Why Battery Testing is Critical for the Transition to Electric Vehicles

Over the past three years, the United States of America (U.S.) has made aggressive commitments and investments to reduce greenhouse gas (GHG) emissions that are contributing to climate change. One way in which the U.S. is seeking to reduce the amount of GHG emissions being generated, and thereby reduce the rate of climate change, is by reducing the use of fossil fuels within the transportation sector. According to the U.S. Environmental Protection Agency (EPA), the transportation sector is responsible for 15% of global GHG emissions, and 95% of the world's transportation energy comes from petroleum-based fuels.[1] In the U.S., according to an article published by the MIT Energy Initiative, "passenger vehicles generate about 16% of total anthropogenic GHG emissions and consume about 40% of the total petroleum used in the United States."[2] Therefore, because passenger vehicles in the U.S. consume a large volume of the total amount of fuel used in the U.S. and are responsible for a relatively large portion of the total GHG emissions entering the atmosphere, U.S. policymakers have taken concrete steps to invest in and mandate the development and adoption of battery electric vehicles (BEVs) powered by vehicle traction batteries, which will reduce or eliminate the burning of fossil fuels in the transportation sector.

Examples of the aggressive commitments to reduce GHG emissions strongly suggest that BEVs will rapidly proliferate on U.S. roadways in the coming years. In 2020, California Governor, Gavin Newsom, signed an executive order that would require 100% of in-state new passenger car and truck sales to be zero-emission by 2035.[3] President Joe Biden signed a similar executive order in 2021 that set the goal that 50% of all new passenger cars and light trucks sold in 2030 be zero-emission vehicles.[4] These commitments, which have been supported by several state governments and automakers, are causing an unprecedented transition away from internal combustion engine (ICE) vehicles to BEVs.[5] Consequently, there has been a dramatic increase in the demand for vehicle traction batteries, battery components, and the critical materials that are used in the manufacturing of batteries.

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[1] United States Environmental Protection Agency (EPA), *Global Greenhouse Gas Emissions Data*, EPA United States Environmental Protection Agency, (Nov. 16, 2023), https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector.

[2] Nancy W. Stauffer, *US passenger cars: Designing policies to curb fuel use, GHG emissions*, MIT Energy Initiative, January. 10, 2012, (Nov. 16, 2023), https://energy.mit.edu/news/us-passenger-cars/.

[3] Executive Department of the State of California, *Executive Order N-79-20*, Governor Gavin Newsom, Sep. 23, 2020, (Feb. 12, 2024), https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf.

[4] Strengthening American Leadership in Clean Cars and Trucks, 86 Fed. Reg. 43583, (Aug. 5, 2021).

[5] Michael Wayland, *General Motors plans to exclusively offer electric vehicles by 2035*, CNBC, Jan. 28, 2021, (Nov. 16, 2023), https://www.cnbc.com/2021/01/28/general-motors-plans-to-exclusively-offer-electric-vehicles-by-2035.html.

While the total number of BEVs still only represents a small overall percentage of the entire passenger vehicle population in the U.S., the number of vehicles containing vehicle traction batteries is growing exponentially and making up larger percentages of the total vehicle population in the U.S. According to the U.S. Department of Energy (DOE), there were 283,509,000 registered light duty vehicles within the U.S. in 2022.[6] Of this population, 2,442,300 vehicles were fully electric (EV), 1,012,400 vehicles were plug-in-hybrid electric (PHEV), and 6,291,800 were hybrid electric (HEV).[7] This is a significant change from 2020 where there were only 1,018,900 EVs, 594,400 PHEVs, and 4,813,700 HEVs.[8] Therefore, the number of BEVs on U.S. roadways is beginning to represent a larger share of passenger vehicles in the U.S., which is only anticipated to grow in the coming years as demand for BEVs increase and older ICE vehicles reach their end-of-life.

	2022	*% total*	2020	*% total*	*% Change*
Total	**283,509,000**	***100.00%***	**278,299,200**	***100.00%***	***1.87%***
BEV	**9,746,500**	***3.44%***	**6,427,000**	***2.31%***	***51.65%***
Full EV	2,442,300	*0.86%*	1,018,900	*0.37%*	*139.70%*
PHEV	1,012,400	*0.36%*	594,400	*0.21%*	*70.32%*
HEV	6,291,800	*2.22%*	4,813,700	*1.73%*	*30.71%*

Fig. 1: U.S. Registered light duty vehicles in 2022 vs 2020

The transition from ICE vehicles to BEVs has the capability to positively transform the U.S. transportation sector by drastically reducing U.S. reliance on fossil fuels and reducing GHG emissions associated with transportation. That said, a successful transition from ICE vehicles to BEVs will demand that the existing benefits of ICE vehicles be carried over and built upon by BEVs. ICE vehicles have been incredibly successful in providing U.S. vehicle owners with access to transportation, which positively correlates with an increase in opportunities and economic outcomes.[9] Access to personal vehicles is so important in the U.S. that 95% of U.S. households own a vehicle and that 91.2% of Americans use a personal vehicle to get to work.[10] Over the past several decades, American households have had unprecedented access to motor

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[6] U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy, *Alternative Fuels Data Center: Vehicle Registration Counts by State*, U.S. Department of Energy, (Nov. 16, 2023), https://afdc.energy.gov/vehicle-registration.
[7] *Id*.
[8] *Id*.
[9] Urban Institute, *Transportation Access*, Urban Institute, Dec. 28, 2021, (Nov. 16, 2023), https://upward-mobility.urban.org/transportation-access.
[10] Robin Chase, *Does Everyone in America Own a Car?*, Embassy of the United States of America, March 2010, (Nov. 16, 2023), https://static.america.gov/uploads/sites/8/2016/04/You-Asked-Series_Does-Everyone-in-America-Own-a-Car_English_Lo-Res_508.pdf.
Bureau of Transportation Statistics, *Table 1 Mode of Transportation Used to Commute to Work in the Past Week*, United States Department of Transportation, Dec. 21, 2011, (Nov. 16, 2023), https://www.bts.gov/archive/publications/highlights_of_the_2001_national_household_travel_survey/table_01.

vehicles because vehicles are affordable to finance, insure, and repair. Furthermore, vehicles and their components are durable products that serve multiple owners over their lengthy service lives and have predictable reliability and value.

> *"While vehicle owners throughout the vehicle value chain can easily predict the value of used ICE vehicles, one of the biggest challenges facing mainstream BEV adoption is that owners throughout the value chain lack a clear understanding as to the quality, performance, and remaining service life of a traction battery–the costliest component of the BEV in some cases."*

While vehicle owners throughout the vehicle value chain can easily predict the value of used ICE vehicles, one of the biggest challenges facing mainstream BEV adoption is that owners throughout the value chain lack a clear understanding as to the quality, performance, and remaining service life of a traction battery–the costliest component of the BEV in some cases.[11] A thriving and robust BEV industry from the sale of a new car all the way until a vehicle traction battery is reused and finally recycled is essential for mainstream and more equitable adoption of sustainable transportation. Proper testing and evaluation of a vehicle traction battery will be essential for a successful transition from ICE vehicles to BEVs, which will help to ensure the continuation of easy and affordable access to passenger vehicles in the U.S.

I. Overview of the lifecycle of an internal combustion engine vehicle

Over the last century, ICE vehicles have allowed for the development of an economically viable product lifecycle that prioritizes affordability, encourages maximization of existing resources, and enables recyclability. A general overview of the lifecycle of an ICE vehicle is as follows: (1) manufactured by an original equipment manufacturer (OEM); (2) sold as a new car; (3) maintained by original owner or sold as a used vehicle; (4) reach its end-of-life (EOL) either due to accident or due to the vehicle no longer functioning and being uneconomical to repair; (5) acquired by an automotive recycler/dismantling facility to be dismantled for the purpose of reusing repair parts; and (6) the remainder of the vehicle will be crushed and shredded for the reclamation of recyclable materials.

[11] Jamie Fox, *Which EV Component Increased Price the Most in 2022*, Interact Analysis, Oct. 2022, (November 21, 2023), https://interactanalysis.com/insight/which-ev-component-increased-price-the-most-in-2022/.

Fig. 2: Overview of ICE Vehicle lifecycle

1) Vehicle manufactured by an original equipment manufacturer

According to the U.S. Bureau of Transportation Statistics, 10,500,000 passenger and commercial vehicles have been produced in the U.S. on average annually since 1960.[12] While the assembly of a vehicle by an OEM may take place in one country, the manufacturing of motor vehicles is an interconnected global endeavor that requires robust, resilient, and reliable supply chains. To highlight the complexity involved in manufacturing a motor vehicle and its individual components, McKinsey & Company found that the average OEM "has around 250 tier-one suppliers, but the number proliferates to 18,000 across the full value chain."[13] Therefore, even minor disruptions in the global supply chain for new OEM automotive components can have a significant effect on new motor vehicle production, new motor vehicle sales, used car sales, replacement parts market, repair costs, and insurance markets. Fortunately, there is a robust, resilient, and reliable supply chain for ICE vehicles that can mitigate negative consequences of single-point supply chain disruptions. It will be critically important for the proliferation of BEVs that similarly robust supply chains be established.

2) Vehicle sold as a new car

The U.S. Bureau of Transportation Statistics reports that 11,930,000 new passenger and commercial vehicles are sold each year on average since 1960.[14] It must be noted that this data only accounts for vehicles produced in the U.S., Canada, and Mexico. Therefore, the true number of new vehicle sales in the U.S. is higher than represented in the Bureau of Transportation Statistics. Traditionally, new vehicles are typically sold or leased by franchised new-car dealerships.[15] However, the traditional notion that a new car will be sold by a franchised dealership to its first owner is being challenged. More and more state laws are being modified to allow OEMs to sell vehicles directly to consumers.[16] These changes in state law have had a

[12] Bureau of Transportation Statistics, *Annual U.S. Motor Vehicle Production and Domestic Sales*, United States Department of Transportation, (Nov. 29, 2023), https://www.bts.gov/content/annual-us-motor-vehicle-production-and-factory-wholesale-sales-thousands-units.
[13] Thomas Baumgartner, et. al., *Reimagining industrial supply chains*, McKinsey & Company, Aug. 11, 2023, (Nov. 29, 2023), https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/reimagining-industrial-supply-chains.
[14] Bureau of Transportation Statistics, *Annual U.S. Motor Vehicle Production and Domestic Sales*, United States Department of Transportation, (Nov. 29, 2023), https://www.bts.gov/content/annual-us-motor-vehicle-production-and-factory-wholesale-sales-thousands-units.
[15] Gerald R. Bodisch, *Economic Effects of State Bans on Direct Manufacturer Sales to Car Buyers*, Economic Analysis Group Competition Advocacy Paper, U.S. Department of Justice, Antitrust Division, May 2009, (Nov. 29, 2023), https://www.justice.gov/atr/economic-effects-state-bans-direct-manufacturer-sales-car-buyers.
[16] *Id*.

substantial impact on how new cars are bought and sold due in large part to newer OEMs that only sell EVs.

3) Vehicle operation

Following the sale of a new car, a vehicle owner will drive the vehicle and will either drive the vehicle until its lease term ends, sell the vehicle as a used vehicle, operate the vehicle until it no longer functions, or the vehicle is in a collision. A trend over the last several years is that U.S. vehicle owners are keeping their vehicles for longer. As of 2023, the average age of light vehicles on U.S. roadways is now at a record 12.5 years old.[17] Vehicle owners are keeping their cars longer due to vehicles being more durable,[18] rising interest rates, and the rising cost of new and used cars.[19]

4) Vehicle end of life

Most motor vehicles will typically reach their EOL in one of two ways. First, a vehicle may no longer work or drive. The second way is that vehicles prematurely reach their EOL due to a collision and a declaration by an insurance company that the vehicle is a total loss, which will result in an insurer paying out a claim to the insured. Total loss vehicles will generally be sold through a salvage auction or a vehicle owner may sell the vehicle to an automotive recycling/dismantling facility or scrap processor. Approximately 10-15 million vehicles reach their EOL annually and enter the U.S. reuse and recycling infrastructure.[20]

5) Acquisition by an automotive recycler/dismantler

Every year, the approximately 10,000 automotive recycling/dismantling facilities throughout the U.S. process millions of EOL vehicles and determine what makes the most economic sense for each vehicle and their components through the principles of highest and best use.[21] A highest and best use analysis works by identifying the maximum value for each vehicle component, which is also often correlated with the best environmental outcome.

Throughout the last century, automotive recyclers/dismantlers have played a critical role in creating a recycled original equipment motor vehicle replacement parts market, a remanufactured

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[17] Nishant Parekh and Todd Campau, *Average Age of Light Vehicles in the US Hits Record High 12.5 years, according to S&P Global Mobility*, S&P Global Mobility, May 15, 2023, (Nov. 29, 2023), https://www.spglobal.com/mobility/en/research-analysis/average-age-of-light-vehicles-in-the-us-hits-record-high.html.

[18] Dexter Ford, As Cars Are Kept Longer, 200,000 Is New 100,000, The New York Times, Mar. 16, 2012, (Feb. 5, 2024), https://www.nytimes.com/2012/03/18/automobiles/as-cars-are-kept-longer-200000-is-new-100000.html.

[19] Tom Krisher, As car prices soar beyond reach, Americans keep their vehicles longer than ever, USA Today, May 15, 2023, (Feb. 6, 2024), https://www.usatoday.com/story/money/cars/2023/05/15/new-used-car-prices-soar-forcing-drivers-keep-vehicles-longer/70220510007/.

[20] B.J. Jody et al., End-of-Life Vehicle Recycling: State of the Art of Resource Recovery from Shredder Residue, Argonne National Laboratory, Energy Systems Division, 1, Sep.2010, (Feb. 12, 2024) (https://publications.anl.gov/anlpubs/2011/02/69114.pdf.

[21] This is an industry estimate by the Automotive Recyclers Association (ARA). It is difficult to accurately capture the full scope of the industry due to the differences in state laws and licensing requirements.

vehicle parts market, and a recycled materials market. By finding value and promoting the reuse, remanufacturing, and recycling of all components on EOL vehicles, automotive recyclers/dismantlers have built a circular economy for ICE vehicles that also increases access to transportation by increasing competition in the replacement parts market. In the case of the U.S. vehicle reuse and recycling market, there is an economic incentive to responsibly and safely process EOL ICE vehicles and the ideal environmental outcome of reuse and recycling. According to SAE, 84% of vehicles by weight have their components reused, remanufactured, and recycled.[22] It is critically important that the success of the existing EOL ICE reuse and recycling market be maintained and replicated moving forward.

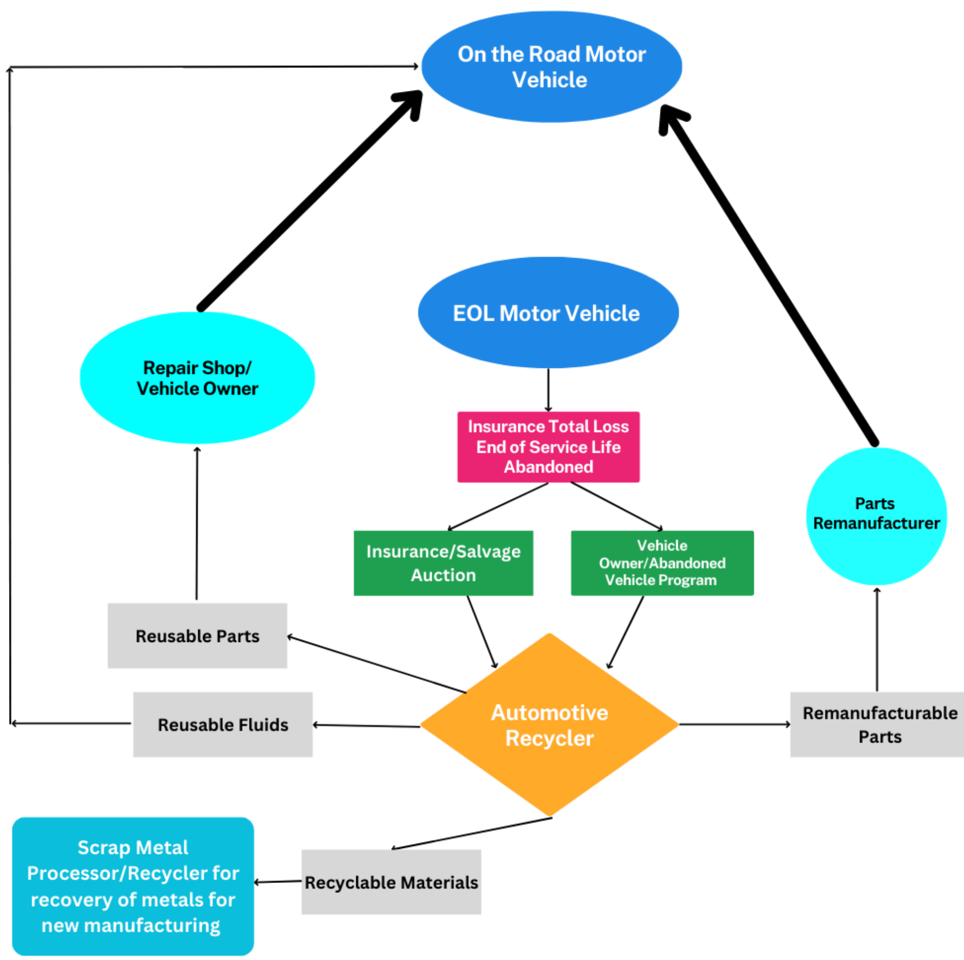

Fig. 3: Existing pathway for end-of-life motor vehicles

6) Component upcycling, scrap, and recycling

An automotive recycler/dismantler processes an EOL vehicle to maximize placing the vehicle components to their highest and best use. After this occurs, the remainder of the vehicle will be

[22] Vehicle Recycling, Reuse, and Recovery: Material Disposition from Current End-of-Life Vehicle, SAE International, 1.

sent to a scrap processing facility that will recover the recyclable metals that will be later used for new manufacturing or industrial applications. A scrap metal processor utilizes machinery and equipment for processing and manufacturing iron, steel, or nonferrous metallic scrap into prepared grades and whose principal product is scrap iron, scrap steel, or nonferrous metallic scrap to sell for remelting purposes. According to SAE, 95% of all vehicles removed from service in the U.S. enter the North American recycling infrastructure.[23] The U.S. Geological Survey found that 15 million tons of steel is recycled from automobiles annually.[24] Recycled steel is so important to U.S. manufacturing and infrastructure that an average 93% of structural steel produced in the U.S. contains recycled steel scrap.[25] Besides serving as a primary source for recycled steel, automotive recyclers are a primary source for recyclable aluminum. According to the Worcester Polytechnic Institute, the overall recycling rate for automotive aluminum is 91%[26] and the Aluminum Association finds that 80% of U.S. aluminum production comes from recycled aluminum.[27]

It must also be noted that there is a financial necessity for automotive recyclers/dismantlers to maximize recovery of each component on the vehicle by putting each component to its highest and best use. The financial return achieved by an automotive recycler/dismantler from an EOL vehicle determines how much the automotive recycler/dismantler can afford to pay when acquiring a vehicle. Unless an automotive recycler/dismantler can achieve a high recovery rate, they will be unable to acquire vehicles in quantity when bidding against other market segments such as vehicle rebuilders or vehicle exporters. Both of these competing market segments can be significant buyers of EOL vehicles. In the case of BEV vehicles, the ability to acquire vehicles when competing with other industry segments is critically dependent upon whether an automotive recycler/dismantler can put a traction battery to its highest and best use.

II. How BEVs fit (or don't fit) the highest and best use hierarchy

The highest and best use hierarchy, which represents the maximization of existing resources in the most economically and environmentally beneficial manner is as follows, from highest use to lowest use: (1) reused as originally intended and unmodified; (2) repaired or reconditioned for original reuse; (3) repurposed for secondary applications; (4) recovered for raw materials for manufacturing; and (5) disposal. Highest and best use has allowed for the U.S. to establish a successful and economically viable framework for managing EOL vehicles. The Worcester Polytechnic Institute also found that automotive recyclers/dismantlers help to drive a circular

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[23] Claudia M. Duranceau & Susan Sawyer-Beaulieu, Vehicle Recycling, Reuse, and Recovery: Material Disposition from Current End-of-Life Vehicles, SAE International, 1, April 12, 2011.

[24] U.S. Geological Survey, *Mineral Commodity Summaries: Iron and Steel Scrap*, 1, January 2021. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-iron-steel-scrap.pdf.

[25] American Institute of Steel Construction, *Why Steel: Sustainability*, (Feb. 12, 2024)https://www.aisc.org/why-steel/sustainability/#:~:text=Structural%20steel%20produced%20in%20the,loss%20of%20its%20physical%20properties.

[26] Sean Kelly and Diran Apelian, *Automotive Aluminum Recycling at End of Life: A Grave-to-Gate Analysis*, Worcester Polytechnic Institute, 6, Center for Resource Recovery and Recycling (CR3), (Feb. 12, 2024), https://www.aluminum.org/sites/default/files/2021-10/Final-Report-Automotive-Aluminum-Recycling-at-End-of-Life-A-Grave-to-Gate-Analysis.pdf.

[27] The Aluminum Association, *Infinitely Recyclable*, (Feb. 12, 2024),https://www.aluminum.org/Recycling.

economy in auto manufacturing and that the automotive recycling/dismantling industry has a negative carbon footprint.[28]

There has been a concerted effort from governments and industry to increase recycling capacity in order to deal with the impending tsunami of retiring BEV batteries and establish domestic supply chains of battery materials. However, recycling is not a silver bullet for dealing with BEV batteries that have served their initial purpose. Aside from the huge investments required to build up the necessary battery recycling infrastructure, there are major challenges ahead for the battery recycling industry. These challenges include transportation and safety, battery pack dismantling, and the applicability of recycling technologies to the various battery chemistries. For instance, the efficiency and profitability of recycling processes are impacted by the chemistry of the cathode: lithium iron phosphate (LFP) batteries can cost up to a few dollars per pound to recycle, while nickel-rich chemistries are closer to net positive or breaking even with the resale of the raw materials and black mass.[29,30] Dunn et. al promotes a battery material use hierarchy, where repurposing and reusing a retired EV battery before recycling are favorable to a straight-to-recycling approach from a life-cycle analysis (LCA) perspective.[31] Findings from a life-cycle analysis (LCA) study by the Energy and Efficiency Institute at University of California, Davis shows that traction battery reuse and repurposing prior to recycling reduces environmental impacts compared to a direct-to-recycling pathway. The study shows that a repurpose before recycling pathway can yield about 25% of the CO2e emissions compared to a direct-to-recycle pathway on a per 1kWh unit.[32]

> *"Following the Battery Material Use Hierarchy ensures that the automotive recycling/dismantling industry can maximize existing resources, provide affordable vehicle repair parts, and create a sustainable and circular economy as the transportation industry electrifies."*

The Battery Material Use Hierarchy, produced by Automotive Recyclers Association and Argonne National Laboratory and shown in Figure 4 emphasizes the need for highest and best use for batteries after they have served their initial purpose. A vehicle traction battery that has reached its end-of-first-life (EOFL) that is in good health can and should be reused in a vehicle. A battery can be remanufactured and put back in a vehicle under a limited warranty, while a medium health battery may be well suited for a stationary energy storage system (ESS) application where the environment is less stressful than mobility applications. Use cases encompass utility-scale energy storage, behind-the-meter commercial & industrial storage, residential applications, as well as portable and off-grid battery systems. Each use case is unique

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[28] Muhammad Siddiq *et al.*, *Assessing the Environmental Impact of Automotive Recyclers of Massachusetts*, i, Apr. 27, 2017, (Feb. 12, 2024) http://armmass.com/wp-content/uploads/2017/10/Full-Study.pdf.

[29] Nicole Willing, Argus Media. *NMC to LFP transition poses battery recycling challenge*, Argus Blog., Nov. 29, 2023, https://www.argusmedia.com/en/news/2513976-nmc-to-lfp-transition-poses-battery-recycling-challenge.

[30] Gaines, Linda et. al., Tracking Flows of End-of-Life Battery Materials and Manufacturing Scrap. Batteries 2023, 9(7), 360, (Feb. 12, 2024),https://doi.org/10.3390/batteries9070360.

[31] Dunn, J., Ritter, K., Velázquez, J. M., & Kendall, A. Should high-cobalt EV batteries be repurposed? Using LCA to assess the impact of technological innovation on the waste hierarchy. Journal of Industrial Ecology, 27, 1277–1290. 2023. https://doi.org/10.1111/jiec.13414

[32] *Id*.

and can be optimized by utilizing different battery types of varying ages. A battery in poor health would be sold for a lower price, or recycled, the lowest preference on the highest and best use hierarchy. Following the Battery Material Use Hierarchy ensures that the automotive recycling/dismantling industry can maximize existing resources, provide affordable vehicle repair parts, and create a sustainable and circular economy as the transportation industry electrifies.

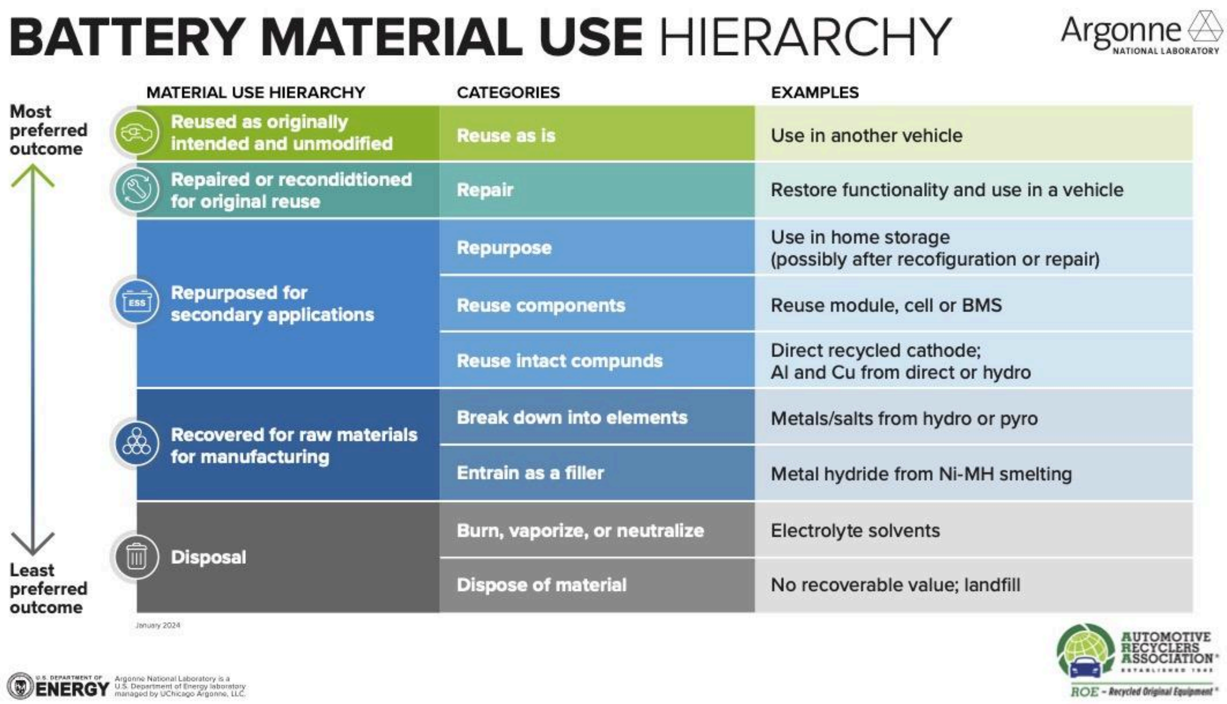

Fig. 4: Battery Material Use Hierarchy that highlights highest and best use

BEV traction batteries age over time and usage, but it's difficult to assess the health of a battery with today's commercially available technologies. Unlike an ICE vehicle, where the number of miles on a vehicle's odometer serves as a good metric for what the vehicle should be valued at due to a direct correlation to the mechanical wear of an engine and transmission, an odometer reading does not provide satisfactory details as to the condition of a BEV or the condition of the battery pack. Battery life and condition can change due to temperature, humidity, usage, and charging conditions – mileage alone cannot adequately assess the condition of a traction battery.

1) BEV battery types, chemistries, and configurations

Before diving into the intricacies of EOL, it is important to understand one of the highest value components of a BEV: the high-voltage traction battery. Different BEVs have different battery configurations, sizes, and chemistries (see Figure 5 below). In addition, each battery type will have varying electrical, mechanical, and software interfaces that need to be accounted for. For instance, a Tesla Model 3 may have either a lithium iron phosphate (LFP) battery pack or a nickel cobalt aluminum (NCA) battery pack, depending on the model year and trim level. A 2011 Nissan LEAF had 24 kWh lithium manganese oxide (LMO) battery pack, a 2013 Nissan LEAF had a 30 kWh LMO battery pack, while a 2017 Nissan LEAF had a 42 kWh or a 60 kWh nickel manganese cobalt (NMC) battery pack. A Nissan LEAF battery pack is configured from battery modules ranging from 8V nominal to 22V nominal depending on the vehicle generation. Meanwhile, older generation Tesla Model 3 battery packs have four 85V to 95V battery modules, and the newer generation battery packs, some of which have cell-to-pack design, may not have individual battery modules at all. All of these aforementioned BEV models utilize batteries with a "400V" battery pack architecture, but a Hyundai Ioniq BEV uses an "800V" battery pack architecture. In addition, each of these battery systems have their own battery management system (BMS) and interfacing software, much of which is proprietary to each OEM.

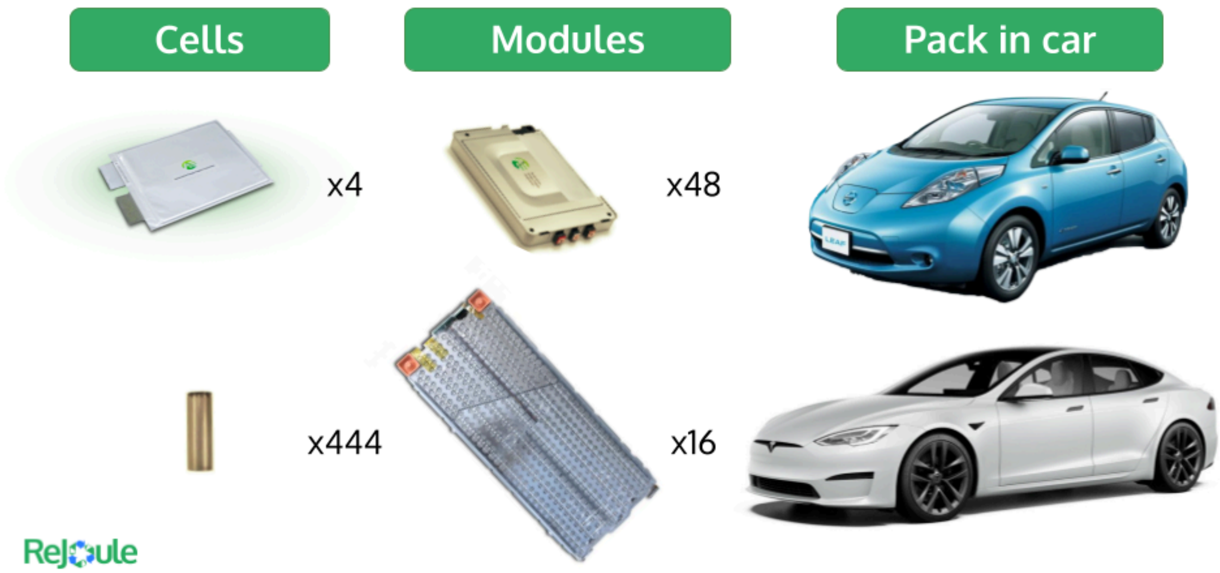

Fig. 5: Comparison of Nissan LEAF and Tesla Model S battery cell and module, configurations

To put it simply, there is no standardization in the design of BEV battery systems. Full EVs have been on the market for less than 15 years but global EV sales didn't hit 1 million until 2017.[33] With continuous improvements in battery technology and manufacturing capabilities, and with growing geopolitical tensions affecting supply chains, OEMs' approach to battery design will further diverge before they begin to standardize. This has repercussions downstream in the BEV aftermarket and EOL value chains that impact how and whether highest and best use can be applied to BEVs. For example, as current BEV batteries age and OEMs no longer manufacture or support specific battery types, there will be demand for reuse of batteries to support aging vehicles in addition to demand for repurposing of batteries for ESS.

2) Gaps in battery state-of-health (SOH) evaluation

While some OEMs display some indication of battery state of health (SOH), this is known to be unreliable and is generally less accurate the older the battery.[34] These health predictions are based

[33] IEA, *Global electric car sales by key markets, 2010-2020*, May 18, 2020, (Feb. 12, 2024), https://www.iea.org/data-and-statistics/charts/global-electric-car-sales-by-key-markets-2015-2020.
[34] Bercibar, M. et al., *Critical review of state of health estimation methods of Li-ion batteries for real applications,* Renewable and Sustainable Energy Reviews, Volume 56, Apr. 2016.

on lab-based models and not a result of a real test on the battery. Additionally, historical data from vehicles is often unavailable and unreliable. Some EV enthusiasts report their vehicle's estimated EV range on online forums to offer knowledge about battery degradation.[35] These studies have found that certain vehicle traction batteries degrade faster than others.[36]

There are many factors that affect battery degradation. In lithium-ion batteries, chemical changes play a significant role, including lithium plating, where solid lithium forms on the anode, and Solid-Electrolyte Interphase (SEI) growth, which hinders ion movement. Cycling-related degradation occurs due to repeated charge/discharge cycles, leading to chemical and structural changes in the electrodes. Extreme heat and cold, fast charging, and lack of "rest" can cause a battery to degrade faster, leading to premature battery replacement. The average state of charge (SOC) of a battery also influences degradation, where extreme overcharge and overdischarge states cause stress on electrodes. Calendar aging, which is natural degradation over time, and dendrite formation, microscopic needle-like growth on electrodes, are additional factors. Mechanical stress, such as bending or compression, and chemical reactions also impact degradation.[37]

Determining the overall health of a battery is challenging due to many factors, including limited availability or utilization of advanced diagnostic tools, infrequency of testing, and the absence of real-time monitoring systems to detect sudden changes during the battery's operation.[38] Additionally, inaccurate data interpretation, insufficient historical data on the battery's past performance, and incomplete consideration of actual environmental factors can contribute to deficiencies in the evaluation process.

Addressing these issues involves implementing comprehensive evaluation processes, utilizing advanced diagnostic tools, ensuring regular monitoring, and incorporating relevant environmental and usage considerations. Standardized guidelines and effective communication of results are crucial for closing the gaps in battery state-of-health evaluations and enhancing the overall effectiveness of the assessment. Unfortunately, existing solutions to this challenge are not scalable to the larger industry.

3) Limitations in battery testing

The industry-standard in battery health testing is cycling, which requires completely charging and discharging a battery. It can take more than ten hours to test a single battery using this approach. For example Tesla allows their customers to test the health of the battery in their vehicles, but the operation requires the vehicle to be plugged into a Level 2 charger for up to 24

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[35] Erin Yurday, *A Study on Real-Life Nissan Leaf Battery Deterioration*, Nimblefins, Nov. 1, 2023, (Feb 12, 2024), https://www.nimblefins.co.uk/study-real-life-nissan-leaf-battery-deterioration.

[36] PushEVs, Nissan Leaf battery degradation data: 24 vs. 30 kWh batteries, https://pushevs.com/2018/03/20/nissan-leaf-battery-degradation-data-24-vs-30-kwh-batteries/ , 2021.

[37] Preger, Y. et al.,*Perspective—On the Safety of Aged Lithium-Ion Batteries,* Journal of the Electrochemical Society, 169 030507, (2022), https://iopscience.iop.org/article/10.1149/1945-7111/ac53cc/pdf..

[38] Ge, M et. al.,*A review on state of health estimations and remaining useful life prognostics of lithium-ion batteries*, Measurement", Volume 174, (2021 https://doi.org/10.1016/j.measurement.2021.109057.

hours and to have the vehicle below 50% charge.[39] Most consumers don't have that level of patience, and no used car dealers or repair shops have the capability to perform this procedure beyond a one-off test.

For batteries removed from vehicles, cycle testing is not a scalable solution due to the high cost of equipment, time, and human resources involved. To perform cycle testing at scale, there must be capital resources and infrastructure in place. A battery test facility needs sufficient space to receive, store, and test all the batteries needed at any given time. The right system is necessary to create a unique ID for each battery, ideally tying back to its original application and any historical usage data, and an inventory system is needed to track and locate batteries. High voltage and high power test equipment, and the staff capable of operating the equipment, needs to be installed on site. Training on safe battery handling is required for many, if not all, staff members, with some needing hazmat certification.

The inefficiency and cost of this type of operation makes these test methods challenging for the approximately 10,000 automotive recycling/dismantling facilities throughout the U.S. This creates a major challenge when putting a vehicle traction battery to its highest and best use.

4) End of first life battery test and shipping standards

Depending on the intended use, there might be additional requirements to meet certifications and standards. For instance, UL 1974 is the "Standard for Evaluation for Repurposed Cells for Stationary Applications."[40] This standard addresses the evaluation and testing of repurposed cells, which refers to batteries that were originally used in one application, such as electric vehicles, and are then repurposed for stationary energy storage applications. The goal of UL 1974 is to provide safety and performance requirements for these repurposed cells to ensure their suitability for stationary applications. Unfortunately, acquiring the proper certification to UL 1974 is costly and complex. Additionally, each battery manufacturer and OEM may have their own battery test protocol, which further complicates the picture.

Regulations around the collection, storage, and transportation of disposed batteries is also complex. Lithium-ion batteries are considered class 9 hazardous waste, which means there are specific rules dictating the packaging and transport of battery feedstock.[41] The U.S. Environmental Protection Agency (EPA) also classifies disposed batteries as universal waste, which prohibits landfilling of batteries, and prohibits the storage of disposed lithium batteries for more than one year. To put it simply, following the highest and best use practices for battery end-of-life management can be very expensive without rapid and accurate battery testing.

[39] EM Tesla, Tesla Battery Health Test | Enter Service Mode Yourself | Model Y | Model 3", November 13, 2022, https://www.youtube.com/watch?v=fVWfmvgDtaY.
[40] Standard Evaluation for Repurposing or Remanufacturing Batteries, UL 1974, 2023.
[41] Hazardous Materials Regulations, Lithium cells and batteries. 49 CFR 173.185, 2022.

III. The impact of unreliable health data on the BEV lifecycle

The ability to understand the condition of a battery is essential for the transition to BEVs. Not having a clear understanding of the condition of vehicle traction batteries will: (1) hinder the development of a viable used vehicle market; (2) impede an affordable insurance market; (3) neglect environmentally sound and responsible EOL vehicle processing; (4) fail to create an affordable vehicle repair market; and (5) result in increased waste without strengthening a domestic supply of batteries and battery materials.

1) Lackluster used electric vehicle market

In the past decade, EV prices have fallen significantly, closing the pricing gap between BEV and ICE vehicles to less than $3,000 before incentives from over $10,000 in years past.[42] While EVs are near cost parity with ICE vehicles, this doesn't paint the complete picture of vehicle affordability. Used car sales represent about 75% of total vehicle sales in the U.S., where those with lower income are more likely to buy a used car.[43] Without a dependable and reliable measure of the condition of used traction batteries, EVs will remain out of reach and less appealing for most Americans.

> *"Not having a clear understanding of the condition of vehicle traction batteries will:hinder the development of a viable used vehicle market; impede an affordable insurance market; neglect environmentally sound and responsible EOL vehicle processing; fail to create an affordable vehicle repair market; and result in increased waste without strengthening a domestic supply of batteries and battery materials."*

Matt Harrison, Toyota Motor Corp.'s Chief Operating Officer in Europe, says that there "isn't used-car demand for EVs," something that is "really hurting the cost-of-ownership story." Dirk Weddingen von Knapp, the head of a group representing VW and Audi dealers, says that "part of the problem is that the industry is handling secondhand EVs for the first time. While combustion-engine cars can be quickly valued via their age and mileage, there are no tests in widespread use that determine the quality of a battery." This lack of reliable method to evaluate used BEV residual value will cause the used BEV market to suffer and, overall, will slow mass BEV adoption.[44]

2) High insurance premiums for BEVs

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[42] Cox Automotive, *New-Vehicle Transaction Prices Decline Further in September, Led by Price Cuts at Tesla, According to Kelley Blue Book Report*, Oct. 11, 2023, (Feb. 12, 2024), https://www.coxautoinc.com/market-insights/kbb-atp-september-2023/.

[43] Aliza Vigderman, *New vs. Used-Car Value Statistics*, Auto Insurance.com, Mar. 10, 2023, (Feb. 12, 2024), https://www.autoinsurance.com/research/new-vs-used-car-value-statistics/

[44]Monica Raymunt & Bloomberg *, No one wants to buy used EVs and they're piling up in weed-infested graveyard.*, Fortune December 22, 2023. shttps://fortune.com/2023/12/22/no-one-wants-to-buy-used-ev-piling-weed-infested-graveyards-tesla-bmw-vw/.

There are many factors that property casualty insurance companies consider when writing policies for motor vehicles. One primary factor is the type of car to be insured and what the costs to repair and replace the type of car have been in the past. As of right now, insurance premiums for EVs are 27% more than ICE vehicles in the US.[45] The higher cost to insure an EV are due in part to the fact that there is not a competitive replacement parts market – especially in the case where a battery pack needs to be replaced. According to Mitchell International, 88.85% of repairable EVs use OEM parts as opposed to 67.48% for ICE repairs.[46] This leaves vehicle owners and insurers with few options in the market to source replacement batteries, which are primary drivers of the cost to repair an EV. As the current generation of EVs begin to age it will be increasingly important for vehicle owners to have a competitive market for replacement vehicle traction batteries that includes recycled original equipment batteries.[47]

As an EV ages, the cost of a new OEM battery will increase relative to the total remaining value of the vehicle, which may cause older EVs to be declared total losses at a rate that will outpace their ICE counterparts. Even the smallest road bumps can cause a repair to become so costly to deem the vehicle a total loss. Interviews were conducted to industry stakeholders, and Shannon Bain, Holman Aftersales Director, gave a stark example of such a statement with a new vehicle that was just shipped to his facility. He claimed that oftentimes the battery is at the bottom of the vehicle, so driving over the wrong type of debris can cause a dent in the undercarriage that holds the battery: A dent that is 3mm or more in the wrong place can require a total battery pack replacement which can cost upwards of $50,000.

3) Unaffordable reuse and repair

There is a large and mature ecosystem of dealerships, service garages, automotive recyclers/dismantlers, and aftermarket auto parts retailers that can service and provide critical component replacements for ICE vehicles. Within this ecosystem are a network of companies that can provide routine maintenance checks and component replacements for everything from windshield wipers to transmissions and engines. There are a multitude of options and vendors available, and it's well understood that it may cost $4,000 to $10,000 to get that engine replaced. [48]

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[45] Nick Carey, Paul Lienert & Sarah Mcfarlane, *Insight: Scratched EV battery? Your insurer may have to junk the whole ca*r, Mar. 20, 2023, (Feb. 12, 2024), https://www.reuters.com/business/autos-transportation/scratched-ev-battery-your-insurer-may-have-junk-whole-car-2023-03-20/

[46] Michelle Thompson, *Mitchell: Q3 report indicates EV total loss rates on par with luxury ICE vehicles*, Repairer Driven News, November 9, 2023, https://www.repairerdrivennews.com/2023/11/09/mitchell-q3-report-indicates-ev-total-loss-rates-on-par-with-luxury-ice-vehicles/.

[47] Stephen Rivers, *BMW i3 Owners Shocked by $30,000 Battery Replacement, One Quoted $71,000*, Car Scoops, Feb. 11, 2024, (Feb. 12, 2024), https://www.carscoops.com/2024/02/bmw-i3-owners-asked-to-pay-over-30k-for-battery-replacement-and-one-gets-quoted-71k/#.

[48] Dustin Hawley, *How Much Does It Cost To Replace A Car Engine?*. JD Power, Dec. 29,2022, (Feb. 12, 2024),https://www.jdpower.com/cars/shopping-guides/how-much-does-it-cost-to-replace-a-car-engine#:~:text=Replacing%20The%20Engine,the%20decision%20to%20your%20mechanic.

As BEVs become more prevalent on U.S. roadways, vehicle owners will need access to affordable replacement traction batteries to reduce the cost of vehicle repairs and keep their vehicles operating. BEV owners need alternative sources for vehicle traction batteries besides ones sourced from OEMs, improving vehicle affordability over its service life. Batteries sourced from EOL vehicles provide an enormous opportunity to ensure that vehicle owners can repair and replace damaged or worn-out traction batteries. However, the SOH and condition of batteries removed from EOFL vehicles must be assessed in order to determine if it would be suitable as a replacement part.

Furthermore, a battery module, even an OEM part of the same form, fit, and function, cannot simply be inserted into a vehicle battery pack without potentially experiencing "organ rejection" from the host vehicle. This is because battery modules within a pack must be matched in state-of-charge (SOC) and SOH within a battery pack. Mismatched SOC and SOH can lead to reduced vehicle range, a need to prematurely replace a battery, or, in a worst case, severe safety incidents due to heightened risk of overcharge and undercharge.[49]

4) Remanufacturing of batteries

Over the next few years, an ever-increasing number of BEVs will begin reaching their EOL and their batteries will reach their EOFL. In some cases, an EOFL battery removed from an EOL vehicle will not be in a condition that would allow for reuse in a vehicle or use in an ESS. This may be due to physical damage to components, inadequate SOH, or some combination of the two. Consequently, there may still be value in that battery to extract in the form of remanufacturing. Remanufacturing is the process when a vehicle component is restored to meet the specifications of the original manufactured product. In this case, batteries can be remanufactured so that a battery can eventually be reused.

5) Unrealized battery value

When a traction battery is removed from the vehicle, it may retain over 80% of its initial energy content and can still satisfy the less stressful needs of battery stationary storage for years to come.[50] They can be repurposed to store and dispatch power generated by renewables, reducing reliance on harmful fossil-fuel plants.[51] In fact, McKinsey & Company suggests that by 2030, so many traction batteries will be retired from passenger vehicles alone that the supply could meet the demand for utility-scale energy storage.[52] This is a massive opportunity for automotive

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[49] Fred Lambert, *A look at Tesla battery degradation and replacement after 400,000 miles,* Electrek, Jun. 6 2020, (Feb. 12, 2024), https://electrek.co/2020/06/06/tesla-battery-degradation-replacement/.

[50] Katherine de Guia, *WHAT HAPPENS TO LITHIUM-ION BATTERIES AT THE END OF THEIR LIFE?,* Cummins Newsroom, Sep. 23, 2021, (Feb. 12, 2024), https://www.cummins.com/news/2021/09/23/what-happens-lithium-ion-batteries-end-their-life.

[51] PSE,*Opportunities for Replacing Peaker Power Plant with Energy Storage Across Nine States,*Press Release, May, 14, 2020, (Feb. 13, 2024), https://www.psehealthyenergy.org/opportunities-for-replacing-peaker-power-plant-with-energy-storage-across-nine-states/.

[52] Engel, Hawke, et. al., *Second- life EV batteries: The newest value pool in energy storage*, Mckinsey & Company, Apr. 2019, (Feb. 12, 2024), https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage.

recyclers/dismantlers and second-life ESS companies, but, again, a lack of scalable testing methodologies may threaten this second-life battery industry from ever taking off.

Retired BEV traction batteries may be used in most energy storage applications, including portable energy applications, microgrids, behind-the-meter commercial and industrial storage, and utility-scale storage. The market for microgrids is forecast to more than double by 2028, reaching $79 billion.[53] The market for batteries in utility-scale storage is growing at an even faster pace. California's battery deployments expanded tenfold from 2020 to 2023, while Texas's grew thirteenfold.[54] Unfortunately, the global supply chain for new lithium-ion batteries is centered overwhelmingly outside the United States. The U.S. needs the capacity to build energy storage systems domestically, and $63 billion of public and private funding has been earmarked to spur a U.S.-based battery manufacturing and supply chain since the passing of the Inflation Reduction Act (IRA).[55] Still, these factories will take years to plan, permit, construct, and ramp up, leaving a gap between battery supply and demand for stationary energy storage applications. EOFL traction batteries represent a burgeoning and locally available feedstock to accelerate the nation's transition to sustainable energy.

However, there are numerous challenges to battery repurposing. There is a wide gap between the BEV battery and the eventual buyer. A buyer, when purchasing a battery, wants assurances that they are getting quality product for their money, and the retired battery needs to be shipped, tested, and certified before it can make its way to a repurposed battery system.[56] The repurposed battery needs to compete against new batteries not only on cost, but also on performance on metrics such as power and energy ratings, longevity, energy density, and reliability. For larger projects, financing terms need to be secured, and project construction and commissioning needs to be planned months to years in advance. All this needs to happen before a repurposed battery can generate revenue for a system site or offtaker. Overcoming any of these obstacles means overcoming the first major challenge of reliable and efficient battery testing at scale.

IV. Rapid battery testing: a better way forward

ReJoule is an advanced battery diagnostic company with the mission of creating a circular BEV battery economy by enabling battery reuse, remanufacturing, and repurposing. ReJoule has pioneered an advanced battery test technique to accurately, quickly, and reliably estimate a battery's SOH. The cutting edge diagnostic technology employs electrochemical impedance spectroscopy (EIS) to estimate the degradation of a battery through its complex impedance. This

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[53] MarketsandMarkets, *Microgrid Market Size*, Jul 2022, (Feb. 13, 2024), https://www.marketsandmarkets.com/Market-Reports/micro-grid-electronics-market-917.html.
[54] Julian Spector, Maria Virginia Olano, *Chart: The remarkable rise of California's grid battery capacity*, Canary Media, Sep. 22, 2023, (Feb. 13, 2024),https://www.canarymedia.com/articles/batteries/chart-the-remarkable-rise-of-californias-grid-battery-capacity.
[55] Garrett Hering, *IRA at 1: US climate law cues $63B spending spree on battery factories*, S&P Global, Aug. 9, 2023, (Feb. 13, 2024),https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/ira-at-1-us-climate-law-cues-63b-spending-spree-on-battery-factories-76839524.
[56] E. Fonseca et al.,*Challenges in Deploying a Second-Life Battery System: Engineering, Fire Safety, UL Certifications, and NFPA Requirements*, IEEE EESAT Conference, 30 Jan 2024.

enables a test time reduction from hours to less than 5 minutes. ReJoule's hardware product is coupled with machine learning algorithms to correlate a battery's complex impedance to its SOH. ReJoule's technology has consistently achieved over 98% accuracy in its SOH assessment for multiple battery types of different chemistries and can test at the cell, module or pack level (see virtual demo). In addition, ReJoule has developed a version of its diagnostic technology that can plug into the DC fast charging port of an EV to provide rapid and accurate testing on traction batteries that are still inside their vehicles. This family of diagnostic products not only speeds up the testing process, but it also transforms battery management strategies, paving the path for proactive measures like predictive maintenance, assessing residual value, and forecasting future EOFL traction battery feedstock. By quickly identifying the core issue of degradation, more vehicles can be tested, which reduces the overall cost. Once the battery's SOH is determined, charts like the one below can assist in quickly directing batteries to the highest value use case. This can transform today's used BEV market, make it easier to buy insurance for BEVs, improve repairability and repurposability of high voltage traction batteries, and reduce overall emissions by improving the economics of reuse, remanufacturing, and repurposing.

ReJoule has demonstrated the effectiveness of its technology on Nickel Manganese Cobalt (NMC) cells and modules, and various Lithium Iron Phosphate (LFP) cells and modules and on various battery types: cylindrical, pouch, and prismatic constructions. The hardware product can be compatible with a wide range of battery voltages, from low voltage cells (~3.5V), to modules (~50V), to high voltage packs (>400V). As of the beginning of 2024, ReJoule has tested over 5MW of retired EV batteries on 3 continents with its rapid diagnostic technology, with the bulk of that testing done in 2023 alone. ReJoule expects to test over 10 MWh in 2024, and is on track to be able to test over 10 GWh of retired batteries per year before the end of the decade.

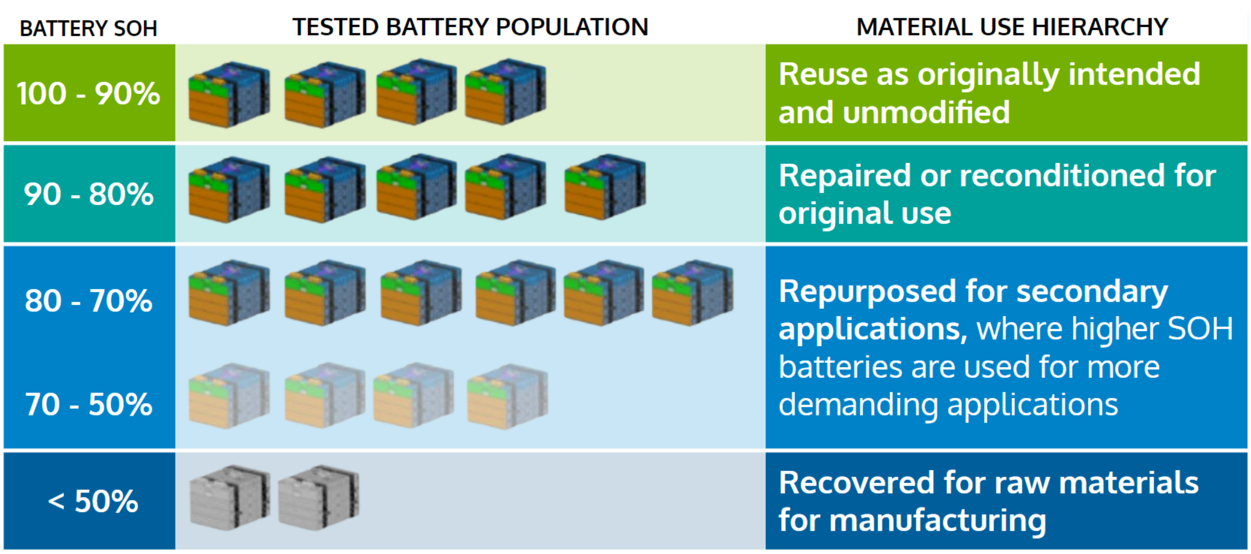

Fig. 6: How battery SOH maps to the battery material use hierarchy

V. Automotive recycling industry putting batteries to their highest and best use

Since 1943, ARA has represented professional automotive recyclers. Professional automotive recyclers/dismantlers supply Recycled Original Equipment (ROE) motor vehicle replacement parts to consumers around the world. In addition to the critical role professional automotive recyclers/dismantlers play in the automotive supply chain and replacement parts market, professional automotive recyclers/dismantlers play a valuable role in the efficient and environmentally friendly recycling of EOL vehicles. Professional automotive recyclers/dismantlers are the largest collective owners of EOL vehicles and are subsequently the largest generator of source material for scrap metal recyclers. As the main recipient of EOL vehicles, automotive recyclers/dismantlers are the largest collective owners of EOFL lead acid, nickel metal hydride, and lithium-ion vehicle traction batteries. Automotive recycling/dismantling preserves natural resources, reduces the demand for scarce landfill space, and plays an important role in reducing air and water pollution.

ARA and its members are taking the lead by actively advancing the national imperative of highest and best use of BEV traction batteries. Through its strategic relationship with the National Salvage Vehicle Reporting Program (NSVRP), ARA and its certified high voltage vehicle trained members are participating in the NSVRP battery registry program. This program is designed to help ensure that BEV traction batteries that have served their initial purpose are directed to their highest and best use whenever possible.

VI. The road ahead

As BEV sales continue to grow, the necessity for comprehensive and deliberate action to overcome challenges is needed. The future requires an ambitious strategy in which the expansion of EVs is integrated with circular principles, which urge us to reconsider, reassess, and redefine how we use resources to minimize the environmental effects of vehicle electrification. On top of investing in technological development, we need to ensure that our workforce is educated and trained for the transition to BEVs, and that policies are put in place that encourage the highest and best use principles.

1) Workforce of the future

When it comes to creating an environment that will allow for the successful reuse and recycling of BEVs and their components, education and training will be essential to ensuring a safe environment for automotive recyclers/dismantlers. ARA and its Certification Committee has been educating automotive recyclers/dismantlers about safely and responsibly processing BEVs through its Certified Automotive Recyclers (CAR) program. The CAR program includes high voltage vehicle training that prepares automotive recyclers/dismantlers to acquire and process BEVs. Along with its high voltage vehicle training and certification, ARA has developed and provides automotive recyclers/dismantlers with an *Electric and Hybrid Vehicle Technology*

Training Guide.[57] ARA has also developed and provides automotive recyclers/dismantlers with an *EV Readiness Checklist*,[58] *Hybrid and Electric High Voltage Vehicle Handling and Dismantling Protocol*,[59] and an *EV Battery Database*.[60] The *EV Battery Database* contains access to information for 1,650 models from 65 manufacturers specific to over 7,700 different high voltage batteries. ARA encourages manufacturers and other stakeholders to contribute to this training and certification program that provides necessary information for the proper handling and storage of EV Batteries. ARA's training and safety information can be found at https://arauniversity.org. In the coming years, it will become critical that automotive recycling/dismantling facilities are equipped and trained to work with high voltage batteries.

Education is a major piece of this puzzle. Having a highly skilled workforce is crucial for encouraging innovation, adopting sustainable practices, and addressing the obstacles that come with transitioning to BEVs with high voltage batteries. As we move forward, it is crucial to provide individuals with education to equip the industry with the necessary expertise. This will drive advancements and establish a strong foundation for a sustainable future. Currently, there is a shortage of high voltage trained technicians to handle the deluge of testing that is to come. The shortage of mechanics is compounded by the fact that technician training programs have not been updated to include BEV technology. Shannon Bain, Aftersales Director, for 3 dealerships' parts and services departments, works with Universal Technical Institute (UTI), and they have implemented BEV training into their program. However, it is a for-profit college that is about $35-$40k for roughly a 10-month program. Shannon is also on the advisory board of Miramar Community College technician program. Just 2 years ago, they worked to get funding from the state for hands-on hybrid training. Miramar and most programs still don't have full BEV training available, or it's only theory. The options are basically costly private or for-profit schools but sadly training programs for technicians at public schools, even in California, do not offer hands-on training which is hindering the ability to find a qualified workforce.

2) Policies to promote testing and battery reuse and repurposing

As the U.S. continues its transition away from fossil fuel based energy in transportation, it will be essential for federal and state governments to promote and enact policies that ensure that the already successful U.S. vehicle reuse and recycling market can be replicated for BEVs. This means that special attention and focus must be paid to efforts to maximize the useful life of batteries that have reached their EOFL. Therefore, focus and attention should be paid to promoting viable battery reuse, remanufacturing, and repurposing markets. Not only will this reduce the carbon footprint associated with the manufacture of BEV traction batteries but it will

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[57] The Automotive Recyclers Association, Electric and Hybrid Vehicle Technology Guide, (2020). https://arauniversity.org/wp-content/uploads/2021/03/Electric-Vehicle-Training-Final.pdf.

[58] Automotive Recyclers Association University, EV Readiness Checklist, https://img1.wsimg.com/blobby/go/ce5f5a84-ace1-49a2-8823-f959ad0cdb84/downloads/EV%20Readiness%20CHECKLIST.pdf?ver=1643919686139.

[59] Automotive Recyclers Association University, Hybrid and Electric High Voltage Vehicle Handling and Dismantling Protocol, https://img1.wsimg.com/blobby/go/ce5f5a84-ace1-49a2-8823-f959ad0cdb84/downloads/Hybrid%20and%20Electric%20High%20Voltage%20Vehicle%20Handl.pdf?ver=1643919686139.

[60] Automotive Recyclers Association University, EV Battery Database, https://arauniversity.org/resources/ev-battery-data-base/.

also reduce U.S. dependence on critical minerals, reduce the need for newly manufactured batteries, and provide vehicle owners with affordable replacement batteries. It is essential that government policy emphasize reuse, remanufacturing, and repurposing in order to allow for a successful transition to BEVs. Additionally, evaluating the health and lifespan of traction batteries, whether ongoing during operation or at EOFL, is vital for determining whether a battery should be reused, repaired or reconditioned, repurposed, or recycled. To be economical and beneficial, these evaluations need to be efficient, dependable, and adaptable across diverse battery chemistries and form factors. Policies that promote the battery material use hierarchy should also mandate minimum accuracy and reliability of these evaluations, and these evaluation criteria should be standardized as much as possible.

Existing policies, in some cases, may inadvertently discourage circular principles. For example, the newly approved European Battery Regulation mandates that new battery cells contain a minimum percentage of recycled battery content – starting at 6% for lithium and nickel and 16% for cobalt by 2031.[61] These mandates may encourage automakers and others in the vehicle aftermarket to embrace a direct-to-recycling approach to avoid fines. At the same time, it's important to note that there is no single strategy aligning each of the actors, and that a policy and its intentions are often in contrast with economic reality and the actual flow of retired BEVs. For instance, retiring battery feedstock is owned by individuals or by companies who own the vehicles, and each of these players wants to maximize the value of their assets–this means these actors will sell their vehicle to the highest bidder, which may be a repair shop on the other side of the globe.

In the first half of 2023 alone, Ukraine imported 12,844 mostly used electric vehicles.[62] Used vehicles from the U.S. and Europe "are increasingly being shipped to Ukraine and a handful of other countries to be repaired and given a second life" because they are willing to pay more for the scrapped vehicle than a domestic buyer.[63] The same is occurring closer to home. Second-hand vehicle imports from the U.S. represent "nearly 30 percent of Mexico's light-duty vehicles", and those Mexico bound exports will increasingly include high-value traction battery packs from BEVs.[64] To encourage a domestic battery supply chain, policy makers should propose legislation to incentivize localized highest and best use of retiring EV batteries–reusing, repairing, and repurposing–so this battery feedstock, ideally, stays within the U.S. before ultimately being recycled within the U.S. Otherwise, the flow of retired EV batteries will continue to move to the highest bidder, which may not be domestic.

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[61] Benchmark Source Minerals,*Can the EU meet its proposed battery metals recycling targets?* Jan. 2023, (Feb. 13, 2024), https://source.benchmarkminerals.com/article/can-the-eu-meet-its-proposed-battery-metals-recycling-targets.
[62] Ed Ballard,*Getting Written Off Isn't the End for EVs*, The Wall Street Journal,Jan. 2023,(Feb. 13, 2024), https://climate.cmail19.com/t/d-e-viihuhl-iiltillyz-r/.
[63] Aarian Marshall and Gregory Barber, *Why Teslas Totaled in the US Are Mysteriously Reincarnated in Ukraine,* WIRED, Nov. 17, 2023, (Feb. 13, 2024), https://www.wired.com/story/why-teslas-totaled-in-the-us-are-mysteriously-reincarnated-in-ukraine/.
[64] Olguín F. P. et. al., *US-Mexico second-hand electric vehicle trade: Battery circularity and end-of-life policy implications*, Transportation Research Part D. Energy and Efficiency Institute, University of California Davis, 2023, https://doi.org/10.1016/j.trd.2023.103934

"For electric vehicles to follow a similarly circular and sustainable lifecycle, we need collective efforts, inventive solutions, and a commitment to a standardized process. Battery recycling, while critical, is only the final step in the battery lifecycle. Before recycling, we need to ensure that retired traction batteries can be reused as is, repaired, remanufactured back into vehicles, and repurposed into second-life applications. Proper testing and evaluation of a vehicle traction battery will be essential."

VII. Conclusion

Over the past century, ICE vehicles have facilitated the creation of an economically sustainable product lifecycle that emphasizes affordability, resource optimization, and recyclability. For electric vehicles to follow a similarly circular and sustainable lifecycle, we need collective efforts, inventive solutions, and a commitment to a standardized process. Battery recycling, while critical, is only the final step in the battery lifecycle. Before recycling, we need to ensure that retired traction batteries can be reused as is, repaired, remanufactured back into vehicles, and repurposed into second-life applications. Proper testing and evaluation of a vehicle traction battery will be essential. ReJoule's cutting edge diagnostic technology enables rapid, reliable, and accurate battery testing throughout a battery's lifecycle. Its products can evaluate batteries at the cell, module, pack, and vehicle levels, and have been validated by customers on multiple continents. The ability to easily and reliably test the condition of a battery then becomes essential to support a thriving used BEV market. Additionally, it is necessary to leverage the existing, and highly successful, automotive recycling/dismantling infrastructure so more people can benefit from affordable, insurable, and repairable BEVs. Only by creating an ecosystem where BEVs and their batteries follow the material use hierarchy can we promote responsible end-of-life BEV processing while encouraging a truly domestic battery supply chain. To actively engage in the battery circular economy, you can contact ReJoule and the Automotive Recyclers Association for further details and potential cooperation opportunities.

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