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Scaling up battery reuse and recycling: challenges and policy approach

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Executive Summary

This report provides an overview of the opportunities and challenges for reusing and recycling batteries from global light-duty and heavy-duty electric vehicle fleets. It estimates the potential of the global battery reuse and recycling markets up to 2050. Building on a review of the literature, it analyzes the technological and economic feasibility of battery reuse and recycling practices. Furthermore, the research discusses key policies that governments are introducing to support the development of a robust battery reuse and recycling industry. Finally, it formulates actionable recommendations for governments to scale up battery reuse and recycling. These recommendations include encouraging domestic reuse and recycling capacity, introducing standards for battery performance and safety, defining clear responsibilities regarding end-of-life battery collection, and supporting R&D to optimize lithium-ion battery reuse and recycling processes.

Keywords: materials, recycling, second-life battery, supply chain, regulation

1 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 future demand for battery reuse and recycling, this paper estimates the total volume of light-duty and heavy-duty electric vehicle batteries reaching end of life. This enables an estimate of the capacity 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 [1], 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 [2]. 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 described in this report.

- 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 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-based batteries (NMC811 and NMC955) are assumed to increase to a 46% market share by 2030, while the share of lithium iron phosphate (LFP)-based batteries is assumed to increase to 37% [3]. Consequently, the share of NMC532-, NMC622-, and lithium nickel cobalt aluminum oxide (NCA)-based batteries are expected to decrease. The market shares of chemistries are assumed to remain constant from 2030–2050.
- 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 and Parliament's provisional agreements for the upcoming Battery Regulation [4].

Based on the assumptions described above, Figure 1 below shows the potential of the global battery reuse market from the cumulative capacity of end-of-life electric vehicle batteries that could be reused in second applications up to 2050.

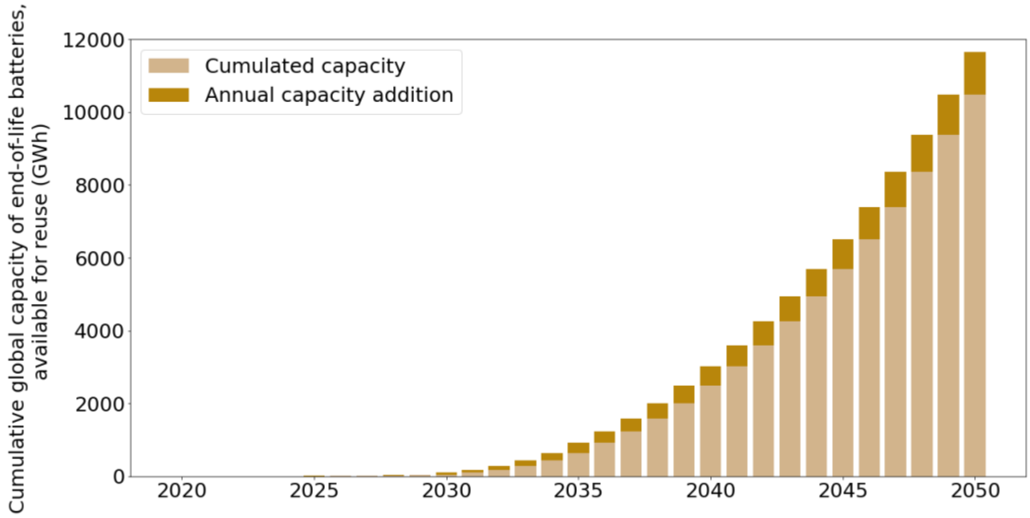

Figure 1: Projected cumulative global capacity of end-of-life electric vehicle batteries available for reuse applications.

When assuming that 50% of end-of-life batteries would be used in second-life applications for 10 years, the global storage capacity of the reused batteries 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 world's largest source of installed storage capacity, was about 8,500 GWh in 2020 and could be increased to 11,700 GWh by 2026 [5]. 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 for raw materials for newly manufactured batteries.

Recycling remains crucial to ensure that materials in electric vehicle end-of-life batteries are recovered and used to support mineral supply chains. Using the assumptions described above, Figure 2 shows how recycling can reduce the demand for raw materials needed to manufacture new electric vehicle batteries.

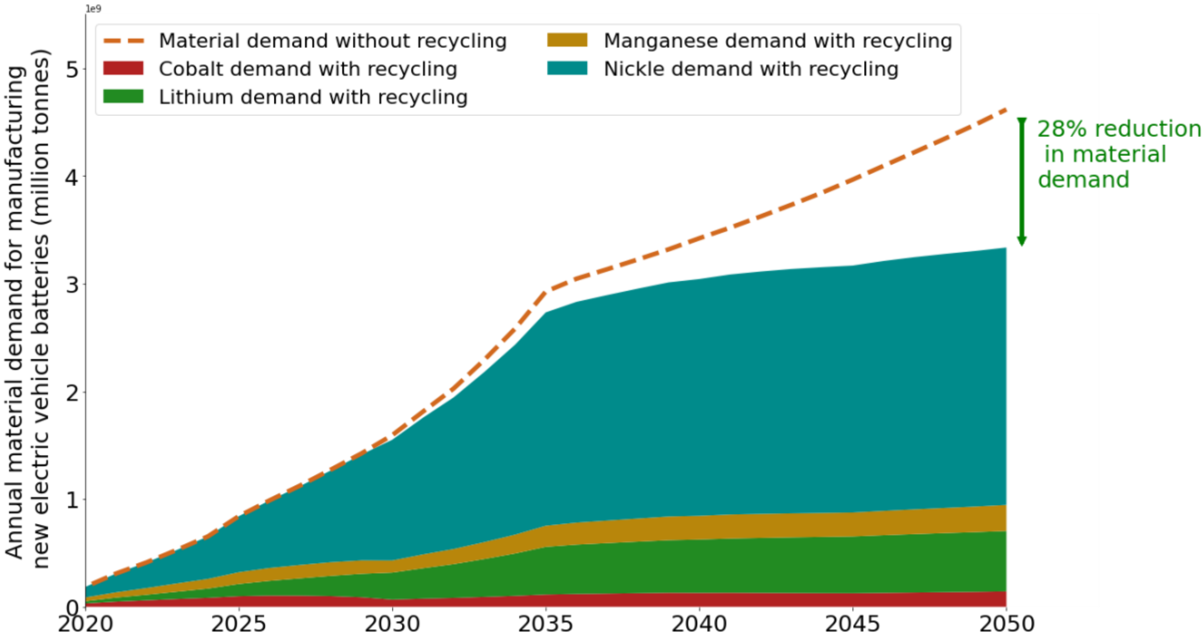

Figure 2: Annual battery material demand for global sales of light-duty and heavy-duty BEVs and PHEVs.

As shown in Figure 2, the annual demand for battery materials increases sharply from 2020 to 2035, as several of the leading electric vehicle markets move toward 100% of new light-duty vehicle sales being electric. However, given the delay between production and end-of-life, 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 for raw materials despite the ongoing increase in electric vehicle battery production.

2 Applications and challenges for battery reuse

2.1 Challenges and barriers to battery reuse

2.1.1 Technological 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 assessment and inspection; 4) sorting and regrouping; and 5) battery system reconfiguration.

Figure 3: Key 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 [6]. 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 [6] [7]. Furthermore, regulations that clearly define how to collect, handle, and store end-of-life electric vehicle batteries safely are often missing. 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 [6].

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 [8]. Several manufacturers have also announced their intentions for further advancing structurally integrated battery design in their upcoming models, which could make battery removal more difficult [9]. 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 [9].

<u>Battery transport</u>. 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, especially when crossing borders, the more expensive the process becomes[10]. 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 [11]. 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. Safety regulations at all levels typically classify lithium-ion batteries under Class 9 miscellaneous hazardous materials [6][12]. 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 subject to the Basel Convention, which controls the international movement of hazardous wastes [13].

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 an end-of-life battery, it becomes subject to hazardous waste regulations [6]. 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 [6].

<u>Battery inspection</u>. 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 [14][15]. 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 [14][15].

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, the manufacturer may even delete it 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 [14][15].

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 [14]. The testing typically requires fully charging and discharging the battery, a lengthy and labor-costly process [14][15]. 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 [14][16].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 also needs to 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 [14][16].

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 [14][17]. 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 [14].

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 [14]. 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 [14][18].

2.1.2 Economic feasibility of battery reuse

To date, limited research has compared 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 [19]. 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[20]. 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 [20][21].

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 [22]. For comparison, a new electric vehicle battery pack cost $198 per kWh on average in 2018 [21]. [23] 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 [23]. 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% [21]. 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 the 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 [7].

Beyond the selling price of second-life batteries when compared to new ones, the electricity costs or the remaining lifespan of second-life batteries are also critical parameters to consider when studying the economic feasibility of battery reuse. [24] 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 [25].

2.2 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 in secondary applications. California has adopted standards for electric vehicle battery durability requiring 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 [26]. 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 [26].

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 [27][28]

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 [29]. 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 [30]. 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 [31][32].

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 [33]. Similar extended producer responsibility (EPR) regulations are also being considered in several jurisdictions, including the European Union, California, British Columbia and Québec [43][35][36].

Regulations that support battery removability are also important, especially considering manufacturer intentions to move toward a more integrated battery design [9]. In China, the government has developed non-mandatory standards to facilitate electric vehicle battery dismantling [37].

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 standard safety requirements specific to end-of-life electric vehicle batteries and to streamline licensing requirements across regional jurisdictions [6].

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 [34].

3 Pathways and challenges for battery recycling

3.1. Challenges and barriers along the battery recycling process

3.1.1 Technical feasibility of battery recycling

Recycling reduces dependency on raw material imports while creating jobs and potentially reducing the cost of electric vehicles. While several battery recycling initiatives have started to emerge worldwide, much more 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.

Figure 4 summarizes the main steps in the recycling of lithium-ion batteries. As shown, up to the battery disassembly stage, the steps involved in recycling lithium-ion batteries are similar to those described in this report's battery reuse section (see Figure 3). So only the subsequent steps (battery disassembly and recycling) will be described in this section.

Figure 4: Main steps of the electric vehicle battery recycling process

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, manual disassembly could be replaced by automated processes, which would reduce these risks and further increase efficiency [38].

Battery recycling. In broad terms, three main pathways can be distinguished: pyrometallurgical recycling, which includes also hydrometallurgical steps, conventional hydrometallurgical recycling, and direct recycling [38][39]. 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. [38]. 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 by leaching the alloy in acids. Cobalt, copper, and nickel can be recovered at high rates of about 95% [39]. Aluminum and lithium remain in the furnace slag and are usually not recovered, although research is ongoing for lithium recovery. Therefore, the electrolyte, plastics, and graphite burn in the furnace and are not recoverable.

A typical hydrometallurgical recycling pathway does not include a pyrometallurgical step [38]. 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. Electrolytes, plastics, and graphite are typically not recovered but could be through process optimization [40].

A direct recycling pathway does not include pyrometallurgical or hydrometallurgical processes. 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 [38]. Unlike 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 [41].

3.1.2 Economic feasibility of battery recycling

Several studies have investigated the economic feasibility of battery recycling. [42] 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 equipment, material, and labor. The study finds that the 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.

Another study assessed the economic feasibility of hydrometallurgical recycling in China[43]. The study finds that using recycled material for battery production costs $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 materials is the price that the recycler pays for the end-of-life battery. Here, the analysis found that the recycling process remains profitable if end-of-life batteries cost no more than $2.87 per kg of battery[43].

3.2 Current policy approaches to support battery recycling

Europe

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[34]. After the European Parliament and the European Council proposed changes to this proposal, they reached a provisional agreement with the Commission in December 2022 [44].

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 [44]. 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, the proposal by the European Commission considers that 65% of all material (by weight) in a battery needs to be recovered from 2025, which will increase to 70% from 2030 [34].

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 European Commission’s proposal considers element-specific targets for key battery materials. From 2030, companies selling batteries in the EU will need to ensure that for all lithium-ion batteries with a capacity larger than 2 kWh, at least 12% of the cobalt, 4% of the lithium, and 4% of the nickel used in the battery cell are recycled material. From 2030, these proposed targets will increase to 20% for cobalt, 10% for lithium, and 12% for nickel [34].

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. 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 [45].

In 2018, the government launched 17 pilot projects on battery collection, reuse, and recycling (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 [46].

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[47]. 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 [47].

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[48]; Québec has also proposed EPR for electric vehicle batteries but has not yet adopted specific regulations [36]. Several of the largest battery recycling plants in North America operate in Canada, including a 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.

4 Conclusion

More than a million batteries could reach end-of-life in 2030, this increasing to 14 million in 2040 and 50 million in 2050, making this a critical time for governments to develop a supportive policy framework for battery reuse and recycling. To facilitate battery reuse and ensure an efficient recycling, this research indicates that governments could consider the following:

<u>Incentivizing domestic capacity for battery reuse and recycling.</u> 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. 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. Harmonizing licensing requirement for the transport and handling of end-of-life electric vehicle batteries could also reduce costs.

<u>Setting standards for durability, safety, and information accessibility</u> 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). Making this

information more readily available can reduce costs associated with reuse or recycling by reducing costly state-of-health testing and allowing the 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 European Union. 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.

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, manufacturers are shifting towards chemistries with a lower cobalt and nickel content. 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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