

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

Project Report

Prepared for



Prepared by



in association with



and



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List of Acronyms

Ah	ampere hour
ANL	Argonne National Laboratory
APTA	American Public Transportation Association
ARA	Automotive Recyclers Association
B2U	Battery Second Use
BEB	battery electric bus
BEV	battery electric vehicle
BMS	battery management system
BNEF	Bloomberg New Energy Finance
BSS	Battery Safety Solutions
CED	cumulative energy demand
Cg	graphite
C&I	commercial and industrial
CMD	chemical manganese oxide
CO ₂ eq	carbon dioxide equivalent
CMI	Critical Materials Institute
DOD	depth of discharge
DOE	US Department of Energy
DRC	Democratic Republic of Congo
EEl	Edison Electric Institute
EIA	US Energy Information Administration
ELV	end-of-life vehicle
EMM	electrolytic manganese metal
EOL	end-of-life
EPR	extended producer responsibility
EPRI	Electric Power Research Institute
ESS	energy storage system
EU	European Union
EV	electric vehicle
GHG	greenhouse gas
GW	gigawatt
GWh	gigawatt-hour
GWP	global warming potential
HEV	hybrid electric vehicle
ICE	internal combustion engine
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Lab
INO	Sudbury Integrated Nickel Operations

ITAP	IT Asset Partners
kW	kilowatt
kWh	kilowatt-hour
LCA	life cycle assessment
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
LIB	lithium-ion battery
Li-ion	lithium-ion
LMO	lithium manganese oxide
LTO	lithium titanate oxide
MJ	megajoule
MOQ	minimum order quantity
MOU	memorandum of understanding
MRF	material recycling facility
MSRP	manufacturer's suggested retail price
MW	megawatt
MWh	megawatt-hour
NAATBatt	National Alliance for Advanced Technology Batteries, and Rechargeable Battery Association
NCA	lithium nickel cobalt aluminum oxide
NiCd	nickel cadmium
NiMH	nickel-metal hydride
NMC	lithium nickel manganese cobalt oxide
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PET	polyethylene terephthalate
PHEV	plug-in hybrid electric vehicle
PNGV	Partnership for a New Generation of Vehicles
PRBA	The Rechargeable Battery Association
PUC	Public Utilities Commission
PV	photovoltaic
RBC	Responsible Battery Coalition
RMC	Raw Materials Company
R&D	research and development
SDTC	Sustainable Development Technology Canada
SNT	Spiers New Technologies
SoH	state of health
UL	Underwriters Laboratory
USABC	US Advanced Battery Consortium
US EPA	US Environmental Protection Agency
Wh	watt-hour
WPI	Worcester Polytechnic Institute

Executive Summary

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.

The study identified that almost 690,000 electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) were sold in the US in 2018. EV sales are projected to grow to an estimated market penetration rate of 8% by 2025, resulting in sales of 1.3 million PHEVs and BEVs in that year in the US. The adoption of EVs is moving rapidly in the US and across the globe as EV battery technology improves and the costs of the batteries, and therefore the costs of EVs decrease. It is projected that when the costs of EV batteries reach a range of \$80/kWh to \$100/kWh the costs of EVs will reach parity with similar ICE models. EV battery costs are projected to reach \$100/kWh anywhere from 2020 to 2025. This may lead to increased EV sales and eventually more EV batteries requiring end of life (EOL) management.

Based on historical EV sales from 2000 to 2018, and current EV sales projections to 2023, it is estimated that about 525,000 EV batteries will reach EOL in 2025 with over 1 million units projected to be at EOL by 2030. While most of the batteries in the EOL EVs will be nickel metal hydride (NiMH) batteries from HEVs for the next few years, by 2025 most EOL EV batteries will be li-ion based. Recycling options are different for these two battery chemistries, with NiMH batteries directed to nickel operations whereas li-ion batteries are of more interest to cobalt recovery companies.

There is no established collection infrastructure for EV batteries in the US at this time, as the numbers are low and they are scattered in small numbers at vehicle dealerships, repair shops and scrap metal shredding facilities located throughout the country. EV batteries are beginning to show up at scrap yards in sufficient numbers to raise concerns about proper management through either reuse or recycling.

EV battery reuse 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 (energy storage systems, back-up power, EVs and various other applications such as wheelchairs and drones, etc.) for the foreseeable future because of the favourable economics.

The study research did not find any evidence 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 to date, and reuse is already proven to result in a positive cash flow. However, the business case for EV battery recycling needs to be developed in more detail than is currently available to better understand the economics of this approach.

Traditional li-ion battery recycling focuses on recovering the cathode metals (nickel and cobalt in

particular) in metal form. Decisions on recovering other materials depend on metal content of various side streams from the process (e.g. fluff with 65% steel) and available markets. Various slags produced from the recycling operation are either used for construction or landfilled. Plastics are either burned or landfilled but are not recycled and the graphite is not recycled at this time. The metals recovered from the processes are sent to smelters for further recovery through pyrometallurgical (heat based) processes. The recovery rate through the smelting process is generally around an average of 50% measured by weight, but can range from 40% to 80% depending on metal content and markets.

A number of new EV battery recycling technologies currently in development attempt to increase the recovery rate for various metals such as cobalt and nickel through the recycling system. These technologies focus on hydrometallurgical processes, which are less energy intensive than pyrometallurgical processes. The new EV battery recycling technologies commit to increasing recycling rates to a reported 90%+. Results to date are from small scale operations recycling pure production scrap or small batches of EV batteries as a feed stream. It is considered unlikely that metal recovery rates of 99% or 100% are sustainable when mixed loads of EV batteries are processed. The companies developing these new EV battery recycling technologies are most interested in direct recycling or cathode-to-cathode recycling to recover chemicals and chemical powders suitable for direct sale back to battery manufacturers. Some of these companies only process battery cathodes, leaving the discharging and dismantling of the EV battery to a separate company. None of these technologies are yet operating at scale.

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 metal such as cobalt which is essential for EV battery production using current technologies, but which is sourced from unstable countries such as the Democratic Republic of Congo which has most of the global reserves of cobalt. While a number of 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, for both EV battery reuse and recycling.

Both reuse and recycling of EV batteries share the technical challenge associated with the availability of a wide range of battery formats, designs, compositions and chemistries, and a lack of design for easy dismantling and recycling. This makes standard approaches virtually impossible at this time, and requires customized approaches. Both reuse and recycling also suffer from a lack of collection infrastructure to bring accumulated EV batteries to a central location where large numbers would lead to economies of scale.

Compared to the US, other countries spend considerably more on supporting research into new EV battery technologies and recycling, as they see battery development as a potential 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 which includes governments and private sector partners to build battery giga-factories and research battery recycling.

The opinions in this report are based on best available information available as of mid-2019. The EV field is evolving rapidly therefore this report needs to be updated in mid-2020 to remain current.

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1 Background and Objectives to the Study

As more consumers and businesses move to electric vehicles (EVs), the number of EV batteries reaching end-of-life (EOL) has started to increase and is projected to grow dramatically in the next 5 to 10 years. While many companies are gearing up for this opportunity, the infrastructure to collect and process these batteries at EOL in North America is not yet in place, and various actors along the supply chain have different concerns, particularly with a move to new EV battery chemistries that contain less cobalt and are therefore less valuable to recyclers. The reuse of EV batteries, especially for energy storage applications, is gaining traction, extending the life of these products for a number of years before they require recycling.

In January 2019, API commissioned Kelleher Environmental to conduct a study on the current and near-term future processes employed in the reuse and recycling of EV batteries. The goal is to provide API with a better understanding of the potential technical, environmental, energy and cost issues associated with battery recycling and second-life uses that may arise from the expected global growth in EVs over the next two decades.

The key objectives of this study are to:

1. Identify differences in EV battery technologies with respect to size, component configuration, chemistry, material composition and other factors that might impact on the energy, environmental and cost impacts of recycling these batteries at EOL;
2. Identify 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 their end-of-useful life;
3. Identify the potential technical, environmental, cost and energy impacts associated with EV battery recycling and second-life applications including any engineering or financial obstacles or other barriers;
4. Identify knowledge gaps and areas that could be further investigated; and
5. Document the study findings in a clearly laid out and easy-to-follow report.

2 Methodology

The methodology used in this study involved the following elements:

- An extensive review of trade journal and web-based news articles, announcements and other literature;
- An academic literature search carried out by York University, and a review of the academic literature identified by York University carried out by the Kelleher Environmental team;
- E-mail communication with various contacts in industry and industry associations identified through the research;
- Interviews with key informants who could fill in information gaps and provide different perspectives on information collected through the literature review;
- Analysis of the information collected; and
- Incorporate feedback and comments received from API into the final project report.

A list of references can be found at the end of this document.

3 EV Battery Sales, End-of-Life Projections, Management Options, and Future Designs

This section provides a range of projections for future EV sales in the US to 2030, an estimate of end-of-life (EOL) EV batteries available for reuse or recycling to 2030, and broad descriptions of reuse and recycling options (addressed in more detail in Sections 4 and 5, respectively). It also addresses potential future trends in EV battery chemistry and costs, all of which would impact on EV sales.

Given the rapidly changing nature of the EV market, these projections should be updated on an annual basis until the steady state of mature market situation for EV sales is clearer. A series of Appendices (A to H) to this report contain background information on EV battery design, composition, chemistries used in different vehicles, etc., which may be valuable for some readers.

3.1 EV Sales in the US 2011 to 2018

Table 1 presents information on the total number of EVs sold in the US from 2011 to 2018. The information is presented graphically in Figure 1. The table and figure show that hybrid electric vehicles (HEVs) accounted for most of the annual EV sales until about 2013, and that sales of HEVs levelled off as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) (where the battery provides the sole means of propulsion) entered the market after 2012. Much of the dramatic increase in EV sales in the US in 2018 is related to Tesla reaching its target of selling 200,000 EVs in the US. The table shows the types of batteries used in the three different types of EVs (described in more detail in Appendix A), generally:

- Either nickel-metal hydride (NiMH) or lithium-ion (li-ion) in HEVs; and
- Li-ion in all PHEVs and BEVs.

Appendix E shows the specific batteries used by different HEV, PHEV and BEV manufacturers. It is worth noting that Toyota has traditionally preferred nickel-based batteries, whereas most other manufacturers have trended towards li-ion batteries.

Table 1 Total EV Sales in the US (2011-2018) ¹

Electric Vehicle Type	Battery Type	Unit Sales							
		2011	2012	2013	2014	2015	2016	2017	2018
Hybrid Electric Vehicle (HEV)	NiMH or Li-ion (~50:50 split in 2018) See Appendix E.	266,345	434,813	495,529	452,172	384,404	346,948	370,685	326,994
Plug-in Hybrid Electric Vehicle (PHEV)	Li-ion	7,671	38,585	49,043	55,345	43,296	72,970	93,118	122,491
Battery Electric Vehicle (BEV)	Li-ion	9,754	14,022	48,464	67,093	72,769	85,643	106,700	238,816
Total		283,770	487,420	593,036	574,610	500,469	505,561	570,503	688,301

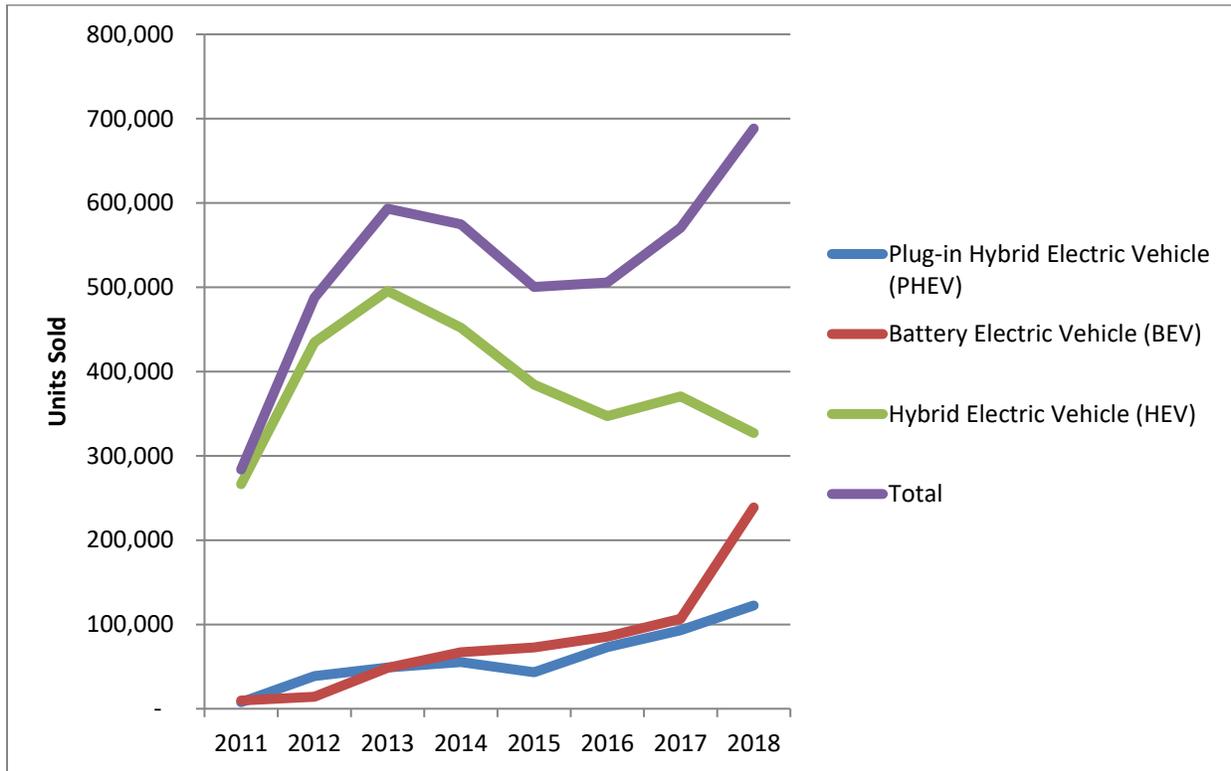


Figure 1 Unit Sales of HEVs, PHEVs and BEVs Sold in the US (2011-2018)²

¹ PHEV and BEV sales data taken from <https://insideevs.com/monthly-plug-in-ev-sales-scorecard-historical-charts/>
 HEV sales data taken from two sources. For 2011-2017: <https://afdc.energy.gov/data/10301>. For 2018: Sales Dashboard at <https://www.hybridcars.com>

² Ibid

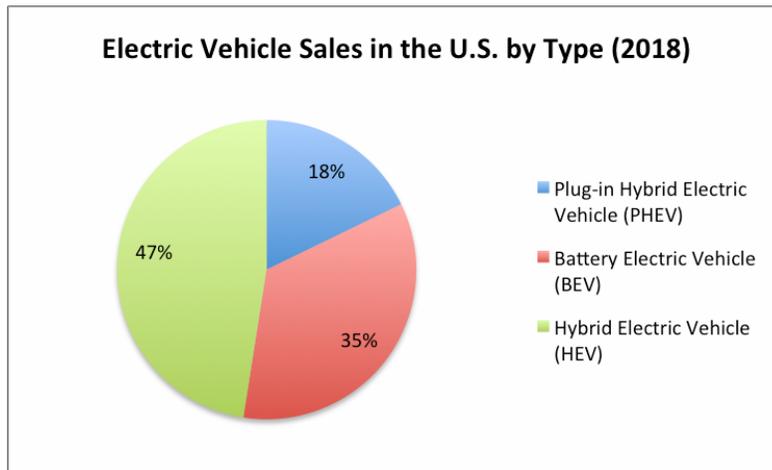


Figure 2: Total EV Sales in the US in 2018 (%)³

3.2 Projections of EV Adoption Rates in the US

Potential penetration rates of EVs into the US marketplace have been and continue to be the subject of numerous studies, with the assumptions and results changing virtually on a monthly basis, with experts having wide ranging opinions on the factors that may influence wide scale EV adoption. Table 2 presents a range of EV sales projections (available as of mid-July, 2019) for the US in the next 10 to 20 years.

As an example of the wide range of predictions published at this time, the US Energy Information Administration (EIA)'s latest numbers predict that in 2025 sales of BEVs and PHEVs will reach 1.3 million, or about 8% of projected total vehicle sales. At the other end of the spectrum, JP Morgan predicts that EV sales will account for over 38% of total vehicle sales in 2025.

The wide discrepancies among the projections are based on differences in methodologies and assumptions about variables such as future gas and battery prices, government policy commitments, improvements in battery range, charger speed and availability, the supply of new EV models, the availability and supply of EV batteries, the growth of shared mobility services, etc.

³ ibid

Table 2: Annual Sales and Market Share Projections of EVs in the US

Projection of Annual EV Sales (Units) in US (Based on total annual light-duty vehicle sales of approximately 17.2 million units)⁴	Source
1.4 million in 2025 3.5 million by 2030 (> 20% of total vehicle sales) ³	Edison Electric Institute for Electric Innovation (2018) ⁵
38% of total EV sales (BEVs, PHEVs and HEVs) in 2025	JP Morgan (2018) ⁶
1.3 million BEVs and PHEVs in 2025 (8% of total vehicle sales)	US Energy Information Administration (EIA) (2019) ⁷
1.5 million in 2025 (8.82% market share) 3 million by 2028 (17.65% of new auto sales)	Loren McDonald/EVAdoption.com (2019) ⁸
9.8% of all new car sales by 2025 59.6% by 2040	Bloomberg New Energy Finance (2019) ⁹
1.28 million by 2026 (7.6% of total US vehicle sales) ⁹	IHS Markit (2019) ¹⁰
20% to 30% PHEVs or BEVs by 2030 ¹¹ 50% to 60% including “mild and full” hybrids by 2030	Boston Consulting Group (2019) ¹²
650,000 by 2025 120 BEV models available	LMC Automotive (2018) ¹³
16% (reference case) by 2040 to 64% (technology case) by 2040 BEV and PHEV in Canada	Canada’s National Energy Board (2019) ¹⁴
8% EV (of new vehicles sold) in the US by 2030 under the New Policies Scenario 29% EV (of new vehicles sold) in Canada by 2030 under the New Policies Scenario > 30% of all vehicles sold in the US and Canada by 2030 under the EV30@30 Scenario	International Energy Agency (IEA) (2019) ¹⁵

In addition, some groups include all types of EVs (HEV, PHEV and BEV) in their projections whereas others

⁴ 18.7 million EVs on the road by 2030 (7% of the 259 million vehicle US stock by 2030)

⁵ Edison Electric Institute. “Report: Electric Vehicle Sales Forecast and the Charging Infrastructure Required Through 2030.” <http://www.edisonfoundation.net/iei/publications/Documents/IEI_EEI%20EV%20Forecast%20Report_Nov2018.pdf>

⁶ J.P. Morgan. October 10, 2018. “Driving into 2025: The Future of Electric Vehicles.” <<https://www.jpmorgan.com/global/research/electric-vehicles>>

⁷ Annual Energy Outlook 2019 with projections to 2050.” <<https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf>>

⁸ EV Adoption. “EV Sales Forecasts.” <<https://evadoption.com/ev-sales/ev-sales-forecasts/>>

⁹ Bloomberg NEF. “Electric Vehicle Outlook 2019.” <<https://about.bnef.com/electric-vehicle-outlook>>

¹⁰ IHS Markit forecasts EV sales to reach US market share of 7.6% in 2026.” <<https://ihsmarkit.com/research-analysis/--ihs-markit-forecasts-ev-sales-us.html>>

¹¹ This projection estimates that 7% to 12% of all vehicles will be plug-in hybrid or pure electric by 2030

¹² Electric Vehicles are a Multibillion-Dollar Opportunity for Utilities.” <http://image-src.bcg.com/Images/BCG-Electric-Vehicles-Are-a-Multibillion-Dollar-Opportunity-for-Utilities-Apr-2019_tcm9-218439.pdf>

¹³ “LMC Automotive’s EV Outlook.” December 3, 2018. <<https://www.autobeatdaily.com/articles/lmc-automotives-ev-outlook>>

¹⁴ National Energy Board. “Canada’s Energy Future 2018: Energy Supply and Demand Projections to 2040.” <<https://www.cer-rec.gc.ca/nrg/ntgrtd/ft/2018/index-eng.html>>

¹⁵ International Energy Agency. “Global EV Outlook 2019.” <<https://www.iea.org/publications/reports/globalevoutlook2019/>>

KELLEHER RESEARCH STUDY ON REUSE AND RECYCLING OF BATTERIES EMPLOYED IN ELECTRIC VEHICLES

FINAL REPORT

include only BEVs. Appendix G describes various factors that may impact on future EV sales projections.

Based on the research conducted for this study, conclusions on future EV sales projections are listed below:

- It is considered realistic to use a projection of new EV sales scenarios to 2025 (6 years from now). Despite the fact that many organizations offer projections beyond 2025, estimating sales beyond this year is not considered reliable, as many factors affecting EV sales are changing rapidly, both in the US market and globally, some of which are unpredictable at this time;
- EVs are still more expensive than ICE vehicles. Sales and adoption rates will likely increase and the technology will “diffuse” more broadly when price parity with ICE vehicles as well as a comfort level with the technology (which usually occurs when friends and family have already used a technology) occur. Price parity of EVs with ICE equivalent models is projected to occur when the cost of EV batteries reaches \$80/kWh to \$100/kWh. Various sources predict that this will occur anywhere from 2020 to 2025.
- There will always be certain situations where ICE vehicles will be preferred to EVs, particularly in northern parts of the US with colder winters, and with consumers who prefer to service their own vehicles.
- It is reasonable to assume that up to 8% of new vehicles sold in the US by 2025 will be either PHEVs or BEVs. Based on annual sales of about 17.2 million light duty vehicles, this translates to total sales of BEVs and PHEVs of 1.3 million. This value was projected by US EIA and is close to values predicted by Edison Institute and IHS Markit.
- The US EIA projections show hybrids increasing in the US market and levelling off to sales of about 1 million units per year (from the current level of about 327,000 units in 2018). HEVs are likely to continue to be popular as they offer some fuel efficiency but provide a full ICE. However, as the price of batteries falls, PHEVs will offer the advantage of being electric but with the same back-up ICE option, therefore HEVs may not gain further sales.
- These projections should be updated annually based on new data sources available to remain current. The next update should be carried out in August, 2020.

3.3 Estimated Amounts of End-of-Life EV Batteries Projected for the US

EV batteries generally have a lifespan of 8 years or 100,000 miles (or more), and EV manufacturers typically offer battery warranties that cover at least this service life. In practice, however, it appears that EV batteries can last much longer than originally predicted.¹⁶ While a small number of EV batteries reach EOL sooner than 8 years as a result of battery failure or vehicle collisions, these are estimated at about 1% to 3% of the EV stock based on discussions with industry representatives. Generally, reasons for EV battery failure include manufacturing defects from extrusion problems, heat stress, faulty charging,

¹⁶ Personal communication with Panasonic staff

damage to electrolyte or separator, and long-term, repeated cycling degradation.

Table 3 and Figure 3 present estimates of EV batteries reaching EOL from 2019 to 2030. These estimates were developed by Kelleher Environmental using a simple Lifespan Model based on a linear projection of the number of EV batteries reaching EOL reflecting HEV, PHEV and BEV sales from 2011 to 2018, as well as an assumption on EV sales from 2018 to 2023 outlined below. An elaborate material flow and lifespan model that accounts for a more granular distinction amongst changes in unit weights and different EV battery chemistries over time is beyond the scope of this study, but should be considered as a future research project and is included as a suggestion in Section 9. The EOL EV battery estimates presented in Table 3 were based on the following assumptions:

- Unit sales of HEVs into the US market from 2000 to 2010 from various sources;
- Unit sales of HEVs, PHEVs and BEVs sold into the US market shown in Table 1;
- 50% of HEVs have NiMH batteries and 50% have li-ion batteries (based on 2018 data);
- All PHEVs and BEVs have li-ion batteries;
- Sales of PHEVs and BEVs combined would reach 1.3 million units in 2025. The assumed split between the two types of vehicles was assumed to be 500,000 PHEV units and 800,000 BEV units. Linear projections were used from 2018 to 2025;
- It was assumed that the lifespans of NiMH and Li-ion EV batteries would have similar lifespans;
- It was assumed that one third of all EV batteries would last 8 years, one third would have lifespans of 9 years and one third would have lifespans of 10 years for the EOL modelling;
- Early retirement rates of 1% to 3% related to accidents and product failures were not included in this preliminary estimate.

Table 3: Preliminary Estimate of EV Batteries Reaching EOL in the US (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

The table shows that over 280,000 EV batteries are expected to reach EOL in the US in 2019. Most of these will be NiMH batteries from HEVs sold eight to 10 years prior to 2019, and some will be li-ion batteries sold in early PHEVs or BEVs. By 2025 an estimated 526,000 EV batteries are estimated to reach EOL. Less than 200,000 of these will be NiMH batteries from HEVs. The remaining 340,000 will be li-ion batteries from PHEVs and BEVs and some from HEVs.

Over 1 million EV batteries are expected to reach EOL by 2030. The Kelleher model has assumed that HEV sales remain constant at about 320,000 units/year after 2019, therefore a constant number of NiMH batteries would continue to reach EOL annually from 2028 on.

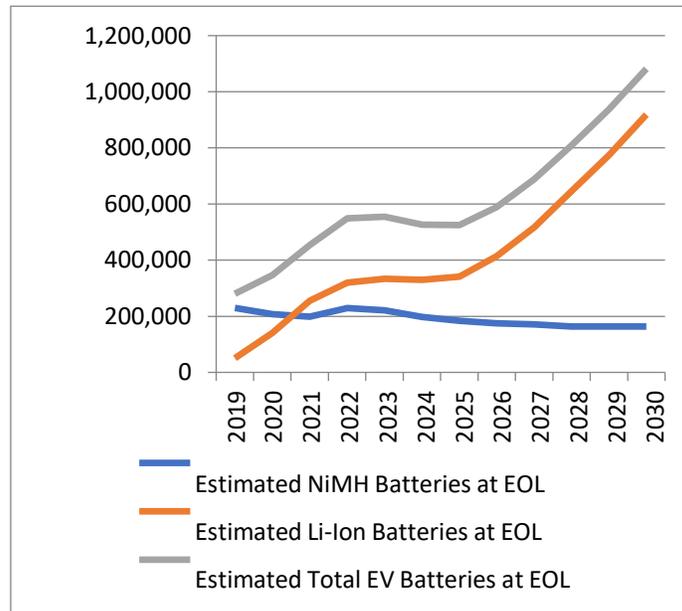


Figure 3: Estimated EV Batteries at End-of-Life in the US 2019 to 2030

3.4 Batteries from Electric Buses in the US

There were an estimated 300 battery electric buses (BEBs) in operation in the US at the end of 2017, representing less than 0.5% of the 65,000 buses in public transit agencies’ fleets. To date, most city transit agencies in the US have purchased BEBs in small numbers, to test them for reliability and compare them to traditional buses. The American Public Transportation Association (APTA), representing all of the major public transit agencies in the country, has stated that the economics of BEBs are shifting, although the price point for individual buses remains a barrier to overtaking diesel or other fuel systems. Cities pledging to shift their entire fleets to BEBs by specific dates in the future include Los Angeles County (by 2030), Seattle (King County, by 2040), San Francisco (by 2035), and New

York (by 2040). Table 4 presents a list of cities/transit agencies that have reportedly purchased BEBs or are planning to in the near future.

Table 4 Battery Electric Bus (BEB) Purchases in the US

City or County (Transit Agency)	BEBs Purchased	Delivery Date (Manufacturer)
Stockton, CA (SJRTD)	17	2017 (Proterra)
Los Angeles, CA (LADOT)	95	2015 - 2017 (BYD)
Northern Los Angeles County, CA (Antelope Valley Transit Authority)	112	2018 (35 from New Flyer, unknown numbers from Proterra and BYD)
Los Angeles, CA (L.A. Airports Authority)	20	April 2018 (BYD)
San Gabriel and Pomona Valleys, CA (Foothill Transit)	15	2017 (Proterra)
Boulder, CO	1	Summer 2018 (unknown)
Washington, DC (WMATA)	14	April 2018 (Proterra)
Chicago, IL (CTA)	20	2019-2020 (Proterra)
New York, NY (NYC Transit Authority)	10	Date unknown (5 from Proterra, 5 from New Flyer)
Dallas, TX (DART)	7	July 2018 (Proterra)
Columbus, OH (COTA)	10	2019 or 2020 (Proterra)
San Francisco, CA (SF Metropolitan Transit Authority)	9	Fall 2018 (various manufacturers)
St Louis, MO	2	Late 2020 (Gillig)
Anchorage, AK (MOAPTD)	1	January 2018 (Proterra)
Hoboken, NJ (Columbia University shuttle system)	6	2018 (New Flyer)
Seattle, WA (King County Metro Transit)	20	2018, 2019 (Proterra, BYD, and New Flyer)
Louisville, KY (River City Transit Authority)	15	2017 (Proterra)
Madison, WI (Metro Transit)	3	2019 (unknown)
Indianapolis, IN (IndyGo)	21	2018 (unknown)
Philadelphia (Southeastern Pennsylvania Transportation Authority)	25	2019 (Proterra)
Rhode Island Public Transit Authority (RIPTA)	3	2018 (Proterra)

Batteries used in electric buses weigh about 3.5 tons¹⁷ and approximately 89% are lithium iron phosphate (LFP) chemistry¹⁸, which is considered “fire safe.” BYD, currently the largest electric bus manufacturer, claims that LFP batteries can last up to 7,200 charge/discharge cycles, corresponding to a 20-year lifespan if cycled once daily.¹⁹ Proterra, another significant player in the electric bus manufacturing business, suggests a mid-life cycle replacement of their lithium titanate oxide (LTO) battery after six years.

Given the very minimal numbers of electric buses in the US at this time, limited short-term (five years) projected growth, and wide variation in projected lifespans, very few EOL BEB batteries will require management by 2025, or even 2030. Management of batteries from BEBs is unlikely to emerge as an issue in the next 10 years, and therefore it is not considered further in this report.

3.5 Options for EV End of Life Batteries

When an EV battery reaches EOL for the purposes of an EV, it can be directed to either reuse or recycling:

- **Reuse** – EOL EV batteries still have significant capacity (typically 70% to 80%)²⁰ after they are removed from an EV, and can be reclaimed for a “second-life” in many applications. Various “second uses” are being explored by companies ranging from large OEMs to small one-person operations. These second-life applications may extend the lifespan of EV batteries by between six to 30 years.²¹ Reuse options are discussed in more detail in Section 4 of this report.
- **Recycling** – Some EOL EV batteries are sent directly to recycling, where the EV battery is dismantled and hydrometallurgical, pyrometallurgical and/or other technologies are used to recover valuable chemicals and metals such as cobalt, nickel and aluminum. Recycling is discussed in more detail in Section 5 of this report.

Figure 4 shows a depiction of EOL pathways for EV batteries, but does not show the EV batteries being refurbished and reused in EVs which is another application discussed in Section 4. The relative proportions of EV batteries currently at EOL that are reused vs. recycled is unknown. The numbers of EOL EVs are relatively small to date. Some are managed by OEMs who send them to either reuse or recycling discussed

¹⁷ Grütter Consulting. December 2014. “Real World Performance of Hybrid and Electric Buses: Environmental and Financial Performance of Hybrid and Battery Electric Transit Buses Based on Real World Performance of Large Operational Fleets.” <<http://www.slocat.net/sites/default/files/report.pdf>>

¹⁸ Atak, A. & Grande, Dr. L. March 2018. “Li-ion Batteries for Electric Buses 2018-2028: Technology, Market Trends, Forecasts and Key Players.” <<https://www.idtechex.com/en/research-report/li-ion-batteries-for-electric-buses-2018-2028/595>>

¹⁹ California Environmental Protection Agency Air Resources Board. August 22, 2016. “Advanced Clean Transit Battery Cost for Heavy-Duty Electric Vehicles – Discussion Draft.” <https://ww3.arb.ca.gov/msprog/bus/battery_cost.pdf>

²⁰ UL. “The Afterlife of Electric Vehicle Batteries.” Available at <www.ul.com/inside-ul/the-afterlife-of-electric-vehicle-batteries/>

²¹ Casals, L.C., García, B.A., and Canal, C. (2019). “Second life batteries lifespan: Rest of useful life and environmental analysis.” *Journal of Environmental Management*, 232: 354-363. <<https://doi.org/10.1016/j.jenvman.2018.11.046>>

in Sections 4 and 5. Other EV batteries are scattered throughout the country. Anecdotally, those interviewed for this study comment that most scrap yards have a few hybrid batteries being stored at their facilities (which have large areas of storage space) until a solution is found. In some cases, brokers will take the batteries from the scrap yards and auto recyclers. It is not known for certain where these batteries go after this occurs, although it is assumed that viable cells or batteries are sold into reuse applications. Based on our interviews for this study, small numbers of EOL EV batteries have been received by recyclers to date. A concern about possible illegal dumping as the numbers get larger in the next few years prompted California officials to run a workshop on the issue in April, 2018 (discussed in more details in Sections 4 and 5), and a paper is being written by staff to address the issue. The target date for release of the paper is Q4, 2019.

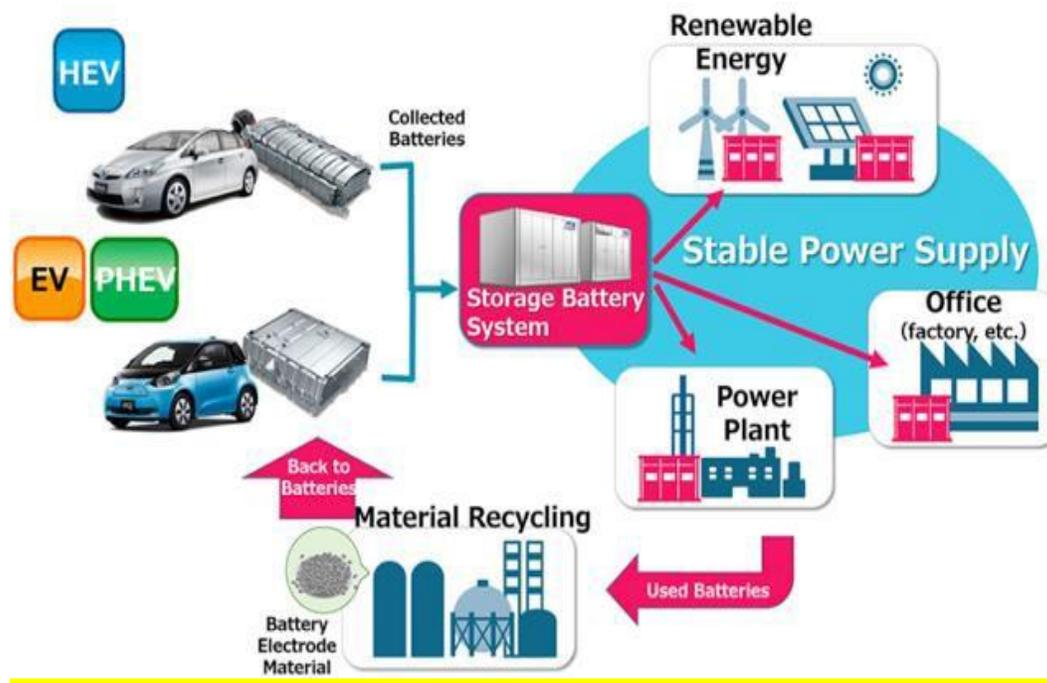


Figure 4 End-of-Life Options for EV Batteries

3.6 Collection of EV Batteries

For EV battery reuse or recycling to be efficient, an established collection infrastructure to consolidate batteries in a number of locations from which they can be transported to reuse companies or recyclers is needed. This collection infrastructure does not currently exist in the US or Canada, and EV batteries are scattered in small numbers in locations throughout the two countries. While the numbers are modest to date, the total number of EOL EV batteries is projected to reach over 525,000 by 2025 and over 1 million by 2030. At these levels some form of collection system will be needed to bring EOL EV batteries to central locations where they can either be reused or recycled.

Most EV batteries at EOL will come through the auto dismantling or auto recycling supply chain. While some may come through independent auto service and repair facilities, the more common route will likely be through official OEM channels such as Toyota, GM, Ford and other dealers, given the need for trained mechanics to service EVs.

For EVs that do not pass through official dealer hands at EOL, they likely will be sent to small dismantling facilities (junkyards). These small facilities, which typically recover valuable used parts from ICE vehicles for sale to individuals or vehicle repair shops, are generally not familiar with how to manage EVs. Through discussions with the Automotive Recyclers Association (ARA) and Automotive Recyclers of Canada (ARC) (the associations which represent these small facilities in the US and Canada), it is clear that the numbers of EV batteries appearing at these sites are beginning to increase and operators do not know how to handle them. In response to this increase, both ARA and ARC now offer training courses for both emergency first responders and scrap yard staff on how to recognize and safely discharge EV batteries. The current focus is on HEVs, as these are the types encountered most often. As an indication of the current interest in better management of EV batteries, the two days of courses on Hybrid/Electric Vehicle Dismantlers Training offered by the Ontario Automotive Recyclers Association in August, 2019 was fully subscribed with a waiting list before being officially advertised.²² The 6-hour 1-day training is specifically designed for vehicle recyclers and is accredited by the Waste Management Industry Training and Advisory Board. The course covers the following topics: hybrid vehicle and EV explanation; common features of most hybrids; high voltage safety; electric shock potential; moving and towing a hybrid; de-powering the high voltage system; and battery storage and best management practice. In short, safety concerns are highlighting the need for development of an infrastructure to collect, dismantle and deliver EOL EV batteries to reuse or recycling companies.

3.7 Future Li-ion Battery Chemistries

NMC and NCA chemistries are the most commonly used in the EVs sold in North America. NCA batteries, which typically use a combination of 80% nickel, 15% cobalt, and 5% aluminum, are made by Panasonic and so far are only used in Tesla models.²³ NMC batteries take several forms, such as NMC111 (based on equal parts nickel, manganese, and cobalt) and NM532/622 (higher energy density and lower price than NMC111 due to a lower cobalt content). NMC cathodes currently account for nearly 28% of global EV sales, and it has been predicted that market share will grow to 63% by 2027.²⁴

As the price of cobalt increases, it is predicted that the trend towards NMC and NCA types of li-ion batteries and away from other chemistries will continue. When it comes to recycling li-ion EV

²² Personal communication with Steve Fletcher, Executive Director of Automotive Recyclers of Canada, July, 2019

²³ Maloney, P. 1 August 2018. "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/>>

²⁴ "NMC batteries dominating EV – sales to reach 63% of global market." 19 October 2018. <<http://www.mining.com/nmc-batteries-dominating-ev-sales-reach-63-global-market/>>

batteries at EOL, the chemistry is critically important as some materials – like cobalt – are very valuable, whereas others offer little or no value to the traditional recycler. It should be noted that the price of cobalt dropped significantly in 2018 as a result of a temporary over-supply, but generally the trend is expected to increase.

Figure 5 presents a projection by Benchmark Minerals Intelligence that anticipates a substantial move to NMC chemistries by 2026, with the ideal NMC chemistry being NMC811. NeoMetals (described in Section 5) presented this outlook to investors in March, 2019.

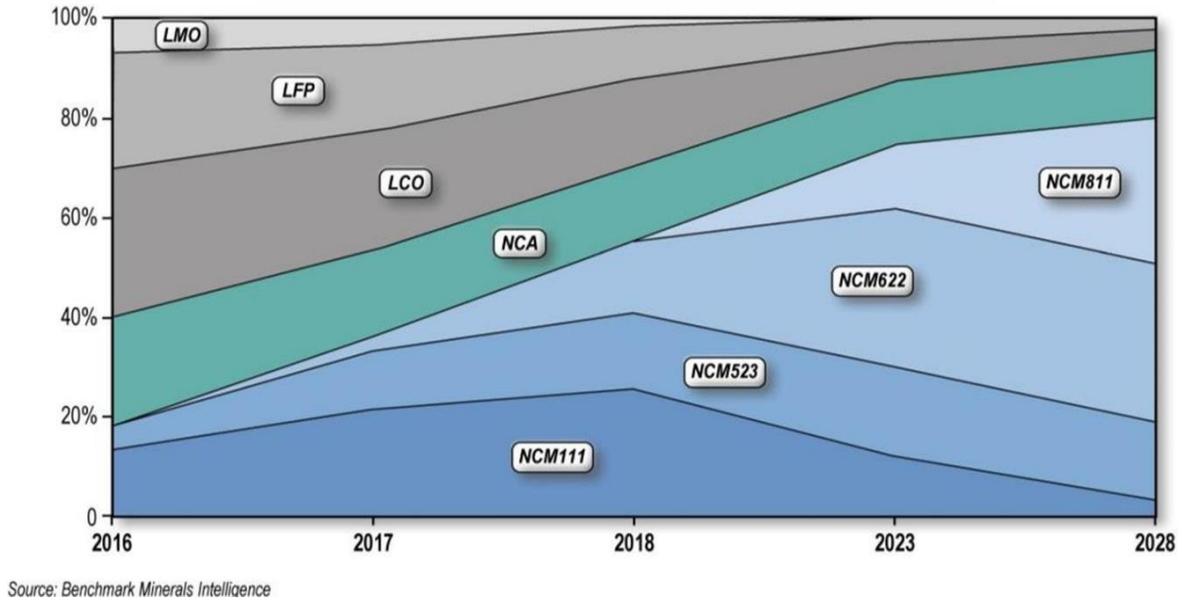


Figure 5 Cathode Trends in Lithium Battery Megafactories, 2016 to 2028²⁵

Figure 6 presents a projection of the share of cathode technologies by 2025, which was published by T&D world in February, 2019.

²⁵ Neometals Presentation at Euroz Institute, March, 2019 <<https://www.neometals.com.au/announcements.php>>

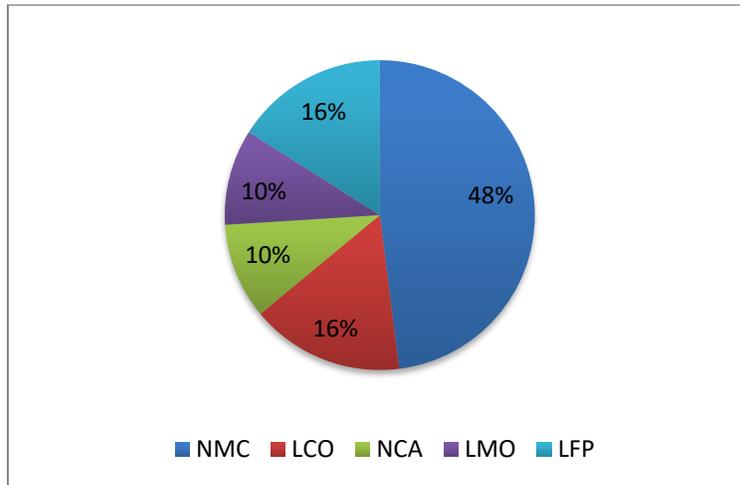


Figure 6 Projected Share of Different Li-ion Battery Chemistries by 2025²⁶

Tables 5 and 6, taken from a presentation at an EV battery recycling business meeting in Norway in June, 2019, show the expected evolution of NMC battery chemistries from 2015 to 2030, reflecting a projected decrease in overall cobalt content. The projections show that while cathode chemistries will move to NMC622 and NMC811, overall li-ion batteries are still anticipated to contain about 3.2% cobalt on average by 2030.

Table 5 Evolution of Lithium Battery Chemistries (2015-2030)²⁷

	2015	2020	2025	2030
NMC 111	90%	60%	25%	17%
NMC 433	5%	19%	20%	12%
NMC 532	3%	15%	30%	12%
NMC 622	2%	4%	15%	33%
NMC 811	0%	2%	10%	26%

Table 6 Evolution of Cobalt Content in Lithium Batteries (2015 – 2030)²⁸

	2015	2020	2025	2030
Cobalt content	4.4%	4.2%	3.6%	3.2%

In anticipation of increasing demand for NMC811 cathodes in the future, LG Chem and SK Innovation are

²⁶ Zaheer, H. February 28, 2019. "Evolution of Li-ion Batteries: From the Garage to the Grid." <<https://www.tdworld.com/energy-storage/evolution-li-ion-batteries-garage-grid>>

²⁷ Chanson, C. 12 June 2019. "Business opportunities and risks for the recycling industry." PowerPoint Presentation. <<https://www.eucobat.eu/sites/default/files/2019-06/05%20Claude%20Chanson%20RECHARGE.pdf>>

²⁸ ibid

increasing their NMC811 production capacity. Tesla already uses NMC811 cathode technology in its Tesla Powerwall.²⁹

3.8 Future EV Battery Designs

A number of other battery formats are being explored at this time. The anticipated date for these design changes to be commercialized is uncertain.

Solid-State Batteries

In solid-state batteries, the liquid/polymer electrolyte in today's li-ion batteries is replaced with a solid, non-flammable electrolyte.³⁰ This reduces the safety risks associated with current li-ion technology, such as the potential for EVs to overheat, explode or catch fire due to short-circuiting.

In terms of performance, these batteries could double the energy density offered by current technology, allowing for increased energy generation, faster recharging, longer lifespan, lower material requirements (which results in lower prices), compact cell size of 3-4 microns instead of 20-30 microns today, and a possibility of quick charging without dendrite formation.

Advantages to the car owner and industry would include reduced charging time and reduced space requirements in the vehicle. Although a growing number of manufacturers, including Toyota, BMW, Honda, Hyundai, and Nissan, are working on developing these batteries, none are automotive production ready.³¹ Toyota is planning to use solid-state batteries in some models by 2020. James Dyson, who is best known for vacuum cleaner production, is planning to launch three EVs in 2022, all with solid-state batteries. Fisker is also exploring the use of solid-state batteries in the EV models that they intend to produce in the 2021+ timeframe.

Fluoride-ion Batteries

Honda recently published a report³² on new fluoride-ion batteries that it is developing. According to

²⁹Zaheer, H. February 28, 2019. "Evolution of Li-ion Batteries: From the Garage to the Grid." <https://www.tdworld.com/energy-storage/evolution-li-ion-batteries-garage-grid>

³⁰ RBC Capital Markets. May 11, 2018. "RBC Electric Vehicle Forecast Through 2050 & Primer." <http://www.fullertreacymoney.com/system/data/files/PDFs/2018/May/14th/RBC%20Capital%20Markets_RBC%20Electric%20Vehicle%20Forecast%20Through%202050%20%20Primer_11May2018.pdf>

³¹³⁰ RBC Capital Markets. May 11, 2018. "RBC Electric Vehicle Forecast Through 2050 & Primer." <http://www.fullertreacymoney.com/system/data/files/PDFs/2018/May/14th/RBC%20Capital%20Markets_RBC%20Electric%20Vehicle%20Forecast%20Through%202050%20%20Primer_11May2018.pdf>

³² Davis, V.K. et al. (2018). "Room-temperature cycling of metal fluoride electrodes: Liquid electrolytes for high-energy fluoride ion cells." *Science*, 362: 6419, 1144-1148. <<https://science.sciencemag.org/content/362/6419/1144>>

Honda, a stable liquid fluoride electrolyte made of tetraalkylammonium fluoride salts dissolved in an organic, fluorinated ether solvent, can be used in a cell to conduct electricity at room temperature to provide power and to recharge. The cathode is a nano-structure made of copper, lanthanum, and fluorine that resists the formation of dendrites that can lead to premature failure in a li-ion cell.³³ The company believes that the cells can reach energy densities up to 10 times higher than currently available lithium batteries, which could allow automakers to build cars with 300 miles of range or more with smaller, lighter, and cheaper battery packs.³⁴

Innolith Batteries³⁵

Innolith, a startup based in Switzerland, has created a battery with a capacity of 1,000 Wh/kg or 1kWh/kg and allows 600 miles on one charge. Innolith technology is already in service in Hagerstown, Maryland for PJM Grid, which operates the regional utility grid for all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. The Innolith “Grid Bank” battery is being tested at scale in Hagerstown. Testing is still underway with commercial production anticipated by 2020. Like conventional li-ion batteries, the Innolith battery uses a wet electrolyte but the organic and highly flammable solvent used in li-ion batteries is replaced with an inorganic salt-like material that is more stable and less flammable. This also allows the construction of a more dense battery pack.

Non-Copper Anodes

Graphite-coated copper has been used as an anode in li-ion batteries since the 1990s. Two developments in anode design could replace copper anodes:

- Lithium Titanate (LTO) Anode: LTO anodes have a higher power density and allow a higher number of charging/discharging cycles than copper anodes. Toshiba announced its 50Ah prototype of this type of battery and claims it will retain 90% of its capacity after 5000 cycles.³⁶
- Silicon Anode: Silicon anode technology provides high energy density and power rating potential at a potentially lower cost than current graphite anodes. Samsung SDI and Panasonic are already working with this technology but a longer time to market is anticipated.

33 Everts, E. December 21, 2018. “Honda presents new battery chemistry that could succeed lithium-ion.”

<https://www2.greencarreports.com/news/1120563_honda-presents-new-battery-chemistry-that-could-succeed-lithium-ion>

34 Everts, E. December 21, 2018. “Honda presents new battery chemistry that could succeed lithium-ion.”

<https://www2.greencarreports.com/news/1120563_honda-presents-new-battery-chemistry-that-could-succeed-lithium-ion>

35 <https://cleantechnica.com/2019/04/04/swiss-startup-innolith-claims-1000-wh-kg-battery-breakthrough/> and

<https://www.theverge.com/2019/4/4/18293989/innolith-ev-battery-breakthrough-lithium-ion>

36 Zaheer, H. February 28, 2019. “Evolution of Li-ion Batteries: From the Garage to the Grid.” <<https://www.tdworld.com/energy-storage/evolution-li-ion-batteries-garage-grid>>

Nanomaterials (Graphene) in Battery Cells

Graphene properties such as hardness, flexibility and very high thermal and electrical conductivity, make it suitable for use in battery cells.

Phosphorous Encapsulated Nano-Tube Electrodes³⁷

Toyohashi University in Japan has proposed phosphorous encapsulated nano-tube electrodes. The claim is that they have doubled charging capacity during experimentation and the cells maintained high structural integrity after repeat charges. The technology is very much at the experimental stage.

3.9 Projections of Future Cost of EV Batteries

The impacts of battery chemistry on EV battery costs is shown in Figure 7. Significant research efforts are focused on cost reduction through battery chemistry modifications, thereby making the EV more cost-competitive with ICE vehicles. As discussed elsewhere, the crossover point for price parity between EV and ICE models is believed to be when EV batteries reach a cost of \$100/kWh.

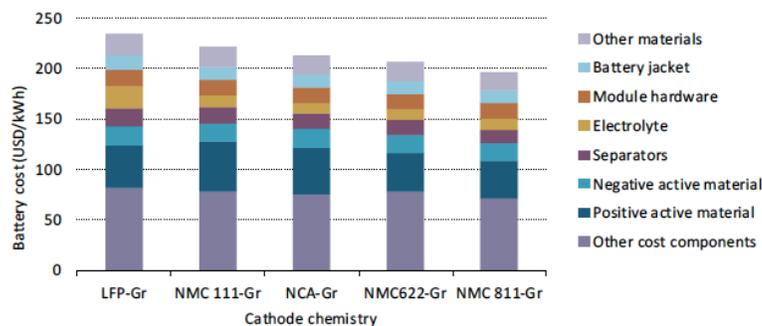


Figure 7 Effect of Change in EV Battery Chemistry on Costs of EV Batteries³⁸

Figures 8 and 9 show various projections of EV battery costs to 2030. The figures show the dramatic reduction in li-ion battery costs from about \$1,200/kWh in 2010 to less than \$400/kWh in 2015 and values below \$200/kWh today.

³⁷ AZoNano. May 15, 2018. "Phosphorous-Encapsulated Carbon Nanotubes Enhance Performance of Li-Ion Batteries." <<https://www.azonano.com/news.aspx?newsID=36175>>

³⁸ International Energy Agency. 2018. "Global EV Outlook 2018: Towards Cross-Modal Electrification." <<http://www.oecd.org/publications/global-ev-outlook-2018-9789264302365-en.htm>>

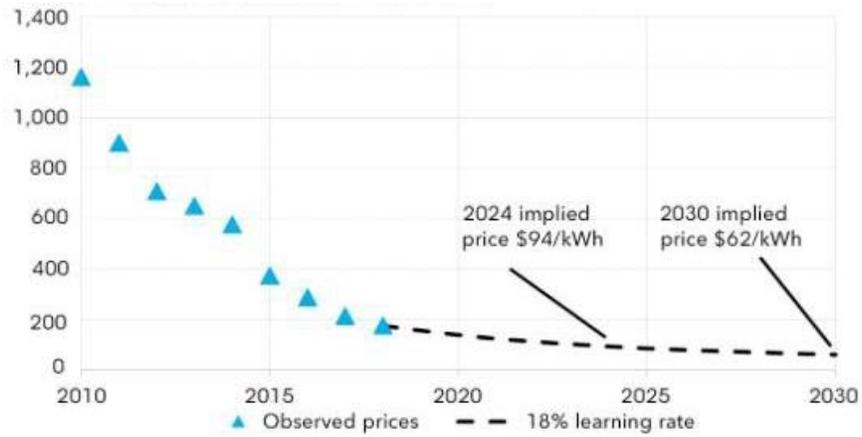


Figure 8 Li-ion Battery Pack Price Outlook to 2030 (real 2018 \$/kWh)³⁹

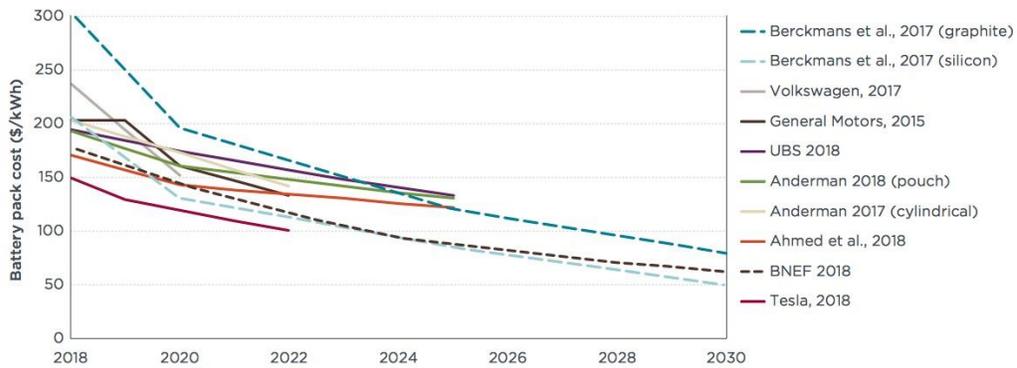


Figure 9 EV Battery Pack Cost Projections from a Variety of Technical Studies and Automaker Statements³⁹

The costs of new li-ion battery packs have a significant impact on the economics of EV battery reuse discussed in Section 4).

³⁹ Goldie-Scot, L. 5 March 2019. "A Behind the Scenes Take on Lithium-ion Battery Prices." *Bloomberg New Energy Finance*. <<https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/>>

4 EV Battery Reuse

4.1 EV Battery Reuse Terminology

Many different terms are used to indicate that an EV battery is directed to a second-life application after it is no longer suitable for an EV. These include:

- Reconditioning, which generally refers to replacing dead cells or packs in order to reuse the assembly as an EV battery;
- Refurbishing, which basically means the same thing as reconditioning;
- Repurposing in other applications (e.g., energy storage), where some cells and packs are replaced but the battery is directed to a stationary application;
- Reusing, where the battery is torn down to the pack or cell level, with the individual cells re-deployed to a wide variety of applications which use battery cells.

4.2 EV Battery Reuse Examples

Reuse applications for end of life EV batteries include both stationary and mobile options, and vary from applications which split the used EV into its constituent parts down to the cell or pack level, or whether the unit is maintained intact with low performing cells removed and replaced with new or reconditioned cells. Table 7 provides some examples of second life applications (reuse) for EV batteries initiated by either vehicle or battery OEMs, sometimes in partnership with utilities or other companies. Figure 10 shows an example of a forklift powered by reused EV batteries.

Table 7 Examples of EV Batteries in Reuse Applications⁴⁰

Company	EV Battery Reuse Application	Location
Accelaron	Energy storage	UK, Barbados
Audi	Forklifts and factory tugs	Ingolstadt, Germany ⁴¹ (see image below)
Audi	Battery storage	Berlin, Germany ⁴² (see image below)
BJEV (b)	EV charging and back-up power	Not identified
BMW (a)	Energy storage farm	Leipzig, Germany
BMW (b)	Grid scale energy storage, back-up power	Not identified
BMW and Pacific Gas and Electric (PG&E) (a)	BMW i ChargeForward Project to use second-life EV batteries and EVs themselves to stabilize grid through demand response (DR)	San Francisco Bay Area
Box of Energy	Stores energy from rooftop solar panels to run elevators and lights	Sweden ⁴³
BYD (Build Your Dream), China (a)	Energy storage	Shenzhen, China
BYD	Grid scale energy storage, back-up power	
Chengan (b)	Back up power	
Chevrolet (a)	Back up power at a GM's Enterprise Data centre	Michigan, US
Daimler (b)	Grid scale energy storage; commercial and industrial (C&I) energy storage	
Eaton (a)	Energy storage	South Africa
EcarACCU (a)	Solar energy storage	Cameroon
EVgo (a)	EV charging	California, US
Florida Power & Light (a)	Grid management	Florida, US
Fiat/IT Asset Partners (ITAP)	With ITAP. batteries are broken down into the individual cells which are then resold or repurposed	
General Motors	Remanufacturing	
GreatWall Power	Backup power, energy storage	Shanghai
Hyundai/Wärtsilä	Grid scale energy storage; C&I energy storage	
Honda/American Electric Power (a)	Grid integration of energy storage ⁴⁴	Ohio
ITAP (IT Asset Partners)	Salvaged solar panels and combined with EV batteries to supply power for recycling facility	Chatsworth, California
Mitsubishi	C&I energy storage	
Nissan	Remanufacturing; C&I energy storage, EV charging	
Nissan/Eaton/Mobility House (a)	Energy storage	Amsterdam, Netherlands

⁴⁰ Stringer, D. & J. Ma. June 27, 2018. "Where 3 Million Electric Vehicle Batteries Will Go When They Retire?" <www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire> and Melin, H.E., Circular Energy Storage. (n.d.). "The lithium-ion battery end-of-life market – A baseline study." <http://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf>

⁴¹ Everts, E. March 15, 2019. "Audi plans to put old EV batteries to work in factory tugs." <https://www.greencarreports.com/news/1122092_audi-plans-to-put-old-ev-batteries-to-work-in-factory-tugs>

⁴² "Audi Opens Battery Storage Unit on Berlin EUREF Campus." May 24, 2019. <<https://www.audi-mediacenter.com/en/press-releases/audi-opens-battery-storage-unit-on-berlin-euref-campus-11681>>

⁴³ Box of Energy. <<http://www.boxofenergy.se/english>>

⁴⁴ Kane, M. May 16, 2019. "Honda to Study 2nd Life of Used EV Batteries in Ohio." <<https://insideevs.com/news/349906/honda-2nd-life-used-ev-batteries/amp/>>

Nissan/Eaton with EDF Energy (a)	Commercial energy storage with French firm Powershift platform	UK
Nissan/Sumitomo (a)	Street lighting	Namie, Japan
Nissan/Sumitomo (a)	Large-scale power storage	Japan
Nissan	Back-up power for camping trailers	Not identified ⁴⁵
PSA	C&I energy storage	
Relectrify	Residential solar storage, commercial peak shaving, grid support	Australia ⁴⁶
Renault (b)	EV charging, residential energy storage, grid scale energy storage	
Renault (a)	Renewable storage	Porto Santo Island
Renault (a)	Backup power for elevators	Paris, France
Renault / Connected Energy (a)	EV charging	Belgium
Rivian Automotive/Honnold Foundation	Stationary energy storage units in a microgrid project	Adjuntas, Puerto Rico ⁴⁷
SAIC	Back-up power	
Toyota	C&I energy storage, grid scale energy storage (NiMH)	
Toyota	Reuse of Prius hybrid batteries to run refrigerators in 7-Eleven stores	Japan ⁴⁸
Volkswagen Audi	C&I energy storage	
Volkswagen	Mobile charging station	Wolfsburg, Germany ⁴⁹
Volvo	Residential energy storage	
Yin-Long	Back-up power; C&I energy storage	
<i>Note: Most examples are taken from two references: Stringer and Ma (2018)⁵⁰– identified as (a) or Circular Energy Storage (2019)⁵¹ identified as (b).</i>		

⁴⁵ Lee, T. February 18, 2019. "Nissan Will Reuse EV Batteries To Power Camping Trailers." <<https://www.ubergizmo.com/2019/02/nissan-reuse-ev-batteries-camping-trailers/>>

⁴⁶ 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

⁴⁷ Alvarez, S. June 13, 2019. "Rivian set to debut energy storage project using 'second life' batteries from vehicles." <<https://www.teslarati.com/rivian-debuts-energy-storage-from-second-life-ev-batteries/>>

⁴⁸ Everts, E. July 16, 2018. "As used electric-car batteries set to flood market, Automakers ramp up reuse efforts." <https://www.greencarreports.com/news/1117705_as-used-electric-car-batteries-set-to-flood-market-automakers-ramp-up-reuse-efforts>

⁴⁹ Kane, M. March 5, 2019. "Volkswagen Reveals Its Mobile Fast Charging Station in Geneva." *InsideEVs*. <<https://insideevs.com/news/343194/volkswagen-reveals-its-mobile-fast-charging-station-in-geneva/>>

⁵⁰ Stringer, D., and J. Ma. June 27, 2018. "Where 3 Million Electric Vehicle Batteries Will Go When They Retire." *BNN Bloomberg News*. <<https://www.bnnbloomberg.ca/where-3-million-electric-vehicle-batteries-will-go-when-they-retire-1.1099962>>

⁵¹ Melin, H.E., Circular Energy Storage. (n.d.). "The lithium-ion battery end-of-life market – A baseline study." <http://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf>



Figure 10 Forklifts Using EV Batteries from Audi EVs⁵²



Figure 11 Volkswagen Portable EV Charging Station⁵³

⁵² McCandless, K. April 15, 2019. "Still got it: How reuse and recycling can give EV batteries a new lease of life." <<https://www.automotive-logistics.media/still-got-it-how-reuse-and-recycling-can-give-ev-batteries-a-new-lease-of-life/37938.article>>

⁵³ *ibid.*



Figure 12 Audi's Battery Storage Unit on Berlin EUREF Campus⁵⁴

From the table, the types of reuse options already in place for EOL EV batteries include:

- Reuse in EVs;
- Reuse of cells or packs in other battery applications (e.g., drones, wheelchairs, etc.);
- Residential energy storage (combined with solar PV system);
- Commercial and industrial (C&I) energy storage;
- Grid scale energy storage;
- Energy storage for renewable energy systems (solar and wind);
- Back-up power; and
- EV charging (stationary or mobile).

Examples of these applications are provided in the sections that follow.

4.2.1 Reuse in EVs

The supply chain for EOL EV batteries is controlled by auto dismantlers and auto manufacturers, with auto repair shops and auto mechanics feeding in small amounts of EOL EV batteries.

A refurbishment and reuse business exists for EV batteries, sometimes carried out by do-it-yourselfers, informal recyclers and small businesses. Auto dismantlers who receive an EOL EV battery generally try to sell the EV battery to auto dealers or auto repair shops, and in some cases to brokers. It is not known what the brokers do with the EOL EV batteries but it is assumed that they deploy them to various reuse applications where the most money can be made.

⁵⁴ "Audi Opens Battery Storage Unit on Berlin EUREF Campus." May 24, 2019. <<https://www.audi-mediacycenter.com/en/press-releases/audi-opens-battery-storage-unit-on-berlin-euref-campus-11681>>

Some small operators assess spent batteries and create a new battery from the packs and cells that have sufficient capacity remaining. These refurbished batteries are typically sold on eBay and other websites. Battery OEMs such as Panasonic and others have serious concerns about liability and safety, especially where the cell history is not known. Combining cells of different age and degradation into one pack without a proper battery management system (BMS) and proper ventilation can lead to over-heating and eventually potentially cause fires.

A number of professional and established companies (such as Spiers New Technologies (SNT) described in detail later in this section) carry out a systematic process to grade the cells and packs from EVs for various applications, including in EV batteries.

Nissan takes back all spent EV batteries for its Leaf model in Japan for testing and refurbishment. The company rationale is that a refurbished battery is good for a vehicle with a few years of life left, and Nissan provides this option for customer retention. A new Leaf battery is reported to cost about \$6,500⁵⁵ and Nissan offers refurbished batteries in Japan for a cost of \$2,900.⁵⁶ However, this option does not appear to be available in North America at this time.

Honda was contacted as part of the research to ask if they have plans to repurpose EV batteries in North America, but declined a request for an interview or responding to questions by email for confidentiality reasons. Other industry players interviewed for the project indicated that GM also creates new EV batteries from cells harvested from EOL EV batteries. However, this could not be confirmed through direct contact with GM representatives.

4.2.2 Reuse of Individual Battery Cells

Reuse of EV battery cells is carried out by reliable companies such as Spiers New Technologies (SNT) Inc. and IT Asset Partners (ITAP) (described in detail later in this section), but also by small or individual operators who carry out their businesses with no standards or oversight.

As an example, a Tesla battery consists of over 7,000 separate 18650 cells (named for its size: 18 mm in diameter and 65 mm high) combined into packs, which are then combined to form the battery along with the BMS. Tesla designed the original EV battery to be made up of standard sized cells that were readily available in the market, so that there would not be a risk of a shortage of cells for their batteries. Battery OEMs manufacture “billions” of the standard 18620 cells each year for a broad range of applications including laptops, etc., therefore there is a significant market for reconditioned cells.

Some amateur operators will take apart a Tesla battery, test and sell the cells separately for \$5 to

55 “Nissan LEAF batteries replacement program launched in Japan; remanufactured and new.” January 8, 2019.

<<https://greentecauto.com/repurposed-batteries/nissan-leaf-battery-replacement-program>>

56 Everts, E. May 14, 2018. “Nissan begins offering rebuilt Leaf battery packs.” https://www.greencarreports.com/news/1116722_nissan-begins-offering-rebuilt-leaf-battery-packs

\$6/cell. In theory, if 80% of the cells are in good condition, these amateurs could make \$15,000 from a used Tesla battery. These operators are of significant concern to Panasonic, the manufacturer of Tesla's cells, because of the risk and liability associated with distribution of cells without proper standards and management.

There are already serious concerns about vaping equipment and e-cigarettes exploding and injuring consumers. The reason is that the device, BMS and batteries for the vaping equipment are manufactured by different companies and are not fully integrated. A reused cell could easily be purchased for vaping or other applications and cause injury.

4.2.3 Reuse in Energy Storage Systems

Energy storage systems (ESS) provide numerous benefits to the power grid including system peak shaving, load management, back-up power, frequency regulation and many other applications. Energy storage also secures the viability of renewable energy sources such as solar and wind, as ESSs allow generated energy to be stored for later use. For this reason, at least 11 US states have mandated energy storage as part of the power system development on a go-forward basis. State level policy actions on energy storage include setting procurement mandates, establishing incentives, and requiring incorporation of storage into long-term planning mechanisms. States that are subsidizing storage and/or mandating its adoption, or that have set targets for energy storage include: Maryland, New Jersey, Nevada, Oregon, New York and Massachusetts. In 2013, California set a mandate for its investor-owned utilities to procure 1,325 MW of energy storage across transmission, distribution and customer levels by 2020. There is currently 0.4 GWh of energy storage in California. An estimated 85% of this energy storage is supplied by li-ion batteries.

The earliest large-scale battery storage installations in the US used nickel cadmium (NiCd) batteries and sodium-based batteries. Lead-acid batteries were also used for many years, and continue to be used in many ESSs, as electrical utility operators are comfortable with them. Since 2011, most installations have opted for li-ion batteries. Today, greater than 80% of US large scale battery storage power capacity is provided by li-ion batteries. Installed power capacity through energy storage has nearly doubled every two years since 2011, and by 2017, 708MW was in operation in the US.

Use of EOL EV batteries in ESSs can reportedly extend the life of the EV battery or some of its cells for a time period of anywhere from six to 15 years or more depending on the exact application.

EV batteries could be used to create home storage systems similar to the Tesla Powerwall, which provides back-up power during power outages, and can store energy produced by solar systems for later use in the house, or to feed back into the electric grid at peak pricing times. Figure 13 shows projections of EV battery conversions to home ESSs globally between now and 2025. The prediction was carried out in 2016 and is now considered somewhat out of date.

Plenty of Old EV Batteries Coming Soon

Can be converted to home energy storage

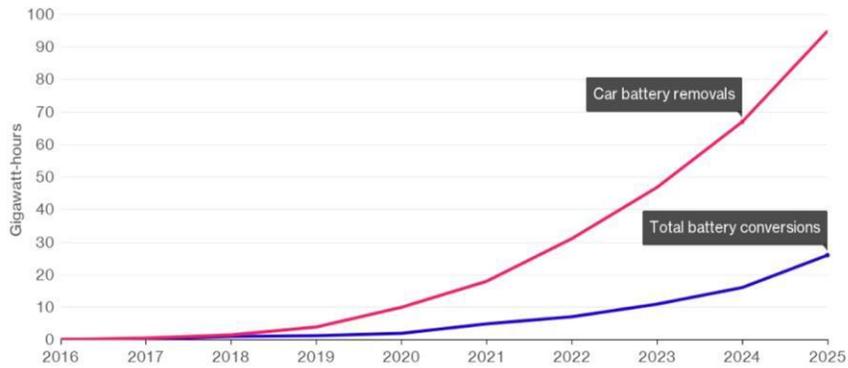


Figure 13 Potential Conversion of EV Batteries to Energy Storage Systems by 2025⁵⁷

While this figure shows the global trend and may not be directly applicable to the US, it serves to illustrate the general potential for this second use of EOL EV batteries. The figure predicts that about 1/3 of EV batteries are projected to be re-purposed by 2025. Based on the economics of reuse vs recycling discussed later in this report, and more recent publications discussed elsewhere in the report, it is our opinion that most EV batteries will be directed to reuse where practical because the economics of reuse are more favourable than the economics of recycling, as long as issues such as liability and standards can be resolved.

Figure 14 shows an energy storage facility where GM is using repurposed Chevrolet Volt batteries for energy storage from solar and wind generation at its vehicle testing facility in Milford, Michigan. The Volt batteries supply power to its Milford data center, and excess energy is returned to the grid supplying the rest of the facility. A similar scheme is in place in Japan, where Japanese trading company Sumitomo has a joint venture with Nissan Motors to reuse EV batteries.⁵⁸

⁵⁷ Kane, M. October 15, 2016. "Bloomberg New Energy Finance: 95 GWh of EV Batteries To Be Extracted From Cars By 2025." <<https://insideevs.com/bloomberg-new-energy-finance-95-gwh-of-ev-batteries-to-be-extracted-from-cars-by-2025/>>

⁵⁸ Blackman, J. September 20, 2016. "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>>



Figure 14 Energy Storage Facility Using Chevrolet Volt Batteries at GM Facility in Milford, Michigan

The University of California, Davis (UC Davis) offers another US example of spent EV batteries being used for energy storage. In January 2019, researchers UC Davis commissioned a commercial-scale assembly of used Nissan Leaf batteries to store energy from a local solar array.⁵⁹ The second-life storage

⁵⁹ Feller, G. June 25, 2019. "The Power of Reusing Electric Vehicle Batteries." <<https://www.tdworld.com/electrification/power-reusing-electric-vehicle-batteries>>

system, developed by Professor Jae Wan Park and his graduate students at the UC Davis Green Technology Laboratory, is reducing the on-peak energy use and carbon footprint of the UC Davis Robert Mondavi Institute – a combined winery, brewery, and food processing complex. The team assembled 15 used Nissan Leaf battery packs (combined energy capacity of 300kWh, or an average of 20kWh per pack) in a shipping container next to the winery, and control algorithms direct the batteries to charge with excess power from a 200kW rooftop solar system. The batteries discharge during the evening to reduce the facility’s energy use by at least 20%.⁶⁰



Figure 15 US Davis Energy Storage System⁶¹

Rivian provides another very recent and upcoming example of EOL EV batteries being used for energy storage. In June 2019, the company announced that it has teamed up with the Honnold Foundation, which funds solar power initiatives, for a project that will turn Rivian’s second-life EV batteries into an ESS for a solar power microgrid in Adjuntas, Puerto Rico, a city that was significantly impacted by Hurricane Maria in 2017.⁶² The project will use Rivian’s 135kW battery packs from its development vehicles and move them into small modules that can collect power from solar panels or other resources, reducing reliance on the grid. Rivian expects this project to launch in 2020.⁶³

Figure 16 shows how Toyota is installing EOL batteries from EVs such as Prius HEVs to power a 7-Eleven

⁶⁰ Ibid.

⁶¹ Ibid.

⁶²Fisher, C. June 14, 2019. “Rivian will repurpose used EV batteries for solar power in Puerto Rico.” <<https://www.engadget.com/2019/06/14/rivian-second-life-battery-storage-microgrid-puerto-rico/>>

⁶³ Krok, A. June 14, 2019. “Rivian’s used batteries will help support energy independence in Puerto Rico.” <<https://www.cnet.com/roadshow/news/rivian-used-batteries-energy-independence-project/>>

store in Japan⁶⁴.



Figure 16 Reused EV Batteries Power a 7-Eleven Store in Japan

Other examples of energy storage applications for EV batteries are presented in Appendix I.

4.3 Examples of EV Battery Reuse Companies

In the US and elsewhere, there are a number of companies at the forefront of the EV battery repair, refurbishment, and reuse industry, described in the following sections.

As described in Appendix E, EV battery designs vary by vehicle manufacturer. Tesla batteries are composed of multiple cells (which provides an incentive for third party actors to get into the business of re-selling each cell), while other EV batteries are made up of packs that have different use options.

Refurbishing EV batteries for reuse starts with partial disassembly of the battery pack. The next step, in the case of Tesla batteries, involves identification of cells that are no longer working, replacing them with other cells capable of holding a sufficient charge, and reassembly of the battery pack,⁶⁵ either in its original format or in a newer format suitable to the new application. This 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

⁶⁴ "First raft of EV batteries hits the end of the road. Here's where they go to 'die.'" January 18, 2019. <<https://nationalpost.com/news/first-batch-of-ev-batteries-hitting-the-end-of-the-road-so-where-do-they-go-to-die>>

⁶⁵ Elkind, E.N. September 2014. "Reuse and Repower: How to Save Money and Clean the Grid with Second-Life Electric Vehicle Batteries." <www.law.berkeley.edu/files/ccelp/Reuse_and_Repower_--_Web_Copy.pdf>

and discharging conditions during its use in a vehicle.⁶⁶ This is one of the most time-consuming steps of EOL EV battery reclamation and is one where the EV battery reuse market has opportunities for increasing efficiencies and thereby lowering costs. Spiers New Technologies (SNT) of Oklahoma City is the largest company involved in EV battery reuse in the US (further detail in Section 4.3.1). Other companies involved in battery reuse include ITAP and Smart Metals, which reuse batteries from consumer electronics. Both were contacted for this study. ITAP confirmed that they reuse EV battery components and Smart Metals indicated that they receive a minimal number of EV batteries.

4.3.1 Spiers New Technologies (SNT), Oklahoma City, US

A number of Kelleher contacts have visited SNT's plant and report that it is a very professional, well-run and impressive operation which is at scale. Members of the Kelleher team also attended a presentation made by Dirk Spiers in April, 2019.

Established in 2014 and based in Oklahoma City, SNT is one of the more prominent EV battery reuse companies in North America. According to owner Dirk Spiers, the company's mission is to 'extend the economic life of battery packs and then offer a closed loop system' for EOL management after first use. In a February 2019 article⁶⁷, Frost & Sullivan, a battery market research company, stated that SNT is the only market participant that handles repairing, repurposing, refurbishing, and remanufacturing (4Rs) of EV batteries for almost all automotive OEMs in the US. The company also engages in some cathode-to-cathode-recycling.

Most of the battery packs SNT receives come from dealers' warranty replacements as well as from test projects. The used EV batteries it receives are directed to three reuse pathways:

- Some are returned to vehicle use under a warranty replacement;
- Some are repurposed (SNT will assess feasibility of different repurposed deployments); or
- Some are broken down into their constituent parts and the materials recycled (SNT notes there is a lot of capacity for recycling EV batteries in the market in April, 2019).

⁶⁶ UL. "The Afterlife of Electric Vehicle Batteries." <www.ul.com/inside-ul/the-afterlife-of-electric-vehicle-batteries/>

⁶⁷ Frost & Sullivan. February 6, 2019. "SNT Commended by Frost & Sullivan for Leading the North American EV/PHEV Market through a Strong Market Expansion Strategy." <<https://www.newswire.ca/news-releases/snt-commended-by-frost-amp-sullivan-for-leading-the-north-american-ev-phev-market-through-a-strong-market-expansion-strategy-819629292.html>>

SNT is working to build a cradle-to-cradle solution that closes the loop with EV batteries being prepared for return to a battery function. SNT manufactures ESSs with both new and second-life battery modules and cells. From both new and reclaimed EV battery cells, SNT creates these remanufactured battery modules, packs, and storage systems for various applications:

- redeployment in vehicles;
- second-life deployment in non-vehicle applications⁶⁸ such as renewable energy sources;
- custom advanced battery pack programs for auto OEMs; and
- high-voltage power trains and ESSs for vehicles.

To accomplish its closed-loop vision, SNT has set up a number of systems⁶⁹:

- Logistics management for returned EV battery packs and modules, including monitored, climate-controlled storage, dealer network management, and EOL recycling preparation.
- Qualitative analysis and safety screening for battery packs removed from their original vehicle; this includes a root cause analysis to determine issues and to repair, if possible, for warranty returns.
- Decision-tree analysis, to decide between remanufacturing, refurbishing or repurposing, based on SNT’s custom classification and grading process, to identify packs good enough to return to vehicle use versus those better suited for second-use applications such as stationary energy storage.
- For packs with significant wear and no useful life left, a teardown process gets to smallest possible components and then recycles these to obtain metals from the li-ion cells.

Table 8 presents a partial list SNT’s clients as of April, 2019:

Table 8 Partial List of SNT Clients (April, 2019)⁷⁰

<ul style="list-style-type: none"> • Argonne National Laboratory • Audi • General Motors • Ford • Fiat Chrysler • Nissan • Habitat for Humanity • US Department of Energy 	<ul style="list-style-type: none"> • KTM • Eaton • XL • Volkswagen • Oak Ridge National Laboratory • EVgo • Greenlots • OGE Energy Corp 	<ul style="list-style-type: none"> • Dorman • Honda • Jaguar • Land Rover • Nuvation Energy • Toyota • Volvo
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⁶⁸ Reagent Power. “Dirk Spiers: Refurbishment Specialist & Bus Maintenance Partner.” <<http://regent-power.com/dirk-spiers-bio.html>>

⁶⁹ Ruoff, C. March 1, 2016. “Second life: Spiers New Technologies develops advanced battery classification techniques.” <<https://chargedevs.com/features/second-life-spiers-new-technologies-develops-advanced-battery-classification-techniques/>>

⁷⁰ Dirk Spiers, CEO, Spiers New Technologies, *Total Life Cycle Management of Advanced Battery Packs*, presented at “From Cradle to Grave: Addressing EOL Management for PV Panels and Batteries for Electric Vehicles and Energy Storage,” April 3, 2019, CA Public Utilities Commission Auditorium.

SNT appears to have one of the larger monthly throughputs of EV batteries in the US at this time. As of Q1 2019, it reports receiving 2,000-2,500 battery packs per month. From this incoming material, SNT reports they have learned that degradation of EV batteries is a relatively small problem. According to Dirk Spiers, the issues seen with EV batteries depend on the cooling system used in a vehicle and varies significantly.

All batteries that leave SNT's headquarters in Oklahoma are upgraded so they hold sufficient energy capacity for its remanufactured purpose. This level is determined by the client on a case-by-case basis. This may be 80%, or lower for other parties. About 30% of batteries received on-site are below the remanufacturing threshold, one of which is having 70-80% energy capacity. If this is the case, they are shipped to a major recycler in Europe. A notable advantage of SNT is that it is the only licensed remanufacturing company in the US that may ship batteries by airplane. In an interview with Recycling International in June, 2018 Gert-Jan van der Have (managing director of SNT's new facility in Ede, the Netherlands) stated that the company delivers around six remanufactured battery packs per week.⁷¹

In addition to reconditioning batteries for clients such as Nissan, General Motors and Ford, SNT also transforms batteries into 'watt towers' which are a smart energy storage solution that can be the primary power source for households and businesses, shown in Figure 17.



Figure 17 Speirs New Technologies Watt Tower⁷²

⁷¹ Linnenkoper, K. June 26, 2018. "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/>>

⁷² Speirs New Technologies. <http://www.spiersnewtechnologies.com/energy-storage>

SNT also has a proprietary database (ALFRED) for managing EV battery information. ALFRED is a PHP / MySQL web application that collects, manages, and processes battery and battery related information. ALFRED receives input data from a wide variety of sources including SNT test equipment, SNT proprietary battery research equipment, production operators, OEM engineers and stakeholders, dealerships, logistics companies, and major shipping companies. In a typical 24-hour time period, ALFRED manages the production of refurbished battery packs in five facilities on two continents, coordinates forward and reverse logistics to support thousands of dealerships, sends hundreds of e-mails, and provides on-demand data analysis and report generation to hundreds of users.

4.3.2 IT Asset Partners (ITAP), Chatsworth, California (US)

IT Asset Partners (ITAP) is a Los-Angeles-based electronics and EV battery recycling company. Working with the largest automotive OEMs, ITAP designs products that are customized with their OEM partners' battery chemistries and specifications using second-life BEV, PHEV or HEV battery packs. ITAP has solutions for lithium polymer, li-ion, cylindrical cells, prismatic cells, and pouch cells, laptop batteries, cellphone batteries and EV batteries and for most chemical and physical formats as long as there is a salvage ratio of reusable cells. If the batteries have any remaining life cycles, ITAP claims to be able to find the best solutions. ITAP will pick up anywhere in North America if sufficient volume is available.

Eric Lundgren, the former CEO and founder of ITAP confirmed in July, 2019 that the company is active in EV battery reuse. Mr. Lundgren noted in earlier correspondence that factories that buy cells from him want 50,000 matching cells as the minimum order quantity (MOQ), and that battery reuse works best when scaled to high volumes of similar product. ITAP finds that 90%+ of the broken batteries it receives are salvageable in some format. Aggregation of matching cells to reintegrate into new products at large scale is the key to ITAP's success.

Battery testing in the ITAP Cadex machine involves measuring the MAh and Ohm ratio to determine the life cycle and health of the cells which are graded and reintegrated into new products. For example, an 18650 cell (used in Tesla vehicles) may have been 3,000 MAh when new but when degraded to a lower level, it still has appropriate uses, for instance⁷³:

- At 2,600 MAh - it can be used in an eWheelchair;
- At 2,400 Mah - it can be used in a drone;
- At 2,200 MAh - it can be used in a solar powered video doorbell unit;
- At 1,500 MAh - it can be used in a very strong LED TorchLight.

At 1,100 MAh remaining capacity the cell is recycled for commodity value. All scrap is sent to a refinery for recycling.

Batteries that ITAP creates from cells harvested from EVs, laptops, power tools and smartphones are

⁷³ Email correspondence with Eric Lundgren, former CEO of ITAP, January, 2018

sold under the RIXI brand after being de-branded and rewrapped with the ITAP QC Grade. They are then reintegrated into new products which are branded and sold around the world.

Mr. Lundgren stressed during an email exchange that the key is to ensure that battery grades aren't mixed. He also noted that the battery packs will only work as well as their weakest link. A bad cell will bottleneck a pack, so the testing and grading process is very important.

Fiat has worked with ITAP to identify options for batteries from its electric 500e model. ITAP staff open up the battery packs and pull out the individual flat cells, test the cells to identify their current capacity, and either resells or repurposes them.⁷⁴

ITAP runs their facility in Chatsworth, California using power from salvaged solar panels mounted on the facility's roof with energy stored in battery packs comprised of reused EV cells. Plans were announced in 2017 to expand the capacity of the system to 1MW which would not only supply all the power needs of the facility but also allow it to supply emergency electricity to the local utility.⁷⁵

4.3.3 Other Battery Reuse Companies

Sybesma's Electronics, Holland, MI

Initially established as an automotive and electronics repair company, Sybesma's Electronics now also offers li-ion and nickel-based battery refurbishment, repair, and recycling services for BEVs and PHEVs. Sybesma's services include returning logistics of high voltage battery modules from dealers and dismantlers, recycling preparation, cell grading, and balancing of cells for secondary use.⁷⁶

Battery M.D. Inc., Sacramento, CA

Battery M.D., Inc. owns and operates a battery laboratory and electric, hybrid and fuel cell vehicle repair facility.⁷⁷ According to its website, Battery M.D. was selected as the exclusive battery repair company by GM, Ford, Chrysler, and Toyota for approximately 4,000 EVs from 1999 to present. In addition to performing high-voltage battery pack repairs, the company specializes in HEV battery remanufacturing (reconditioning), component harvesting and verification, and battery recycling.⁷⁸

⁷⁴ Cunningham, W. December 5, 2017. "For dead EV batteries, reuse comes before recycle." <<https://www.cnet.com/roadshow/news/for-dead-ev-batteries-reuse-comes-before-recycle/>>

⁷⁵ Ibid.

⁷⁶ Global Battery Solutions. <<http://www.globalbatterysolutions.com>>

⁷⁷ Battery M.D. <<http://www.batterymd.com/about.html>>

⁷⁸ Battery M.D. <<http://www.batterymd.com/hybridservices.html>>

4.4 Costs of EV Battery Reuse

The US Department of Energy (DOE)'s Vehicle Technologies Office funded the National Renewable Energy Laboratory (NREL) to develop a model to calculate costs of EV battery reuse – the B2U Repurposing Cost Calculator⁷⁹, which was released in June, 2015. The Excel workbook cost model allows businesses to determine capital, labour and other business costs and profitability from refurbishing PHEV batteries. While the research was carried out on PHEV rather than BEV batteries, the conclusions are likely applicable to BEV batteries as the same battery chemistries are used, but the PHEV batteries are smaller.

The main assumptions in the model are:

- Batteries would be collected from a catchment area within a round trip of 320 miles from the facility (8-hour round trip for collection);
- The facility would have a throughput of 1 million kWh each year;
- It would process 547 modules/day (200,000 modules/year);
- Capital costs are \$15 million for a 15,000 sq. ft. building;
- Labour, testing and material costs were estimated for a battery pack with a nameplate capacity of 5kWh; a nameplate energy density of 150Wh/L; nameplate specific energy of 115Wh/kg; and a mass of 43.5kg with remaining capacity of 3.5kWh at the time of repurposing; and
- The facility has 83 employees and 199 technicians.

The NREL study for which the model was constructed stated that PHEV batteries can be repurposed for as little as \$20/kWh or \$500 per battery. The model details include repurposing costs of \$24/kWh and battery purchase costs of \$20/kWh for a total reuse cost of \$44/kWh. This can be compared to new battery purchase costs of about \$350/kWh at the time the analysis was carried out. A 2017 Bloomberg report states the price of a li-ion battery in 2014 was \$540/kWh and in 2015 was \$350/kWh. By 2016 this had declined to \$273/kWh.

Industry representatives interviewed for this study felt that the dynamics of the EV battery reuse market would change when the cost of new EV batteries fell to \$100/kWh. There are differing predictions on when this might happen. Bloomberg data presented in Section 7 shows that the cost of new EV batteries is projected to be about \$94/kWh in 2024 and \$62/kWh by 2030. Meanwhile Lei Zhang, founder of Envision Energy, expects the cost of manufacturing EV battery cells to fall below \$100/kWh by 2020.⁸⁰ The same article also states that Arun Majumdar of Stanford predicts that sub-\$100/kWh prices are unlikely to occur for five to seven years (2023 to 2025).

The NREL analysis and other information reviewed for this study show a clear case for maximizing the reuse of EV batteries given the positive economics of this option compared to recycling

⁷⁹ NREL. "Battery Second Use for Plug-in Electric Vehicles." <<https://www.nrel.gov/transportation/battery-second-use.html>>

⁸⁰ Hanley, S. December 7, 2018. "Envision Energy Says EV Battery Cell Costs Will Fall Below \$50/kWh By 2025." <https://cleantechnica.com/2018/12/07/envision-energy-says-ev-battery-cell-costs-will-fall-below-50-kwh-by-2025/>

(discussed in Section 5).

While the NREL study⁸¹ and research is four years old, it provides some guidance on broad cost ranges for EV battery reuse, and the model can be easily updated with current costs. The latter is a recommendation which we make with respect to potential areas for future research.

The NREL study concluded the following regarding PHEV battery reuse in 2015:

- The most promising application was found to be to replace grid connected combustion turbine peaker plants and provide peak shaving services;
- Compared to automotive service, use in peak shaving applications would entail relatively benign duty cycles, where the second-life battery would be expected to last an additional 10 years;
- Community benefits would include: decreased cost of peaker plant operation, reduced GHG emissions and fossil fuel consumption, and deferral of battery recycling.

Some contacts interviewed for this study felt that the market for reconditioned batteries will decline as the price of new li-ion batteries drops to \$100/kWh. However, a report by Element Energy anticipates that the economics of the reuse stream will remain favorable even at a new li-ion battery cost of below \$100/kWh and that up to 70% of EOL EV batteries could enter this pathway. Concerns raised about liability and insurance risks related to reconditioned units in energy storage applications could impact these predictions.⁸²

A June 2019 report from Circular Energy Storage based in London, UK states that “the most important reason for second-life of EV batteries becoming the norm is that the values of the batteries that go into reuse are much higher than batteries sent for recycling.”⁸³ The report quotes the current value of second-life EV batteries at \$60 to \$300 per kWh, depending on the market and application. It anticipates that these values will follow the downward trend of new EV battery costs and drop to \$43/kWh in 2030. These estimates fall in line with predictions made by Bloomberg New Energy Finance⁸⁴ and by Element Energy.⁸⁵

Element Energy carried out a recent EU study on the relative economics of reuse vs. recycling of EOL EV batteries. This study predicted that in 2030, under the baseline recycling case and baseline uptake scenario, the estimated price paid by the end-customer for repurposed batteries would be \$40.4/kWh⁸⁶ compared to the purchase price of \$70/kWh for new EV batteries. The economic analysis included

⁸¹ National Renewable Energy Laboratory. Neubauer, J., Smith, K., Wood, E., and A. Pesaran. February 2015. “Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries.” <<https://www.nrel.gov/docs/fy15osti/63332.pdf>>

⁸² Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). “Design and Analysis of the Use of Re-Purposed Electric Vehicle Batteries for Stationary Energy Storage in Canada.” *Batteries*, 5(14), 1-19.

⁸³ 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

⁸⁴ Goldie-Scot, L. 5 March 2019. “A Behind the Scenes Take on Lithium-ion Battery Prices.” Bloomberg New Energy Finance. <<https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/>>

⁸⁵ 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

⁸⁶ Ibid.

consideration of extended producer responsibility (EPR) fees paid by obligated producers in Europe under various future scenarios and concluded that EV battery reuse would considerably lower the producer’s compliance costs with the legislation. As discussed in Section 7, legislation is already in place in the EU obligating producers to pay the full cost of EOL management of EV batteries. The cost components in the analysis are presented in Figure 18.

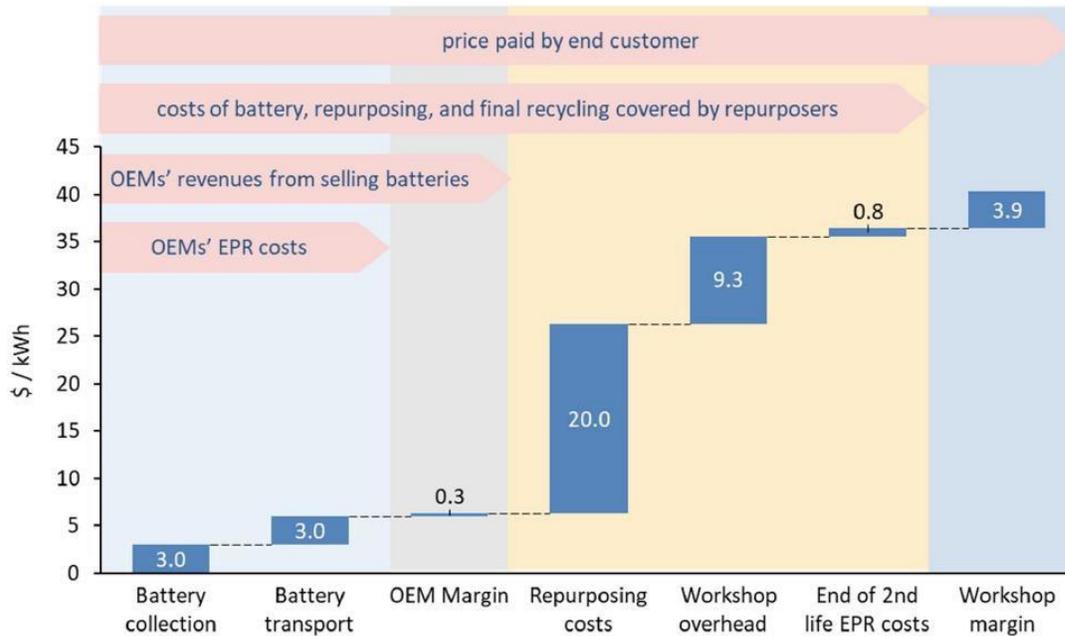


Figure 18 Cost Components for a Repurposed EV Battery in the EU in 2030

Several publications in the literature addressed the appropriate market price for second-life batteries, considering the cost of battery purchase when retired from the EV, transportation costs, logistics, testing, refurbishment costs, etc. Table 9 is taken from a report by Circular Energy Storage (2019), which has estimated costs related to various batteries and scenarios. The author, Hans Eric Melin, notes that “the area is moving very fast, which means that both cost and revenue calculations can soon only be outdated, which can also affect the actual dynamics in the market.”⁸⁷

⁸⁷ Melin, H.E., Circular Energy Storage. 2019. “State-of-the-art in reuse and recycling of lithium-ion batteries – A research review.” <<https://circularenergystorage.com/news/2019/7/9/report-for-swedish-energy-agency-about-lithium-ion-battery-research-available-in-english>>

Table 9 EV Battery Reuse Cost Estimates (Circular Energy Storage, 2019)

New Battery Price	Second Life DoD	Vehicle	Second Life Health Factor	Refurbished Battery Market Price (\$/kWh)	Used Battery Salvage Value (\$/kWh)	Cost of Refurbishment (\$/kWh)
\$250/kWh	60%	BEV75	0.33	83	51	32
		PHEV20	0.29	73	43	30
	50%	BEV75	0.72	180	131	49
		PHEV20	0.65	163	117	46
\$150/kWh	60%	BEV75	0.33	50	24	26
		PHEV20	0.29	44	19	25
	50%	BEV75	0.72	108	72	36
		PHEV20	0.65	98	64	34

4.5 Technical and Policy Issues with EV Battery Reuse

4.5.1 Additional Lifespan in Second Use

EV battery reuse keeps the battery in operation for a number of additional years and saves resources that would be required to manufacture a new battery for the same application. Generally, second-life applications are possible until the battery has 60% of its charge remaining, or is at a reasonable SoH for the application in which it has been reused.

One technical issue in evaluating policies aimed at EV battery reuse is the paucity of data on the length of time these batteries are deployed in second use applications before being recycled. There are currently no real-life examples to draw on as EV batteries have not yet been through their first or second life cycle in practice. Therefore lifespan data is 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 curves which vary significantly by battery chemistry, and the effect of capacity fade and calendar aging, among others. Many of the models used to estimate second use lifespan only consider cyclic aging (i.e. number of cycles the battery undergoes).

In a study funded by the Spanish government and presented in an academic article in the Journal of Environmental Management (February, 2019), lifespans were modeled for four potential reuse applications for EV batteries. Based on the theoretical modeling, the researchers estimated lifespans in a number of second use applications. A number of other studies have also estimated lifespans in second use applications. The dates of these studies range from 2009 to 2015, and many more studies

are currently underway on this topic. Results identified to date are summarized in Table 10.

Table 10 Lifespans Reported for EV Batteries in Reuse Applications⁸⁸

Second Life Application of EV Battery	Additional Years of Lifespan 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 applications	3-15 years and 8-20 years depending on application

Research carried out by NREL in 2015 suggested that EV batteries could last an additional 10 years in energy storage applications. Although it is now considered out of date, research published in the UK in 2014 suggested lifespans of three to 15 years for various network and energy management applications⁸⁹. A research paper published in 2019 analyzed additional battery lifespans for four different stationary applications and concluded that second life batteries used for EV charging support could last about 30 years, compared to only six years when used in a grid service application.⁹⁰

A lack of confirmed data on EV lifespans in second use is listed as a research gap for future study in Section 9 of this document.

4.5.2 Provenance and Tracking of Reused EV Batteries and Cells

Knowing the provenance of a battery cell or pack is key to understanding how it can be integrated into various reuse applications. Everledger, a UK-based company, has developed a blockchain application to track the provenance of battery cells and packs throughout their life cycles. Through the Global Battery Alliance it is using the blockchain to track EV batteries through the reuse supply chain for large auto OEMs such as Audi, as well as auto industry suppliers such as Johnson Controls and Saft.

⁸⁸Casals, 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

⁸⁹ Strickland, D., Chittock, L., Stone, D.A., Foster, M.P., and B. Price. (2014). "Estimation of Transportation Battery Second Life for Use in Electricity Grid Systems." *IEEE Transactions on Sustainable Energy*, 5(3): 795-803. <http://publications.aston.ac.uk/id/eprint/25152/1/Estimation_of_transportation_battery_second_life_for_use_in_electricity_grid_systems.pdf> DOI: 10.1109/TSTE.2014.2303572

⁹⁰ 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

4.5.3 Standards, Safety and Standardized Terminology

Currently, when an EV reaches EOL, the batteries are sent to automotive recyclers, along with the rest of the vehicle. Automotive recyclers are generally not familiar with the hazards of storing and managing EOL EV batteries and are currently unable to determine the SoH of the battery packs. Auto dealers have technicians and trained mechanics on-site who can assess and replace EOL EV batteries if needed. However, dealers often send the EV batteries to battery reuse companies, described earlier in this section. There are no established and recognized definitions and standards in place to classify repurposed batteries so that all players in the supply chain clearly understand the product performance and characteristics. This is needed to ensure product safety for repurposed EV batteries. A recent study noted the need for standardization of approaches through the supply chain.⁹¹ There are a few established, professional companies now in the EV battery reuse business who understand SoH testing. These companies do not use a standardized protocol for describing batteries in the reuse market at this time. As it stands now, only vehicle manufacturers and dealers have the ability to check the diagnostic codes displayed by the packs to assess their SoH.

As refurbishing EV batteries has become more common in the last five years or so, standardized procedures and safety precautions are slowly becoming an industry norm. Refurbishing EV batteries can put untrained workers at risk of electric shock that can result in serious injury or death. Battery systems may also contain chemicals that can be harmful to human health if released. For this reason, a number of organizations including Automotive Recyclers Association (ARA), Automotive Recyclers of Canada, and Underwriters Laboratories (UL) are putting considerable effort into training courses and safety manuals.⁹² Other groups that have contributed resources to further worker health and safety for EV battery reuse and recycling include the NREL, the Electric Power Research Institute (EPRI), the US Advanced Battery Consortium (USABC), the Fire Protection Research Foundation, and the Society for Automotive Engineers.

A series of fires at material recycling facilities (MRFs) (facilities that process recyclable materials such as paper and plastic from residential as well as commercial sources) in the last few years has raised concerns about the dangers of storing li-ion batteries. Ryan Fogelman, Vice President of Strategic Partnerships at Fire Rover which sells fire detection and suppression systems, has been tracking fires reported at waste and recycling facilities since 2016. His data show that in 2018 alone, 365 fires were reported at waste management facilities across the US and Canada, particularly MRFs processing residentially collected paper and plastic.⁹³ Fogelman notes that li-ion batteries “present an increased level of risk because they’re more difficult to control: while gas tanks can be emptied, li-ion batteries...create their own oxygen so they can start fires anywhere - in screens, in conveyors, and at any of the process.”⁹⁴

⁹¹ Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). “Design and Analysis of the Use of Re-Purposed Electric Vehicle Batteries for Stationary Energy Storage in Canada.” *Batteries*, 5(14), 1-19.

⁹² Personal communication Steve Fletcher, 17th April, 2019

⁹³ Maile, K. July 2, 2019. “Using a combinational approach to prevent facility fires.” *Waste Today*. <<https://www.wastetodaymagazine.com/article/preventing-fires-waste-recycling/>>

⁹⁴ Dust Safety Science. “DSS014: Fire Hazards in Waste and Recycling Facilities with Ryan Fogelman.” <https://dustsafetyscience.com/fire-hazards-waste-recycling-ryan-fogelman/>

The Portable Rechargeable Battery Association (PRBA) has issued a statement on reconditioned li-ion cells and batteries that outlines the safety and operational conditions which must be met for battery reuse and refurbishment to take place.⁹⁵

The EU has also issued a recent report exploring possible criteria for standards for performance and durability assessment of both first life and second-life EV batteries (in advance of a possible EU Ecodesign Regulation).⁹⁶

This EU study, with regard to second use applications, calls for a standard to:

- Define battery EOL for clarity between those working in first and second use applications, and definition of second use applications;
- Standardize criteria and guidelines for evaluating battery status (e.g., SoH), safety) and suitability for second use applications at EOL; and
- Develop guidance and standard practices on handling used batteries (e.g., for safe dismantling, storing).⁹⁷

Underwriters Laboratories UL 1974

UL published its *Standard for Evaluation for Repurposing Batteries*⁹⁸ in October 2018. This standard seeks to advance battery safety as a manufacturing process standard. The standard addresses methods used to determine the safety and performance of batteries, modules, and cells from used EV battery systems that will be repurposed into second-use battery applications,⁹⁹ such as for ESSs and other uses for the battery packs, modules, cells and electrochemical capacitors.

This ANSI-approved standard covers the sorting and grading process of battery packs, modules and cells and electrochemical capacitors. It includes application specific requirements for repurposed battery packs/systems and battery packs/systems utilizing repurposed modules, cells and other components. UL 1974 does not cover the process for remanufactured batteries (also known as refurbished or rebuilt batteries).

⁹⁵ The Rechargeable Battery Association. "PRBA – The Rechargeable Battery Association Position on Reconditioned Lithium ion Cells and Batteries." <<http://www.prba.org/publications/position-on-reconditioned-lithium-ion-cells-and-batteries/>>

⁹⁶ Ruiz V. & Di Persio F. (2018). "Standards for the performance and durability assessment of electric vehicle batteries: Possible performance criteria for an Ecodesign Regulation." <<http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113420/kjna29371enn.pdf>>

⁹⁷ Ibid.

⁹⁸ UL. "UL 1974: Standard for Evaluation for Repurposing Batteries." <https://standardscatalog.ul.com/standards/en/standard_1974>

⁹⁹ Johnson, M.H. "Energy Storage and Battery System Services." *Powerpoint Presentation*. NATTBatt 2019 Member Update. https://naatbatt.org/wp-content/uploads/2019/03/R3_MUP_UL-LLC-NATTBatt.pdf

4.5.4 Liability

Where EV batteries are repurposed for subsequent non-EV uses, there may be unresolved questions concerning liability that might flow back through to the vehicle and/or the battery manufacturers (or vehicle owner), should the batteries or cells fail in a way causing significant harm to human health or the environment. Repurposed batteries are considered a greater risk of failure, therefore one research paper published in 2019 notes that insurance premiums are higher for their use.¹⁰⁰ The paper raises the issue of liability related to second-life EV batteries stating:

As defects to the repurposed battery may cause some damage to people or property through fires or leaks, the question of who would be liable in such a situation is important. Battery and electric vehicle manufacturers develop the battery and related software and hardware to insure that the battery performs as intended in the vehicle. However, these corporations do not design their systems with the intent of third parties who would use the battery packs for second uses. If the second-life uses of the battery result in damages, then the automotive manufacturers may be liable as current regulations and standards are unclear. Because of this lack of clarity around their liability, original equipment manufacturers (OEMs) are hesitant to allow their EV batteries to be re-purposed for grid storage applications, resulting in them being recycled or sent to a wrecking yard.

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.¹⁰¹

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 explained in a recent academic paper:

*Battery and electric vehicle manufacturers develop the battery and related software and hardware to insure that the battery performs as intended in the vehicle. However, these corporations do not design their systems with the intent of third parties who would use the battery packs for second uses. If the second-life uses of the battery result in damages, then the automotive manufacturers may be liable as current regulations and standards are unclear.*¹⁰²

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, resulting in them either being recycled or sent to a scrap yard.

¹⁰⁰ Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). "Design and Analysis of the Use of Re-Purposed Electric Vehicle Batteries for Stationary Energy Storage in Canada." *Batteries*, 5(14), 1-19

¹⁰¹ Ibid.

¹⁰² Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). "Design and Analysis of the Use of Re-Purposed Electric Vehicle Batteries for Stationary Energy Storage in Canada." *Batteries*, 5(14), 1-19.

4.5.5 Variability of Chemistries and Cell/Pack Formats

Li-ion EV batteries are manufactured by many different companies with different design configurations, including variations in energy, capacity, and chemistry, as well as the number and type of cells and physical shape (see Appendix E for descriptions). 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 refurbishers nor recyclers know which kind of battery they are receiving.¹⁰³ Each EV battery has a 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 bulk¹⁰⁴, and the process of repurposing batteries necessitates reassembling them into different configurations with controllers that are unique to the application and battery.¹⁰⁵ A paper published in 2018 noted that “standardization of diagnostics, health monitoring, packing and labeling could simplify the process, but as common standards could interfere with competition between manufacturers this is a sensitive issue.”¹⁰⁶

4.5.6 Transportation and Logistics

Transport and logistics is another potential technical challenge to EV battery reuse, as used EV batteries can be classified as hazardous waste, which makes transport expensive and highly regulated. These restrictions can pose a challenge for second-life uses, as well as recycling.¹⁰⁷

The best information on this topic was found in a trade journal article where a shipping company executive explained the rules¹⁰⁸. Key quotes from these articles are summarized below.

According to Achim Glass, senior vice-president and global head of automotive vertical at Kuehne and Nagel Management, damaged EV batteries need to be classified by the shipper as either ‘damaged but not critical’ or ‘damaged and critical’.

“The differentiation must be determined based on a scientific examination of the battery, such as reading the battery protocol,” he says.

Glass says that, depending on the classification – which cannot be done by the logistics service provider – one of two different supply chain solutions is required.

¹⁰³ 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

¹⁰⁴ http://webcache.googleusercontent.com/search?q=cache:t4knY1efHZ8J:www.dot.ca.gov/sustainability/docs/2018-03-26_battery_disposal.pdf+&cd=11&hl=en&ct=clnk&gl=ca&client=safari

¹⁰⁵ Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). “Design and Analysis of the Use of Repurposed Electric Vehicle Batteries for Stationary Energy Storage in Canada.” *Batteries*, 5(14), 1-19.

¹⁰⁶ 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

¹⁰⁷ Ibid.

¹⁰⁸ <<https://www.automotivelogistics.media/still-got-it-how-reuse-and-recycling-can-give-ev-batteries-a-new-lease-of-life/37938.article>>

“The ‘damaged but not critical’ battery pack must be transported in a UN-approved container, including packaging material that prevents the evolution of heat,” he explains. “The ‘damaged and critical’ battery requires a special steel container for transportation, which includes a built-in fire extinguishing system. To uninstall the battery from the vehicle and to package the battery into the container, you need a certified high-voltage expert present, as the energy density is so high and the battery could spontaneously combust, resulting in an immediate fire. In both scenarios, the container or package must be labelled with the UN Class 9 label for lithium-ion batteries and a UN Material Data Safety Sheet must also be filled out.

If the critical battery is also classified as end-of-life (as opposed to second-life), the transport is subject to waste regulation, which requires the availability of respective licenses and, in certain cases, the approval of the relevant authorities. This includes specifying which routes can be used.

“Kuehne and Nagel has valid waste transport brokerage licenses for over 20 European countries, which is important as there is very limited capacity for the recycling of lithium-ion batteries,” comments Glass.

“That, again, results in a lot of cross-border trucking activities. National trucking companies often do not have the license to operate in another country, and violations against waste regulations are subject to high penalties and fines.”

Cross-border transport and recycling

Cross-border transport of lithium batteries is a particularly complex operation, requiring a fully documented recycling certificate.

With this in mind, environmental services provider Interseroh and waste management service provider Saubermacher have created what they say is the first global recycling service for lithium-ion batteries, known as SimpLi Return, which provides all services along the entire waste management chain.

The online portal centralises all data and documentation, giving companies the ability to follow their batteries step by step on their recycling journey. Special containers for safe transport are also provided, and batteries are packaged onsite.

“The availability of special steel containers for critical batteries is limited and the asset is up to ten times more expensive compared to the non-critical package,” continues Glass. “The transport available to move the critical battery is also limited and comparatively expensive, as legislation requires a special vehicle with special equipment and specially-trained drivers. In both cases, transport is subject to the respective dangerous goods regulations.”¹⁰⁹

¹⁰⁹ Ibid.

4.5.7 Battery Storage Technology Changes Rapidly

According to Tesla's former Chief Technology Officer, JB Straubel, one of the most significant barriers of using used PEV batteries in energy storage applications is that the technology found in these batteries will be a decade old by the time they would make it to the second-use market.¹¹⁰ He argues that used batteries will be prone to failure and won't be able to provide the reliability necessary for storage applications, and that the batteries are not designed to cycle multiple times a day (which is a characteristic required by energy storage batteries). In Straubel's view, the energy storage market will ultimately be dominated by specialty batteries as opposed to repurposed ones.¹¹¹ It should be noted that Straubel has since left Tesla to form his own battery recycling company called Redwood, mentioned briefly in Section 5 (no further details are available to date). When contacted by the Kelleher Environmental research team in March, 2019, the company representative indicated that any announcements were about six months away.

¹¹⁰ http://webcache.googleusercontent.com/search?q=cache:t4knY1efHZ8J:www.dot.ca.gov/sustainability/docs/2018-03-26_battery_disposal.pdf+&cd=11&hl=en&ct=clnk&gl=ca&client=safari

¹¹¹ http://webcache.googleusercontent.com/search?q=cache:t4knY1efHZ8J:www.dot.ca.gov/sustainability/docs/2018-03-26_battery_disposal.pdf+&cd=11&hl=en&ct=clnk&gl=ca&client=safari

5 EV Battery Recycling

5.1 High Level Description of Recycling Processes and Steps

As previously mentioned, today's EV batteries can be either NiMH (for HEVs only) or li-ion (needed for PHEVs and BEVs).

Although the exact mix of rare elements in the hydride may vary slightly, NiMH batteries all have very similar chemistry. For this reason, there is no need to differentiate among NiMH batteries, which simplifies the recycling process. Li-ion batteries contain a wider variety of materials in each cell, which makes the recycling process more complex, including:

- Zinc, lithium, manganese, copper, aluminum, steel, cobalt
- Plastic components: polypropylene, PET
- Graphitic carbon
- Solvent, electrolyte (sulfuric acid)
- Fiberglass
- Coolant/battery management system.

All of these materials must be separated from each other during recycling.

The paragraphs that follow describe the different types of processes that are currently used to recycle li-ion batteries:

Manual processes: Because EV batteries come in a large variety of formats and chemistries, the first step in EV battery recycling is to sort and identify battery chemistries based on visual inspection and/or shipping information, and direct the batteries to safe workbenches for dismantling. Trained technicians manually disassemble the battery packs to the cell or module level¹¹², with assembly pieces, wiring and circuitry separated from actual battery cells. Manual disassembly is carried out using small-to medium-sized manual and power tools, though several parties interviewed for this report mentioned that some battery packs – and even battery cells – are designed with complicated, welded casings or mechanical fasteners that deter disassembly. This makes it more difficult to prepare EOL EV batteries for further processing, which increases the costs incurred. Safety training is critical for anyone involved in storing or dismantling EV batteries. The dismantling instructions provided by the EV battery maker are the optimal source of data for the manual disassembly process.

¹¹² Email correspondence from Kathy Bruce, Senior Vice President, Retrie Technologies Ltd., kbruce@retrievtech.com, Trail, BC, with Kelleher Environmental, April 30, 2019.

Mechanical processes: Mechanical processes are used to safely remove the electrolyte and break the EV battery components apart to concentrate the metals and make them easier to process. Batteries may be fed via a conveyor into equipment like a shredder that can break the battery components into small pieces that are then directed to recycling.

Hydrometallurgical processes: This refers to the aqueous processing of the metal-containing streams, in order to recover metals. The metals output from mechanical separation (which contain cathode metals) is further chemically processed to produce a solution, which undergoes electrolysis, or other treatment, in order to separate out the dissolved metals, which results in metal salts. Companies involved in hydrometallurgical processes keep their chemical and aqueous phase formulations and procedures quite proprietary. The metal salts are marketable commodities which are sent to smelters to recover materials such as nickel and cobalt.

Pyrometallurgical processes: Pyrometallurgical processes use high temperatures to transform, separate and purify metals. Because achieving these high temperatures requires sophisticated, capital-intensive equipment with strict safety and environmental controls, pyrometallurgical extraction occurs at a smelter, not in smaller operations. There is no generic method for recycling batteries pyrometallurgically and each of the existing methods is unique to the company involved. Some facilities, such as Umicore, can process entire small-format batteries in their smelters. Alloy metals are recovered, which have greater market value than metal salts (as they require less processing to be returned to commerce).

5.2 Major Traditional Nickel and Lithium Battery Recyclers

The EV battery recycling landscape is in a state of dynamic change. At present, there is a proven suite of established technologies for EV battery recycling at a well-established stage, an area of emerging technologies in very early market stages, and an aspirational ‘dream’ technology in the research stage. In traditional li-ion battery recycling, up to 40% of the materials are not recovered. “New” battery recycling technologies (none yet at scale) aim to recover up to 90%+ of the battery materials without pyrometallurgical processes, which are energy intensive.

A research paper completed by NREL in 2016 and published in 2018, identified 23 companies globally that recycled EVs in 2016: 12 in Europe; five in North America; and six in Asia.¹¹³

¹¹³ Mayyas, A., Steward, D., Mann, M. (2019). “The case for recycling; Overview and challenges in the material supply chain for automotive li-ion batteries.” *Sustainable Materials and Technologies*, 19. <https://doi.org/10.1016/j.susmat.2018.e00087>

As shown in Table 11, there are only a few key companies serving the North America market with the established technology and capacity to process NiMH and li-Ion batteries from EVs. More detailed descriptions of Retrie, INMETCO and Glencore are provided later in this section.

Table 11 North American EV Battery Recycling Capacities in 2016¹¹⁴

Company	Location	Capacity (tonnes/year)	Batteries Processed/Recycled
Retrie	Trail, British Columbia, Canada	4,500	Li-ion
Retrie	Lancaster, Ohio, United States	4,000	Li-ion
INMETCO	Pennsylvania, United States	6,000	NiMH only
Glencore	Sudbury, Ontario, Canada	n/a	Li-ion, NiMH
Total		14,500	

Table 12 presents the capacity available in 2016 in Europe to recycle li-ion batteries. Umicore is a significant player in Europe in terms of capacity. It is the only company with European operations that accepts deliveries of EV batteries for recycling from North America (after some pre-processing to remove the outer casing and any metals than can readily be locally recycled prior to shipment). Umicore's main interest is in metals such as nickel, cobalt or aluminum contained in the cathodes. Glencore, which has a large smelter in Canada, also has a large smelter in Norway.

Table 12 European EV Battery Recycling Facility Capacities in 2016¹¹⁵

Company	Location	Capacity (tonnes/year)	Batteries Processed/Recycled
Umicore	Belgium	7,000	Li-ion, NiMH
Accurec Recycling GmbH	Denmark	6,000	Li-ion, NiMH, NiCd
Glencore (formerly Xstrata)	Norway	7,000	Li-ion
Recupyl S. A	France	110	Li-ion
AET Technology	UK	n/a	Li-ion
SNAM	France	300	Li-ion NiMH, NiCd
AkkuSer Oy	Finland	1,000	Li-ion
AkkuSer Oy	Finland	4,000	NiCd, NiMH, Zn alkaline
Batrec Industries AG	Switzerland	200	Li-ion
Euro Dieuze/SARP	France	200	Li-ion
Valdi (ERAMET)	France	20,000	Li-ion
G&P Batteries	UK	n/a	Li-ion various
Total		45,810	

¹¹⁴ Ibid.

¹¹⁵ Ibid.

Table 13 presents data on available Asian capacity in 2016. While there are likely many more players in the Asian market, the table presents those that NREL was able to identify in 2016. None of these companies are actively recycling batteries in North America at this time.

Table 13 Asian EV Battery Recycling Facility Capacities in 2016¹¹⁶

Company	Location	Capacity (tonnes/year)	Batteries Processed/Recycled
Sony Electronics Inc. Sumitomo Metals and Mining Co	Japan	150	Li-ion
Nippon Recycle Centre Corp	Japan	n/a	Li-ion, NiCd, NiMH, alkaline
Dowa Eco-System Co Ltd.	Japan	1,000	Li-ion various
JX Nippon Mining and Metals Co. Ltd.	Japan	5,000	Li-ion, various
Shenzhen Green Eco Manufacturer Hi Tech Co	China	20,000 - 30,000	Li-ion, NiMH
Hunan BRUNP	China	3,600 - 10,000	Li-ion, NiMH, various >6k t/y
Total		29,750-46,150+	

The operations of a number of recycling companies serving the North American market are described in this section. The information was compiled from a detailed literature review and confirmed through follow up interviews.

5.2.1 Retrieval

Retrieval is one of the largest EV battery recyclers in North America, receiving not just lithium but all EV batteries and chemistries, and directing them to its various facilities depending on location and capacity. The company has a corporate objective to be the best battery recycler in North America and sees battery recycling as a growth opportunity. The company's lithium battery recycling services started over 25 years ago by processing lithium primary (non-rechargeable) batteries only.

Retrieval provides prototype destruction and recycling services for battery design and manufacturing companies. The company uses its in-house database to track all cells, modules and packs received to date. Many battery manufacturers have multiple different packs depending on the vehicle for which the battery was designed. To date, Retrieval has disassembled, analyzed, and processed over 100 distinctly different battery packs for EVs, including one-off experimental designs by battery makers that did not go into full production.

Retrieval's processes for recovery from various EV battery chemistries are outlined in Table 14.

¹¹⁶ Ibid.

Table 14 Retrieval Battery Recycling Services, 2019

Retrieval Facility	Battery Chemistries and Services	Recycling Lines	Regulatory	Notes
Lancaster, Ohio, US	Processes NiCd, NiMH and lead acid chemistries. Recover nickel, lanthanum and yttrium from NiMH.	For large-format batteries. 4,000 tonne capacity ¹¹⁷	US RCRA Part B permitted TSD facility. EPA classifies it as Best Demonstrated Available Technology for Cadmium recovery.	Output is sold to rare earth, stainless steel or specialty alloy companies, e.g., aerospace applications with superior corrosion resistance.
Trail, British Columbia, Canada	Processes lithium chemistries (rechargeable and non-rechargeable) and scrap from lithium battery manufacturing	All consumer and large-format batteries. 4,500 tonne capacity ¹¹⁸	Meets all Canadian requirements	Employs 35 people. Recycling only – no reuse is done.
Baltimore, Ohio, US	Sorts and segregates alkaline, NiCd, NiMH, lead acid, lithium and less common battery types for further processing	Sorts, identifies, packages, and ships all battery types prior to recycling	LQ UW Handling facility	

Lithium Chemistries^{119 120}

Li-ion batteries are processed at the Trail, BC facility with a proprietary combination of manual and completely automated hydrometallurgical and materials separation techniques.¹²¹ As of 2018, Retrieval had processed over 25 million pounds of lithium batteries. For the large-format battery packs from HEVs, PHEVs and BEVs the process begins with manual disassembly of the battery packs by trained technicians to the cell or module level¹²². Safety training emphasizes proper equipment to avoid any mishaps. Retrieval notes that “some EV battery packs are designed in such a way as they can not be disassembled.” Design features which hamper dismantling include welded casings and mechanical fasteners that can’t be opened, and at the battery cell level, some cells are welded together or potted and cannot be disassembled.¹²³

117 The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries, Ahmad Mayyas, Darlene Steward, Margaret Mann, National Renewable Energy Laboratory. Published in Sustainable Materials and Technologies 17 (2018) e00087.

118 Ibid.

119 <http://www.retrievaltech.com/recycling/lithium-ion>

120 E-mail correspondence from Kathy Bruce, Senior Vice President, Retrieval Technologies Ltd., kbruce@retrievaltech.com, Trail, BC, with Kelleher Environmental, April 11, 2019.

121 <http://www.retrievaltech.com/recycling-technology>

122 Email correspondence from Kathy Bruce, Senior Vice President, Retrieval Technologies Ltd., kbruce@retrievaltech.com, Trail, BC, with Kelleher Environmental, April 30, 2019.

123 Email correspondence from Kathy Bruce, Senior Vice President, Retrieval Technologies Ltd., kbruce@retrievaltech.com, Trail, BC, with Kelleher Environmental, March 23, 2019.

The mechanical phase feeds separated cells and smaller packs (e.g., laptop, power tool, and cell phone) by conveyor to an automated hammer mill crusher. The crusher operates under a lithium brine process solution to prevent fugitive emissions and to reduce the reactivity of processed batteries. This dissolves electrolyte and lithium salts. The process stream is then separated from the li-ion “fluff”, which is a mixture of plastics and some steel. If the steel content is sufficient the fluff is sent for steel recovery, otherwise it is disposed. The steel content can be as high as 65% depending on the feedstock.

The process stream then passes through a shaker table to produce a copper cobalt product (a mixture of copper, aluminum and cobalt). This product is sold to primary metal producers. The slurry is then added to a mix tank and/or holding tank. The slurry is passed through a filter press to produce a cobalt filter cake (a mixture of cobalt and carbon), which is sent to a cobalt smelter, generally Glencore in Sudbury, Ontario, the only cobalt smelter in North America. There are no effluents or discharges from these water-based lines; all process water is re-circulated and cleaned up.

The remaining slurry is sent to the primary process line to recover lithium in the form of lithium carbonate. Cryo-milling (low-temperature processing) is carried out for lithium primary processes only. Some batteries are frozen in liquid nitrogen to lower the reactivity of the batteries as they go through the shredding process. The acidic cathode components are neutralized with sodium hydroxide if necessary. After removal of debris and carbon, lithium is precipitated from solution as lithium carbonate. There is no freezing in Retrie’s li-ion process.

Four output streams are produced:

- Copper cobalt product (copper, aluminum, and cobalt);
- Cobalt filter cake (cobalt and carbon);
- Li-ion ‘fluff’ (mix of plastics and some steel); and
- Lithium brine (dissolved electrolytes and lithium salts).

The technical-grade lithium carbonate (>99% purity¹²⁴) that is produced at the Trail, BC facility is generally sold to a steel manufacturer.

The estimated recycling efficiency rate through the process ranges from 65% to 80% of the incoming battery weight depending on the batteries processed.

Retrie generally receives a battery pack from a supplier or manufacturer for initial analysis. A full report is issued on the steps and time required to disassemble the pack down to the cell level, which are all processed within Retrie’s Trail, BC facility. Retrie conducts a full analysis on each cell to determine the contained metal values, which are used in the valuation process. Depending on metal content and current metal market values, it is then determined if a tipping fee (sometimes referred to as a gate fee or charge) must be charged to the battery owner or whether a credit is owed to account for the fact

¹²⁴ Prices are not readily available publicly, but have been \$1,500 to \$4,500 per tonne in the past.

that the material revenues covered the recycling costs. As a result of today's comparatively low values for nickel and cobalt, a tipping fee is now charged for most li-ion batteries, whereas in the past these batteries were sometimes processed for a credit where the generator was paid for the metal value minus a processing fee.

Nickel Chemistries¹²⁵

Retriev's recycling of NiMH batteries focuses on recovering the valuable nickel components using a proprietary pyrometallurgical process for component separation. Physical disassembly of large format, industrial-type NiMH batteries occurs on a manual line. Anode and cathode plates are separated and consolidated by material type, and sent on to additional metal refining. In the pyrometallurgical process, nickel-containing batteries are heated to a temperature enabling cadmium recovery and final removal of all battery separator materials. The constituent materials are captured using engineered environmental controls. Resulting marketable outputs are cobalt-nickel filter cake and a nickel-enriched iron material that can be reused as a raw material in many applications, including stainless steel production. All other hazardous elements are recovered and managed in compliance with regulatory requirements.

Other Services

In addition to recycling EV batteries, Retriev offers the following services to automakers engaged in selling and servicing EVs:¹²⁶

- Specialized facilities for storing and maintaining new or unused EV batteries for replacement;
- Trained dedicated personnel who coordinate return of non-functioning EV batteries and new EV battery replacement;
- Logistics services for a variety of customers;
- A consulting services division related to EV battery recycling, safety and staying ahead of regulations; and
- A research and development (R&D) division in Folcroft, PA.

5.2.2 Umicore

Umicore is a global mining and metallurgy company working on EV battery recycling as well as recycling of other large quantities of metal waste. The company has 48 production and 14 R&D sites around the globe with over 10,000 employees. Umicore recently invested €660 million in China and Europe to bring its total processing capacity to at least 175,000 metric tons by 2021. As a mining company, it sees EV batteries as a critical source of cobalt, and is recycling EV batteries in its industrial-scale pilot plant in Europe, which has a

¹²⁵ <http://www.retrievtech.com/recycling/nicad-and-nimh>

¹²⁶ <http://www.retrievtech.com/batteries/electric-and-hybrid-vehicles>

rated capacity of approximately 7,000 tonnes/year.¹²⁷

In email correspondence during study research, Umicore representatives confirmed that 7,000 metric tonnes is the rated capacity on a yearly basis for processing li-ion and NiMH battery materials which include consumer battery material, automotive battery material, storage battery material and battery manufacturing scrap. Umicore does not comment on the actual throughput but can confirm that the majority of the material processed today is consumer type batteries and battery manufacturing scrap. The Hoboken smelting facility is an industrial prototype for Umicore to test out the technology. Umicore is committed to serve the end of life battery material industry as they supply cathode materials directly to battery manufacturers. When the flow of end of life batteries coming from the automotive applications reaches a critical quantity, Umicore will invest in larger facilities that would have capacities of 70,000 metric tonnes yearly in three regions: North America, Europe and Asia¹²⁸.

Umicore uses a combination of pyrometallurgy and hydrometallurgy to recover rare earth elements, cobalt, nickel, and copper from spent EV batteries. Umicore has four drop-off points for EV batteries in North America and a consolidation facility for EV batteries in Raleigh, North Carolina which accepts both NiMH and li-ion batteries from EVs of all types including buses and e-bikes.¹²⁹

Dismantling of EV batteries is carried out manually in Umicore's Hanau, Germany facility, to remove metals which can easily be recycled locally (steel casings and copper wiring). After pre-treatment and dismantling (to the module or cell level), battery packs and/or battery cells (depending on size) are consolidated for shipment to the Umicore facility in Hoboken, Belgium where they are processed in the Umicore smelter (which is a patented high-temperature design). Outputs from the smelter's pyrometallurgical process include:

- Slags, which include aluminum, manganese, lithium and rare earth metals; and
- Alloys, which contain cobalt, nickel, copper and ferrous metal.

Some slags are used in construction projects. Slag from li-ion batteries can be integrated in standard lithium recovery flowsheets, and slag from NiMH batteries can be processed to recover rare earth elements concentrate that is further refined through a cooperation with Solvay. Alloys (specifically designed for Umicore's downstream hydrometallurgical process) are sent for alloy refining in Olen, Belgium and from there are sold to battery manufacturers to make active cathode materials for new rechargeable batteries.¹³⁰ The smelter includes specially designed gas treatment (a confidential Umicore design) to ensure full dust removal and no formation of volatile organic compounds.

Lithium is not currently recovered from the slag, as it does not make economic sense to do so. Should the price of lithium increase in the future, Umicore would evaluate additional processes to recover

¹²⁷ Umicore presentation, March 2019, NAATBatt International Annual Meeting & Conference, Arizona, https://naatbatt.org/wp-content/uploads/2019/03/R1_MUP_Umicore.pdf. and confirmed through communication with Mark Caffaray of Umicore by email August, 2019

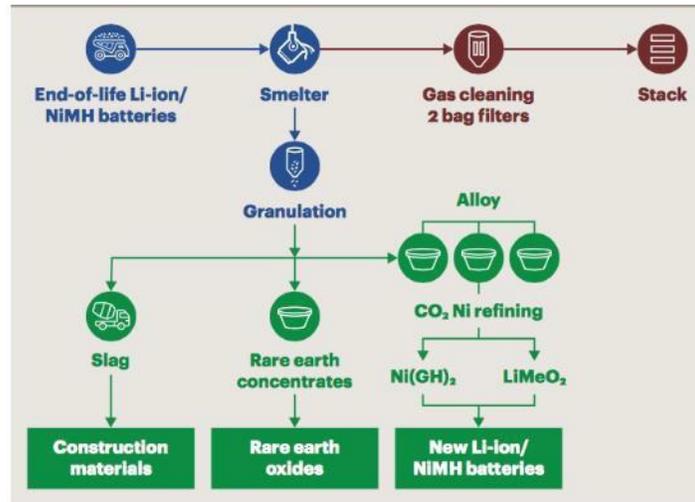
¹²⁸ E-mail correspondence with Mark Caffarey, President of Umicore USA, August, 2019

¹²⁹ Umicore. "E-mobility." <<https://csm.umicore.com/en/recycling/battery-recycling/e-mobility/>>

¹³⁰ Umicore. "Our recycling process." <<https://csm.umicore.com/en/recycling/battery-recycling/our-recycling-process>>

lithium in a pure form. Ultimately, when EOL EV battery volumes are sufficiently high, Umicore plans to locate three facilities globally (one in each of Europe, North America and Asia) to consolidate EV batteries for shipment to Belgium.

Figure 19 depicts Umicore’s process for battery recycling. In 2012, Umicore’s recycling technology was awarded with the European Business Award for the Environment in the process category for the best available technology (BAT) at that time for the recycling of rechargeable batteries.¹³¹



Note: (GH)₂ in the schematic should be Ni (OH)₂ – nickel hydroxide

Figure 19 Schematic of Hoboken, Belgium Umicore Facility Process

5.2.3 INMETCO, Pennsylvania (US)

INMETCO (International Metals Reclamation Company, LLC) is located in Ellwood City, Pennsylvania, 35 miles northwest of Pittsburgh. The company is a subsidiary of American Zinc Recycling Corp. and has been in business since 1978. It is a fully permitted recycling facility with US RCRA (Resource Conservation and Recovery Act) Part B hazardous waste storage status and up-to-date state regulatory compliance.¹³²

INMETCO purchases and processes NiMH batteries (used in HEVs such as the Toyota Prius) only (company staff confirmed by phone in mid-May, 2019 that they do not accept or handle li-ion batteries for EVs). The costing structure for EV battery recycling and processing depends on the battery and the value of the recovered metal. The company generally provides a credit for nickel- based batteries if the

¹³¹ <http://aip.scitation.org/doi/pdf/10.1063/1.4961898>

¹³² <http://azr.com/inmetco>

value is sufficiently high.¹³³

Nickel, chrome, and iron from EOL NiMH batteries are all recycled at INMETCO, and are processed and reclaimed into a stainless steel remelt alloy product. The input is mixed with coke and sent through a two-step furnace (rotary hearth). The output is a 25-lb (11-kg) metal bar (referred to as a “pig”), which is 13% nickel and 13% chrome, with the balance consisting of iron. The nickel and chrome are expensive and are essential to the stainless steel-making process. Any battery with nickel is therefore valuable to IMMETCO.

5.2.4 Glencore-Sudbury Integrated Nickel Operations, Sudbury, Ontario (Canada)

Sudbury Integrated Nickel Operations (INO), a subsidiary company of global mining company Glencore (which merged with Xstrata in 2013), operates a large nickel and copper smelter in Sudbury, Ontario.¹³⁴ The smelter’s capacity is 550,000 tonnes/year and it can produce 95,000 tonnes/year of nickel, copper and cobalt matte.

While Sudbury INO has historically processed mostly small portable batteries, it is now handling large-format EV batteries as well. EV batteries do not represent a significant percentage of what Sudbury INO processes, but are a niche market that it wants to grow, specializing in cobalt-bearing batteries (the company invested \$30 million in a rotary kiln incinerator to allow the processing of a wider range of battery types.).

Batteries are processed either by direct introduction to a converter, or to a rotary kiln. Processing options for loads of batteries packaged in plastic are limited by the flammability of the plastic; these loads are directed to the rotary kiln where plastics are burned off, and all off-gases are treated through the afterburner to ensure that no dioxins are released.

The company usually asks collectors to pre-treat the batteries to de-activate them, as well as break them down into small components (battery packs with 6 or 12 cells, or individual battery cells) due to the input feed size limitations of the rotary kiln. The cells or packs, once suitably sized, are introduced to the kiln/calcliner for metals recovery in a pyrometallurgical process.

The temperature in the molten metal bath is 1300 degrees Celsius. Lithium is captured in the slag (and is lost), and cobalt goes to the matte phase, where matte is produced through a hydrometallurgical chlorine process. Sudbury INO ships the cobalt matte to Glencore’s Nikkelverk Refinery in Kristiansand, Norway for further treatment.¹³⁵

Glencore has stringent safety policies for evaluating new materials. They have put pressure on large battery designers and manufacturers to consider EOL when designing batteries and new battery

¹³³ INMETCO. “Battery Recycling.” <<http://azr.com/inmetco/products-recycling/battery-recycling/>>

¹³⁴ Glencore. “Who We Are: Our history.” <<https://www.glencore.com/who-we-are/our-history>>

¹³⁵ Sudbury Integrated Nickel Operations. “Recycling.” <http://www.sudburyino.ca/en/recycling/Pages/home.aspx>

chemistries.

Compared to the smaller format batteries it is used to processing, Sudbury INO considers EV batteries to present a much higher risk because of the range of chemistries involved. As an example, the LFP battery (manufactured by A123) is very different from other li-ion battery chemistries, and does not contain a lot of metals of interest to Glencore. As a result, the company would not process these batteries unless they were paid to do so (through a tipping fee, or treatment charge).

Sudbury INO charges a “treatment charge” for processing. It offers a significant cobalt credit back to customers sending batteries. When a load comes in, staff have a rough idea of what the cobalt content should be, but Sudbury INO pays based on an assay carried out at an on-site laboratory. Some lithium batteries used to contain 18% to 22% cobalt if the plastic is taken away, but this number is dropping rapidly.

5.2.5 Battery Solutions, Wixom, Michigan (US)

Based in Wixom, Michigan (formerly Howell, MI), Battery Solutions collects and processes EOL batteries (50 million pounds last year) and repurposes the secondary commodities for reuse in steel manufacturing, agriculture, and new battery manufacturing, among other applications.¹³⁶ Every battery they collect is identified, classified, and manually sorted. In addition to manual sorting, the company claims to be the first and only North American based company using automated battery sorting and data collection technology.¹³⁷ This technology allows them to sort batteries based on any criteria they select (i.e., chemistry, brand, commercial demand).

With regards to processing, Battery Solutions recycles several types of batteries, including portable batteries, stationary and backup batteries, special purpose batteries, and EV batteries. The company has its own fleet and a nationwide network of more than 200 service providers who can provide on-site service, removal, packaging, and transportation and recycling. Once picked up, EV batteries are disassembled in a way that ensures that each piece of the battery, including the housing, electronics, and wiring are separated and recycled in a compliant manner.¹³⁸

For li-ion batteries, the company uses a specialized “room temperature, oxygen-free” mechanical process to separate the battery components into three end products: a) cobalt and lithium salt concentrate; b) stainless steel; and c) copper, aluminum, and plastic. All of these products are sold to manufacturers to be reused in new products.¹³⁹

For NiMH batteries, Battery Solutions removes the plastics from the cell portion prior to the recycling

¹³⁶ Battery Solutions. “About Us.” <<https://www.batterysolutions.com/about/>>

¹³⁷ Battery Solutions. “Sorting.” <<https://www.batterysolutions.com/capabilities/sorting/>>

¹³⁸ Battery Solutions. “HEV & EV Batteries.” <<https://www.batterysolutions.com/services/hev-ev-batteries/>>

¹³⁹ Battery Solutions. “How are Batteries Recycled?” <<https://www.batterysolutions.com/recycling-information/how-are-batteries-recycled/>>

process. The cells go through a drying process to remove moisture from the cell. Once the cells are dried, they become a valuable feedstock for the stainless steel and/or alloy manufacturing industries. The metals and plastic are then returned to manufacturers to be reused in new products.¹⁴⁰

Battery Solutions staff confirmed through email during project research that they serve multiple automotive customers for EV/HEV battery recycling.

5.2.6 Raw Materials Company Inc. – Port Colborne, Ontario (Canada)

Raw Materials Company Inc. (RMC) is a private corporation that operates a battery handling and recycling facility in Port Colborne, Ontario and a collection facility in Buffalo, New York. RMC accepts all battery chemistries, including large-format EV batteries, but processes only alkali batteries on-site in Ontario. US loads can be consolidated into one notice-for-Environment-Canada report at the Buffalo, New York location and then shipped across the US border to Port Colborne, Ontario for management. RMC accepts NiMH and li-ion batteries from EVs, generally received from auto dealers or parts companies. Neither NiMH or Li-ion batteries are processed on-site, but are sent to proprietary downstream partners for recycling. RMC pays for NiMH batteries and sometimes for li-ion batteries, depending on chemistry. The company charges a fee for non-cobalt-containing lithium batteries.¹⁴¹

In 2016, RMC signed a contract with Refind Technologies (a technology company based out of Gothenburg, Sweden) for three OBS600 optical battery sorters. The machines (the first of which was delivered and installed in early summer 2017) are capable of recording the brand and chemistry types of the batteries it sorts, providing valuable market share data back to RMC. The units work in parallel to sort 30 batteries per second or 1,800 kg/hour, greatly increasing the throughput of batteries processed at the facility.

5.2.7 EV Battery Recycling by Tesla¹⁴²

Tesla plans to offer a complete closed-loop solution for EOL management of the batteries from its EVs, in which it wants to take-back its own batteries for recycling. The supply risk for materials such as nickel, manganese and cobalt is identified by the US government and research is on-going on how to develop domestic sources of these materials. It is believed by the study team that Tesla has assessed that sourcing battery materials from EOL is more important to the company than revenues it could gain from reusing the cells. While not publicly stated at this time (August, 2019) it is considered likely that Tesla is using a direct recycling, cathode-to-cathode technology (discussed later in this section) to recover higher value materials from cathodes for direct use in battery manufacture.

¹⁴⁰ Ibid.

¹⁴¹ Personal communication with Andrew Paupst, Raw Materials Company, May 22, 2019. 905-835-1203 apaupst@rawmaterials.com.

¹⁴² Jon Weisman, Global Supply Chain & Battery Cell Supply Chain Manager (Battery Engineer), Tesla, *An Automaker and Solar Developer's Perspective*, presented at "From Cradle to Grave: Addressing EOL Management for PV Panels and Batteries for Electric Vehicles and Energy Storage," April 3, 2019, CA Public Utilities Commission Auditorium.

Tesla is investing in a fully closed-loop operation for its li-ion batteries. It will manufacture batteries for its products in its Reno, Nevada facility, sell the batteries in its EV, stationary storage, and solar applications, take them back when the charge is too depleted for first use, and then recycle the materials into new batteries. The company hopes that using recycled materials will reduce the cost of battery manufacturing. Tesla does not show interest in reuse at this time, and its goal is to recover as much of the battery's value and materials as possible. Figure 20 shows Tesla's closed-loop vision for the li-ion battery life cycle. A request was sent to Tesla regarding the planned capacity of the facility but no response was received.

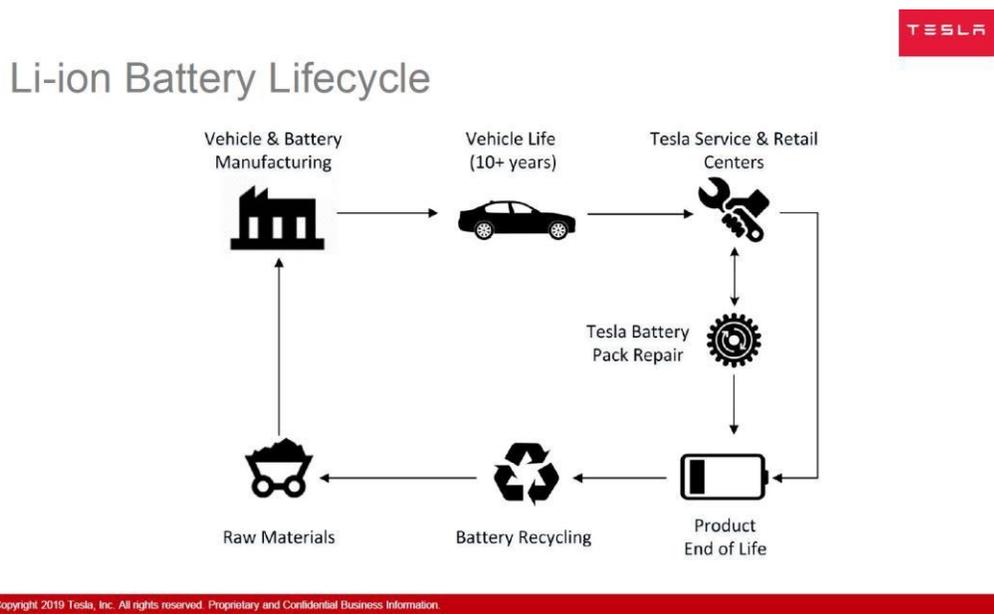


Figure 20 Tesla's Closed Loop Vision for its Battery Life Cycle¹⁴³

Tesla anticipates a 10-year life for both its vehicles and their batteries but notes that it is still determining the actual real-world EOL behavior of the batteries. Tesla has its own service centers, where it services vehicles and batteries exclusively and where its trained technicians can repair parts of a battery pack.

Tesla is primarily recovering its own factory floor scrap from its battery manufacturing. For the returned EV batteries, first it discharges and renders the battery inert and then the batteries are disassembled. The next step is mechanical destruction or separation techniques, where Tesla's highest priority is the recovery of critical cathode materials (nickel, cobalt, and lithium), which are returned to elemental form for use in new EV batteries. Tesla also recovers aluminum, copper, steel, and other metals. The company prefers hydrometallurgical processes, which they note result in lower emissions and higher recovery rates. Tesla is currently using a series of vendors in North America for the

¹⁴³ Weisman, J. April 3, 2019. "Tesla LIB and PV Recycling Programs." PowerPoint Presentation.

discharge and disassembly of its batteries. Nickel and cobalt recovery are carried out for Tesla by a third-party refinery now, but the company hopes to soon centralize vertical integration for all battery recycling at its factory in Nevada. Figure 21 shows Tesla’s current process flow for its battery recycling efforts, with an architectural drawing of the planned Reno, NV battery manufacturing and recycling facility.



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Figure 21 Tesla Battery Recycling Program in Reno, Nevada

5.2.8 SungEel MCC Americas (SMCC), Endicott, New York (US)

In September, 2018, Empire State Development (ESD) announced a \$1.75 million grant for SungEel MCC Americas (SMCC), a partnership between South Korean recycling company SungEel HiTech and White Plains-based electronics recycler and broker Metallica Commodities Corp., to establish a new li-ion battery recycling facility at the Huron Campus, formerly the IBM-Endicott complex.¹⁴⁴

According to its website, SMCC is the US’s “first and only chemical-based recycler of li-ion batteries.” The company claims to offer the following services:

- Efficient process for li-ion battery recycling
- Complete battery life cycle solutions – SMCC will collect, safely store and discharge, process, and recycle spent batteries
- Partnerships with manufacturers and retailers who are legally required to collect spent li-ion batteries

¹⁴⁴ Empire State Development Announces \$1.75 Million to Create New Lithium-ion Battery Recycling Facility.” September 27, 2018. <<https://esd.ny.gov/esd-media-center/press-releases/empire-state-development-announces-175-million-create-new-lithium>>

- Collection partnerships with communities, schools, colleges, and waste management agencies.

With a processing capacity of 5,000 tonnes of li-ion batteries per year, the new recycling site will complement the Imperium3 New York, Inc. giga-factory in Endicott, which will make li-ion batteries. SungEel HiTech will provide the recycling technology and Metallica Commodities Corp. will broker incoming batteries and the products of the new business. SMCC says the recycling facility will create over 100 research, engineering, and manufacturing jobs.¹⁴⁵ In total, the company will invest \$22 million on specialized M&E and \$1.3 million on construction and renovation. Very little information is available since the initial announcement.

5.2.9 Battery Resourcers, Worcester, Massachusetts (US)

Founded in 2015, Battery Resourcers, a spin-off of Worcester Polytechnic Institute (WPI) based in Worcester, MA, has developed a recycling process with an exclusive license from WPI that recovers cathode materials from a mixture of EOL li-ion batteries. It involves both physical separation and hydrometallurgical processing. Battery Resourcers' process begins with discharging and shredding the batteries into small pieces. Sieves are then used to separate the metals (steel, copper, aluminum, graphite) and plastics from the powders, which include the cathode materials. The powders then enter a proprietary hydrometallurgical process that recovers lithium, nickel, manganese, and cobalt by chemical leaching. The pH of the leached solution is adjusted to remove impurities and precipitate out new cathode materials.

Battery Resourcers' process to recycle li-on batteries (regardless of size, shape, or chemistry) is done at low temperatures and without creating toxic waste while recovering over 90% of the battery and 70% of the battery material value. As stated in a February 2017 article by the National Science Foundation, "a unique feature of Battery Resourcers' hydrometallurgical process is that the ratio of nickel, manganese, and cobalt can be adjusted, which allows a diverse stream of li-ion batteries to be recycled and a consistent NMC end product to be recovered, such as NMC 532 or NMC 111." The company reports that the NMC 532 and NMC 111 it has recovered on a lab scale has the same impurity concentrations, density, and electrochemical properties as commercial materials.

This technology was initially developed in 2012 in the lab of Yan Wang, William Smith Foundation Dean's Associate Professor of Mechanical Engineering at WPI. In 2018, led by CEO Eric Gratz, the WPI team scaled the technology from the bench scale, 50 kg of end-of-life batteries per batch, to the pilot scale where the current facility can process 500 kg of EOL batteries per day (equivalent to one EV battery pack per day). The pilot plant is processing batteries from major vehicle OEMs as well as production scrap from

¹⁴⁵ New York Battery and Energy Storage Technology Consortium. November 20, 2018. "NY-BEST Newsletter – November 20, 2018." <<https://www.ny-best.org/newsletter/ny-best-newsletter-november-20-2018>>

leading battery manufacturers. The next step is to open a facility to process 5 tons/day of EOL EV batteries, scheduled to come on line in early 2020.

5.3 Developing EV Battery Recycling Technologies and Businesses

Traditional li-ion battery recycling focuses on recovering the cathode metals (nickel and cobalt in particular) in metal form. Decisions on recovering other materials depend on metal content of various side streams from the process (e.g., fluff with 65% steel) and available markets. Various slags produced from the recycling operation are either used for construction or landfilled. Plastics are either burned or landfilled but are not recycled and the graphite is not recycled. The metals recovered from the processes are sent to smelters for further recovery through pyrometallurgical processes. The recovery through the process is generally around an average of 50% measured by weight, but ranging from 40% to 80% depending on metal content and markets.

A number of new recycling technologies are in development at this time with the expressed objective of achieving higher recovery (quoted by different companies as >90%) of various metals (nickel, cobalt, copper, aluminum, etc.), but ideally in a form suitable to sell directly back to battery makers, and without the pyrometallurgical step which is energy intensive. The approach used by these new companies is referred to as direct recycling or cathode-to-cathode recycling.

Selling directly to end markets avoids having to send the batteries to smelters first, allowing the recycling company to make much higher revenues. The “new” recycling companies also claim that they will recycle the plastic and graphite. Discussions with Panasonic staff as part of this project indicated that the graphite used in battery production is so pure it would be unlikely that recycling back to batteries is viable, although the graphite might be used in other industries. Discussions with Li-Cycle staff confirmed that recycling graphite still needs considerable R&D. Some of the new companies will take the complete EV battery and tear it down to its various components (which will be recycled in traditional markets) and then take the cathodes to high value recycling, whereas other companies (e.g., American Manganese) are only interested in the cathode materials.

Many new li-ion battery recycling technologies are at the R&D or early commercialization stage, but none are yet operating at scale. In general, details of the technologies used (mostly all hydrometallurgical processes) are not known and considered confidential. Numerous players are involved in research in the area of recycling EV batteries to achieve higher yields (higher than the current 50% level). These include universities, combinations of universities and private sector companies, auto or battery companies, and government supported research in the US, Canada and overseas.

A few companies in the “new” EV battery recycling business are described in the sections that follow. The information presented was collected through a combination of literature review, attending presentations by company representatives, reviewing videos of presentations by company representatives and interviews with representatives of the companies involved, including CEOs, members of the Board of Directors, technical staff or those helping to raise financing for the companies. The descriptions show the range of efforts being made by different companies to establish new EV battery recycling businesses achieving higher recovery of materials in EV batteries, and also that there are common elements in the approach used by each of the companies

The area of most research interest is cathode-to- cathode or direct cathode recycling.

Various processes are used to recover cathode materials from EOL EV cathodes as a chemical combination which can be sold back to battery makers, rather than recovering some form of metal which is then sold back to refineries for further processing. Recoveries quoted by these companies are from the cathode material only, rather than as a percentage of the full battery. These companies (a few of which are described later in this section) are most interested in just receiving the cathodes recovered from another company who would dismantle the EV battery and remove the BMS and outer casings.

Cobalt is the most valuable metal in the EV battery at this time. One factor which makes the EV battery recycling business complex is efforts by vehicle and battery OEMs to reduce the cobalt content of EV batteries. Panasonic has already reduced the cobalt content of the cells in Tesla batteries to 3% and hope to soon create a battery cell with no cobalt. While this will decrease the cost of EVs (one of the factors needed to increase EV adoption), it eliminates the incentive for recycling companies to get involved in recycling EV batteries as the high revenue stream from metals recovery will be reduced.

5.3.1 American Manganese Inc.

American Manganese¹⁴⁶ is based in Surrey, British Columbia, Canada and has been in business since 1987.¹⁴⁷ The company has manganese mining operations in Arizona and started the recycling business as a result of testing new ways to recover more manganese (one component of EV batteries) from mining deposits. For many years, American Manganese has been involved with the US Bureau of Mines to identify methods of recovering manganese from low-grade deposits. Manganese is an essential element required for the steel industry and because most manganese-producing countries are considered a supply risk for the US, developing domestic reliable sources is a high priority. For this reason, manganese, along with some other metals found in li-ion batteries, is on the US critical metals list.

¹⁴⁶ <https://americanmanganeseinc.com/>

¹⁴⁷ It is a public company traded on various stock exchanges (TSX.v:AMY; OTC US: AMYZF; FSE:2AM). It has a market cap \$32.4 million undiluted; \$39.9 million diluted, with 161.8 million shares (25 million held by insiders). The share price has fluctuated from \$0.13 to \$0.35 in last 12 months.

American Manganese is part of a consortium involved in the *Lithium Ion Battery Disassembly, Remanufacturing and Lithium and Cobalt Recovery Project* lead by the Critical Materials Institute (CMI) which in turn is an Energy Innovation Hub, led by Ames Laboratory and supported by the US DOE, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office. Other partners in the consortium include Oak Ridge National Laboratory (ORNL), Idaho National Lab (INL)¹⁴⁸, Purdue University, and Case Western Reserve University.

The company signed a MOU with Battery Safety Solutions (BSS) of the Netherlands in December, 2018 to use BSS technology to discharge li-ion EV batteries.¹⁴⁹ After discharging the batteries, American Manganese processes the cathodes for direct cathode, or cathode-to-cathode recycling. Their current efforts are focused on NMC and NCA chemistries. They take metal salts of nickel, cobalt and manganese, recover these from cathodes and reformulate the recovered chemical mixtures to meet battery manufacturers' specifications. This reduces production costs for the battery manufacturers, as a reported 50%+ of the material costs in EV batteries is from the cathode.¹⁵⁰

American Manganese's li-ion process originated from the development of the company's Artillery Peak manganese property in Arizona. The Company contracted Kemetco Research Inc. to develop a process that could recover electrolytic manganese metal (EMM) economically from a low-grade (2-3%) manganese deposit. Kemetco was successful, and also was able to successfully produce working li-ion battery prototypes utilizing the chemical manganese dioxide (CMD) from Artillery Peak.



Figure 22 American Manganese Electrolytic Manganese Dioxide Recovery Pilot Plant (by Kemetco) for Low-Grade Manganese Ores

¹⁴⁸ Located in Idaho Falls, Idaho, the nation's leading center for nuclear energy research and development performs work in energy systems, national security, science and environment.

¹⁴⁹ Fitzgerald, D. December 11, 2018. "American Manganese takes step toward forming lithium-ion reuse partnership with Battery Safety Solutions." <<https://ca.proactiveinvestors.com/companies/news/210991/american-manganese-takes-step-toward-forming-lithium-ion-reuse-partnership-with-battery-safety-solutions-210991.html>>

¹⁵⁰Personal communication Larry Reaugh, CEO and Zarko Mesaldzija, CTO, American Manganese, 1st August, 2019

This research provided momentum to continue developing the hydrometallurgical pilot plant in Figure 28. The process has since been patented under US Patent No. 8460681, Canada Patent No. 2808627, Chinese Patent No. 201180050306.7, and Republic of South Africa Patent No. 2013/01364.

Key aspects described in the US patent application (awarded December, 2018) are:

- Treatment of several cathode chemistries such as LCO, NMC and NCA.
- Methods for achieving 100% recoveries of cobalt, nickel, manganese, aluminum for all cathode chemistries tested.
- Method for achieving 100% lithium recovery by a novel locked cycle process.

The US Patent examiner deemed American Manganese’s technology “novel” and “inventive” as it enables the recycling of valuable cathode metals (namely cobalt, nickel, manganese, aluminum and lithium) while converting these materials back to fresh cathode materials for manufacture of new li-ion batteries. Staff interviewed for this project indicated that approval of the first patent took 13 months, as the patent office needed to carefully search and confirm that no other companies were doing something similar. The second patent took 81 days, considerably shorter as the Patent Office was comfortable that no other company was doing exactly the same thing.

A simplified flow sheet of American Manganese’s recycling process is illustrated in Figure 23.

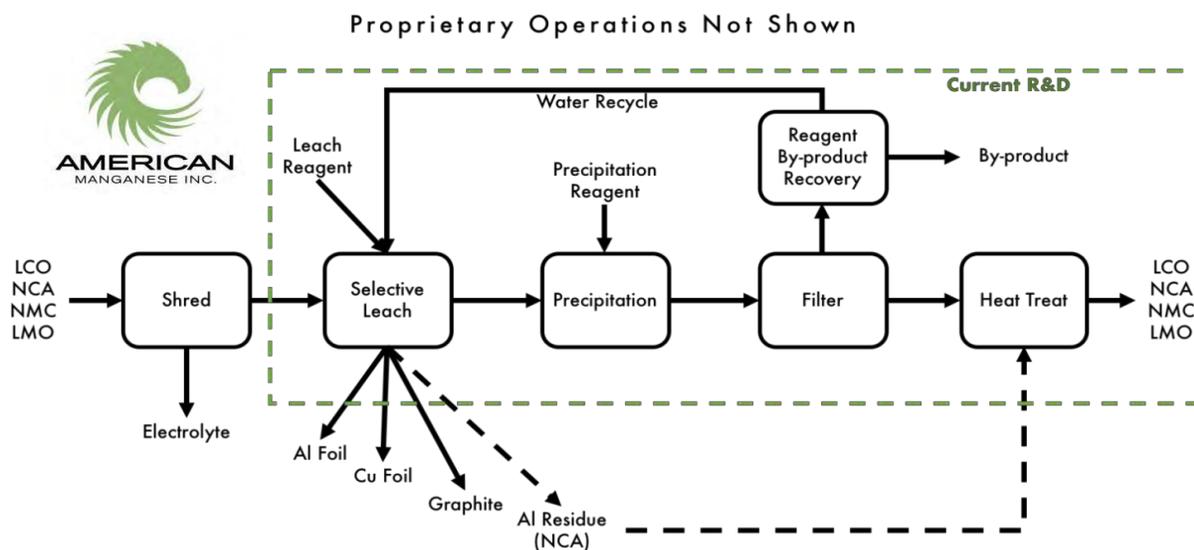


Figure 23 American Manganese Battery Recycling Flow Sheet ¹⁵¹

The American Manganese process treats cathode material containing a combination of lithium,

¹⁵¹ American Manganese Business Plan December, 2018 . <https://americanmanganeseinc.com/investor-info-2/amy-business-plan/>

cobalt, nickel, manganese, and aluminum. The cathode materials are treated with a unique combination of reagents and unit operations to provide high extraction, high purity, and minimum use of water. A base metal oxide is recovered separately from lithium carbonate. The base metal oxide and lithium carbonate are reportedly recovered at a battery grade purity and can be used directly back into remanufacturing new battery cathode. The various outputs from the American Manganese process are presented in Figure 24.



Figure 24 Outputs from American Manganese EV Battery Recycling Process

Pilot plant testing is currently underway at a rate of 1kg/hour¹⁵² to replicate real-world closed-circuit conditions in a continuous operation to simulate and de-risk production of the commercial plant in the next phase of operation. Commercial plant construction is slated to start once the pilot plant testing is concluded. The commercial plant could potentially be co-located near a recycling facility or battery manufacturing facility for efficient access to scrap material. Discussions with senior staff indicate that they are interested in constructing a commercial plant with a capacity of 3 tons/day, 5 tons/day or 10 tons/day in the US, Canada or the European Union (EU), with the US being the most likely location. Staff is hopeful that a commercial plant will be in place within a year, or in late 2020.

The commercial plant's planned processing capacity would be 1,200 tons/year of scrap cathode material

¹⁵²Rate confirmed 1st August, 2019 through discussions with American Manganese staff

at a cost of \$10 million. The estimated revenue generated during the operation of the commercial plant, highlighted in the American Manganese Financial Plan, would pay back the initial capital investment in a little over a year. Financial details are included later in this chapter where costs of EV battery recycling are addressed.

American Manganese carried out an assessment of their competitors, shown in Table 15. Of interest is the fact that they did not identify or see a number of market players (such as Li-Cycle, Neometals, etc.) as competitors. The competitive analysis included Retrieval, Umicore and Neometals, all described elsewhere in this section.

Table 15 American Manganese Assessment of Competitors in the EV Battery Recycling Business

	Proof of Concept	Patents	Recoveries		*Recovery Method
American Manganese Inc. (Surrey, BC, Canada)	Completed	Notice of Allowance Issued: December 14, 2018	Cobalt (100%)	Lithium (100%)	Hydrometallurgy
Retrieval Technologies	Completed	Not Found	Small Amount Not Recovered	Not Recovered	Hydrometallurgy
Worcester Polytechnic Institute (Battery Resources)	Completed	US Patent Application Applied for: November 22, 2016	Not Reported	Not Reported	Hydrometallurgy
International Islamic University Malaysia	Completed	Not Found	<25%	<50%	Hydrometallurgy Plus High Cost Calcining
Neometals Ltd.	Completed	Patent Pending	99.2%	Not Reported	Hydrometallurgy
University of California San Diego	Completed	Not Found	Not Reported	Not Reported	Heat Treating
Umicore	Current Method of Disposal of Most Batteries	Not Patentable	40-70% Not Reusable in Batteries	Nil	High Cost of Smelting 'Not Environmentally Responsible'

While 100% recovery has been measured in laboratory and pilot scale tests using predominantly production scrap, recoveries are likely to be lower for loads containing a mix of EV batteries.

5.3.2 Neometals

Neometals Ltd. is an Australian lithium mining and refining company which made a strategic decision to become involved in recovering metals and other materials from lithium batteries through recycling. Figure 25 presents the Neometals vision of where battery recycling fits within their corporate structure.

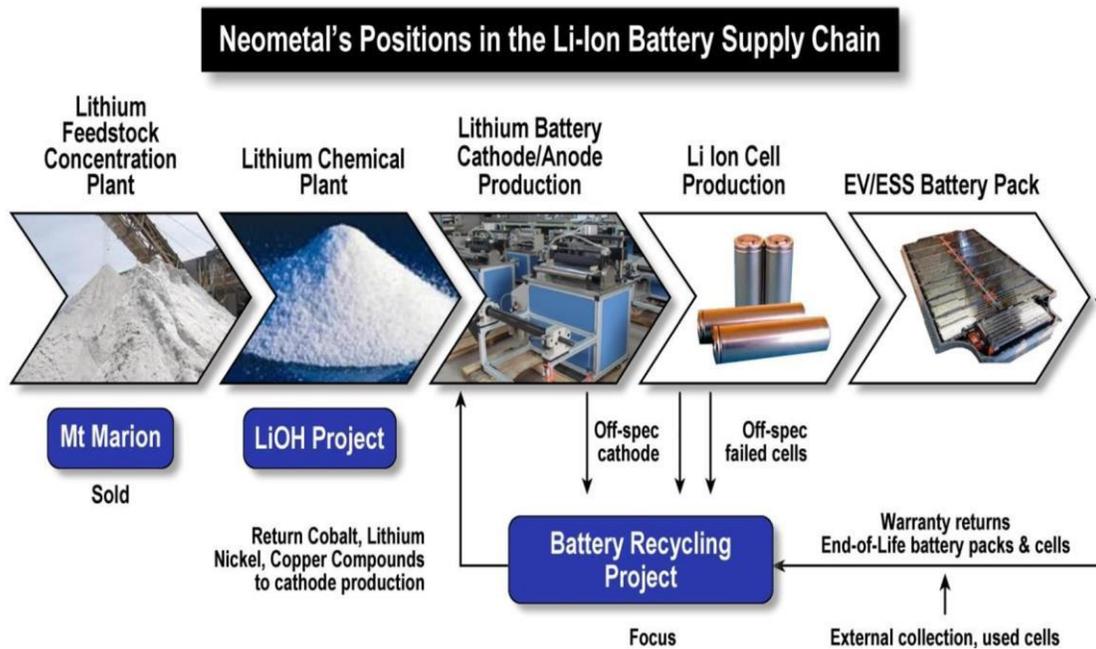


Figure 25 Location of Battery Recycling Project Within Neometals Corporate Structure

Neometals carried out a li-ion battery pilot and feasibility study in parallel with a market qualification, partner and approval processes. A 2017 Scoping Study carried out by SGS Engineers showed the potential for viable processes to recover cobalt from phone and laptop computer batteries (also li-ion but different chemistries than EV batteries) for less than \$5/lb of cobalt. Process design sheets were developed to recover multiple critical metals from LCO and NMC batteries. Expanded flow sheets were developed to address NCA/NMC volumes as these batteries accelerate. The process does not address LFP batteries. As discussed elsewhere, LFP batteries do not contain materials and metals of value to recyclers. Figure 26 presents a photograph of the Neometals pilot plant.



Figure 26 Neometals Pilot Plant

Neometals is currently running a modular pilot plant (100kg/day) at SGS Canada in Lakefield, Ontario, where the SGS laboratories are located. In February, 2019 Neometals announced a partnership with SGS Canada and construction of a small plant in Lakefield with a target opening date of December, 2019. Attempts to contact SGS Canada representatives to receive an update on timing of the project were not successful. Figure 27 shows the flow schematic and simplified process flow chart for the proposed plant.

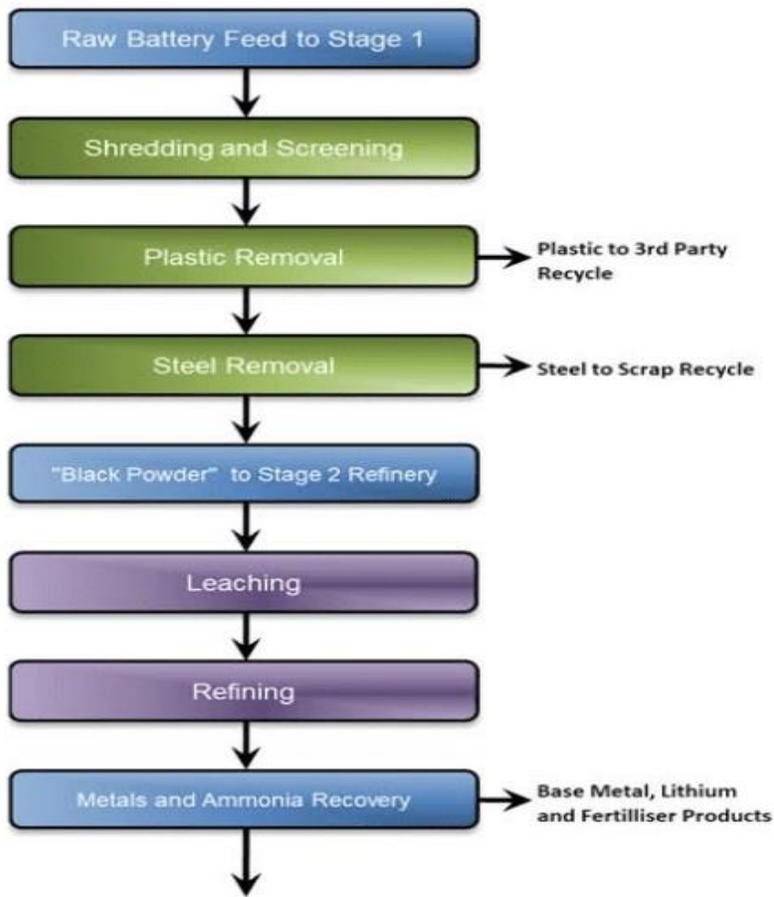


Figure 27 Neometals Process Flow Chart For Proposed Plant

Figure 28 shows a schematic for the Neometals plant. The estimated CapEx for the plant is \$4.5 million. Company literature indicate that it had estimated processing costs of \$4/lb for cobalt (which was updated in June, 2019 – see below) which the company estimated it could sell for \$25/lb. It is worth noting that the price of cobalt has ranged widely recently; it dropped in 2018 due to an over-supply, and increased dramatically a few years earlier when DRC instituted a trade restriction.

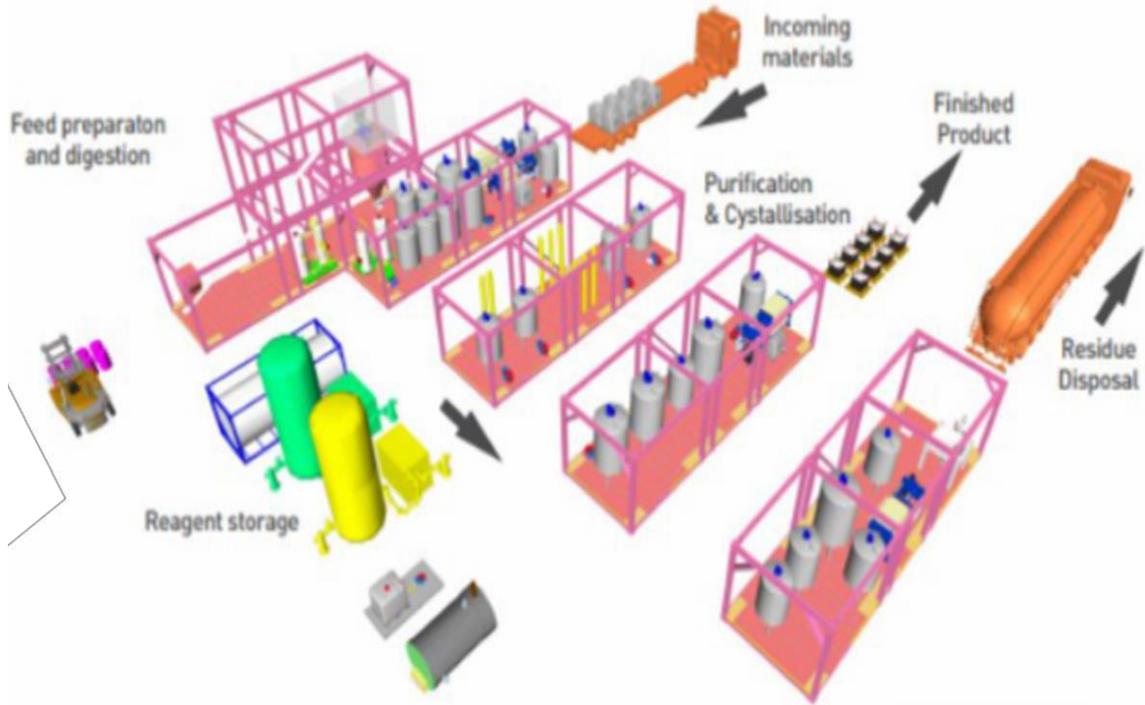


Figure 28 Schematic and Layout for Future Neometals EV Battery Recycling Plant

The plant footprint is 30x50 metres, or 100' by 160' approximately.

In June, 2019, Neometals announced a number of updates to their plans, based on completion of a *Lithium Battery Recycling Scoping Study*.¹⁵³ Key updates from earlier estimates include:

- Based on expected changing battery chemistries (discussed in Section 3 of this report) Neometals adjusted their approach and designed a completely new process with flexibility to process both LCO and NMC battery types. The current design is based on a feedstock of 50:50 LCO:NMC ratio;
- The proprietary process can recover cobalt, nickel, lithium, copper, iron and manganese from both scrap and li-ion batteries;
- Process recovers cobalt, nickel, copper and lithium as high purity sulphate products with estimated operating costs of less than US\$7/lb (US\$15/kg) of contained cobalt as cobalt sulphate before by-product credits;
- The study looked at both 10 ton/day and 50 ton/day designs with battery shredding and hydrometallurgical processing as well as removal of metal casings and plastics in the feed preparation and concluded that 50 tons/day (18,250 tonnes/year) was a more

¹⁵³ http://member.afraccess.com/media?id=CMN://6A932699&filename=20190604/NMT_02111415.pdf

- efficient scale for commercial operation;
- Estimated 88% cobalt recovery and 70% lithium recovery;
 - Cobalt recovery contributes 70% of the revenue;
 - Leaching, recovery and refining will produce chemical products including cobalt sulphate (assumed selling price US\$6,151/tonne); copper sulphate (\$2,030/tonne); lithium sulphate (\$5,000/tonne) and nickel sulphate (\$3,298/tonne)
 - Provisional patents are pending in Australia and Europe;
 - Pilot test in Canada is on schedule and will be followed by planned Class 3 Engineering and Feasibility studies (with a target start date of 2019/2020);
 - Feed preparation is based on processing cylindrical 18650 battery cells through a two-stage shredding process followed by drying and beneficiation to separate coarse metal and plastic materials from feed for processing in the hydrometallurgical section of the plant. The metal materials are drummed for sale as scrap metal for recycling;
 - The feed referred to as black powder is processed in the leach circuit to facilitate dissolution of cobalt, nickel, manganese, copper and lithium. The pregnant leach solution (PLS) is separated from the solid leach residue;
 - Further extraction and purification of PLS results in the recovery of cobalt, nickel and high purity sulphates suitable for potential sale directly back into the li-ion battery supply chain;
 - The design generates high value chemicals rather than intermediates;
 - Other products including lithium and copper sulphates could supply standard existing refineries for those metals;
 - The solid leach residue contains the graphite anode material which will be dried and drummed for sale; and
 - Demonstration scale operation prior to commercial deployment will be considered either in Montreal (Canada) at the Neometals industrial facility, an Australian location or at the site of a commercial partner.

Figure 29 shows the schematic for the updated June, 2019 facility and Figure 30 presents a high level flow sheet.

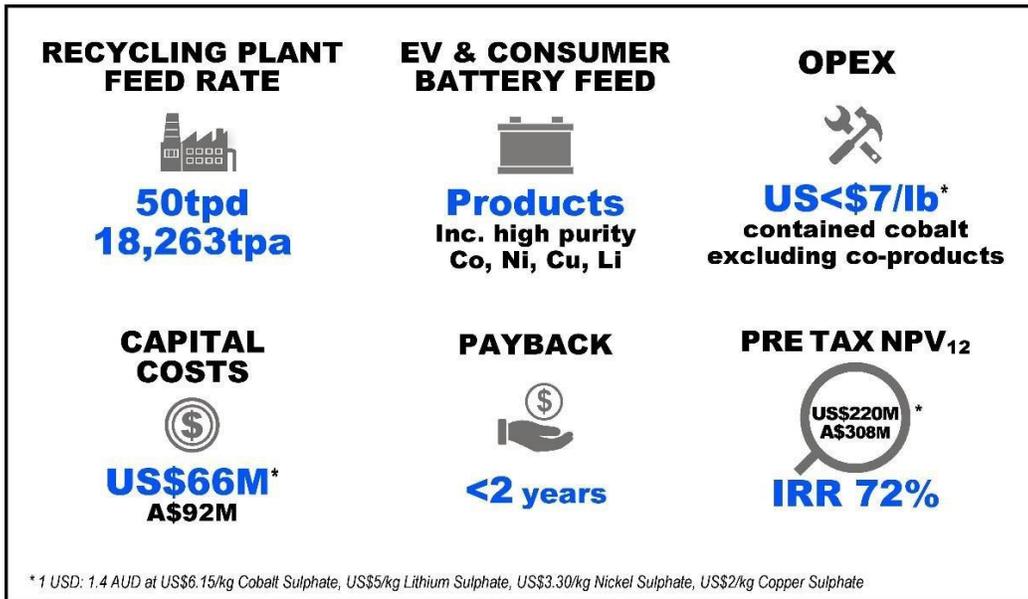


Figure 29 Key Highlights of Neometals Scoping Study for a Lithium Battery Recycling Plant (June, 2019)

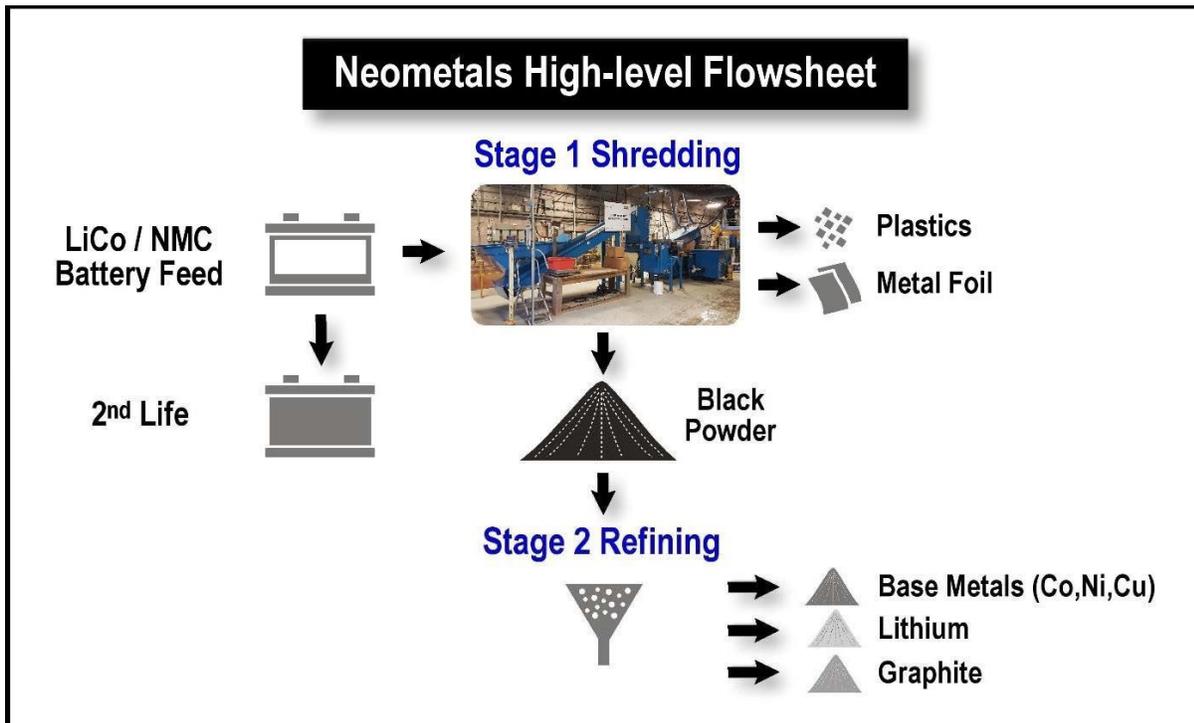


Figure 30 High-level Flow Sheet for Neometals Feed Preparation and Hydrometallurgical Processing Facilities (June, 2019)

5.3.3 Li-Cycle

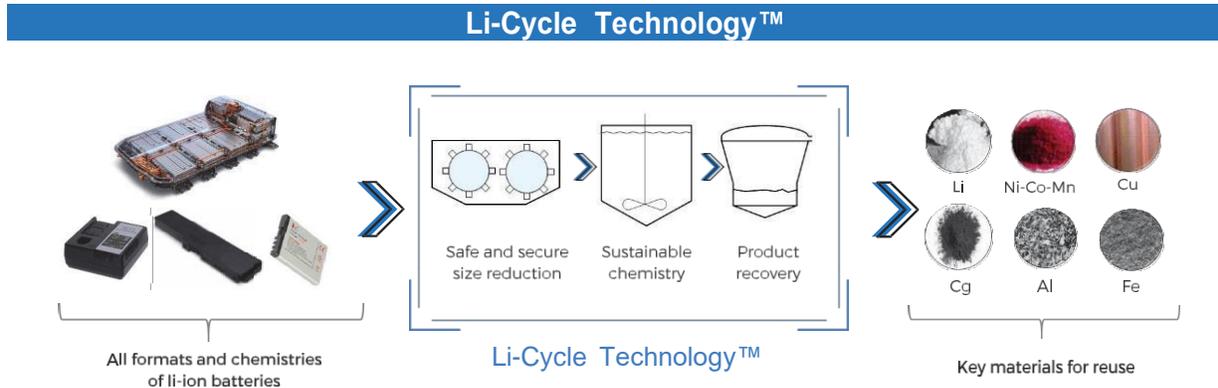
Li-Cycle¹⁵⁴, a company based in Mississauga, Ontario, has a vision of recovering 80% to 100% of material from EV batteries through recycling. The founders come from a primary lithium mining and refining background at Hatch Consulting Company.¹⁵⁵ Li-Cycle has received CAD\$2.7 million from Sustainable Development Technology Canada (SDTC) to build a pilot plant in Kingston, Ontario. This effort included an additional \$4.1 million of in-kind support for a \$6.5 million project in total. The demonstration/pilot plant is located with a laboratory as partner and is currently reportedly processing production scrap; they also work with global automotive manufacturers to receive packs for processing and testing.

Li-Cycle has raised a Series B round to construct one 5,000 tonne/year facility or potentially two plants. Construction has apparently started on the plant in Rochester, New York and a second plant may be constructed in the Greater Toronto Area (not Eastern Ontario as previously planned). After permits have been finalized, construction of these plants will take about nine months. The plant will have a mechanical capacity of 15 tonnes/day (5,000 tonnes/year) with a hydrometallurgical capacity of 1 tonne/day (200 tonnes/year). Figure 31 shows some promotional material developed by Li-Cycle to explain their process.

¹⁵⁴ <https://www.li-cycle.com/about-us.html>

¹⁵⁵ www.hatch.com

Li-Cycle Technology™ is a closed loop and industry-leading lithium-ion battery recycling solution.



Li-Cycle's Capabilities



Closed Loop Battery Resource Recovery



Qualitative Battery Analysis



Damaged Battery Management



- Resource recovery preparation Li-Cycle Technology™ resource recovery, enabling 80-100% recycling efficiency and sustainable handling

	Li-Cycle™	Traditional Lithium-ion Battery Recycling
Cost	<ul style="list-style-type: none"> • Lowest cost recycling • 'Fit-for-purpose' for lithium-ion battery recycling 	<ul style="list-style-type: none"> • High cost recycling • Not tailored for lithium-ion battery recycling
Safety	<ul style="list-style-type: none"> • Safe and automated solution for the dismantling of all lithium-ion batteries 	<ul style="list-style-type: none"> • Manual dismantling with a high risk of explosion and fire; high level of liability
Environmental Impact	<ul style="list-style-type: none"> • No solid waste • All water reused in the facility • Zero impact air emissions • Low energy consumption 	<ul style="list-style-type: none"> • Significant solid waste (slag) • Effluent water • Heavy metals in air emissions • High energy consumption
Recycling Efficiency	<ul style="list-style-type: none"> • 80-100% recycling efficiency rate/recovery • Closed loop recycling 	<ul style="list-style-type: none"> • 30-40% recycling efficiency rate/recovery • Substantial waste generation

Figure 31 Details of Li-Cycle Technology

No details are available on the technologies used in the Li-Cycle process. Interviews with the company's CEO carried out for this project indicated that all technical details are proprietary. He did, however, mention that the mechanical component is the "secret sauce" which makes the process different to other recyclers. Key outputs from the Li-Cycle process are:

- Lithium as lithium carbonate: For now, this material will be sent to South Korea as an input to battery production;
- Nickel-Cobalt-Manganese hydroxide product as cake: This material will be sent to a smelter in South Korea for now, but future processes will recover cobalt sulfate and nickel sulfate as separate streams;
- Copper;
- Graphite: this material is unlikely to go back into batteries because of very stringent quality needs. The CEO indicated that quite a lot of research was required to make this stream sellable;
- Aluminum; and
- Ferrous metal – which will go to a secondary market.

In a recent patent [A. Kochhar, T. G. Johnston, A Process, Apparatus, and System for Recovering Materials from Batteries, WO2018218358A1 (2018)], seven main components (cobalt, lithium, copper, graphite, nickel, aluminum, and manganese) were reported to comprise >90% of the economic value of a spent li-ion battery: Co (39%) and Li (16%, as LCE equivalent) followed by Cu (12%), graphite (10%), Ni (9%), Al (5%) and Mn (2%).¹⁵⁶ As with other companies that claim a potential 100% recovery of materials through recycling, while this value might have been measured in laboratories with a homogeneous feed stream of production scrap, it is not considered achievable with a heterogeneous mixture of EV batteries.

5.3.4 Fortum, Finland

Using a hydrometallurgical process, Fortum – the state-owned energy services company in Finland – reported in March, 2019 that it is able to recycle up to 80% of a li-ion battery.¹⁵⁷ The company's efforts are focused primarily on high energy density NMC batteries of the type used in EVs. A sludgy mixture of lithium, manganese and cobalt known as a 'black mass' remains after plastics, copper and aluminum have been removed for recycling. Fortum claimed it has developed a unique process for recovering these precious materials, which it has already implemented "on an industrial scale" at a facility in Harjavalta, Finland. Start-up Crisolteq developed the technology for Fortum.

¹⁵⁶ Pagliaro, M., & F. Meneguzzo. (2019). "Lithium battery reusing and recycling: A circular economy insight." *Heliyon*, 5(6), e01866. <<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6582158/>>

¹⁵⁷ Colthorpe, A. March 26, 2019. "'Black mass' battery recycling process makes 90% CO2 reduction possible, Fortum claims." <<https://www.energy-storage.news/news/black-mass-battery-recycling-process-makes-90-co2-reduction-possible-fortum>>

5.3.5 Lithion Recycling Inc.

Lithion Recycling Inc. (Lithion) is developing a solution to recover and isolate over 95% of battery components, including high value elements like cobalt, lithium and graphite. With a CAD\$3.8 million grant from SDTC, Lithion is planning a three-phase scale up to commercialization, beginning with a pilot plant. Lithion technology uses an innovative combination of hydro- and electrometallurgy-based extraction processes. The result is a low-carbon process generating zero effluent. The plants operating this technology will be very compact, modular, and affordable. Lithion is supported by a strong consortium of partners in the SDTC funded project consisting of: Seneca experts-conseils; Call2Recycle; Hydro-Québec's Center of Excellence in Transportation Electrification and Energy Storage (CEETES) and Centre d'étude des procédés chimiques du Québec (CÉPROCQ). Together with the partners and the SDTC contribution, the value of the project is estimated at CAD\$12 million. Lithion plans worldwide commercialization of its technology, which will begin with the construction of a 200 tons/year capacity pilot plant in Quebec, Canada in 2019.

5.4 Costs of EV Battery Recycling

For reasons of confidentiality, EV battery recyclers interviewed for this study would not share information on costs associated with battery recycling. Costs presented in this section were found through interviews with battery collectors; technical, trade and literature reviews; as well as a review of business and financial plans of companies developing EV battery recycling technology. Figure 32 presents the Neometals li-ion value chain analysis to show the value of sourcing cathode materials through recycling rather than buying them on open markets. The figure shows how the economics of battery production are altered when raw material costs are eliminated (through use of recycled materials). However, the recycled materials are not provided at zero cost, rather they are recovered through recycling processes which are shown elsewhere to have a net cost. This is one of the limitations of the analysis.

Two main sources of comparative costs of recycling EV batteries were found through the literature. The first was an extensive financial analysis of their future recycling facility (not yet constructed) by American Manganese, and available through their December, 2018 Business Plan. The second is a paper published by Chinese researchers in 2017 which is not included in the body of this report as it was not considered directly relevant to North America. However, it is included in Appendix J as it provides some interesting information on comparative costs of different process inputs. A lack of reliable data on current EV recycling costs, and a lack of sufficient data to identify the business case for EV battery recycling is identified as a research gap in Section 9.

	Raw Materials	Processed Materials	Electrodes	Cells	Battery Pack	Total
Value (\$/kWh)	\$50 [\$0]	\$118 [\$84]	\$28	\$146* (cum. \$342*)	\$74	\$416 [\$332]
Share [With recycled materials]	12% [0%]	28% [25%]	7% [8%]	35% [44%]	18% [22%]	100% [100%]
Currently Produced	Globally	Globally	Regionally	Globally	Regionally	
Supply Chain Issues	-Supply risk of some critical materials (e.g., Co, Li and Gr) -Demand may exceed supply in the near-term	-Critical to produce quality cells -Demand assurance -Recycling can help narrow the gap between supply and demand	-Critical to quality -Regional supply chain clusters in Asia -Emerging supply chains in North America and Europe	-Critical to quality -Regional supply chain clusters in Asia -Emerging supply chains in North America and Europe	-Proximity to customers: shipping costs, exchange of technical specifications	

Figure 32 Neometals Li-ion Battery Value Chain Analysis in 2016 (\$US/kWh) ¹⁵⁸

5.4.1 American Manganese Cost Analysis

Detailed costs for recycling different EV battery chemistries and production scrap using a new patented technology (not yet constructed or operating at scale) were estimated by American Manganese (described earlier in this section) and presented in their 2018 Business Plan. Estimated costs for a 1,200 ton/year plant for four different feedstocks are summarized in Table 16. The costs were based on the following assumptions:

- Capital cost of US\$10 million for the 1,200 ton/day plant;
- Metal prices as of 3 December, 2018;
- Cost of delivered scrap is estimated at 25% of ultimate intrinsic value;
- The commercial plant would operate 24 hours/day and require three shifts of four plant operators working an 8-hour shift at a rate of \$45/hour;
- Additional staff such as office administrator, an accountant, shipping and receiving, an assistant manager and a manager are all included at \$45/hour;
- Total labour cost per day is estimated at \$5,760 plus an additional \$3,168/day for general and administrative expenses;
- One maintenance person at \$60/hour is included in each of three 8-hour shifts per day;

¹⁵⁸ Neometals

- Utilities are based on current experience scaled up from pilot testing and laboratory costs. These will be firmed up during pilot testing.

Labour costs are the same for the four scenarios. The financial analysis clearly shows the difference in material revenues based on the EV BMS battery chemistry feedstock to the plant. In most cases the feedstock contains some production scrap which is much easier to handle than batteries which require discharge and some manual removal of BMSs and outer casings.

Table 16 American Manganese Cost Scenarios for 1,200 Ton per Year Plant with Different Feedstocks (Li-ion Battery and Production Scrap) (\$US millions)

	LCO (lithium cobalt oxide) EV Batteries and Production Scrap	NCA (lithium nickel manganese cobalt aluminum oxide) EV Batteries and Production Scrap	NMC111 (lithium nickel manganese cobalt oxide) EV Batteries and Production Scrap	NMC622 (lithium nickel manganese cobalt oxide) EV Batteries and Production Scrap
Estimated Annual Revenue (\$US) for 1,200 tons/day	\$42.24	\$17.43	\$21.10	\$17.88
Lithium Carbonate	\$5.81	\$5.92	\$5.90	\$5.87
Cobalt	\$36.43	\$5.57	\$12.32	\$7.36
Nickel	\$0.00	\$5.91	\$2.45	\$4.40
Manganese	\$0.00	\$0.00	\$0.42	\$0.25
Aluminum	\$0.00	\$0.03	\$0.00	\$0.00
Estimated Annual Operating Expenses (\$US)	\$15.55	\$9.35	\$10.27	\$9.46
Purchase of Feed Materials (Based on Metal Value)	\$10.56	\$4.36	\$5.27	\$4.47
Reagents	\$1.08	\$1.08	\$1.08	\$1.08
Labour and General and Administrative	\$3.26	\$3.26	\$3.26	\$3.26
Utilities	\$0.13	\$0.13	\$0.13	\$0.13
Maintenance	\$0.53	\$0.53	\$0.53	\$0.53
Estimated Annual Operating Profit	\$26.69	\$8.08	\$10.83	\$8.41
Operating Profit Margin	63%	46%	51%	47%

Table 17 (adapted from material in the American Manganese Business Plan) shows the estimated value in \$US/kWh for cathode materials using different battery chemistries. Appendices to this report present a

range of battery chemistries and kWh used in many different EVs.

Table 17 Value of Metals in EV Batteries by Chemistry¹⁵⁹

Cathode Chemistry	kg/kWh				\$US/kWh
	Lithium	Cobalt	Nickel	Manganese	
LCO	0.113	0.959	0.000	0.000	\$76
NCA	0.112	0.143	0.759	0.000	\$22
NMC-111	0.139	0.394	0.392	0.367	\$38
NMC-622	0.126	0.214	0.641	0.200	\$27
NMC-811	0.111	0.094	0.750	0.088	\$19

Note: LCO = Lithium-Cobalt-Oxide, NCA = Nickel-Cobalt-Aluminum, NMC = Nickel-Manganese-Cobalt

Figure 33 summarizes the American Manganese cashflow projections for different EV cathode feedstocks and shows that the LCO chemistry with high cobalt content reaches a positive cash flow the fastest.

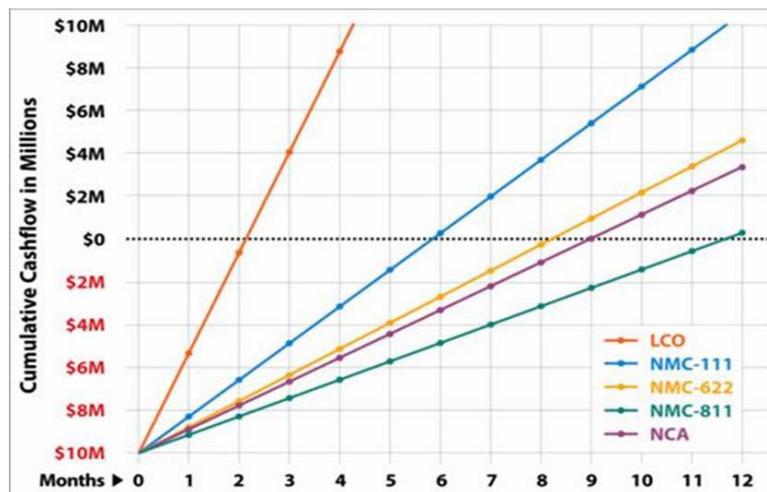


Figure 33 Cash Flow Projections for 1,200 Ton per Year Plant Recycling Different EV Battery Cathode Chemistries¹⁶⁰

Other Cost Data Points

One literature source identified the cost of fully recycling an EV battery at close to €1/kg which is about 51 cents/lb; the value of the raw materials that can be reclaimed is only a third of that.¹⁶¹

¹⁵⁹ Adapted from Table 1 in American Manganese Business Plan Table June 28, 2018 (Fessler, 2018)

¹⁶⁰ American Manganese Inc Company Business Plan. Updated December 14th, 2019

In North America, recycling costs have been quoted at 1-4 cents/lb¹⁶², with credits given for the value of recovered metals. The higher end of the range was for a LFP battery where the recovered materials have no value. These costs are a shock to traditional car battery recyclers who deal with lead-acid batteries used for SLI (starting, lighting, ignition), and who are used to being paid 30-60 cents/lb or \$15 to \$30/unit because of the high value of the lead.

Argonne National Laboratory (ANL) estimated recycling costs for li-ion batteries at \$4,000 to \$5,000/tonne.¹⁶³ ANL has a recycling cost model called Everbatt¹⁶⁴, similar to the reuse cost model discussed in Section 4. EverBatt is an Excel-based model that evaluates cost and environmental impacts for the various life cycle stages of a li-ion battery. It can be used to compare impacts of virgin batteries to those with recycled content, to compare processes, and to identify sensitivities to various parameters. The model could not download during this study. It was suggested by Responsible Battery Coalition (RBC) that work is underway on the model and it is not public at this time. Life cycle research that has provided inputs to the model has recently been published.¹⁶⁵ RBC is working with ANL staff to identify and fill in the gaps in the current data, then run assessments on several next generation chemistries and synthesize the results with the RBC Green Principles developed by RBC.¹⁶⁶

5.4.2 Element Energy Cost Analysis

A report was prepared by Element Energy for an industry consortium including Renault to understand obligations under the EU Batteries Directive (described in Section 7) and identify how EV battery reuse and recycling could help address obligations. The report addressed the potential role of EV batteries in the EU power system. Figure 34 from the Element Energy report illustrates the various components of EV battery recycling costs (without specific values).

¹⁶¹Gardiner, J. August 10, 2017. "The rise of electric cars could leave us with a big battery waste problem" <www.theguardian.com/sustainable-business/2017/aug/10/electric-cars-big-battery-waste-problem-lithium-recycling>

¹⁶² Discussed at Canadian Battery Association AGM 17th April, 2019

¹⁶³ Battery University. "BU-705a: Battery Recycling as a Business." <https://batteryuniversity.com/learn/article/battery_recycling_as_a_business>

¹⁶⁴ Argonne National Laboratory. "EverBatt Download." <<https://www.anl.gov/egs/everbatt-download>>

¹⁶⁵ Arbabzadeh, M et al. May 2019. "Green principles for responsible battery management in mobile applications." <<https://www.sciencedirect.com/science/article/pii/S2352152X19302956>>

¹⁶⁶ E-mail correspondence with Steven Christensen, Responsible Battery Coalition, July, 2019

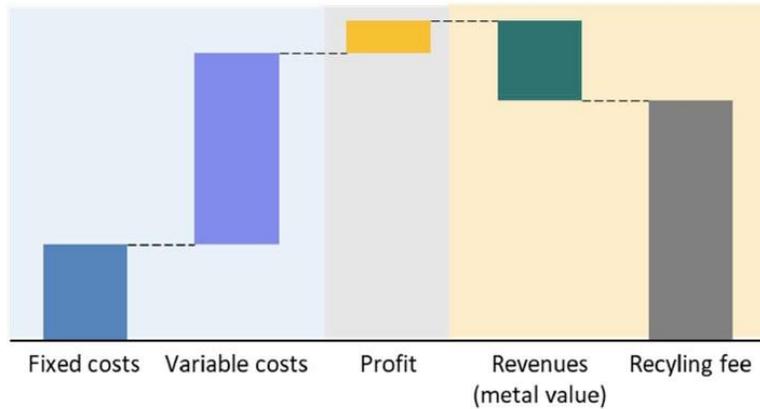


Figure 34 Element Energy Business Model Concept for Battery Recyclers¹⁶⁷

The net cost of recycling is influenced by a variety of factors. These include the size of the recycling facilities and related economies of scale; the value of metals that are routinely recovered by recyclers; the composition of the EV batteries processed and the efficiency of the recycling process; as well as commodity prices. The interaction of these various factors is illustrated in Figure 35.

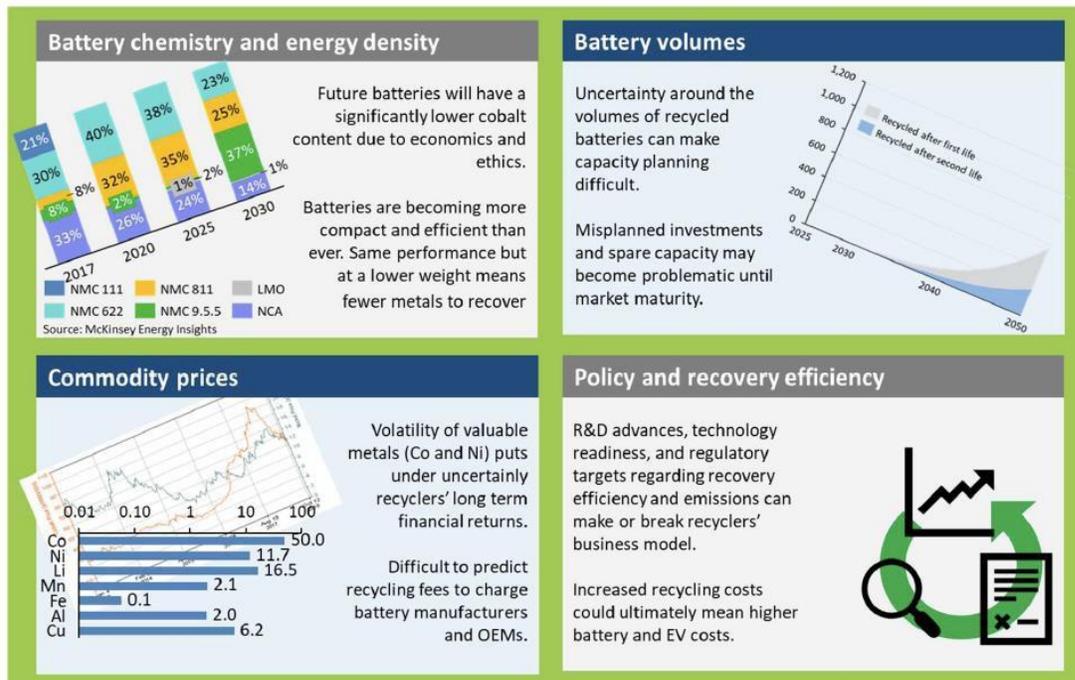


Figure 35 Factors That Impact on Costs of Recycling EV Batteries¹⁶⁸

¹⁶⁷ Element Energy. 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>

The analysis carried out by Element Energy estimated that recycling fees will decrease from about \$1,700-\$2,000/tonne today to around \$480/tonne in 2030. The range of future recycling costs under various scenarios are presented in Figure 36. The analysis projected that the cost of reused EV batteries would reach about \$40/kWh in 2030, compared to the purchase price of \$62/kWh for new EV batteries, and recommended reuse as a cost reduction strategy for obligated EU companies. While the study was carried out in a European context, the fees are worth noting as there is no equivalent data or analysis available for North America at this time.

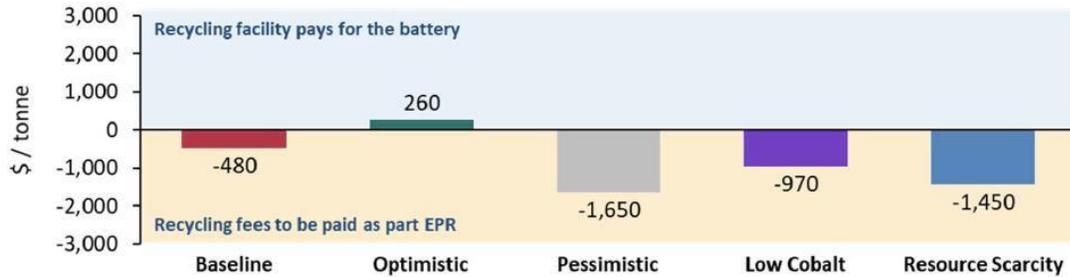


Figure 36 Potential Range of EV Battery Recycling Costs¹⁶⁹

5.5 Technical Challenges with EV Battery Recycling

As the EV battery (li-ion, specifically) recycling infrastructure continues to evolve, some of the challenges faced by auto shops, intermediate parties, smaller recyclers, and even larger battery recyclers, include:

- Difficulty in identifying battery chemistry;
- Difficulty in estimating battery SoH and remaining battery lifespan;¹⁷⁰
- Uncertainty regarding safe dismantling;
- Lack of automated battery dismantling process (unlike lead-acid batteries);
- Lack of knowledge on how electronics work in the battery cells in non-specialized shops; and
- Uncertainty regarding aftermarket values for the metals recovered, particularly as battery chemistries are changing over time.

While the market for EV battery recycling has significant potential, it is constrained by several technical barriers, each of which is described below. It is worth noting that some of these are similar to those facing the battery reuse market, discussed previously in Section 4.

¹⁶⁸ Element Energy. 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>

¹⁶⁹ Element Energy. 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>

¹⁷⁰ www.researchgate.net/publication/327980984_Reuse_of_Lithium-Ion_Electric_Vehicle_Batteries_for_Stationary_Applications_ReLIEVe, 9/18.

Variety of EV Battery Chemistries and Formats: There is a wide range of chemistries and battery cell and pack designs currently in use.¹⁷⁴ Moreover, the materials in each cell are not standardized and are constantly evolving; although batteries with higher nickel content may eventually predominate the market, even these will have unique formulations that have different relative proportions, with varying particle structures.¹⁷⁵ The lack of standardization of EV battery types makes reliable recycling a challenge, since each could require a different recycling procedure and potentially even separate facilities.¹⁷⁶ Ideally, direct recyclers prefer to run one chemistry at a time through their hydrometallurgical process for best product quality output and chemical use; this will not be possible until all EV battery chemistries are clearly labelled, which does not appear to be the case at this time;

Lack of EV Battery Standard Structure and Design: Ideally, the recycling process could be simplified if all the packs and modules were similar, enabling construction of automated disassembly lines to separate the input stream into objects of a size suitable for further processing.¹⁷¹ Standardization would also facilitate sorting and possibly enable cell disassembly instead of size reduction.¹⁷² However, automakers have legitimate competitive reasons to resist standardization.¹⁷³ In addition, experimenting with different battery types and designs helps drive economic and technical innovations in EV development, and is expected to be ongoing for the foreseeable future.

Lack of Design for Recycling: Rajit Gadh, PhD, professor at UCLA's Henry Samueli School of Engineering and Applied Science explains that “ the first generation of EV batteries were designed with energy density, power density, weight, performance, number of cycles, reliability and safety in mind, however, not enough thought was given to their reuse, recycling, demolishing or disassembly.”¹⁷⁴ The way in which an EV battery is designed can limit the ability of valuable raw materials, like nickel, lithium and cobalt, to be recovered and recycled. Examples of design elements that can hinder recycling include permanent assembly methods, like spot-welding the battery pack instead of using nuts and bolts, or holding cells in place using a potting compound.¹⁷⁵ Current recycling technologies may not be able to recover the lithium and cobalt in batteries manufactured with these methods without damaging the components inside.¹⁷⁶ Gaines et al. (2018) notes in their article on ‘Key Issues for Li-ion Battery Recycling’ that actual practice has not yet produced easily recyclable batteries.¹⁷⁷

¹⁷⁴Gaines, L., Richa, K., & Spangenberg, J. (2018). “Key issues for Li-ion battery recycling.” *MRS Energy & Sustainability*, 5. doi:10.1557/mre.2018.13 [sci-hub.tw/10.1557/mre.2018.13](https://doi.org/10.1557/mre.2018.13)

¹⁷² ibid.

¹⁷³http://webcache.googleusercontent.com/search?q=cache:t4knY1efHZ8J:www.dot.ca.gov/sustainability/docs/2018-03-26_battery_disposal.pdf+&cd=11&hl=en&ct=clnk&gl=ca&client=safari

¹⁷⁴ Keller, M. 2018. “Recyclability of Electric Vehicle Batteries Scrutinized.” <https://lamprecycling.veoliaes.com/newsletter/October2017/5>

¹⁷⁵ Gaines, L., Richa, K., & Spangenberg, J. (2018). “Key issues for Li-ion battery recycling.” *MRS Energy & Sustainability*, 5. doi:10.1557/mre.2018.13

¹⁷⁶International Institute for Sustainable Development. March 2019. [fe-cycle-is-more-important-than-the-battery-lifetimes_ReLIEveonment.org/sites/https://www.iisd.org/sites/default/files/publications/sustainability-second-life-cobalt-lithium-recycling.pdf](https://www.iisd.org/sites/default/files/publications/sustainability-second-life-cobalt-lithium-recycling.pdf)

¹⁷⁷ Gaines, L., Richa, K., & Spangenberg, J. (2018). “Key issues for Li-ion battery recycling.” *MRS Energy & Sustainability*, 5. doi:10.1557/mre.2018.13

Lack of Collection Infrastructure to Deliver Large Numbers of EV Batteries to Recycling Facilities: The challenge of inefficient collection infrastructure and lack of steady supply hampers market development for EV battery recycling.

Lowering or Eliminating Cobalt in EV Batteries: Li-ion batteries have historically contained large amounts of high-value cobalt, which is one of the key motivators for recyclers. Battery and vehicle OEMs are re-designing batteries to have lower cobalt content in an effort to reduce the cost of EV batteries. This reduces the incentive for recyclers to recycle li-ion batteries, and results in them needing to charge a gate fee to process EV batteries rather than take or buy them for the cobalt content.

6 Environmental, Energy, and Cost Impacts of EV Battery Reuse and Recycling

A review of the academic literature has been undertaken to identify the environmental and energy impacts of EV battery reuse and recycling. While extensive work has been done on the environmental impacts of EV batteries, most of this work is focused on the use phase of the EV battery. Some references were found focusing specifically on energy and environmental impacts of EV battery reuse and recycling. Many of the studies combine both energy and environmental impacts of reuse vs. recycling in the same figures. Where this is the case, no effort has been taken to split out energy from environment or recycling from reuse discussions.

6.1 Energy and Environmental Impacts of EV Battery Reuse

Using second-life EV batteries for energy storage allows energy providers to reduce the environmental impacts associated with producing and using new batteries, which have traditionally been lead-acid battery,¹⁷⁸ although most utilities have started using li-ion batteries for energy storage systems (ESS).

A number of studies have been carried out to quantify the life cycle environmental impacts of reusing EV batteries in less demanding applications, in particular as stationary ESSs. A study of an urban EV in Spain in 2013¹⁷⁹ evaluated reuse of an LFP battery (with a $\text{Li}_4\text{Ti}_5\text{O}_{12}$ anode and LiFePO_4 cathode) as an energy storage unit in a smart building with solar photovoltaic (PV) panels. The study found that there was an overall positive environmental benefit associated with reusing the existing EV battery in the smart building application compared to manufacturing a new one for the same purpose.¹⁸⁰

A similar study published in 2019¹⁸¹ analyzed four second-life application scenarios for a LFP battery by combining the following assumptions and conditions:

- (i) reuse of the EV battery or manufacturing of a new battery as energy storage unit in a smart building application; and
- (ii) use of the Spanish electricity mix or energy supply by solar PV panels.

¹⁷⁸ Richa, K., Babbitt, C. W., Nenadic, N. G., & Gaustad, G. (2015). Environmental trade-offs across cascading lithium-ion battery life cycles. *The International Journal of Life Cycle Assessment*, 22(1), 66–81. doi:10.1007/s11367-015-0942-3 (sci-hub.tw/10.1007/s11367-015-0942-3)

¹⁷⁹ Genikomsakis, K.N., Ioakimidis, C.S., Murillo, A., Trifonova, A., and Simic, D. (2013). "A life cycle assessment of a Li-ion urban electric vehicle battery." In *Proceedings of the 2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, Barcelona, Spain, 17–20 November 2013

¹⁸⁰ *ibid.*

¹⁸¹ Ioakimidis, C.S., Murillo-Marrodan, A., Bagheri, A., Thomas, D., and K.N. Genikomakis. "Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios." doi:10.3390/su11092527

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The results showed that there is significant environmental benefit from reusing the existing EV battery in the secondary application instead of manufacturing a new battery to be used for the same purpose and time frame.

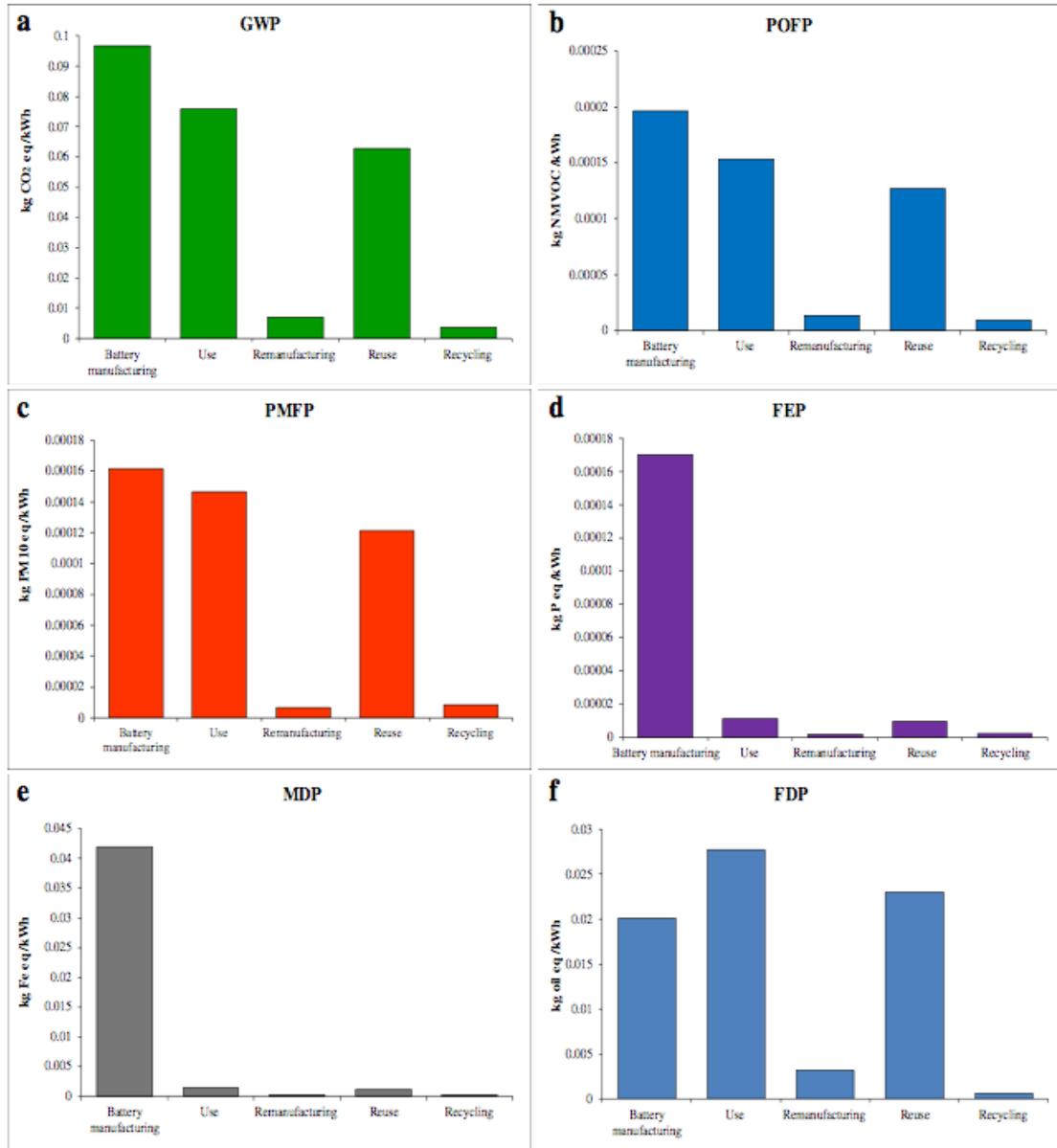
A Canadian study published in 2019¹⁸² estimated that repurposing EV batteries for stationary energy storage applications resulted in a potential 56% reduction in GHG emissions or 24 tonnes of CO₂eq, over the total 18-year lifetime of the EV battery. The GHG emission savings primarily come from the use of PHEVs over conventional gas-powered vehicles and by offsetting the use of coal and natural gas power with the potential use of renewable power supported by a second-use EV battery.¹⁸³

An LCA study conducted by Ahmadi et al. (2017)¹⁸⁴ examined the second-life application of a li-ion battery with a LiFePO₄ cathode and graphite anode. The study's scope included the entire manufacturing sequence of li-ion battery, first use in the EV, re-purposing, second use in ESS, and recycling. This includes all major processes, significant materials and energy flows to the point where materials are extracted from or emitted to the natural environment. Assuming that battery production and vehicle production occurred in East Asia, and that the use, remanufacturing and reuse phases occurred within Ontario, Canada, the study found that the total amount of GHG emissions associated with a li-ion battery over its life cycle is 0.25 kg CO₂eq per kWh delivered by the battery pack, and battery reuse accounts for 26% of this total. Figure 37 from the study shows the estimated environmental impacts of a li-ion battery pack during its entire life cycle, including reuse.

¹⁸² Catton, J.W.A., Walker, S.B., McInnis, P., Folwer, M., Fraser, R.A., Young, S.B., and B. Gaffney. (2019). "Design and Analysis of the Use of Re-Purposed Electric Vehicle Batteries for Stationary Energy Storage in Canada." *Batteries*, 5(14), 1-19.

¹⁸³ Ibid.

¹⁸⁴ Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* 2017, 22, 111–124.



A) global warming potential (GWP); (B) photochemical oxidation formation potential (POFP); (C) particulate matter formation potential (PMFP); (D) freshwater eutrophication potential (FEP); (E) metal depletion potential (MDP); and (F) fossil-resource depletion potential (FDP).

Figure 37 Life Cycle Impacts per kWh of Power Delivered by Li-ion Battery Pack Cascaded Use¹⁸⁵

An article published by Richa et al.¹⁸⁶ in the *Journal of Industrial Ecology* estimated the net benefit of reusing 1,000 EOL EV li-ion battery packs in the US first through redeployment in EVs and then through a cascading reuse of energy storage applications. Figure 38 shows the assumptions regarding

¹⁸⁵ Ahmadi, L.; Young, S.B.; Fowler, M.; Fraser, R.A.; Achachlouei, M.A. "A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in energy storage systems." *Int. J. Life Cycle Assess.* 2017, 22, 111–124.

¹⁸⁶ Richa, K., Babbitt, C.W., & G. Gaustad. (2017). "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy." *Journal of Industrial Ecology*, 21(3), 715-730. < <https://doi.org/10.1111/jiec.12607> >

material flow on which the analysis was based. In the figure C1 refers to the starting year of the EOL EV battery flow; C2 is 5 years later and C3 is 9 years after the starting year. The analysis assumes the first additional use is for 5 years and a second cascaded use could last an additional 4 years.

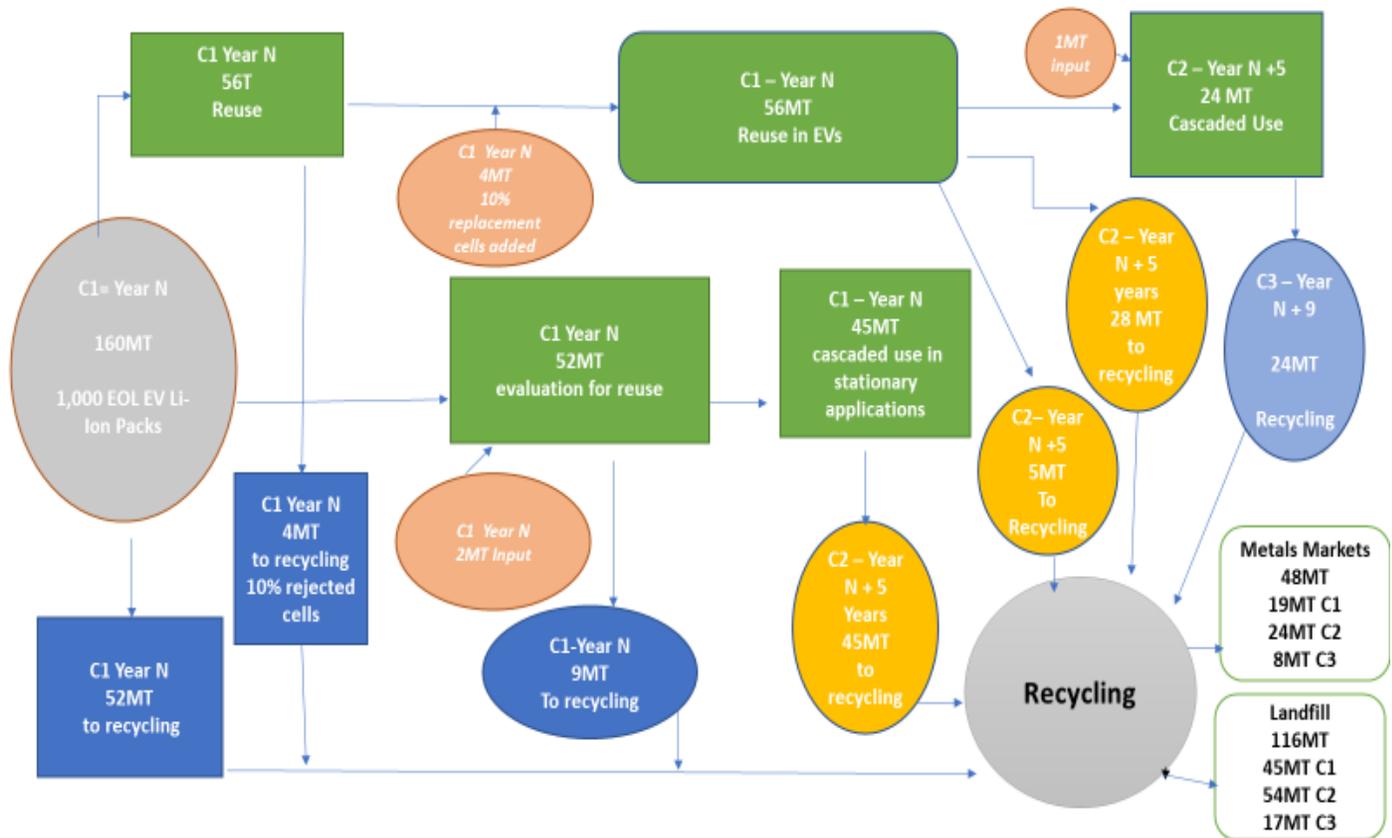


Figure 38 Material Flow Assumptions on Which Energy Analysis is Based (Adapted from Richa et al)¹⁸⁷

The study estimated that 200,000 MJ of cumulative energy demand (CED) would be saved through EV battery reuse in an older EV for an additional 4.5 years, which the authors estimated is equivalent to avoiding the production of 11 new EV battery packs (18kWh each). The EV mix modeled in the study consisted of 25% BEV, 36% long range PHEV and 39% short range PHEVs. LMO battery chemistry was assumed. It was concluded that for long range battery packs the avoided CED impact of li-ion production exceeded the CED of charge-discharge losses, replacement cells and li-ion battery testing by a net benefit of 3,200 MJ for an EV pack and 73 MJ for a PHEV pack.¹⁸⁸ The energy and environmental impacts of EV battery reuse and recycling quantified in the study are presented in Figure 39.

¹⁸⁷ Richa, K., Babbitt, C.W., & G. Gaustad. (2017). "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy." *Journal of Industrial Ecology*, 21(3), 715-730. < <https://doi.org/10.1111/jiec.12607>> - Figure adapted for this report.

¹⁸⁸ Ibid.

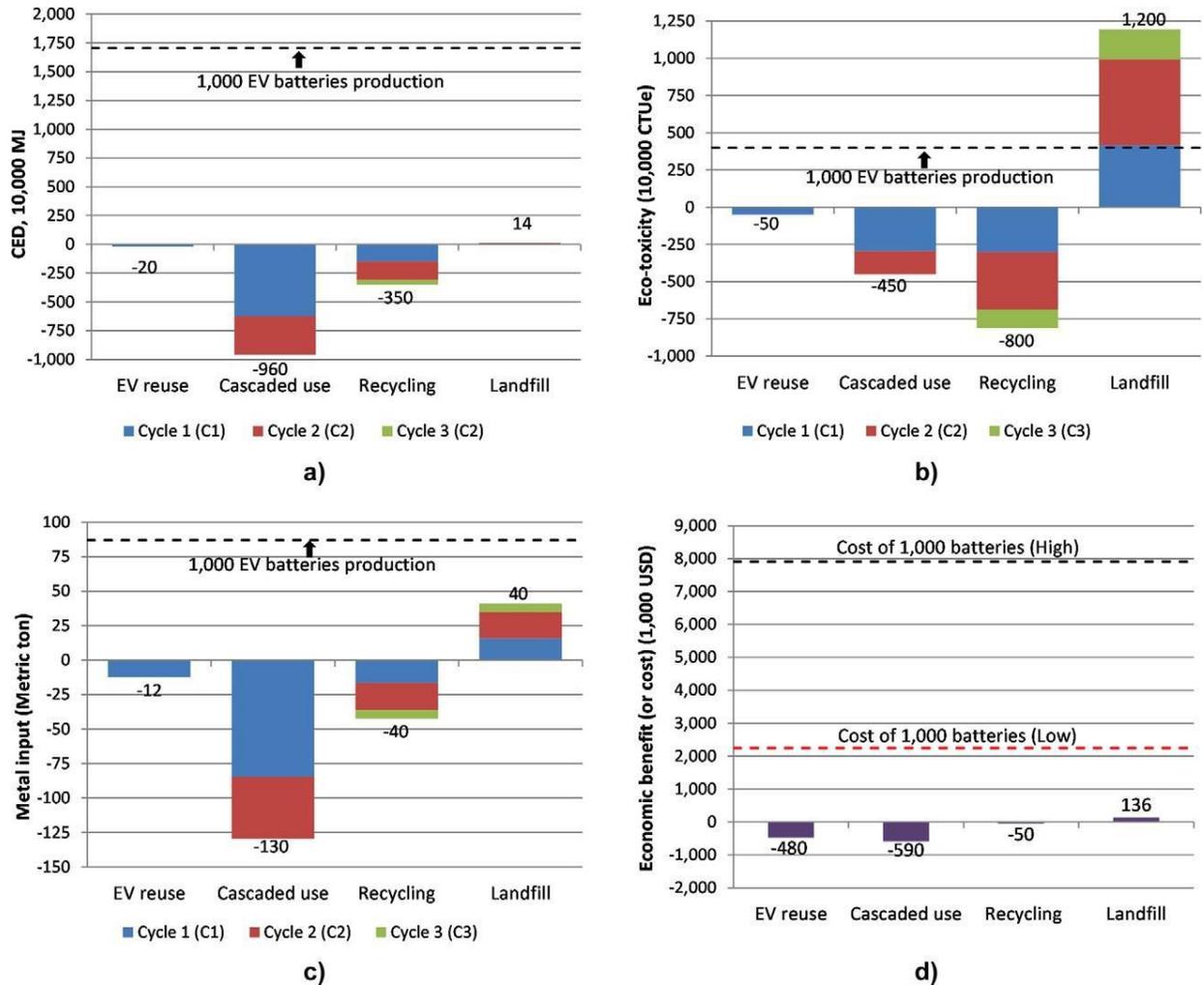


Figure 39 Estimated Environmental and Energy Impacts of the Reuse and Recycling of 1,000 EV Batteries in the US¹⁸⁹

The authors of the study found that these benefits are magnified almost tenfold when used EV batteries are cascaded in a second use for stationary energy storage. Assuming that a stationary energy system would operate for 5 years, the study found that a net CED benefit of 1,330 MJ/kWh and an eco-toxicity benefit of 626 CTUe/kWh can be achieved by cascaded use of li-ion EV batteries and by avoiding the production and use of less-efficient lead-acid batteries. If this number is scaled to the entire 1,000 EOL battery stream, a potential net CED benefit of 9.6 million MJ and 4.5 million CTUe was estimated. One limitation of the study is that it compares the energy and environmental impacts of reused li-ion batteries to purchasing new lead-acid batteries for ESS. While lead-acid batteries have been the standard battery used for energy storage by US utilities for decades, new ESSs generally use li-ion batteries, which makes the research somewhat outdated. To reflect these new realities, the research

¹⁸⁹ Richa, K., Babbitt, C.W., & G. Gaustad. (2017). "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy." *Journal of Industrial Ecology*, 21(3), 715-730. < <https://doi.org/10.1111/jiec.12607> >

needs to be updated to compare the reuse of EV li-ion batteries with purchasing new li-ion batteries for ESS.

Figure 40 presents the environmental impacts of EV battery reuse estimated by Richa et al. in 2017. The study estimated that cascaded reuse of 1,000 EV batteries provided eco toxicity credits of about 4.5 million units, with reuse of the reconditioned batteries in EVs only providing eco-toxicity benefits of 0.5 million units. Given that the technology and battery chemistries have changed so much in the last few years, an update of the analysis is needed.

An earlier study by Richa et al¹⁹⁰ found that extending the lifespan of an EV li-ion battery through a second use provides an overall CED credit of 12,850 MJ, a net reduction of 15% over the battery’s life cycle. The study assumed that 50% of the EV li-ion battery cells can be converted for stationary use application and that the stationary battery will have a 5-year life span. The dotted line in Figure 40 reflects the impact of the EV li-ion battery life cycle with no reuse in stationary application. The analysis was carried out using a 24kWh LMO battery pack weighing 223kg and providing 100,000-mile operation during its lifetime. The mileage was considered equivalent to an 8- year service life. The LMO chemistry was chosen as it was used in the Nissan Leaf and Chevrolet Volt vehicles at the time (2014). The refurbished li-ion battery system was assumed to have a capacity of 450kWh, and weigh 4,446 kg, compared to an equivalent lead-acid battery system which would weigh 13,044 kg.

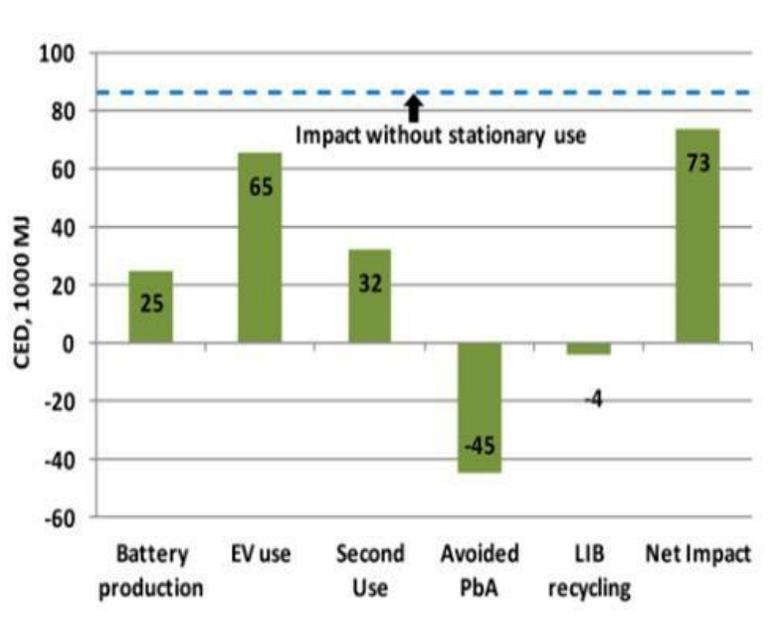


Figure 40 Estimated Comparative Energy Impacts of EV Battery Reuse ¹⁹¹

Figure 41 shows the environmental results from the 2017 study discussed above¹⁹². The study analyzed the environmental trade-offs of cascading reuse of a li-ion battery in an older EV followed by reuse in stationary energy storage at EV EOL. The study found that the environmental benefits outweighed

¹⁹⁰ Richa, K., Babbitt, C. W., Nenadic, N. G., & Gaustad, G. (2015). Environmental trade-offs across cascading lithium-ion battery life cycles. *The International Journal of Life Cycle Assessment*, 22(1), 66–81. doi:10.1007/s11367-015-0942-3 (sci-hub.tw/10.1007/s11367-015-0942-3)

¹⁹¹ Ibid.

¹⁹² Ibid.

the potential costs of EV battery reuse, with a cumulative Global Warming Potential (GWP) credit of 740 kg CO₂eq. The dotted line in the figure reflects the impact of the battery life cycle with no reuse in stationary application. One of the limitations of the study is that it compared cascading reuse of li-ion batteries with using new lead-acid batteries.

The authors concluded that EV li-ion battery reuse in stationary applications has the potential for dual benefit—both from the perspective of offsetting initial manufacturing impacts by extending battery life span as well as avoiding production and use of a less-efficient lead-acid battery system. It is noted as a research gap that studies were carried out using a comparison with lead-acid batteries and should be carried out comparing the net energy and environmental benefits of cascaded reuse of li-ion batteries to using new li-ion batteries.

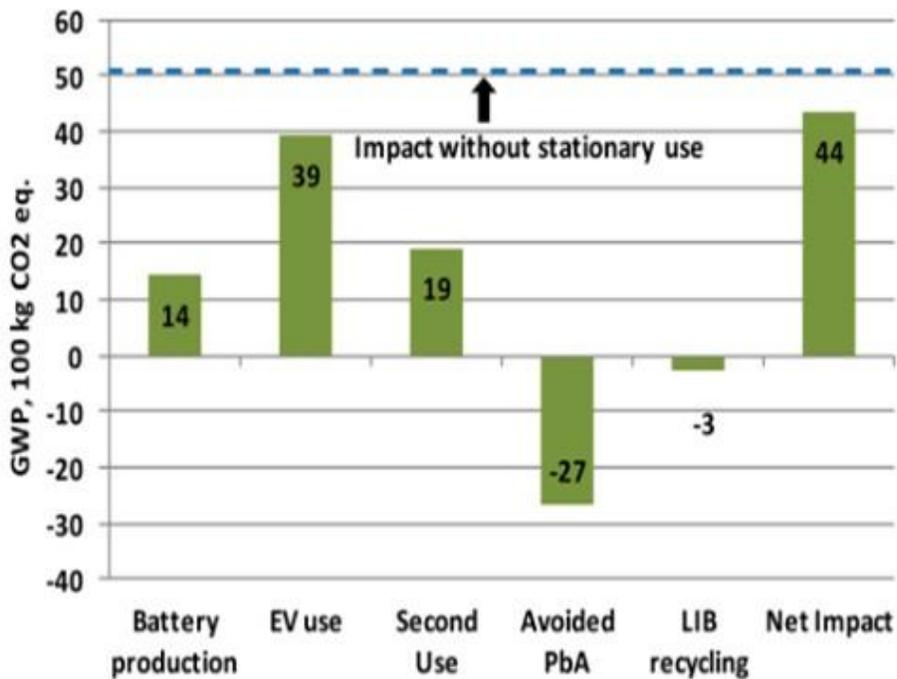


Figure 41 GWP (Global Warming Potential) Impacts of Cascading Reuse of an EV Li-ion Battery¹⁹³

6.2 Energy Impacts of EV Battery Recycling

A number of studies compare the energy impacts of EV battery reuse vs. recycling. These are presented in Section 6.1. This section will focus on studies that specifically addressed the energy impacts of recycling alone.

¹⁹³ Ibid.

A research study published in 2012¹⁹⁴ calculated the energy consumed when recovering LiMn_2O_4 , aluminum, and copper from li-ion batteries through three recycling processes. Figure 42 taken from the 2012 academic paper, presents estimates of energy required to produce recycled LiMn_2O_4 from the three different processes (hydrometallurgical, intermediate physical, and direct physical recycling) compared to the energy required for production of virgin LiMn_2O_4 in Nevada and Chile. The energy associated with the recycling processes is shown in the black outlined boxes in the figure and indicates that the production of virgin LiMn_2O_4 is likely more energy intensive than production through any of the three recycling approaches. The authors explain that although the hydrometallurgical process itself is not very energy intensive, consumption of citric acid and hydrogen peroxide (counted in the LCA) contributes significantly to the energy consumption of the overall process.

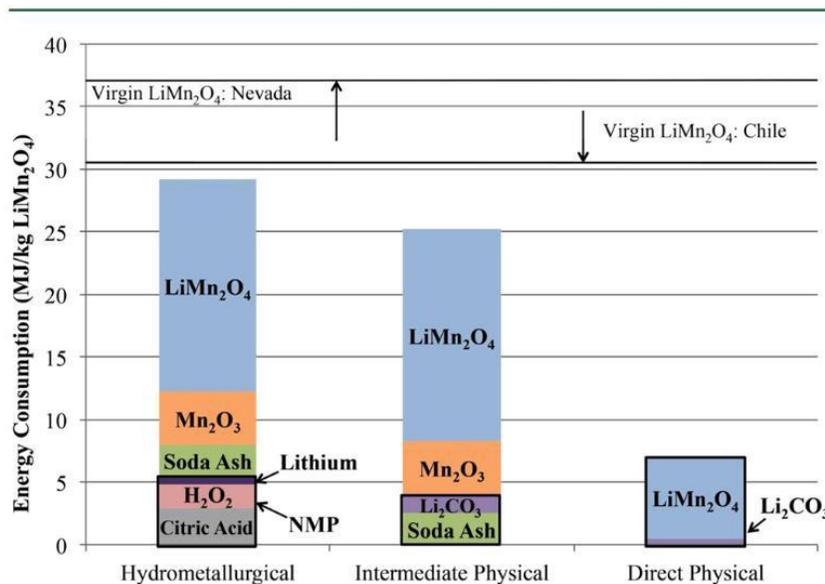


Figure 42 Estimated Energy Consumption to Produce LiMn_2O_4 Through EV Battery Recycling¹⁹⁵

Note: Components in framed boxes are produced (Li , Li_2CO_3 , LiMn_2O_4) or consumed (H_2O_2 , citric acid, soda ash) in the recycling processes. Components outside the black boxes are consumed during upgrading of recovered lithium compounds to cathode material.

Figure 43, taken from the same academic paper, illustrates the estimated potential reduction in total energy consumption when combinations of LiMn_2O_4 , aluminum, and copper are recycled in a closed-loop system. The study authors estimated a 48% reduction in total cradle-to-gate energy demand when cathode material, aluminum, and copper are recycled in a direct physical recycling process. The study did not quantify the energy benefit of recovering other battery materials (e.g., carbon, electrolyte) in the intermediate and direct physical recycling processes and the authors note that recovering these materials would yield additional energy, environmental, and potential economic benefits.

¹⁹⁴ Dunn, J. B., Gaines, L., Sullivan, J., & Wang, M. Q. (2012). "Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries." *Environmental Science & Technology*, 46(22), 12704–12710. doi:10.1021/es302420z

¹⁹⁵ Dunn, J. B., Gaines, L., Sullivan, J., & Wang, M. Q. (2012). "Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries." *Environmental Science & Technology*, 46(22), 12704–12710. doi:10.1021/es302420z

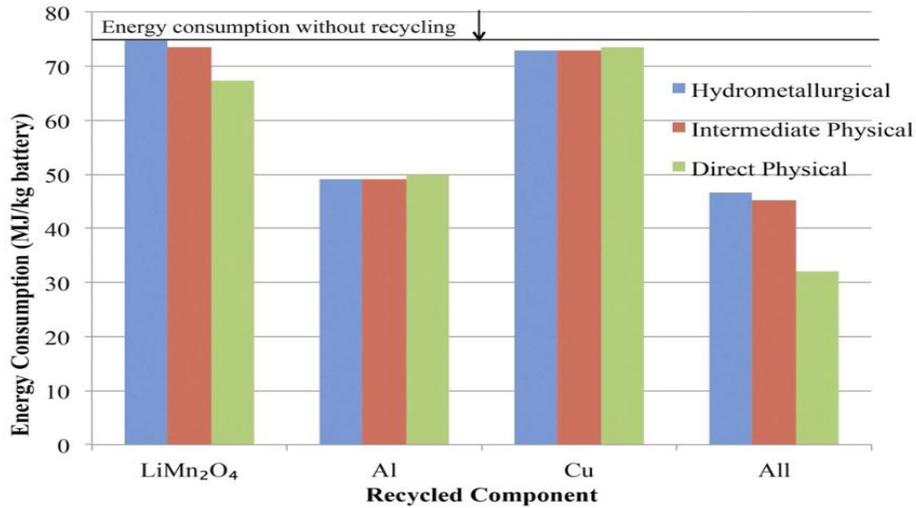


Figure 43 Total Estimated Energy Consumption (MJ/kg battery) Using Recycled vs Virgin Materials¹⁹⁶

An academic study published by Richa et al in 2017¹⁹⁷ found that recycling li-ion EV batteries provided CED credits of approximately 3.5 million MJ (see Figure 44), and that hydrometallurgical recycling provided 25% higher CED credits compared to the pyrometallurgical process, as pyrometallurgical processes require four times the energy of hydrometallurgical processes. The results also showed that for a mixed waste stream of equal fractions of LMO, NMC, and LFP batteries, the CED savings can be as high as 4 million MJ owing to slightly higher energy savings from recycling the NMC and LFP chemistries.¹⁹⁸

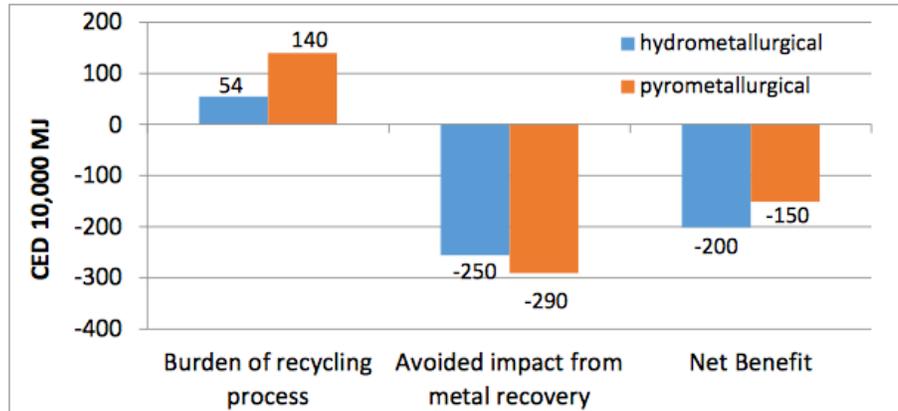


Figure 44 Net Energy Benefit of EV Battery Recycling (CED)¹⁹⁹

¹⁹⁶ Ibid.

¹⁹⁷ Richa, K., Babbitt, C.W., & G. Gaustad. (2017). "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy." *Journal of Industrial Ecology*, 21(3), 715-730. < <https://doi.org/10.1111/jiec.12607>>

¹⁹⁸ Ibid.

¹⁹⁹ Ibid.

6.3 Environmental Impacts of EV Battery Recycling

EV battery recycling is an important source of secondary metals and can reduce the need of extracting primary metals. As a result, EV battery recycling and the use of recycled metals in new batteries may offer GHG emissions savings and other environmental benefits. Almost all of the available LCA studies focus on the production and use phase of the EV batteries, as there is limited access to publicly available and transparent data on any of the existing recycling processes.²⁰⁰ To date, the recycling of EV batteries has not generally been included within the system boundaries of the LCAs of EV batteries due to lack of data on this pathway.²⁰¹

Other factors that contribute to the uncertainty and varying results of LCAs include what chemistries are assumed in the flow; the assumed quality of the output; and modelling choices. In addition to these parameters, the fact remains that there are no large-scale flows of li-ion batteries from vehicles to assess, which means that the scale-up of results to industrial size is left out or based on assumptions.²⁰²

A study published in *Nature* in 2019²¹⁰ compared the GHG emissions from manufacturing and recycling li-ion batteries using pyrometallurgical, hydrometallurgical, and direct cathode recycling methods for three cathode chemistries:

- nickel manganese cobalt oxide (NMC622) (60% nickel, 20% manganese and 20% cobalt);
- nickel cobalt aluminum oxide (NCA); and
- iron phosphate (LFP)

For both the hydrometallurgical and direct recycling processes, the authors assumed that any materials not recovered through the recycling process (e.g., transition metals, lithium or cathode materials) or as scrap (cell hardware and current collectors) were incinerated. Parts (a) and (b) of Figure 45, taken from the research paper, show the CO₂eq emissions associated with each kilogram of cylindrical battery manufactured and recycled using each recycling process for the US average power grid, as well as the medians and 95% confidence intervals for the GHG emissions avoided when using each recycling process. Parts (c) and (d) of Figure 45 show the results for pouch cells.

For LFP cells, the study found that all of the recycling methods and cell formats considered resulted in net increases in CO₂eq emissions when accounting for the GHG emissions caused by incinerating non-valuable materials. For both nickel- and cobalt-containing cathodes, the median result was a net increase in GHG emissions, and these increases were statistically significant except for cylindrical NCA

²⁰⁰ Ellingsen, L. A.-W., Hung, C. R., & Strømman, A. H. (2017). "Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions." *Transportation Research Part D: Transport and Environment*, 55, 82–90. doi:10.1016/j.trd.2017.06.028 [sci-hub.tw/10.1016/j.trd.2017.06.028](https://doi.org/10.1016/j.trd.2017.06.028)

²⁰¹ Ellingsen, L. A.-W., Hung, C. R., & Strømman, A. H. (2017). "Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions." *Transportation Research Part D: Transport and Environment*, 55, 82–90. doi:10.1016/j.trd.2017.06.028 [sci-hub.tw/10.1016/j.trd.2017.06.028](https://doi.org/10.1016/j.trd.2017.06.028)

²⁰² Romare, M., Dahllof, L., IVL Swedish Environmental Research Institute. (2017). "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles." <<http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emission+s+from+lithium+ion+batteries+.pdf>>

cells, where the combination of cathode materials that are recoverable through the pyrometallurgical process (manganese is not recovered, but nickel and cobalt are) and the cell hardware resulted in some ambiguity. About 22% of the scenarios resulted in net reductions in CO₂eq emissions per kilogram, and these scenarios occurred when the recycled content of the nickel and cobalt offset was low and embodied emissions were high.

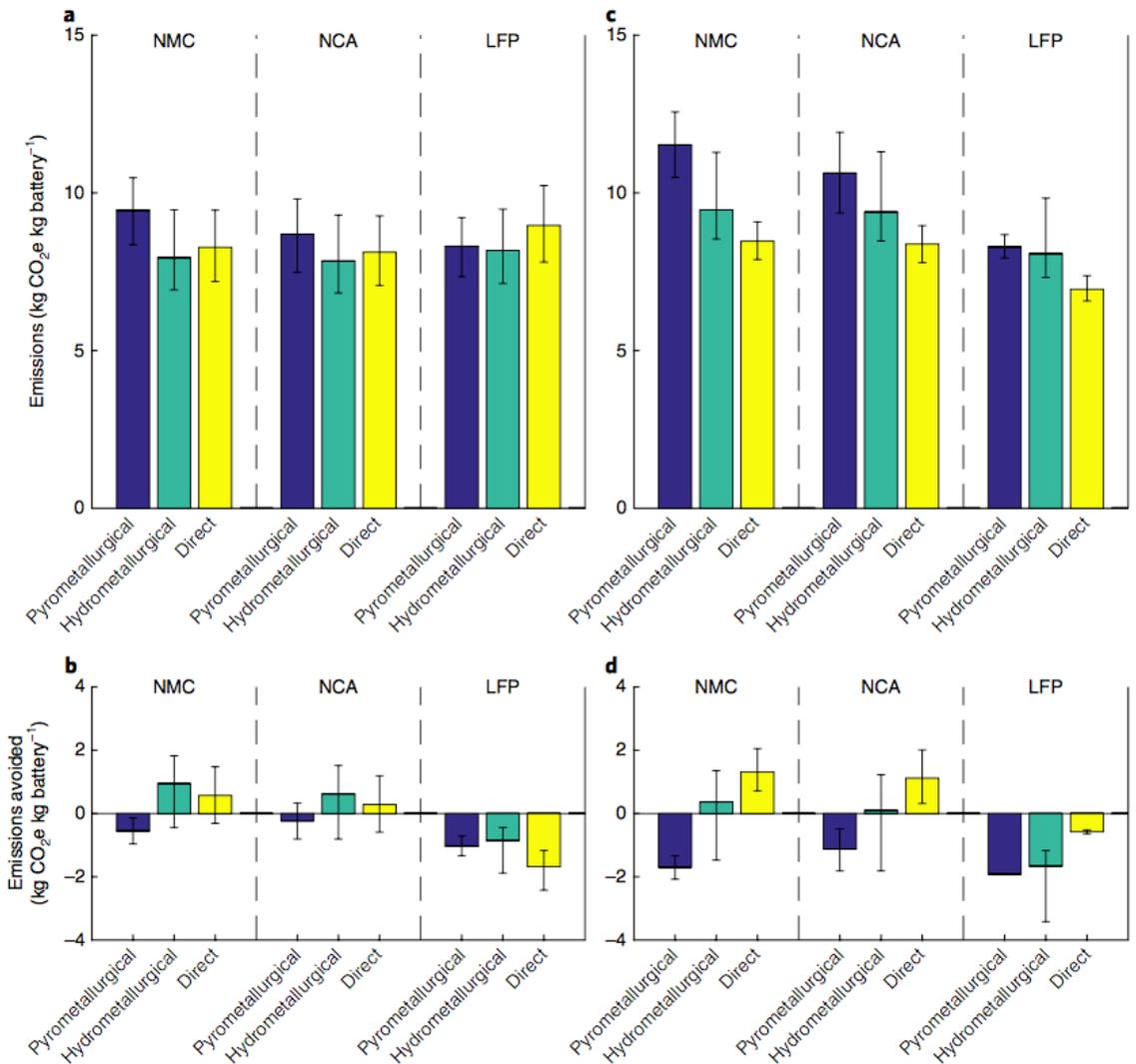


Figure 45 EV Battery Recycling Emissions from Different Recycling Processes for Cylindrical Cells (a,b) and Pouch Cells (c,d)²⁰³

The above findings by Ciez and Whitacre²¹² assume that the direct recycling process recovers 100% of the cathode material, but the authors were also interested in determining how much cathode material must be recovered to result in GHG emissions reductions. Therefore, they also compared the GHG emissions reductions from a direct cathode recycling method (at various yield rates) over not recycling the manufactured cells.

The study found that using direct cathode recycling for NMC cells offered slightly larger emissions savings than using the direct cathode recycling process for NCA cells. The results also found that recycling LFP cells (both cylindrical or prismatic cells) does not result in net reductions in GHG emissions because of the incineration of non-valuable materials and the lack of nickel and cobalt content. The conclusions

²⁰³ Ciez, R.E., & J.F. Whitacre. 2019. "Examining different recycling processes for lithium-ion batteries." *Nature Sustainability*, 2, 148-159. doi: 10.1038/s41893-019-0222-5

regarding CO₂ reductions by chemistry and battery type were:

- For cylindrical NMC cells, an estimated 78% (53-115%) of the cathode material must be recovered to result in a net CO₂eq emissions reduction;
- For NCA cells, 88% (58-133%) of the cathode would need to be recovered to result in a net CO₂eq emissions reduction; and
- For pouch cells, 59% (49-74%) of NMC cathodes or 63% (48-87%) of NCA cathodes must be recovered to result in a net CO₂eq emissions reduction.

The study also found that since the hydrometallurgical recycling process offers median reductions in CO₂eq emissions, the recovery rate of cathode material from a direct recycling process required to result in more CO₂eq offsets is high (>40%). However, since pyrometallurgical recycling results in net increases in GHG emissions, the cathode yield rate from a direct cathode recycling process can be lower and still result in lower GHG emissions increases than pyrometallurgical recycling.²⁰⁴

A study published by Berg et al in 2019²⁰⁵ assessed the environmental impacts of *in silico*²⁰⁶ designed lithium metal batteries (LMBs) compared to existing li-ion battery designs in a vehicle perspective. The study found that LMBs based on NMC chemistry resulted in the lowest climate impact for both a Nissan Leaf and Tesla EV. However, it also found that the recycling climate gains are relatively small compared to the use and production phase impacts for all types of the batteries considered in the analysis (see Figure 46 and 47).

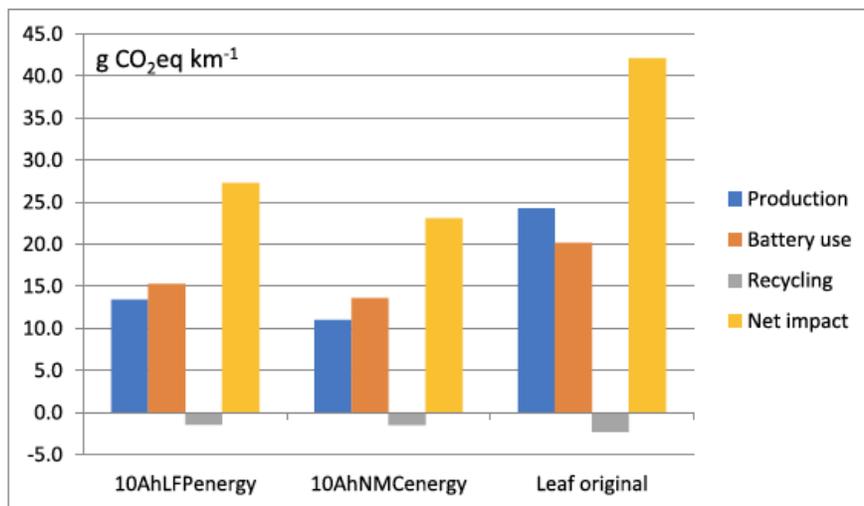


Figure 46 Estimated Climate Impacts Through Production, Use and Recycling for Three Different Batteries for Nissan Leaf²⁰⁷

²⁰⁴ Ciez, R.E., & J.F. Whitacre. 2019. "Examining different recycling processes for lithium-ion batteries." *Nature Sustainability*, 2, 148-159. doi: 10.1038/s41893-019-0222-5

²⁰⁵ Berg, H., & Zackrisson, M. (2019). *Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle traction batteries. Journal of Power Sources*, 415, 83–90. doi:10.1016/j.jpowsour.2019.01.047 ([sci-hub.tw/10.1016/j.jpowsour.2019.01.047](https://doi.org/10.1016/j.jpowsour.2019.01.047))

²⁰⁶ Refers to a theoretical modelled value rather than one measured in real world applications

²⁰⁷ Berg, H., & Zackrisson, M. (2019). *Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle traction batteries. Journal of Power Sources*, 415, 83–90. doi:10.1016/j.jpowsour.2019.01.047 ([sci-hub.tw/10.1016/j.jpowsour.2019.01.047](https://doi.org/10.1016/j.jpowsour.2019.01.047))

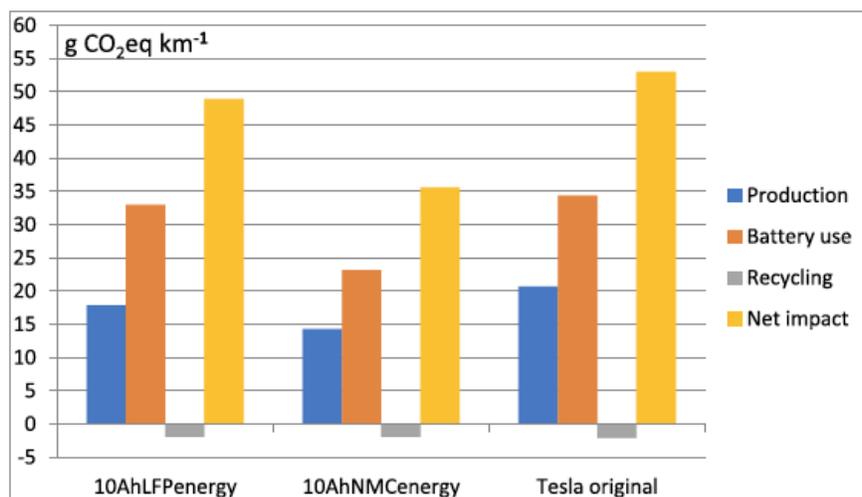


Figure 47 Estimated Climate Impacts of Tesla Original, 10Ah LFP and NMC Battery Designs Through Production, Use and Recycling²⁰⁸

Qiao et al. (2019) also attempted to quantify the environmental impacts of recycling EV batteries. The authors concluded, “since the energy consumption and GHG emissions of battery recycling is relatively high, battery recycling seems to contain low environmental benefits.” They noted, however, that EV battery recycling can provide recycled cathode active material, which is the most important and expensive part in the EV battery. They also emphasized that the environmental benefits of EV battery recycling are likely to be improved with the development of new technologies. They further noted that other research papers conclude that SO_x emissions during the production of NMC/LFP cathode materials can be reduced by nearly 100% if they are recycled rather than produced from virgin materials. The reduction rate is high even for pyrometallurgical process which consumes huge amounts of energy because of the high amount of SO_x is emitted directly and indirectly during the manufacturing process.

Cusenza et al. (2019)²⁰⁹ estimated the life cycle environmental impacts of a li-ion PHEV battery pack made of an LMO-NMC composite cathode (with a nominal capacity of 11.4kWh able to be used for about 140,000 km of driving). Assuming the battery was recycled through a pyrometallurgical process, the results of the analysis showed that recycling the battery pack contributes less than 11% to all of the assessed impact categories (e.g., ozone depletion potential, GWP, etc.), with the exception of freshwater ecotoxicity (60%). The authors’ findings on environmental impacts are quoted below:

“Besides generating potential environmental impacts, recycling results in environmental credits due to recoverable products... The environmental credits associated with materials recovered through battery recycling processes exceed the associated environmental impacts linked to the recycling process in all the impact categories examined, with the exception of ozone depleting

²⁰⁸Berg, H., & Zackrisson, M. (2019). Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle traction batteries. *Journal of Power Sources*, 415, 83–90. doi:10.1016/j.jpowsour.2019.01.047 ([sci-hub.tw/10.1016/j.jpowsour.2019.01.047](https://doi.org/10.1016/j.jpowsour.2019.01.047))

²⁰⁹ Cusenza, M.A., Bobba, S., Ardente, F., Cellura, M., & F. Di Persio. (2019). “Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles.” *Journal of Cleaner Production*, 215, 634-649. <https://doi.org/10.1016/j.jclepro.2019.01.056>

potential, ionizing radiation, and freshwater ecotoxicity. The environmental credits are particularly relevant to the impact categories of marine eutrophication (-27%), human toxicity (about -20% for human toxicity no cancer effect and -40% for human toxicity cancer effect), particulate matter (-17%) and abiotic resource depletion (-16.4%). This outcome confirms the environmental benefits of recovering Li-ion battery materials, as reported in previous studies.”

The Cuzenza et al. (2019) article²¹⁰ also acknowledges that the environmental benefits of recycling could be increased further if the other cell components/materials, such as graphite, electrolyte and aluminum, were recovered (i.e., by designing battery cells for disassembly and making it easier to separate cell components).

A 2014 study by Dunn et al²¹¹ examined the GHG and SO_x reductions for different cathode materials recovered from pyrometallurgical, indirect physical, and direct physical recycling processes as compared to producing them from virgin materials. In the case of the commercial pyrometallurgical process, which the authors analyzed only for the case of LCO-containing batteries, the study found that GHG reductions for producing the cathode material could be between 60-75%. If recycled LCO were incorporated into EV batteries that would have used virgin LCO prepared hydrothermally, the cathode material contribution to overall battery GHG intensity would decline from 57% to 25% and overall battery GHG intensity would decline by 43%. The results also showed that the SO_x intensity of recycled LCO is nearly 100% lower than from production of virgin LCO. As stated by the study's authors:

“this significant SO_x reduction holds true even for the energy-intensive pyrometallurgical process because the SO_x-intensive smelting step that occurs during recovery of virgin Co is completely avoided.”

Another key finding of the study was that the direct recycling process has the potential to reduce GHG and SO_x emissions from cathode material production by 81-98% and 72% to nearly 100%, respectively. These findings indicate that, particularly for cobalt- and nickel-containing cathode materials, recycled cathode materials are likely less GHG- and SO_x-intensive than cathode materials produced from scratch.²¹² In the case of LMO cathode material, which is the least energy- and GHG-intensive to produce, the study found that using recycled cathode material from the intermediate and direct recycling processes could reduce overall battery GHG emissions by 2% and 16%, respectively.

²¹⁰ Cuzenza, M.A., Bobba, S., Ardente, F., Cellura, M., & F. Di Persio. (2019). “Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles.” *Journal of Cleaner Production*, 215, 634-649. <https://doi.org/10.1016/j.jclepro.2019.01.056>

²¹¹ Dunn, J.B., Gaines, L., Kelly, J.C., James, C., and K.G. Gallagher. (2014). “The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction.” doi: 10.1039/c4ee03029j

²¹² Ibid.

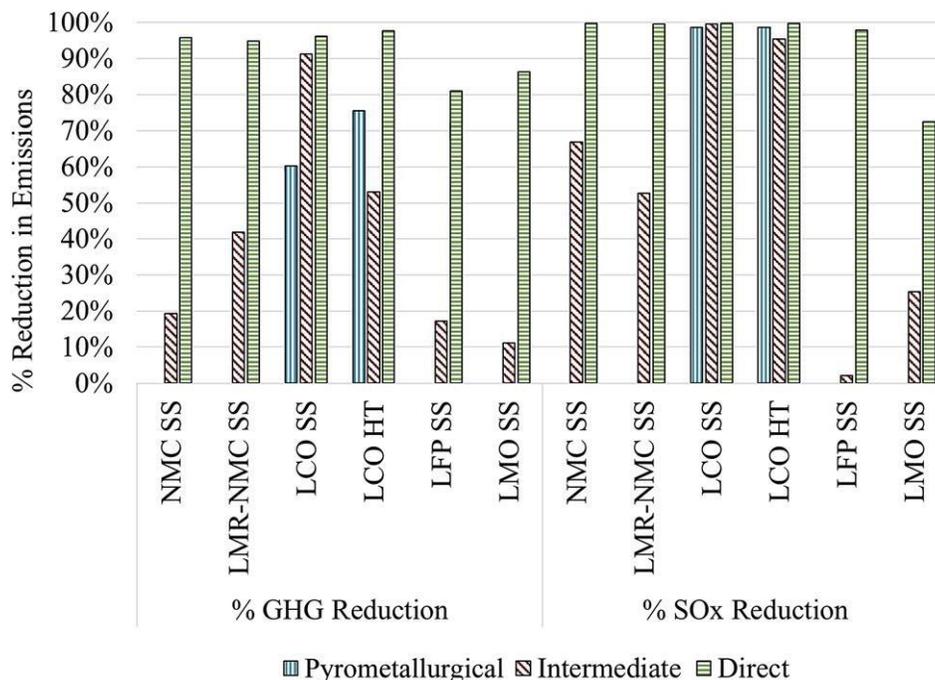


Figure 48 Estimated GHG and Sox Reductions for Cathode Materials Recovered from Li-ion Battery Recycling Processes Compared to Production from Virgin Materials²¹³

A study published by Dunn et al in 2012²¹⁴ calculated the air emissions generated when recovering LiMn_2O_4 , aluminum, and copper from li-ion batteries in three recycling processes (hydrometallurgical, intermediate physical, and direct physical recycling) and examined the effects of closed-loop recycling on environmental impacts of battery production. Figure 49, taken from the article, shows the corresponding reduction in GHG emissions when recycled cathode materials, aluminum, and copper are used in li-ion batteries. The results show that obtaining LiMn_2O_4 from the hydrometallurgical process yields negligible GHG emissions reductions in part because of the calcining step, which emits GHGs from the burning of PVDF and carbon. In a closed loop recycling scenario that would use LiMn_2O_4 , copper, and aluminum recovered from the direct physical recycling process, GHG reductions from a scenario with no recycling are approximately 54%.²¹⁵ The research in the study is now considered out of date as chemistries, technologies and other factors have changed considerably since it was published.

²¹³ Dunn, J.B., Gaines, L., Kelly, J.C., James, C., and K.G. Gallagher. (2014). "The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction." doi: 10.1039/c4ee03029j

²¹⁴ Dunn, J. B., Gaines, L., Sullivan, J., & Wang, M. Q. (2012). "Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries." *Environmental Science & Technology*, 46(22), 12704–12710. doi:10.1021/es302420z

²¹⁵ Ibid.

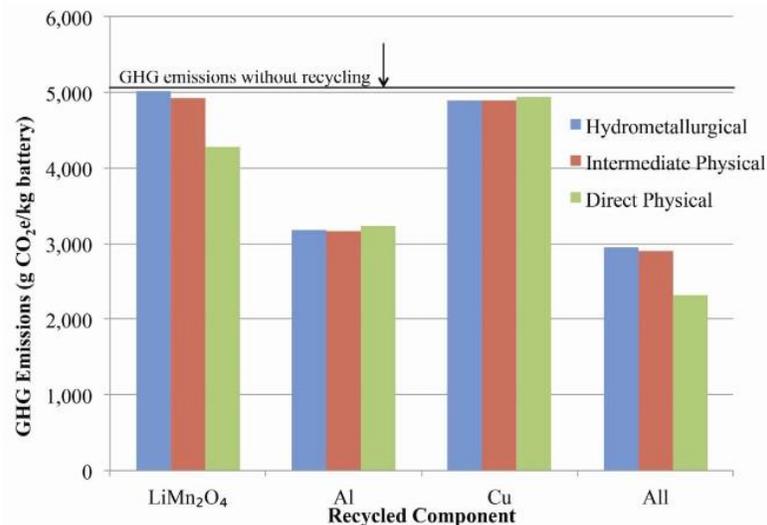


Figure 49 Total Estimated Cradle-to-Gate GHG Emissions of an EV Battery Made from Virgin Materials with Recycled Cathode Materials, Recycled Aluminum and Recycled Active Material and Aluminum (2012)²¹⁶

The US EPA and US DOE²¹⁷ carried out a LCA of li-ion batteries in BEV and PHEV applications to identify the process (including materials extraction, and processing, manufacturing, use, recycling and disposal) that had the largest impacts on public health and the environment. For the recycling stage LCA, three recycling technologies for li-ion batteries (hydrometallurgical, pyrometallurgical, and direct recovery processes) were assessed based on a best- case scenario, with life cycle inventory data primarily obtained from the relevant battery recyclers. The final data were the average of the three results; the individual impact of each process was not shown.

The US EPA study found that recycling lowered the overall life cycle impacts, especially in the category of ozone depletion potential. These benefits came from the use of secondary materials instead of raw materials in the extraction and processing stage. The report also highlighted several opportunities to reduce the environmental impacts of EV batteries, among which recycling was identified as beneficial to lowering the environmental impact when battery manufacturers maximize the use of recycled materials in the manufacture of new battery materials, thus closing the loop of material flows.²¹⁸

A report recently published by Element Energy²¹⁹ identified the GHG impacts of different recycling processes on two types of batteries: LMO and a mix of 35% NMC, 35% NCA and 30% LFP. Table 18 summarizes the results. The data in the table are based on several literature sources and industry inputs used in a Swedish study. The table shows that all recycling processes except pyrometallurgical result in CO₂ emissions savings.

²¹⁶ Ibid.

²¹⁷ US Environmental Protection Agency. April 24, 2013. "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles." <https://www.epa.gov/sites/production/files/2014-01/documents/lithium_batteries_lca.pdf>

²¹⁸ Ibid.

²¹⁹ https://www.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf

Table 18 Comparison of GHG Emissions from Different Recycling Processes for Li-ion Batteries²²⁰

Process	Battery Chemistry	gCO ₂ eq/kg battery
Hydrometallurgical	Mix	-1,035
Pyrometallurgical	Mix	+1,244
Pyrometallurgical + Hydrometallurgical	LCO	-1,500
Hydrometallurgical	LCO	-2,000
Intermediate Physical	LCO	-2,000
Direct Physical	LCO	-2,500

6.4 Comparison of Energy and Environmental Impacts of EV Battery Reuse vs. Recycling

The studies presented in this section were found through an extensive technical and academic literature search and review. None of the studies identified directly compared the net environmental impacts of EV battery reuse vs. EV battery recycling vs. using new EV batteries (currently li-ion designs of various chemistries, and expected to remain for the next 5-10 years). This lack of clear, focused information is identified as a research gap in Section 9 of this report. API could commission a study, ideally through a university research team, to address this exact question.

From the analysis carried out in this study, the following can be concluded:

EV battery reuse offers many advantages in terms of resource conservation if it can be proven effective in the longer term. Any reuse projects in place now have not been running for the 5-, 10-, 15- or 20-year lifespan predicted for these batteries, therefore at this time it is not known with certainty if any technical issues could arise. Issues around liability have been raised but not resolved.

If successful in reuse applications, reuse of EV batteries offers many advantages:

- It displaces or delays the need to mine new materials such as nickel, cobalt and manganese to make new li-ion batteries by a number of years. This has environmental benefits which are not fully captured in the LCA studies reviewed for this report, therefore a separate research project should be initiated to properly quantify these benefits;
- It provides considerable revenue by effectively re-selling well performing li-ion battery

²²⁰ Romare, M., Dahllof, L., IVL Swedish Environmental Research Institute. (2017). "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles." http://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emission_s+from+lithium+ion+batteries+.pdf

components rather than recycling them for metal recovery. Reuse is higher on the waste management hierarchy than recycling therefore this path follows an environmentally responsible principle.

Not all of these advantages have been properly quantified in research papers reviewed to date.

One possibility is that the chemistry of EV batteries changes when used in long-term ESS applications, and this may impact on recycling process efficiencies. Given that the “new” EV battery recycling technologies are not yet operating at full scale, and no li-ion batteries have yet been through the full EV cycle followed by 5-20 years as ESS devices, the answer to this question is not known.

Energy related studies found through the research generally focused on the amount of energy used or saved when an EV battery is directed to an energy storage application vs. through recycling of the battery. Again, while research papers were found which addressed specific aspects of this question none were found that addressed the issue in a holistic way.

The information presented in this section clearly indicates that EV battery recycling has both environmental and energy benefits. However, some of the studies are a few years old and therefore out of date given that battery technology and chemistries have developed rapidly in the last few years.

A need to update the environmental and energy analysis of EV battery reuse vs. recycling is identified as a research gap in Section 9 of this report. The literature review has identified a few research institutes that have carried out extensive LCA studies on both EV battery recycling and reuse. One limitation of some of the studies by Richa et al. is that they have compared reuse of li-ion EV batteries to buying new lead-acid batteries for ESS. The current practice is to use li-ion batteries for ESS, therefore an updated analysis is needed.

The analyses carried out to date identify a clear benefit of direct cathode recycling, however the research for this project has identified that this practice is not yet in place at full scale. Companies like American Manganese, Neometals and others described in Section 5 are currently pilot testing this technology but no full-scale facilities are in place at this time.

6.5 Economic Impacts of EV Battery Reuse vs. Recycling

The analysis in this report clearly identifies that EV battery reuse has a distinct economic advantage over EV battery recycling where EV battery reuse is technically viable. For an EV battery weighing 400kg with 50% remaining capacity (an assumption used for modelling in some of the papers reviewed), recycling can cost anywhere from \$500 to \$1,500 per battery, whereas directing the battery to reuse can generate revenues of at least \$50/kWh. Table 19 below presents a range of values for revenues from reuse and costs for recycling of three of the most popular BEV batteries and two of the most popular PHEV batteries in 2018. Reuse revenues are estimated at 50% to 80% redeployment of cells.

From values presented in Section 4, NREL estimated that reuse costs \$24/kWh with an additional \$20/kWh assumed for B EV battery purchase. This \$20/kWh cost may not be the current market situation. This is one of the research gaps noted in Section 9. Assuming the net cost of reusing the EV batteries is \$44/kWh, the scenarios in the table assume different profits from \$10 to \$40/kWh. At the low range this translates to a sale price of \$54/kWh of the reused battery compared to purchase of a new battery at \$145/kWh for cells and \$190/kWh for packs in 2018.²²¹ At the \$40/kWh profit level, the reused battery would be sold for \$84/kWh, still considerably lower than the purchase price of a new battery. As the costs of new li-ion batteries decrease, it is not known what price reused batteries will be sold for, but a Swedish analysis anticipates that the reuse market will continue, and that sale prices will drop to \$40/kWh.

All batteries in Table 19 use li-ion chemistries. The recycling costs are shown without considering revenue from recovered materials which vary by process and battery content, as shown in Section 5.

Table 19 Estimated Comparative Costs and Revenues for Reusing and Recycling EV Batteries (\$)

Model Type of Vehicle % of US Market in 2018	Chemistry	Battery Size (kWh)	Battery Weight (kg)	Reuse Value at 50% Reuse and \$10/kWh	Reuse Value at 60% Reuse and \$20/kWh Profit	Reuse Value at 70% Reuse and \$30/kWh Profit	Recycling Cost at \$1,000/t	Recycling Cost at \$2,000/ t	Recycling Cost at \$3,000/t
Tesla Model 3 B EV	NCA	80.5	478	+\$403	+\$966	+\$1,691	-\$478	-\$956	-\$1,434
Chevrolet Bolt B EV 8%	C/NMC	60	435	+\$300	+\$720	+\$1,260	-\$435	-\$870	-\$1,305
Nissan Leaf B EV 6%	C/NMC	40	303	+\$200	+\$480	+\$840	-\$303	-\$606	-\$909
Toyota Prius Prime PHEV 23%	C/NMC	8.8	120	+\$44	+\$106	+\$185	-\$120	-\$240	-\$360
Chevrolet Volt (Generatio n 2) PHEV	C/NMC- LMO	18.4	183	+\$92	+\$221	+\$1,159	-\$183	-\$366	-\$549

As an example, for a Chevrolet Bolt with a capacity of 60kWh when new, the net profit in the reuse market would be \$300 in a worst-case scenario and almost \$1,300 in a best-case scenario. Recycling costs on the other hand range from \$400 to \$1,300 per unit before material credits.

One of the significant uncertainties is the actual costs of EV battery recycling. Different references have quoted these costs at \$1,000 to \$5,000/tonne, with the latter value coming from Argonne National Laboratory (ANL), which is considered a reliable source. Research carried out during this study could not identify firm costs as recyclers and customers interviewed considered the information commercially sensitive and confidential. The analysis in Table 19 was carried out for recycling values of \$1,000 to \$3,000/tonne. Battery pack costs are levied by weight, compared to the reuse analysis which

²²¹ Hanley, S. December 7, 2018. "Envision Energy Says EV Battery Cell Costs Will Fall Below \$50/kWh by 2025." <<https://cleantechnica.com/2018/12/07/envision-energy-says-ev-battery-cell-costs-will-fall-below-50-kwh-by-2025/>>

uses kWh.

One of the key strategic issues regarding EV battery recycling is that it provides companies such as Tesla with a supply of strategic materials, particularly cobalt. For this reason, Tesla favours recycling over reuse and is in the process of establishing an EV battery recycling facility at one of their locations. On the other hand, large companies with the capital available to invest are reluctant to invest in large scale recycling at this time until there is more certainty regarding future battery chemistries and an assured supply of material through an established collection infrastructure. Given the significant interest in cathode material specifically, a case could be made for two sets of future market players – dismantlers and low-grade scrap recovery with the valuable cathodes sold to a more sophisticated direct cathode recycler.

The conclusion of the analysis in Table 19 is that EV battery reuse is a much more economically attractive option for EV battery owners for the foreseeable future compared to EV battery recycling. As the supply of EV batteries increases, and more standards are imposed on the reuse industry, the cost structure may change. An updating of EV reuse costs is identified as a research gap in Section 9.

Based on the research carried out for this study, 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 more favourable for the foreseeable future. We see no evidence that recycling will be carried out at a positive value at the EV battery level in the next five years, as the technologies that promise to achieve this have not yet been proven at commercial scale (see Section 5), and reuse is proven to result in a positive cash flow.

7 Ongoing Research, Current and Future Legislation

Many organizations are working on options for EOL management of EV batteries, some supported by private industry, national governments or large multi-national bodies such as the EU. Some of these are described in this section along with current and potential future legislation focused on EV batteries.

7.1 Selected Research in the US

Numerous efforts are underway by governments and universities as well as private sector companies across the US to identify better ways to recycle and reuse EOL EV batteries, as well as to design better batteries. A selection of these efforts is described in this section.

7.1.1 US DOE Lithium Battery Research Initiative

The US government is interested in capitalizing on the growing interest from investors, automakers, and inventors in the EV battery recycling market, as well as in protecting the supply of strategic materials used in industry, defence, and the wider economy. In late January 2019, US DOE Secretary Rick Perry announced funding for a Battery Recycling Research & Development Center, as well as a Lithium-Ion Battery Recycling Prize. The DOE's Vehicle Technologies Office (VTO) within the Office of Energy Efficiency and Renewable Energy cited the need to recover and recycle critical materials such as cobalt and lithium from lithium-based batteries used in consumer electronics, defence, energy storage, and transportation applications. Citing Executive Order 13817, which calls on reducing "the Nation's vulnerability to disruptions in the supply of critical minerals, which constitutes a strategic vulnerability for the security and prosperity of the United States²²²," the DOE set a goal for the Prize and the R&D Center of developing technologies that can profitably capture 90% of all lithium-based battery technologies in the US.

The further goal is to find innovative solutions to collecting, storing, and transporting discarded li-ion batteries for eventual recycling – all within the US. Cash prizes totaling \$5.5 million will be awarded to contestants over three progressive phases, focusing successively on solutions from concept to prototype to demonstration. An additional \$15 million is earmarked to establish a Lithium Battery R&D Recycling Center, called the ReCell Center.²²³ Its mission is "to grow a sustainable advanced battery recycling industry by developing economic and environmentally sound recycling process that can be adopted by industry for li-ion and future battery chemistries." Part of its effort is to research and develop cost-effective recycling processes to recover lithium battery materials, with a goal of potentially recovering all active battery materials.

²²² "Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals." December 20, 2017.

<www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/>

²²³ <http://recellcenter.org/>

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The Center will be led by ANL along with the NREL, Oak Ridge National Laboratory, and several universities including Worcester Polytechnic Institute, University of California at San Diego and Michigan Technological University.²²⁴ Key research and development goals for the ReCell Center are to:

1. Establish a national 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.
2. Create new electrode and cell designs, enabling cell rejuvenation and more effective material recovery during recycling.
3. Develop new processes to enable cathode-to-cathode recycling of cathode powders using temperatures below 900° Celsius.
4. Develop new processes to recover battery materials that are currently not recovered and end up in the waste stream.
5. Assess the economic value and impacts on the recycling stream of EOL options, in hopes of decreasing the cost and incentivizing sale of EVs.²²⁵

ReCell researchers will focus on four specific research areas to further their goals, and to enable profitable li-ion battery recycling for industry adoption:

1. Direct cathode recycling – for recycling processes to generate materials used directly in new batteries, without costly reprocessing (closed-loop applications);
2. Cost-effective technologies – to recycle other battery materials, providing additional revenue streams;
3. Design for recycling – new battery design initiatives to ease future battery recycling; and
4. Modelling and analysis tools – to help direct efficient research and development work and for validation of research.²²⁶

Research teams are investigating cobalt-free batteries for EVs. While this has the advantage of reducing dependence on the unstable but primary source of cobalt from the Democratic Republic of the Congo, a disadvantage is that it could eventually undermine current models for EV battery recycling as the economic driver is in cobalt recovery at present. As well, during the start-up phase, the ReCell Center is exploring the question of ‘what should the long-term research be to avoid conflicts coming into

²²⁴ *Energy Department Announces Battery Recycling Prize and Battery Recycling R&D Center*, January 17, 2019, www.energy.gov/articles/energy-department-announces-battery-recycling-prize-and-battery-recycling-rd-center, and www.washingtonpost.com/national/environment/correction-lithium-ion-batteries-recycling-story/2019/02/16/658af708-31fd-11e9-8781-763619f12cb4_story.html?utm_term=.5d8960446c33

²²⁵ <http://recellcenter.org/about/>

²²⁶ <https://waste-management-world.com/a/doe-launches-uss-first-lithium-ion-battery-recycling-rd-center>

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the market for long-term for battery recycling.²²⁷

7.1.2 US Advanced Battery Consortium

The US Advanced Battery Consortium (USABC)²²⁸ is a collaborative organization between Fiat-Chrysler, Ford Motor Company and General Motors²²⁹. This initiative is a subsidiary of the United States Council for Automotive Research LLC (USCAR), enabled by a cooperative agreement with the US DOE. The USABC's mission is to develop electrochemical energy storage technologies that support commercialization of HEV, PHEV, BEV and fuel cell vehicles. In support of its mission, USABC has developed mid- and long-term goals to guide its projects and measure its progress.²³⁰

In November, 2018, a materials engineering research team at Worcester Polytechnic Institute (WPI) was awarded a grant to extend development of its process to recycle spent li-ion batteries and produce new cathode materials that are increasingly being adopted by automotive battery makers to reduce cost and increase energy density.²³¹

Building on a successful phase 1 (completed earlier in 2018), the contract award, which includes a 50% cost share, funds a 24-month phase 2 project. This contract will enable WPI to demonstrate the ability of its process to recycle spent Li-ion batteries and produce new cathode materials to generate a higher nickel cathode powder. This material is of increasing relevance in the current market shift towards higher nickel content in EV batteries.

The WPI team, led by Yan Wang, William Smith Foundation Dean's Associate Professor of Mechanical Engineering, has developed a patented closed-loop recycling process in which the batteries are first shredded. After the shredded materials are separated, the cathode powders are dissolved. By adjusting the chemistry of the solution, new materials, in the desired ratios, can be precipitated out as precursor and used to make cathode material for new batteries. Other materials recovered from the shredded batteries, including steel, graphite, and plastics, can also be recycled, thus improving the overall business model.

As part of the phase 1 USABC project, Wang took the process developed in his lab and proved that it can be scaled up to produce cathode materials that are equal in quality to those available commercially, and that those recovered materials can be used to make new EV batteries that are comparable to units sold by OEMs for use in HEVs and BEVs.

²²⁷ Maggie Mann, Transportation Infrastructure Team Lead, Nat'l Renewable Energy Laboratory, *PV and Battery Recycling Research at DOE National Labs*, presented at "From Cradle to Grave: Addressing EOL Management for PV Panels and Batteries for Electric Vehicles and Energy Storage," April 3, 2019, CA Public Utilities Commission Auditorium.

²²⁸ United States Council for Automotive Research LLC. "U.S. Advanced Battery Consortium LLC." <<https://www.uscar.org/guest/teams/12/U-S-Advanced-Battery-Consortium-LLC>>

²²⁹ United States Council for Automotive Research LLC. November 7, 2018. "News Release: USABC Awards \$1.08 Million Li-ion Battery Recycling Project to Worcester Polytechnic Institute." <<https://www.uscar.org/guest/news/952/News-Release-USABC-AWARDS-1-08-MILLION-LI-ION-BATTERY-RECYCLING-PROJECT-TO-WORCESTER-POLYTECHNIC-INSTITUTE>>

²³⁰ For more information, visit <http://www.uscar.org/usabc>.

²³¹ "US Advanced Battery Consortium funds extension of lithium-ion battery recycling process." November 7, 2018. <https://www.eurekalert.org/pub_releases/2018-11/wpi-uab110718.php>

The WPI recycling process was shown to be effective in recycling batteries that contain the most commonly used cathode materials at the time the research was completed to produce new cathode powders. But over the past few years, battery makers and car manufacturers have increasingly been moving towards higher nickel cathode formulations in efforts to reduce the quantity of cobalt contained in the cathode powders.

The switch to nickel is resulting in better batteries, as nickel-rich cathodes offer higher energy density (a greater ability to store energy) than cobalt-rich cathodes. But, Wang noted, producing nickel-rich cathodes is a more demanding process that requires additional steps not required for cobalt-rich cathodes. With the new USABC award, Wang and his team want to demonstrate their ability to produce high-quality nickel-rich cathode powders from materials recovered from recycled batteries, and that those cathode powders can be incorporated into batteries with electrochemical performance on par with OEM control units made with commercial powder. This direct cathode-to-cathode recycling is a similar approach to that described for American Manganese and Neometals in Section 5 of this report. The WPI team will also explore how different anode materials, including lithium, silicon, and titanium dioxide, as well as adhesives used in battery manufacture, affect the recycling process.

As in the original USABC-funded project, the work of making and testing new automotive batteries using the high-nickel cathode powders produced by Wang's team will be subcontracted to A123 Systems and Battery Resources (described in Section 5), a company that has licensed WPI's patented li-ion battery recycling process.

WPI is the first and only university to be granted an award from the USABC. The consortium's funding usually goes to industry, because the focus is always on innovations that can be commercialized and used by the automotive industry.

7.1.3 NAATBatt International

NAATBatt International (NAATBatt) is a not-for-profit trade association of companies, associations and research institutions commercializing advanced electrochemical energy storage technology for emerging high tech applications. NAATBatt states that there are three reasons why recycling li-ion EV batteries is important in North America:

- First, recycling EV batteries is an important practice if one of the principal purposes of vehicle electrification is to protect the environment. The argument for electric cars is seriously undermined if one of the consequences of electrification will be an increasing amount of battery waste consigned to landfills, junkyards and roadsides.
- Second, disposal of high voltage li-ion batteries raises serious environmental concerns. Although li-ion batteries themselves are environmentally benign relative to some other automotive components, such as lead acid starter batteries (excepting, perhaps, the fluorines in electrolytes), used high voltage lithium-ion batteries come with a special hazard: the

possibility of stranded energy. A used battery lying in a junkyard or by the side of the road poses a potentially fatal hazard to a person that touches it by design or by accident. It is essential for public safety that all high voltage li-ion batteries be completely decommissioned and irreversibly discharged at EOL. This is the first step of the recycling process.

- Finally, used li-ion batteries are a source of energy materials, which may be in short supply in North America. The US produces relatively minimal amounts of the lithium, Class I nickel, natural graphite and cobalt used in most li-ion batteries. Anyone manufacturing li-ion battery cells in the US will need to rely, almost entirely, on foreign sources of energy materials for those cells. This tenuous source of supply could put domestic manufacturing of li-ion cells at serious risk. Recycling could be part of the answer. NREL reports that by 2040 the US may be able to source up to 65% of its need for cobalt for li-ion batteries from recycling. This supply buffer could substantially de-risk and help make possible the domestic manufacture of li-ion batteries at scale.

The NAATBatt Workshop on Lithium-Ion Battery Recycling, on July 9-10, 2019, in Buffalo, New York, involved an in depth assessment of four major problems in li-ion battery recycling: collection of batteries; separation and sorting; transportation and storage, and recycling technologies. NAATBatt states that each of these four problems needs better solutions than those available today in order to ensure that a significant percentage of the li-ion batteries soon to come out of EVs at the end of their lives are responsibly recycled.

7.2 Research Initiatives in Other Countries

7.2.1 The Faraday Institution – Faraday Battery Challenge

In the United Kingdom (UK), several projects have been launched within the framework of the Faraday Battery Challenge. One of the first flagship projects was the Recycling of Lithium-ion Batteries (ReLiB) project, a £42 million initiative to accelerate EV uptake by overcoming the related battery challenges.²³² This project, which is being led by the University of Birmingham in collaboration with seven other universities (Leicester, Newcastle, Cardiff, Liverpool, Oxford Brookes, Edinburgh) and 14 industrial partners, aims to find the most economically efficient and environmentally friendly methods to recycle and reuse li-ion batteries and to advise on legislation and policies related to this.²³³ The goal is to enhance the overall efficiency of the supply chain and ensure that the UK has the facilities needed for safe, economic, and environmentally sound management of the materials contained in li-ion batteries.

²³²<https://www.findaphd.com/phds/project/phd-studentship-in-the-recycling-of-li-ion-battery-cathodes-faraday-institution/?p97587>

²³³ <https://www.findaphd.com/phds/project/phd-studentship-in-the-recycling-of-li-ion-battery-cathodes-faraday-institution/?p97587>

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The key components of the project are²³⁴:

- a ‘triage’ system for used battery assessment;
- fully autonomous gateway testing and robotic sorting;
- an assessment of the relative engineering and economic gains for various second-life applications;
- the development of recycling technologies to segregate and purify the different materials into a useful form for direct reuse in batteries or other applications (e.g., stationary energy storage);
- life cycle analysis and techno-economic assessment of each recycling route developed;
- development of new business models to promote the collection and sorting of batteries;
- review of the regulatory framework for battery recycling in the UK and analysis of which EU waste laws should be retained law in the UK after Brexit; and
- full characterization of active materials from cells near and at EOL and recycled materials recovered from used batteries, with respect to chemical composition (elemental concentration and distribution), particle size and morphology.

The project is expected to be complete in 2021.

Within the framework of The Faraday Institute, a large number of smaller projects are also being carried out, including the lifetime extension of batteries (Advanced battery life extension), modular battery packs (AmplifII-2), new smart BMS (BABE), new recycling method for EV batteries (CALIBER), re-manufacturing of batteries (R2Lib), as well as efficient value chains for re-manufacturing and recycling of EV batteries (VALUABLE).²³⁵

7.2.2 EU Innovation Deal

In March 2018, the EU Commission made a deal with eight partners to review regulations governing EV battery recycling and reuse scenarios.²³⁶ This Innovation Deal, titled *“From e-mobility to recycling: the virtuous loop of the electric vehicle”*, will analyze whether existing EU law hinders the recycling or reuse of EV propulsion batteries and will also look at any issues in the transposition of these laws to national and regional level.²³⁷ The partners will also investigate possible ways of overcoming barriers to the use of such batteries in a second-life application, and evaluate their feasibility to implement. The main objective of this Innovation Deal is to make the use of propulsion batteries more environmentally and industrially efficient, as well as to increase access to EVs by reducing their total cost, which can be done through optimizing battery usage through its full life cycle.²³⁸

²³⁴The Faraday Institution. “Recycling and Reuse.” <<https://faraday.ac.uk/research/recycle-reuse/>>

²³⁵ Circular Energy Storage. 2019. “State-of-the-art in reuse and recycling of lithium-ion batteries – A research review.”

<<https://cdn.qualenergia.it/wp-content/uploads/2019/07/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf>>

²³⁶ “EU inks Innovation Deal for battery regulation.” March 14, 2018. <<https://www.electrive.com/2018/03/14/eu-inks-innovation-deal-for-battery-regulation/>>

²³⁷ European Commission. “From e-mobility to recycling: the virtuous loop of the electric vehicle.” <https://ec.europa.eu/info/research-and-innovation/law-and-regulations/innovation-deals/signed-innovation-deals_en>

²³⁸ “European Commission selects proposal Renault and LmboXnet for first Innovation Deal.” February 27, 2017.

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7.2.3 European Battery Alliance

The European Battery Alliance (EBA) was launched by European Commission Vice President, Maroš Šefčovič, in October 2017 to promote investment and growth in Europe's EV battery manufacturing value chain. So far, the companies and organizations involved have announced up to €100 billion (\$113 billion) of total private investment in battery ventures, including producing primary and secondary materials in the EU, and building battery cell giga-factories.²³⁹

7.2.4 European Commission's Horizon 2020

The European Commission's Horizon 2020 research fund gave €315 million to battery research from 2014 to 2018, including €164 million to li-ion research. Its latest Horizon 2020 call for proposals has set aside a further €114 million for battery research, including around €30 million for advanced li-ion cells, €13 million for li-ion cell materials and transport modeling, and €2 million for a network of li-ion cell pilot lines.²⁴⁰ It also sets aside about €25 million for solid-state batteries for EVs.²⁴¹ The decision about which projects will receive EU funding will be made by the end of September 2019.²⁴²

7.2.5 AutoBatRec2020

Launched in January 2018 by Germany's Fraunhofer Institute with EU funding from EIT RawMaterials²⁴³ the 'Automotive Battery Recycling 2020' (AutoBatRec2020) project aims to identify efficient recycling practices for EV batteries that are environmentally and ecologically sound and scalable. The overall goal of the project is to develop a thorough understanding of the efficiency, economic feasibility, and overall sustainability of existing processes for EV battery recycling and then recompose them to design an economically attractive EU-wide value chain, and add to a secure supply of raw materials through the recovery of valuable materials from waste streams.²⁴⁴

This project is one of the first of its kind and can be of significant importance for the European end-of-life market if the results are successful.²⁴⁵ The researchers will investigate every aspect of the battery recycling chain, from the collection of EOL batteries to separation of materials, and from existing mechanical crushing and shredding methods to new electrohydraulic solutions that can be combined

<<https://smartsolarcharging.eu/en/european-commission-selects-proposal-renault-and-lomboxnet-for-first-innovation-deal/>>

²³⁹ Insight from Brussels: EU aims to become powerhouse of battery production and recycling." May 2, 2019.

<<https://blogs.platts.com/2019/05/02/eu-powerhouse-battery-production/>>

²⁴⁰ Insight from Brussels: EU aims to become powerhouse of battery production and recycling." May 2, 2019.

<<https://blogs.platts.com/2019/05/02/eu-powerhouse-battery-production/>>

²⁴¹ Ibid.

²⁴² European Commission. "€114 million available under Horizon 2020 for next-generation batteries projects." January 24, 2019.

<<https://ec.europa.eu/inea/en/news-events/newsroom/€114-million-available-under-horizon-2020-next-generation-batteries-projects>>

²⁴³ Fraunhofer Institute for Silicate Research ISC. May 28, 2018. "Smart Recycling of Waste Traction Batteries from Electric Vehicles – EU Funding for New Resource-Efficient Solution" <<https://idw-online.de/de/attachmentdata65714.pdf>>

²⁴⁴ Ibid.

²⁴⁵ Circular Energy Storage. 2019. "State-of-the-art in reuse and recycling of lithium-ion batteries – A research review."

<<https://cdn.qualenergia.it/wp-content/uploads/2019/07/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf>>

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with sophisticated sorting technology.²⁴⁶ The researchers will also develop concepts for the reuse of battery components as a whole instead of individual material fractions, which will increase both the efficiency and profitability of materials cycles.²⁴⁷ Lastly, the researchers will look at elements of smarter battery design to facilitate recycling in the future and render it even more efficient.²⁴⁸

7.2.6 Norwegian LIBRES Project

Although oil accounts for 43% of its total exports, 21% of the country's revenue, and is the largest contributor to GDP at 17%, Norway is highly committed to electrification of its vehicle fleet, and to supporting EV and EV battery research. In 2018, EVs represented 31% of vehicle sales in Norway.

The Norwegian LIBRES (Battery Recycling in a Circular Economy) project brings the entire lithium battery recycling value chain together, including players from the collector (Batteriretur), to the downstream receiver (Glencore Nikkelverk and Keliber OY). Norsk Hydro is also involved in the project. Together with R&D partners Elkem Technology, IME RWTH Aachen, MIMI Tech, Agder University and NTNU, the aim of the project is to develop and commercialize a new lithium battery recycling process suitable for the anticipated volumes of batteries that will reach of life and to ensure significantly higher material recovery rates than is achieved with the present day state-of-the-art technology.²⁴⁹

7.2.7 Swedish Projects

A number of major research projects are ongoing in Sweden. Two of them, both focused on the recycling of li-ion batteries, are managed in Luleå. The first one, called *Resource efficient recycling routes for discarded lithium ion batteries* is being led by Luleå University of Technology and aims to develop a concept that facilitates efficient recycling of metals such as cobalt, nickel, copper, and lithium from EOL li-ion batteries. The following description of the project is available on its website²⁵⁰:

"The proposed project covers identification and assessment of resource-efficient methods for metallurgical recovery of metals. The metallurgical focus will be on treatment of black mass from spent Li-ion batteries including improving the physicochemical properties of black mass through mechanical activation followed by thermal treatment and refining to recover its valuable materials content. The impact on the needs and restrictions for the design of the supply network of end of life batteries to the recycling facilities will be analysed."

The second project, Re-LiOn, is led by Swerea MEFOS and aims to demonstrate that li-ion batteries can be

²⁴⁶ Reintjes, M. June 13, 2018. "How to bring car battery recycling to a higher level?" <<https://recyclinginternational.com/e-scrap/how-to-bring-car-battery-recycling-to-a-higher-level/15963/>>

²⁴⁷ Ibid.

²⁴⁸ Fraunhofer Institute for Silicate Research ISC. May 28, 2018. "Press release: Smart Recycling of Waste Traction Batteries from Electric Vehicles – EU Funding for New Resource-Efficient Solution." <<https://idw-online.de/de/attachmentdata65714.pdf>>

²⁴⁹ http://mission-innovation.net/our-work/ideas-and-innovators__trashed/mission-innovation-breakthroughs/libres-battery-recycling-in-a-circular-economy/

²⁵⁰ <http://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?projectid=26776>

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recycled in a circular system to minimize environmental impact and extraction of virgin raw materials. The 3-year project, which began on January 1, 2017, will investigate and assess process chains where suitable intermediate projects from recycling can be handled as early as possible by energy-efficient, large-scale industrial facilities.²⁵¹ In the project description, it says that the system must be able to handle cobalt, copper, aluminum, lithium oxide, manganese and nickel. This work will be conducted in the form of literature studies, LCA studies, thermodynamic calculations, lab-scale and pilot-scale development, and industrial-scale trials and will cover the entire value chain from recovery to new raw materials.²⁵²

A research project titled 'Second-use of Li-ion batteries from hybrid and electric vehicles'²⁵³ is underway (2018-2020) to investigate the technical and economic conditions for reuse of vehicle batteries in energy storage applications. The project is a collaboration between companies throughout the value chain, from vehicle manufacturers to energy storage developers, end users and recyclers (project partners are: Volkswagen, Stena Metall, Ferroamp, Chalmers, Stena Fastigheter, Stena Renewable and Northvolt).

7.3 Existing Legislation Targeting EV Batteries

This section describes the existing legislation mandating recycling of EV batteries in place in the EU and China. Potential future legislation in North America is discussed in Section 7.4.

7.3.1 European Union Batteries Directive

There are two separate European Union (EU) Directives that target EV batteries: the Batteries Directive (discussed in this section), which targets EV batteries reaching EOL before the vehicle does, and the End-of-Life Vehicles (ELV) Directive, which targets batteries as part of an EOL vehicle (discussed in Section 7.3.2).

Management of EOL batteries in EU countries is regulated by the Batteries Directive (2006/66/EC), which has been transposed into the national legislation of all European Member States. The Directive's primary objective is to *"minimise the negative impact of batteries and waste batteries on the environment to help protect, preserve and improve the quality of the environment."* Under this Directive, EV batteries are categorized as industrial batteries, along with batteries for e-bikes and local energy storage systems (e.g., power walls).²⁵⁴ Other classes of batteries covered by the Directive include portable batteries (e.g., for laptops, smartphones) and automotive batteries used for starting

²⁵¹ SWERIM. January 16, 2017. "4.7 million kronor for research in battery recycling." <<https://www.swerim.se/en/news/47-million-kronor-for-research-in-battery-recycling>>

²⁵² "Second-use of Li-ion batteries from hybrid and electric vehicles." <https://research.chalmers.se/en/project/8366>

²⁵³ Ibid.

²⁵⁴ European Commission. Commission Staff Working Document on the evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.

<https://ec.europa.eu/environment/waste/batteries/pdf/evaluation_report_batteries_directive.pdf>

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a car's engine or powering its lighting system.

Among other things, the Batteries Directive prohibits placing batteries and accumulators with a certain mercury or cadmium content on the market and establishes rules for the collection, recycling, treatment, and disposal of waste batteries and accumulators.²⁵⁵ The Directive also specifies collection and recycling efficiency rates for certain types of batteries. For industrial batteries, collection rates are not quantified; instead it is stated that *"The disposal of industrial and automotive batteries and accumulators in landfill sites or by incineration should be prohibited."* With regards to recycling efficiency rates, the Directive stipulates that 'other waste batteries' – including li-ion – should achieve a minimum recycling efficiency of 50%. This rate is weight-based, which means that 50% of the weight of the battery must be recycled, and does not guarantee the recovery of particular elements.²⁵⁶

In addition to the above, the Batteries Directive also requires vehicle manufacturers to assist in collecting and recycling EV batteries at the end of vehicle life; a concept called extended producer responsibility (EPR).²⁵⁷ However, the Directive provides no indication regarding battery repurposing and second-life usage, leaving the responsibility for recycling at the end-of-the-second-life out of the legislative framework.²⁵⁸

As part of a process that could lead to the Directive's revision, the European Commission recently completed an evaluation of the Batteries Directive, the results of which were published in April 2019.²⁵⁹ In the light of technical and scientific progress, the evaluation concluded that the current classification of lithium batteries under 'other batteries' does not reflect their growing importance. The evaluation also concluded that the recycling efficiency target for 'other' batteries (50%) is not appropriate to ensure a high level of material recovery, and that valuable components of batteries other than lead and cadmium (e.g., cobalt lithium or critical raw materials) are not specifically considered. As noted in the report²⁶⁸ of the evaluation, *"these batteries contain significant amounts of lithium and cobalt, but the Directive's current provisions do not set strong incentives to promote their recovery. This is a growing issue in particular in light of the expected increased electric vehicles deployment in the next years..."* Another key finding was that the Directive does not address the second-life of advanced batteries: *"Second life of batteries is currently not considered in the Directive as it is an unexpected technical development that current legislation cannot incorporate."*²⁶⁰

²⁵⁵ https://circular-impacts.eu/sites/default/files/D4.4_Case-Study-EV-batteries_FINAL.pdf

²⁵⁶ Drabik, E., and V. Rizos. 2018. "Prospects for electric vehicle batteries in a circular economy." <https://circular-impacts.eu/sites/default/files/D4.4_Case-Study-EV-batteries_FINAL.pdf>

²⁵⁷ Element Energy. 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>

²⁵⁸ Ibid.

²⁵⁹ European Commission. April 9, 2019. "Commission Staff Working Document on the evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC." <https://ec.europa.eu/environment/waste/batteries/pdf/evaluation_report_batteries_directive.pdf>

²⁶⁰ Ibid.

7.3.2 European Union End-of-Life Vehicles (ELV) Directive

The End-of-Life Vehicles (ELV) Directive (2000/53/EC) mandates that the dismantling and recycling of ELVs be carried out in an environmentally responsible manner. Under the Directive, producers are expected to manufacture new vehicles without hazardous substances, thus promoting the reuse, recyclability, and recovery of EOL vehicles. The ELV Directive also sets clear targets for reuse, recycling, and recovery of ELVs and their components (including batteries).²⁶¹ Specifically, each European Member State is required to meet the following recycling and recovery targets: 80% and 85% by 2006 and increasing to 85% and 95%, respectively, by 2015.²⁶² Furthermore, the Directive create a favourable framework such that the last owner of an EV can return the vehicle to an authorized treatment facility a no cost. As per Article 5(4) of the Directive, producers are expected to meet “all, or a significant part of, the costs of the implementation of this measure.”

One concern that has been raised about the ELV Directive is that its current definition of reuse only considers the recovered components used for the same purpose and that component repurposing is not considered at all.²⁶³ There is some concern that this strict definition may restrict the recovery of EV batteries and usage for other applications, like energy storage, which could hamper the take-off of the second-life battery market.²⁶⁴

The European Commission launched a review of the ELV Directive in October 2018, to bring it up to date and eliminate overlaps with other EU legislation dealing with waste, including the Batteries Directive. The review is expected to be complete by the end of 2019.²⁶⁵

7.3.3 Mandatory Recycling of EV Batteries in China

As part of its efforts to tackle environmental pollution from waste batteries, in July 2018, China’s Ministry of Industry and Information Technology announced the launch of a pilot program for repurposing and recycling EV batteries in 17 major regions and cities (including the Beijing-Tianjin-Hebei region, Shanxi Province, and Shanghai).²⁶⁶ The pilot scheme applies EPR principles and encourages EV manufacturers to take advantage of their after-sales service channels to establish regional collection and recycling systems for spent batteries in collaboration with car dealers, battery producers, vehicle dismantlers and battery second use recycling companies.²⁶⁷

²⁶¹ Element Energy. 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>
<https://www.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf>

²⁶² <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN>

²⁶³ Element Energy. 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>

²⁶⁴ Ibid.

²⁶⁵ <https://chemicalwatch.com/70938/commission-launches-review-of-end-of-life-vehicles-directive>

²⁶⁶ Reuters. July 25, 2018. “China launches pilot EV battery recycling schemes.” <<https://www.reuters.com/article/us-china-autos-batteries/china-launches-pilot-ev-battery-recycling-schemes-idUSKBN1KF375>>

²⁶⁷ Ibid.

Under the new rules, car makers must also establish a maintenance service network allowing consumers to repair or exchange their old batteries conveniently.²⁶⁸ In addition, battery makers are encouraged to adopt standardized battery designs that are easily dismantled, to facilitate the recycling process. They must also provide technical training for carmakers to store and dismantle old batteries.²⁶⁹ The aim of the pilot recycling scheme is to control new companies involved in battery recycling, to optimize the use of already existing facilities, and promote sustainable development of the sector.²⁷⁰ The Ministry has also pledged to draw up policies to support battery recycling, including the introduction of tax incentives and innovative new financing methods.

China has recently implemented a regulation referred to as a *Battery Recycling and Traceability Management Platform*. This regulation, which is aimed at tracking the entire life cycle of EV batteries from production through to sales, usage, scrapping/second use and recycling, introduces an ID system for EV batteries enabling the identification of owners of discarded batteries and clarifying who is responsible for handling and recycling batteries at EOL.^{271, 272} Under this new system, EV battery manufacturers will code the batteries according to the National Standard - Coding Regulation for Automotive Traction and stakeholders along the value chain will be required to update and upload the battery information onto the traceability management platform.²⁷³

7.4 Current Consultation Processes and Potential Legislation in the US and Canada

7.4.1 California

In 2019, California's Department of Resources Recycling and Recovery (known as CalRecycle) convened a workshop on EOL management for EV batteries, with presentations and participants from most key stakeholder groups (no one from the auto industry presented). A member of the Kelleher team attended the workshop and some of the material presented and discussed at the workshop is included in Sections 4 and 5 of this report.

By way of background to the workshop, California has aggressive goals for adoption of EVs as part of the state's air pollution and climate reduction strategies. Trying to stay in advance of a potential waste problem, CalRecycle is working with the California Department of Toxic Substances Control (DTSC) on a White Paper on EOL management for EV batteries, due in Q4 2019, which is expected to outline the regulatory status for EV batteries' storage, transportation, handling, and management, as well as

²⁶⁸ Reuters. February 26, 2018. "Chinese electric vehicle makers told to sort tide of waste batteries."

<<https://www.scmp.com/news/china/economy/article/2134737/chinese-electric-vehicle-makers-told-sort-tide-waste-batteries>>

²⁶⁹ Ibid.

²⁷⁰ Regulations on the Battery Recycling and Traceability Management Platform

²⁷¹ Reuters. February 26, 2018. "Chinese electric vehicle makers told to sort tide of waste batteries."

<<https://www.scmp.com/news/china/economy/article/2134737/chinese-electric-vehicle-makers-told-sort-tide-waste-batteries>>

²⁷² Jiao, N. Dr. September 25, 2018. "All EV batteries born after August 2018 in China will have unique IDs."

<<https://www.idtechex.com/en/research-article/all-ev-batteries-born-after-august-2018-in-china-will-have-unique-ids/15455>>

²⁷³ Ibid.

propose a program for EOL management

CalRecycle staff noted that any EOL program for EV batteries must be adaptable and responsive to changes in technologies; staff acknowledged that California's laws governing EOL management of electronic devices have not been responsive to changing technologies.

In February 2018, the California State Assembly introduced a bill, "AB 2832 Recycling and Reuse: Lithium-Ion Batteries," with a specific focus on li-ion batteries in EVs.²⁷⁴ If passed, this law would establish a proper disposal mechanism for EV batteries with no cost to EV owners (As of June 2018, the bill is awaiting approval at the California State Senate.²⁷⁵). The bill requires the California DTSC to work with stakeholders, including other state agencies, to identify a plan to reuse or recycle EV batteries at the end of their useful life. The plan needs to be submitted to the Legislature by July 1, 2020.²⁷⁶ Bill 2832 also promulgates the establishment of a grant program for developing EOL avenues, which battery manufacturers can apply for.²⁷⁷ The bill also requires the Secretary for Environmental Protection, on or before April 1, 2019, to convene the *Lithium-Ion Car Battery Recycling Advisory Group* to review, and advise the Legislature on, policies pertaining to the collection and recycling of EV li-ion batteries that would ensure that as close to 100% as possible of li-ion batteries in the state are reused or recycled at EOL in a safe and cost-effective manner.²⁷⁸ The group continued to canvass for volunteer members in late July, 2019. Its report on options for recycling in California is due by April 2022.²⁷⁹

Driven by a concern about the safety of li-ion batteries in recycling facilities (after expensive and damaging fires), the California legislature is advancing Assembly Bill 1509²⁸⁰ which would require industry to set up a stewardship program for li-ion batteries from electronic devices. The bill specifically excludes li-ion batteries from motor vehicles. While it is unlikely this law would be expanded to include EV batteries in the near future, that could happen once EVs penetrate the market more, especially if there are problems with illegal dumping (as is the case with PV panels in California). If Bill 1509 passes, it will accelerate the pressure to develop responsible EOL infrastructure for li-ion batteries. As of late July 2019, the bill has passed out of the State Assembly and is under consideration in the California Senate.²⁸¹

²⁷⁴ Gaines, L., Richa, K., and Spangenberg, J. 2018. "Key issues for Li-ion battery recycling." *MRS Energy & Sustainability*, 5. <<https://www.cambridge.org/core/journals/mrs-energy-and-sustainability/article/key-issues-for-liion-battery-recycling/F37D3914A1F5A8FD0ED3EF901664D126/core-reader>>

²⁷⁵ Assembly Passes Dahle Bill to Tackle Hazardous Waste from Electric Vehicles." June 4, 2018. <<https://www.susanvillestuff.com/assembly-passes-dahle-bill-to-tackle-hazardous-waste-from-electric-vehicles/>>

²⁷⁶ Ibid.

²⁷⁷ Gaines, L., Richa, K., and Spangenberg, J. 2018. "Key issues for Li-ion battery recycling." *MRS Energy & Sustainability*, 5. <<https://www.cambridge.org/core/journals/mrs-energy-and-sustainability/article/key-issues-for-liion-battery-recycling/F37D3914A1F5A8FD0ED3EF901664D126/core-reader>>

²⁷⁸ State of California. "Assembly Bill-12832 Recycling: lithium-ion vehicle batteries: advisory group." https://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB2832

²⁷⁹ Stewart, L. June/July 2019. "Depleted, Not Dead: Second Life for Electric Vehicle Batteries." *Bay Area Monitor*. <<https://bayareamonitor.org/article/depleted-not-dead-second-life-for-electric-vehicle-batteries/>>

²⁸⁰ State of California. "Assembly Bill-1509 Solid waste: lithium-ion batteries." https://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB1509

²⁸¹ Staub, C. July 30, 2019. "Bill supports proper recovery of MRF hazard." *Resource Recycling*. <<https://resource-recycling.com/recycling/2019/07/30/bill-supports-proper-recovery-of-mrf-hazard/>>

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7.4.2 Provinces of Ontario and BC (Canada)

On May 9, 2019, the Government of Ontario released draft regulations for recycling of batteries under the *Resource Recovery and Circular Economy Act, 2016* (RRCEA) on the Environmental Registry of Ontario.²⁹¹ The comment period for these draft regulations ended on June 23, 2019.

The intent of these new regulations is to make producers responsible (both physically and financially) for the collection and management of their products at EOL, and to create a circular economy where resources are reused and/or recovered instead being disposed. While the regulation proposal does not specifically mention EV batteries, it is interpreted by industry members to include EV batteries. The draft regulation identifies three defined categories of batteries to be covered by the regulations:²⁸²

1. Small single use batteries weighing 5 kg or less
2. Small rechargeable batteries weighing 5 kg or less
3. Large batteries weighing more than 5 kg.

Under these proposed regulations, EV batteries would be considered ‘large batteries.’ The regulations would create several new legal obligations for producers of EV batteries, including:²⁸³

- Establishing collection networks (e.g., collection depots, collection events, curbside collection, and mail-back programs);
- Achieving resource recovery (i.e., reduction, reuse, and recycling) targets;
- Educating consumers to increase consumer awareness;
- Registering with and reporting to the Resource Productivity and Recovery Authority (agency responsible for oversight, compliance, and enforcement under the RRCEA); and
- Other requirements, including record keeping and third-party audits.

In addition to the above, the regulations would encourage producers to reduce the waste associated with the regulated products they place on the Ontario market²⁸⁴.

The BC government already has extensive battery EPR regulations in place and will launch a consultation program to add a range of materials to the existing EPR regulations, including possibly EV batteries. The consultation was scheduled for spring, 2019 but has been delayed with the focus on plastics.

²⁸² Government of Ontario. “Regulations for Recycling of Electrical and Electronic Equipment (EEE) and Batteries under the Resource Recovery and Circular Economy Act., 2016.” <<https://ero.ontario.ca/notice/019-0048>>

²⁸³ Resource Productivity & Recovery Authority. May 10, 2019. “Draft regulations for waste electronics and batteries posted.” <https://rpra.ca/2019/05/draft-regulations-for-waste-electronics-and-batteries-posted/>

²⁸⁴ <https://ero.ontario.ca/notice/019-0048>

8 Conclusions

This research project involved a detailed literature review as well as interviews to identify the current and near-term future processes employed for the reuse and recycling of EV batteries. EV battery technologies and chemistries currently used and likely to be used in the near future, as well as the potential technical, environmental, energy and cost issues associated with EV battery recycling and second-life uses were addressed. Conclusions from the study are summarized below:

- An estimated 688,000 HEVs, PHEVs and BEVs were sold in the US in 2018. EV sales are likely to grow to a market penetration rate of 8% by 2025, resulting in sales of 1.3 million PHEVs and BEVs in that year in the US.
- EOL EVs will reach about 525,000 units in 2025 and over 1 million units in 2030. While most of these batteries will be NiMH for the next few years, by 2025 most will be li-ion based.
- There is no established collection infrastructure for EV batteries in the US at this time. The EOL EV batteries are beginning to show up at scrap yards in sufficient numbers to now raise concern about proper management.
- EV battery reuse appears to be a viable business model with good profit margins if issues around liability can be addressed.
- While recycling of small sized li-ion consumer batteries is well established in the US, the recycling of li-ion EV batteries is much more complex as the units are heavy (up to 400-500kg for many models), dangerous until fully discharged, and require a lot of dismantling. Costs to recycle EV batteries are not well identified or understood, but it appears that recycling EV batteries using today's technologies incurs a cost rather than generates revenue based on metal values. Traditional recyclers charge EV battery owners a fee based on the time it takes to recycle the battery, and pay a credit back based on metal values recovered.
- Limited information was found on the current costs of recycling EV batteries using either traditional or new approaches. A business case should be developed that identifies the costs and risks associated with traditional approaches to EV battery recycling, which are likely to be the only options available for the next few years.
- Based on the research carried out for this study, 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 favourable for the foreseeable future. We see no evidence that recycling will be carried out at a positive value at the EV battery level in the next five years, as the technologies that promise to achieve this have not yet been proven at commercial scale (see Section 5), and reuse is proven to result in a positive cash flow.
- The environmental benefits of reuse relate to extending the lifespan of the battery and reducing

the demand for virgin materials to manufacture new EV batteries. The benefits of EV battery recycling include the energy saved and the environmental impacts accrued by avoiding the mining of virgin metals. While a number of studies were found identifying environmental and energy impacts of reuse and recycling of EV batteries, none reflected current conditions and current battery chemistries, and all are considered not directly applicable to current conditions and are out of date.

- Both reuse and recycling of EV batteries share the technical challenge associated with the availability of a wide range of battery formats, designs, compositions and chemistries. This makes standard approaches virtually impossible at this time, and requires customized approaches. Both reuse and recycling also suffer from a lack of collection infrastructure to bring accumulated EV batteries to a central location where large numbers would lead to economies of scale.
- A limitation of LCA studies reviewed in the project research is that the analysis is carried out comparing refurbished li-ion batteries to lead-acid batteries for ESSs. None of the LCAs identified compared the cost, environmental or energy impacts of new vs. recycled vs. reused EV batteries, and this research is needed in order to reflect current conditions in the EV market.
- Compared to the US, other countries spend considerably more on supporting research into new EV battery technologies, as they see battery development as a potential large business in the future and want to be leaders in technology development and deployment.
- Legislation in California may require EV producers to be responsible for the EOL management of EV batteries. California staff are working on a White Paper which is scheduled for completion at the end of 2019. When the direction in California is clearer, it is likely to be pursued by other states also. This would provide a reliable supply of EOL EV batteries for future recycling and reuse businesses.

The opinions in this report are based on best available information available as of mid-2019. The EV field is evolving rapidly therefore the information in this report needs to be updated in mid-2020 to remain current.

9 Data Needs and Research Gaps

A number of data and research gaps were noted during this study:

- This research project developed a simple Lifespan Model to estimate the number and type of EV batteries reaching EOL to 2030. A more detailed and elaborate material flow and lifespan model should be developed to develop more accurate estimates of EOL EV batteries in future years. The more detailed model should account for the different li-ion battery chemistries used in different EV models, and changes in unit weights and EV battery chemistries on an annual basis over time. This level of detail was beyond the scope of this study, but should be considered as a future research project.
- The second-life of EV batteries directed to reuse is not known. All information available to date is based on modelling but no real-life examples of how EV batteries degrade in second-life are yet available.
- The NREL study²⁸⁵ and research which identified detailed costs for EV battery reuse is four years old and is based on PHEV batteries only. The cost model and research should be updated with current costs to include HEV, PHEV and BEV batteries.
- Research should identify a firm sense of when EV battery costs might reach \$100/kWh and how the lower costs of new EV batteries might change the dynamics of the EV new vehicle market. The projections in this study assumed growth of the EV market to 1.3 million units sold by 2025 based on an assessment of a number of studies available at this time. These estimates are likely to be low should EVs reach cost parity with ICE vehicles sooner than projected.
- 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 on the energy and environmental impacts of EV battery reuse compared to recycling, and also on the relative LCA impacts of EV battery recycling vs. buying a new battery needs to be carried out using current data and assumptions.
- A detailed business case needs to be developed to more fully identify the costs, economics and financial as well as technical risks associated with the EV battery recycling business, taking future potential regulation of mandatory EV battery recycling into account, the evolution of EV battery recycling technology, the lack of collection infrastructure as well as the geographic distribution of the EOL EV battery supply into consideration.

²⁸⁵National Renewable Energy Laboratory. Neubauer, J., Smith, S., Wood, E., and A. Pesaran. February 2015. "Technical Report: Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries." <<https://www.nrel.gov/docs/fy15osti/63332.pdf>>

- The EV field is evolving rapidly therefore the information in this report is considered reliable in 2019 but needs to be updated annually to account for the many changes in the rapidly evolving world of EVs and EV batteries. The next update should be carried out in mid-2020 to remain current.

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344. Zhang, X., Li, L., Fan, E., Xue, Q., Bian, Y., Wu, F., & Chen, R. (2018). "Toward sustainable and systematic recycling of spent rechargeable batteries." *Chemical Society Reviews*, 19, doi:10.1039/c8cs00297e .
345. Zheng, X., Zhu, Z., Lin, X., Zhang, Y., He, Y., Cao, H., & Z. Sun. (2018). "A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries." *Engineering*, 4, 361-370. <<https://doi.org/10.1016/j.eng.2018.05.018>>
346. Zhu, J., Wierzbicki, T., & W. Li. (2018). "A review of safety-focused mechanical modeling of commercial lithium-ion batteries." *Journal of Power Sources*, 378, 153-168. <<https://doi.org/10.1016/j.jpowsour.2017.12.034>>
347. Ziemann, S., Müller, D.B., Schebek, L., & M. Weil. (2018). "Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach." *Resources, Conservation, and Recycling*, 133: 76-85.
348. Zubi, G., Dufo-López, R., Carvalho, M., & G. Pasaoglu. (2018). "The lithium-ion battery: State of the art and future perspectives." *Renewable and Sustainable Energy Reviews*, 89, 292-308. <<https://doi.org/10.1016/j.rser.2018.03.002>>

Appendix A: Types of Electric Vehicles

There are three main types of electric vehicles (EVs) on the market today, classed by the degree that electricity is used as their fuel source:

- **Hybrid-electric vehicle (non plug-in) (HEV):** By far the most common type of EV available today, HEVs rely on two complementary drive systems – a gasoline engine and fuel tank, and an electric motor, battery and controls.²⁸⁶ The main difference between HEVs and other EV types is that they cannot be recharged from the electricity grid; instead, their energy comes entirely from gasoline and regenerative braking. When the vehicle brakes, some of the energy is stored in the battery, which can later be used to power the electric motor and assist the gasoline engine. The most popular hybrid is a Toyota Prius, however nearly every vehicle manufacturer including Ford, Honda, Volkswagen, Porsche, Hyundai (and others) offer many different hybrid models to choose from.
- **Plug-in hybrid electric vehicle (PHEV):** Also known as an extended-range EV, a PHEV has both a rechargeable battery pack and a gasoline engine. Unlike a HEV, it runs mostly on the battery that is recharged by plugging it into the electrical grid. When the battery pack is depleted, the vehicle operates similar to a HEV, storing braking energy in the battery and assisting the gasoline engine.²⁸⁷ Examples include the Chevrolet Volt, Mitsubishi Outlander, and Toyota Prius.
- **Battery electric vehicle (BEV):** A BEV runs entirely on a battery and electric drive train, and does not have a gasoline engine, fuel tank, or exhaust pipe. They generate zero vehicle-based emissions, and unlike PHEVs, once the battery is depleted, they must be plugged into the electrical grid in order to recharge the battery.²⁸⁸ Examples of BEVs are the Tesla Model S, the Nissan Leaf, and the Chevrolet Bolt.

Figure 50 presents a simple schematic to illustrate the differences between the three types of EV design.

²⁸⁶CAA. "Types of Electric Vehicles." <<https://www.caa.ca/electric-vehicles/types-of-electric-vehicles/>>

²⁸⁷ Electric Power Research Institute. "Industry Terms." https://et.epri.com/ResearchAreas_IndustryTerms.html

²⁸⁸ Electric Power Research Institute. "Industry Terms." <https://et.epri.com/ResearchAreas_IndustryTerms.html>

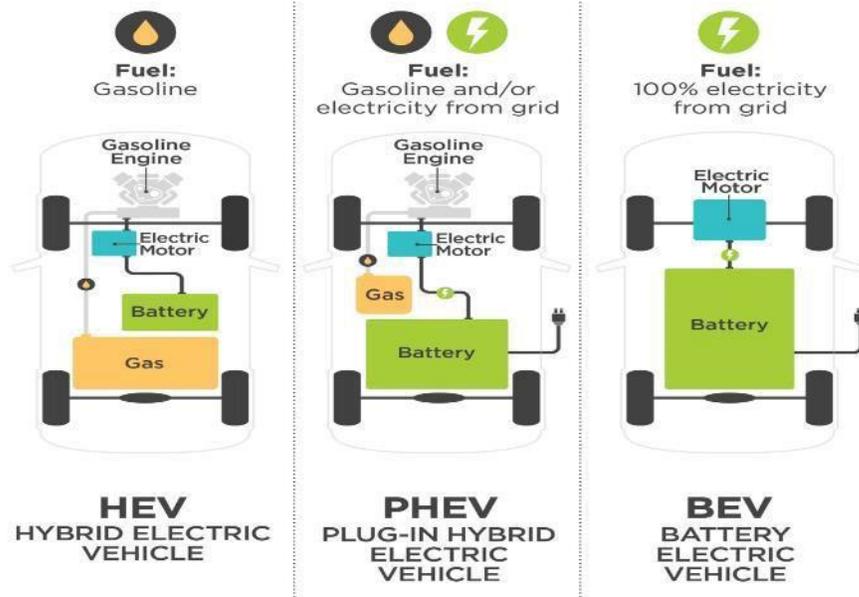


Figure 50 Schematic Showing Elements of HEV, PHEV and BEV²⁸⁹

²⁸⁹ "Revolt Electric Vehicles." <<https://www.kpcoop.com/content/revolt-electric-vehicles>>

Appendix B: Lithium-ion Battery Components

Li-ion batteries are made up the following main components:

- **Anode:** negative electrode in the battery in which oxidation occurs²⁹⁰. The current dominant anode material is artificial or high-quality natural graphite (carbon), although some battery manufacturers are using non-graphite anodes such as lithium titanate, which offers a longer cycle life.²⁹¹
- **Cathode:** positive electrode in the battery; the most common cathode materials used are cobalt oxides and manganese oxides, but it is also possible to use other metals, such as an iron phosphate, nickel, or aluminum (note: there have been various efforts to eliminate cobalt because of cost).²⁹² The combination of different materials results in significantly different battery characteristics.
- **Electrolyte:** a mixture of organic solvents and lithium salts. Common lithium salts include lithium-hexafluorophosphate, lithium-perchlorate, and lithium-hexafluoroarsenate, while common organic solvents include ethyl-methyl-carbonate, dimethyl-carbonate, diethyl-carbonate, propylene-carbonate, and ethylene-carbonate.²⁹³
- **Separator:** intended as a safety component between the anode and the cathode, the separator is usually made up of micro-porous polyethylene or polypropylene that allows the passage of lithium ions during the cycling process.
- **Other Elements – Insulators, Vents, etc.:** Li-ion cells can also include other elements, such as components that strengthen the cell mechanically, insulators on the edges of the electrodes where short-circuiting is likely to occur, and vents for air pressure relief.²⁹⁴

The exact mass and chemical compositions of each component vary between different manufacturers, but the cathode typically comprises 25–30% of the battery’s total weight, while the anode represents 15–30%. An outer casing composed of steel, aluminum, or plastic isolates the inner components from the outside environment.²⁹⁵

Li-ion batteries have many advantages, including high power-to-weight ratio, high-energy efficiency, and good high-temperature performance. What this means is that li-ion batteries store a lot of energy for their weight; this is important for EVs because the less weight they carry, the farther the car can travel on a single charge. Li-ion batteries also have a low “self-discharge” rate, which makes them better than

²⁹⁰ RBC Capital Markets. May 11, 2018. “RBC Electric Vehicle Forecast Through 2050 & Primer.”

<http://www.fullertreacymoney.com/system/data/files/PDFs/2018/May/14th/RBC%20Capital%20Markets_RBC%20Electric%20Vehicle%20Forecast%20Through%202050%20Primer_11May2018.pdf>

Zubi, G., Dufo-Lopez, R., Carvalho, M., and G. Pasaoglu. (2018). “The lithium-ion battery: State of the art and future perspectives.” *Renewable and Sustainable Energy Reviews*, 89, 292-308²⁹¹

²⁹² <https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf>

²⁹³ Zubi, G., Dufo-Lopez, R., Carvalho, M., and G. Pasaoglu. (2018). “The lithium-ion battery: State of the art and future perspectives.” *Renewable and Sustainable Energy Reviews*, 89, 292-308.

²⁹⁴ Ibid.

²⁹⁵ Winslow, K.M., Laux, S.J., & T.G. Townsend. (2018). “A review on the growing concern and potential management strategies of waste lithium-ion batteries.” *Resources, Conservation & Recycling*, 129, 263-277. <<https://doi.org/10.1016/j.resconrec.2017.11.001>>

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other batteries at holding a full charge over time.²⁹⁶

Figure 51 presents a schematic of how a li-ion battery works. During the charging process, the lithium ions move from the cathode, through the electrolyte, to the anode to create electric current. During discharge, this process reverses.²⁹⁷ As the battery discharges, the lithium ions move from higher potential energy at the anode to lower potential energy at the cathode. The electrolyte separator controls how fast the lithium-ions can migrate between the two electrodes.²⁹⁸

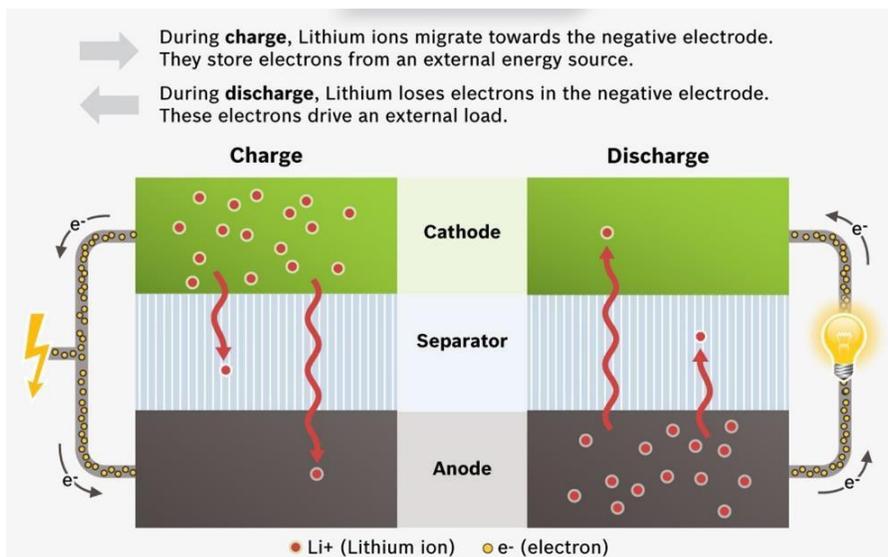


Figure 51 Schematic Showing How a Li-ion Battery Works²⁹⁹

²⁹⁶ EnergySage. "How to electric car batteries work?" <<https://www.energysage.com/electric-vehicles/101/how-do-electric-car-batteries-work/>>

²⁹⁷ Zubi, G., Dufo-Lopez, R., Carvalho, M., and G. Pasaoglu. (2018). "The lithium-ion battery: State of the art and future perspectives." *Renewable and Sustainable Energy Reviews*, 89, 292-308.

²⁹⁸ Winslow, K.M., Laux, S.J., & T.G. Townsend. (2018). "A review on the growing concern and potential management strategies of waste lithium-ion batteries." *Resources, Conservation & Recycling*, 129, 263-277. <https://doi.org/10.1016/j.resconrec.2017.11.001>

²⁹⁹ Bosch. February 9, 2015. "Press release: Facts about battery technology for hybrid and electric powertrains." <<https://www.bosch-press.de/pressportal/de/en/facts-about-battery-technology-for-hybrid-and-electric-powertrains-42846.html>>

Appendix C: Lithium-ion Battery Chemistries and Composition

There are several different types of li-ion batteries, each of which offers different voltages, power and energy performances, with trade-offs between cost, efficiency, and safety. The main difference between them is their cathode chemistry. Either alone or in conjunction with one another, the main chemistries used in the industry at the moment, along with examples of vehicle models in which they are deployed, are summarized in Table 20.

Table 20 Descriptions of Various Li-ion EV Battery Chemistries

Cathode Chemistry	Acronym	Chemical Composition	EV Model Example	Description
Lithium Cobalt Oxide	LCO	LiCoO ₂	Tesla Roadster, Smart Fortwo electric drive	<p>LCO is rarely (if at all) used in EVs anymore due to the high cobalt content (about 60%).</p> <p>Due to their high energy density, long life cycle, and ease of manufacturing, lithium cobalt oxide has been the positive electrode material of choice in lithium batteries for many years, and is used in most personal electronics (e.g., laptops, cameras, tablets, etc.).</p> <p>However, these batteries are very reactive and suffer from poor thermal stability and must be monitored during operation to ensure safe use. These characteristics have limited their use in EVs.</p> <p>The limited availability of cobalt also makes it more expensive and difficult to be a viable option for use in EVs. ^{300 301}</p>

³⁰⁰ Miao, Y., Hynan, P., von Jouanne, A., and A. Yokochi. (2019). "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements." *Energies*, 12, doi:10.3390/en12061074

³⁰¹ "Understanding Battery Chemistries – Q&A with Simon Moores." 30 July 2018. <<https://www.theassay.com/insight-2/understanding-battery-chemistries-qa-simon-moores/>>

Lithium Nickel Manganese Cobalt Oxide	NMC	LiNiMnCoO ₂	Chevrolet Bolt, Nissan Leaf	<p>NMC-cathodes, a combination of nickel-manganese-cobalt, have high energy density and reliability.</p> <p>The key drawback is the high cobalt content, which exposes EV manufacturers to price risks and challenges related to sustainable and ethical sourcing.</p> <p>Within NMC, there are a number of sub-chemistries, all of which have different ratios of nickel, manganese, and cobalt.</p> <p>Companies have switched from NMC111 to NMC442 to NMC622, and now NMC811 is slated for introduction.</p>
Lithium Iron Phosphate	LFP	LiFePO ₄	Used in China because of low cost	<p>Li-ion phosphate technology is used in BYD e-buses.³⁰²</p> <p>Improved thermal and chemical stability compared to oxides. Considered to offer greater safety than other li-ion technologies. Less susceptible to thermal runaway under abuse conditions. Good electrochemical performance with low resistance as well as a long cycle life. Downsides include lower energy density.³⁰³</p>

Lithium Manganese Oxide	LMO	LiMn ₂ O ₄	Chevrolet Volt, BMW i3	<p>Lithium manganese oxide spinel offers a higher cell voltage than cobalt-based chemistries as well as higher temperature stability.³⁰⁴</p> <p>Other advantages include lower cost and higher rate capability.</p> <p>Lower energy density (about 20% less)</p>
Lithium Nickel Cobalt Aluminum Oxide	NCA	LiNiCoAlO ₂	Tesla models	<p>Shares similarities with NMC by offering a long life span, high specific energy density and reasonably good specific power (the rate at which the battery can deliver energy).</p> <p>Not as safe as other li-ion battery types and require special safety monitoring measures to be employed for use in EVs.</p> <p>More costly to manufacture, limiting their viability for use in other applications.³⁰⁵</p>

Multiple studies in the literature report on the metal composition of different li-ion battery types, either by weight, by kWh, or some other metric. As an example, Figure 52 shows the variations in metal content as a % of total metal in the battery per kWh. The figure includes a number of NMC batteries with different numbers, which represent the ratio of nickel:manganese:cobalt in each particular blend.

³⁰²“Understanding Battery Chemistries – Q&A with Simon Moores.” 30 July 2018. <<https://www.theassay.com/insight-2/understanding-battery-chemistries-qa-simon-moores/>>

³⁰³ Johnson Matthey Battery Systems. 2015. “Our Guide to Batteries: 3rd Edition.” <<http://www.jmbatterysystems.com/JMBS/media/JMBS/Documents/JMBS-23946-Battery-Guide-Update-August-2015-Web.pdf>>

³⁰⁴ Johnson Matthey Battery Systems. 2015. “Our Guide to Batteries: 3rd Edition.” <<http://www.jmbatterysystems.com/JMBS/media/JMBS/Documents/JMBS-23946-Battery-Guide-Update-August-2015-Web.pdf>>

³⁰⁵ Miao, Y., Hynan, P., von Jouanne, A., and A. Yokochi. (2019). “Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements.” *Energies*, 12, doi:10.3390/en12061074

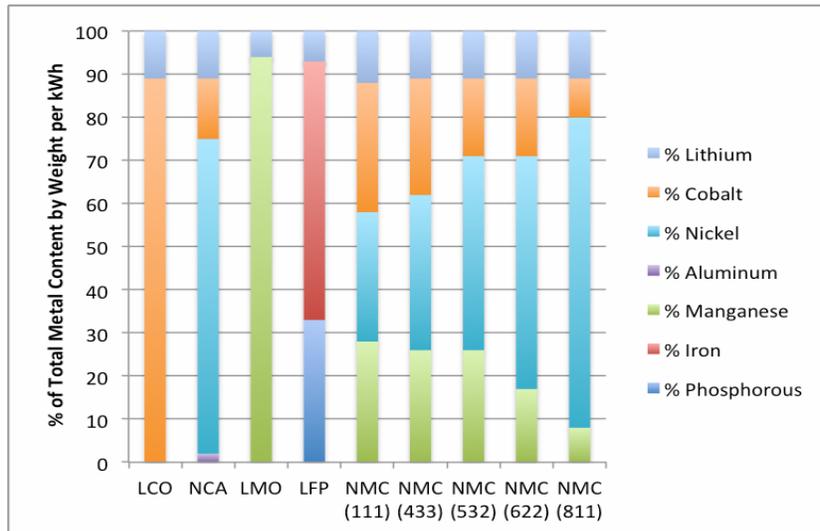


Figure 52 Metal Content of Li-ion Batteries by Cathode Chemistry, % of Total Metal Content by Weight by kWh³⁰⁶

Table 21 below presents the mass concentrations of materials in different types of li-ion batteries as reported from multiple studies.³⁰⁷ As the authors of the report from which this table was taken from note, compositions will often vary depending on the types of materials used for the cathode, anode, separator, and casing as well as the intended application of the battery.

306Bloomberg New Energy Finance. September 2017. "EV market trends and outlook: Shift Up a Gear." <<https://www.transportenvironment.org/sites/te/files/EV%20market%20trends%20and%20outlook%20%28by%20Colin%20McKerracher%29.pdf>>

307Winslow, K.M., Laux, S.J., & T.G. Townsend. (2018). "A review on the growing concern and potential management strategies of waste lithium-ion batteries." Resources, Conservation & Recycling, 129, 263-277. <https://doi.org/10.1016/j.resconrec.2017.11.001>

Table 21 Elemental and Material Concentrations in Different Types of Li-ion Batteries as Reported from Multiple Studies³⁰⁸

Research Group	Complete Battery, $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ cathode (Gaines et al., 2011)	Complete Battery, LiMn_2O_4 cathode (Gaines et al., 2011)	Complete Battery, LiNiMnCoO_2 cathode (Richa, 2016)	Complete Battery, LiCoO_2 cathode (Wang et al., 2016)	Complete Battery, LiFePO_4 cathode (Wang et al., 2016)
Metals	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)
Aluminum	21.9	21.7	22.72	5.2	6.5
Cobalt	2.3	0.0	8.45	17.3	0
Copper	13.3	13.5	16.6	7.3	8.2
Iron/Steel	0.1	0.1	8.79	16.5	43.2
Lithium	1.9	1.4	1.28	2.0	1.2
Manganese	0.0	10.7	5.86	0	0
Nickel	12.1	0.0	14.84	1.2	0
Other	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)	Conc. (mass %)
Binder	3.8	3.7	1.39	2.4	0.9
Carbon (non-graphite)	2.4	2.3	3.47	6.0	2.3
Electrolyte + solvent	11.7	11.8	1.66	14.0	14.9
Fluoride	-	-	4.99	-	-
Graphite	16.5	16.3	-	23.1	13.0
Thermal Insulation	1.2	1.2	-	-	-
Oxygen	8.3	12.4	4.52	-	-
Phosphorous	-	-	2.04	0	5.4
Plastics	4.2	4.5	3.29	4.8	4.4
- means not reported or analyzed					

308 Winslow, K.M., Laux, S.J., & T.G. Townsend. (2018). "A review on the growing concern and potential management strategies of waste lithium-ion batteries." *Resources, Conservation & Recycling*, 129, 263-277. <<https://doi.org/10.1016/j.resconrec.2017.11.001>>

Appendix D: Lithium-ion EV Battery Design and Configuration

The smallest component of li-ion batteries used to power EVs is the battery cell. Three main types of cell design have evolved for EV applications:

- **Cylindrical Cells** (Figure 53): Many consumer products use cylindrical type cells (such as the AA format). Although applications for vehicles are less common, Panasonic produces cylindrical cells for Tesla.
- **Pouch Cells** (Figure 54): The active material is packaged in flexible housing made from a material composite that includes aluminum foil. Some major battery cell manufacturers, including LG Chem and SK Innovation currently use this design.
- **Prismatic Cells** (Figure 55): These cells are the most commonly used in EV battery packs today and are produced by Samsung SDI as well as CATL.³⁰⁹

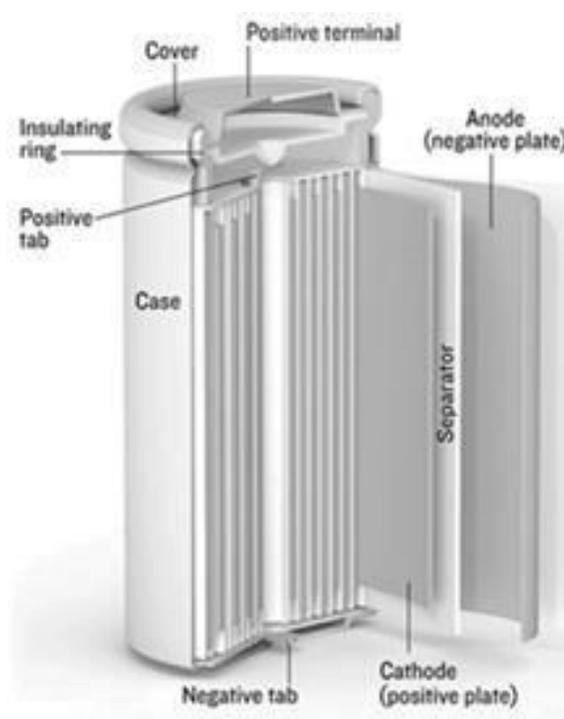


Figure 53 Li-ion Battery Cell - Cylindrical Design³¹⁰

³⁰⁹ The Boston Consulting Group. September 2018. "The Future of Battery Production for Electric Vehicles." <https://eu-smartcities.eu/sites/default/files/2018-10/BCG-The-Future-of-Battery-Production-for-Electric-Vehicles-Sep-2018%20%281%29_tcm81-202396.pdf>

³¹⁰ ³²⁰ UBS Limited. November 19, 2018. "Q-Series: Tearing down the heart of an electric car: Can batteries provide an edge, and who wins?" <<http://xqdoc.imedao.com/16764c45aca1ea83fdfe1636.pdf>>

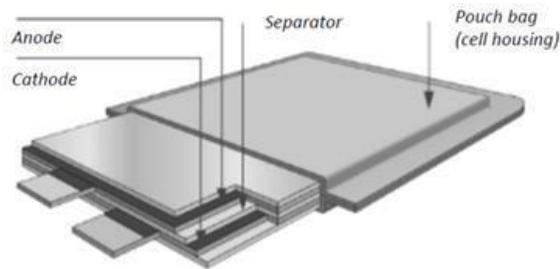


Figure 54 Li-ion Battery Cell – Pouch Design³¹¹

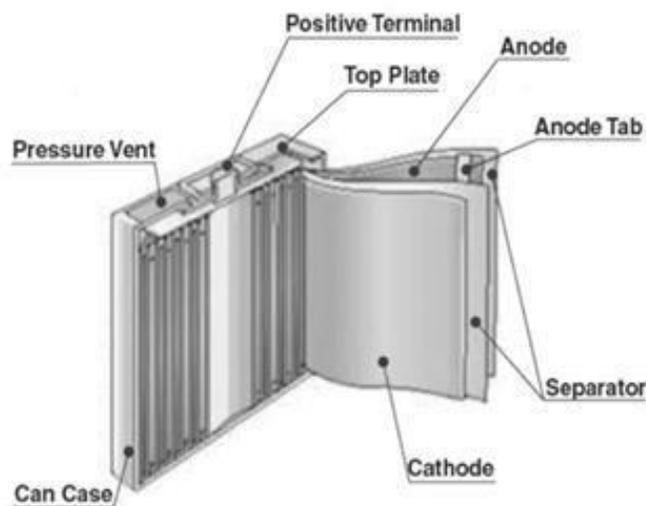


Figure 55 Li-ion Battery Cell – Prismatic Design³¹²

Multiple cells in a case with terminals attached form a module. The number of battery cells per module varies depending on the manufacturer and cell type.³¹³ The modules in a Nissan Leaf battery pack, for example, use four cells, while Samsung SDI puts 12 cells into its modules.³¹⁴

³¹¹ Ibid.

³¹² Ibid.

³¹³ Coffin, D., & J. Horowitz. December 2018. "The Supply Chain for Electric Vehicle Batteries." <https://www.usitc.gov/publications/332/journals/the_supply_chain_for_electric_vehicle_batteries.pdf>

³¹⁴ Ibid.

The final stage of EV battery production is pack assembly. Battery packs of different sizes can be made by including different numbers of modules. Battery pack designs for EVs are complex and vary widely by manufacturer. Figure 56 shows a Chevrolet Bolt battery pack, which uses NMC chemistry in pouch type format.³¹⁵

A July 2018 article³¹⁶ describes the design of the Bolt's battery pack as follows:

“The Bolt pack assembly consists of a strong steel underside casing and cross members and a fiberglass or composite top cover, attached with bolts and sealed along its complete perimeter. The Battery Management System (BMS) controller is mounted inside the pack enclosure on top and at the rear...The cell BMS is connected to the controller via a set of wire harnesses. Power relays are the only other devices inside the pack. Unlike the Model 3, the other high-voltage units, high-voltage controller, and DC–DC converters are separate and mounted in other areas of the vehicle.

When looking down on the pack as it is mounted in the car, pouch cells are oriented like books on a bookshelf, in groups. The pack consists of ten modules, two in a row. The modules on the bottom are labelled and divided into eight 5.94 kWh modules and two upper 4.75 kWh modules, for a labelled total of 57.02 kWh. Each module is composed of 3p (three in parallel) pouch cells contained in its own metal enclosure, like a book with pages. Eight of the modules contain ten 3p books, and two modules contain eight 3p, for a total of 96s, 3p.

The pack consists of pouch cells, flat like a sheet of paper but thicker, like cardboard, housed three inside their own metal mechanical box assembly like a book. The pouch books are stacked to make modules like rows of books in a bookshelf. The 3p pouch boxes are held together at the ends by long bolts. The pack thermal management is regulated by sensing temperature via thermistors located at the ends of the modules. There are liquid coolant channels at the base of the pack. There are also metal sheets extending between the 3p pouch books. The vertical cooling plates are attached to the horizontal base cooling plate.

The pack has a stacked module arrangement at the rear. The rear of the pack stacks modules on top, giving it the look of pillows on a bed. The upper shelf has its own base cooling plate attached with hoses to the liquid coolant loop and lower base cooling plate.”

³¹⁵ Arcus, C. 8 July 2018. “Tesla Model 3 & Chevy Bolt Battery Packs Examined.” <<https://cleantechnica.com/2018/07/08/tesla-model-3-chevy-bolt-battery-packs-examined/>>

³¹⁶ UBS Limited. November 19, 2018. “Q-Series: Tearing down the heart of an electric car: Can batteries provide an edge, and who wins?” <<http://xqdoc.imedao.com/16764c45aca1ea83fdfe1636.pdf>>



Figure 56 Chevrolet Bolt Battery Pack³¹⁷



Figure 57 Pouch Cells Used in Chevrolet Bolt Battery Pack

Figure 58 shows a 85 kWh battery pack from a Tesla S, which has a very different design from the Chevrolet Bolt. The Tesla S battery pack consists of 16 modules each containing 444 cells for a total of 7,104 cells. The cells are 18650 cylindrical battery cells made by Panasonic in Asia, and is

³¹⁷ Cobb, J. 11 January 2016. "Chevy Bolt EV's Battery Is As Big As A Tesla's." <<https://www.hybridcars.com/chevy-bolt-evs-battery-is-as-big-as-a-teslas/>>

the same format of cells found in laptops and some other electronic devices.³¹⁸ These cells were chosen specifically by Tesla to ensure that there would not be a shortage of battery materials for their EVs when they went into full production. While Panasonic makes the cells, Tesla actually designed the EV battery. These cells are small (18mm in diameter and 65mm tall), slightly larger than standard AA battery cells.³¹⁹ Tesla's 100 kWh battery pack, which is used in its Model S and X, has 16 modules for a total of 8,256 cells per pack.³²⁰



Figure 58 Photograph of a Tesla S Battery Pack³²¹



³¹⁸ Lambert, F. 25 April 2019. "Tesla battery supplier Panasonic is considering switching 18650 cell production to 2170 cells." <<https://electrek.co/2019/04/25/tesla-battery-supplier-panasonic-18650-2170-cell-production/>>

³¹⁹ Pressman, M. 6 August 2017. "Understanding Tesla's Lithium Ion Batteries." <<https://evannex.com/blogs/news/understanding-teslas-lithium-ion-batteries>>

³²⁰ Lambert, F. 24 August 2017. "Tesla Model 3: Exclusive first look at Tesla's new battery pack architecture." <<https://electrek.co/2017/08/24/tesla-model-3-exclusive-battery-pack-architecture/>>

³²¹ Lambert, F. February 3, 2016. "Tear down of 85 kWh Tesla battery pack shows it could actually only be a 81 kWh pack [Updated]." <<https://electrek.co/2016/02/03/tesla-battery-tear-down-85-kwh/>>

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Figure 59 Panasonic 18650 Cylindrical Battery Cells Used in a Tesla Model S and X³²²

In June 2017, Panasonic started producing a new, bigger 2170 (21mm in diameter and 70mm long) battery cell format for Tesla's new Model 3 at Gigafactory 1 in Nevada. The bigger cell design allows for higher energy density and Tesla's battery packs made of 2170 cells are capable of a higher charge rate.³²³ Tesla's standard 50 kWh Model 3 battery pack is comprised of 2,976 of the 2170 battery cells in groups of 31 cells per "brick." The bricks go into 4 separate modules, two of which contain 23 bricks and the other two with 25 bricks. See Figure 60. Unlike the Model S and X battery pack, the Model 3 battery pack is not easily swappable as there are bolts, which are only accessible by removing trims from the interior of the car.³²⁴

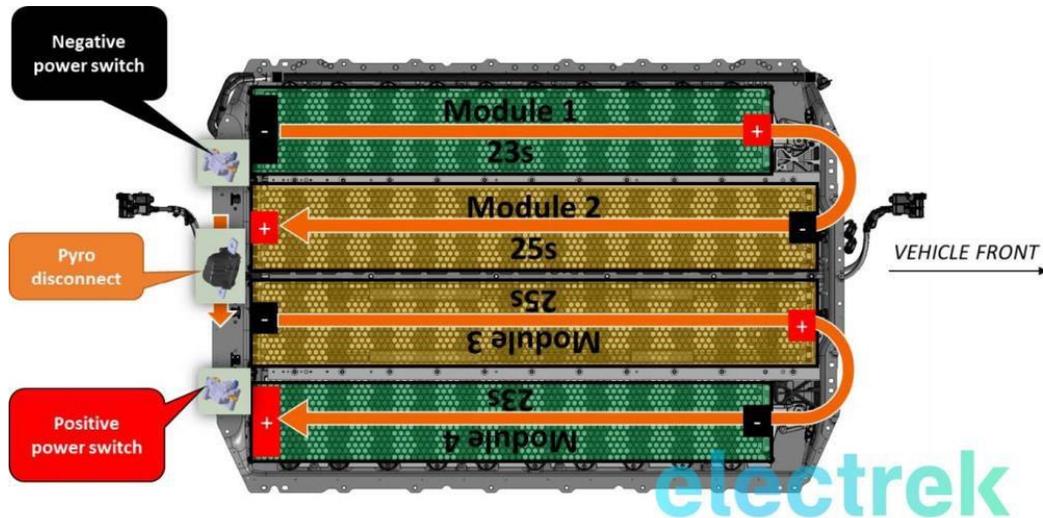


Figure 60 Distribution of Cells in a Tesla Model 3 Battery Pack³²⁵

Figure 61 shows the battery pack inside a BMW i3. The packs contain eight modules, each of which has 12 prismatic battery cells (for a total of 96 cells) made from Samsung SDI.³²⁶

³²² Pressman, M. August 6, 2017. "Understanding Tesla's Lithium Ion Batteries." <https://evannex.com/blogs/news/understanding-teslas-lithium-ion-batteries>

³²³ Lambert, F. April 25, 2019. "Tesla battery supplier Panasonic is considering switching 18650 cell production to 2170 cells." <https://electrek.co/2019/04/25/tesla-battery-supplier-panasonic-18650-2170-cell-production/>

³²⁴ Lambert, F. August 24, 2017. "Tesla Model 3: Exclusive first look at Tesla's new battery pack architecture." <https://electrek.co/2017/08/24/tesla-model-3-exclusive-battery-pack-architecture/>

³²⁵ Ibid.

³²⁶ Lima, P. September 5, 2018. "LION Smart shows off a BMW i3 with a 100 kWh battery." <https://pushevs.com/2018/09/05/lion-smart-shows-off-a-bmw-i3-with-a-100-kwh-battery/>



Figure 61 BMW i3 Battery Pack

Appendix E: Battery Chemistry in Different HEVs, PHEVs and BEVs

Tables 22, 23 and 24 present information on the type and weight of batteries used in the top 10 best-selling HEVs, PHEVs and BEVs sold in the US in 2018. Each manufacturer bases the decision on which battery to use on a number of factors including requirements for weight, energy density, charging characteristics and costs of materials.

Table 22 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 Liftback	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	1.6 (NiMH) 1.0 (Li-ion)	n/a
Toyota Highlander Hybrid	5%	NiMH	4.5	n/a
Hyundai Ioniq Hybrid	5%	Li-ion	1.6	n/a
Honda Accord Hybrid	4%	Li-ion	1.3	n/a
Lexus RX 400/450h	4%	NiMH	1.9	n/a
Ford C-Max Hybrid	3%	Li-ion	1.4	n/a

Table 23 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 SE ALL4	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 = LiNiCoAlO₂ (Lithium nickel cobalt aluminum oxide); NMC = LiNiMnCoO₂ (Lithium nickel manganese cobalt oxide); LMO = LiMn₂O₄ (Lithium manganese oxide); LCO = LiCoO₂ (Lithium cobalt oxide) ; LTO = Li₄Ti₅O₁₂ (Lithium titanate)

Table 24 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-Class Electric Drive B250e	0%	C/NCA	28 ³²⁸	n/a

³²⁷ Depending on the model (S 75D, 90D, 100D, or P100D)

³²⁸ Manual switch to 31.5 kWh

Appendix F: Supply Chain for Materials in EV Batteries

A li-ion cell is part of a long supply-chain that includes all major materials needed to form a battery pack. A simple schematic of this supply chain is presented in Figure 62.

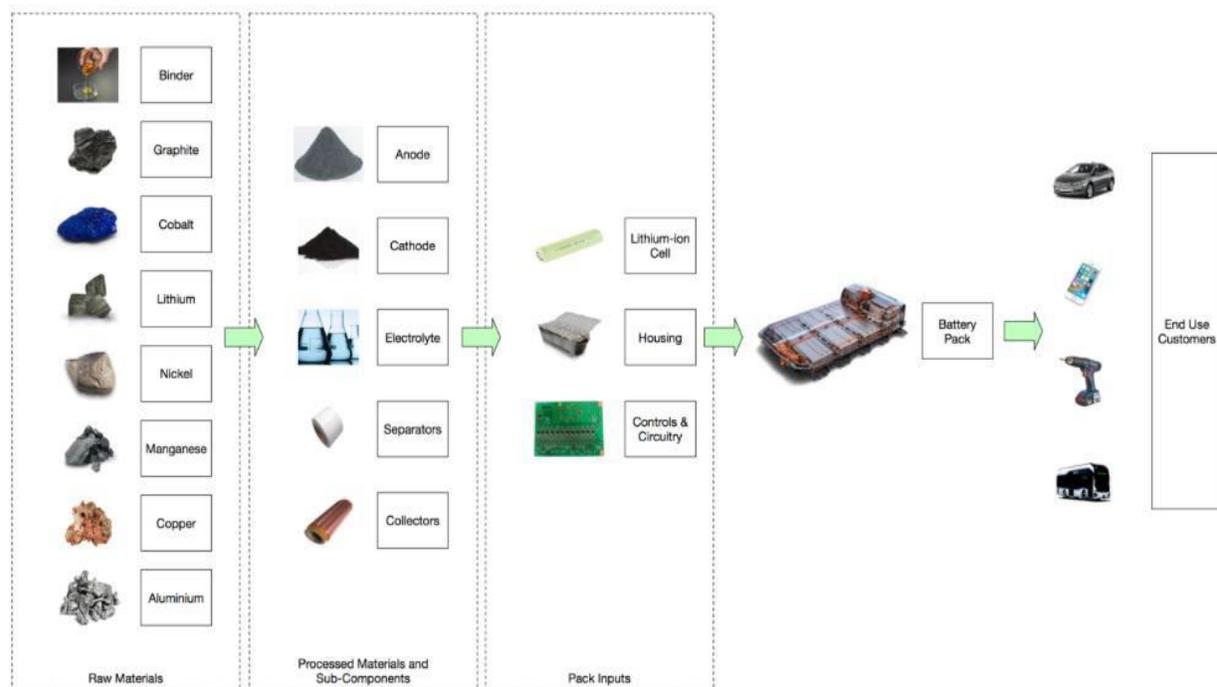


Figure 62 Li-ion Battery Supply Chain³²⁹

There are five key materials used in most EV batteries: cobalt, nickel, aluminum oxides, lithium, and graphite. The discussion will focus on cobalt and nickel due to their economic importance, which provides a significant incentive for recycling.

In the EV sector, cobalt is used in both NMC and NCA batteries. As a minor metal, cobalt is almost always produced as a by-product of copper and nickel production.³³⁰ Currently, the most prominent deposit is in the Democratic Republic of Congo (DRC), where 51% of global cobalt production is mined through the copper-mining industry.³³¹ China, Canada, Russia, and Australia each supply about 5% of the global cobalt demand, while the remaining share is fragmented

³²⁹ Dougher, C. 23 April 2018. "Breaking Down the Lithium-Ion Cell Manufacturing Supply Chain in the U.S. to Identify Key Barriers to Growth." <<https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/16600/US%20Lithium%20Ion%20Cell%20Manufacturing%20Supply%20Chain.pdf?sequence=1>>

³³⁰ Agora Verkehrswende. March 2018. "Ensuring a Sustainable Supply of Raw Materials for Electric Vehicles: A Synthesis Paper on Raw Material Needs for Batteries and Fuel Cells." <https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Nachhaltige_Rohstoffversorgung_Elektromobilitaet/Agora_Verkehrswende_Rohstoffstrategien_EN_WEB.pdf>

³³¹ Drabik, E. and V. Rizos. July 2018. "Research Report: Prospects for Electric Vehicle Batteries in a Circular Economy." No 2018/05. <https://www.ceps.eu/system/files/RR%202018_05_Circular%20Impacts_batteries.pdf>

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among other countries.³³² With the rise in EV sales, cobalt demand has been increasing at a rate of 3-4% annually since 2010, which has had a significant impact on its price. The increasing demand and subsequent rising prices are leading some battery manufacturers to reduce the cobalt content of their batteries. This is particularly true for the NMC type li-ion batteries, which previously employed a ratio of 1:1:1 (nickel, manganese, cobalt), but are now moving to 6:2:2 or 8:1:1. Figure 63 shows the sources of cobalt globally. There is a strong interest by all EV manufacturers to find their own secure sources of cobalt outside of the DRC. One of the big drivers for EV battery recycling is to create a secure supply chain for the various materials needed to manufacture batteries.

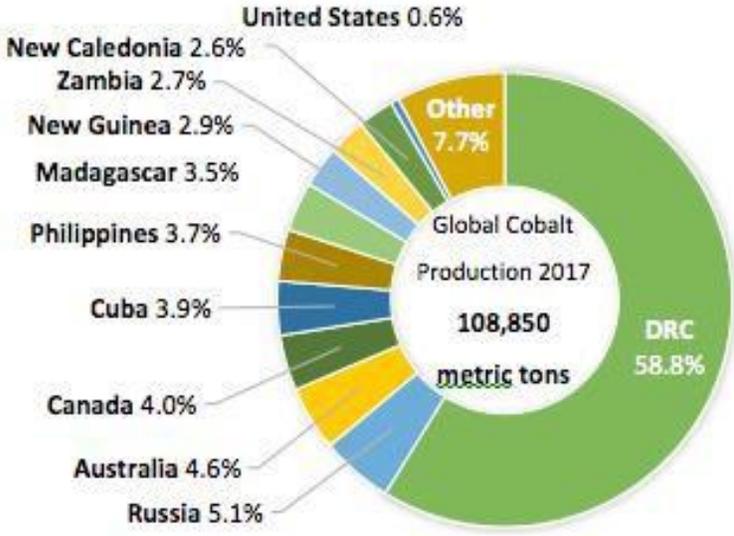


Figure 63 Sources of Cobalt Globally (2017)³³³

Like cobalt, nickel is used in both NMC and NCA batteries, but not in LFP batteries. It makes up around 80% of an NCA cathode used in Tesla models and around 33% in NMC 1:1:1 cathodes, but in the future it is projected to make up around 80% of the cathode in the shift towards NMC 8:1:1 batteries.³⁴³ According to Simon Moores, Managing Director at Benchmark Mineral Intelligence, the demand for nickel is set to increase up to 19 times if under-construction li-ion production facilities come online as planned.³³⁴ “Nickel demand from EV batteries is set to grow by between 30-40% a year, making it the fastest-growing battery raw material,” said Moores.³³⁵

Unlike cobalt, nickel production is spread more evenly between a greater number of countries –

³³² Zubi, G., Dufo-Lopez, R., Carvalho, M., and G. Pasaoglu. (2018). “The lithium-ion battery: State of the art and future perspectives.” *Renewable and Sustainable Energy Reviews*, 89, 292-308.

³³³ American Manganese Business Plan December 2018. Original source USGS, 2017. <https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2017-cobal.pdf>

³³⁴ <https://investingnews.com/daily/resource-investing/base-metals-investing/nickel-investing/nickel-tipped-fastest-growing-battery-metal-boom/>

³³⁵ <https://investingnews.com/daily/resource-investing/base-metals-investing/nickel-investing/nickel-tipped-fastest-growing-battery-metal-boom/>

with Indonesia and the Philippines accounting for 40% of production. Other key nickel-producing countries include Canada (10%), Australia (10%), New Caledonia (7%), and others (33%), which include China and Russia (see Figure 64).

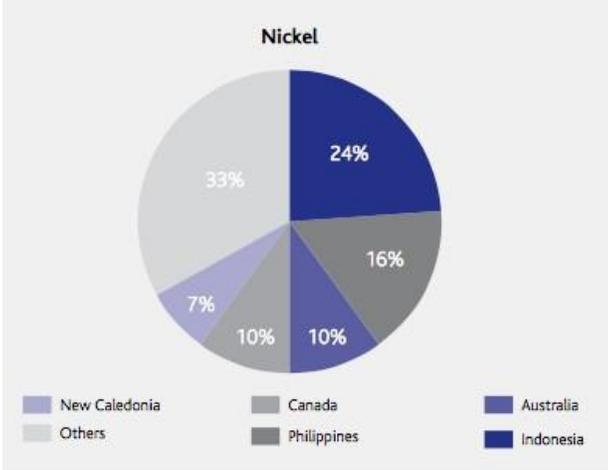


Figure 64 Global Producers of Nickel for Battery Applications³³⁶

³³⁶ <https://www.trafigura.com/media/365090/trafigura-responsible-sourcing-in-the-electric-vehicle-battery-supply-chain.pdf>
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Appendix G: Factors Influencing EV Adoption

The development of the global EV market includes overcoming various technical, social, and economic barriers. These barriers are typically summed up as limited availability of electric models, higher cost, inconvenience related to charging options, limited range and range anxiety, and consumer awareness and understanding about EVs. While some of these barriers will prove more challenging to overcome than others, at least five key factors will need to come together to drive mass adoption of EVs. CleanTechnica uses the “CARMA” framework to summarize these factors³³⁷

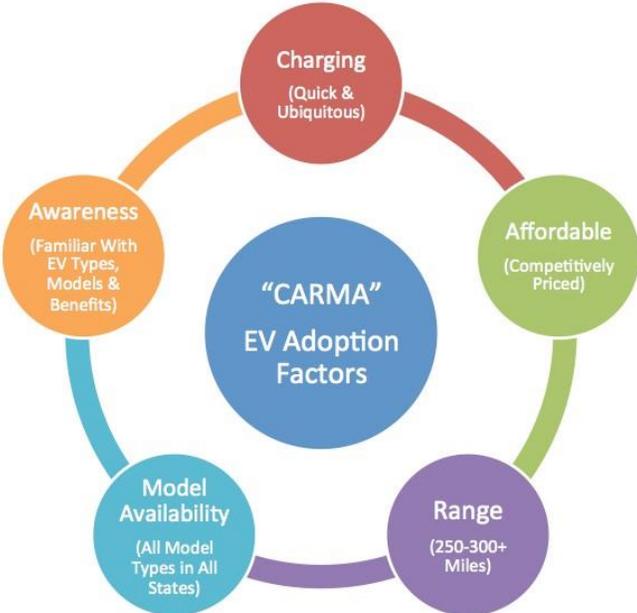


Figure 65 CARMA – EV Adoption Factors

C = Charging Speed and Availability: After cost, available charging infrastructure is likely the largest driver of EV sales. The two key barriers are in the availability of charging stations and the time required to charge.³³⁸ These barriers can be overcome through the establishment of an expanded charging infrastructure network, including home, workplace, and public locations, with sufficiently fast charging. Greater charging availability increases user confidence in EVs and makes greater range and functionality possible. Claiming to have Superchargers within 150 miles of 99% of the US population³³⁹, Tesla has made significant progress towards solving this problem. A number of utilities and auto manufacturers are also focused on installing charging stations. Over the next few years, the expansion of charging stations at workplaces and retail locations will be key in

³³⁷ McDonald, L. 4 January 2017. “CARMA’ – An EV Adoption Framework For US Auto Buyers.” <<https://cleantechnica.com/2017/01/04/carma-ev-adoption-framework-us-auto-buyers/>>
³³⁸ International Council on Clean Transportation. May 2018. “Power Play: How Governments are Spurring the Electric Vehicle Industry.” <<https://www.theicct.org/publications/global-electric-vehicle-industry>>
³³⁹ Kane, M. 11 August 2018. “Tesla: ‘99% of U.S. Population Is Within 150 Miles Of A Supercharger.’” <<https://insideevs.com/tesla-99-of-u-s-population-is-within-150-miles-of-a-supercharger/>>

reducing range concerns, especially for those living in multi-family complexes who tend to lack convenient charging access at “home.” Figure 66 shows the evolution of public and workplace charging points for EVs in the US from 2008 to 2017.

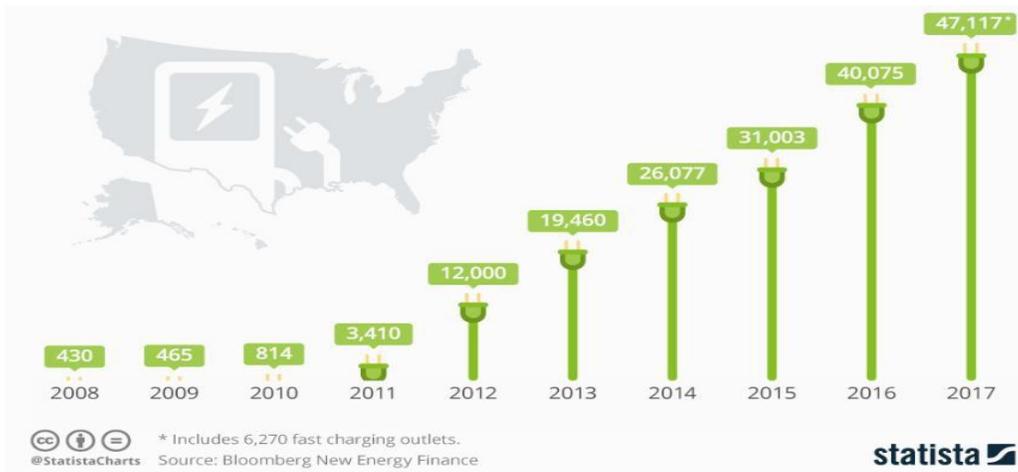


Figure 66 Number of Public and workplace Charging Points for EVs in the US (2008 to 2017)³⁴⁰

A = Affordability: The direct cost of EVs and uncertainty about the total cost of ownership (fuel savings, maintenance costs, and resale value) are other major barriers to the adoption of EVs, which have greater initial upfront costs than comparable gasoline vehicles. For example, for the 2019 model year, the plug-in Ford Fusion Hybrid SE has a starting MSRP of US\$27,555³⁴¹ compared with a starting MSRP of US\$24,120³⁴² for the conventional Ford Fusion SE. The key factor affecting affordability in the next few years will be the cost of the EV batteries, which are estimated to be the single largest cost in the manufacture of EVs.³⁴³ The price of li-ion batteries has already decreased substantially as their production scale has increased and as manufacturers have developed more cost-effective methods. It is estimated that when EV batteries reach \$100/kWh, the costs of EVs will reach parity with equivalent ICE models. Another key factor affecting affordability is the availability of financial incentives such as rebates, tax credits, or tax exemptions, all of which can lower the purchase or lease price of EVs and make them more comparable in cost to conventional vehicles. In the US, the federal government provides up to \$7,500 in income tax credits for new EVs purchased; the size of the credit depends on the size of the vehicle and its battery capacity.³⁴⁴ Some consumers are also eligible to receive EV incentives from their state, city or utility (see Figure 67).

³⁴⁰ McCarthy, N. 9 April 2018. “Evolution of U.S. Electric Vehicle Charging Points.” <<https://www.statista.com/chart/13466/the-evolution-of-us-electric-vehicle-charging-points/>>

³⁴¹ Ford Motor Company. “2019 Fusion Hybrid SE.” <<https://www.ford.com/cars/fusion/models/fusion-hybrid-se/>>

³⁴² Ford Motor Company. “2019 Fusion SE.” <<https://www.ford.com/cars/fusion/models/fusion-se/>>

³⁴³ McDonald, L. 4 January 2017. “‘CARMA’ – An EV Adoption Framework For US Auto Buyers.” <<https://cleantechnica.com/2017/01/04/carma-ev-adoption-framework-us-auto-buyers/>>

³⁴⁴ US Office of Energy Efficiency and Renewable Energy. “Electric Vehicles: Tax Credits and Other Incentives.” <<https://www.energy.gov/eere/electricvehicles/electric-vehicles-tax-credits-and-other-incentives>>

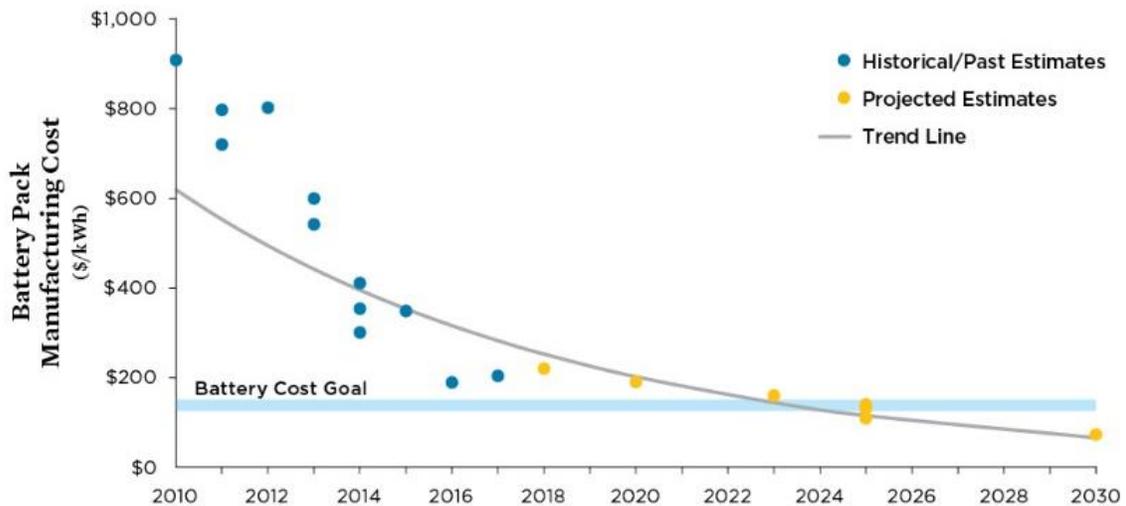


Figure 67 Battery Pack Manufacturing Cost 2010 to 2030) (\$/kWh)³⁴⁵



Figure 68 EV Tax Incentives By State in the US³⁴⁶

R = Range: Limited driving range is another key barrier to EV adoption. A survey conducted by the National Renewable Energy Laboratory (NREL) in 2015 found that 56% of Americans won't consider buying an EV unless it has at least 300 miles (483 km) of range. Over the next 5 years, it is expected that increases in battery efficiency and declining costs will result in an increase in the average range of a non-luxury EV to 200+ miles, with many at or above 250 miles. For higher-end

³⁴⁵ "Electric Vehicle Battery: Materials, Cost, Lifespan." <<https://www.ucsusa.org/clean-vehicles/electric-vehicles/electric-cars-battery-life-materials-cost#.XGxQJK3MwUt>>

³⁴⁶ Thomson Reuters. "Will Electric Vehicles Really Create a Cleaner Planet?" <<https://www.thomsonreuters.com/en/reports/electric-vehicles.html>>

luxury EVs, the average range is expected to increase to 350-400 miles.³⁴⁷ By moving closer to the driving range of conventional gasoline vehicles, increased driving range will translate into higher EV adoption rates. Table 25 shows the range reported for PHEVs. This is generally a short distance but the vehicles have an ICE back-up system so are not dependent on charging. Table 26 presents ranges reported for a number of EVs in February, 2019. While Tesla are extending range to 300 miles or more, some small EVs quote short ranges of 60 to 90 miles, and are therefore only suitable for short urban trips.

Table 25 Ranges Reported for Selected PHEVs in the US, February, 2019 (miles)

Make and Model	Electric Range of 2018 Models (or latest model available)
Audi A3 Sportback e-tron (PHEV)	16 miles
BMW i8 (PHEV)	18 miles
BMW X5 xDrive40e (PHEV)	14 miles
BMW 330e (PHEV)	14 miles
BMW 530e (PHEV)	15 miles
BMW 740e (PHEV)	14 miles
Cadillac ELR (PHEV)	37 miles
Cadillac CT6 (PHEV)	31 miles
Chevrolet Volt (PHEV)	53 miles
Chrysler Pacifica (PHEV)	33 miles
Ford C-Max Energi (PHEV)	20 miles
Ford Fusion Energi (PHEV)	22 miles
Honda Accord (PHEV)	13 miles
Honda Clarity Plug-in Hybrid (PHEV)	48 miles
Hyundai Sonata (PHEV)	27 miles
Hyundai Ioniq (PHEV)	29 miles
Kia Optima (PHEV)	29 miles
Kia Niro (PHEV)	26 miles
Mini Cooper Countryman SE ALL4 (PHEV)	12 miles
Mercedes S550 (PHEV)	20 miles
Mercedes GLE 550e (PHEV)	12 miles
Mercedes C350e (PHEV)	9 miles
Mercedes GLC 350e (PHEV)	21 miles
Mitsubishi Outlander (PHEV)	22 miles
Porsche Panamera S-E (PHEV)	16 miles
Porsche Panamera E-Hybrid (PHEV)	31 miles
Porsche Cayenne S-E (PHEV)	27 miles
Porsche 918 Spyder (PHEV)	12 miles
Toyota Prius (PHEV)	11 miles
Toyota Prius Prime (PHEV)	25 miles
Volvo XC90 (PHEV)	17 miles
Volvo XC60 (PHEV)	17 miles
Volvo S90 T8 (PHEV)	21 miles

³⁴⁷ McDonald, L. 4 January 2017. "CARMA' – An EV Adoption Framework For US Auto Buyers." <<https://cleantechnica.com/2017/01/04/carma-ev-adoption-framework-us-auto-buyers/>>

Table 26 Ranges Reported for Selected BEVs in the US, February, 2019 (miles)

Make and Model	Electric Range of 2018 Models (or latest model available)
BMW i3 (BEV)	114 miles
Chevrolet Bolt (BEV)	238 miles
Chevrolet Spark EV (BEV)	82 miles
Fiat 500e (BEV)	84 miles
Ford Focus Electric (BEV)	115 miles
Honda Fit (BEV)	82 miles
Honda Clarity Electric (BEV)	89 miles
Hyundai Ioniq (BEV)	124 miles
Jaguar I-Pace (BEV)	336 miles
Kia Soul (BEV)	111 miles
Mercedes B-Class Electric Drive B250e (BEV)	87 miles
Mitsubishi i-MiEV (BEV)	62 miles
Nissan Leaf (BEV)	151 miles
Smart ED (BEV)	58 miles
Tesla Model S (BEV)	259 to 335 miles
Tesla Model X (BEV)	238 to 295 miles
Tesla Model 3 (BEV)	325 miles
Toyota Rav4 EV (BEV)	100 miles
Volkswagen e-Golf (BEV)	125 miles

M = Model Availability: Research has shown that there is a significant positive correlation between a country’s EV market share and the number of models available in the market.³⁴⁸ There were only 4 EV models available to North American consumers in 2008. By 2017, this had increased to 54.³⁴⁹ Although this is still a small fraction of total available vehicle models, nearly every major automaker has committed to multi-billion dollar investments to develop a spectrum of new models over the coming years. Figure 69 shows how the choice of models has increased over time

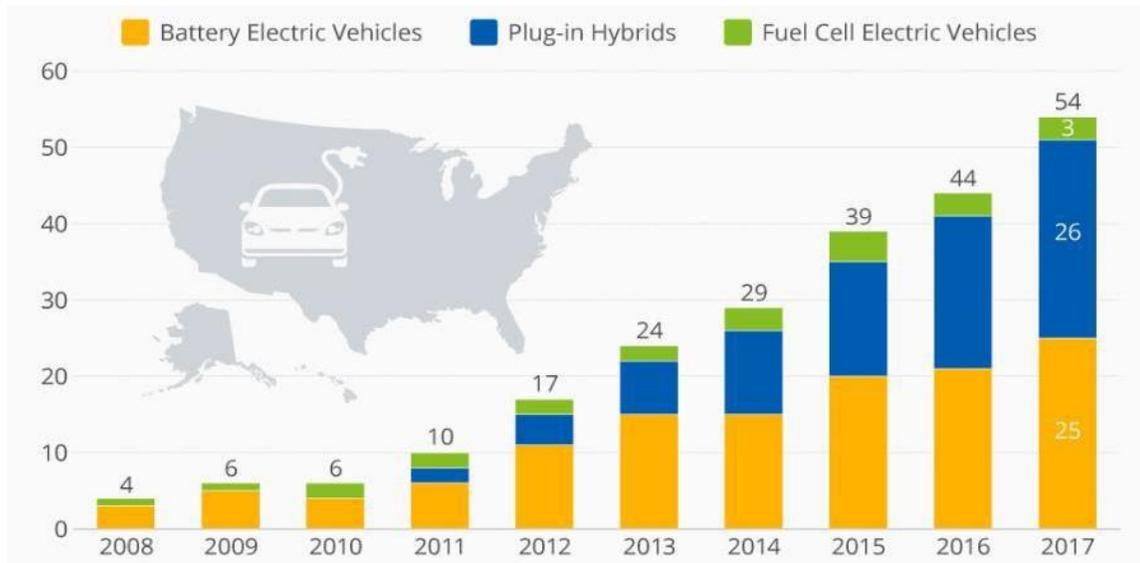


Figure 69 Number of EV Models Available to Consumers in North America, 2008-2017³⁶⁰

Figure 69 Number of EV Models Available to Consumers in North America, 2008-2017³⁵⁰

A = Awareness: An overall lack of consumer awareness and understanding of EVs is another barrier to mass EV adoption. According to a 2017 consumer survey by Altman Vilandrie & Co³⁵¹, 60% of Americans are unaware of the existence of plug-in EVs and 80% have never ridden in one. In addition to this lack of awareness and familiarity with EVs, many consumers don’t understand the differences between the three different types of EVs, such as the benefits and costs of each. This barrier can be overcome through public awareness and outreach activities, such as National Drive Electric Week, which allows customers to take test drives and ask questions of both EV owners and dealership staff (among other things).³⁵² Research by the California Plug-in Electric Vehicle Collaborative found that 9% of survey respondents purchased or leased an EV within

³⁴⁸Kim, S., Lee, J., and C. Lee. 2017. “Does Driving Range of Electric Vehicles Influence Electric Vehicle Adoption?” *Sustainability*, 9(10). <<https://www.mdpi.com/2071-1050/9/10/1783>>

³⁴⁹Richter, F. 9 April 2018. “Electric Vehicle Buyers Have the Agony of Choice.” Statista. <<https://www.statista.com/chart/13465/electric-vehicle-models-available-in-north-america/>>

³⁵⁰ Richter, F. 9 April 2018. “Electric Vehicle Buyers Have the Agony of Choice.” Statista. <<https://www.statista.com/chart/13465/electric-vehicle-models-available-in-north-america/>>

³⁵¹ Ayre, J. 1 January 2017. “Survey: 60% of Americans Aren’t Aware of Plug-in Electric Vehicles...At All.” <<https://cleantechnica.com/2017/01/01/survey-60-americans-arent-aware-plug-electric-vehicles/>>

³⁵² Plug In America, Sierra Club and Electric Auto Association. “2018 Highlights.” <<https://driveelectricweek.org>>

three months of a test drive.³⁵³

Future Projections of EV Adoption Rates

The following is a non-exhaustive list of factors that can may impact on US EV sales projections:

- **Battery costs, which influence EV cost competitiveness (price parity) with gasoline powered (ICE) vehicles:** Some forecasters believe that investments being made by companies such as Tesla and Volkswagen will lead to a significant reduction in EV battery costs, which in turn will make EVs being more cost competitive with ICE vehicles and increase EV sales. However, if costs do not fall and government mandates are not enacted then it is possible that EVs will remain a niche product, more prevalent among high-end cars, performance vehicles, and fleets.³⁵⁴ In JP Morgan’s EV sales projection, it is assumed that battery costs will fall to around \$100/kWh by the middle of the next decade or earlier.³⁵⁵ Bloomberg New Energy Finance (NEF) expects price parity between EVs and ICEs by the mid-2020s as well.³⁵⁶
- **New EV model introductions:** Historically, the majority of annual EV sales growth in the US has come from new model introductions.³⁵⁷ The prediction made by Loren McDonald/EVAdoption.com assumes that a “significant number of ‘affordable’ EVs will be introduced in the 2020-2022 time frame.
- **Future battery manufacturing capacity:** Bloomberg NEF’s projections assume that battery manufacturing capacity grows only enough to supply 10 million EVs annually by 2025 and there does not appear to be scope for future growth of battery manufacturing capacity in its modeling.³⁵⁸ Our assessment is that battery manufacturing capacity is unlikely to be a limiting factor given all the recent announcements of new battery manufacturing coming on line.
- **Overall vehicle sales:** The prediction made by Loren McDonald/EVAdoption.com assumes that overall vehicle sales will experience a modest decline over the next several years as a result of a slowing economy, changing purchase behaviour including consumers keeping cars longer and forgoing second and third cars by sharing, as well as the increased use of ride-sharing services.³⁵⁹ Bloomberg NEF’s projection is also based on an assumption that shared mobility services will continue to grow, gradually reducing demand for private vehicle ownership. An overall decline in vehicle sales likely means slower growth for EVs as well, though an increase in market share.³⁶⁰
- **Charging speed:** Charging power, which determines the time required to charge an EV, can vary across charge points and will depend on how much money is invested into expanding charging infrastructure, particularly DC fast charging points. The prediction made by Loren McDonald/EVAdoption.com assumes that a DC fast charging time to 80% battery level will reduce to about 15-20 minutes by around

³⁵³ The International Council on Clean Transportation. July 2018. “The Continued Transition to Electric Vehicles in U.S. Cities.” <https://www.theicct.org/sites/default/files/publications/Transition_EV_US_Cities_20180724.pdf>

³⁵⁴ National Rural Electric Cooperative Association. 2018. “Will Electric Vehicles Take Charge in Co-op Nation?” <<https://www.cooperative.com/programs-services/bts/documents/advisories/memberadvisoryevmarketupdatefeb2018.pdf>>

³⁵⁵ J.P. Morgan. October 10, 2018. “Driving into 2025: The Future of Electric Vehicles.” <<https://www.jpmorgan.com/global/research/electric-vehicles>>

³⁵⁶ BloombergNEF. “Electric Vehicle Outlook 2019.” <<https://about.bnef.com/electric-vehicle-outlook/>>

³⁵⁷ McDonald, L. January 20, 2019. “Forecast: 2019 US EV Sales Growth Will Drop to ~12%.” <<https://cleantechnica.com/2019/01/20/forecast-2019-us-ev-sales-growth-will-drop-to-12/>>

³⁵⁸ Holland, M. May 19, 2019. “BNEF’s Latest ‘Embarrassingly’ Lowball EV Outlook.” <<https://cleantechnica.com/2019/05/19/bnefs-latest-embarrassingly-lowball-ev-outlook/>>

³⁵⁹ EVAdoption. “EV Sales Forecasts.” <<https://evadoption.com/ev-sales/ev-sales-forecasts/>>

³⁶⁰ McDonald, L. January 20, 2019. “Forecast: 2019 US EV Sales Growth Will Drop to ~12%.” <<https://cleantechnica.com/2019/01/20/forecast-2019-us-ev-sales-growth-will-drop-to-12/>>

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2022.

- **Availability of charging points:** Bloomberg NEF's projection assumes that a portion of urban dwellers who may not have access to a plug at home or work will not be able to participate in EV ownership in the near future.³⁶¹
- **Demographics of demand:** The current EV market is highly segmented; early adopters tend to be relatively affluent, environmentally conscious, and often own a second or third vehicle. Once the demand in this demographic is saturated, it is unclear how fast it will spread to other consumer segments. As noted by David Keith, an engineer and professor at the MIT Sloan School of Management, "the nightmare scenario for EVs is that the appeal won't spread fast enough beyond 'technies and greenies' to sustain the growth of the early market."³⁶² Currently EVs also appeal to the "fashion driver" – a consumer who always buys the latest iPhone or other new gadget or electronic product as a fashion/lifestyle statement.
- **Fuel efficiency standards and environmental regulations:** JP Morgan's projection is partly based on the assumption that "tougher fuel economy regulation will likely push automakers to expand their EV offerings." In contrast, the US EIA's projection assumes that laws and policies remain unchanged.³⁶³
- **Economic incentives:** The US has a patchwork of state and federal incentives that can encourage EV adoption, which are subject to change every year.
- **Overall health of the economy:** When the economy slows down, people keep their existing cars longer so fewer EVs and therefore EV batteries would get retired prematurely.

The history of technology adoption in US households suggests that once market penetration of a new technology passes a threshold of around 2.5% to 5%, it then diffuses at a rapid rate.³⁶⁴ As shown in Figure 70, the adoption of automobiles moved from 2.5% to 50% in around 12 years, while color TV diffused at about the same rate, as did microwave ovens, cell phones, and the internet.³⁶⁵

For EVs, the rise in adoption from 2.5% to 30% has already occurred in Norway, taking 7 years or so. However, while the high number is true for Norway, and the country is often used as an example, it should be noted that many EVs in Norway are second cars which are used for short urban trips such as driving the kids to school, etc. and EV owners in Norway receive numerous benefits such as free parking, no vehicle tax, etc. making an EV cost competitive and as convenient, particularly in urban areas with a good charging infrastructure, as ICE vehicles. China passed a 2.5% EV adoption or penetration rate in 2017-2018 and the market penetration rate is expected to exceed 10% in late 2019 or 2020 (taking around 2.5 years).³⁶⁶ While the US may be lower on the EV adoption curve, it is still following the same pattern.

³⁶¹ Holland, M. May 19, 2019. "BNEF's Latest 'Embarassingly' Lowball EV Outlook." <<https://cleantechnica.com/2019/05/19/bnefs-latest-embarassingly-lowball-ev-outlook/>>

³⁶² Coren, M. May 18, 2019. "Researchers have no idea when electric cars are going to take over." <<https://qz.com/1620614/electric-car-forecasts-are-all-over-the-map/>>

³⁶³ Geman, B. January 28, 2019. "New report says the future of EVs in the U.S. looks grim." <<https://www.axios.com/electric-vehicle-adoption-united-states-eia-report-d70f8e0e-a87a-4825-be52-d8201aa649f5.html>>

³⁶⁴ Holland, M. May 19, 2019. "BNEF's Latest 'Embarassingly' Lowball EV Outlook." <<https://cleantechnica.com/2019/05/19/bnefs-latest-embarassingly-lowball-ev-outlook/>>

³⁶⁵ Desjardins, J. February 14, 2018. "The Rising Speed of Technological Adoption." <<https://www.visualcapitalist.com/rising-speed-technological-adoption/>>

³⁶⁶ Holland, M. May 19, 2019. "BNEF's Latest 'Embarassingly' Lowball EV Outlook." <https://cleantechnica.com/2019/05/19/bnefs-latest-embarassingly-lowball-ev-outlook/>

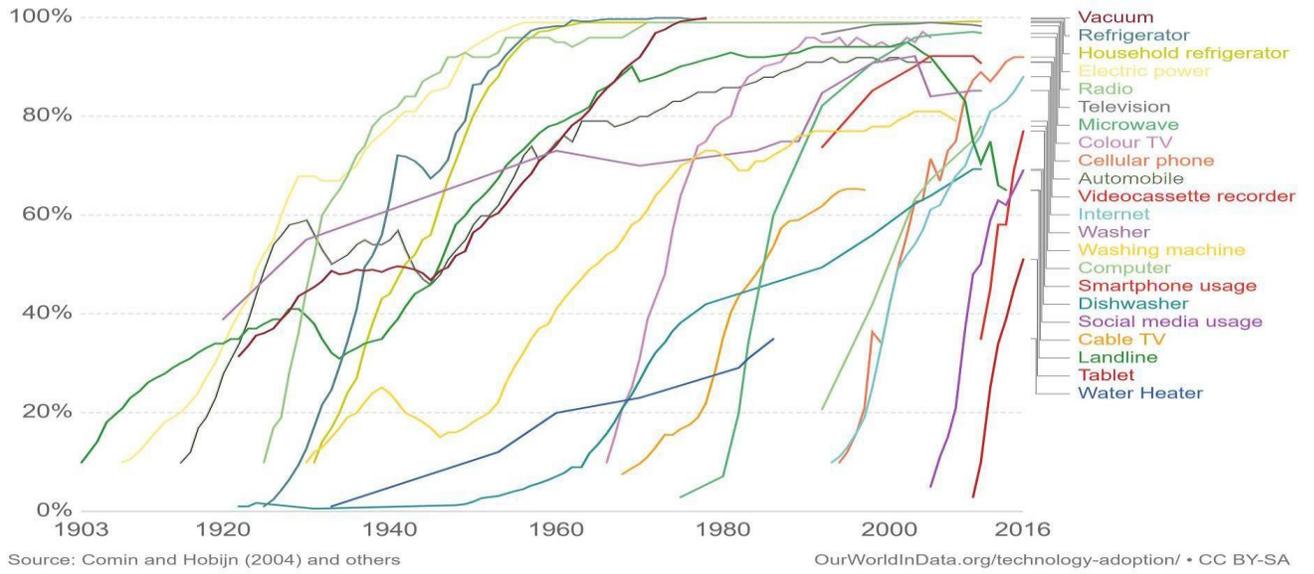


Figure 70 Timescale for Adoption of New Technologies by US Households (1903-2016)³⁶⁷

³⁶⁷ Desjardins, J. February 14, 2018. "The Rising Speed of Technological Adoption." <<https://www.visualcapitalist.com/rising-speed-technological-adoption/>>
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Appendix H: Commitments by Auto Makers to Increase EV Manufacture

As the costs of EV battery production have decreased, automakers throughout the globe have committed to putting numerous EVs on the North American and global markets.

Figure 71 presents EV commitments made by automakers as of December, 2017. The figure shows that automakers had already committed to developing their EV models and announcing this publicly in 2017. Table 27 presents a summary of commitments by automakers to EVs as of mid-2019. The two sources show that commitments to EV development have moved forward rapidly with public announcements totalling almost \$168 billion in investment commitments by early 2019.

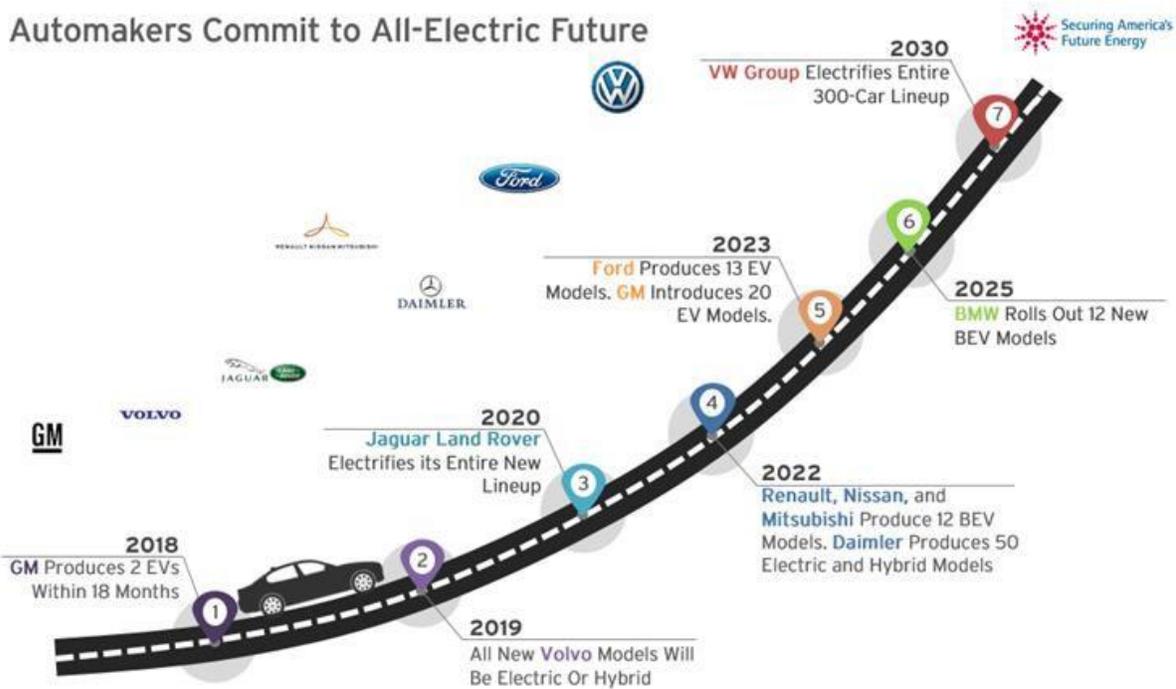


Figure 71 Commitments To EVs Made by Major Global Automakers (2018-2030)³⁶⁸

368 SAFE Policy Team. 5 December 2017. "Key Charts Highlighting Significant Growth in U.S. EV Market." <<http://energyfuse.org/safe-fact-pack-kelleher-research-study-on-reuse-and-recycling-of-batteries-employed-in-electric-vehicles>>

Table 27 Announced Investments by Selected Major Automakers in Electric Vehicles, Battery Technology and/or Battery Manufacturing Plants, February, 2019 (\$US billion)

Automaker	Announcement	Investment Amount
Audi	<ul style="list-style-type: none"> • \$16 billion through 2023 in autonomous driving, digitalization, and electric cars (December, 2018). • In May 2018, the company announced its plan to offer 20 new electrified cars, including hybrids, by 2025. In addition, it has announced plans to sell 800,000 electrified cars by 2025.³⁶⁹ • In 2015, then Audi of America president Scott Keogh said that by 2025, at least one-quarter of all Audi cars sold in the U.S. will be electric.³⁷⁰ 	<ul style="list-style-type: none"> • \$16 billion
BMW Group	<ul style="list-style-type: none"> • In January 2018, committed to having 12 all-electric and 13 hybrids in its line-up by 2025³⁷¹ • Aims to sell 500,000 plug-in electric cars by the end of 2019³⁷² • Expects that between 15-25% of vehicles sold by 2025 will have an electric drive train.³⁷³ • In December 2018, the company launched a 200 million euros (USD\$225 million) investment at its Munich factory to bring to production the new BMW i4 electric car.³⁷⁴ BMW expects that this early investment in “buildings, production facilities and logistics systems” will enable them to achieve series production of the i4 in 2021. 	<ul style="list-style-type: none"> • \$0.225 billion
Daimler	<ul style="list-style-type: none"> • In December 2018, announced it is issuing over \$20 billion worth of battery cell supply contracts to support its electric vehicle plans³⁷⁵ • Plans for more than 10 different all-electric vehicles by 2022, taking the total to 50 overall³⁷⁶ • 15-25% electric vehicle share of sales by 2025³⁷⁷ 	<ul style="list-style-type: none"> • \$20 billion
Dyson	<ul style="list-style-type: none"> • In 2018, Dyson announced it would build its new electric cars in Singapore at a new factory to be constructed by 2020, and start production in 2021. The company has committed to spending \$2.6 billion to launch its automotive business and plans to hire 500 staff.³⁷⁸ Of particular note is that Dyson plans to use solid state batteries in the EVs 	<ul style="list-style-type: none"> • \$2.6 billion
Fiat Chrysler Automobiles	<ul style="list-style-type: none"> • In June 2018, the company announced it will develop 12 battery-electric, plug-in and hybrid propulsion systems by 2022³⁷⁹ • In June 2018, announced plans to spend 9 billion euros (\$10.5 billion) or 20% of 	<ul style="list-style-type: none"> • \$10.5 billion

³⁶⁹ <https://www.industryleadersmagazine.com/audi-announces-to-invest-16-billion-in-self-driving-car-tech/>

³⁷⁰ <https://www.industryleadersmagazine.com/audi-announces-to-invest-16-billion-in-self-driving-car-tech/>

³⁷¹ Bubbers, M. 26 January 2018. “You and i.” <<https://www.theglobeandmail.com/globe-drive/news/industry-news/bmw-unveils-electric-car-plans-for-2021-andbeyond/article37703938/>>

³⁷² Kane, M. 7 April 2018. “BMW Commits More Money Than Ever to EVs.” <<https://insideevs.com/bmw-commits-money-ever-evs/>>

³⁷³ Boeriu, H. 10 July 2018. “BMW: “By 2025, 15-25% of our cars will have electric drivetrains.” <<https://www.bmwblog.com/2018/07/10/bmw-by-2025-15-25-of-our-cars-will-have-electric-drivetrains/>>

³⁷⁴ <https://electrek.co/2018/12/12/bmw-i4-electric-car-investment-production/>

³⁷⁵ <https://electrek.co/2018/12/11/daimler-billion-battery-cells-electric-vehicle/>

³⁷⁶ Daimler. “Plans for more than ten different all-electric vehicles by 2022: All systems are go.” <<https://media.daimler.com/marsMediaSite/en/instance/ko/Plans-for-more-than-ten-different-all-electric-vehicles-by-2022-All-systems-are-go.xhtml?oid=29779739>>

³⁷⁷ “Daimler: all-electric vehicles to account for 15-25% of total unit sales by 2025.” 30 January 2018.

<https://www.marklines.com/en/report/rep1667_201801>

³⁷⁸ https://www2.greencarreports.com/news/1123042_dyson-patents-show-possible-tesla-model-x-competitor

³⁷⁹ <https://www.triplepundit.com/story/2019/reviewing-automakers-sustainability-and-ev-commitments/81991>

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	its total budget for capital expenditures through 2022 to develop electrified vehicles ³⁸⁰	
Ford Motor Company	<ul style="list-style-type: none"> Ford announced it would invest \$4.5 billion in EV production and introduce 13 new models by 2020. Just over two years later, in January 2018, the company announced it would up both of these totals to \$11 billion in investments and 40 hybrid and fully electrified vehicles by 2022.³⁸¹ 	<ul style="list-style-type: none"> \$11 billion
Geely	<ul style="list-style-type: none"> In February 2018, the Chinese car manufacturer signed a contract for the construction of a new \$5 billion production complex for EVs and PHEVs in the province Zhejiang. 	<ul style="list-style-type: none"> \$5 billion
General Motors	<ul style="list-style-type: none"> In October 2017, GM announced it would be developing 20 new all-electric vehicles by 2023.³⁸² To facilitate that goal, GM is investing \$28 million in its Warren, Michigan battery lab as the company continues to improve its EV battery technology.³⁸³ In October 2018, the company called on the US federal government to establish a national electric vehicle policy; says EVs should be 25% of all new cars by 2030³⁸⁴ 	<ul style="list-style-type: none"> \$0.028 billion
Honda Motor Company	<ul style="list-style-type: none"> As part of its 2030 Vision Plan, the company aims to electrify two-thirds of its automobiles by 2030, which includes hybrids, plug-in hybrids, battery electric, and fuel cell vehicles.³⁸⁵ Honda expects this would equate to roughly 3 million vehicles annually at its present global sales levels.³⁸⁶ 	<ul style="list-style-type: none"> N/A
Hyundai/Kia	<ul style="list-style-type: none"> At the end of 2017, Hyundai and Kia announced that they aim to bring 38 “green car” models to market in the next 8 years, with 7 of them planned for the next 5 years³⁸⁷ In November 2018, Hyundai Motor and Grab, a Southeast Asian ride-sharing company, announced a deal in which Hyundai and Kia Motors will invest an additional \$250 million in Grab and create a partnership to pilot electric vehicle programs across the Southeast Asian region. The pilot projects will focus on utilizing EVs to lower costs for Grab’s driver-partners.³⁸⁸ 	<ul style="list-style-type: none"> \$0.250 billion
Jaguar	<ul style="list-style-type: none"> In September 2017, the company announced plans to launch only electric or hybrid lines from 2020³⁸⁹ In June 2018, Jaguar Land Rover announced it would be investing a total of 13.5 billion pounds (USD\$18 billion) worldwide over the next 3 years as part of its plan to be able to offer electric versions of all its models. This represents a 26% increase from 10.7 billion pounds over the three previous years through March 2018.³⁹⁰ 	<ul style="list-style-type: none"> \$18 billion
Nissan Motor	<ul style="list-style-type: none"> In late 2017, the company announced it intends to build 12 new zero-emission vehicles through its partnership with Mitsubishi and Renault by 2022. In doing 	<ul style="list-style-type: none"> \$11.5 billion

³⁸⁰ <https://europe.autonews.com/article/20180605/ANE/180609919/flat-chrysler-will-spend-10-5-billion-on-greener-cars>

³⁸¹ <https://www.triplepundit.com/story/2019/reviewing-automakers-sustainability-and-ev-commitments/81991>

³⁸² <https://www.triplepundit.com/story/2019/reviewing-automakers-sustainability-and-ev-commitments/81991>

³⁸³ [https://www.futurecar.com/2632/General-Motors-Investing-\\$28-Million-to-Expand-its-EV-Battery-Lab](https://www.futurecar.com/2632/General-Motors-Investing-$28-Million-to-Expand-its-EV-Battery-Lab)

³⁸⁴ <https://www.forbes.com/sites/sebastianblanco/2018/10/26/gm-calls-for-national-electric-vehicle-policy-says-evs-should-be-25-of-all-new-cars-by-2030/#5df2de531cf0>

³⁸⁵ *ibid*

³⁸⁶ <https://www.autonews.com/article/20180607/OEM/180609806/gm-honda-team-up-on-next-gen-ev-batteries>

³⁸⁷ <https://cleantechica.com/2018/10/08/top-3-automakers-their-electric-vehicle-plans/>

³⁸⁸ <https://www.greencarcongress.com/2018/11/20181107-grab.html>

³⁸⁹ Cox, J. 7 September 2017. “Jaguar Land Rover commits to all vehicles being electric or hybrid from 2020.”

<https://www.independent.co.uk/news/business/news/url-jaguar-land-rover-electric-hybrid-cars-vehicles-2020-a7933681.html>

³⁹⁰ <https://www.detroitnews.com/story/business/autos/mobility/2018/06/26/jaguar-invest-electric-vehicles/36402445/>

Company	so, the alliance intends to make a \$11.5 billion investment to develop new powertrains and electric technologies. ³⁹¹	
Porsche	<ul style="list-style-type: none"> Announced in 2018 that it would double its investment in plug-in hybrids and pure EVs to more than 6 billion euros (USD\$7.43 billion) by 2022³⁹² 	<ul style="list-style-type: none"> \$7.43 billion
Tesla	<ul style="list-style-type: none"> The company plans to plan to spend between \$2.5 and 3 billion per year for the next two fiscal years at Gigafactories 1, 2 and 3, and in “other infrastructure growth”³⁹³ 	<ul style="list-style-type: none"> \$2.5 to \$3 billion
Toyota Motor Company	<ul style="list-style-type: none"> Under its Environmental Challenge 2050 strategy, the company has promised to eliminate most—if not all—carbon dioxide emissions in the company’s new vehicles no more than 31 years from now.³⁹⁴ In April 2018, announced it would be marketing and selling more than 10 electrified models around the world by the end of 2020.³⁹⁵ In December 2017, announced it plans to sell more than 5.5 million electrified vehicles per year, including 1 million zero-emission vehicles, by 2030³⁹⁶ Has promised to invest approximately \$13 billion in to the development of battery technology through 2030³⁹⁷ 	<ul style="list-style-type: none"> \$13 billion
Volkswagen AG	<ul style="list-style-type: none"> Announced it will gradually phase out the internal combustion engine following the release of its next generation of gas and diesel cars in 2026³⁹⁸ In May 2018, announced it plans to invest \$48 billion into an electrification transition by 2030³⁹⁹ Over 30 new electric models to launch by 2025, which translates to 15 million EVs on the roads⁴⁰⁰ Expects to be selling 2-3 million electric cars per year by 2025, representing 20-25% of the company’s total sales⁴⁰¹ In January 2019, announced plans to invest \$800 million to expand an electric vehicle plant in Chattanooga, Tennessee⁴⁰² 	<ul style="list-style-type: none"> \$48.8 billion
Volvo	<ul style="list-style-type: none"> Announced it will aim for 50% of sales to be fully electric by 2025⁴⁰³ In October 2018, Volvo bought a stake in FreeWire technologies, a California-based EV charging business⁴⁰⁴ 	<ul style="list-style-type: none"> N/A
Total Announced Investments By Selected Automakers		\$164.5 to \$167.6 billion

³⁹¹ <https://www.triplepundit.com/story/2019/reviewing-automakers-sustainability-and-ev-commitments/81991>

³⁹² <https://www.theverge.com/2018/2/5/16975752/porsche-electric-cars-investment-smart-mobility>

³⁹³ <https://cleantechnica.com/2018/11/08/tesla-plans-to-spend-up-to-3-billion-a-year-on-gigafactories-over-next-24-months/>

³⁹⁴ <https://www.triplepundit.com/story/2019/reviewing-automakers-sustainability-and-ev-commitments/81991>

³⁹⁵ <https://cleantechnica.com/2018/10/29/worlds-10-biggest-automakers-their-ev-plans/>

³⁹⁶ <https://newsroom.toyota.co.jp/en/corporate/20353243.html>

³⁹⁷ <https://cleantechnica.com/2018/10/29/worlds-10-biggest-automakers-their-ev-plans/>

³⁹⁸ *ibid*

³⁹⁹ <https://cleantechnica.com/2018/09/07/how-serious-is-volkswagen-about-electric-revolution/>

⁴⁰⁰ <https://www.autonews.com/article/20181116/OEM05/181119778/vw-s-ev-commitment-is-15-million-vehicles-not-50-million>

⁴⁰¹ <https://cleantechnica.com/2018/10/29/worlds-10-biggest-automakers-their-ev-plans/>

⁴⁰² <https://www.ccn.com/tesla-faces-squeeze-as-volkswagen-invests-800-million-in-us-electric-car-plant>

⁴⁰³ <https://electrek.co/2018/04/25/volvo-electrification-plan-fully-electric/>

⁴⁰⁴ <https://www.cnn.com/2018/10/25/volvo-buys-a-stake-in-electric-charging-firm-freewire.html>

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Appendix I: Examples of EV Batteries Used in Energy Storage Projects

Renault and Powervault

In 2017, Renault, Europe's largest EV manufacturer, partnered with domestic battery provider Powervault Ltd. to reuse its EV batteries in home energy storage units.

Nissan Leaf Energy Storage Projects

Nissan has been heavily involved in a number of energy storage projects using batteries from their Leaf EV. In 2015, Nissan partnered with Eaton, a power management company, for its EV batteries to be reused for home energy storage.⁴⁰⁵ The home battery system, called XStorage, connects to a residential power supply and charges up when either renewable energy is available or when energy from the grid is at its cheapest.⁴⁰⁶ The XStorage Home System has a nominal capacity of 4.2kWh and is based around LMO battery chemistry. It is intended to be used either in combination with rooftop solar or to offset grid consumption in areas with time-of-day pricing.⁴⁰⁷ The units, which are assembled in Morocco but are produced in Sunderland, UK, cost approximately US\$6,500 (£5,000) and come with a 5-year warranty.⁴⁰⁸

Figure 72 shows the Johann Cruyff Arena in Amsterdam, Netherlands, which has a 3MW/2.8MWh back-up power supply made up of 148 Nissan Leaf batteries - 63 used EV battery packs and 85 new battery packs, charged by solar panels on the roof stadium.⁴⁰⁹

⁴⁰⁵ Siegel, RP. December 1, 2017. "System Gives Used EV Batteries a Second Life in the Solar PV Storage Market."

<<https://www.designnews.com/electronics-test/system-gives-used-ev-batteries-second-life-solar-pv-storage-market/118990020757905>>

⁴⁰⁶ Sit, S.-S. May 5, 2017. "Man City gets behind recycled car batteries." <<https://www.cips.org/supply-management/news/2017/may/nissan-launches-home-battery-in-the-uk-to-rival-teslas-powerwall/>>

⁴⁰⁷ Siegel, RP. December 1, 2017. "System Gives Used EV Batteries a Second Life in the Solar PV Storage Market."

<<https://www.designnews.com/electronics-test/system-gives-used-ev-batteries-second-life-solar-pv-storage-market/118990020757905>>

⁴⁰⁸ Jutti, K. June 1, 2017. "Xstorage Home Battery Launched by Nissan." <<http://www.catalyst-commercial.co.uk/energy-blog/xstorage-home-battery-launched-by-nissan/>>

⁴⁰⁹ Hutt, R. July 6, 2018. "This Dutch football stadium creates its own energy and stores it in electric car batteries."

<https://www.weforum.org/agenda/2018/07/netherlands-football-johan-cruyff-stadium-electric-car-batteries/>

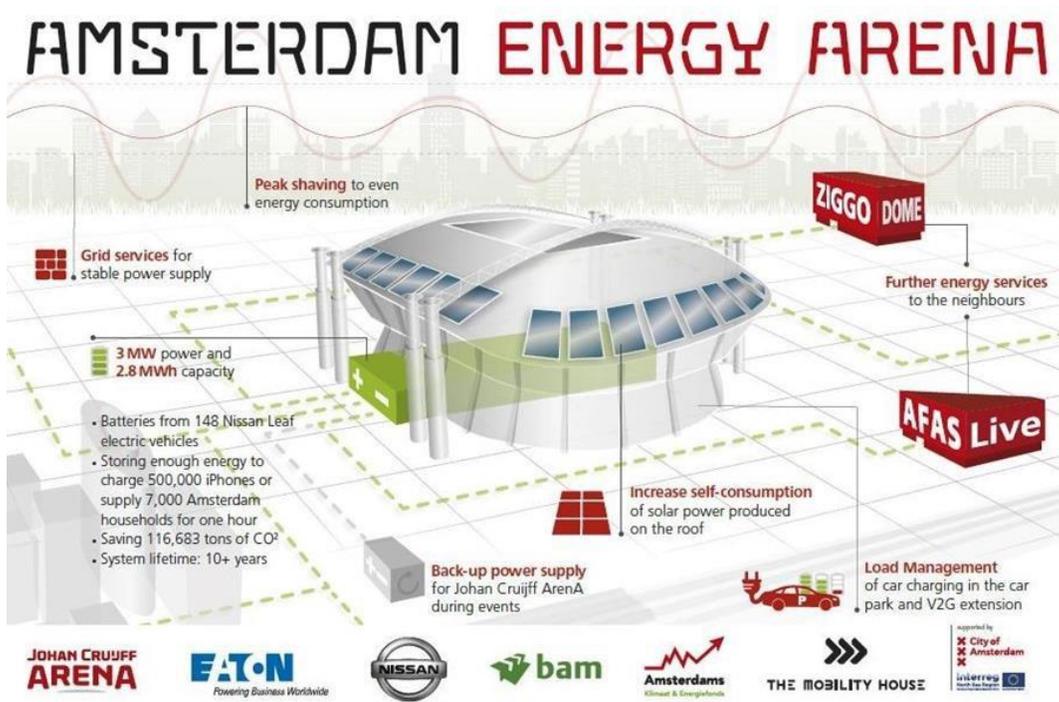


Figure 72 Nissan EV Batteries Used in Back-Up Power System at Amsterdam Johann Cruyff Arena



Figure 73 The Mobility House – EV Batteries Used for Energy Storage in Nissan-Eaton Partnership⁴¹⁰

EDF Energy has partnered with Nissan on a joint project to test the business case around using retired batteries from Nissan EVs for commercial battery storage. According to Nissan, a trial site has been identified in the UK. While the types of application being considered more widely have not been restricted, the first project will be at a commercial and industrial site. The system, under development with EDF Energy, would utilize the French firm's Powershift platform to quickly release stored electricity into the grid under DSR schemes in the UK. It will also test how it can support on site generation while providing greater control and flexibility over energy use and additional revenue streams. Francisco Carranza, director of energy services for Nissan Europe, said: "We believe electric cars are just the start, and our second life programme ensures batteries from our cars continue to provide energy storage capacity in other applications – in houses, businesses, football stadiums even – long after their life in cars. Nissan has already launched a home energy storage unit with Eaton. The new agreement with Nissan also comes as EDF president Jean-Bernard Lévy detailed the group's strategic plans on electric transport, which refer to the UK-based partnership with Nissan for "the development of shared offerings in the areas of electric mobility, smart charging, second-life battery use, energy storage and renewable energy sources".

For Nissan, the partnership marks the latest push in the UK following the launch of Nissan Energy Solar in May, offering homeowners a combined solar-plus-storage package utilising its own xStorage battery system developed with long-term partner Eaton.

⁴¹⁰ <https://www.energy-storage.news/news/edf-calls-on-nissans-2nd-life-batteries-to-power-commercial-projects-in-the-UK>⁴²⁰

Fortrum, Finland

Fortum, part of the state-owned energy company in Finland is piloting the repurposing of EV batteries for stationary storage applications. Makers of many stationary storage systems – particularly in the residential space – tend to favour LFP battery chemistry, which have less energy density than NMC, but also do not carry the risk of thermal runaway, or use cobalt in their production. Companies that favour LFP cells are also not tied to the demand and supply chain for EVs, with some stationary storage companies that do use NMC experiencing shortages last year, according to various sources. Nonetheless, there is often an upfront cost advantage for NMC cells, particularly if they can be reused after their function as an EV battery is over. Fortum is also behind the Nordic region’s largest energy storage projects involving batteries to date, announcing a 6.2MWh system to be deployed at a hydropower plant in Sweden in November. It follows the successful commissioning in March 2017 of the 1MWh ‘Batcave’ frequency regulation project in Järvenpää, Finland⁴¹¹.

⁴¹¹ <https://www.energy-storage.news/news/black-mass-battery-recycling-process-makes-90-co2-reduction-possible-fortum>
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Appendix J: Findings from Chinese EV Battery Recycling Cost Research

In an academic paper⁴¹² researchers from technical institutes in Beijing and Shenzhen, China, developed detailed estimates of the economic profitability of recycling EV batteries at EOL.

The paper focused on the costs of two types of batteries - LiFePO₄ and NMC - which together made up nearly 95% of the Chinese market in 2015. The NMC523 battery was used for the recycling cost, revenue and profit estimates in the research paper as it accounts for almost 75% of NMC batteries in China.

Battery composition and recovery rates assumed were taken from literature reviews and manufacturer data, and should be considered theoretical. Commodity metals prices were taken from the Shanghai nonferrous metal website in November, 2017 to estimate the values of cobalt, nickel, lithium and other metals.

The analysis assumed that the energy capacity of an EV is about 50kWh, and that the battery weighed 500 kg. This weight and energy capacity is higher than those noted in appendices this report for typical North American EVs.

Table 28 presents the estimated costs of recycling the two chemistries. The table shows that the costs are the same for most activities except for the metal recovery cost for the NMC which is estimated to cost \$1,784/ton. Depreciation was assumed to be 10 years for equipment and 30 years for buildings, with 5% asset value remaining at the end of the depreciation period. Labour rates and transportation costs were for Shenzhen, China. Costs were estimated with the recycling facility running at full capacity.

⁴¹² Xiaoming Ma et al. (2018). "The Recycling of Spent Power Battery: Economic Benefits and Policy Suggestions" *IOP Conference Series: Earth and Environmental Science*, 159. <https://iopscience.iop.org/article/10.1088/1755-1315/159/1/012017>

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Table 28 Estimated Recycling Costs for LFP and NMC523 Batteries from EVs⁴¹³

	Item	Content	Cost (yuan/metric ton) ⁴¹⁴		Cost (\$US/metric ton)	
			LFP	NMC	LFP	NMC
Variable Costs	Material recovery cost	Spent battery	0	12,018	0	1,784
	Accessory material cost	Solution and extraction solvent	2,500	2,500	371	371
	Fuel cost	Electricity, natural gas, etc.	620	620	92	92
	Pre-treatment cost	Crushing and separation	500	500	74	74
	Environmental expenses	Waste water treatment	330	330	49	49
	Handling expenses	Residue and ash disposal cost	120	120	18	18
	Labour charges	Salary	470	470	70	70
	Transportation expenses	Fuel fees, Toll, etc.	2,000	2,000	297	297
Fixed Costs	Fixed costs	Maintenance of equipment	100	100	15	15
		Depreciation allowances	536	536	80	80
Total Costs			7,176	19,194	1,065	2,860

Note: Totals in US may not add up due to rounding of individual costs

Table 29 presents an analysis of the value of various materials in the EV batteries in both Chinese yuan and also US dollars, and estimates the potential revenue from recycling the two battery chemistries. Recycling rates assumed for each material are also shown in the table. No attempt has been made to adjust the values in the table for this current study; it is simply presented as one of the few publicly available cost assessments for EV battery recycling.

The numbers serve to illustrate two key points regarding the economics of recycling EV batteries on a comparative basis:

- The profitability of EV battery recycling is highly dependent on both the cost and quantity of cobalt, copper and nickel in the batteries. The amount of lithium is likely to stay relatively constant for the foreseeable future.
- The value assigned to lithium looks like the value of pure lithium, whereas recycling processes generally recover lithium carbonate which has a lower value than shown in the table.
- The assumed percentage recovery values are considered unrealistic given current technical

⁴¹³ The Recycling of Spent Power Battery: Economic Benefits and Policy Suggestions, Xiaoming Ma et al., 2018 IOP Conference Series: Earth and Environmental Science, 2017

⁴¹⁴ ibid

capabilities, but illustrate how the economics change at high recovery rates, hence the push by many companies to find technologies that achieve high material recovery rates.

Table 29 Recycling Commodity Value and Recycling Rate Assumed for Financial Analysis of Recycling LFP and NMC523 Batteries from EVs

	Commodity Value		Composition (kg/100kWh)		Recycling Rate (%)	Recycling Revenue (yuan/100kWh)		Recycling Revenue (\$US/100kWh)	
	yuan/ton ⁴²⁴	\$US/ton	LFP	NMC523		LFP	NMC523	LFP	NMC523
Metal									
Cobalt	443,000	65,776	0	48.48	89%	0	19,114.21	0	2,838.04
Nickel	98,275	14,592	0	80.8	62%	0	4,923.18	0	730.98
Lithium	860,000 ⁴²⁵	127,691	8.99	9.59	80%	6,185.12	6,597.92	918.35	979.65
Manganese	10,900	1,618	0	30.13	53%	0	174.06	0	25.84
Iron	660	98	71.95	0	52%	24.69	0	3.67	0
Aluminum	15,380	2,284	65	87	42%	420	562	62.36	83.44
Copper	53,510	7,945	82	112	90%	3,949	5,394	586.34	800.89
Total						10,578.81	36,765.38	1,570.72	5,458.85

Notwithstanding some limitations, the table is very useful to show that the LFP chemistry provides very little revenue compared to the NMC523 chemistry which contains cobalt, nickel and copper at amounts which yield positive revenues. The amount of aluminum is minimal. The table also shows that recovery of manganese provides minimal revenue.

Table 30 presents the net profit analysis in the Chinese paper. As discussed above, the analysis is theoretical with higher than realistic recovery rates for the metals. The value for lithium used is for a pure lithium – likely medical grade – which is not produced by battery recycling which produces lithium carbonate. If these adjustments are made then recycling of the LFP battery would incur a net cost. Labour rates used for China would be much lower than for North America, but this is one of the few cost analyses that could be found through the literature search.

Table 30 Net Profit from Recycling of LFP and NMC523 EOL EV Batteries

EV Battery Chemistry	Net Profit (yuan/metric ton)	Net Profit (\$US/metric ton)	Revenue (yuan/metric ton)	Revenue (\$US/metric ton)	Cost (yuan/metric ton)	Cost (\$US/metric ton)
LFP	3,394	504	10,570	1,569	7,176	1,065
NMC	17,571	2,599	36,765	5,459	19,194	2,860

This information is provided as supplementary to other sources which are considered more reliable and relevant to North America. Beyond converting quoted costs to US \$, it was not considered useful to adjust for US labour rates and lithium carbonate costs and materials recovery rates because commodity values change frequently and there are many other factors that are unknown in the analysis. For this reason, a recommendation is included in the report to carry out a detailed financial analysis of different recycling approaches to EV batteries using US labor rates, commodity values and other regional factors to make the cost estimate more realistic for a US setting.