End-of-life management of lithium-ion batteries from electric vehicles: Selected references on problem scope, regulatory environment, and circular economy opportunities

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September 23, 2021

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Executive summary

Search strategy

In addition to the references that I had already compiled on the end-of-life (EOL) issues associated with lithium-ion batteries (LiBs), I did an internet search specifically for those used in electric (EV) and hybrid vehicles. I also searched DOE's Alternative Fuels Data Center to locate relevant data sets. Although LIBs also power many other devices (see the Problem Scope section), I focused my search specifically on EV batteries. The summary findings include only U.S. regulatory and policy information, although the annotated bibliography also contains references to policies in the EU and UK.

Summary findings

Problem scope

LiBs are powerful, relatively inexpensive, and lightweight energy sources that power a wide variety of electronics and portable tools. LiB applications in consumer electronics include wireless headphones, cell phones, laptops, tablets, handheld gaming devices, hearing aids, calculators, hoverboards, e-cigarettes, portable tools, cameras, and other devices. They are also found in larger products such as electric vehicles (EVs) and energy storage systems. (O'Connor, 2021). This literature review focuses on LiBs in EVs, specifically in light-duty vehicles/cars.

According to the International Energy Agency (IEA), sales of light-duty EVs in the U.S. have increased dramatically in the last decade. Over the last decade, U.S. light-duty EV sales topped 1.7 million. In 2011, there were 17,730 light-duty EVs sold in the U.S. By 2020, that number reached nearly 300,000. IEA projects that sales will continue to increase to 1.2 million per year by 2025 and nearly 2.5 million per year by 2030 (International Energy Agency, 2021). These data show that end-of-life LiBs will increasingly pose a major waste management issue for states. By 2030, there could be 11 million tonnes of lithium-ion battery waste from electric vehicles alone — enough to fill London's Wembley Stadium almost 20 times over (Fall, 2020).

Current regulatory environment

Decommissioned LiBs that are discarded and not directly reused may be subject to U.S. federal, state, and/or local solid waste and hazardous waste (Curtis et al., 2021). North Carolina, California, and Hawaii are the only U.S. states with policies that directly address reuse and EOL management options for LiBs used in mobile and stationary battery energy storage systems (Curtis et al., 2021). To date, none have issued policy recommendations.

North Carolina DEQ submitted their final report to the legislature in January 2021. The report concluded that LiBs exhibit hazardous characteristics and that existing regulations for managing hazardous batteries applied to energy storage system batteries (North Carolina Department of Environmental Quality, 2021).

In November 2019, CalEPA convened the Lithium-Ion Car Battery Recycling Advisory Group to jointly study and address management of EV LiBs. The group is required to meet quarterly between April 1, 2019 and April 1, 2022 and consult with universities and research institutions that have conducted research in the area of battery recycling, with manufacturers of electric and hybrid vehicles, and with the recycling industry. By April 1, 2022, the group must submit policy recommendations to the California state legislature for ensuring that close to 100% as possible of EOL EV LiBs in the state are reused or recycled in a safe, cost-effective way. In addition to the mandated study and policy recommendations, the California Public Utilities Commission, the California Department of Resources Recycling and Recovery, the California Energy Commission, and the California Air Resources Board signed on to a Memorandum of Understanding to cooperate on the development of uniform approaches to waste from EV batteries, energy storage batteries, and related equipment (Curtis et al., 2021).

In Hawaii, the Governor signed a law in June 2021 which requires a comprehensive study to determine best practices for disposing of and recycling clean energy materials, including batteries (Relating to Energy, 2021).

A circular economy for EOL LiBs: Opportunities & barriers

The Faraday Institution ReLiB Project estimates that the first life of an EV battery ranges from 8 to 10 years. (Ahuja et al., 2020). At end of the original vehicle’s service life (approximately 15 years), the battery will have approximately 70% of its initial capacity remaining. Its second use service life is highly sensitive to the second life duty cycle, climate, battery thermal management, and other factors, but could potentially exceed 10 years under favorable conditions (Neubauer et al., 2015).

EOL EV batteries can be remanufactured, repurposed, or recycled. Remanufacturing refers to refurbishing EV batteries and deploying them in their original applications. Repurposing involves reconfiguring batteries for second life use in less stressful applications. Recycling of EV LiBs can be complex because the architectures of packs, modules, and cells, as well as the chemical composition of active materials, can vary significantly by manufacturer (Chen et al., 2019).

The ReCell Center, DOE’s lithium-ion recycling R&D center based at Argonne National Laboratory, focuses on research topics to enable profitable recycling for industry adoption. One of the center’s research goals is closed-loop recycling, where materials from spent batteries are recycled directly into the vehicle battery manufacturing process, which minimizes energy use and material waste by eliminating mining and processing steps (Lattanzio & Clark, 2020).

Establishing a circular economy for batteries can support the development of the clean energy sector. Affordable energy storage is a key component to ensuring that mini-grids are more widely adopted. A research team from Utah State University has already developed a system that uses retired EV batteries for solar power storage, which could reduce costs by up to 50% (Viglairolo, 2021). Utilities could also use second use batteries to replace grid-connected combustion turbine peaker plants and provide peak-shaving services (Neubauer et al., 2015). Data centers and telecommunications infrastructure use LiBs to support back-up power systems because of their ability to operate without needing to be cooled (Fall, 2020).

Another advantage of encouraging a circular economy for LiBs is that recycling-based resource recovery diverts valuable materials from landfills. Domestic recovery of critical materials (e.g., lithium, cobalt, nickel, manganese, and graphite) from LiBs could reduce U.S. dependence on foreign markets and imports and bolster domestic production and manufacturing. Further, extending the useful life of LiBs through reuse lowers lifecycle environmental impacts by reducing energy output and the costs of obtaining, transporting, and refining virgin materials required to manufacture new LiBs (Curtis et al., 2021).

Unfortunately, the reuse and recycling market for LiBs in the U.S. is nascent and there is currently limited motivation for private investment in new and expanded market opportunities. The complex regulatory environment for LiBs also makes it difficult to determine viable secondary use applications and there are limited examples of projects that clearly demonstrate the quality, performance, safety, and technical viability of reused and refurbished LiBs. Finally, federal and state solid waste and federal transportation laws often regulate LiBs destined for resource recovery in the same way as LiBs destined for disposal. This disincentivizes reuse and recycling because the economics and accessibility of disposal are more favorable (Curtis et al., 2021).

Cited references

Ahuja, J., Dawson, L., & Lee, R. (2020). A circular economy for electric vehicle batteries: Driving the change. *Journal of Property, Planning and Environmental Law*, *12*(3), 235–250. https://doi.org/10.1108/JPPEL-02-2020-0011

Chen, M., Ma, X., Chen, B., Arsenault, R., Karlson, P., Simon, N., & Wang, Y. (2019). Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries. *Joule*, *3*(11), 2622–2646. https://doi.org/10.1016/j.joule.2019.09.014

Curtis, T., Smith, L., Heath, G., & Buchanan, H. (2021). *A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations* (NREL/TP-6A20-77035). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/77035.pdf

Fall, T. (2020, December 18). Renewable energy growth depends on a circular economy for batteries. *GreenBiz*. https://www.greenbiz.com/article/renewable-energy-growth-depends-circular-economy-batteries

International Energy Agency. (2021). *Global EV Data Explorer*. IEA. https://www.iea.org/articles/global-ev-data-explorer

Lattanzio, R. K., & Clark, C. E. (2020). *Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles* (CRS-R46420; Congressional Research Service Reports). Congressional Research Service. https://sgp.fas.org/crs/misc/R46420.pdf

Neubauer, J., Smith, K., Wood, E., & Pesaran, A. (2015). *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries* (NREL/TP--5400-63332, 1171780). https://doi.org/10.2172/1171780

North Carolina Department of Environmental Quality. (2021). *Final Report on the Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment*. North Carolina General Assembly Environmental Review Commission. https://files.nc.gov/ncdeq/Environmental%20Management%20Commission/EMC%20Meetings/2021/jan2021/attachments/AttachA-21-05-H329---FINAL-REPORT-Ellen--1-.pdf

O'Connor, P. (2021). *An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling* (EPA 530-R-21-002). U.S. Environmental Protection Agency Office of Resource Conservation and Recovery. https://www.epa.gov/recycle/importance-sending-consumers-used-lithium-ion-batteries-electronic-recyclers-or-hazardous

Relating to Energy, Pub. L. No. Hawaii Act 092 (2021). https://www.capitol.hawaii.gov/measure_indiv.aspx?billtype=HB&billnumber=1333&year=2021

Viglairolo, B. (2021, May 3). Solar power storage could get a whole lot cheaper with used electric vehicle batteries. *TechRepublic*. https://www.techrepublic.com/article/solar-power-storage-could-get-a-whole-lot-cheaper-with-used-electric-vehicle-batteries/

Annotated bibliography

Overview/problem scope

Ambrose, H., & O'Dea, J. (2021). *EV Battery Recycling*. Union of Concerned Scientists. https://www.ucsusa.org/resources/ev-battery-recycling

Strategies for recycling lithium-ion batteries will help the continued deployment of electric vehicles.

Diaz, M. N. (2020). Electric Vehicles: A Primer on Technology and Selected Policy Issues (CRS R46231; Congressional Research Service Reports). Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R46231

As an emergent technology area, EVs present a number of issues for consideration. The fuel sources used to generate the electricity to charge PHEVs and AEVs are a major factor in determining EV greenhouse gas emissions relative to ICEVs. Per-mile EV emissions vary geographically and with the time of day and year that charging takes place. Growing demand for lithium-ion batteries also shifts the material requirements of the vehicle market from fuels for combustion to minerals and other materials for battery production. A growing EV market may encourage new strategies around the supply and refining of raw materials, ability to manufacture batteries, and end-of-life management for batteries that are no longer suitable for use in vehicles.

Fall, T. (2020, December 18). “Renewable energy growth depends on a circular economy for batteries.” *GreenBiz*. https://www.greenbiz.com/article/renewable-energy-growth-depends-circular-economy-batteries

As the renewable energy sector grows, high-capacity long-life battery storage is fundamental to its success. How these batteries are designed and made will define their environmental impact for generations to come. Creating a circular economy for batteries is crucial to prevent one of the solutions to the current environmental crisis becoming the cause of another.

Gottesfeld, P. (2021, January 21). “Electric Cars’ Looming Recycling Problem.” *Undark*. https://undark.org/2021/01/21/electric-car-looming-recyclability-problem/

Financial incentives to recycle spent electric vehicle batteries are eroding. That could spell environmental disaster.

Hunnicutt, T., & Scheyder, E. (2021, June 5). “Biden’s electric vehicle plan includes battery recycling push.” *Reuters*. https://www.reuters.com/business/autos-transportation/exclusive-bidens-electric-vehicle-plan-includes-battery-recycling-push-2021-06-04/

President Joe Biden’s strategy to make the United States a powerhouse in electric vehicles will include boosting domestic recycling of batteries to reuse lithium and other metals, according to government officials.

Jacoby, M. (2019, July 14). “It’s time to get serious about recycling lithium-ion batteries.” *Chemical & Engineering News* 97(28). https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

A projected surge in electric-vehicle sales means that researchers must think about conserving natural resources and addressing battery end-of-life issues.

Kelleher Environmental. (2019). *Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries*. American Petroleum Institute. https://www.api.org/~/media/Files/Oil-and-Natural-Gas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf

In January 2019 , API commissioned Kelleher Environmental (Kelleher) to conduct a study involving an extensive trade journal and literature search as well as interviews with industry representatives to identify the current and near-term future processes employed for the reuse and recycling of EV batteries, and to identify existing available information on the technical, environmental, energy and cost issues associated with EV battery reuse and recycling.

Lattanzio, R. K., & Clark, C. E. (2020). *Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles* (CRS-R46420; Congressional Research Service Reports). Congressional Research Service. https://sgp.fas.org/crs/misc/R46420.pdf

Increased deployment of battery electric vehicles (BEVs) and other alternative-fueled vehicles in the United States could have a variety of effects on energy security, the economy, and the environment. To address certain environmental concerns, including climate change, some Members of Congress and some stakeholder interest groups have expressed interest in the promotion of these technologies—specifically BEV technologies. This interest may include an analysis of the environmental effects of BEVs from a systems perspective, commonly referred to as "life cycle assessment" (LCA).

Melin, H. E. (2018a). ***The lithium-ion battery end-of-life market – A baseline study*****. Global Battery Alliance.**
http://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf

The purpose of this baseline study is to give an overview of the status of the end-of-life market today and how it is predicted to evolve during the next decade. The data and analysis is retrieved from the report "The lithium-ion battery end-of-life market 2018-2025, which is published by Circular Energy Storage and written by the same author as this study

Melin, H. E. (2018b). ***The lithium-ion battery end-of-life market 2018-2025: Analysis of volumes, players, technologies and trends*****. Circular Energy Storage Research and Consulting.**
https://static1.squarespace.com/static/587657ddbe659497fb46664c/t/5b511b990e2e7239c2bc7b0b/1532042145266/Table+of+content+The+lithium-ion+battery+end-of-life+market.pdf

This report covers the three pillars in the lithium-ion battery end-of-life market: How lithium-ion batteries reach end-of-life and how they are collected; How lithium-ion batteries are recycled; How lithium-ion batteries are reused in new or old applications. Based on this research we have worked out forecasts on how much batteries that will be recycled and reused, which end-products that will come from the different processes and how much raw materials from recycling that will be available for the lithium-ion battery supply chain.

Melin, H. E. (2019). ***State-of-the-art in reuse and recycling of lithium-ion batteries*****. Swedish Energy Agency. https://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf**

This report aims to give an overview of the current knowledge about reuse and recycling of lithium-ion batteries. The work has been commissioned by the Swedish Energy Agency with the purpose to identify any gaps in knowledge and technical know-how required to make the end-of-life chain for lithium-ion batteries more efficient in order to ensure that future funding of research in the area is used effectively and where it is mostly needed.

Melin, H. E. (2021*). The lithium-ion battery life cycle report 2021*. Circular Energy Storage Research and Consulting. https://static1.squarespace.com/static/587657ddbe659497fb46664c/t/5fdaa991dc2ddb6396c30fa6/1608165783527/The+lithium-ion+battery+life+cycle+report+sample.pdf

This report is about what happens with lithium-ion batteries when they are placed on the market, how they are used, reused and recycled. We are outlining both the current and future development of the volumes of batteries as they go through the different stages of their lifecycle.

Niese, N., Pieper, C., Arrora, A., & Xie, A. (2020, August 31). *Case for a Circular Economy in Electric Vehicle Batteries*. BCG Global. https://www.bcg.com/publications/2020/case-for-circular-economy-in-electric-vehicle-batteries

Recycle or reuse? That's the decision for companies looking to profit from millions of retiring EV batteries. What's the business case?

O'Connor, P. (2021). An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling (EPA 530-R-21-002). U.S. Environmental Protection Agency Office of Resource Conservation and Recovery. https://www.epa.gov/recycle/importance-sending-consumers-used-lithium-ion-batteries-electronic-recyclers-or-hazardous

This report was written to explore the growing number of fires caused by lithium-ion batteries (LIBs) in the waste management process. Anecdotal information has shown that materials recovery facilities (i.e., recycling centers or "MRFs") and other waste facilities have seen an increased number of fires due to LIBs, but there has been limited data on fire incidents at a national level. This report will help fill in this research gap.

***ReLiB: Recycling and reuse of EV lithium-ion batteries*. (s.d.). The Faraday Institution. https://www.faraday.ac.uk/research/lithium-ion/recycle-reuse/**

Transport is currently the largest source of greenhouse gas emissions in the UK. To meet legal commitments to reduce emissions to Net Zero by 2050, major reductions are required. To meet government's aim of moving towards a more circular economy, keeping resources in use as long as possible, minimising waste and promoting resource efficiency, the infrastructure for managing lithium-ion batteries when they are removed from electric vehicles (EVs) must be developed. The project aims to ensure that the UK has the facilities and regulations required for the safe, economic and environmentally sound management of the materials contained in lithium-ion batteries at the end of their first life and so enhance the overall efficiency of the raw materials supply chain.

Thomas, S. (2021, September 9). "Commentary: EVs from the recycling perspective—Recycling Today." ***Recycling Today*****.** **https://www.recyclingtoday.com/article/emr-scrap-automobile-recycling-uk-batteries-co2-emissions**

Steve Thomas of EMR Ltd. considers the challenges and opportunities awaiting recyclers who will confront end-of-life electric vehicles.

Woollacott, E. (2021, April 26). "Electric cars: What will happen to all the dead batteries?" ***BBC News*****.** **https://www.bbc.com/news/business-56574779**

Recent proposals from the European Union would see EV suppliers responsible for making sure that their products aren't simply dumped at the end of their life, and manufacturers are already starting to step up to the mark.

Regulation & policy

Ahuja, J., Dawson, L., & Lee, R. (2020). "A circular economy for electric vehicle batteries: Driving the change." ***Journal of Property, Planning and Environmental Law*** **12(3), 235–250.** **https://doi.org/10.1108/JPPEL-02-2020-0011**

Purpose: With the UK's accelerating plans to transition to electric mobility, this paper aims to highlight the need for policies to prepare for appropriate management of electric vehicle (EV) lithium-ion batteries (LIBs) as they reach the end of their life. Design/methodology/approach This is a regulatory review based on projections of EV LIBs coming off the market and associated problems of waste management together with the development of a servitisation model. **Findings:** Circular economy in EV LIBs is unlikely to shape itself because LIB recycling is challenging and still in development. LIB volumes are insufficient for recycling to be currently profitable and a circular economy here will need to be driven by regulatory intervention. Ignoring the problem carries potentially high environmental and health costs. This paper offers potential solutions through new EV ownership models to facilitate a circular economy. Research limitations/implications The authors suggest a new EV ownership model. However, despite environmental benefits, re-shaping the fundamentals of market economies can have disruptive effects on current markets. Therefore, further exploration of this topic is needed. Also, the data presented is based on future projections of EV markets, battery lifespan, etc., which are uncertain at present. These are to be taken as estimates only. **Originality/value:** The paper proposes regulatory interventions or incentives to fundamentally change consumer ideas of property ownership for EVs, so that EV automotive batteries remain the property of the manufacturer even when the consumer owns the car.

Boxerman, S., & de Knop, S. (2021, April 12). "U.S., EU Rules as EV Batteries Reach End of Road." *WardsAuto*. https://www.wardsauto.com/powertrain/us-eu-rules-ev-batteries-reach-end-road

The still-evolving regulatory landscape governing these issues in the U.S. and European Union will be critically important to vehicle and battery manufacturers, fleet owners and battery recyclers.

Halleux, V. (2021). *New EU regulatory framework for batteries* (EU Legislation in Progress Briefings). European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf

Given the important role they play in the roll-out of zero-emission mobility and the storage of intermittent renewable energy, batteries are a crucial element in the EU's transition to a climate neutral economy. The proposal presented by the European Commission is designed to modernise the EU's regulatory framework for batteries in order to secure the sustainability and competitiveness of battery value chains. It would introduce mandatory requirements on sustainability (such as carbon footprint rules, minimum recycled content, performance and durability criteria), safety and labelling for the marketing and putting into service of batteries, and requirements for end-of-life management. The proposal also includes due diligence obligations for economic operators as regards the sourcing of raw materials.

Illinois Sustainable Technology Center. (2020). *Salvage Yard Environmental Guidebook and Self-Audit Checklist*. Illinois Sustainable Technology Center. https://hdl.handle.net/handle/2142/106119

To improve environmental protection, the Illinois Sustainable Technology Center (ISTC) developed this environmental guidebook and self-audit checklist. Using the guidebook and checklist will help you better understand the environmental issues, comply with state and federal environmental regulations, and implement best management practices to minimize risks and liabilities. Includes information on the regulations associated with recycling spend LiBs.

Lithium-ion Car Battery Recycling Advisory Group. (n.d.). CalEPA. Retrieved September 16, 2021, from https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/

The Lithium-ion Car Battery Recycling Advisory Group was created to advise the Legislature on policies pertaining to the recovery and recycling of lithium-ion vehicle batteries sold with motor vehicles in the state. It is being led by the California Environmental Protection Agency (CalEPA), the Department of Toxic Substances Control (DTSC), and the Department for Resources Recycling and Recovery (CalRecycle). Additional members come from the environmental community, auto dismantlers, public and private representatives involved in the manufacturing, collection, processing and recycling of electric vehicle batteries, and other interested parties.

North Carolina Department of Environmental Quality. (2021). ***Final Report on the Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment*****. North Carolina General Assembly Environmental Review Commission.**
https://files.nc.gov/ncdeq/Environmental%20Management%20Commission/EMC%20Meetings/2021/jan2021/attachments/AttachA-21-05-H329---FINAL-REPORT-Ellen--1-.pdf

This final report is the culmination of the Department's consideration of the nine matters set out in Section 2(a) of HB329 to inform the development of rules governing the management of end-of-life (EOL) photovoltaic (PV) modules and energy storage battery systems and the decommissioning of utility-scale solar projects and wind energy facilities ("renewable energy equipment"). The information presented herein is also informed by the active participation of more than 100 stakeholders representing the renewable energy industry, investor-owned utilities, local governments, materials recyclers, academia, not-for-profit organizations, and state agencies.

Relating to Energy**, Pub. L. No. Hawaii Act 092 (2021).**
https://www.capitol.hawaii.gov/measure_indiv.aspx?billtype=HB&billnumber=1333&year=2021

Requires the Hawaii Natural Energy Institute, in consultation with the Department of Health, to conduct a comprehensive study to determine best practices for disposal, recycling, or secondary use of clean energy products in the State.

Slattery, M., Clark, B., & Scheff, E. (2019). ***Reuse and Recycle: Preparing California for a Battery-Reliant Energy System*****. University of California-Davis.**
https://energy.ucdavis.edu/wp-content/uploads/Reuse-and-Recycle-Preparing-California-for-a-Battery-Reliant-Energy-System-1.pdf

Lithium ion batteries will play a central role in the transition to a carbon-free economy, powering growing fleets of electric vehicles and providing large-scale storage to balance out the intermittent energy from renewable sources. Given California's ambitious climate goals, a paradigm-shifting transition to a battery-reliant economy is inevitable. It is therefore critical that policymakers be informed about the potential implications of ramping up lithium production, taking proactive steps to ensure that current electrification policies do not lead to unintended environmental degradation. This paper explores current trends in battery material sourcing and end-of-life disposal, as well as the market opportunities for repurposing and recycling Li-ion batteries. Finally, we recommend several policies the state can adopt to encourage the responsible management, reuse, and disposal of batteries.

Circular economy R&D

Bai, Y., Muralidharan, N., Sun, Y.-K., Passerini, S., Stanley Whittingham, M., & Belharouak, I. (2020). "Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport." ***Materials Today*** **41, 304–315. https://doi.org/10.1016/j.mattod.2020.09.001**

The emergence and dominance of lithium-ion batteries in expanding markets such as consumer electronics, electric vehicles, and renewable energy storage are driving enormous interests and investments in the battery sector. The explosively growing demand is generating a huge number of spent lithium-ion batteries, thereby urging the development of cost-effective and environmentally sustainable recycling technologies to manage end-of-life batteries. Currently, the recycling of end-of-life batteries is still in its infancy, with many fundamental and technological hurdles to overcome. Here, the authors provide an overview of the current state of battery recycling by outlining and evaluating the incentives, key issues, and recycling strategies. The authors highlight a direct recycling strategy through discussion of its benefits, processes, and challenges. Perspectives on the future energy and environmental science of this important field is also discussed with respect to a new concept introduced as the Battery Identity Global Passport (BIGP).

Bobba, S., Mathieux, F., & Blengini, G. A. (2019). "How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries." ***Resources, Conservation and Recycling*** **145, 279–291. https://doi.org/10.1016/j.resconrec.2019.02.022**

Although not yet developed in Europe, second-use of traction batteries enables an extension of their lifetime and potentially improves life cycle environmental performance. Li-ion batteries (LIBs) offer the most promising chemistry for traction batteries in electric vehicles (xEVs) and for second-use. Due to the novelty of the topic and the expected increase of e-mobility in the next decades, more efforts to understand the potential consequences of second-use of batteries from different perspectives are needed. This paper develops a dynamic, parameterised Material Flow Analysis (MFA) model to estimate stocks and flows of LIBs after their removal from xEVs along the specific processes of the european value-chain. Direct reuse, second-use and recycling are included in the model and parameters make it customisable and updatable. Focusing on full and plug-in electric vehicles, LIBs and energy storage capacity flows are estimated. Stocks and flows of two embedded materials relevant for Europe were also assessed (cobalt and lithium). Results showed that second-use corresponds to a better exploitation of LIBs' storage capacity. Meanwhile, Co and Li in-use stocks are locked in LIBs and their recovery is delayed by second-use; depending on the slower/faster development of second-use, the amount of Co available for recycling in 2030 ranges between 9% and 15% of Co demand and between 7 and 16% for Li. Uncertainty of inputs is addressed through sensitivity analysis. A variety of actors can use this MFA model to enhance knowledge of second-use of batteries in Europe and to support the effective management of LIBs along their value-chain.

Chandan, A. (2020, July 17). "Solving the Problem of Renewable Energy Waste: A Circular Economy Approach to Sustainable Batteries." *NextBillion*. https://nextbillion.net/circular-economy-approach-to-sustainable-batteries/

The batteries that underpin localised renewable energy have a limited lifespan, contributing to the e-waste problem. Here's a more sustainable alternative.

Chen, M., Ma, X., Chen, B., Arsenault, R., Karlson, P., Simon, N., & Wang, Y. (2019). "Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries." *Joule* 3(11), 2622–2646. https://doi.org/10.1016/j.joule.2019.09.014

Lithium-ion batteries (LIBs) play a significant role in our highly electrified world and will continue to lead technology innovations. Millions of vehicles are equipped with or directly powered by LIBs, mitigating environmental pollution and reducing energy use. This rapidly increasing use of LIBs in vehicles will introduce a large quantity of spent LIBs within an 8?10-year span. Proper handling of end-of-life (EOL) vehicle LIBs is required, and multiple options should be considered. This paper demonstrates that the necessity for EOL recycling is underpinned by leveraging fluctuating material costs, uneven distribution and production, and the transport situation. From a life-cycle perspective, remanufacturing and repurposing extend the life of LIBs, and industrial demonstrations indicate that this is feasible. Recycling is the ultimate option for handling EOL LIBs, and recent advancements both in research and industry regarding pyrometallurgical, hydrometallurgical, and direct recycling are summarized. Currently, none of the current battery recycling technologies is ideal, and challenges must be overcome. This article is anticipated as a starting point for a more sophisticated study of recycling, and it suggests potential improvements in the process through mutual efforts from academia, industry, and governments.

Cready, E., Lippert, J., Pihl, J., Weinstock, I., & Symons, P. (2003). *Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications* (No. SAND2002-4084, 809607; pp. SAND2002-4084, 809607). Sandia National Laboratory. https://doi.org/10.2172/809607

The technical and economic feasibility of applying used electric vehicle (EV) batteries in stationary applications was evaluated in this study. In addition to identifying possible barriers to EV battery reuse, steps needed to prepare the used EV batteries for a second application were also considered. Costs of acquiring, testing, and reconfiguring the used EV batteries were estimated. Eight potential stationary applications were identified and described in terms of power, energy, and duty cycle requirements. Costs for assembly and operation of battery energy storage systems to meet the requirements of these stationary applications were also estimated by extrapolating available data on existing systems. The calculated life cycle cost of a battery energy storage system designed for each application was then compared to the expected economic benefit to determine the economic feasibility. Four of the eight applications were found to be at least possible candidates for economically viable reuse of EV batteries.

These were transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power. There were no major technical barriers found, however further study is recommended to better characterize the performance and life of used EV batteries before design and testing of prototype battery systems.

Curtis, T., Smith, L., Heath, G., & Buchanan, H. (2021). *A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations* (NREL/TP-6A20-77035). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/77035.pdf

In this report we analyze drivers, barriers, and enablers to a circular economy for lithium-ion batteries (LiBs) used in mobile and stationary BES systems in the United States. We also analyze federal, state, and local legal requirements that apply to the reuse, recycling and disposal of LiBs as well as the legal liability associated with noncompliance. Finally, we provide an overview of policies and initiatives in the United States that expressly address reuse/recovery and disposal of large-format LiBs.

D'Adamo, I., & Rosa, P. (2019). "A structured literature review on obsolete electric vehicles management practices." *Sustainability* 11(23). https://doi.org/10.3390/su11236876

The use of electricity for transportation needs offers the chance to replace fossil fuels with greener energy sources. Potentially, coupling sustainable transports with Renewable Energies (RE) could reduce significantly both Greenhouse Gas (GHG) emissions and the dependency on oil imports. However, the expected growth rate of Electric Vehicles (EVs) could become also a potential risk for the environment if recycling processes will continue to function in the current way. To this aim, the paper reviews the international literature on obsolete EV management practices, by considering scientific works published from 2000 up to 2019. Results show that the experts have paid great attention to this topic, given both the critical and valuable materials embedded in EVs and their main components (especially traction batteries), by offering interesting potential profits, and identifying the most promising End-of-Life (EoL) strategy for recycling both in technological and environmental terms. However, the economics of EV recycling systems have not yet been well quantified. The intent of this work is to enhance the current literature gaps and to propose future research streams.

Fujita, T., Chen, H., Wang, K.-T., He, C.-L., Wang, Y.-B., Dodbiba, G., & Wei, Y.-Z. (2021). "Reduction, reuse and recycle of spent Li-ion batteries for automobiles: A review." *International Journal of Minerals, Metallurgy and Materials* 28(2), 179–192. https://doi.org/10.1007/s12613-020-2127-8

The demand for Li-ion batteries (LIBs) for vehicles is increasing. However, LIBs use valuable rare metals, such as Co and Li, as well as environmentally toxic reagents. LIBs are also necessary to utilize for a long period and to recycle useful materials. The reduction, reuse, and recycle (3R) of spent LIBs is an important consideration in constructing a circular economy. In this paper, a flowsheet of the 3R of LIBs is proposed and methods to reduce the utilization of valuable rare metals and the amount of spent LIBs by remanufacturing used parts and designing new batteries considering the concept of 3R are described. Next, several technological processes for the reuse and recycling of LIBs are introduced. These technologies include discharge, sorting, crushing, binder removal, physical separation, and pyrometallurgical and hydrometallurgical processing. Each process, as well as the related physical, chemical, and biological treatments, are discussed. Finally, the problem of developed technologies and future subjects for 3R of LIBs are described.

Gaines, L. (2018). "Lithium-ion battery recycling processes: Research towards a sustainable course." *Sustainable Materials and Technologies* 17, e00068. https://doi.org/10.1016/j.susmat.2018.e00068

There is a need to develop technology to enable a resource-efficient and economically feasible recycling system for lithium-ion batteries and thus assure the future supply of the component materials. Lithium-ion batteries are complex products, and designs and materials are still evolving, which makes planning for future recovery more challenging. Several processes for recycling are proposed or operating, and each has advantages and disadvantages. This paper compares these processes on technical and economic bases, elucidating differences in benefits as a function of cathode composition. Since none of the existing processes is ideal, research areas are suggested that could enable development of improved recycling methods. The most promising research areas are separation technologies.

Gaines, L., Richa, K., & Spangenberger, J. (2018). "Key issues for Li-ion battery recycling." *MRS Energy & Sustainability* 5(1), 12. https://doi.org/10.1557/mre.2018.13

Concerted efforts by stakeholders could overcome the hurdles and enable a viable recycling system for automotive LIBs by the time many of them go out of service. Lithium-ion batteries (LIBs) were commercialized in the early 1990s and gained popularity first in consumer electronics, then more recently for electric vehicle (EV) propulsion, because of their high energy and power density and long cycle life. Their rapid adoption brings with it the challenge of end-of-life waste management. There are strong arguments for LIB recycling from environmental sustainability, economic, and political perspectives. Recycling reduces material going into landfills and avoids the impacts of virgin material production. LIBs contain high-value materials like cobalt and nickel, so recycling can reduce material and disposal costs, leading to reduced EV costs. Battery recycling can also reduce material demand and dependence on foreign resources, such as cobalt from Democratic Republic of the Congo, where much production relies on armed aggression and child labor. Several companies are finding ways to commercialize recycling of the increasingly diverse LIB waste stream. Although Pb-acid battery recycling has been successfully implemented, there are many reasons why recycling of LIBs is not yet a universally well-established practice. Some of these are technical constraints, and others involve economic barriers, logistic issues, and regulatory gaps. This paper first builds a case as to why LIBs should be recycled, next compares recycling processes, and then addresses the different factors affecting LIB recycling to direct future work towards overcoming the barriers so that recycling can become standard practice.

"Groupe Renault, Veolia & Solvay partner to recycle end-of-life EV battery metals in a closed loop." (2021, March 19). *Green Car Congress*. https://www.greencarcongress.com/2021/03/20210319-renauklt.html

Groupe Renault, Veolia and Solvay are partnering to enable the circular economy of EV battery metals in Europe through closed-loop recycling. The existing Veolia and Solvay consortium, created in September 2020 (earlier post), is thus reinforced with Groupe Renault's position and experience in circular economy and in the life cycle of EV batteries.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., & Anderson, P. (2019). "Recycling lithium-ion batteries from electric vehicles." *Nature* 575(7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5

Rapid growth in the market for electric vehicles is imperative, to meet global targets for reducing greenhouse gas emissions, to improve air quality in urban centres and to meet the needs of consumers, with whom electric vehicles are increasingly popular. However, growing numbers of electric vehicles present a serious waste-management challenge for recyclers at end-of-life. Nevertheless, spent batteries may also present an opportunity as manufacturers require access to strategic elements and critical materials for key components in electric-vehicle manufacture: recycled lithium-ion batteries from electric vehicles could provide a valuable secondary source of materials. Here we outline and evaluate the current range of approaches to electric-vehicle lithium-ion battery recycling and re-use and highlight areas for future progress.

Hua, Y., Liu, X., Zhou, S., Huang, Y., Ling, H., & Yang, S. (2021). "Toward Sustainable Reuse of Retired Lithium-ion Batteries from Electric Vehicles." *Resources, Conservation and Recycling* 168. https://doi.org/10.1016/j.resconrec.2020.105249

As attractive energy storage technologies, Lithium-ion batteries (LIBs) have been widely integrated in renewable resources and electric vehicles (EVs) due to their advantages such as high energy/power densities, high reliability and long service time. Although EVs basically do not produce pollution, the end-of-life (EOL) issues of LIBs cannot be ignored due to their potential economic benefits and environmental risks. Current methods for the retired batteries mainly include disposal, recycling and reuse. EV LIBs can be reused in a variety of applications with less demanding. Compared with recycling and disposal, reuse process can obtain better economic and environmental benefits. Many second life EV LIBs projects have been undertaken and demonstrated the great potential of reuse. However, the reuse should consider economic, environmental, technical, and various market perspectives. Technical challenges that must be faced include safety issues, assessment methods, screening and restructuring technologies, and comprehensive management during the reuse process. Economic feasibility issues, comprehensive supply chains, and the lack of relevant regulations also hinder large-scale development of reuse. It is foreseeable that improvements including standardization, big data and cloud-based technologies are desperately needed to maximize the industrialization of reuse and recycling.

Hua, Y., Zhou, S., Huang, Y., Liu, X., Ling, H., Zhou, X., Zhang, C., & Yang, S. (2020). "Sustainable value chain of retired lithium-ion batteries for electric vehicles." ***Journal of Power Sources*****, 478. https://doi.org/10.1016/j.jpowsour.2020.228753**

Lithium-ion batteries (LIBs) have been widely used in electric vehicles due to the advantages of high energy/power densities, high reliability and long service life. However, considering that a massive number of LIBs will likely retire and enter the waste stream in the near future, the handling of end-of-life LIBs must be taken carefully. The effective utilization of retired LIBs, which still remain about 70–80% of the initial capacity, can extend battery life, conserve natural resources and protect the environment. Herein, this review provides a systematic discussion on the circular value chain (CVC) of spent LIBs, and proposes a 5R principle entailing reduce, redesign, remanufacturing, repurpose and recycling in the CVC process. Then the state-of-the-art technologies for remanufacturing, and a thorough summary of key issues and applications of repurpose process, are presented in detail. Subsequently, this article presents a comprehensive discussion on the recycling process, including pre-treatments and mainstream recycling technologies, from the prospects of technical, economic and regulation perspectives. Advanced technologies such as big data, block chain and cloud-based services, as well as the improvement of regulation and standardization processes, are required to solve the issues. Finally, the future challenges and prospects for sustainable CVC are highlighted.

Kunz, T. (2019, February 15). "DOE launches its first lithium-ion battery recycling R&D center: ReCell". Argonne National Laboratory Press Releases. https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell

The launch of the U.S. Department of Energy's (DOE) first lithium-ion battery recycling center, called the ReCell Center, will help the United States grow a globally competitive recycling industry and reduce our reliance on foreign sources of battery materials.

Liu, C., Lin, J., Cao, H., Zhang, Y., & Sun, Z. (2019). "Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review." ***Journal of Cleaner Production*** **228, 801–813. https://doi.org/10.1016/j.jclepro.2019.04.304**

Due to the rapid expanding of plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs) and electric vehicles (EVs), the projectfed demand for lithium-ion batteries (LIBs) is huge and might result in supply risks for natural lithium-containing reserves. After the service life, spent LIBs continuously accumulate in the market, and they are excellent secondary resources for lithium recovery. To alleviate resource shortage and to decrease potential environmental pollution caused by improper solid waste disposal, recycling of spent LIBs is motivated world widely in recent years. Previous studies have usually focused on the recovery of cobalt and nickel, which create high economic benefit. Recovery of lithium, however, has not been highlighted. In this article, state-of-the-art on spent LIBs recycling is discussed with emphasis on lithium recovery. In addition to understanding underlying mechanisms and physiochemistry features of various recycling methods, the possibility for industrial realization of each method is also evaluated. The complex processing steps limit the industrial implementation of hydrometallurgy-dominant methods, which usually reclaim lithium in the last step, resulting in a poor recovery efficiency of lithium. The pyrometallurgy-dominant approach is readily to scale up but lithium is lost in the slag phase. Therefore, the mild recycling (cleaner production) methods are recommended for future study since they take advantages of traditional pyrometallurgy and hydrometallurgy, and could decrease treatment temperature as well as acid/alkaline usage.

O'Neill, M. (2021, February 3). "Green Li-Ion Technology Could Be the Solution to Recycling Lithium Ion Batteries." ***Business Insider*****.** **https://www.businessinsider.com/green-li-ion-technology-could-be-the-solution-to-recycling-lithium-ion-batteries-2021-2**

As CTO and cofounder of Singapore-based start-up Green Li-ion, Reza Katal is putting his chemical and environmental engineering background to work on tackling a growing environmental problem: how to recycle Lithium-ion (Li-ion) batteries. The company has developed a patented multi-cathode processor – the GLMC-1 – that the company says can speed up current recycling processes, while at the same time lowering costs, and is the only technology to fully rejuvenate every type of Li-ion battery cathode.

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**

Driven by the rapid uptake of battery electric vehicles, Li-ion power batteries are increasingly reused in stationary energy storage systems, and eventually recycled to recover all the valued components. Offering an updated global perspective, this study provides a circular economy insight on lithium-ion battery reuse and recycling.

Richa, K., Babbitt, C. W., Gaustad, G., & Wang, X. (2014). "A future perspective on lithium-ion battery waste flows from electric vehicles." ***Resources, Conservation and Recycling*** **83, 63–76.** **https://doi.org/10.1016/j.resconrec.2013.11.008**

As a proactive step towards understanding future waste management challenges, this paper presents a future oriented material flow analysis (MFA) used to estimate the volume of lithium-ion battery (LIB) wastes to be potentially generated in the United States due to electric vehicle (EV) deployment in the near and long term future. Because future adoption of LIB and EV technology is uncertain, a set of scenarios was developed to bound the parameters most influential to the MFA model and to forecast "low," "baseline," and "high" projections of future end-of-life battery outflows from years 2015 to 2040. These models were implemented using technology forecasts, technical literature, and bench-scale data characterizing battery material composition. Considering the range from the most conservative to most extreme estimates, a cumulative outflow between 0.33 million metric tons and 4 million metric tons of lithium-ion cells could be generated between 2015 and 2040. Of this waste stream, only 42% of the expected materials (by weight) is currently recycled in the U.S., including metals such as aluminum, cobalt, copper, nickel, and steel. Another 10% of the projected EV battery waste stream (by weight) includes two high value materials that are currently not recycled at a significant rate: lithium and manganese. The remaining fraction of this waste stream will include materials with low recycling potential, for which safe disposal routes must be identified. Results also indicate that because of the potential "lifespan mismatch" between battery packs and the vehicles in which they are used, batteries with high reuse potential may also be entering the waste stream. As such, a robust end-of-life battery management system must include an increase in reuse avenues, expanded recycling capacity, and ultimate disposal routes that minimize risk to human and environmental health.

Tabelin, C. B., Dallas, J., Casanova, S., Pelech, T., Bournival, G., Saydam, S., & Canbulat, I. (2021). "Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives." ***Minerals Engineering*****, 163. https://doi.org/10.1016/j.mineng.2020.106743**

The demand for lithium has skyrocketed in recent years primarily due to three international treaties—Kyoto Protocol, Paris Agreement and UN Sustainable Development Goals—all of which are pushing for the integration of more renewable energy and clean storage technologies in the transportation and electric power sectors to curb CO2 emissions and limit the adverse effects of CO2-promoted climate change. Over 60% of lithium produced in 2019 were utilised for the manufacture of lithium-ion batteries (LIBs), the compact and high-density energy storage devices crucial for low-carbon emission electric-based vehicles (EVs) and secondary storage media for renewable energy sources like solar and wind. In 2019, the global market value of lithium reached around US$213 B and is forecasted to grow by around 20–25% until 2025. In this review, the current state of global lithium resources, global lithium material flow, and forecasts of future lithium supply–demand dynamics are discussed. Persistent challenges in mining, processing and **industrial-scale recycling operations** *[LB note: section 4 of the article]* are also examined and recent innovations to address these issues are introduced. Finally, unconventional lithium sources like submarine/deep-sea ferromanganese (Fe-Mn) nodules and crusts, industrial wastes (e.g., desalination brines, geothermal brines and coal fly ashes), mining wastes and effluents, and extra-terrestrial materials are explored.

Tan, W. J., Chin, C. M. M., Garg, A., & Gao, L. (2021). "A hybrid disassembly framework for disassembly of electric vehicle batteries." ***International Journal of Energy Research*** **45(5), 8073–8082. https://doi.org/10.1002/er.6364**

In a recent study, it was determined that the usage of Li-Ion batteries in electric vehicles (EVs) represent a huge portion of the overall usage. In order to foster a sustainable future, Li-Ion batteries in EVs generally undergo a disassembly during the recycling process, which is intended for secondary purposes or recover useful materials and components. However, the current disassembly process is significantly time consuming and expensive. Hence in this research, a disassembly framework is presented, which focuses on improving the disassembly efficiency. The framework consists of a hybrid disassembly workstation that utilizes modified automated robotic arms and a specialized tool to allow an improvement in the disassembly time. The framework focuses on optimizing several identified parameters. These parameters (Design, Safety, and Cost) were identified through a comprehensive review and analysis of the schematics and properties of conventional EV battery packs along with the disassembly procedures being currently in practice. Additionally, the framework also consists of a conceptualized disassembly procedure developed based on the potential improvements of the hybrid disassembly. The framework proposed would allow a 5-step reduction in the overall disassembly steps, and thus would be highly suited to be adopted in the EV disassembly industry.

Tang, Y., Zhang, Q., Li, Y., Li, H., Pan, X., & Mclellan, B. (2019). "The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism." ***Applied Energy*****, 251, 113313. https://doi.org/10.1016/j.apenergy.2019.113313**

With the increasing popularity of Electric Vehicles (EVs), many EV batteries are intensively reaching their end-of-life, which has posed substantial challenges in ecological protection and sustainable development. However, the traditional subsidy mechanism is not effective in the current recycling market. Moreover, it is not conducive for guiding the EV industry to reduce dependence on the governmental financial support. As the reward-penalty mechanism has been successfully applied in similar fields, such as the recycling of waste portable batteries, it is expected to become a feasible alternative policy to promote the recycling of retired EV batteries. Therefore, this study aims to investigate the social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanisms by developing a Stackelberg game theoretical model. Three scenarios are proposed and compared: S1 no policy intervention, S2 subsidy mechanism, and S3 reward-penalty mechanism. The obtained results show that:(i) Compared with the subsidy mechanism, the reward-penalty mechanism presents greater effects on recycling rate and the social welfare; (2) Under the subsidy mechanism, consumer surplus and the profit of EV manufacturer are two main driving factors of the social welfare. Under the reward-penalty mechanism, the reduced environmental burden tends to be another key contribution; (3) A relatively low minimum recycling rate favors the environmental benefit, consumer surplus and profit of EV manufacturer, while a relatively high minimum recycling rate is beneficial to reduce both the policy implementation cost and environmental burden caused by untreated EV batteries.

Titirici, M.-M. (2021). Sustainable Batteries—Quo Vadis? *Advanced Energy Materials* 11(10). https://doi.org/10.1002/aenm.202003700

Over the past 20 years, a revolution has been seen in battery research culminating with a much-awaited Nobel Prize in Chemistry in 2019 for the development of Li-ion batteries. New Li-ion battery materials have been developed recently with improvements in performance. New Li battery chemistries have also emerged, exhibiting high energy density such as Li-S, Li-O2, Li-metal with solid state electrolytes as well as zero-excess Li anode metal batteries. This is tremendous progress and batteries are becoming more efficient and cheaper each year. Yet, most research in batteries is entirely focused on performance while the sustainability of all battery components making up the cell, as well as the battery chemistry itself are much overlooked. In this essay some perspectives are discussed and opinion is provided on the advancement of sustainability in battery research.

Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M., & Serna-Guerrero, R. (2019). "A critical review of lithium-ion battery recycling processes from a circular economy perspective." *Batteries* 5(4). https://doi.org/10.3390/batteries5040068

Lithium-ion batteries (LIBs) are currently one of the most important electrochemical energy storage devices, powering electronic mobile devices and electric vehicles alike. However, there is a remarkable difference between their rate of production and rate of recycling. At the end of their lifecycle, only a limited number of LIBs undergo any recycling treatment, with the majority go to landfills or being hoarded in households. Further losses of LIB components occur because the state-of-the-art LIB recycling processes are limited to components with high economic value, e.g., Co, Cu, Fe, and Al. With the increasing popularity of concepts such as "circular economy" (CE), new LIB recycling systems have been proposed that target a wider spectrum of compounds, thus reducing the environmental impact associated with LIB production. This review work presents a discussion of the current practices and some of the most promising emerging technologies for recycling LIBs. While other authoritative reviews have focused on the description of recycling processes, the aim of the present was is to offer an analysis of recycling technologies from a CE perspective. Consequently, the discussion is based on the ability of each technology to recover every component in LIBs. The gathered data depicted a direct relationship between process complexity and the variety and usability of the recovered fractions. Indeed, only processes employing a combination of mechanical processing, and hydro-and pyrometallurgical steps seemed able to obtain materials suitable for LIB (re)manufacture. On the other hand, processes relying on pyrometallurgical steps are robust, but only capable of recovering metallic components.

Viglairolo, B. (2021, May 3). "Solar power storage could get a whole lot cheaper with used electric vehicle batteries." ***TechRepublic*****.** **https://www.techrepublic.com/article/solar-power-storage-could-get-a-whole-lot-cheaper-with-used-electric-vehicle-batteries/**

A research team from Utah State University has developed technology to utilize retired EV batteries for solar power storage, which it said could reduce costs by up to 50%.

Yang, J., Gu, F., & Guo, J. (2020). "Environmental feasibility of secondary use of electric vehicle lithium-ion batteries in communication base stations." ***Resources, Conservation and Recycling*****, 156.** **https://doi.org/10.1016/j.resconrec.2020.104713**

Repurposing spent batteries in communication base stations (CBSs) is a promising option to dispose massive spent lithium-ion batteries (LIBs) from electric vehicles (EVs), yet the environmental feasibility of this practice remains unknown. Life cycle assessment (LCA) is used in this study to compare the environmental impacts of repurposed EV LIBs and lead-acid batteries (LABs) used in conventional energy storage systems (ESSs) of CBSs. The economic-based allocation method is used in the multi-functional system. The LCA results suggest that the manufacturing and reusing stages are the dominant contributors to the environmental impacts of repurposed LIBs, whereas battery recycling can reduce environmental impacts. In addition, the secondary use of EV LIBs results in less environmental impact than the use of LABs in all selected categories, except for metal depletion, which is attributed to the large lead consumption and low energy density of LABs. A sensitivity analysis is conducted to measure the influences of two alternative allocation methods (i.e., cut-off allocation and 50/50 allocation), the cycle life, and the electricity sources on the results. It is found that repurposing spent LIBs with 50/50 allocation method has the poorest environmental performance and is not sufficiently advantageous over using LABs. Moreover, extending the cycle life of repurposed LIBs and using a cleaner energy mix significantly reduce environmental impacts. This study offers implications to mitigate the end-of-life management problem of EV LIBs, including a life cycle management platform, an effective integration of the supply chain, and references for the ongoing "green" transition of the communication industry.

Young, C. (2021, August 10). "Tesla Says It Can Now Recycle 92% of Battery Cell Materials." ***Interesting Engineering*****.** **https://interestingengineering.com/tesla-says-it-can-now-recycle-92-of-battery-cell-materials**

Tesla claims it has the capacity to recover approximately 92 percent of battery cell materials thanks to ongoing improvements to its recycling process.

Zhao, Y., Pohl, O., Bhatt, A. I., Collis, G. E., Mahon, P. J., Rüther, T., & Hollenkamp, A. F. (2021). "A Review on Battery Market Trends, Second-Life Reuse, and Recycling." ***Sustainable Chemistry*****, 2(1).** **https://doi.org/10.3390/suschem2010011**

The rapid growth, demand, and production of batteries to meet various emerging applications, such as electric vehicles and energy storage systems, will result in waste and disposal problems

in the next few years as these batteries reach end-of-life. Battery reuse and recycling are becoming urgent worldwide priorities to protect the environment and address the increasing need for critical metals. As a review article, this paper reveals the current global battery market and global battery waste status from which the main battery chemistry types and their management, including reuse and recycling status, are discussed. This review then presents details of the challenges, opportunities, and arguments on battery second-life and recycling. The recent research and industrial activities in the battery reuse domain are summarized to provide a landscape picture and valuable insight into battery reuse and recycling for industries, scientific research, and waste management.

Statistics & data sets

Alternative Fuels Data Center. (2020). *Light-Duty AFV, HEV, and Diesel Model Offerings, by Technology/Fuel 1991-2019*. https://afdc.energy.gov/data/10303

This chart shows the number of light-duty alternative fuel vehicles (AFVs), hybrid electric vehicles (HEVs), and diesel models offered by vehicle manufacturers from 1991 through 2019. Vehicles capable of using E85 (up to 85% ethanol, 15% gasoline) have represented the largest share of models offered from 2003 until 2017, when electric vehicles (EVs) overtook them. This was largely because the technology required for E85 vehicles is comparatively inexpensive and compatible with gasoline vehicles. 2016 was the first quantitative decrease in the number of new AFVs offered after five years of steady increases. Contributing factors to this decrease could be low gasoline prices, the Volkswagen diesel emissions scandal, and the phase-out of Corporate Average Fuel Economy (CAFE) credits for flexible-fuel vehicles (FFVs). Since then, increases in EV offerings have made up for the loss in E85 offerings.

Alternative Fuels Data Center. (2021, June). *Electric Vehicle Registrations by State*. Alternative Fuels Data Center. https://afdc.energy.gov/data/10962

This chart shows the vehicle registration counts of all-electric vehicles (EVs) by state as of December 31, 2020. California has the greatest number of EVs, approximately 42% of EVs nationwide. Florida has the second highest count, followed by Texas. **Illinois has 26,000.** Does not include hybrid electric or plug-in hybrid registrations.

Argonne National Laboratory. (n.d.). *Light Duty Electric Drive Vehicles Monthly Sales Updates*. Retrieved September 10, 2021, from https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates

During July 2021, 74,398 HEVs (26,113 cars and 48,285 LTs) were sold in the United States, up 70.1% from the sales in July 2020. A total of 52,114 plug-in vehicles (35,213 BEVs and 16,901 PHEVs) were sold during July 2021 in the United States, up 84.1% from the sales in July 2020. PEVs captured 4.04% of total LDV sales in this month.

Bibra, E. M., Connelly, E., Gorner, M., Lowans, C., Paoli, L., Tattini, J., & Teter, J. (2021). ***Global EV Outlook 2021*****. International Energy Agency. https://www.iea.org/reports/global-ev-outlook-2021**

The Global EV Outlook is an annual publication that identifies and discusses recent developments in electric mobility across the globe. Combining historical analysis with projections to 2030, the report examines key areas of interest such as electric vehicle (EV) and charging infrastructure deployment, energy use, CO2 emissions and battery demand. The report includes policy recommendations that incorporate learning from frontrunner markets to inform policy makers and stakeholders that consider policy frameworks and market systems for electric vehicle adoption. This edition also features an update of the electric heavy -duty vehicle models coming onto commercial markets and slotted for release in the coming few years, and on the status of development of megachargers. It compares the electric vehicle supply equipment per EV with the recommended AFID targets. It also analyses the impact of EV uptake on governments' revenue from fuel taxation. Finally, it makes available for the first time two online tools: the Global EV Data Explorer and Global EV Policy Explorer, which allow users to interactively explore EV statistics and projections, and policy measures worldwide.

International Energy Agency. (2021). ***Global EV Data Explorer*****. IEA. https://www.iea.org/articles/global-ev-data-explorer**

Explore and download the full data behind the Global EV Outlook.

Zhou, Y., Mintz, M., Stephens, T., Aeschliman, S., & Macal, C. (2020). ***Electric Vehicle Adoption in Illinois*** **(ANL-20/38, 1658594, 161819; p. ANL-20/38, 1658594, 161819). https://doi.org/10.2172/1658594**

At the request of ComEd, this study analyzed a scenario in which plug-in electric vehicles (PEVs) are adopted at an accelerated rate in Illinois. Postulating a goal that 15% of on-road vehicles would be PEVs by 2032, we examined successful PEV adoption policies implemented elsewhere in the United States and abroad, characterized trajectories of new PEV sales and turnover of the existing vehicle fleet, projected PEV utilization and charging patterns, and computed resulting effects on energy demand, greenhouse gas emissions, and charging load. Based on the scale and scope of the goal, the body of evidence from the academic literature, and the dynamics of vehicle sales and replacement, we conclude that it will take a combination of strong incentives to achieve 15% PEV penetration in Illinois.