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SCALING UP REUSE AND RECYCLING OF ELECTRIC VEHICLE BATTERIES: ASSESSING CHALLENGES AND POLICY APPROACHES

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EXECUTIVE SUMMARY

An increasing number of governments are supporting the deployment of battery electric vehicles (BEVs) and plug-in hybrids (PHEVs) to reduce greenhouse gas emissions and air pollution. With the resulting demand in lithium-ion batteries, the availability of raw materials, as well as the environmental and social impacts related to the battery supply chain, manufacturing, and disposal become of key importance for policymakers, industries, and consumers. The global demand for raw materials and these associated impacts could be substantially reduced through battery reuse and recycling practices. In the long term, developing these practices may also unlock new domestic value streams and job opportunities, and reduce the cost of batteries. However, as of 2022, both reuse and recycling practices for electric vehicle batteries are limited, and technical and economic uncertainties persist.

This report provides an overview of the opportunities and challenges for the reuse and recycling of batteries from the global light-duty and heavy-duty vehicle fleets. It estimates the potential of the global battery reuse and recycling markets up to 2050. Building from a literature review, it analyzes the technological and economic feasibility of battery reuse and recycling practices. The report also discusses key policies that governments are introducing to support the development of a robust battery reuse and recycling industry. The report provides the following high-level findings:

Availability of end-of-life batteries is low but is expected to grow considerably. An estimated 1.2 million batteries from light- and heavy-duty BEVs and PHEVs will reach their end of life in the year 2030 globally, rising to 14 million in 2040, and 50 million in 2050, making this a critical time to create a supportive policy environment for the reuse and recycling of these batteries. Reusing 50% of the end-of-life vehicle batteries for energy storage could offer a capacity of 96 GWh in 2030, 3,000 GWh in 2040, and 12,000 GWh by 2050. An efficient recycling of end-of-life vehicle batteries, in some cases after their prolonged usage in second-life applications, could reduce the combined annual demand in new lithium, cobalt, nickel, and manganese mining by 3% in 2030, 11% in 2040, and 28% in 2050.

China and the European Union are leading in creating a framework to ensure that end-of-life batteries are handled responsibly. Policies in China and upcoming policies in the European Union (EU) include extended producer responsibilities that make manufacturers responsible for the collection of end-of-life batteries. China has also introduced a platform that traces batteries throughout their lifetime, therefore further ensuring that batteries will get collected when they reach end of life. For the recycling, China sets voluntary recovery targets for lithium, cobalt, nickel, and manganese, while the EU's upcoming Battery Regulation will mandate recovery targets for lithium, cobalt, copper, and nickel. In the EU, minimum shares of recycled materials in new battery production will further help to ensure a high purity of the recycled material, which is crucial to prevent downcycling.

The research further leads to the identification of four policy areas for governments to consider to enable the acceleration of reuse and recycling practices:

Incentivizing domestic capacity for battery reuse and recycling. In jurisdictions that do not have the domestic capacity for the reuse or recycling of end-of-life electric vehicle batteries, batteries will have to be shipped long distances. This would result in high transport costs, which represent the largest cost component of battery reuse or recycling. Developing domestic capacity to reuse and recycle batteries could therefore significantly reduce costs while stimulating local economies and reducing the dependency on international supply chains. To the extent possible, governments could develop incentive programs, create supportive tax and trade provisions, and develop public-private partnerships to support domestic capacity for reuse and recycling.

Updating and standardizing regulations on the transport and handling of end-of-life electric vehicle batteries could also reduce costs and encourage growth.

Establishing standards for battery durability, safety, and information accessibility that optimize reuse and recycling processes. Information about the technical characteristics, state of health, and operation history of batteries is critical for optimizing reuse and recycling processes and ensuring safety along these processes. Governments could require that battery manufacturers disclose and track information on batteries, like the battery passport initiatives in the EU. To support the economic feasibility of battery reuse, governments could further standardize state-of-health metrics to inform decisions on second-life applications. Moreover, mandatory battery durability requirements can incentivize the production of long-lasting batteries and thereby support second-life usage. Finally, defining safety standards for reuse and recycling can also be crucial for reducing risks.

Supporting research and development in lithium-ion battery recycling technologies to expand the range of materials that can be recovered. Current industrial-scale battery recycling plants typically follow a pyrometallurgical pathway (with some hydrometallurgical steps) or a fully hydrometallurgical pathway to recover materials. While both pathways allow the recovery of metals like cobalt, copper, and nickel, the recovery of aluminum and lithium is typically only achieved in the hydrometallurgical pathway. Hydrometallurgical pathways may further allow the recovery of graphite and plastics. A third recycling pathway under development, but not yet realized on a commercial level, is direct recycling, which involves direct recovery of the cathode and anode materials. Governments could support ongoing research and development efforts on recycling processes to broaden the range of battery materials that can be recovered, to increase their recovery rate, and to improve their environmental impact.

Introducing mandatory recovery rates and recycled content targets to ensure efficient recycling of all key battery materials. The cost competitiveness of recycling depends on the content of expensive materials that are contained in the end-of-life electric vehicle battery, such as cobalt, nickel, or lithium. Yet, as of 2022, facing unstable supply chains and trying to cut material costs, manufacturers are shifting towards chemistries with a lower cobalt and nickel content, or those that are cobalt- and nickel-free, such as lithium iron phosphate (LFP) batteries. This might challenge the overall profitability of recycling operations. For this reason, governments could consider mandatory element-specific recovery targets to ensure an efficient recycling of all key battery materials. Such targets would further avoid the recovery of only those materials that are profitable. To ensure a high purity of the recycled material, element-specific minimum shares of recycled materials in the production of new batteries could be introduced.

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INTRODUCTION

The transition to electric vehicles is well underway, with governments supporting this technology to achieve climate, air quality, energy security, and industrial policy objectives. Over their entire life, including battery manufacturing and electricity production, a battery electric vehicle (BEV) is responsible for much less greenhouse gas (GHG) emissions than a comparable internal combustion engine (ICE) vehicle (Intergovernmental Panel on Climate Change, 2022; Bieker, 2021). A combination of falling production costs, growing consumer demand, and concerted policy efforts has moved electric vehicles toward the mainstream market, and governments are increasingly setting targets to fully phase out new ICE vehicle sales in the 2025–2040 timeframe (International Council on Clean Transportation, 2022a).

The core technology enabling the transition to electric vehicles is the lithium-ion battery, which can store electricity from the grid to enable hundreds of miles of range. Alongside the introduction of electric vehicles, battery technology has improved considerably. For example, the specific energy of lithium-ion batteries at the cell level increased from 80 Wh/kg in 1991 to 256 Wh/kg in 2015, while the volumetric energy density increased from 200 Wh/L to 697 Wh/L (Placke et al., 2017). Alongside these technology improvements and economies of scale, costs of this key component have also fallen: The global industry average price of lithium-ion battery packs has declined from US $732 per kilowatt-hour (kWh) in 2013 to US $151 per kWh in 2022, equivalent to a 80% decrease in cost (Bloomberg New Energy Finance, 2022).

Despite this technological progress, there remain significant concerns amongst the public, industry, and governments regarding lithium-ion batteries. These concerns span costs, potential raw material shortages, and the negative environmental and social impacts of raw material mining. Reducing the demand for raw materials through battery reuse and recycling has the potential to mitigate many of these issues. With a natural lag between new electric vehicle sales and battery retirements, the current growth in electric vehicle sales is expected to be mirrored in an exponential increase of vehicle battery reuse and recycling volumes in the upcoming decades. To be able to fully realize the benefits of battery reuse and recycling, governments need to prepare the legislative environment and industrial infrastructure. Therefore, the expected volumes, as well as the logistical, technological, and social-economic challenges of battery reuse and recycling need to be understood.

This report summarizes how battery reuse and recycling can strengthen the environmental and social benefits of a global transition to electric vehicles. It estimates the volumes of end-of-life vehicle batteries that could be reused in second-life applications up to 2050. Similarly, it estimates the global demand of battery raw materials for electric vehicles and by how much it can be reduced by establishing an efficient recycling environment. The report also describes the techno-economic opportunities and challenges that are faced in the 2022 market and discusses the policy framework that is needed to scale up battery reuse and recycling practices. It concludes with an overview of policy approaches seen in China, the European Union, and the United States, and provides actionable recommendations to scale up reuse and recycling practices.

The report estimates the impact of reuse and recycling based on the global demand for lithium-ion batteries for light-duty and heavy-duty electric vehicles. In addition to battery electric vehicles (BEVs), the report considers plug-in hybrid electric vehicles (PHEVs) as electric vehicles, as PHEVs correspond to a significant share of the overall lithium-ion battery demand (EV-Volumes, 2022). However, it should be acknowledged that the average electric driving share of PHEVs in real-world operation is significantly lower than considered in official numbers (Isenstadt et al., 2022; Plötz et al., 2020; Plötz et al., 2022). Therefore, their GHG emission reduction benefits over internal combustion engine vehicles are limited (Bieker, 2021; Bieker et al., 2022).

All monetary values are expressed in Unites States (U.S.) dollars unless otherwise stated.

MOTIVATION

BATTERY DEMAND OF A GROWING ELECTRIC VEHICLE MARKET

The demand for lithium-ion batteries is growing alongside the global sales of electric vehicles. Figure 1 plots the annual total capacity in gigawatt-hours (GWh) of batteries used in new BEVs and PHEVs from 2010 to 2021 worldwide, including light-duty passenger and commercial vehicles and heavy-duty vehicles (EV-Volumes, 2022). In 2021, the battery capacity used for new vehicles exceeded 320 GWh, more than 5 times the amount used 5 years earlier in 2016, and more than 200 times the amount used 10 years earlier in 2011. The figure does not include the batteries used for electric 2- and 3-wheelers, e-bikes, or off-road equipment.

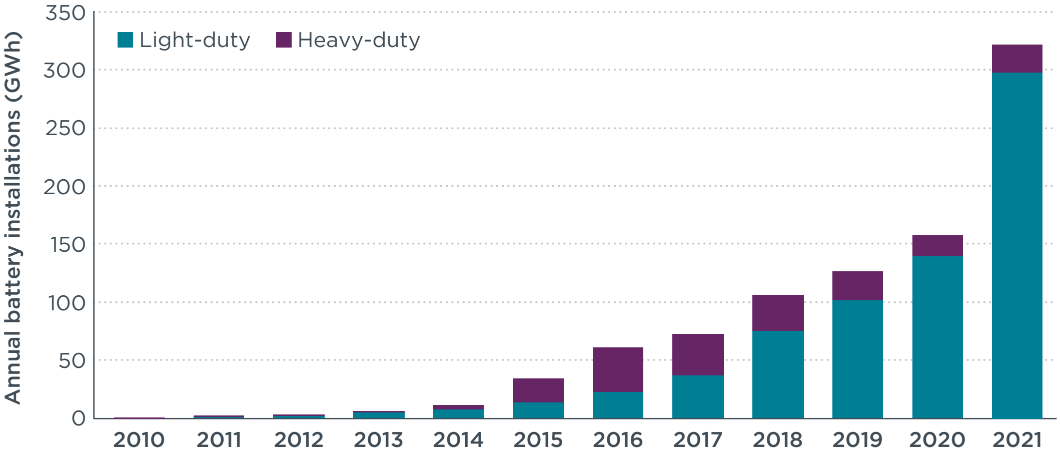

Figure 1. Global installations of batteries for new battery electric vehicles and plug-in hybrids.

The growing demand in batteries for the global light-duty and heavy-duty vehicle electrification is directly linked to an increasing demand in battery materials, such as lithium, cobalt, manganese, and nickel. For some of these materials, especially cobalt and lithium, the majority of the current mining capacities, as well as future reserves, are regionally concentrated in only a few countries. To reduce the corresponding dependence on raw material imports, it can be of strategic interest for an economy to utilize the full lifespan of end-of-life vehicle battery in second-life applications, and to ramp-up the recycling infrastructure for efficient recovery of those materials (Slowik et al., 2020).

Lithium-ion batteries are used in many applications beyond electric vehicles. Through 2014, consumer electronics represented the vast majority of total lithium-ion battery demand; however, growth in this segment is now limited. Since 2018, most of the demand for lithium-ion batteries has come from electric vehicles (Melin, 2018). Batteries are increasingly being used for power storage to provide resiliency and buffer inconsistent renewable energy production; in 2021, new stationary battery installations amounted to 6 GWh, a 60% increase from 2020 (International Energy Agency, 2022a). This total represents only 3% of the amount of battery capacity used for electric light-duty and heavy-duty vehicles. Still, the stationary storage market is expected to grow rapidly with falling costs and increasing renewable energy penetration. As battery costs fall, additional applications may become feasible, including industrial activity and maritime transport.

Despite these additional uses, which might also be met by other battery technologies, electric vehicles are projected to remain the largest source of lithium-ion battery demand in the coming decades (Melin, 2018). This suggests that policymakers supporting the transition to electric vehicles have a key role to play in addressing the environmental and social impact of lithium-ion battery raw material supply, manufacturing, and recycling.

MISCONCEPTIONS REGARDING THE SUSTAINABILITY OF ELECTRIC VEHICLE BATTERIES

Researchers and governments have identified common misconceptions about electric vehicles. These misconceptions can be partially explained by the relative novelty of electric vehicles to the automotive industry and the fast-paced technology development it has been subject to since the early 2010s.

One common misperception of electric vehicles is that they pollute more than internal combustion engine vehicles because lithium-ion battery manufacturing is carbon intensive. While it is true that manufacturing lithium-ion batteries increases the emissions of producing vehicles by 20%–40%, electric vehicles typically make up for that difference within the first one to two years of usage (Bieker, 2021). This can be explained by the higher energy efficiency of an electric motor (around 80%) compared to an internal combustion engine vehicle (less than 30%), which results in a large difference in emissions during the use phase, even when the charging happens with a share of non-renewable sources in the grid mix. However, it is important to note that decarbonizing the electric grid remains critical to realizing the full emissions reduction benefits of electric vehicles (International Council on Clean Transportation, 2021; U.S. Environmental Protection Agency, 2022; Spencer and Funk, 2021; United Kingdom Office for Low Emission Vehicles, 2022).

Another common misconception is that electric vehicle batteries cannot be recycled and will end up in landfills. This misconception forms part of the motivation of this study, which aims to describe existing technological processes that are developed to reuse and recycle electric vehicle batteries, expose the challenges that are faced, and provide recommendations for governments to upscale such practices (U.S. EPA, 2022; United Kingdom Office for Low Emission Vehicles, 2022).

CLIMATE BENEFITS FROM RECYCLING ELECTRIC VEHICLES BATTERIES

In 2021, Bieker published extensive research on the life-cycle GHG emissions of passenger cars in China, Europe, India, and the United States. The study found that over their lifetime, BEVs correspond to 66%–69% lower emissions than gasoline cars in Europe, and to a reduction of 60%–68% in the United States, 37%–45% in China, and 19%–34% in India (Bieker, 2021). With continuous decarbonization of the electricity grid in the upcoming decades, the climate benefit of BEVs will further increase. For PHEVs, however, the life-cycle GHG emissions benefit over internal combustion engine vehicles is limited due to their low electric drive share during real-world usage (Bieker, 2021; Bieker et al., 2022).

Bieker (2021) found that GHG emissions from battery manufacturing correspond to a small share of the total life-cycle emissions of a BEV. For an average BEV sold in Europe or the United States in 2021, the battery corresponds to 12%–17% of the life-cycle GHG emissions (Bieker, 2021). The contribution of the production of the rest of the vehicle is about twice as high, at 20%–32%. The largest contributor to the life-cycle GHG emissions of a BEV is from the electricity consumption, which amounts to 47%–64%. In China or India, where emissions from electricity consumption are higher, battery production only corresponds to 5%–8% of a BEV's total life-cycle GHG emissions. Nevertheless, the growing demand for electric vehicle batteries, as shown in Figure 1 above, suggests that their overall climate impact will be non-negligible. Battery recycling can reduce the GHG emissions impact of electric vehicle batteries, but the magnitude of reductions that can be achieved through recycling vary depending on the battery chemistry, the share of recycled content used in the production of new batteries, and the recycling process used to recover the battery material, as discussed in the section on the challenges along the recycling process below.

SUPPORTING AN ELECTRIC VEHICLE TRANSITION THAT IS JUST AND SOCIALLY RESPONSIBLE

From a social impact perspective, the necessity of mitigating climate change and avoiding millions of premature deaths through the reduction of air pollution from the transport sector are invaluable. When considering the raw material supply chain for lithium-ion batteries specifically, however, the transition to battery electric vehicles comes with opportunities and challenges. Achieving an electric vehicle transition that is just and socially responsible involves the creation of quality jobs throughout the reuse and recycling industries, but also the introduction of measures that would improve the working conditions of mine extraction workers and ensure that they can afford a living.

As will be assessed in more detail in an upcoming ICCT report, the mining of battery materials can stimulate the economy, create jobs, and support infrastructure development, therefore improving the livelihoods of the communities involved (Mancini and Sala, 2018). In contrast, the extraction of raw materials for batteries could contribute to challenges including, but not limited to, the displacement of local communities, health impacts, and human rights abuses. A frequently cited example is that of cobalt mining in the Democratic Republic of the Congo, where artisanal mining operations outside of authorized mining zones, which correspond to about 20% of total cobalt mining in the country, typically lack legal protection for the workers, involve child labor, and are conducted without proper safety equipment (Amnesty International, 2016). The exposure to dust containing cobalt and other metals frequently results in respiratory diseases (Amnesty International, 2016). For large-scale, industrial mining operations, which correspond to about 80% of cobalt mining in the Democratic Republic of the Congo, excessive working hours, low wages, and cases of violence have been reported (Rights and Accountability in Development, 2021).

MARKET POTENTIAL OF BATTERY REUSE AND RECYCLING

The importance of battery reuse and recycling will grow alongside the number of electric vehicles reaching their end of life. In the next several years, the majority of lithium-ion battery recycling will continue to be composed of battery production scrap. With an increase in electric vehicle production, the volumes of recycling from production scrap will also increase. In the longer term, with more electric vehicles reaching their end of life, end-of-life vehicle batteries are expected to become the main source of battery recycling. Therefore, understanding the timeline and scale of batteries reaching the end of their usage in electric vehicles is important for guiding public and private sector investments in research and development, processing reuse and recycling facilities, and ensuring a sufficient supply of raw materials to continue building the electric vehicle market.

To better understand the potential volumes of end-of-life vehicle battery reuse and recycling, this paper estimates the total capacity of light-duty and heavy-duty electric vehicle end-of-life batteries that would be available for reuse in a second-life application, such as in stationary energy storage, and the amount of recycled material that would be available to reduce the demand in raw material for the global electric vehicle market. The analysis builds from the methodology used in Slowik et al. (2020), updates projections of battery material demand for the global light-duty BEV and PHEV sales through 2050 and adds the respective projections for the heavy-duty vehicle market. Key updates and assumptions are summarized below:

» Global light-duty and heavy-duty BEV and PHEV sales were projected up to 2050, considering implemented and proposed transport policies as of 2022 (International Council on Clean Transportation, 2022b). It is estimated that annual sales of electric light- and heavy-duty vehicles will increase to 42 million by 2030, 84 million in 2040, and 106 million in 2050. These projections are based only on adopted and proposed policies and are not a market forecast; electric vehicle sales may proceed more quickly, and at a more consistent pace than shown here.

» The battery capacity per vehicle is assumed to increase by 1% annually until 2030 and remain constant afterward. For the global average of light-duty BEV batteries, for instance, this corresponds to a growth from 50 kWh in 2020 to 55 kWh by 2030, where it remains constant until 2050.

» Due to high uncertainty regarding potential future battery chemistries, such as solid-state or sodium-ion batteries, this study only considers battery chemistries that are used in electric vehicles as of 2022. Among these, nickel-rich lithium nickel manganese cobalt oxide (NMC811 and NMC955)-based batteries are assumed to increase to 46% by 2030, while the share of lithium iron phosphate (LFP)-based batteries is assumed to increase to 37% (compare International Energy Agency, 2022b). Consequently, the share of NMC532-, NMC622-, and lithium nickel cobalt aluminum oxide (NCA)-based batteries are expected to decrease. The 2030 market shares of chemistries are assumed to remain constant until 2050.

» The electric vehicle retirement rate as a function of vehicle age is assumed to remain the same as observed for vehicles today. For light-duty vehicles, the battery is expected to be used for the entire vehicle lifetime, while for heavy-duty vehicles, the battery is replaced once after a 10-year period.

» It is assumed that 90% of batteries from retired electric vehicles can be collected. This number considers a share of electric vehicles reaching their end of life in countries where measures for battery collection are more relaxed.

» It is assumed that 50% of the collected electric vehicle batteries are first used in second-life applications for 10 years before being recycled, and the other 50% are directly recycled.

» For the recycling process, lithium is assumed to be recovered at a rate of 50% from 2027 to 2030 and 80% from 2031 up to 2050. The assumed recovery rate for cobalt, manganese, and nickel is 90% from 2027 to 2030 and 95% from 2031 to 2050. These recovery rates are based on the European Commission, Council, and Parliament's provisional agreements for the upcoming Battery Regulation (European Commission, 2022b).

Figure 2 presents the projected annual global sales of new light-duty and heavy-duty electric vehicles. Based on current policies, they are expected to increase rapidly from 2020 to 2035, mainly driven by the leading electric vehicle markets, as they aim to reach 100% light-duty vehicle sales by 2035. Post 2035, electric vehicle sales continue to grow but at a slower pace, mainly reflecting the vehicle electrification rates observed in emerging markets and developing economies.

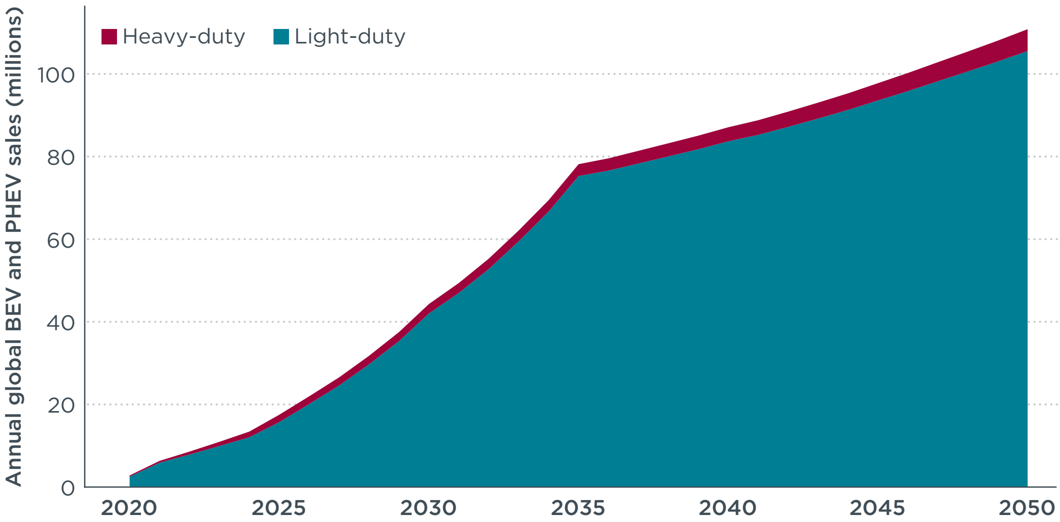

Figure 2. Projected annual global new light-duty and heavy-duty BEV and PHEV sales.

Based on the assumptions described above, Figure 3 below shows the potential of the global battery reuse market based on the cumulative capacity of end-of-life electric vehicle batteries that could be reused in second applications up to 2050.

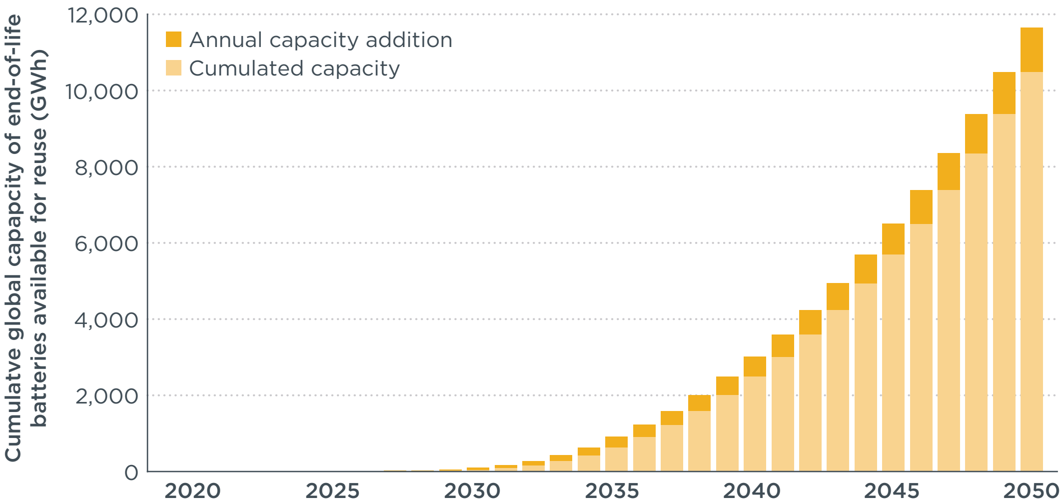

Figure 3. Projected cumulative global capacity of end-of-life electric vehicle batteries available for reuse applications.

When assuming that batteries would be used in second-life applications for 10 years, the global storage capacity of all reused batteries still available in a given year accumulates to 96 GWh in 2030, 910 GWh by 2035, 3,000 GWh by 2040, and 12,000 GWh by 2050. For comparison, the global capacity of pumped storage hydropower, the largest source of installed storage capacity in the world, was about 8,500 GWh in 2020 and could be increased to 11,700 GWh by 2026 (International Energy Agency, 2021). In addition to the economic value of using end-of-life electric vehicle batteries in second-life applications, environmental benefits could be achieved by reducing the demand in raw material for newly manufactured batteries.

Recycling, however, remains crucial to ensure that materials in end-of-life electric vehicle batteries are recovered and used to support mineral supply chains. Figure 4 shows how recycling can reduce the demand for raw materials needed to manufacture new electric vehicle batteries. It is assumed that 50% of collected end-of-life batteries for a given year are directly recycled, while the other 50% are reused in second applications for 10 years before being available for recycling.

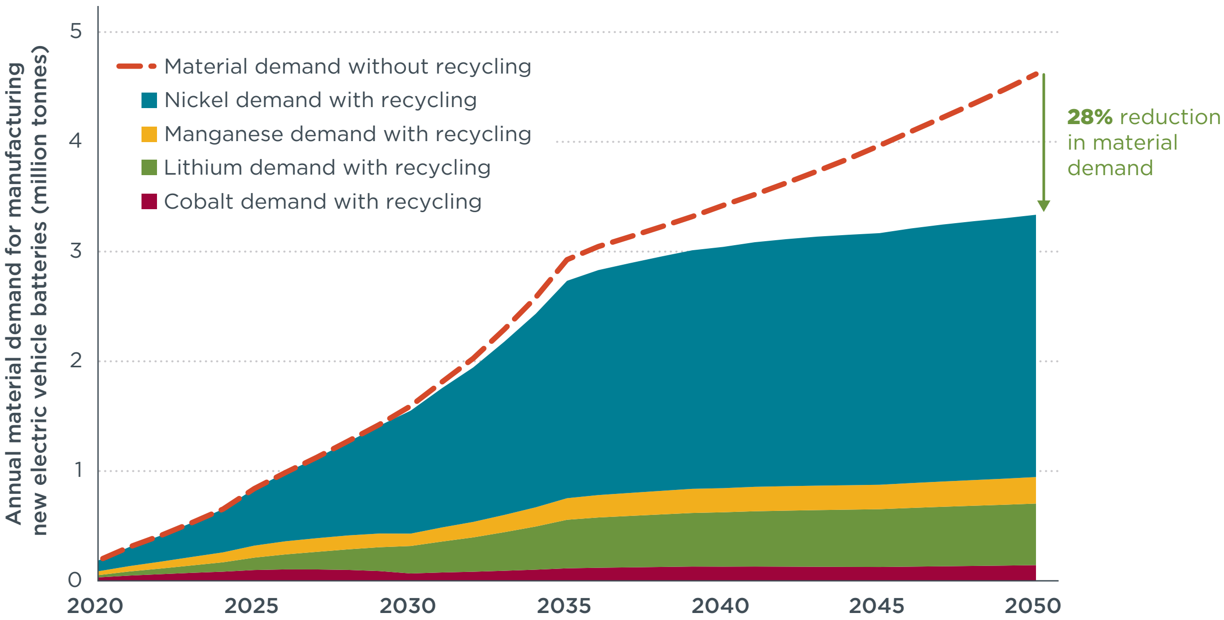

Figure 4. Annual lithium, nickel, cobalt, and manganese demand for global sales of light-duty and heavy-duty BEVs and PHEVs.

As shown in Figure 4, the annual demand for battery materials increases sharply from 2020 to 2035, as several of the leading electric vehicle markets get closer to achieving 100% of new light-duty electric vehicle sales. However, given the delay of a vehicle's lifetime, it is not until the early 2030's that recycling of end-of-life electric vehicles would start to ramp up. After 2035, the slower increase in electric vehicle sales and the increasing availability of recycled material could lead to significant reductions in new materials needed. Overall, the analysis finds that recycling could reduce the combined annual demand for raw cobalt, lithium, manganese, and nickel by 3% in 2030, 11% in 2040, and 28% in 2050. Efficient recycling practices could thereby stabilize the annual demand in raw materials despite the ongoing increase in electric vehicle battery production.

These savings distribute differently over the individual materials. With the assumed shift to LFP and high-nickel NMC cathodes, the total demand in cobalt and manganese would grow at a slower pace than for lithium and nickel. Therefore, recycling would be able to meet a higher share of the future demand for cobalt and manganese than for lithium and nickel. While the annual demand in cobalt and manganese mining could be reduced by 10% and 7% in 2030, 19% and 16% in 2040, and 34% and 31% in 2050, respectively, the demand in lithium and nickel would be reduced by only 1% and 2% in 2030, 9% and 11% in 2040, and 24% and 28% in 2050, respectively. These numbers also acknowledge that recovering lithium from battery recycling is more difficult than the recovery of cobalt, manganese, and nickel.

While these reductions in raw material demand translate into important economic and environmental benefits, they also indicate that battery recycling will not close the mineral supply loop. Overall, with the aforementioned, conservative assumption that only battery technologies available in the market today will be used throughout 2050, the accumulated demand in raw materials from 2020 to 2040, with or without recycling, would amount to 11 or 12 million tons of lithium, 48 or 55 million tons of nickel, 3 or 4 million tons of cobalt, and 5 or 6 million tons of manganese. In the case of lithium, nickel, and cobalt, this corresponds to about half of the global reserves that are economically recoverable already as of 2022 and about 13%–18% of the total estimated resources (U.S. Geological Survey, 2022). For this reason, stable supply chains across mining operations, the development of battery chemistries less reliant on critical minerals, and complementary policies to reduce demand for new vehicles remain crucial for keeping demand for raw minerals in check.

While this analysis shows that there is ample potential for battery reuse and recycling, there are several economic and technical uncertainties that must be resolved to enable a sufficient ramp-up of the respective infrastructure. The extent to which these challenges are addressed in the coming years will determine the amount of retired vehicle batteries that can be reused and recycled. The following sections of this report describe these challenges and discuss policy approaches that can help to address them.

APPLICATIONS AND CHALLENGES FOR BATTERY REUSE

This section reviews recent developments in the reuse of end-of-life electric vehicle batteries, identifies key technical barriers and challenges, and evaluates the economic potential. The section concludes with a discussion on current policy approaches to scale up battery reuse practices.

OVERVIEW OF ELECTRIC VEHICLE BATTERY REUSE APPLICATIONS

The current generation of lithium-ion batteries is expected to last for at least 3,000 full charge and discharge cycles before their capacity is less than 70%–80% of their initial value—a point that is typically considered as the battery end-of-life (Harlow et al. 2019; Rallo et al., 2020). For electric vehicles with a of range of 200 to 400 km, 3,000 cycles correspond to 600,000 to 1,200,000 km, which is several times higher than the lifetime mileage currently observed for combustion engine passenger cars (cf. Bieker, 2021). Therefore, BEV batteries are generally expected to last longer than the useful life of their respective electric vehicles. Rather than immediately being recycled, electric vehicle batteries can be reused.

Several battery reuse applications have been implemented across the globe. Small-scale applications commonly take the form of battery storage for residential settings, storage systems at electric vehicle charging stations, or street lighting. Medium-scale applications typically consist of energy supply storage for industrial sites or power traction batteries for maritime applications. Large-scale applications commonly involve the electricity grid, where end-of-life electric vehicle batteries are reused as energy storage units capable of providing several services, including avoiding renewable energy curtailment, peak shaving, frequency control, and transmission line congestion alleviation. Battery reuse for large-scale utility applications has become increasingly popular (Ambrose, 2020; Zhu et al., 2021). Table 1 lists notable examples of electric vehicle battery reuse projects launched since 2014, although the list is not comprehensive.

Table 1. Examples of electric vehicle battery reuse projects.

	Project lead(s)	Location	Year announced/ operation started	Description
Street lighting	Nissan	Namie, Japan	2018 (project launch)	Nissan plans to repurpose batteries from end-of-life Nissan Leafs to power streetlights. The project referred to as "The Light Reborn," uses a solar panel to charge the battery (Nissan, 2018).
Electric vehicle charging stations	Jaguar Land Rover and Pramac	Gaydon, United Kingdom	2022 (operation started)	Jaguar and Pramac have developed a solar-powered, off-grid portable battery charging station. The system can be configured as a Type 2 22-kW AC charger for electric vehicles (Jaguar Land Rover, 2022).
	Volkswagen and Electrify America	United States	2022 (announced)	Volkswagen intends to utilize batteries from used electric vehicles for energy storage at Electrify America charging stations (Banner, 2022).
Maritime and airport	The Seine Alliance and Renault	Paris, France	2019 (operation started)	The Seine Alliance has partnered with Renault to deploy electric boats powered by 15-kW second-life electric vehicle batteries (Richardson, 2019).
	Neoline Développement	Nantes, France (headquarters)	2020 (pilot project launched)	The Neoline project consists of the development of an electric sail cargo fleet that uses second-life electric vehicle batteries for propulsion (Renault Group, 2020).
	Carwatt and Renault	Coignières, France (headquarters)	2014 (operation started)	In 2014, Carwatt partnered with Renault to convert combustion engine ground-support equipment vehicles at airports into electric vehicles that use second-life electric vehicle batteries (Renault Group, 2019).
Industrial site	RWE and Audi	Herdecke, Germany	2021 (pilot project launched)	Audi and the energy company RWE launched an energy storage system made from 60 second-life Audi e-tron batteries. The system can provide about 4.5 MWh of stored electricity to support the industrial site's operations (Winter, 2021).
	Renault and Connected Energy	West Sussex, United Kingdom	2018 (announced)	In 2018, Renault and Connected Energy announced the "SmartHubs" pilot project in the United Kingdom. It consists of a 360-kWh energy storage system made from the batteries of end-of-life electric vehicles to reduce electricity cost by optimizing the use of renewable energy at industrial, commercial, and residential sites (Hampel, 2020).
Utility-scale grid storage	Renault	France and Germany	2018 (announced)	Announced by Renault in 2018, the Advanced Battery Storage project is taking place at different sites in Europe. It uses a combination of used and new electric vehicle batteries to provide up to 50 MWh of energy storage capacity to balance the electricity supply from renewable energies (Hampel, 2020).
	Enel and Nissan	Melilla, Spain	2019 (in operation)	Enel, an electric utility company, partnered with Nissan to build a 4-MW energy storage facility in Melilla, Spain, referred to as the Second Life project. The battery storage comprises 78 Nissan Leaf batteries (48 at end of life and 30 brand new) that store renewable energy to improve the reliability of the grid (Enel, 2022).

Table 1 indicates that as of 2022, several automakers have shown interest in reusing end-of-life batteries. However, the electric vehicle battery reuse market remains relatively small due to the currently limited supply of end-of-life electric vehicle batteries and the technological and economic challenges related to preparing a battery for a second application. Those challenges and barriers are detailed in the subsection below.

CHALLENGES AND BARRIERS TO BATTERY REUSE

While there have been several battery reuse initiatives initiated worldwide, many more will be needed to allow a reuse of the tens of millions of electric vehicle batteries which will exit the on-road fleet in the coming decades. Scaling up the electric vehicle battery reuse market will require addressing the different technical challenges and barriers of battery reuse, and also ensuring the process is more cost-effective than using new, purpose-built batteries.

Technical feasibility of battery reuse

The technical process of battery reuse involves a series of steps that may differ from one reuse center to another, as research and development efforts are continuously being deployed to optimize the process. The process described in this report is not the most optimized, but it provides a useful framework to understand the challenges that third-party reuse centers have faced up to the 2022 market. This battery reuse process, illustrated in Figure 5 below, includes five major steps: 1) battery collection; 2) battery transport; 3) battery inspection; 4) sorting and regrouping; and 5) battery second-life placement.

Figure 5. Main steps in the electric vehicle battery reuse process.

Battery collection. The first step of the process is to collect the battery. Battery collection can be challenging because, as of 2022, many jurisdictions do not have the mechanisms to ensure the battery can be traced over its lifetime and is collected once the electric vehicle reaches its end of life (Dominish et al., 2021). Additionally, many jurisdictions do not have regulations that clearly define who is responsible for the battery once it reaches its end of life. Without those elements in place, there is a higher chance that electric vehicle batteries will end up in landfills, where they become contamination hazards and a waste of critical mineral resources (Dominish et al., 2021; Engel et al., 2019). Furthermore, electric waste, or e-waste, regulations that clearly define how to collect, handle, and store end-of-life electric vehicle batteries safely have often not been introduced. For third parties interested in collecting these batteries, improper handling could lead to further contamination of lands and waterways, which can negatively impact human health (Dominish et al., 2021).

Another challenge is the removal of the lithium-ion battery from the vehicle. The battery may have been subject to impacts during use, due to being located underneath the vehicle, which may have deformed the battery cover (Rejoule, 2022a). Several manufacturers have also announced their intentions for further advancing structural integrated battery design in their upcoming models, which could make battery removal more difficult (Halvorson, 2021). Safety during battery removal is also a concern, as the high current and high voltage of an electric vehicle battery means that safety protocols need to be defined and executed by trained professionals (Rejoule, 2022a).

Battery transport. Once the battery is collected, it must be transported to a reuse center, where it can be processed for a second-life application. The longer the traveling distance to a reuse center is, which may include transboundary movements, the more expensive the process becomes (Slattery et al. 2021). Furthermore, transportation logistics need to follow safety standards defined at the international level by several organizations, including the International Electrotechnical Commission, the Institute of Electrical and Electronics Engineers (IEEE), the United Nations, or the Society of Automotive Engineers (Haram et al. 2021). Meanwhile, jurisdictions like the European Union and U.S. federal government have also defined safety standards for transporting lithium-ion batteries, which must be adhered to along with the international standards. Whether set at the international or jurisdiction levels, safety regulations typically classify lithium-ion batteries under Class 9 miscellaneous hazardous materials (Dominish et al., 2021; U.S. Department of Transportation, 2021). This is due to the risks associated with the leakage of toxic substances and the high flammability of lithium-ion batteries. Such classification makes them relevant to the Basel Convention, which controls the transboundary movement of hazardous wastes (Secretariat of the Basel Convention, 2022).

While safety is important, these safety regulations make transporting electric vehicle batteries complex and costly. For example, in the European Union, under the European Commission Battery Directive of 2008/2015 (currently being reassessed), if a battery is classified as end-of-life battery, it becomes subject to hazardous waste regulations (Dominish et al., 2021). This implies that transporters must apply for a specific license and receive authorizations from the different parties involved to transport the battery. Further complications come from the fact that licenses differ from one jurisdiction to another, making cross-border battery shipping cumbersome. In addition, the vehicles used to transport the battery need to be equipped with special handling equipment, and drivers must receive special training (Dominish et al., 2021).

In the United States, the Department of Transportation regulates end-of-life batteries under its Hazardous Materials Regulations (HMR). The battery must adhere to the United Nations' Manual of Test and Criteria, Section 38.3, which requires the manufacturer to meet requirements on different safety criteria including altitude, thermal test, overcharge, or shock. Upon passing this test, the battery can be transported but is subject to additional safety requirements, such as being placed in an outer packaging that can resist atmospheric pressure, loadings, and shocks that typically occur during transportation (United Nations, 2019; U.S. Department of Transportation, 2021).

Slattery et al. (2021) found that the transportation cost of electric vehicle batteries varies greatly from one market to another, ranging between 5% to 63% of the total costs of the battery reuse or recycling project. It is worth noting that several studies reviewed by Slattery et al. (2021) also included battery collection costs.

Battery inspection. Once a battery arrives at a reuse center, information about the battery's initial technical characteristics (e.g., nominal voltage, capacity, chemical composition), as well as its level of degradation and remaining capacity, the state of health (SOH), will determine its suitability for a second-life application (Zhu et al. 2021; Rejoule, 2020b). Gathering such information, however, is challenging because most markets do not require electric vehicle manufacturers to make it readily available to third-party reuse centers. This creates inefficiencies, which result in higher costs of the reuse process (Zhu et al., 2021; Rejoule, 2020b).

In principle, the SOH of a battery can be determined from data on its usage history (e.g., charging history, average temperature, reasons for retirement, and average state of charge), which can be accessed through the battery management system. However, accessing information in this system can be challenging, as it requires specialized software and permissions. In some cases, it may even be deleted by the manufacturer once the battery reaches end of life. For this reason, third-party reuse centers often need to perform a series of tests to determine the SOH (Zhu et al., 2021; Rejoule, 2020b). Determining the SOH at the battery pack level through non-destructive testing is more cost-effective than having to disassemble the battery and determine the SOH of each module or cell before regrouping them into battery packs (Zhu et al. 2021). The testing typically requires fully charging and discharging the battery, a lengthy and labor costly process (Zhu et al., 2021; Rejoule, 2020b). Further complications stem from a lack of a standardized approach of how to determine the SOH, which means that the value can be calculated or interpreted differently across different parties (Zhu et al., 2021; Rejoule, 2020c). In cases where the SOH is judged unsuitable for reuse applications, the battery could either be refurbished and placed back into an electric vehicle if needed repairs are moderate, or directly sent to a recycling center if required repairs are severe.

In addition to the gathering of information described above, the battery needs to also be physically inspected. This is another critical step to identifying any damages to the battery, such as dents or leakage, and developing a protocol to handle it safely.

The inspection is typically done through the human eye, which can make the process inefficient and dangerous (Zhu et al., 2021; Rejoule, 2020c).

Battery disassembly (optional step): Depending on the second-life application, disassembly of the battery to the module or cell level could be performed. However, if batteries are not designed to be detachable, the process can require separating modules and cells that are tightly glued or welded together (Zhu et al., 2021; Rejoule, 2020b). This process can take up to 6 to 10 hours, translating to high labor costs. Rallo et al. (2020) found that the costs of disassembling a battery range between $34 and $80 per kWh of original capacity, with disassembly down to the cell level being more expensive. This is equivalent to about 23%–53% of the average price of $151 per kWh for a newly manufactured battery in 2020 (Bloomberg New Energy Finance, 2022). For this reason, second-life applications using intact battery packs are usually preferred by the industry (Zhu et al., 2021).

Battery disassembly is further complicated by the large variety of electric vehicle battery designs currently on the market, which implies that third-party reuse centers cannot plan ahead to optimize disassembly processes and decide on the best second-life application (Zhu et al., 2021; Rallo et al., 2020; Rejoule, 2020a).

Sorting and regrouping. Once the battery cells, modules, or packs have passed SOH and safety assessment tests, they are sorted and regrouped according to their performance (e.g., SOH, internal resistance, or thermal behavior), as variations between the cells and modules of a battery pack would negatively affect the performance of the second-life battery. In case of high imbalance in the SOH of the battery cells, for example, the overall battery pack performance would be limited by the battery cell with the lowest SOH (Zhu et al., 2021; Rejoule, 2020d). A key challenge of this sorting and regrouping step is the choice of the most suitable indicators. Another challenge involves the development of an effective sorting algorithm. Since the degradation of batteries upon usage involves several parallel mechanisms, it is challenging to create an algorithm that encompasses all corresponding indicators (Zhu et al., 2021).

Battery second-life placement. Once the battery is placed in a second-life application, it will not behave like a new battery, so adapted control strategies would be required to, for example, stabilize power output or limit overheating events (Zhu et al., 2021). Furthermore, equalization strategies will need to be designed to reduce inconsistencies between the electrochemical behavior of individual cells or modules, as these are expected to increase throughout a battery's second-life usage. Finally, advanced fault-diagnosis algorithms must be developed for safety purposes to detect eventualities such as internal short circuits. While such algorithms have already been developed for new batteries, their effectiveness has not yet been determined for second-use batteries (Zhu et al., 2021; Rejoule, 2020e).

Table 2 below summarizes the challenges encountered through the battery reuse process.

Table 2. Challenges encountered through battery reuse processes.

Battery reuse process	Challenges encountered
Battery collection	• Lack of traceability mechanisms to ensure the battery is collected and does not end up in landfills • Battery removability is a growing concern as manufacturers push toward more vehicle-integrated battery design • Lack of regulations that clearly define who is responsible for the battery when it reaches end of life • Lack of information at the very early stage of collection regarding the state of the battery (ownership, SOH, metal content, damages, etc.) to redirect the end-of-life battery in the right destination (repair, reuse, or recycle) and avoid non-needed logistics
Battery transport	• Cumbersome licensing processes • Costly safety measures • Long distances needed to be traveled to reach the reuse center
Battery inspection	• Lack of readily available information on battery design, chemistry, state of health, and usage history may require costly tests and limit ability to optimize reuse processes.
Battery disassembly	• Modules and cells are not designed to be disassembled • Large variety in terms of battery design, so process is labor intensive
Sorting and regrouping	• Identifying the right set of indicators and thresholds to maximize performance of a battery in its second-life application • Developing a sorting algorithm for batteries with similar electrochemical properties
Battery second-life placement	• Adapting control strategies to stabilize power output or to limit events such as overheating or discharging • Developing effective equalization strategies to reduce inconsistencies between the electrochemical behavior of individual cells or modules • Developing fault-diagnosis algorithms adjusted to second-life batteries to quickly detect events such internal short circuits

Economic feasibility of battery reuse

As described above, battery reuse involves processes that are time and labor intensive. This highlights the importance of carefully evaluating the economic feasibility of battery reuse compared to manufacturing a new one.

To date, there has been limited research comparing the market price of second life versus newly manufactured batteries. A study conducted in 2015 by the U.S. National Renewable Energy Laboratory (NREL) found that the selling price of a second-life battery could cost as low as $20 per kWh. The study presented a case where the battery was disassembled to the module level and where no SOH testing needed to be performed, as information on modules SOH was readily available (Neubauer et al., 2015). Another NREL analysis conducted the same year found that the market selling price of battery reuse ranges from $44 to $180 per kWh, which represented between 10% and 43% of the average cost of new lithium-ion batteries at that time (Neubauer et al., 2015; Bloomberg New Energy Finance, 2022).

In 2018, a report by the Global Battery Alliance found that the selling price of a second-life battery ranges between $60 and $300 per kWh, depending on the market and the requirements of the second-life application (Melin, 2018). For comparison, a new electric vehicle battery pack cost $198 per kWh on average in 2018 (Bloomberg New Energy Finance, 2022). Ambrose (2020) found that the selling price of a used battery could be half of a brand-new battery, which at the time was estimated at $157 per kWh. The study noted that the purchase price of the end-of-life battery from its original owner represented the largest share of its market selling price as a second-life battery. Passing this cost to the original owner instead could therefore increase the price competitiveness of the second-life batteries.

Based on the studies mentioned above, the market selling prices of second-life battery range from $20 to $300 per kWh. The significant range in price indicates how the cost of battery reuse ultimately depends on many contextual factors, including whether the used electric vehicle battery needed to be bought, the cost of transport logistics, what level of disassembly was performed, the cost of labor, and what technologies were used. Rethinking business models, such as who is responsible for paying the collection fee of the end-of-life battery, and optimizing battery reuse processes are key factors that would ultimately determine how the price of a second-life battery compares to one that is newly manufactured.

Another important consideration when evaluating the economic feasibility of battery reuse is the decreasing price of new lithium-ion batteries. From 2013 to 2021, the global average price of lithium-ion batteries was reduced by 80% (Bloomberg New Energy Finance, 2022). That trend is expected to continue in the long term, despite the 7% increase in lithium-ion battery price recorded from 2021 to 2022 as a result of high raw material costs (Bloomberg New Energy Finance, 2022). As per this dynamic, there will eventually come a point where the selling price of a new battery compares favorably to the price of a second-life battery. However, through economies of scale and by optimizing battery reuse processes, it could also be that end-of-life batteries remain price competitive compared to newly manufactured batteries (Engel et al., 2019).

Beyond the selling price of second-life batteries when compared to new ones, the electricity costs and the remaining lifespan of second-life batteries are also critical parameters to consider when studying the economic feasibility of battery reuse.

Madlener and Kirmas (2017) studied the 10-year economic profitability of using a second-life electric vehicle battery in a residential energy storage application in Germany. The study found that when assuming an electricity price increase of 4% per year, the break-even price for the battery residential energy storage (price above which the storage system is no longer profitable) was $107 per kWh battery capacity. In a scenario where the electricity price increases 2% per year, the break-even price was $73 per kWh battery capacity. In a high electricity price scenario, where the prices increase 6% per year, the residential storage application was profitable for all the battery pack costs considered in the study (from $30/kWh to $120/kWh).

Mathews et al. (2020) studied the economic feasibility of a utility-scale solar battery storage system in California. They found that using a second-life electric vehicle battery can be more profitable than purchasing a new battery if measures are taken to limit its state of charge to between 65% and 15%, which extends the battery's lifespan to over 16 years, assuming the battery reaches its end of life at 60% of its original capacity. Under these conditions, the project using the second-life battery becomes more profitable than the project using the new battery if its second-life battery market price costs less than $125 per kWh, or 60% of the new battery estimates based on 2017 pricing from the California Independent System Operator (CAISO, 2022).

These studies support the conclusion that battery reuse's economic feasibility depends on several parameters, including the selling price of the end-of-life battery, its lifespan when directed into a second application, and other economic parameters such as the cost of electricity.

CURRENT POLICY APPROACHES TO SUPPORT BATTERY REUSE

As described above, it is technologically possible to reuse end-of-life electric vehicle batteries in second-life applications. However, the challenges described above can make battery reuse practices time-consuming and costly. Many of these challenges can be addressed through a proper set of policies and regulations, which can be described through four main areas of intervention: 1) battery standards, 2) battery traceability and collection, 3) battery transport, and 4) battery information.

Battery standards. As of 2022, there is a critical lack of standards for battery durability, safety, and the processes used to repurpose a battery towards a second-life application. Battery durability standards could support the manufacturing of new batteries that provide longer-term services when directed towards a second application. California and the United Nations Economic Commission for Europe (UNECE) set standards for electric vehicle battery durability. California's approach requires that model year 2026–2029 electric vehicles maintain at least 70% of their certified test-cycle range for 10 years or 240,000 km (150,000 miles), whichever occurs first (California Air Resources Board, 2022a). For 2030 and subsequent electric vehicle model years, the requirement is increased to 80% of their certified test-cycle range for 10 years or 240,000 km (150,000 miles), whichever occurs first (California Air Resources Board, 2022a). The United Nations Global Technical Regulation is less ambitious. It would only require that electric vehicles retain at least 80% of their rated useable energy after 5 years or 100,000 km, and at least 70% of their rated useable energy after 8 years or 160,000 km (United Nations, 2022). These numbers mirror the battery durability provided by most manufacturers' electric vehicle battery warranties in recent years. In the European Union, the UNECE's electric vehicle battery durability requirements are considered in the Commission's proposal for the upcoming Euro 7 standards (European Commission, 2022a).

Another important consideration is the need for a standardized approach for reporting accurate battery SOH data, as it will help inform the best suitability for a second-life application. California and the UNECE cover this aspect in their battery durability standards (California Air Resources Board, 2022b; United Nations, 2022).

Finally, safety standards for end-of-life battery collection, discharge, and disassembly are also needed. Few jurisdictions have adopted such regulations. In 2018, the United States and Canada published the UL 1974 Standard for Evaluation for Repurposing Batteries, which set general safety requirements for sorting and grading used electric vehicle batteries and estimating their SOH (UL Standards, 2018). UL 1974 also set additional requirements for specific second-use applications.

Battery traceability and collection. To ensure that end-of-life electric vehicle batteries are collected, traceability mechanisms combined with regulation that clearly define who is responsible for collecting the battery need to be put in place. In China, the government established a traceability management platform to track electric vehicle batteries throughout their lifetime in 2018 (Reuters, 2018). In 2020, the U.S. Department of Energy awarded funding to Everledger, a digital transparency company, to conduct a pilot project in collaboration with Ford Motor Company. The project aims to track electric vehicle batteries' life cycle using blockchain technologies to support more effective collection protocols when the batteries reach end of life (Everledger, 2020). Similarly, in New Zealand, a battery stewardship program is in development to ensure the circularity of electric vehicle batteries. Within this program, an accredited Product Stewardship Organization would be responsible for collecting end-of-life batteries, a process potentially facilitated by blockchain technologies (New Zealand Battery Industry Group, 2021; New Zealand Ministry of Environment, 2021).

Some jurisdictions are looking into clearly defining responsibility for collecting end-of-life electric vehicle batteries. In China, for example, the government released a set of policies that place this responsibility on electric vehicle and battery manufacturers or importers (Ambrose and O'Dea, 2021). Similar extended producer responsibility (EPR) regulations are also being considered in several jurisdictions, including the European Union, California, and Québec (European Commission, 2020; CalEPA, 2022; Propulsion Québec, 2020).

Regulations that support battery removability are also important, especially considering manufacturer intentions to move toward a more integrated battery design (Halvorson, 2021). In China, the government has developed non-mandatory standards to facilitate electric vehicle battery dismantling (ChineseStandard.net, 2021).

Battery transport. Transport logistics that guarantee safety in the handling of electric vehicle batteries need to be refined to reduce administrative costs and burdens. This requires that relevant stakeholders coordinate efforts to define safety standard requirements specific to end-of-life electric vehicle batteries and to streamline licensing requirements across regional jurisdictions (Dominish et al., 2021).

Battery information. To remain competitive, manufacturers are continuously innovating their battery technologies. This explains the large diversity of battery configurations in design, shape, size, mass, or chemistry that characterizes the 2022 electric vehicle market. The batteries typically arrive at third-party reuse centers as black boxes, and the information needed to optimize reuse practices is hard to access. Policy interventions could therefore require that manufacturers make this information more accessible. In the European Union, the Commission's proposal for the upcoming Battery Regulation discusses the creation of a battery passport linked to a digital platform, through which manufacturers will disclose battery data (European Commission, 2020). The Battery Regulation would also require that legal operators that have purchased end-of-life batteries be given access to all the information needed to determine the SOH of the battery and its expected lifetime (European Commission, 2020). Similarly, the California Advanced Clean Cars II regulations include requirements for manufacturers to disclose all information on batteries via labeling and an online data repository accessible through digital identifiers (California Air Resources Board, 2022c).

Governments could also consider regulations to standardize electric vehicle battery design and chemistries, which would alleviate concerns regarding hard-to-access battery information. Standards for battery pack design would allow automizing the removal of the batteries from vehicles and the battery dismantling, reducing the amount of manual work required and making the process safer and less costly. However, because such regulations could stifle battery innovations that benefit electric vehicle consumers, in the form of longer range and cheaper purchasing prices, it may be preferable to wait to implement design or chemistry standardization requirements until the market is more developed.

PATHWAYS AND CHALLENGES FOR BATTERY RECYCLING

By reducing the demand for raw material, the recycling of electric vehicle batteries contributes to mitigating the negative environmental and social impact of mining. Recycling further reduces dependency on raw material imports while creating domestic jobs and value. While several battery recycling initiatives have started to emerge worldwide, much more recycling capacity will be needed to handle the tens of millions of batteries that will reach their end-of-life in the coming decades. Scaling up electric vehicle battery recycling requires addressing several technical challenges and barriers.

This section reviews electric vehicle battery recycling processes, identifies the key challenges and barriers, and estimates the economic potential of recycling. The section concludes with a discussion on policy levers to scale up recycling practices and presents an overview of policy developments in China, the European Union, and North America.

CHALLENGES AND BARRIERS ALONG THE BATTERY RECYCLING PROCESS

Figure 6 summarizes the main steps in the recycling of lithium-ion batteries. As shown, up to the battery disassembly stage, the steps involved to recycle lithium-ion batteries are similar to the steps described in the battery reuse section of this report (see Figure 5). Common challenges are briefly summarized in this section, with an emphasis on the considerations most relevant to recycling.

Technical feasibility of battery recycling

Figure 6. Main steps of electric vehicle battery recycling process.

Battery collection and transport. Battery collection logistics need to be put in place to ensure that they can be traced through their lifetime and, therefore, safely collected when they reach end of life. Furthermore, transporting electric vehicle batteries can be expensive, particularly when battery recycling takes place abroad, requiring the application of multiple licenses for each jurisdiction crossed. Also adding the transportation costs are the safety measures that electric vehicle batteries are subject to due to their classification as hazardous waste (Dominish et al., 2021; Haram et al., 2021; Lander et al., 2021).

Battery inspection. When an end-of-life electric vehicle battery arrives at a recycling center, information on its chemistry composition and other technical characteristics is often hard to access (Dominish et al., 2021). While hydrometallurgical recycling pathways are typically specialized for a given battery chemistry, direct recycling plants might further be specialized for only a specific battery design. Accessible information on the battery chemistry and design are thus a precondition to an efficient assignment of end-of-life batteries to the respective recycling plants.

Battery disassembly. Most battery recycling processes require the dismantling of battery packs. As the design of the lithium-ion battery packs, modules, and cells used in electric vehicles varies significantly with models and manufacturers, this step is mostly performed manually, which may correspond to health and safety risks for the workers. With a more standardized cell geometry and architecture, the manual disassembly could be replaced by automated processes, which would reduce these risks and further increase efficiency (Sommerville et al., 2021).

Battery recycling. Due to the growing scale and rapid technological development, there are a wide variety of approaches to the recycling of lithium-ion batteries, with ample opportunity for innovation. In broad terms, three main pathways can be distinguished: pyrometallurgical recycling, which includes also hydrometallurgical steps, conventional hydrometallurgical recycling, and direct recycling (Rajaeifar et al., 2021; Sommerville et al., 2021). The steps of these three main pathways can be combined, and mixed variations of the pathways are possible.

In a pyrometallurgical recycling pathway, such as is performed by Umicore in Belgium, lithium-ion battery cells or modules are directly put into a furnace and smelted at a high temperature. Other companies, such as Accurec in Germany, start with a vacuum pyrolysis and then process the cells physically, which may include shredding of the cells and separation of the cell materials by size, density, and magnetism (Sommerville et al., 2021). The pyrometallurgical process results in a mixed metal alloy, including cobalt, copper, nickel, and sometimes iron. In a subsequent hydrometallurgical step, these metals can be recovered through leaching the alloy in acids. Cobalt, copper, and nickel can be recovered at high rates of about 95% (Rajaeifar et al., 2021). Aluminum and lithium remain in the slag of the furnace and are usually not recovered, although research is ongoing for the recovery of lithium. The electrolyte, plastics, and graphite burn in the furnace and are therefore not recoverable. The pyrometallurgical step is energy intensive, which corresponds to comparatively high greenhouse gas emissions, generates toxic gases, and produces a hazardous slag that may need to be disposed of in special facilities. The environmental impact of the subsequent hydrometallurgical process mainly corresponds to the applied acids and requires a wastewater treatment to reduce the environmental risks (Mrozik et al., 2021).

A typical hydrometallurgical recycling pathway does not include a pyrometallurgical step (Sommerville et al., 2021). This recycling pathway is currently performed in small plants by Duesenfeld in Germany, or by Veolia and Recupyl in France. Industrial-scale hydrometallurgical recycling plants are located primarily in China (Mrozik et al., 2021). This recycling pathway is targeted at recovering all metals from the cathode powder, including cobalt, nickel, manganese, aluminum, and lithium, at a high purity level (Harper et al., 2019; Mrozik et al., 2021). The cells are first processed physically, which may include shredding and separation by size, density, and magnetism. The resulting "black mass"—the mix of anode and cathode powder containing graphite, lithium, and, depending on the cathode material, also cobalt, nickel, and manganese—is physically separated from the rest of the battery. In the subsequent hydrometallurgical step, the metals are recovered through acid leaching. High purity aluminum, cobalt, copper, lithium, manganese, and nickel can be recovered. In laboratory conditions, recovery rates of up to 99% are reported (Neumann et al., 2022; Velázquez-Martínez et al., 2019; Zhou et al., 2020). Electrolytes, plastics, and graphite are typically not recovered. With an optimization of the process, however, graphite recycling is also possible (Abdollahifar et al., 2022). The environmental drawbacks from the hydrometallurgical process are the same as described above for this process as part of the pyrometallurgical pathway (Mrozik et al., 2021).

A direct recycling pathway does not include pyrometallurgical or hydrometallurgical processes (Sommerville et al., 2021). Instead, after physical processing, the electrode coatings are recovered and can be reincorporated into a new battery cell. In principle, a direct recycling pathway can recover the cathode and anode material with a high recovery rate, and has the lowest environmental impact (Sommerville et al., 2021). Differing from the mature technologies of pyrometallurgical and hydrometallurgical recycling, however, the direct recycling pathway has only been demonstrated on a pilot scale, for example by Kyburz in Switzerland (CircuBAT, 2022).

Due to the growing demand for lithium-ion battery materials, a full assessment of the environmental impact of recycling lithium-ion batteries needs to consider that the recycled materials can partially replace the mining processing and transport of primary material in the production of new battery cells. Therefore, the recycling efficiency and quality of the recovered materials also determine the overall impact (Mrozik et al., 2021).

In terms of greenhouse gas emissions, as indicated by Mohr et al. (2020) and Yu et al. (2021), pyrometallurgical, hydrometallurgical, and direct recycling offer significant benefits over the use of primary battery materials. While the environmental benefit is highest for direct recycling, pyrometallurgical recycling corresponds to the lowest environmental benefit. The Argonne National Laboratory's GREET model (Argonne National Laboratory, 2022) indicates that the GHG emissions from the production of NMC111-based batteries could be reduced by 26% if as much as 80% of the used lithium, 95% of the cobalt, and 95% of the nickel would come from hydrometallurgical recycling. This compares to a 6% reduction in greenhouse gas emissions by using the same shares of recycled cobalt and nickel that are recovered through a pyrometallurgical pathway. In this pathway, lithium is typically not recovered. When considering the use of a direct recycling pathway that recovers 95% of the cathode material, the greenhouse gas emissions are reduced by as much as 50%. Recycling can reduce other environmental impacts of battery material mining and manufacturing, including but not limited to air pollutant emissions, water contamination, and land-use change. Yu et al. (2021) find similar greenhouse gas emission savings for the three pathways.

Hydrometallurgical and direct recycling pathways require recycling plants to specialize in recycling cells for a given battery chemistry. The continuous evolution in the mix of lithium-ion battery chemistries on the market might thus require regular adjustments of the respective recycling plants (Mrozik et al., 2021). Given the long usage period of batteries currently in the market, however, changes in the mix of battery chemistries from end-of-life electric vehicles are foreseeable for years ahead.

Table 3 summarizes the current opportunities and challenges of pyrometallurgical, hydrometallurgical, and direct recycling pathways.

Table 3. Summary of opportunities and challenges from pyrometallurgical, hydrometallurgical, and direct recycling pathways.

Recycling pathway	Opportunities	Challenges
Pyrometallurgical recycling	• Cobalt, copper, and nickel can be recovered • Mature technology; applied in industrial recycling plants • Flexible; suited for mixed feedstock of battery chemistries	• Aluminum and lithium are usually not recovered; graphite, electrolyte, and plastics cannot be recovered • Pyrometallurgical step: Comparatively high greenhouse gas emissions; production of toxic gases and air pollutants; hazardous solid waste • Hydrometallurgical step: Potential water contamination due to the use of acids; requires water treatment • High capital costs • Large-scale, centralized recycling plants, require long distance transport of batteries
Hydrometallurgical recycling	• Aluminum, cobalt, copper, lithium, manganese, and nickel can be recovered • High purity of recovered metals • Mature technology; applied in industrial recycling plants	• Graphite, electrolyte, and plastics are usually not recovered • Shredding processes: Potential particulate matter emissions and safety requirements • Hydrometallurgical step: Potential water contamination due to the use of acids; requires water treatment • High operating costs • Recycling plants optimized for specific battery chemistries
Direct recycling	• Cathode and anode powder, aluminum, copper, electrolyte, and plastics can be recovered • Cathode structure is retained, can be reused in new battery cell • Applicable to most if not all battery chemistries, including LFP	• Industrial maturity not proven; applied on laboratory and pilot scales • Safety requirements during manual dismantling process • Recycling plants specialize in specific battery chemistries

Sources: Bej et al. (2022); Doose et al. (2021); Beaudet et al. (2020); Gaines (2019); Harper (2019); Neumann et al. (2022)

Economic feasibility of battery recycling

Several studies investigate the economic feasibility of battery recycling. Lander et al. (2021) focuses on different markets including Belgium, China, the United Kingdom, the United States, and South Korea. The authors find that costs or profits of the recycling of batteries and selling the recycled materials range from -$21.43 to +$21.91 per kWh of recycled batteries, depending on the recycling pathway. The main factors that determine the profitability include whether the end-of-life batteries were recycled domestically or abroad, the chemical composition of the end-of-life batteries, and the costs of the recycling processes involved, such as for equipment, material, and labor. The study finds that net profitability of recycling is best achieved when the battery is recycled domestically, contains comparatively high amounts of nickel and cobalt, as in NMC- and NCA-based batteries, and has low disassembly costs. These findings align with Samarukha (2020), which finds that recycling is more profitable in cases where batteries contain a high content of cobalt and nickel. The study also identifies transportation costs as the main factor determining recycling profitability due to long transport distances. Another important factor is the battery pack disassembly process, which typically involves high labor costs.

Xiong et al. (2020) assessed the economic feasibility of hydrometallurgical recycling in China. The study finds that using the recycled material for battery production cost $20.81 per kg of battery on a cell level, which compares to $22.68 per kg for the case where raw materials were used instead. A key parameter that determines whether the use of recycled materials compares favorably to the use of raw material is the price that the recycler pays for the end-of-life battery. Here, Xiong et al. (2020) find that the recycling process remains profitable if end-of-life batteries cost no more than $2.87 per kg of battery.

CASE STUDY: KEY FACTORS TO THE ECONOMIC FEASIBILITY OF A HYDROMETALLURGICAL RECYCLING PLANT IN THE UNITED STATES

To further understand the key factors influencing the economic potential of recycling electric vehicle batteries, we performed a short illustrative analysis based on Argonne National Laboratory's EverBatt model, using default assumptions unless otherwise specified (Argonne National Laboratory, 2020). We consider the case of a hydrometallurgical battery recycling plant in the United States in 2040 that hypothetically processes a mix of LFP-, NCA-, NMC111-, NMC622-, and NMC811-based batteries from currently produced electric vehicles. This case study builds upon the global assessment of the availability of electric vehicle batteries for recycling in 2040 presented earlier in the paper. The plant is considered to have an annual capacity of 10,000 tonnes of black mass, derived from about 25,000 tonnes of battery packs. This capacity corresponds to approximately 81,500 electric vehicle battery packs with an average capacity of 50 kWh. This is a mid-size recycling plant; for reference, Li-Cycle operates plants ranging in capacity from 5,000 tonnes to 15,000 tonnes of batteries across North America as of 2022 and is building a plant with capacity to process 35,000 tonnes of black mass (Li-Cycle, 2022). We assume that batteries will be collected from across the United States, requiring average transport distances of 100 miles from collection to the dismantling site and 1,000 miles from the dismantling site to the recycling site.

For simplicity, we assume that lithium, nickel, manganese, and cobalt recycled from the batteries (using recovery rates of 80% for lithium and 95% for other minerals) is of suitable purity to sell at market rates. We also assume October 2022 commodity prices: $72/kg of lithium carbonate (S&P Global, 2022), $21/kg of nickel (London Metal Exchange, 2022), $3.12/kg of manganese (Jupiter Mines, 2022), and $52/kg of cobalt (London Metal Exchange, 2022). We note that mineral prices, particularly lithium, are currently elevated compared to the 5-year average and are highly volatile. The sale of additional metals such as copper is not considered here but could present an additional revenue stream.

Figure 7 presents the recycling costs and the revenues from recycled mineral sales for this scenario in 2022. These results are presented on a per 50-kWh battery pack basis. The largest source of revenue comes from selling nickel, valued at an average about $580 per pack, followed by cobalt and lithium (each about $280 per pack). Note that in the market average mix of battery chemistries, the nickel- and cobalt-rich cell chemistries, such as NMC622- and NCA-based batteries, contribute more to the average revenue than LFP-based batteries, of which only the value of recycled lithium is considered. The largest costs come from transport of the spent battery material to the plant. This is followed by the facilities costs, including the plant's depreciation (amortized over 10 years), interest, and maintenance. The labor costs, including 50 full-time staff in the recycling plant, is the third-greatest cost.

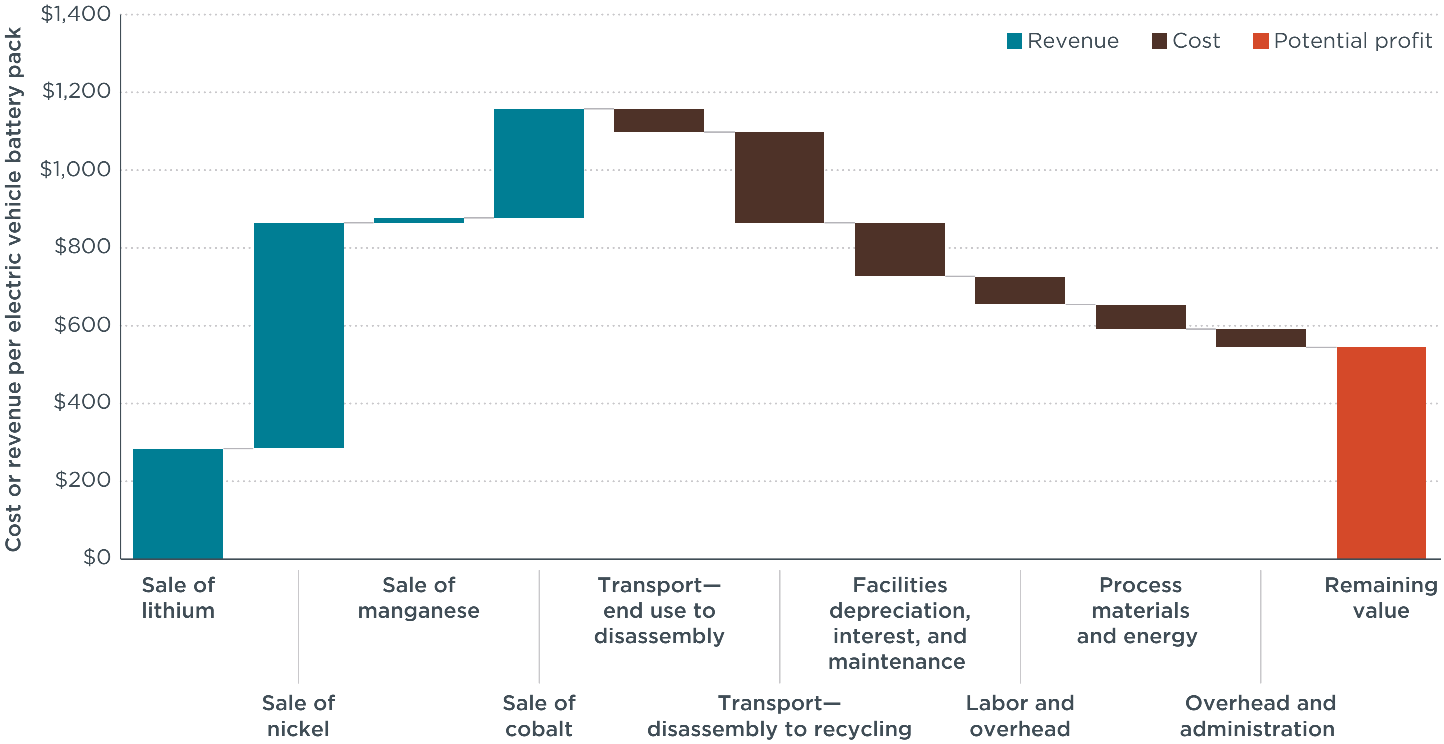

Figure 7. Revenue and costs for battery recycling in the United States in 2040 presented per 50-kWh battery pack.

This analysis suggests total annual revenue at this facility of $94 million and costs of $50 million, equating to revenue of $1,158 per pack and costs of $613 per pack. Under these conditions, the revenue significantly exceeds the costs, with a value of $545 remaining for every battery pack. Notably, the analysis did not include the costs to acquire the battery packs, nor did it include a profit margin for the recycling enterprise; the remaining value could include both these factors. Such analysis includes many uncertainties, particularly around the resale price of minerals, transport arrangements, and the efficiency of the plant. Nonetheless, this illustrative example suggests that recycling has the potential to be a profitable business model that can unlock additional value for electric vehicle owners while also creating jobs.

CURRENT POLICY APPROACHES TO SUPPORT BATTERY RECYCLING

Europe

The European Union has made battery recycling a high priority to reduce the environmental impact of batteries, ensure the long-term availability of materials, and support the domestic battery industry. Within its 2020 proposal for a new Battery Regulation, the European Commission included a comprehensive framework to promote battery collection and recycling, which includes targets for the recovery of key battery materials and the share of recycled content in new batteries (European Commission, 2020). After the European Parliament and the European Council proposed changes to this proposal, they reached a provisional agreement with the Commission in December 2022 (European Commission, 2022b).

Recovery rates. The key metric for battery recycling in the EU's upcoming Battery Regulation are element-specific recovery rates for the most critical raw materials. This policy is particularly important to ensure a high recovery of materials for which recycling is not necessarily profitable. For all collected lithium-ion batteries, the element-specific recovery targets are 50% of the lithium in a battery pack, as well as 90% each of cobalt, copper, and nickel starting in 2027 (European Commission, 2022b). From 2031, these targets will increase to 80% of lithium and 95% of cobalt, copper, and nickel. In addition to the element-specific recovery rates, 65% of all material (by weight) in a battery needs to be recovered from 2025, which increases to 70% from 2030 (European Commission, 2022b).

Share of recycled content. To further support a circular economy in battery production, recycling targets can be accompanied by targets for the use of recycled material during the production of new vehicle batteries. Here, the EU's upcoming Battery Regulation considers element-specific targets for key battery materials. From 2031, companies selling batteries in the EU would need to ensure that for all lithium-ion batteries with a capacity larger than 2 kWh, at least 16% of the cobalt, 6% of the lithium, and 6% of the nickel used in the battery cell are recycled material. From 2036, these proposed targets increase to 26% for cobalt, 12% for lithium, and 15% for nickel (European Commission, 2022b).

The United Kingdom (UK) has continued to harmonize many policies related to battery end of life and recycling with the European Union but is exploring other policy opportunities as well. In the Critical Mineral Strategy released in 2022, the UK aims to be a research and development leader on issues including mineral recovery and recycling of batteries (United Kingdom Department for Business, Energy & Industrial Strategy, 2022). The government is also supporting the growth of a domestic battery recycling ecosystem through the Automotive Transformation Fund and the National Interdisciplinary Circular Economy Research Programme. In addition, the Waste Batteries Regulations ban the disposal of electric vehicle batteries to landfill or incineration, and battery producers are obligated to take back electric vehicle batteries free of charge and treat them at approved facilities (United Kingdom Office for Low Emission Vehicles, 2021). The government is expected to consult on further regulations, including on collection and recovery rates, in the near term.

China

As the world's largest battery producer and electric vehicle market, China is working to jump-start battery recycling through a suite of policies and programs. The national government has created a structure for battery dismantling and recycling enterprises, which are regulated at the provincial level (Bej et al., 2022). Vehicle manufacturers are required to provide technical support to these enterprises and are responsible for selling batteries to a qualified handler for reuse or recycling. A unique code is attached to every battery produced in or imported into China for use in electric vehicles to allow for tracking and proper processing at the end of the battery's first life. If batteries are not properly entered into the management scheme or recycled properly, companies can be fined between ¥10,000 and ¥30,000 (US $1,480 and $4,430) per instance.

To qualify for a voluntary certification, recycling companies in China need to meet element-specific recovery rates of 98% for nickel, cobalt, and manganese, and 85% for lithium (Ministry of Industry and Information Technology, 2019). Differing from the recovery rates in the EU's upcoming Battery Regulation, these targets are not mandatory. The central government also sets standards limiting pollution from the recycling processes.

The central government began pilot projects for battery collection, reuse, and recycling in 2018 with programs in 17 cities and regions (Bej et al., 2022). In 2021, the government began a new round of 2-year pilot projects in 20 cities, in conjunction with automakers and recycling companies, to promote green battery supply chains and efficient tracking of batteries over the entire life cycle (China Automotive Green Dismantling System, 2021). Local governments have also provided support. For example, Shenzhen provides incentives for local battery recycling based on the battery capacity of new vehicles sold, and Jiangsu province has supported close to 1,000 electric vehicle battery recycling centers which are responsible for collection and initial processing.

North America

Among the three largest electric vehicle markets, the United States has been the least active in promoting battery recycling. At the federal level, action has primarily been limited to research and development funding and incentives, including 2021 legislation which made available $60 million for research on battery recycling, and $50 million for local governments and $15 million to retailers to fund battery recycling programs (U.S. Department of Energy, 2022). The U.S. Department of Energy operates the ReCell Center, a battery recycling research and development center with the goal of reducing costs and increasing purity from recycling processes. The new electric vehicle incentives provided by the Inflation Reduction Act of 2022 include criteria for battery material origin that would encourage the use of recycled materials, although these can also be satisfied by using virgin minerals from a select list of markets (U.S. Department of Energy, 2022).

State governments are making strides toward comprehensive frameworks for battery recycling and end of life, although few binding policies have taken effect. In 2019, California established a Lithium-Ion Car Battery Advisory Group, composed of automakers, dismantling companies, battery companies, state agencies, and non-profit and environmental justice groups, to guide the development of policies and regulation. The group proposed recommendations for clear pathways of responsibility of batteries at the end of life to ensure proper reuse and recycling, with the ultimate responsibility resting on the vehicle manufacturer if the vehicle is not acquired by a licensed dismantler (California Environmental Protection Agency, 2022). The report also recommends various supportive policies, including labeling requirements, incentives for establishing recycling facilities, updating waste transport regulations to reduce costs, and recycling workforce development programs. Other states are also working to adopt regulations, such as New Jersey, which is forming its own battery recycling taskforce to investigate, among other things, whether to implement extended producer responsibility (EPR) for electric vehicle batteries (New Jersey Legislature, 2022).

In Canada, policy on battery recycling is also at an early stage and is generally led at the provincial level. As noted previously, British Columbia committed to phasing in EPR for electric vehicle batteries by 2026 through its EPR Five Year Action Plan passed in 2021 (British Columbia Ministry of Environment and Climate Change Strategy, 2021); Québec has also proposed EPR for electric vehicle batteries but has not yet adopted specific regulations (Propulsion Québec, 2021). Several of the largest battery recycling plants in North America operate in Canada, including an Li-Cycle plant in Kingston, Ontario, which contracts with Volkswagen, Honda, and General Motors; Lithion Recycling's plant in Montreal, Québec, which also has a larger plant under construction; and a Retriev Technologies plant in Trail, British Columbia, which recycles Tesla batteries.

SUMMARY OF THE KEY POLICY LEVERS FOR ELECTRIC VEHICLE BATTERY REUSE AND RECYCLING

The analysis presented in this report indicates that battery reuse and recycling could become effective strategies to reduce raw material demand and enhance the environmental benefits of electric vehicles. Table 4 lists the key policy levers to scale up battery reuse and recycling practices and provides worldwide examples of policy development for each. Many of these policies are useful for promoting both battery reuse and recycling, while some are applicable to only one strategy. The list of examples is not exhaustive but is intended to provide examples of how such policies have been implemented in the early market.

Table 4. Overview of the policy levers to scale up battery reuse and recycling practices.

Area of intervention	Policy lever	Examples of existing policy developments
Battery traceability and collection	• Battery removability • Battery traceability mechanisms • Regulations that clearly define who is responsible for the battery when it reaches end of life	• **China:** The government released a set of policies that place the responsibility of collecting electric vehicle end-of-life batteries on manufacturers or importers (Ambrose and O'Dea, 2021). In 2018, a platform was created to trace batteries throughout their lifetime (Reuters, 2018).
Building domestic capacity for reuse and recycling	• Incentives and grants to support the development of domestic capacity for reuse and recycling	• **United States:** The Battery Materials Processing Grants makes more than $3 billion available to state and local governments, for-profit and non-profit entities, and national laboratories to support domestic capacity for the reuse and recycling of batteries through project demonstration and other uses (U.S. Department of Energy, 2022).
Battery information	• Regulations for the disclosure of battery information are needed to optimize the battery reuse and recycling process	• **European Union**: The European Commission proposed a labeling requirement for manufacturers to disclose information on batteries, such as the date of manufacture, chemistry, and hazardous substances. The Commission has developed language for the creation of a battery passport, which links to a digital platform where manufacturers would disclose battery data to facilitate third-party reuse or recycling (European Commission, 2020).
Battery standards	• Standards on battery durability • Standard on accuracy and reporting of the state-of-health metric • Standards on safety when handling end-of-life batteries	• **California:** The Advanced Clean Cars II regulations set battery durability standards require that batteries in electric vehicles of model year 2026 and later maintain at least 80% of their range for 10 years or 150,000 miles (California Air resources Board, 2022a). Furthermore, California proposes an accuracy standard for reporting batteries' state of health (California Air Resources Board, 2022b). • **United States and Canada:** the UL 1974 Standard for Evaluation for Repurposing Batteries sets general safety standards for sorting and grading used electric vehicle batteries and estimating their SOH (UL Standards, 2018).
Recycling mandates	• Element-specific mandates on proportion of material that need to be recovered • Element-specific mandates on recycled material to be used in new manufactured batteries	• **European Union**: the upcoming Battery Regulation will mandate element-specific recovery rates for battery recycling and element-specific shares of recycled material to be used in the production of new batteries (European Commission, 2022b).
Research and development	• Investments in research and development to optimize reuse and recycling processes	• **United Kingdom:** Through its Critical Mineral Strategy, the United Kingdom aims to become a scientific knowledge leader on battery material recovery and recycling. Different funding initiatives are being put in place to support a circular economy (United Kingdom Department for Business, Energy & Industrial Strategy, 2022).

CONCLUSIONS

This study provides a global overview of the techno-economic feasibility of battery reuse and recycling. Key findings from this study include the following:

More than 1 million electric vehicles batteries per year could reach end of life by 2030 globally, rising to about 14 million per year by 2040, making this a critical time to create a supportive policy environment for their reuse and recycling. Due to the natural time lag between new vehicle sales and their eventual disposal, there are currently only limited numbers of end-of-life electric vehicle batteries for reuse and recycling. When the volumes of end-of-life batteries increase, an efficient recycling system can largely reduce the demand for raw material for the production of new batteries. By 2050, recycled materials can reduce the combined annual demand in lithium, nickel, cobalt, and manganese by 28%. With a clear forecast of future volume, the coming years are critical for implementing battery tracing, collection, and processing protocols. While recycling can reduce the demand for raw minerals, such demand will continue to be significant, reaffirming the importance of sustainable supply chains and other policies to slow the demand for new vehicles (and therefore batteries) globally.

China and the European Union are leading in creating a framework to ensure that end-of-life batteries are handled responsibly. The world's two largest electric vehicle markets—China and the European Union—are also leaders in implementing battery policies. Both jurisdictions have set forth clear guidelines on the responsibilities and pathways for handling batteries following retirement from vehicle use. China has established a robust system for tracing information about every battery made or imported into the country. For recycling, China sets voluntary recovery targets for lithium, cobalt, nickel, and manganese, while the EU's upcoming Battery Regulation is expected to mandate recovery rates for lithium, cobalt, copper, and nickel. In the EU, minimum shares of recycled lithium, cobalt, copper, and nickel in new battery production will further help to ensure that these materials are recovered with a high purity and thereby prevent downcycling. Although policies are less advanced in North America, some U.S. states and Canadian provinces are developing battery responsibility policies and other measures.

To facilitate battery reuse and ensure an efficient recycling, this research indicates that governments could consider the following:

» **Incentivizing domestic capacity for battery reuse and recycling.** As of 2022, many jurisdictions do not have the domestic capacity for recycling end-of-life batteries, which means that the batteries have to be shipped long distances. In addition, the batteries are often classified as hazardous waste, and the associated safety precautions add to the transportation and logistics costs. Studies have shown that transportation costs could represent as much as 63% of the total cost of battery reuse or recycling. Developing domestic capacity to reuse and recycle batteries could therefore significantly reduce costs while stimulating local economies and reducing the dependency on international supply chains. To the extent possible, governments could develop incentive programs, create supportive tax and trade provisions, and develop public-private partnerships to support domestic capacity for reuse and recycling. Updating and standardizing regulations on the transport and handling of old electric vehicle batteries could also reduce costs and encourage growth.

» **Setting standards for durability, safety, and information accessibility to optimize reuse and recycling processes.** End-of-life electric vehicle batteries typically arrive at the reuse or recycling center with little information about the batteries' characteristics (e.g., chemistry composition), state of health, or operation history. Making this information more readily available can reduce costs associated with reuse or recycling by reducing costly state-of-health testing and allowing pre-sorting of batteries into more optimized pathways. Governments may require that battery manufacturers disclose information on batteries, like the battery passport initiatives in the EU. Governments could further standardize SOH metrics to help inform the best decisions for second-life applications. Moreover, mandatory battery durability requirements can incentivize the production of long-lasting batteries and thereby support second-life usage. Finally, defining safety standards can be crucial for reducing risks at recycling centers or during battery reuse.

» **Supporting research and development in lithium-ion battery recycling technologies to expand the range of materials that can be recovered.** Current industrial-scale battery recycling plants follow either a relatively GHG emission-intensive pyrometallurgical pathway, which also includes hydrometallurgical processes, or a less carbon intensive hydrometallurgical pathway without pyrometallurgical pretreatment. While both pathways allow the recovery of metals like cobalt, copper and nickel, the recovery of aluminum and lithium is typically only achieved in the hydrometallurgical pathway. Hydrometallurgical pathways may further allow recovery of graphite and plastics. A third recycling pathway, which has not yet been realized on a commercial level, is direct recycling. In principle, this pathway allows the direct recovery the cathode and anode materials. Governments could support ongoing research and development efforts on recycling processes to broaden the range of battery materials that can be recovered, to increase their recovery rate, and to reduce environmental impacts.

» **Consider introducing mandatory recovery rates and recycled content targets to ensure an efficient recycling of all key battery materials.** The cost competitiveness of recycling depends on the content of expensive materials that are contained in the end-of-life electric vehicle battery, such as cobalt, nickel, or lithium. Yet, as of 2022, facing unstable supply chains and trying to cut material costs, manufacturers are shifting towards chemistries with a lower cobalt and nickel content, or those that are cobalt- and nickel-free, such as lithium iron phosphate (LFP) batteries. This might challenge the overall profitability of recycling operations. Governments could consider mandatory element-specific recovery targets to ensure an efficient recycling of all key battery materials. Such targets further avoid a recovery only of those materials that are profitable. To further ensure a high purity of the recycled material, element-specific minimum shares of recycled materials in the production of new batteries could be introduced.

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