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

Summary Report

Prepared for

energy API

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in association with

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and

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Definitions, Acronyms, Abbreviations

BEV	Battery Electric Vehicle
DOE	Department of Energy
ELV	End-of-life Vehicle
EOL	End-of-life
ESS	Energy Storage System
EV	Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
Li-ion	Lithium-Ion
LMO	Lithium Manganese Oxide
NCA	Lithium Nickel Cobalt Aluminum Oxide
NiMH	Nickel-Metal Hydride
NMC	Lithium Nickel Manganese Cobalt Oxide
NREL	National Renewable Energy Laboratory
PHEV	Plug-in Hybrid Electric Vehicle
SoH	State of Health

Overview

This summary report presents the key findings of a study commissioned by the American Petroleum Institute (API) in 2019, which examined the nascent business of reusing and recycling electric vehicle (EV) batteries in North America and identified areas for future research. The study involved an extensive literature review as well as interviews with industry representatives to: (a) identify the processes employed for reusing and recycling EV batteries, and (b) evaluate available information on the technical, environmental, energy and cost implications associated with EV battery reuse and recycling. Our investigation found that the economics of recycling EV batteries using technologies in place in mid-2019 when the report was written is poor and not likely to improve given the current manufacturer focus on reducing the content of valuable battery components (e.g., cobalt-based cathodes). The technologies that promise to achieve high recovery rates for the metals contained in EV battery cathodes have not yet been proven at commercial scale and there is uncertainty regarding aftermarket values for the materials recovered, particularly as battery chemistries continue to evolve. Business economics are generally favorable for repurposing EV batteries for “second life” applications (e.g., energy storage systems) following their end-of-life (EOL) in vehicles. However, there are significant safety concerns in refurbishing and reusing batteries, particularly when their history is unknown. The efficiency and cost-effectiveness of reuse and recycling pathways are hindered by the lack of an established collection infrastructure that is necessary to accumulate large numbers of EV batteries in central locations. There are also technical challenges associated with: (1) a wide range of different (and evolving) battery formats, designs, compositions, and chemistries, and (2) a lack of automated processing for dismantling, recycling, or refurbishment/reuse at commercial scale. Future research is needed to identify the economic, social and environmental implications of EOL EV battery reuse and recycling, as well as the costs and full life cycle impacts of recycling compared to reuse for different EV battery chemistries.

Introduction

As electric vehicles (EV) continue to gain an increasing share of the vehicle market, the number of EV batteries requiring proper management at end-of-life (EOL) is growing, and is projected to rise significantly over the next five to 10 years. While this ever-growing waste stream presents significant opportunities for new companies wanting to enter this space, the infrastructure to collect and process EOL EV batteries in North America is not yet in place. There are also concerns among various stakeholders in the EV supply chain with regards to the economics of recycling EV batteries, since many of the new and emerging chemistries use less cobalt and are therefore less valuable to recyclers. At the same time, the reuse of EV batteries in second-life applications, such as energy storage systems (ESS), is gaining traction.

In 2019, a research study was carried out for API by the Kelleher Environmental team to examine the current and near-term future processes employed for the reuse and recycling of EOL EV batteries. The four key objectives were to identify:

- differences in EV battery technologies with respect to size, component configuration, chemistry and material composition;

- current and near-term (5-10 years) future commercial processes being used or that could be used for the recycling and reuse of EV batteries at the end of their first useful life;
- the potential technical, environmental, energy, and cost implications associated with EV battery recycling and second-life applications, including any engineering or financial obstacles or other barriers; and
- knowledge gaps and areas that could be further investigated.

This document provides a high-level summary of that research, including the current EV battery chemistries being used, and a description of reuse and recycling options for EOL EV batteries. The paper also briefly discusses the energy, environmental, cost, and technical considerations associated with EV battery reuse and recycling, as well as some of the research that is underway on options for EOL management.

Types of Electric Vehicles

There are three main types of EVs on the market today, classed by the degree that electricity is used as their fuel/power source (see Figure 1).

Hybrid-electric vehicles (HEVs), which entered the US market in the late 1990s and early 2000s[1], rely on two complementary drive systems: a gasoline engine and fuel tank, and an electric motor, battery and controls. Their energy comes from gasoline and regenerative braking; when the vehicle brakes, some of the energy is stored in the battery. That energy can be used at a later time to power the electric motor and assist the gasoline engine. The Toyota Prius is an example of a popular HEV.

Around 2010, two new types of EVs began to appear on the market: plug-in hybrid electric vehicles (PHEV) and battery-electric vehicles (BEVs).[2] A PHEV has both a gasoline (or diesel) engine and a battery pack that must be recharged via an external electric power source. When the battery pack on a PHEV is depleted, the vehicle operates in a similar way to a HEV, storing braking energy and assisting the gasoline engine[3]. Examples of PHEVs include the Chevrolet Volt and the Mitsubishi Outlander. Unlike a PHEV, a BEV runs entirely on a battery and electric drive train, and does not have a gasoline engine, fuel tank, or exhaust pipe. Once the battery is depleted, BEVs must be plugged into an electric power source in order to recharge the battery. Examples of BEVs are the Tesla Model S, the Nissan Leaf, and the Chevrolet Bolt.

Data from publicly available sources show that almost 690,000 EVs were sold in the US in 2018.[4]

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[1] Transportation Research Center at Argonne National Laboratory, "U.S. HEV Sales by Model," https://afdc.energy.gov/data/, accessed June 2019.

[2] United States Department of Transportation, "Hybrid-Electric, Plug-in Hybrid-Electric and Electric Vehicle Sales," https://www.bts.gov/content/gasoline-hybrid-and-electric-vehicle-sales, accessed May 2019.

[3] U.S. Department of Energy Alternative Fuels Data Center, "How Do Plug-In Hybrid Electric Cars Work?", https://afdc.energy.gov/vehicles/how-do-plug-in-hybrid-electric-cars-work, accessed Mar. 2020.

[4] Kelleher Environmental, Gracestone Inc., and Millette Environmental, "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," 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

Table 1 shows the total EVs, by type, that were sold in the US from 2012 to 2018. Similar information is presented graphically in Figure 2. As shown in both Table 1 and Figure 2, overall sales of HEVs have declined relative to 2012 while sales of BEVs and PHEVs have increased.

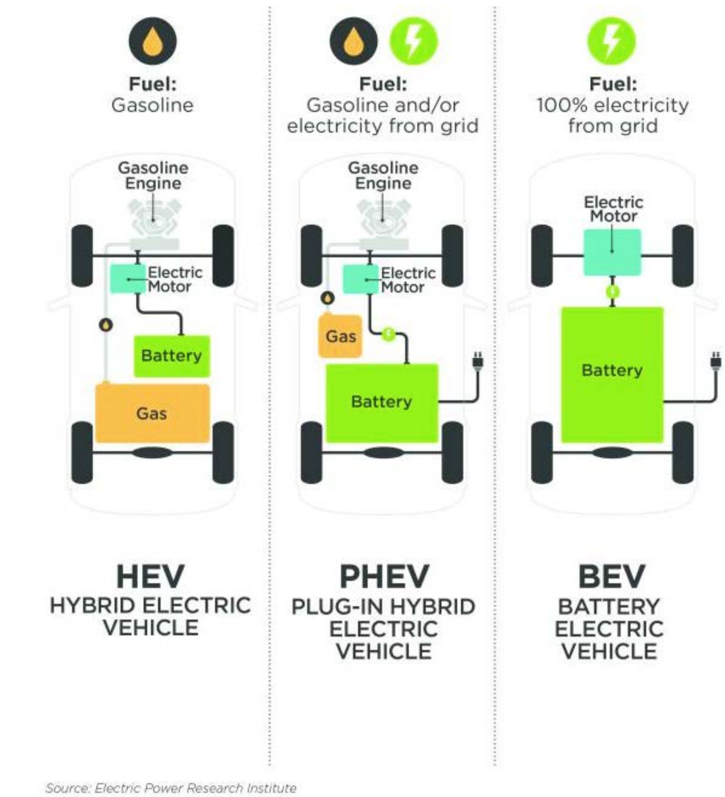


Figure 1: Schematic Showing Elements of a HEV, PHEV and BEV[5]

[5] Electric Power Research Institute, as cited in https://www.midlandpower.coop/ev

Table 1: US Electric Vehicle (EV) Sales, by Type (2012-2018)

EV Type	Battery Chemistry	Sales (units)			
		2012	2014	2016	2018
HEV[6,7]	NiMH or Li-ion	434,813	452,172	346,948	326,994
PHEV[8]	Li-ion	38,585	55,345	72,970	122,491
BEV[9]	Li-ion	14,022	67,093	85,643	238,816
Total		487,420	574,610	505,561	688,301

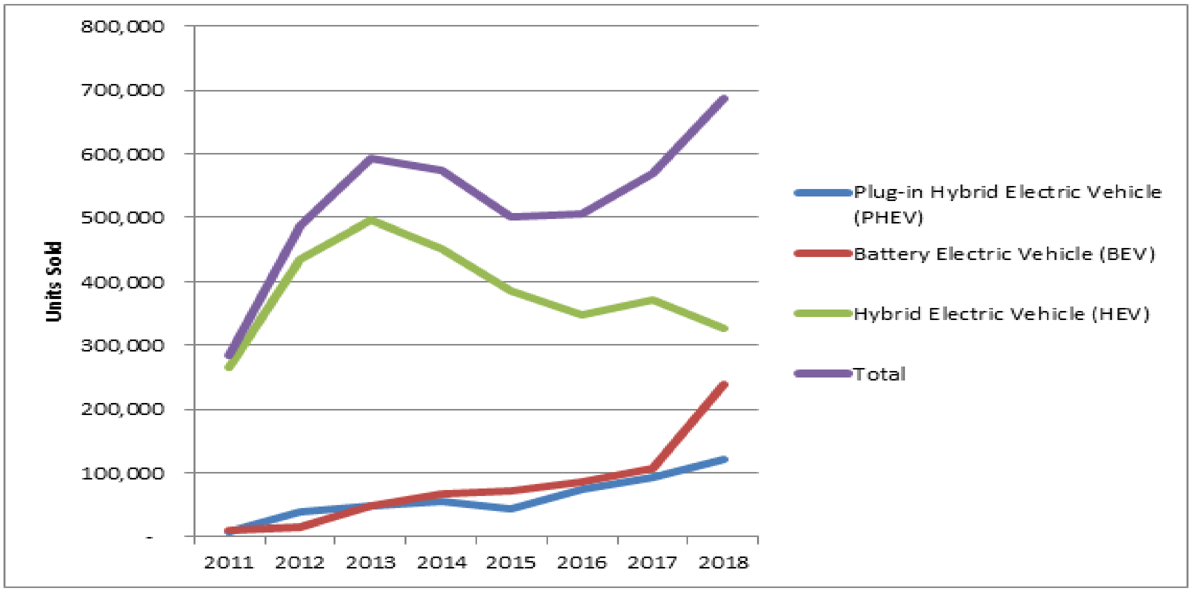


Figure 2: US Electric Vehicle (EV) Sales by Type (2011-2018)

EV Battery Chemistries

There are two types of commonly used chemistries for EV batteries: lithium-ion (Li-ion), which is used in all PHEV and BEVs, and nickel-metal hydride (NiMH), which is used in some HEVs. The choice of which battery chemistry and design to use is manufacturer- and vehicle-specific and is based on several factors including requirements for weight, energy density, charging characteristics, and costs of materials.

[6] Transportation Research Center at Argonne National Laboratory, "U.S. HEV Sales by Model," https://afdc.energy.gov/data/, accessed June 2019.
[7] HybridCars.com, "June 2018 Hybrid Cars Sales Dashboard," https://www.hybridcars.com/june-2018-hybrid-cars-sales-dashboard/, accessed June 2019.
[8] Loveday, S., "Monthly Plug-In EV Sales Scorecard: Historical Charts," https://insideevs.com/news/344007/monthly-plug-in-ev-sales-scorecard-historical-charts/, accessed Dec. 2018
[9] ibid.

While Toyota has traditionally used nickel-based batteries in HEVs, most other manufacturers have trended towards Li-ion batteries.[10] The size and weight of batteries used in EVs, and the different chemistries involved are presented in Appendix A for the top 10 best-selling HEVs, PHEVs, and BEVs in the US in 2018.

There are many variations of Li-ion battery chemistry, each of which offers different voltages, power and energy performances, with trade-offs among cost, efficiency, and safety. The main chemistries currently used in the industry are described below:

- **Lithium cobalt oxide (LCO):** Although rarely used in EVs today due to the high cobalt content (about 60%), LCO was the cathode material of choice for lithium batteries for many years due to its high energy density, long cycle life, and ease of manufacturing.[11] For this reason, LCO batteries will be among the first to arrive at recyclers and auto wreckers as well as metal shredders as they are currently reaching EOL. The Tesla Roadster is one example of an EV using these batteries.

- **Lithium nickel manganese cobalt (NMC):** These batteries have high energy density and reliability, but also have a high cobalt content, which increases their cost. NMC batteries can come in several forms, such as NMC111 (based on equal parts nickel, manganese, and cobalt) and NMC532/622 (which has a higher energy density and is more affordable due to a lower cobalt content).[12] Examples of EVs that use these batteries include the Chevrolet Bolt and Nissan Leaf.

- **Lithium iron phosphate (LFP):** LFP batteries offer good electrochemical performance with low resistance, have a wide temperature range, and are less likely to suffer from thermal runway.[13] Examples of EVs in which these batteries have been used include the Fisker Karma range-extended EV, the GM Spark, and the BYD e6/s6DM.[14]

- **Lithium manganese oxide (LMO):** LMO batteries offer a higher cell voltage than cobalt-based chemistries as well as higher temperature stability. Other advantages include lower cost, but they also are less durable than other chemistries, and therefore have shorter lifespans.[15] They are used in the Chevrolet Volt and BMW i3.

[10] Halvorson, B., "Lithium-ion vs. nickel-metal hydride: Toyota still likes both for its hybrids," https://www.greencarreports.com/news/1120320_lithium-ion-vs-nickel-metal-hydride-toyota-still-likes-both-for-its-hybrids, accessed Mar. 2020.

[11] Azevedo, M., Campagnoi, N., Hagenbruch, T., Hoffman, K., et al., "Lithium and cobalt—a tale of two commodities," https://www.mckinsey.com/~/media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx, accessed Mar. 2020.

[12] Nuamah, Charles. "A Simple Comparison of Six Lithium Ion Battery Types", 19th May, 2019. Accessed 19th May, 2020.https://owlcation.com/stem/Comparing-6-Lithium-ion-Battery-Type.

[13] Miao, Y., Hynan, P., von Jouanne, A., and Yokochi, A., "Review: Current Li-ion Battery Technologies in Electric Vehicles and Opportunities for Advancements," *Energies* 12: 1074, 2019, doi:10.3390/en12061074.

[14] Barai, A., Uddin, K., Chevalier, J., Chouchelamane, G.H. et al., "Transportation Safety of Lithium Iron Phosphate Batteries—A Feasibility Study of Storing at Very Low States of Charge", *Scientific Reports* 7: 5128, 2017, https://doi.org/10.1038/s41598-017-05438-2

[15] Azevedo, M., Campagnoi, N., Hagenbruch, T., Hoffman, K., et al., "Lithium and cobalt—a tale of two commodities," https://www.mckinsey.com/~/media/mckinsey/industries/metals%20and%20mining/our%20insights/lithium%20and%20cobalt%20a%20tale%20of%20two%20commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx, accessed Mar. 2020.

- **Lithium nickel cobalt aluminum (NCA)**: NCA batteries, which typically use a combination of 80% nickel, 15% cobalt, and 5% aluminum[16] are mostly used in Tesla vehicles.[17] These batteries share similarities with NMC chemistries as they offer a long life span and good energy density.[18] Their main drawback is that they are more costly to manufacture.

Figure 3 presents the material content, in percentage by weight, of these five battery types.

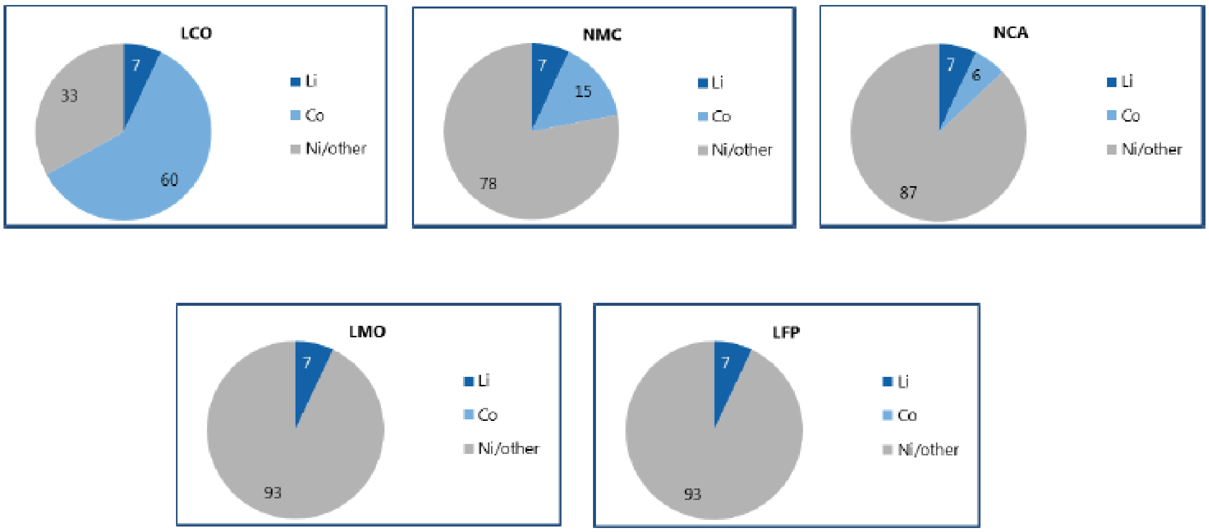


Figure 3: Material Content of Lithium-Ion Battery Types (%)[19]

NMC and NCA are the most common Li-ion chemistries used in EVs in North America. Currently, NMC cathodes account for nearly 28% of EV sales around the globe, and it has been predicted that market share will grow to 63% by 2027.[20] It is also predicted that the trend towards NMC and NCA batteries and away from other chemistries will continue, putting upward pressure on the price of cobalt.

Estimates of EV Batteries Reaching End-of-Life (EOL) to 2030

Potential penetration rates of EVs into the US marketplace have been and continue to be the subject of many studies, with projections changing frequently. The wide variation between current projections are the result of differences in assumptions about future gas and battery

[16] Nickel Institute, "Competitive technologies to high nickel Li-ion batteries – the pros and cons," https://www.nickelinstitute.org/blog/2020/february/competitive-technologies-to-high-nickel-lithium-ion-batteries-the-pros-and-cons, accessed Mar. 2020.
[17] Maloney, P., "Electric vehicle and stationary storage batteries begin to diverge as performance priorities evolve," https://www.utilitydive.com/news/batteries-for-electric-vehicles-and-stationary-storage-are-showing-signs-of/528848/, accessed May 2019
[18] Nuamah, Charles. "A Simple Comparison of Six Lithium Ion Battery Types", 19th May, 2019. Accessed 19th May, 2020. https://owlcation.com/stem/Comparing-6-Lithium-ion-Battery-Type.
[19] http://mric.jogmec.go.jp/wp-content/uploads/2019/01/mrseminar2018_07_01.pdf
[20] Maloney, P., "Electric vehicle and stationary storage batteries begin to diverge as performance priorities evolve," https://www.utilitydive.com/news/batteries-for-electric-vehicles-and-stationary-storage-are-showing-signs-of/528848/, accessed May 2019

prices, automaker and government commitments, technological advancements around battery technology, the development of charging infrastructure, the number of new EV models that will enter the market, the availability of critical materials needed to manufacture EV batteries, and the growth of shared mobility services.

As an example of the wide variations in future EV sales projections, the US Energy Information Administration (EIA)'s 2019 Annual Energy Outlook predicts that in 2025, sales of BEVs and PHEVs will reach 1.3 million, or about 8% of total new vehicle sales.[21] JP Morgan's estimate is much higher, predicting that EV sales will account for over 38% of total vehicle sales in the same year.[22]

For this study, estimates of EV batteries reaching EOL were developed using the Kelleher Lifespan Model. This model uses HEV, PHEV, and BEV sales from 2011 to 2018 (shown in Table 1), as well as the following assumptions regarding EV sales for the period 2018 to 2025 to develop a linear projection of the number of EV batteries reaching EOL:

- HEVs use an equal mix (50/50) of NiMH) and Li-ion batteries, and all PHEVs and BEVs use Li-ion batteries
- Together, PHEV and BEV new vehicle sales would reach 1.3 million units in the US by 2025 (the split between the two types of vehicles was assumed to be 500,000 PHEV units and 800,000 BEV units)
- The lifespans of NiMH and Li-ion EV batteries would be similar
- One-third of EV batteries would last eight years, one-third would last nine years, and one-third would last 10 years.

The results of the EOL modelling exercise are summarized in Table 2 and Figure 4. Most of the more than 280,000 EV batteries that are expected to reach EOL in the US in 2019 will be NiMH batteries from HEVs that were sold eight to 10 years prior to 2019, and some will be Li-ion batteries sold in the some HEV models and in all PHEV or BEV models. The study estimates that by 2025, an estimated 526,000 EV batteries will reach EOL, and that around 64% of these will be Li-ion batteries from PHEVs and BEVs. By 2030, this number will increase to over 1 million. The Kelleher model has assumed that HEV sales remain constant after 2019, therefore a constant number of NiMH batteries will continue to reach EOL each year from 2028 on.

The number of EOL NiMH batteries (which are only in HEVs) begins to decline after 2022, reflecting lower sales of HEVs from 2013 on. The numbers of Li-ion EOL EV batteries available in 2023 and 2024 are somewhat lower than earlier and later years because of a drop in sales of HEVs (some of which use Li-ion batteries) as PHEVs as full BEVs became more prevalent in the market from about 2014 on.

[21] U.S. Energy Information Administration, "Annual Energy Outlook 2019 with projections to 2050," https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf, accessed Mar. 2020.
[22] J.P. Morgan, "Driving into 2025: The Future of Electric Vehicles,' https://www.jpmorgan.com/global/research/electric-vehicles, accessed Mar. 2020.

Table 2: Estimated EV Batteries Reaching EOL in the US, by Battery Chemistry (2019-2030)

Year	Estimated NiMH Batteries at EOL (units)	Estimated Li- ion Batteries at EOL (units)	Total Estimated EV Batteries at EOL (units)
2019	229,694	50,635	280,328
2020	207,009	140,114	347,124
2021	198,852	254,699	453,551
2022	229,181	320,032	549,213
2023	221,277	333,280	554,557
2024	197,006	329,378	526,384
2025	183,632	341,797	525,429
2026	174,091	414,004	588,094
2027	170,779	517,228	688,007
2028	163,497	645,395	808,892
2029	163,497	774,438	937,935
2030	163,497	918,143	1,081,640

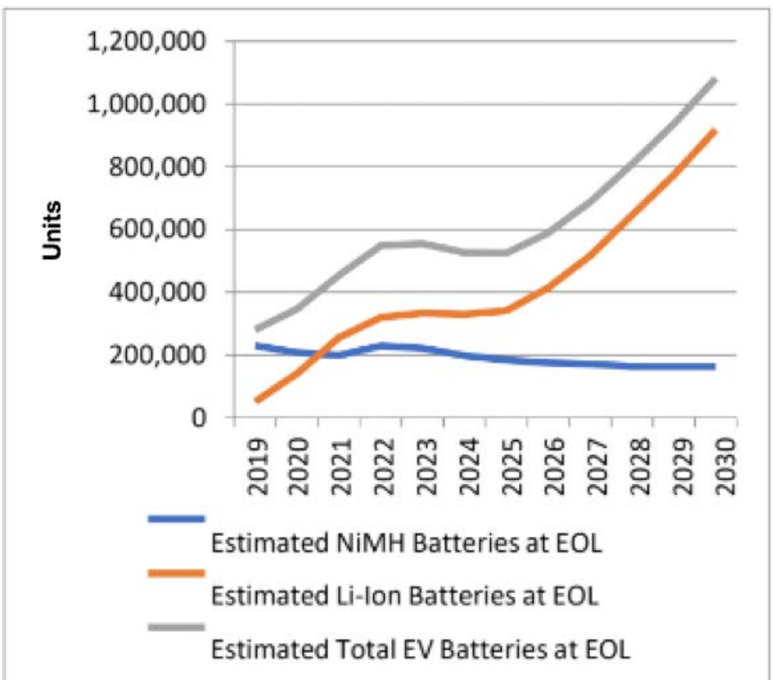


Figure 4: Estimated EV Batteries Reaching EOL in the US, by Battery Chemistry (2019-2030)

EV Battery Reuse

When a battery reaches EOL in an EV application—which is when it loses 15-20% of its initial capacity[23]—it can be directed to either reuse or recycling (see Figure 5). The reuse of EV batteries is discussed below, while the next section addresses EV battery recycling.

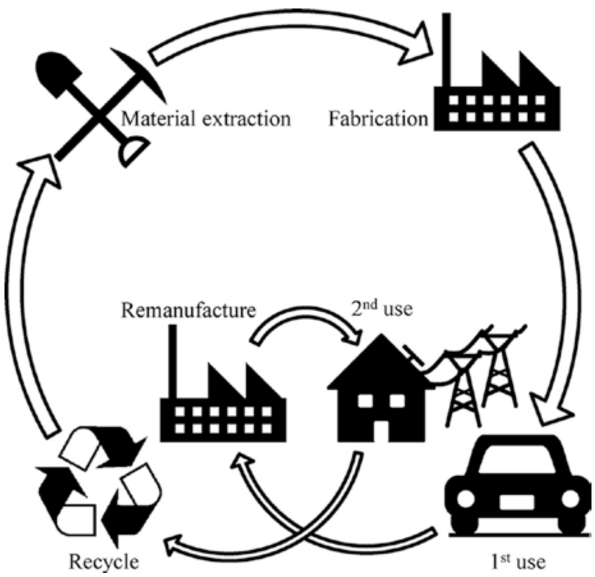


Figure 5: Depictions of End of Life Options for EV Batteries

Reuse (second-life repurposing of EV batteries or their components) extends the lifespan of EV batteries, thereby delaying the need for recycling. Second-life opportunities for EV batteries appear in both stationary and mobile applications, and range from applications that break the used battery down into its constituent parts (cells or battery packs) to applications that keep the unit intact, with low performing cells removed and replaced with new or reconditioned cells.

EOL EV batteries can be reused directly in EVs or cascaded in alternative, lower-demand applications such as residential energy storage, grid-scale energy storage, EV charging, or as battery cells in drones, wheelchairs and other applications. Figure 6 shows an energy storage facility where GM reused Chevrolet Volt batteries to store energy from solar and wind generation at its vehicle testing facility in Milford, Michigan. The EV batteries are used to supply power to its Milford data center, and surplus energy is returned to the grid supplying the rest of the facility. A similar example can be found in Japan, where Sumitomo has a joint venture with Nissan Motors to reuse EV batteries.[24]

[23] Pagliaro, M. and Meneguzzo, F., "Review Article: Lithium battery reusing and recycling: A circular economy insight," *Heilyon* 5: e01866, 2019, https://doi.org/10.1016/j.heliyon.2019.e01866
[24] Blackman, J., "GM touts energy storage and new solar arrays as it commits to 100% renewables by 2050," https://www.energy-storage.news/news/gm-touts-energy-storage-and-new-solar-arrays-as-it-commits-to-100-renewable, accessed Mar. 2020.

Figure 6 Energy Storage Facility Using Chevrolet Volt Batteries

Typically, the first step in EV battery refurbishment is the partial disassembly of the battery pack. The next step involves identifying cells that are no longer working and replacing them with cells capable of holding a sufficient charge. The final step is reassembly of the battery pack, either in its original format or in a newer format suitable for the new application. The process involves diagnostic and screening tests to correctly identify the EV battery chemistries and designs. Generally, each EV battery needs to be evaluated individually, because each one has been exposed to different charging and discharging conditions during its use in an EV.

There are several companies at the forefront of the EV battery repair, refurbishment, and reuse industry. Currently, Spiers New Technologies (SNT), based in Oklahoma City, is the largest company involved in EV battery reuse in the US. Most of the battery packs the company receives come from dealers' warranty replacements as well as from test projects. In addition to reconditioning batteries for clients such as Nissan, General Motors and Ford[25], SNT also tests batteries and battery cells and incorporates them into energy storage systems (such as Watt Towers), that can be used in applications ranging from solar energy installations to general uninterruptible power supply (UPS).[26] Other companies involved in battery reuse include IT Asset Partners (ITAP) and BigBattery.

Given that EV batteries in use today have yet to complete their first or second life cycle, there is currently a lack of real-life data on the length of time that EOL EV batteries or their components can last in second use applications. However, a number of studies have estimated lifespans in second use applications, the results of which are summarized in Table 3.[27] It's important to note that all lifespan data are theoretical, based on lab testing and modeling using various assumptions and professional judgment. Some of the factors that can affect the lifespan of second-life batteries include usage patterns in its first life, battery degradation rates which vary significantly by battery chemistry, and the effect of capacity fade and calendar aging, among

[25] Linnenkoper, K., "SNT: powering up dead car batteries is not a problem," https://recyclinginternational.com/technology/snt-powering-up-dead-car-batteries-is-not-a-problem/16197/, accessed Mar. 2020.

[26] Frost & Sullivan, "SNT Commended by Frost & Sullivan for Leading the North American EV/PHEV Market through a Strong Market Expansion Strategy", https://www.prnewswire.com/in/news-releases/snt-commended-by-frost-amp-sullivan-for-leading-the-north-american-ev-phev-market-through-a-strong-market-expansion-strategy-887155785.html, accessed Mar. 2020.

[27] Casals, L.C., Garcia, B.A., and C. Canal. (2019). "Second life batteries lifespan: Rest of useful life and environmental analysis." *Journal of Environmental Management, 232,* 354-363. DOI: 10.1016/j.jenvman.2018.11.046

other factors. Many of the models used to estimate second use lifespan only consider cyclic aging (i.e. number of cycles the battery undergoes).

Table 3: Lifespans Estimated for EV Batteries in Second Life Applications

Second Life Application	Additional Years of Life After First Use in EV
Energy storage systems (ESS)	EV batteries lose an additional 15% of capacity after an additional 10 years of use
Power support to fast EV charging stations	30 years
Home energy storage	12 years
Grid-oriented service (area regulation and transmission deferral)	6-12 years
Miscellaneous	3-15 years and 8-20 years depending on application

Recycling of EV Batteries

At EOL, some EV batteries go directly to recycling, while others are recycled after the reuse cycle is complete. Traditional Li-ion battery recycling focuses on recovering the cathode metals (nickel and cobalt in particular) in metal form.[28] Decisions on recovering other materials such as steel depend on the metal content of side streams from the recycling process, the location and proximity of markets and the prices paid for the metals at any given time (these vary depending on economic conditions). Slags produced from the recycling operation are either used in road construction or are disposed in landfills. Plastics are either burned or landfilled and the graphite is not recycled at this time. The recovered metals are sent to smelters for further recovery through pyrometallurgical (heat based) processes. The average recovery rate achieved by the smelting process is generally around 50% by weight, but it can range from 40% to 80% depending on metal content and markets.[29]

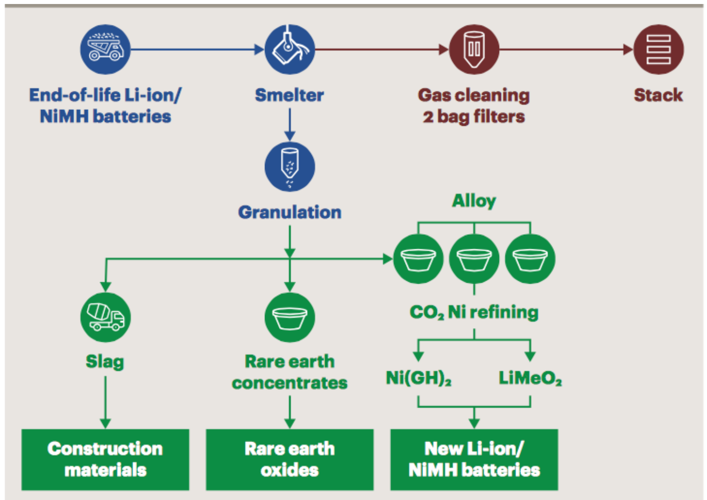
Retriev Technologies is one of the largest players in the Li-ion battery recycling market in North America. The company receives all types of EV batteries and chemistries (not just Li-ion) and directs them to various company facilities depending on processes and capacity available by location. Li-ion batteries are processed at the company's Trail, British Columbia facility in Western Canada using a combination of manual and hydrometallurgical separation techniques.[30]

For large-format EV battery packs, the recycling process begins with trained technicians manually disassembling the battery to the cell or module level. The next step involves conducting a full analysis on each cell to determine the metal content. Depending on metal content and current commodity values, Retriev determines if a tipping fee must be charged to the battery owner or whether the owner receives a credit.

Umicore is another major player in the EV battery recycling market. Based in Europe, Umicore uses a combination of pyrometallurgy and hydrometallurgy to recover rare earth elements, cobalt, nickel, and copper from used EV batteries. The company has four drop-off locations for EV batteries in North America and a consolidation facility in North Carolina, which accepts both

[28] Velázquez-Martínez, O., Valio, J., Santasalo-Aarnio, A., Reuter, M., et al., "A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective," *Batteries* 5:68, 2019, doi:10.3390/batteries5040068
[29] Personal communication with Kathy Bruce, Senior Vice President, Retriev Technologies Ltd, April, 2019.
[30] Retriev Technologies, "Lithium Ion," https://www.retrievtech.com/lithiumion, accessed Mar. 2020.

NiMH and Li-ion batteries. Dismantling of the batteries is carried out at Umicore's Hanau, Germany facility to remove metals that can easily be recycled locally, such as steel casings and copper wiring. Following the pre-treatment stages, battery packs and/or battery cells are consolidated for shipment to Umicore's Hoboken, Belgium facility where they are processed (see Figure 7).



Sources: Umicore website; A.T. Kearney Energy Transition Institute analysis

Figure 7: Schematic of Hoboken, Belgium Umicore Facility Process

Other companies involved in the traditional recycling of Li-ion batteries (mostly from consumer products but more recently from EVs) include INMETCO (International Metals Reclamation Company), Glencore-Sudbury Integrated Nickel Operations, Battery Solutions, SungEel, MCC Americas, and Battery Resources, among others

Several new recycling technologies are currently in development with the aim of achieving higher recovery (quoted by different companies as above 90%) of various metals (nickel, cobalt, copper, aluminum, etc.) from EV batteries. The companies developing these new technologies (none of which are yet operating at commercial scale) are most interested in direct recycling or cathode-to-cathode recycling to recover metals, minerals, chemicals and chemical powders suitable for direct sale back to battery manufacturers. This approach differs from the current approach of producing metal laden materials, which are directed to smelters for refining to recover nickel, cobalt and other cathode materials as separate metals. Some of these companies only process battery cathodes, leaving the discharging and dismantling of the EV battery to a separate company. A few companies in this 'new' EV battery recycling business include American Manganese, Neometals, Li-Cycle, Redwood Materials and Lithion Recycling among others.

Costs of EV Battery Reuse vs. Recycling

The cost of EV battery reuse is expressed in $/kWh. Recycling costs are expressed as $/kg.

Several sources have estimated anticipated costs/revenues from EV battery reuse. In 2015, the National Renewable Energy Laboratory (NREL)[31] modeled the reuse costs of PHEV batteries to be about $44/kWh ($20/kWh for processing and additional $24/kWh for battery purchase) at a time when the cost of new batteries was $350/kWh.

Many market conditions have changed since 2015. The average cost of new EV batteries was $156/kWh in 2019 and is projected to reach $100/kWh by 2023.[32] A June 2019 report prepared by Circular Energy Storage[33] for the Global Battery Alliance predicts that by 2030, the cost of re-purposed EV batteries will drop to about $40/kWh compared to a projected $70/kWh for new batteries. In all cases, the business case for EV battery reuse seems to be favourable economically.

For reasons of confidentiality, EV battery recyclers interviewed for the study would not share information on costs associated with EV battery recycling. However, two main sources of costs were found in the literature, one of which was the December 2018 Business Plan of American Manganese, which provided an extensive financial analysis of its future recycling facility (not yet constructed).[34] The other source of EV battery recycling costs was a report prepared by Element Energy[35] for a consortium of European automakers. The Element Energy study identified the current costs of EV battery recycling at $1,700 to $2,000 per tonne. Given that some EV batteries weigh as much as 400kg to 500kg, this translates to a value of $700 to $1,000 per EV battery.

Based on the research, it is considered more likely that for the foreseeable future, EV batteries will be directed to reuse applications, where practical, because of the favourable economics. The 2019 API study research did not find any evidence to suggest that EV battery recycling will be carried out at a positive value in the next five years, as the technologies that promise to achieve high recovery rates for the metals contained in EV battery cathodes have not yet been proven at commercial scale. With construction of the Li-Cycle facility in Rochester, NY, actual economics will be available from a facility operating at scale.

[31] NREL. "Battery Second Use for Plug-in Electric Vehicles." <https://www.nrel.gov/transportation/battery-second-use.html>

[32] Henze, V., "Battery Pack Prices Fall as the Market Ramps up with market average at $156/kwhr in 2019" accessed at about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/ 19th May, 2020

[33] Melin, H.E. (n.d.) Circular Energy Storage. "The Lithium-Ion battery end of life market – a baseline study." Prepared for the Global Battery Alliance

[34] American Manganese, "Company Business Plan, Updated December 14, 2018," https://americanmanganeseinc.com/wp-content/uploads/2018/12/AMY_BP-12_19_2018.pdf, accessed Mar. 2020.

[35] Element Energy. June 2019. "Batteries on wheels: the role of battery electric cars in the EU power system and beyond." <https://www.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf>

Battery reuse is already proven to result in a positive cash flow, and over time the relative economics of both approaches will become clearer.

Cobalt is the most valuable metal in the EV battery at this time. Efforts are being made by vehicle and battery OEMs to reduce the cobalt content of EV batteries. Panasonic has already reduced the cobalt content of Tesla battery cells to 3% and hope to soon create a battery cell with no cobalt.[36] While reducing the cobalt content will decrease the cost of EV batteries (one of the factors needed to increase EV adoption), it significantly lowers the incentive for recycling as the high revenue stream from metals recovery is diminished.

Technical and Policy Considerations for EV Battery Reuse and Recycling

Regardless of whether an EV battery is directed to reuse or recycling, there are technical challenges associated with the wide range of battery formats, designs, compositions and chemistries currently on the market, and a lack of design for easy dismantling and recycling. This makes the use of standard EOL management approaches virtually impossible and requires the adoption of customized methods, which increase costs.

Both the reuse and recycling of EV batteries are hindered by a lack of collection infrastructure necessary to bring large numbers of batteries to a central location to exploit economies of scale. Transport is expensive and highly regulated as used EV batteries are classified as hazardous waste.

There are various concerns around the reuse of EV batteries or their components in second-life applications. One concern is a lack of established and recognized definitions and standards to classify repurposed batteries. Batteries in EVs often reach EOL before the vehicle itself. In these cases, replacement batteries are installed by dealerships that accumulate small numbers of EV batteries over time. Currently, when an EV reaches EOL, the vehicle and the battery are sent to automotive recyclers. Automotive recyclers are generally not familiar with the hazards of storing and managing EOL EV batteries and are currently unable to determine the state of health (SoH) of the battery packs. Refurbishing EV batteries can put untrained workers at risk of electric shock that can result in serious injury or death. For this reason, standards and standardized terminology are needed to ensure that all players in the supply chain clearly understand the product performance and characteristics. One example of a standard that has been developed for this purpose is UL 1974, *Standard for Evaluation for Repurposing Batteries*, published in October 2018. The standard addresses methods used to determine the safety and performance of components from used EV battery systems that are repurposed into second-use battery applications.

There are also concerns around liability. Where EV batteries are repurposed for subsequent non-EV uses, unresolved questions concerning liability might flow back through to the vehicle

[36] Fortuna, C., "Tesla Cobalt Usage to Drop From 3% Today to 0%, Elon Commits," https://cleantechnica.com/2018/06/17/teslas-cobalt-usage-to-drop-from-3-today-to-0-elon-commits/, accessed Mar. 2020

and/or the battery manufacturers (or vehicle owner), should the batteries or cells fail in a way that causes significant harm to human health or the environment. Repurposed EV batteries are a new technology, which means that there is a lack of statistical data for insurance companies to calculate premiums. Because insurance companies are risk-averse, they are likely to set higher premiums for homeowners using this technology. The question of ownership relates to who would be held responsible in the event that the repurposed battery causes damage to people or property, for example, through fires or leaks. As a result of the lack of clarity around OEM's liability, they may be reluctant to allow their EV batteries to be repurposed for energy storage applications and may prefer to send them directly to recycling.

The variation in chemistries and cell/pack formats make both reuse and recycling of EV batteries challenging. Li-ion EV batteries are manufactured by many different companies with different design configurations, including variations in energy density, capacity, and chemistry, as well as the number and type of cells and the physical shape. Some EV batteries are a prismatic design while others are a pouch design. In addition, the specific chemistry of an EV battery is usually not labelled, and as a result, neither third-party battery re-furbishers nor recyclers know which kind of battery chemistry they are receiving.[37]

Each EV battery has a battery management system (BMS) that regulates critical functions of the battery, and like the batteries themselves, these are not standardized. Because of this variation, batteries from different EVs cannot be easily received, processed, and assessed in bulk, and the process of repurposing batteries necessitates reassembling them into different configurations with controllers that are unique to the application and the battery.

Environmental Impacts of EV Battery Reuse and Recycling

The environmental benefits of EV battery reuse relate to extending the lifespan of the battery and reducing the demand for virgin materials to manufacture new EV batteries. EV battery recycling secures supplies of metals such as cobalt and nickel which is essential for EV battery production using current technologies. Much of the cobalt used today is sourced from the Democratic Republic of Congo, which has an estimated 60% of the global reserves of cobalt.[38] An estimated 70% of mined cobalt production was from DRC in 2019.[39] Sourcing cobalt from DRC is problematic for a number of reasons, including political instability, the use of child labour, and informal mining practices that cause environmental problems, among others.

While several studies were found identifying environmental and energy impacts of reuse and recycling of EV batteries, none reflected current conditions and current battery chemistries. Future research should focus on updating these studies to reflect current conditions in the US.

[37] Olsson, L., Fallahi, S., Schnurr, M., Diener, D., and P. van Loon. (2018). "Circular Business Models for Extended EV Battery Life." *Batteries, 4,*
1-15. doi:10.3390/batteries4040057
[38] USGS, 2017. https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2017-cobal.pdf
[39] US Geological Survey, National Minerals Information Centre, Cobalt Statistics and Information, Mineral Commodities Summary, 2020 https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cobalt.pdf Accessed 20th May, 2020.

Research and Development of New EV Battery Chemistries and Development of Domestic Supply Chains for EV Batteries

Compared to the US, other countries spend considerably more on research into new EV battery technologies and recycling, as they see battery development as a potentially large business in the future and want to be leaders in technology development and deployment. Examples include the UK Faraday Fund, which has dedicated $51 million to Li-ion battery recycling research and $113 billion committed by the European Battery Alliance[40] (which includes governments and private sector partners) to build battery giga-factories and research battery recycling.

Current and Future Legislation Targeting EV Batteries

In the European Union (EU), there are two key pieces of legislation that require EV batteries to be managed in an environmentally sound manner: the *Batteries Directive* and the *End of Life Vehicles Directive.*

In the US, while there is no federal legislation in place, various initiatives are underway to address the safe and environmentally sound management of EOL EV batteries. For example, the California Environmental Protection Agency (CalEPA) has established a *Lithium-Ion Car Battery Recycling Advisory Group* to prepare policy recommendations to maximize safe and cost-effective recycling efforts for EOL Li-ion EV batteries. The Advisory Group will develop its recommendations between now and April 2022 in consultation with universities and research institutions, manufacturers of EVs, and the battery recycling industry.[41]

Ongoing Research on EV Battery Design, Reuse and Recycling

Across the US, numerous efforts are underway by governments, universities and private sector companies to improve EV batteries and identify better ways to recycle and/or reuse them. One such example is the ReCell Center, a national collaboration of industry, academia and national laboratories working together to advance recycling technologies along the entire battery life-cycle for current and future battery chemistries.

[40] Krukowska, E. and Starn, J. "Europe Thinks Like China in Building its own Battery Industry" 3rd July, 2019. https://www.bloomberg.com/news/articles/2019-07-03/europe-thinks-like-china-in-building-its-own-battery-industry

[41] California Environmental Protection Agency Lithium Ion Car Battery Recycling Advisory Group https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/

The ReCell Center has established some key research and development goals, including:

- Establish a national US Department of Energy (DOE) advanced and Li-ion battery recycling R&D center to accelerate recycling research of current and future battery chemistries to drive cost-effective recycling and new battery designs.
- Create new electrode and cell designs, enabling cell rejuvenation and more effective material recovery during recycling.
- Develop new processes to enable cathode-to-cathode recycling of cathode powders using temperatures below 900°Celsius.
- Develop new processes to recover battery materials that are currently not recovered and end up in the waste stream.
- Assess the economic value and impacts on the recycling stream of end-of-life options.[42]

Summary and Conclusions

The research carried out by the Kelleher Environmental team for API in 2019 showed that considerable work is already underway to find new battery chemistries for EVs, and also to identify how to optimize the reuse and recycling of EOL EV batteries to both extend the life of these batteries after first life and to recover valuable materials when they can no longer be used. Since that time, research efforts have expanded considerably because of increased demand for EVs and a concern about global supply chains for critical materials to make battery cells, and an increased interest globally in regionalizing production of EVs and batteries. However, much remains to be done to optimize the use of EOL EV batteries which should be considered as valuable assets, and it is essential to identify viable EOL reuse and recycling options before they are produced in large numbers in the US and elsewhere within the next five years.

In the US, EOL EV batteries will reach about 525,000 units in 2025 and over 1 million units by 2030. These batteries will include NiMH batteries from HEVs, which contain nickel, and Li-ion batteries from PHEVs and BEVs, which contain nickel, cobalt, manganese and other valuable metals of interest to recyclers.

EV battery reuse looks promising and appears to be a viable business model with good profit margins if issues around liability and standards can be addressed. It is considered more likely that EV batteries will be directed to reuse prior to recycling where reuse options are available, as the economics of reuse will continue to be favorable for the foreseeable future. The duration of the second-life of EV batteries directed to reuse is not known. All information available to date is based on modeling since no real-life examples of how EV batteries degrade in second-life applications are yet available. The environmental benefits of reuse relate to extending the lifespan of the battery and reducing the demand for virgin materials to manufacture new batteries.

[42] https://recellcenter.org/about/

The costs involved in recycling EOL EV batteries using traditional approaches are not well identified or documented in public sources, but it appears that the recycling technologies in place today result in a cost to recyclers as opposed to a revenue stream. The costs of recycling EV batteries is currently high because of the amount of dismantling required to recover valuable metals from cathodes to send to smelters. New direct recycling or cathode to cathode recycling approaches are under development to recover cathode materials directly using hydro-metallurgical approaches, which are less energy intensive than current pyrometallurgical approaches. While reducing the cobalt content of batteries will decrease the cost of EVs (one of the factors needed to increase EV adoption), it significantly reduces the incentive for recycling as the high revenue stream from metals recovery is reduced.

While several studies identify the environmental and energy impacts of reuse and recycling of EV batteries, none of the studies reflect current battery chemistries used in EVs. The studies are considered out of date and should be updated with current battery chemistry information. Such a study should include consideration of the energy and GHG aspects of recycling.

Recommendations

A number of data and research gaps were identified during the research, leading to the following recommendations:

- A detailed material flow and lifespan model should be developed to account for the different Li-ion battery chemistries, battery weights and configurations used in EV models over time.
- Available research and modeling of costs associated with EV battery reuse is relatively outdated and limited in scope to PHEV batteries only. Consideration should be given to a study, which updates existing research with current costs that are representative of the broad range of HEV, PHEV, and BEV battery designs and chemistries on the market today.
- Research should explore the business case for EV battery reuse as the costs of new batteries reach $100/kWh or lower, and as energy densities of new Li-ion batteries increase compared to those available in the reuse market.
- Research should be carried to assess the energy and environmental impacts of EV battery reuse compared to recycling, and also on the relative life cycle impacts of EV battery recycling vs. buying a new battery through a comprehensive life cycle analysis (LCA) study.
- A detailed business case needs to be developed to more fully identify the financial and technical risks associated with the EV battery recycling business. Among other things, the business case needs to address the impacts of future potential regulation of mandatory EV battery management at end of life through either reuse and/or recycling, the evolution of EV battery recycling technology, the lack of collection infrastructure and the geographic distribution of the EOL EV battery supply.

Appendix A: Type and Weight of Batteries Used in Top 10 EVs Sold in the US as of May 2019

Table 1: Type and Weight of Batteries Used in the Top 10 HEVs Sold in the US (as of May, 2019)

HEV Make and Model	% of US Market (2018)	Battery Chemistry	Battery Size (kWh)	Battery Pack Weight (kg)
Toyota Prius Lift back	15%	NiMH	1.3	93
Ford Fusion Hybrid	15%	Li-ion	1.4	48 (2013 model)
Toyota RAV4	14%	NiMH	1.6	n/a
Kia Niro Hybrid	8%	Li-ion	1.6	33 (2016 model)
Toyota Camry Hybrid	7%	Li-ion for LE models NiMH for SE and XLE models	1.0 (Li-ion) 1.6 (NiMH)	n/a
Toyota Highlander Hybrid	5%	NiMH	4.5	n/a
Hyundai Ioniq H ybrid	5%	Li-ion	1.6	n/a
Honda Accord H ybrid	4%	Li-ion	1.3	n/a
Lexus RX 400/45 0h	4%	NiMH	1.9	n/a
Ford C-Max Hybrid	3%	Li-ion	1.4	n/a

Table 2: Types and Weights of Batteries Used in Top PHEVs Sold in the US (as of May, 2019)

PHEV Make and Model	% of US Market (2018)	Battery Chemistry	Battery Size (kWh)	Battery Pack Weight (kg)
Toyota Prius Prime	23%	C/NMC	8.8 kWh	120
Honda Clarity Plug-in Hybrid	15%	n/a	17 kWh	n/a
Chevrolet Volt (Generation 2)	15%	C/NMC-LMO	18.4	183
BMW 530e	7%	C/NMC-LMO	9.2	n/a
Ford Fusion Energi	7%	C/NMC-LMO	7.6	124
Chrysler Pacifica	6%	C/NMC	16	168
BMW X5 xDrive40e	4%	C/NMC-LMO	9.2	150
Mitsubishi Outlander	3%	C/NMC	12	185
Kia Niro	3%	n/a	8.9	39
BMW 330e	2%	C/NMC-LMO	7.6	107
Audi A3 Sportback e-tron	2%	C/NMC	8.8	125
Volvo XC60	2%	n/a	10.4	n/a
Porsche Panamera E-Hybrid	2%	n/a	14	n/a
Mercedes C350e	1%	C/NCA	6.2	n/a
Hyundai Ioniq	1%	C/NMC	8.9	123
Mini Cooper Countryman SEALL4	1%	n/a	7.6	91
Volvo XC90	1%	C/NMC	9.2	118
Porsche Cayenne S-E	1%	C/NMC	10.8	142
Mercedes GLE 550e	1%	C/NCA and C/NMC	8.8	n/a
Kia Optima	1%	C/NMC	9.8	131
BMW i8	1%	C/NMC-LMO	7.1, 11.6	n/a
Ford C-Max Energi	0%	C/NMC-LMO	7.6	124
Mercedes GLC 350e	0%	C/NCA	8.7	n/a
Hyundai Sonata	0%	C/NMC	9.8	n/a
Volvo S90 T8	0%	n/a	10.4	n/a
BMW 740e	0%	C/NMC-LMO	9.2	n/a
Cadillac CT6	0%	C/NMC-LMO	18.4	181
Mercedes S550	0%	C/NMC	6.4	n/a
Honda Accord	0%	n/a	6.7	n/a

Notes: C = graphite;
NCA = $LiNiCoAlO_2$ (Lithium nickel cobalt aluminum oxide);
NMC = $LiNiMnCoO_2$ (Lithium nickel manganese cobalt oxide);
LMO = $LiMn_2O_4$ (Lithium manganese oxide);
LCO = LiCo02 (Lithium cobalt oxide) ;
LTO = $Li_4Ti_5O_{12}$ (Lithium titanate

Table 3: Types and Weights of Batteries Used in Top BEVs Sold in the US (as of May, 2019)

BEV Make and Model	% of US Market (2018)	Battery Chemistry	Battery Size (kWh)	Battery Pack Weight (kg)
Tesla Model 3	59%	NCA	80.5	478
Tesla Model X	11%	NCA	75 and 100	n/a
Tesla Model S	11%	NCA	100	506 to 598[327]
Chevrolet Bolt	8%	C/NMC	60	435
Nissan Leaf	6%	C/NMC	40	303
BMW i3	3%	C/NMC-LMO	33	322
Fiat 500e	1%	C/NMC	24	257
Volkswagen e-Golf	1%	C/NMC	24.2 and 35.8	318
Smart ED	1%	C/NMC	18	159
Kia Soul	0%	C/NMC	27	280
Honda Clarity Electric	0%	n/a	25.5	n/a
Ford Focus Electric	0%	C/NMC-LMO	33.5	296
Jaguar I-Pace	0%	n/a	90	603
Hyundai Ioniq	0%	C/NMC	28	284
Mercedes B-ClassElectric DriveB 250e	0%	C/NCA	28[328]	n/a