable materials can be recovered and there will be lower reliance on mining which lessens that environmental impact. Additionally, recycling decreases battery waste which is often toxic and harmful to the environment. Recycling and other end-of-life pathways available for LIBs will help reduce the pressure on the resource supply chain while also protecting the environment and paving the way for a circular economy model: a zero-waste model where products are reused, repaired and remanufactured. This paper will analyze case studies of LIBs' end-of-life pathways will reveal how different countries are progressing towards a circular economy.

Background

The number of electric vehicle batteries is predicted to increase to 150 million by 2035 (Kotak et al., 2021) which makes determining the end-of-life pathway of lithium-ion batteries within these vehicles increasingly important to figure out. After a battery drops below its capacity retention rate, it must be retired from its use in an electric vehicle and moved on to its disposal lifecycle. Batteries in decent condition can be implemented into other applications that require less power than electric cars such as electric bikes, energy storage and even street lights and then recycled once their capacity falls below 30% if its original potential (Liu et al., 2020). In a spent LIB, a recycling company would be interested in the remaining composition of the precious metals which is typically 5-20% cobalt, 5-10% nickel and 5-7% lithium and other metals. If batteries are not placed into a specific disposal pathway and instead abandoned in landfills, precious minerals may cause environmental harm and increase the demand to mine for virgin materials that are already limited in supply. In the past, batteries were gathered hazardously in materials recovery facilities, causing fires from damaged or short-circuited batteries. Around the world, the question of how best to approach recycling and reusing LIBs has been answered in many forms and supported by legislation incentives.

Relevant literature

In the European Union, United States, and China, regulations for how to dispose of LIBs vary greatly. The market for the reuse and recycling of spent LIBs will continue to grow as the number of electric vehicles increases, therefore driving more attention to the state of regulations in these countries. Since the disposal and handling of these batteries is crucial for the safety of the environment and the people involved in their disposal, globally, countries currently categorize LIBs as “Dangerous Goods”. In the European Union, the goals that were outlined for the recycling of LIBs in 2016 are included in the “Batteries Directive” included a goal on the prohibition of automotive batteries disposal to landfill or burning, instead striving for a collection goal. The United States does not have a direct resource recovery directive for LIB waste but states such as California, New York, New Jersey, Florida and Maryland are requiring battery manufacturers provide or fund the recycling of batteries. China’s policies are much more advanced and requires manufactures to create networks for recycling of batteries as well as collecting, storing and transferring old batteries. As these programs have developed, battery makers are starting to follow standardized designs to help simplify the recycling process. These countries paint a picture of the different recycling approaches and the legislation that comes with them.

Currently the economics of recycling lithium from LIBs is much more expensive than mining it. The market for recycled lithium will increase as more batteries come to their end-of-life and companies must figure out how to dispose of them. Companies are started and expanded as these markets are created and many government policies push innovation and business in the necessary areas. China's economy and how the government is supporting the recycling of precious metals is one case study of how the lithium recycling industry may expand in the coming years. Circular economy companies are working with battery manufacturers in order to make this process easier in the future and this will greatly increase the recycling rate of the future (Pagliaro & Meneguzzo, 2019).

While China’s economy is incentivizing the recycling process, LIBs are also being reused in smaller scale applications like e-bikes. While this method holds great potential for reuse, a challenge facing this pathway is the heterogeneity of the retired batteries. Though a manufacturer may recommend a new battery for an electric vehicle when it reaches a 70% capacity of its original health, drivers make the decision on when to get a new battery which will result in a wide range of battery health coming into a reuse program (Kotak et al., 2021). For this reason, until conditions become more stabilized, recycling methods may be the most reliable option.

Recycling has a high initial investment cost and returns have been constant with the use of pyrometallurgy/smelting and hydrometallurgy to accomplish the process (Kotak et al., 2021). Regaining precious metals such as nickel and cobalt have economically driven the technology forward and will continue to do so. The move towards a circular economy in which products are reused and valuable resources are regained is a main motivating factor in the disposal of lithium-ion batteries. Recycling rates are currently very low worldwide and the incoming boom of lithium-ion batteries as more electric cars hit the streets will impact these numbers (Pagliaro & Meneguzzo, 2019).

Methods

Case studies were analyzed for different policies, economic impacts and private sector impacts in each country. In order to narrow down the scope of which countries to analyze, an understanding of the countries with the most dominant lithium markets was developed and then scrutinized for which already have legislation in place to help promote reuse and recycling programs of LIBs. The most dominant lithium markets are those which have displayed an increasing trend in electric vehicle sales. China and the United States drastically demonstrate this trend over the rest of the world and therefore have been selected for case studies for this paper. The majority of the remaining countries that also demonstrated this increased trend (Norway, United Kingdom, France, Netherlands, Germany, Japan, Sweden and Canada) are members of the European Union and were selected as the third case study for this paper.

Once a country was selected, private sector initiatives to enhance recycling and reuse paired with government driven incentives were unpacked and compared alongside other countries. This showed where the world is currently in the development of these programs and helped to highlight what steps could be improved in certain countries. Synthesizing all of these case studies showed how the world is progressing towards a circular economy and the steps that must be taken to continue to move us forward.

Results and Discussion

In order to establish a circular economy, governments enact legislation that drives the industry towards a set of standards. For the recycling of LIBs, these standards come in the form of collection rates, recycling efficiencies and regulations that dictate waste disposal responsibilities and safety requirements (Neumann et al., 2022). If these policies are not implemented, the environment pays the price as companies who lack incentive for safe disposal methods take the easy way out. To avoid negative environmental impacts, governments pass legislation that clearly outlines who is responsible for the end-of-life of products. One type of legislation that is often used is the extended producer responsibility (EPR) which states that the producers are responsible for the end-of-life treatment. EPR separates this responsibility into both physical and financial. Physical responsibility includes the collection, transportation, sorting, reuse, recycling and disposal while financial responsibility are the costs associated with these tasks and the ability to incorporate the waste treatment costs into their prices (Neumann et al., 2022). Regulations surrounding LIB waste disposal vary from country to country which impacts the recycling landscape directly. The differences in policies are shown through the case studies of China, the European Union (EU) and the United States.

China

China's dominance in the lithium-ion battery recycling industry is fueled in part because of the country's large lithium extraction industry. Even though Chile, Argentina and China are the world's leading producers of lithium, the impending lithium demand caused by the increase in electric vehicle sales has led China to question the security of its current lithium supply. China leads the world in production of lithium-ion batteries but it heavily relies on Australia for spodumene ore imports in this process (Costa et al., 2021). In order to increase the domestic lithium market, China has heavily emphasized the closed-loop process, or circular economy model, through its governmental policies. The closed loop model dictates that lithium, once extracted and brought into the market through a lithium-ion battery, for example, will remain in use by recycling the product that it came to the market in and purifying it to a level that it can be re-used in other applications. The benefits of recycling LIBs are further emphasized when the volume of required material is compared to other traditional lithium extraction methods. To extract one ton of lithium, 250 tons of spodumene minerals or 750 tons of brine are required (Qiao et al., 2021). Alternatively, only 28 tons of LIBs that have reached their end-of-life would be needed to produce one ton of lithium (Qiao et al., 2021). To take advantage of the potential that LIB recycling holds, China has acted swiftly to establish a strong LIB recycling infrastructure; as shown in FIGURE XXX. With the help of governmental policies and subsidies to drive more innovation in the recycling industry, China has set the standard for other countries looking to expand their LIB recycling industry.

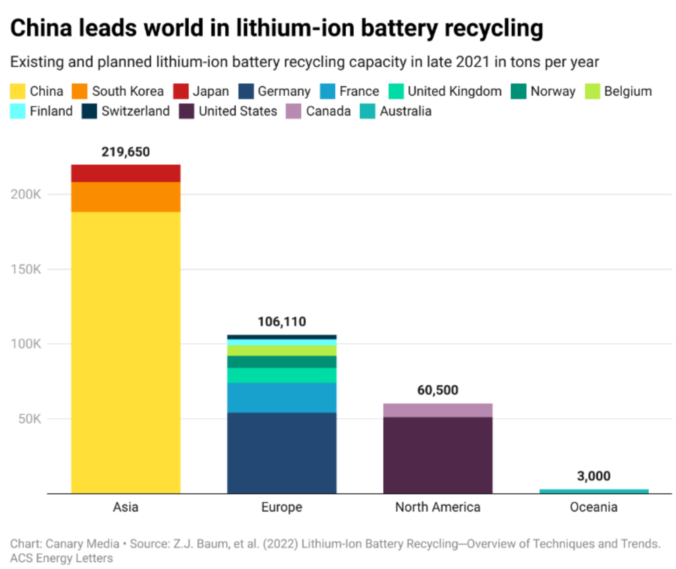

Figure 1. Lithium-ion battery recycling capacity by country
(https://www.canarymedia.com/articles/batteries/chart-china-is-trouncing-the-us-on-battery-recycling)

Though China had previously passed legislation surrounding the waste disposal of batteries including lead-acid batteries, the government did not start establish regulations around recycling of LIBs until the 2010s. Throughout the 2010s, the focus on EPR recycling began and regulations that defined pollution prevention and control techniques for battery recycling were passed (Bird et al., 2022). China encourages this EPR model in order to strengthen the closed-loop supply chain that it creates. With this regulation in place, electric vehicle manufacturers buy LIBs from battery manufacturers and install them into their vehicles for consumer sale (Hao et al., 2022). Once the battery reaches its end-of-life, consumers bring the used LIB to a repair point so the electric vehicle manufacturer can collect the battery, install a new one and then sell the used LIB to a recycling company. After the recycling company takes care of discharging, dismantling, separating and extracting, extracted material can be sold to battery manufacturers and the process can begin anew (Hao et al., 2022). In this closed-loop system, the electric vehicle manufacturer has the most control over how many LIBs are recycled and can implement various trade-in strategies to increase collection rates and therefore recycling rates. The Chinese government provides some amount of electric vehicle battery recycling funds in advance and additionally subsidizes the recycling based on the situation (Hao et al., 2022). China is also collecting data on all stages of the battery recycling process from manufacturers, auto makers and recyclers through its provision put into place in 2018 to determine recycling effectiveness (Bird et al., 2022). This is a major step forward in the planning of future LIB recycling processes in China.

European Union (EU)

Despite the face that the EU does not have as established of a LIB recycling infrastructure as China does, it still has a strong regulatory foundation for battery waste. In 2006, the Battery Directive was put in place and all EU member countries were required to set-up collection schemes for end-of-life portable batteries including those for electric vehicles (Neumann et al., 2022). This is both a physical and financial EPR system where battery producers finance the cost and must take back these batteries to be recycled. Minimum collection targets and recycling efficiencies directives were given along with the requirement to use the best technology to preserve the surrounding environment and protect human health (Neumann et al., 2022).

The 2006 Battery Directive is a reward-penalty system and some member states of the EU have taken their battery recycling systems a step further. In Germany, a fund-and-deposit mechanism mandates that manufacturers use the “sell one, collect one” method for lead-acid batteries where consumers buy new batteries at the same time that they return an old battery (Hao et al., 2022). Currently, the EU does not have explicit regulations for LIB recycling but a proposal was brought forward in 2020 to repeal the 2006 directive and amend it with a new regulation. This proposed regulation is similar to China’s 2018 policy where it collects data on all steps of the recycling process. In the EU’s 2020 proposed policy, manufactures must provide durability and performance data in addition to “battery passports” that allow consumers to know what a battery contains, where those materials came from and what their environmental impacts are to inform the recycling process (Bird et al., 2022). The 2020 proposal is a part of the EU’s Green Deal and other initiatives including the circular economy action plan (European Parliament, 2022).

United States

The United States has very limited federal policies surrounding battery waste management and no federal policy specifically regarding LIB waste. There are only two federal policies that are relevant to the battery waste disposal conversation in the United States: the Universal Waste Rule as a part of the Resource Conservation and Recovery Act (RCRA) and the Battery Act of 1996 (Neumann et al., 2022). The Universal Waste Rule as a part of RCRA was passed in 1995 and lays the framework for the hazardous waste regulations that LIBs recycling will most likely face at the federal level (Bird et al., 2022). Hazardous waste laws in the United States are among the strictest, governing all components of the waste disposal process including handling, storage, treatment and domestic or international transport. The Battery Act of 1996 is the only federal law that details battery recycling but not for LIBs. It focuses on the recycling of nickel-cadmium and small lead-acid batteries and includes a national standardization of labelling requirements (Neumann et al., 2022). This act is viewed as a potential template for LIB recycling policies in the U.S. and has effectively created a closed-loop model for lead, not with more than 95% of lead-acid batteries being recycled but also with lead-acid battery design improving to prepare it for the recycling process (Bird et al., 2022).

Even though the United States does not yet have federal policy for the recycling of LIBs, recent laws have allowed for more funding to go into battery recycling research. In 2021, the Infrastructure Invest and Jobs Act provided $60 million for research into battery recycling, $50 million for local governments and $15 million to retailers to fund battery recycling programs (Bird et al., 2022). This federal funding will aid states who have already begun their own advisory boards to identify the best framework for LIB recycling. California is the farthest along in this process and already has established EPR regulations for rechargeable battery recycling

(Bird et al., 2022). An advisory group was brought together with the goal of "as close to 100% as possible of lithium-ion batteries in the state are reused or recycled at end-of-life in a safe and cost-effective manner (Spector, 2022)." From the advisory board's report published in 2022, 93% voted in favor of a hybrid approach instead of a full EPR approach to LIB recycling which means the responsibility for recycling would not always fall on the manufacturers. Two main scenarios were explained when an electric vehicle reaches its end-of-life: dismantlers can take ownership of the vehicle and would be responsible for ensuring the battery is properly recycled or if the battery is not acquired by a licensed dismantler, the vehicle manufacturer is responsible for its recycling process (Kendall et al., 2022). Though this is a good first step in recommending LIB recycling policies, federal laws would be the most effective way to standardize labelling, for example, in order to streamline the recycling process. As recycling technology continues to advance, legislation will need to mirror and continue to support the industry's innovation.

Comparing policies

As summarized in Table 1, China has lead the way in LIB recycling policy and has benefitted from these legislations by establishing themselves has the predominant LIB recycling market. The United States and the EU look to China's policies to model some of their new legislation while also building on the lessons that China has learned. It is much harder for the EU and the U.S. to pass legislation that would standardize battery labeling, compared to China because it takes time to cohesively unify the many countries and states that are at different stages of regulations for LIBs. China has the huge advantage of time because of its policies in the 2010s and will continue to advance faster than the EU and the United States because of programs such as its 2018 provision that collects data on the various steps of the recycling process.

Table I. Comparing federal policies for the recycling and treatment of EOL batteries

Year	EU	USA	China
1995		Universal Waste Rule as part of the Resource Conservation and Recovery Act (RCRA)	Law of the People´s Republic of China on the Prevention and Control of Solid Waste Pollution
1996		Mercury-Containing and Rechargeable Battery Management Act (Battery Act)	
2006	Battery Directive (Directive 2006/66/EC)		
2012	Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU)		Notice of the State Council on Issuing the Planning for the Development of the Energy-Saving and New Energy Automobile Industry
2014			Guiding Opinions of the General Office of the State Council on Accelerating Promoting and Application of New-Energy Automobiles
2016			Policy on Pollution Prevention Techniques of Waste Batteries Implementation Plan of the Extended Producer Responsibility System
2018			Interim Measures for the Management of Power Battery Recovery and Utilization of New Energy Vehicles
2020	Proposal for a regulation of the European Parlia-ment and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020		

(Neumann, 2022)

Private sector LIB recycling investments

In China, the United States and the EU, LIB recycling companies have been growing to prepare for the surge of batteries that will need to be recycled in the coming years. China already has many established recycling companies and recent announcements such as China's CATL, the world's largest battery company, spending $4 billion USD to build a battery recycling facility in Hubei Provine, China, shows the potential of the industry (Herh, 2022). The recycling business has led to fierce competition in China with companies buying used batteries from abroad while in the United States and EU, recycling is still seen as a waste disposal process that companies want government subsidies for (Deign, 2019). Despite this industry opinion, recycling companies are forging partnerships in the United States and EU to forge ahead in the recycling industry. For example, a Canadian company, Li-Cycle, has signed with LG Energy Solutions to build a factory worth $175 million USD in Rochester, New York which will become the largest LIB recycling hub in North America (Herh, 2022). In the EU, German car parts maker ZF group and the German chemical company BASF have formed a partnership agreement to recycle waste batteries (Herh, 2022). These huge strategic business investments show the urgent need for government policies to support these areas and establish guidelines for these companies to follow.

Conclusion

Over the next few decades, the surge of electric vehicle sales will lead to a dramatic increase in the number of LIBs that will reach their end-of-life. Though reuse into other applications is a possibility, recycling LIBs holds the most potential not only for business profits, but also because of its environmental impacts. Companies will be able to preserve scarce materials and offset some of the cost of LIB manufacturing as well as preventing toxins from improper disposal methods from harming the environment. As shown through the case studies of China, the European Union and the United States, countries are at very different levels of legislation regarding recycling LIBs. China has emerged as an early leader in recycling due to its comprehensive policies and ability to collect data on the wide range of LIB types and recycling methods at each step of the process. The EU has potential for a strong regulatory base because of its success in recycling lead-acid batteries as shown in programs such as Germany’s “sell one, collect one” method. The United States has made investments into research for recycling LIBs and states like California have taken initiative to lay the groundwork for LIB recycling policies. All of these countries are weighing the role of extended producer responsibility (EPR) policies and determining how to enforce their regulations. Future policies must be flexible enough to cover the new recycling technologies that are emerging and continue to support the role of a circular economy in each of these countries. With the help of government legislations, LIB recycling business will benefit from the circular economy model and each country will be able to take a strong step forward in environmental protection.

<u>References</u>

Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022, January 20). The regulatory environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736-740. https://pubs.acs.org/doi/10.1021/acsenergylett.1c02724

Costa, C. M., Barbosa, J. C., Gonçalves, R., Castro, H., Del Campo, F. J., & Lanceros-Mendez, S. (2021). Recycling and environmental issues of lithium-ion batteries: advances, challenges and opportunities. *Energy Storage Materials*, *27*, 433-465. https://doi.org/10.1016/j.ensm.2021.02.032.

Deign, J. (2019, September 16). *How China is cornering the lithium-ion cell recycling market*. Greentech Media. Retrieved April 4, 2023, from https://www.greentechmedia.com/articles/read/how-china-is-cornering-the-lithium-ion-cell-recycling-market

Goldman Sachs. (2023, February 10). *Electric vehicles are forecast to be half of global car sales by 2035*. Goldman Sachs. Retrieved April 5, 2023, from https://www.goldmansachs.com/insights/pages/electric-vehicles-are-forecast-to-be-half-of-global-car-sales-by-2035.html#:~:text=Electric%20vehicles%20are%20forecast%20to%20be%20half%20of%20global%20car%20sales%20by%202035,-10%20FEB%202023&text=The%20adoption%20of%20electric%20vehicles,according%20to%20Goldman%20Sachs%20Research.

Hao, H., Xu, W., Wei, F., Wu, C., Xu, Z. (2022). Reward–Penalty vs. Deposit–Refund: Government Incentive Mechanisms for EV Battery Recycling. *Energies* 2022, 15, 6885. https://doi.org/10.3390/en15196885

Herh, M. (2022, February 28). *Korea, U.S. and China competing in EV Battery Recycling Market*. BusinessKorea. Retrieved April 4, 2023, from http://www.businesskorea.co.kr/news/articleView.html?idxno=88294

Kendall, A., Slattery, M., & Dunn, J. (2022). Lithium ion Car Battery Recycling Advisory Group. *California Environmental Protection Agency.* Retrieved April 2, 2023, from https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf

Kotak, Y., Marchante Fernández, C., Canals Casals, L., Kotak, B. S., Koch, D., Geisbauer, C., Trilla, L., Gómez-Núñez, A., & Schweiger, H.-G. (2021). End of Electric Vehicle Batteries: Reuse vs. Recycle. *Energies*, *14*(8), 2217. https://doi.org/10.3390/en14082217

Liu, Z., Liu, X., Hao, H., Zhao, F., Amer, A. A., & Babiker, H. (2020). Research on the Critical Issues for Power Battery Reusing of New Energy Vehicles in China. *Energies*, *13*(8), 1932. https://doi.org/10.3390/en13081932

Neumann, J., Petranikova, M., Meeus, M., Gamarra, J. D., Younesi, R., Winter, M., & Nowak, S. (2022, January 10). Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling. *Advanced Energy Materials*, *12*(17), 2102917. Retrieved February 3, 2023, from https://onlinelibrary-wiley-com.proxy1.library.virginia.edu/doi/pdf/10.1002/aenm.202102917

European Parliament. (2022, March). *New EU Regulatory framework for batteries: Setting sustainability requirements.* European Parliamentary Research Service. Retrieved April 2023, from https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf

Pagliaro, M., & Meneguzzo, F. (2019). Lithium battery reusing and recycling: A circular economy insight. *Heliyon*, *5*(6), e01866. https://doi.org/10.1016/j.heliyon.2019.e01866

Qiao, D., Wang, G., Gao, T., Wen, B. & Dai, T. (2021). Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050. *Science of The Total Environment*, 764, 142835. https://doi.org/10.1016/j.scitotenv.2020.142835.

Spector, J. (2022, June 15). *How to prepare for the coming flood of used EV batteries*. Canary Media. Retrieved April 3, 2023, from https://www.canarymedia.com/articles/electric-vehicles/how-to-prepare-for-the-coming-flood-of-used-ev-batteries