OECD TRADE AND ENVIRONMENT WORKING PAPERS

Trade Policies to Promote the Circular Economy: A Case Study of Lithium-Ion Batteries

Evdokia Moïsé and Stela Rubínová

Affordable and sustainable Lithium-ion batteries are key to the development of electric vehicles markets and to the green energy transition. Circular economy solutions for end-of-life batteries can help address primary inputs disruptions, while reducing environmental costs associated with the mining of these inputs or with battery production. Circular value chains would also help address waste and disposal problems as Li-ion batteries reach end of life. These chains are in their infancy, as complex battery designs, material chemistries and insufficient waste stocks hamper their viability, but the projected growth should support profitability. International trade in Li-ion batteries waste will remain essential in markets where domestic waste streams are insufficient to achieve the scale necessary for economically viable recycling, or where inadequate infrastructure imposes reliance on recycling capacities abroad. Promoting circular value chains for Li-ion batteries would require greater clarity on the status of these batteries as waste, consistency of transport and storage safety regulations, trade facilitation and harmonisation of standards for battery design, and regulatory targets for waste collection and recycling rates, coupled with stewardship and take-back schemes.

Key words: Electric vehicles, hazardous waste, critical raw materials, green transition

JEL codes: F18, F53, F64, K32, O34, Q38, Q53, Q56

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Executive Summary

The deployment of electric vehicles (EV) can significantly contribute to the global clean energy transition. Lithium-ion batteries (LIB) are a key component of EVs, accounting for up to 40% of their cost. The affordability and accessibility of LIB are thus central factors in EV market development. The concentrated supply of, and prevalence of export restrictions on, primary resource input into LIB make the EV value chain vulnerable to disruptions and price volatility. Recycling LIB can help address these vulnerabilities, while reducing environmental costs associated with the mining of these inputs, as well as the resource intensity and emissions associated with battery production. Recycling would also help address waste and disposal problems, as increasing numbers of LIB reach end of life (EoL). The transition to circular value chain for LIB will thus be critical in supporting the expansion of EV markets.

Circular economy (CE) solutions for EoL batteries include reusing discarded batteries still in good condition and fulfilling their original function; repurposing them to a different function, such as stationary energy storage; and recycling them to recover component materials. The technical and regulatory challenges of collection, transportation, sorting, and dismantling are the same for all types of CE solutions. Additionally, these options are not mutually exclusive: it is both technically possible and economically viable to re-use or repurpose LIBs for EV before recycling them. LIB can be re-used in less energy-intensive applications such as energy storage, back-up power and grid management when their energetic efficiency is too low for use in EVs. LIBs for reuse or repurposing currently retain a much higher value than those sent for recycling, although this is expected to change as the cost of new batteries declines. More mature recycling chains will also need to be developed for batteries at the end of their second life, especially since, at full development of the EV market, the quantity of EoL-LIBs is expected to exceed demand for second-use.

The LIB recycling market is still in its infancy. The complexity of battery design, material chemistries and current lack of sufficient waste stock to supply the LIB recycling industry all hamper its economic viability. But the projected growth should enable sufficient economies of scale to ensure profitability. Innovation and research in the sector is also progressing rapidly, and several established LIB producers are already integrating battery recyclers into their supply chain.

Current global recycling capacity is estimated to greatly exceed the existing supply of waste LIB. To date, this overcapacity has been driven by the People's Republic of China (hereafter "China"), where LIB recycling has been supported by government policies, while other LIB recycling markets are as yet relatively underdeveloped. However, foreign direct investment and new government incentives are expected to gradually expand recycling capacity in Europe and North America, such that the market will become much less concentrated by 2025 and China's share is predicted to drop to around 50%.

At present, international trade in LIB waste remains essential for LIB recycling and is likely to remain so in many markets, as domestic LIB waste streams will often be insufficient to achieve the scale necessary for economic viability. Furthermore, lack of the necessary infrastructure in smaller, developing and emerging economies where many LIBs will come to EoL, will likely see them relying on recycling capacities in other markets.

A number of national and international regulatory requirements apply to the cross-border movement of EoL-LIB, along with a range of policies to promote reuse, repurposing, remanufacturing and recycling. These measures can significantly promote, or hinder, circular economy solutions. A number of actions could promote circular value chains for LIBs, in particular:

- Clarity on the status of EoL-LIB as a waste would result in smoother, less onerous circular value chains, while preserving the efficiency of necessary health and safety controls;
- Consistency of transport and storage safety regulations would remove disincentives for cross-border LIB circular value chains and facilitate the traceability of consignments;

- Trade facilitation approaches, including wider use of pre-consent for multiple shipments to specific facilities, risk assessment of shipments and the gradual digitalization of prior informed consent (PIC) procedures would considerably reduce sunk costs in reverse value chains for LIBs;
- Harmonisation of standards for LIB design would promote expansion of the pool of qualified service providers for used LIBs, support second life solutions and facilitate disassembly and module exchange, but care must be taken to prevent restrictions on innovation which would hinder further improvements. Certification of second-life LIB in relation to performance and safety can help promote market development and consumer trust;
- Regulatory targets for waste collection and recycling rate, coupled with well-functioning stewardship and take-back schemes operated jointly with the private sector could provide incentives for more efficient circular supply chains.

1. Introduction

The deployment of electric vehicles (EV) has the ability to significantly contribute to the global clean energy transition. In the last five years, the global stock of EV has grown at an average annual rate of 52% to reach around 1% of global car stocks and 4.6% of new car sales (International Energy Agency, 2021[1]). In 2020, Europe became the leading market for EV with new registrations doubling to 1.4 million (a total sales share of 10%). China followed with 1.2 million registrations (5.7% sales share), and the United States came third at 295 000 (2% sales share) (International Energy Agency, 2021[1]). While COVID-19 brought some uncertainty to the electric vehicle market with a decline during the first quarter of 2020,[1] a boom in public investment from COVID-stimulus packages[2] spurred further growth. EV sales reached a record high in 2021, with sales nearly doubling to 6.6 million compared to 2020 (a sales share of nearly 9%), bringing the total number of EV on the road to 16.5 million. By December 2022, global EV sales for 2022 are on target to exceed 10 million units and over 15% of global sales (IEA, 2022[2]).

The transition to circular value chain for LIB will be critical in supporting the expansion of EV markets

Lithium-ion batteries (LIB) are a key cost component of electric vehicles, accounting for up to 40% of their costs (Adrian et al., 2021[3]). The affordability and accessibility of LIB are thus central factors in EV market development. The predicted massive expansion of electric vehicle production will result in a correspondingly large increase in demand for primary materials needed for LIB. Currently, these materials include lithium, nickel, cobalt and manganese, of which cobalt and lithium are considered relatively rare. Supply of these materials is also highly concentrated, the most notable example being cobalt, of which the Democratic Republic of Congo (DRC) holds 50% of global reserves and accounts for 68% of global production (United States Geological Survey, 2021[4]).[3]

The concentrated supply of primary resource inputs for LIB makes the electric vehicle value chain vulnerable to disruptions and price volatility. Moreover, restrictions on exports of raw materials are prevalent in several commodity markets that are crucial for LIB production. According to the latest OECD data and the US Geological Survey, 79% of global cobalt supply was produced in countries with a restriction on cobalt exports in 2020. This share is also correspondingly high for global manganese (64%) and nickel (59%) production.

Recycling LIB can help reduce dependence on virgin materials and thus risks associated with price volatility and security of supply (Harper et al., 2019[5]). Recycling also offers an opportunity to reduce the environmental and social costs associated with mining of such materials, as well as the amount of raw material that would have to be extracted and produced to meet projected future increases in demand (Harper et al., 2019[5]). Market projections suggest that secondary material from battery recycling could meet at least 28% of new battery material demand by 2040 (Xu et al., 2020[6]).[4]

[1] In a stark contrast with the decline in overall car sales of 16% due to the COVID-19 pandemic in 2020, EV sales were up 40% (International Energy Agency, 2021[1]).

[2] EVs were targeted in a number of economic recovery plans; for instance Germany committed USD 2.8 billion to EV charging infrastructure and announced new legislation that will oblige all fuel stations to have an EV charging point, in order to address one of the major consumer concerns slowing the progress of the EV market. China committed an additional USD 378 million to supporting EV production.

[3] Nickel mining is concentrated in Indonesia, the Philippines and Russia; lithium mining in Chile, Australia, Argentina and China and manganese mining is predominantly in South Africa, the United States and Gabon.

[4] Depending on their chemical composition, battery recycling is projected to cover the following shares of material demand for new batteries: 28% to 50% of lithium, 36% to 71% of cobalt and 29% to 57% of nickel. These projections are based on a “Stated Policies” scenario formulated by the International Energy Agency that incorporates existing government policies and assumes that there is no reuse of batteries, which would diminish the availability of secondary materials within the specified time horizon (2040).

… and to supporting environmental sustainability objectives

Electric vehicles emit zero direct emissions. Their production, however, does not. Concerns over the resource intensity and emissions associated with the production of EVs have put in question their contribution to achieving global environmental goals. While existing independent studies estimate that, over their total lifecycle, EVs cause less environmental damage than vehicles using internal combustion engines, there is considerable scope for improvement. Emissions associated with electric car production could decrease by 14% to 23% by 2040 if their crucial component – LIBs – were to be recycled and the resulting secondary raw materials used in new battery production.[5]

The rapid growth in demand and production of lithium-ion batteries will result in waste and disposal problems as these batteries reach end of life. Currently, most end-of-life (EoL) LIB are linked to consumer electronics, mainly going to landfills – where 70% of hazardous waste already comes from e-waste (Lohani, 2020[7]). By 2030, it is estimated that more than half of EoL LIB will come from electric vehicles, resulting in 1.6 million tons of total LIB waste (Circular Energy Storage, 2021[8]). Circular economy principles will be critical in helping to manage these volumes of LIB waste.

2. Circular economy solutions for lithium-ion batteries

Circular economy solutions for EoL batteries include reusing, repurposing, and recycling. In this context, reuse means the utilisation by another consumer of a discarded product which is still in good condition and fulfils its original function, such as reusing EV LIB for EV upgrades or conversion of combustion engine vehicles to EVs. Repurposing means using the discarded product or parts thereof in a different function, such as stationary energy storage. Recycling means processing materials from the discarded product to obtain the same or lower quality. Reuse and repurposing contribute to slowing material flows by keeping products in use for a longer period of time, while recycling helps create or close material loops by substituting secondary or recuperated materials for their virgin equivalents (de Sa and Korinek, 2021[9]).

When batteries reach their end of life,[6] the circular economy process starts with (1) collection and transport to facilities where (2) they are sorted. These first two steps exist regardless of whether the objective is recycling, reusing or repurposing. Sorting of LIB is currently a difficult process due to the lack of design standardization and multiplicity of material chemistries.

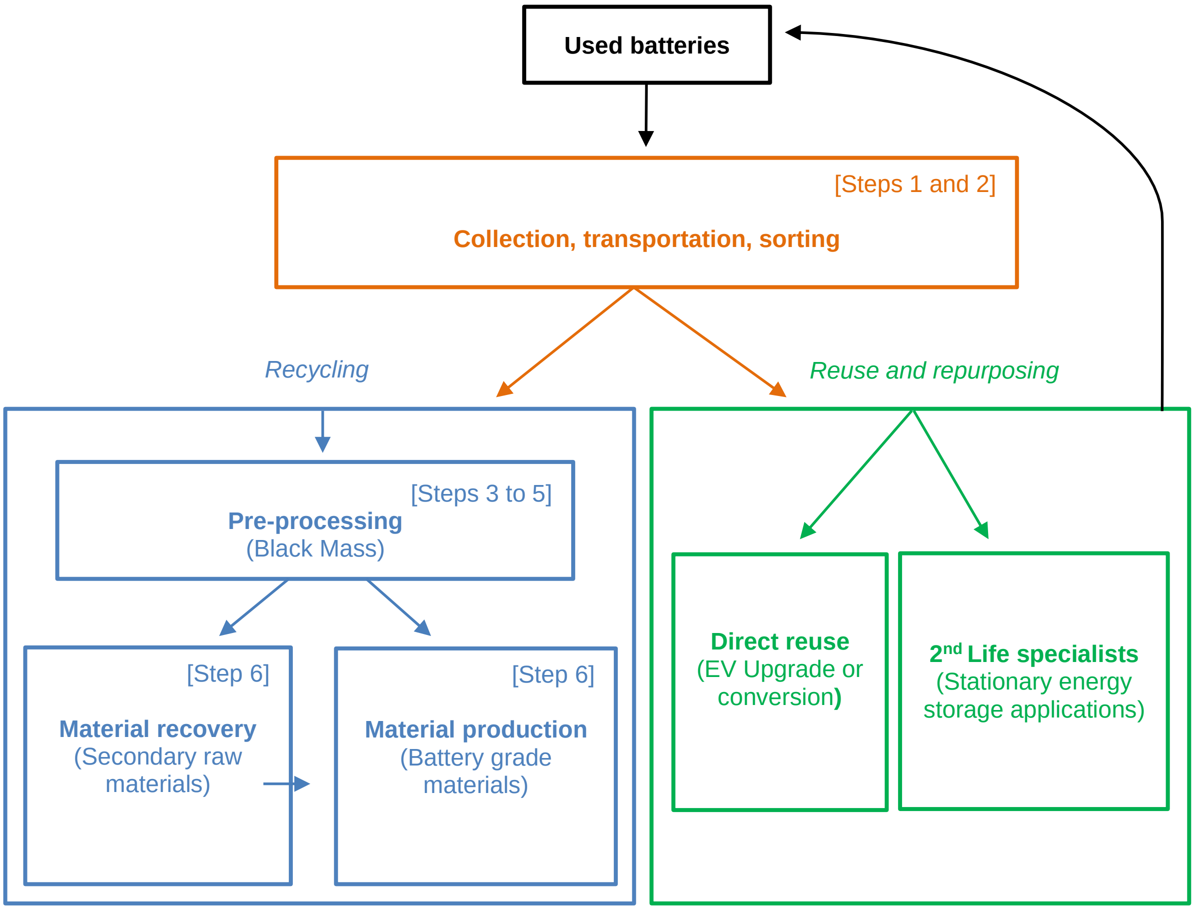
For recycling, the next step is pre-processing, which involves (3) discharging and dismantling, (4) the removal of combustible material to clean the cell and (5) processes such as crushing, solvent removal and mechanical separation, the output of which is aluminium, copper and a powder ("black mass") containing valuable cathode and anode materials. The process of discharging and dismantling requires trained operators and significant manual labour, although the development of robotic disassembly lines is advancing rapidly.

Finally, the highest value stage of the recycling process involves (6) material extraction and refining that allows for the recovery of raw materials such as cobalt, lithium, manganese and nickel which can then flow back to battery cell makers. The most common material extraction processes (pyrometallurgy or hydrometallurgy) require large capital investments and thus scale.

[5] Calculation based on an assumption that recycled materials can meet at least 28% of new battery material demand (Xu et al., 2020[6]), and that replacing 30% of primary material with recycled material can save 15% to 25% of EV production emissions (McKinsey, 2021[40]).

[6]" End-of-life" corresponds to the end of a battery's usefulness or lifespan (typically between 3 to 12 years depending on use), when it no longer operates at sufficient capacity. Capacity "sufficiency" entirely depends on the battery use, with EVs requiring a higher energetic efficiency of minimum 70% to 80% (Kelleher Environmental, 2019[14])

Figure 1. The recycling and reuse process for LIB



2.1. Closed-loop recycling

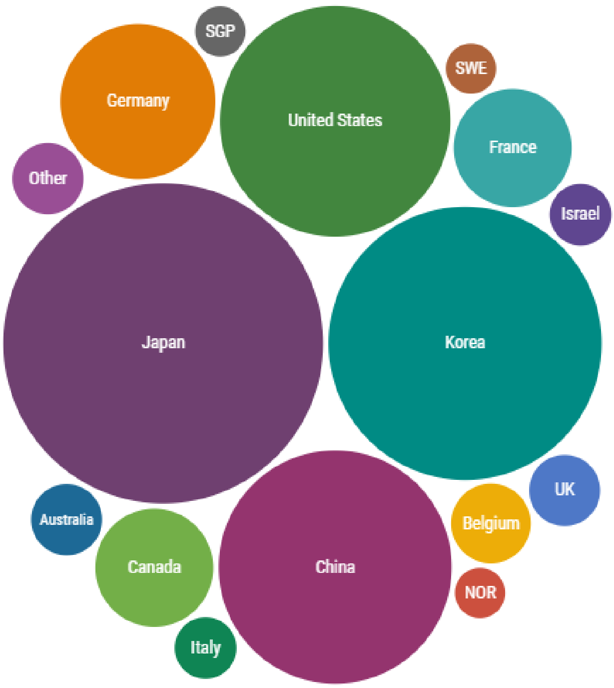
There are divergent views as to the economic viability of LIB recycling: for some, it is not economically attractive because of the complexity of the battery design, material chemistries and current lack of sufficient waste stock to supply the LIB recycling industry (Crompton, 2016[10]), thus pointing to the importance of ensuring efficient collection mechanisms to promote economies of scale. However, other analysts stress that the recent EV boom and projected growth makes now LIB recycling profitable and convenient (Pagliaro and Meneguzzo, 2019[11]).

Many recycling applications remain at the laboratory stage and have not yet been operationalised due to insufficient stock for recycling. Most LIB waste is still composed of small batteries from consumer electronics because batteries from the first generation electric vehicles have not yet reached the recycling market in significant quantity. This has meant that until now only a handful of companies have been able to generate sufficient revenues from EV LIB recycling (Mossali et al., 2020[12]). That said, innovation is rapidly evolving as demonstrated by the growing number of patents linked to LIB recycling filed in recent years, as well as the presence of various start-ups, and joint ventures between established original equipment manufacturers (OEM) and recyclers.[7] These trends show that EV-LIB recycling has significant innovation and upscaling potential that is attracting large players.

[7] For example, in the United States, the ReCell Center is focused on cost-effective and profitable LIB recycling processes through a collaboration between academia and national laboratories (DOE, 2019[38]) (ReCell, 2020[37]). There are also numerous recent examples of joint ventures such as that between Nissan and Sumitomo (named 4R Energy), NorthVolt and Norsk Hydro, Neometals and SMS Group (named Primobius), SungEel and Metallica

There were around 40 worldwide patent applications filed each year between 2017 and 2020 linked to LIB recycling. Japan, the United States, China and Korea dominate the innovation space, followed by Germany, Canada, Belgium and France (Figure 2). Globally, most patent applications are filed by established producers of LIBs (CATL, LG Chem, SK Innovation, Zhongke) and of LIB materials (Basf, Umicore, JX Nippon Mining & Metal, Sumitomo Metal Mining).[8] Recycling companies are driving innovation, notably in North America (for example, Li-Cycle, Li Industries, Urban Mining Company). Overall, the business sector accounts for most LIB recycling innovation but research institutions also play an important role, especially in China, France and the United States (Figure 3). Innovation in most countries primarily focuses on the most profitable stage of battery recycling, which is material recovery and production. Only China, the United States and Japan have a considerable number of inventions that focus on the pre-processing stage of battery recycling, such as the sorting, discharging and shredding of spent batteries (Figure 4).

Figure 2. Innovation in LIB recycling by country, 2017-2020

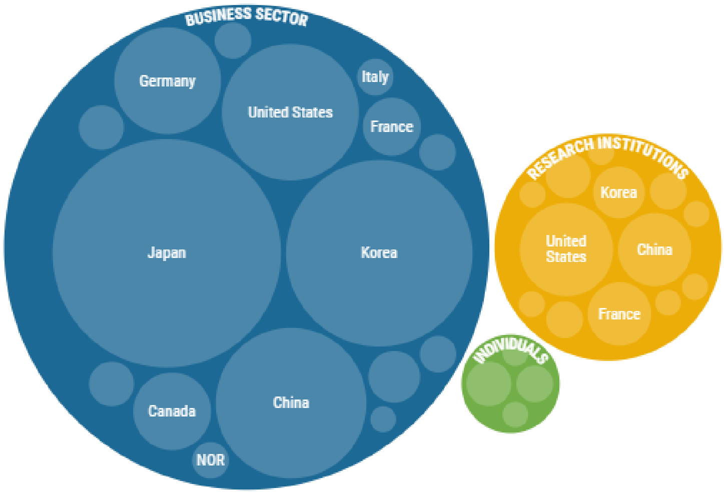


Note: The size of the circles corresponds to the number of Patent Cooperation Treaty (PCT) patent applications with priority date between 2017 and 2020 related to LIB recycling, according to the nationality of the applicant. “Other” include countries with one patent application. These countries are Colombia, Finland, India, and Poland. Singapore is labelled SGP, Norway NOR and Sweden SWE.
Source: OECD calculations based on Google Patents.

Commodities Corp. (named SMCC Recycling), and Suzuki and Toshiba and Denso (named Automotive Electronics Power).

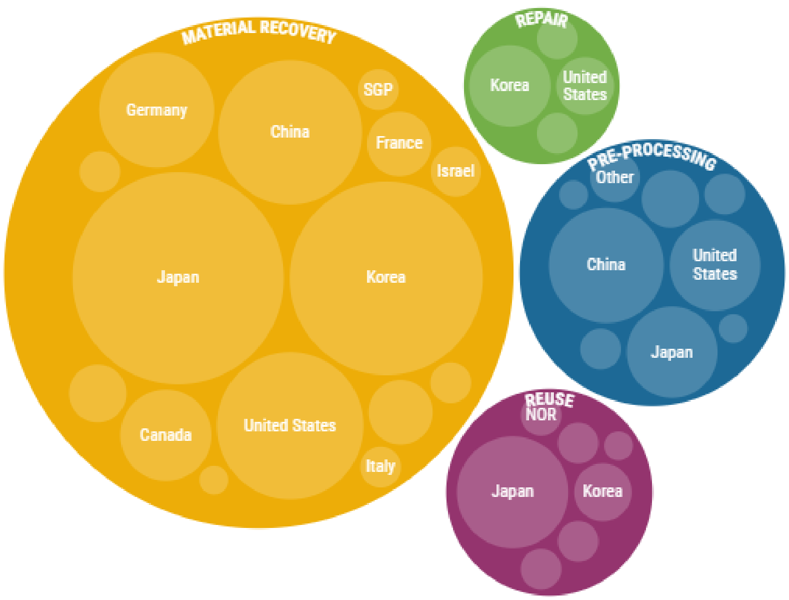
[8] See Table A.A.1 in Annex A for the list of patent applicants with at least two worldwide applications related to LIB recycling.

Figure 3. Innovation in LIB recycling by applicant type, 2017-2020



Note: The size of the circles corresponds to the number of Patent Cooperation Treaty (PCT) patent applications with priority date between 2017 and 2020 related to LIB recycling.
Source: OECD calculations based on Google Patents.

Figure 4. Innovation in LIB recycling by recycling stage, 2017-2020



Note: The size of the circles corresponds to the number of Patent Cooperation Treaty (PCT) patent applications with priority date between 2017 and 2020 related to LIB recycling. “Repair” includes patents related to repair, regeneration and remanufacturing of LIB. “Reuse” includes predominantly patents related to diagnosing the state and health of used LIBs.
Source: OECD calculations based on Google Patents.

The plans announced by recycling companies also suggest that scale is necessary, especially in the material recovery stage of the process. For instance, a large Canadian recycler (Li-Cycle) plans to build spokes around North America to collect used LIB and pulverize them into black mass (steps 1 to 5 described above). This powder will then be transported to large hubs for reprocessing into secondary raw material for battery production (step 6). This process avoids the costs of transporting large and heavy battery packs over long distances while generating sufficient scale for profitable material extraction.

2.2. Reuse and repurposing

It is both technically possible and economically viable to re-use or repurpose EV-LIBs before recycling them (World Economic Forum, 2019[13]). Batteries for EVs require a higher energy density by both mass and volume than LIBs for some other uses and are generally expected to be discarded when their energetic capacity lowers to around 70% to 80% (Kelleher Environmental, 2019[14]). We do not know if that expectation will hold?[9] but prospectively after that they can be re-used in less energy density-intensive applications such as energy storage, back-up power and grid management (Agarwal and Rosina, 2020[15]) (Kelleher Environmental, 2019[14]). The value of batteries that go into various reuse markets is much higher than batteries sent for recycling, although the dynamics of the reuse market are expected to change as the cost of new EV batteries declines. Requirements for second-life uses will vary depending on the specific use and it is estimated that, after being used in EVs, batteries could serve up to 30 additional years in fast EV charging stations, about 12 years for home energy storage, or between 6 and 12 years for grid energy storage if chemical reactions do not lead to other aging effects (Kelleher Environmental, 2019[14]). As a result, automotive companies are not only looking at recycling, but also at integrating second-life applications for energy storage.[10] Notable examples of automotive company endeavours in re-use and recycling include BMW and EVgo, Hyundai and Warsila, and Renault and Seine Alliance (Agarwal and Rosina, 2020[15]).[11]

While reuse and repurposing delays the date of recycling, it does not remove the need to develop more mature recycling chains for batteries that have reached the end of their second life, or that cannot be fed into other applications for reuse. This is particularly the case given that, at full development of the EV market, EoL LIBs are expected to exceed second-use demand. At the same time, since the first stages of reuse and recycle – i.e. collection, transportation and sorting– are the same for all batteries, whether for recycling, reuse or repurposing, it is already pressing to address potential technical and regulatory challenges. To prepare for the upscaling that will happen over the next 5 to 10 years, a robust LIB recycling infrastructure and framework is needed (Hill et al., 2019[16]).

[9] There is limited field data to support the expectation that EV packs will be discarded when the capacity lowers to 70-80%. It is an industry convention that cells are EoL around those ranges, but so long as the vehicles continue to meet use requirements, they could remain in service.

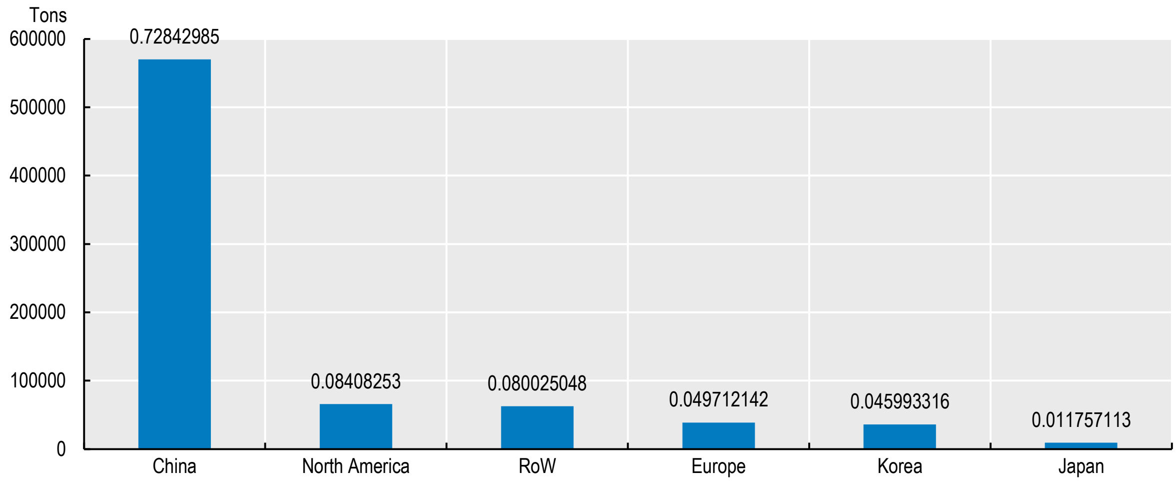
[10] Grid energy storage is a key factor in increasing the proportion of renewable energy sources in the energy mix. One of the major difficulties facing the power grid is that any discrepancy between supply and demand triggers disturbances that can compromise the stability of the frequency of the domestic network. This difficulty increases with the incorporation of various energy sources with sporadic production capacities, like wind or solar power. Stationary energy battery storage acts as a buffer that makes it possible to regulate and stabilise the network by charging the batteries when demand is low, then reinjecting the energy contained in these batteries back into the network as soon as demand is high. For instance, 77% of electrical power storage systems in the United States that operate to stabilize the grid rely on LIBs (Chen et al., 2020[39])

[11] For instance, in 2018 Renault announced a stationary battery storage project spanning several sites in Europe to store at least 60MWh (the storage capacity of around 2 000 electric car batteries and equivalent to a reserve sufficient to cover the electricity usage of more than 5 000 households). The device uses second-life batteries, as well as new batteries, stored in this manner to be used as replacements in the future for after-sales services. The project started with a Renault factory in northern France with 4.7 MWh storage while a second storage opened in November 2020 in a decommissioned coal-fired power plant in Germany, adding further 2.9MWh.

3. The role of international trade in scaling up circular economy solutions

Global LIB recycling capacity in 2020, both in terms of pre-processing and material recovery, was estimated at 843 000 tons, which greatly exceeded the amount of EoL LIB available for recycling (Circular Energy Storage, 2021[8]). However, this global figure hides an enormous disparity between China and the rest of the world. Currently, most recycling players are located in China, with the advantage of reliable supply (a large market for LIB that need recycling) and demand (a large battery market for final consumption), in addition to financial support from the state (Agarwal and Rosina, 2020[15]). China's mix of policy and market incentives has since 2016 created a large recycling spare capacity, whereby China accounts for 73% of global recycling capacity while having only 45% of LIBs available for recycling from domestic sources (Circular Energy Storage, 2021[8]).

Figure 5. The geography of LIB recycling in 2020

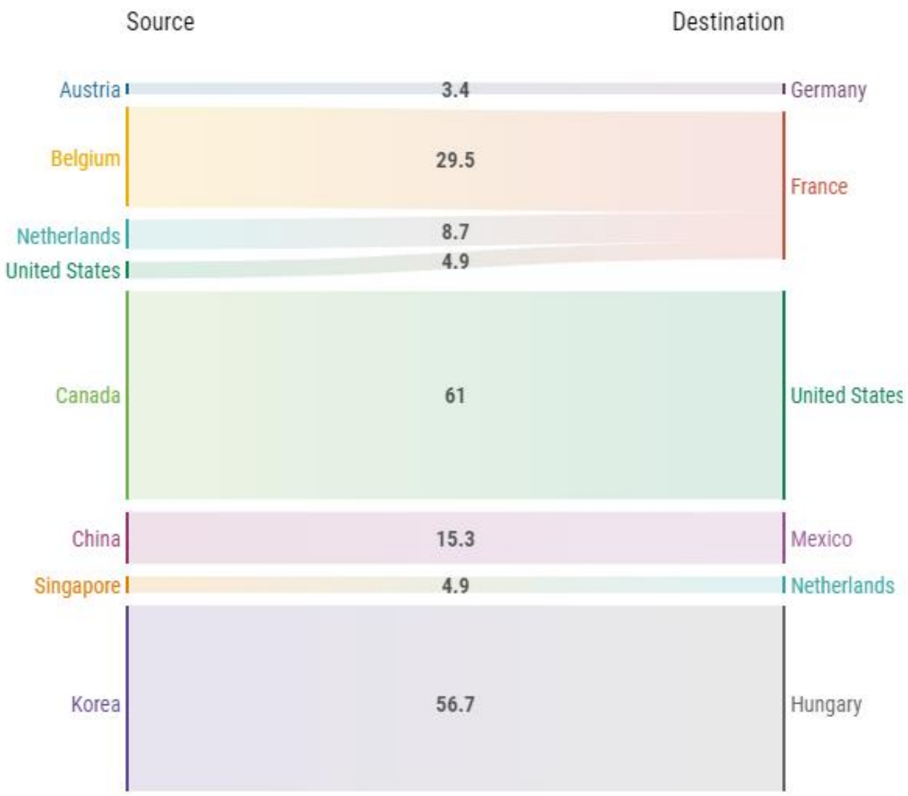


Note: The figure shows regions' shares of global recycling capacity. Rest of the World (RoW) comprises Australia, India, Indonesia, Malaysia, Mexico, the Philippines and Singapore.
Source: Circular Energy Storage Online.

As battery production capacity expands outside China, more recycling capacity is also being built elsewhere, often driven by foreign direct investment. In 2021, several major existing players expanded their investment in Europe and North America. South Korean SungEel more than doubled its investment from 2019 in Hungary, Canadian Li-Cycle further invested in recycling capacity in the United States, and Singaporean TES-Amm, which already operates a recycling plant in France, expanded its investment in Europe by establishing recycling capacity in the Netherlands (Figure 5).[12] In addition, JX Nippon Mining & Metals, the largest company in Japan, has established a new base in Germany to promote the recycling of used LIB for electric vehicles, and Canadian Li-Cycle has formed a joint venture with the Norwegian companies Morrow Batteries and Eco Stor to construct a new LIB recycling facility in Norway. As a result of these investments, global recycling capacity will become much less concentrated by 2025 with China's share predicted to drop to around 50% (Circular Energy Storage, 2021[8]).

[12] Source: fDi Markets.

Figure 6. Foreign direct investment in LIB recycling

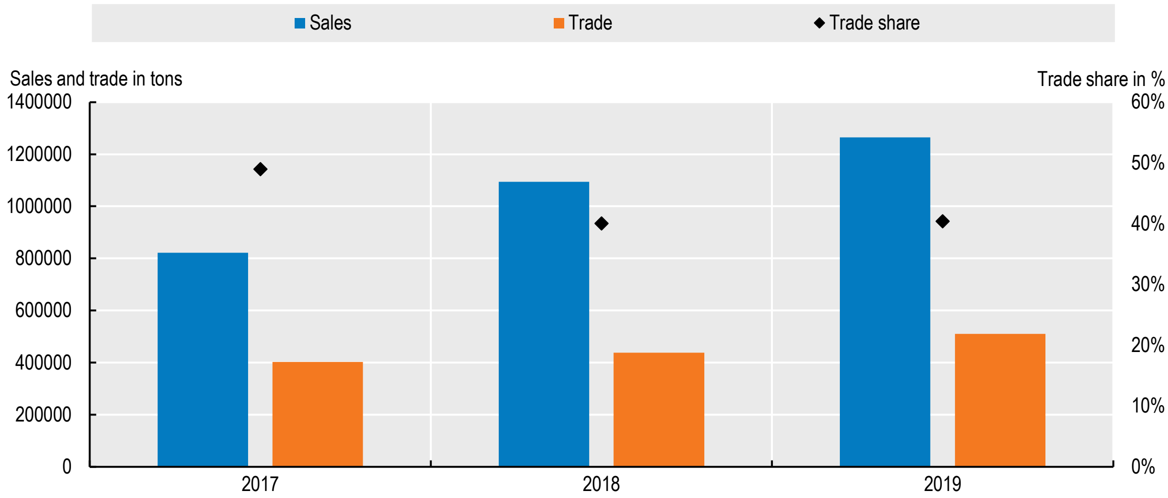


Note: Data coverage from 2017 to 2021, in USD million.
Source: fDi Markets, a service from The Financial Times Limited 2022. All Rights Reserved.

3.1. Trade in lithium-ion batteries

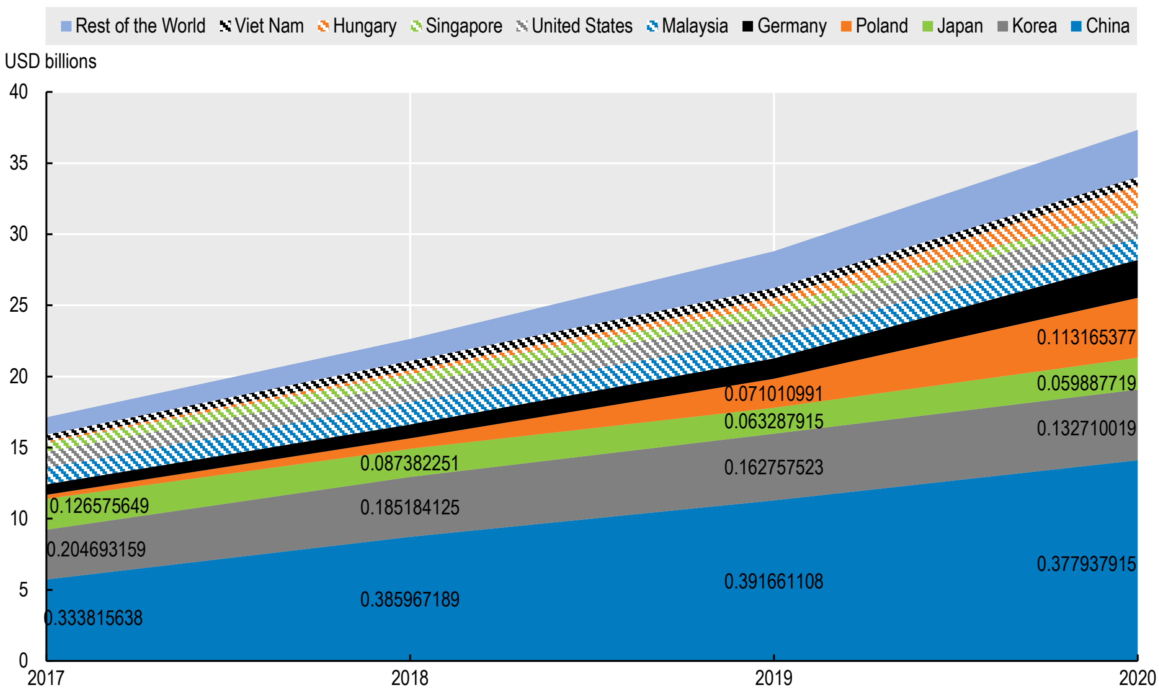
International trade plays an important role in the supply of lithium-ion batteries. In 2019, 45% of LIB in the market were traded internationally (Figure 7). Exports of LIB are highly concentrated; four economies accounted for two-thirds of global exports in 2020 (Figure 8). China alone represented one third of world exports in 2017, rising to 38% in 2020. Trade data also show that the market for LIB is dynamic. While the relative role of Japan and Korea has been declining, Poland's exports increased from less than 2% in 2017 to 11% of global LIB trade in 2020. Imports of LIB are more dispersed and generally correspond to the size of the car and electronics sectors in each country, with China, Germany, the United States and Viet Nam leading the importer rankings (Figure 9). Despite being the main importers of lithium-ion batteries, China and the United States rely much less on imports than European countries, where 63% of LIB sold on the market were imported from outside Europe in 2019 (Figure 10).

Figure 7. International trade and sales of LIB



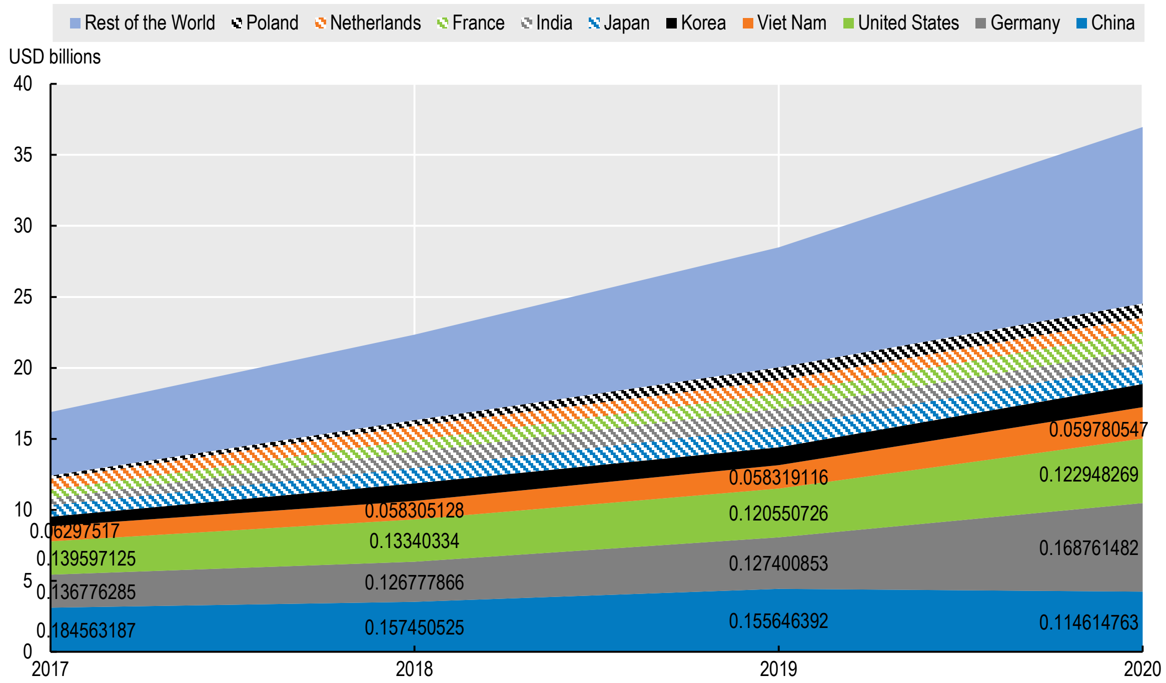
Note: Sales are the sum of all lithium-ion batteries placed on the market.
Source: OECD calculations based on international trade data from CEPII (BACI database) and batteries placed on the market data from Circular Energy Storage Online.

Figure 8. Main exporters of LIB



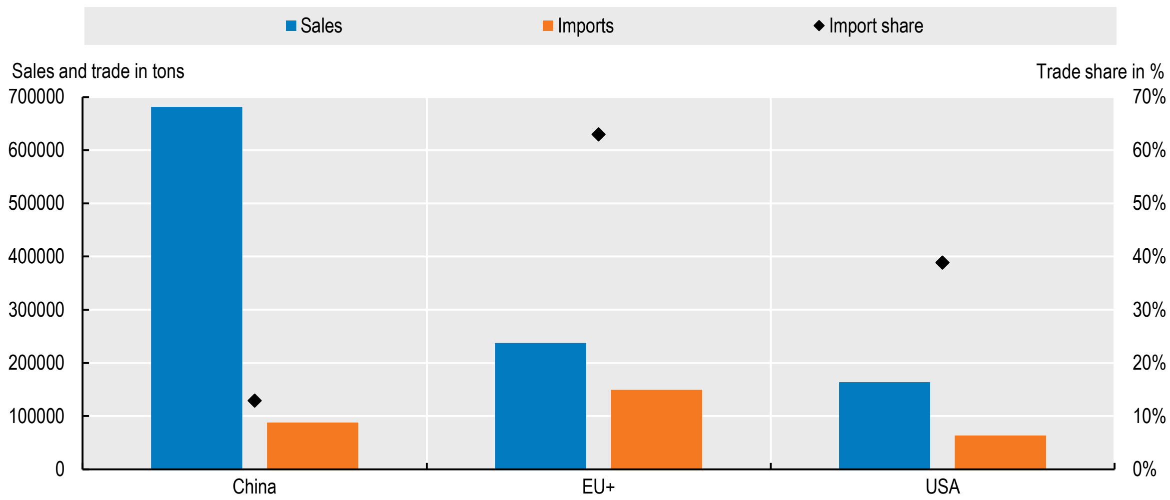
Note: China includes Hong Kong (China).
Source: OECD calculations based on UN Comtrade.

Figure 9. Main importers of LIB



Note: China includes Hong Kong (China).
Source: OECD calculations based on UN Comtrade.

Figure 10. Imports and sales of LIB in three main markets



Note: Data for 2019. China includes Hong Kong (China). EU+ is defined as EU Member countries plus the United Kingdom and EFTA members. Only extra EU+ imports are included.
Source: OECD calculations based on international trade data from CEPII (BACI database) and batteries placed on the market data from Circular Energy Storage Online.

3.2. Trade in spent[13] batteries and battery waste

International trade statistics are too aggregated to provide an accurate picture of trade flows in spent LIB and LIB waste. The most detailed category aggregates both single-use and rechargeable batteries, as well as all battery chemistries. Consequently, the observed trade flows likely reflect life-cycles of batteries other than LIB, such as those of lead-acid car batteries; however, the economics and mechanics of LIB recycling are different from those of lead-acid car batteries. The latter currently have very high levels of recycling (close to 100% in high-income economies), due both to government regulations and the fact that it is cost effective. The reason for its cost-effectiveness lies in the simplicity of the recycling process that does not require advanced technology or skills, and thus can be done at a small scale without large upfront investments. Consequently, most lead-acid battery recycling is done locally and, where domestic recycling capacity is insufficient, trade exists with developing economies which have developed capacity in handling battery waste and scrap. That said, this trade is not without concerns as small-scale recycling of lead-acid batteries in developing countries often causes environmental and health problems.

National statistics are available at a more disaggregated level, providing a more nuanced picture. Eurostat and US Census trade data distinguish between lead-acid and other batteries, both for spent cells and waste. The “other” category for waste nevertheless still includes non-rechargeable batteries and all chemistries that do not include lead. To provide rough estimates of international trade in spent and waste LIB we therefore rely on an analysis by Circular Energy Storage who assess these trade flows using various sources from the industry (Circular Energy Storage, 2021[8]).

The uneven global distribution of recycling capacity for LIBs creates a significant role for international trade. According to data collected by Circular Energy Storage, a large share of LIBs that come to the end of their first life in the European Union or the United States are exported (Circular Energy Storage, 2021[8]). Batteries from Europe are usually shipped to pre-processors in Malaysia, Indonesia or the Philippines. Battery cells from the United States have historically been exported for pre-processing in Korea. The output of pre-processing operations, black mass, serves as an input into material recovery operations. Currently these two activities are typically performed in separate installations, with material recovery from black mass located closer to battery material producers, which are predominantly based in China.[14]

Circular Energy Storage’s estimates suggest that Europe and the United States were net exporters of LIB waste and scrap for pre-processing in 2019, with 16 888 tons and 27 420 tons of net exports, respectively. China, on the other hand, is estimated to be a net importer of 56 559 tons of LIB waste and scrap. This is despite a ban on imports of waste batteries to China. The authors argue that their numbers are plausible because importing LIB for reuse is legal and some of those batteries will end up in recycling because of insufficient quality (Circular Energy Storage, 2021[8]).[15]

[13] While EoL batteries can be repurposed in less energy-efficiency demanding applications, “spent” batteries can only be used for recycling and material recovery.

[14] For example, one of the world's leading e-waste companies, Singaporean TES-Amm, operates a plant in Grenoble where batteries are shredded and in the form of black mass shipped to Singapore. The black mass is processed in a facility which produces nickel, cobalt and manganese sulphates which are then sold to the Chinese battery industry. South Korean SungEel Hitech also sources black mass internationally (from pre-processors in Australia, European Union, India, Malaysia and the United States) to produce nickel, cobalt and manganese sulphates and lithium phosphates in its facilities in Korea.

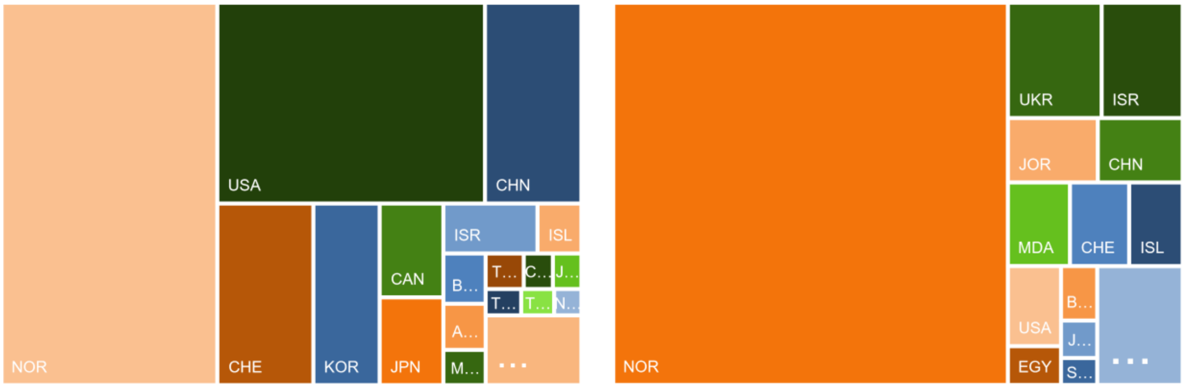
[15] These numbers are also substantially higher than what is recorded in trade statistics as exports or imports of spent batteries and battery waste and scrap. It is nevertheless plausible that batteries that are exported for reuse are recorded as lithium-ion accumulators (HS 8507 60) because trade classifications do not distinguish between used and new LIB. This is corroborated by EU’s trade statistics that show a massive (260%) increase in the exports of lithium-ion accumulators to China in 2018, after the import ban came into force, despite a modest (16%) increase in overall extra-EU exports of this product.

3.3. Trade in used electric vehicles[16]

New electric vehicles are sold predominantly in high-income economies and China, while used electric vehicles are often sold to emerging and developing economies. This implies that LIBs may come to their end of life in economies without the necessary infrastructure and may need to be exported in order to be recycled. This also suggests that any manufacturers' schemes to recover EoL batteries need to be global and not only focus on current high-growth markets where most new electric vehicles are sold.

Norway is the major market for exports of both new and used EVs from the European Union (Figure 11). The rest of EU exports of new EVs goes predominantly to China and high-income markets such as the United States, Switzerland, Korea, Canada and Japan. Used EVs, on the other hand, are exported also to emerging economies such as Ukraine, Jordan, Moldova or Egypt. Similar pattern holds within the European Union where the Member States that acceded after 2004 account for only 4.5% of intra-EU imports of new EVs but they absorb 20% of intra-EU trade in used EVs. Japan's exports of EVs have also a similar structure. Most of its new EVs are sold to established markets such as the United States, European Union Canada and Norway while most used EVs are sold to the Russian Federation (hereafter "Russia") and Georgia (Figure 12).

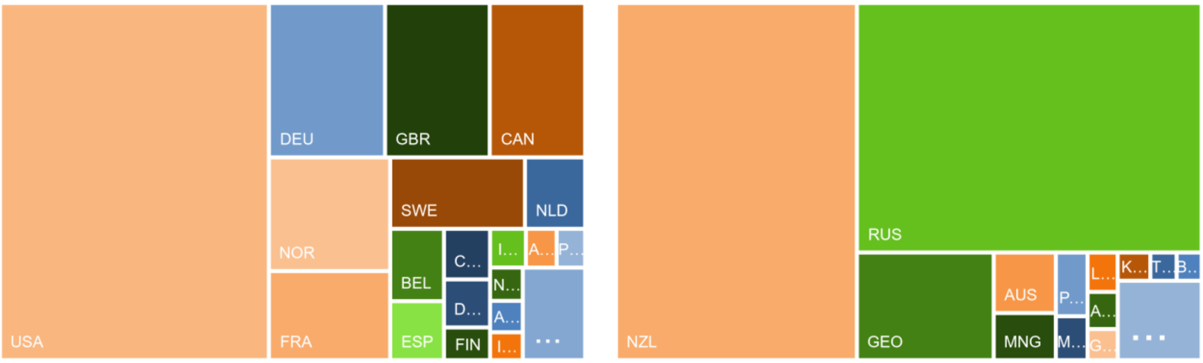
Figure 11. EU exports of new (left) and used (right) electric vehicles 2017-2020



Note: China includes Hong Kong (China). Extra-EU exports of new EVs totalled 559 862 vehicles in 2017-2020 and extra-EU exports of used EVs totalled 42 634 vehicles in 2017-2020. EVs include plug-in spark-ignition hybrid and battery electric vehicles. For consistency, UK's trade is counted as EU in the whole period.
Source: Eurostat.

[16] National statistics allow trade flows disaggregation into new and used vehicles for plug-in spark-ignition engine hybrids (United States, European Union and Japan), plug-in diesel engine hybrids (US) and battery electric vehicles (EU and Japan) – see Box A.A.1 in the Annex. We exclude hybrid vehicles with traction batteries (not capable of plug-in charging) because majority of these vehicles do not yet use LIBs. Instead, they run on Ni-MH batteries (https://www.idtechex.com/en/research-article/hybrid-electric-vehicles-a-stay-of-execution-for-nimh-batteries/22786).

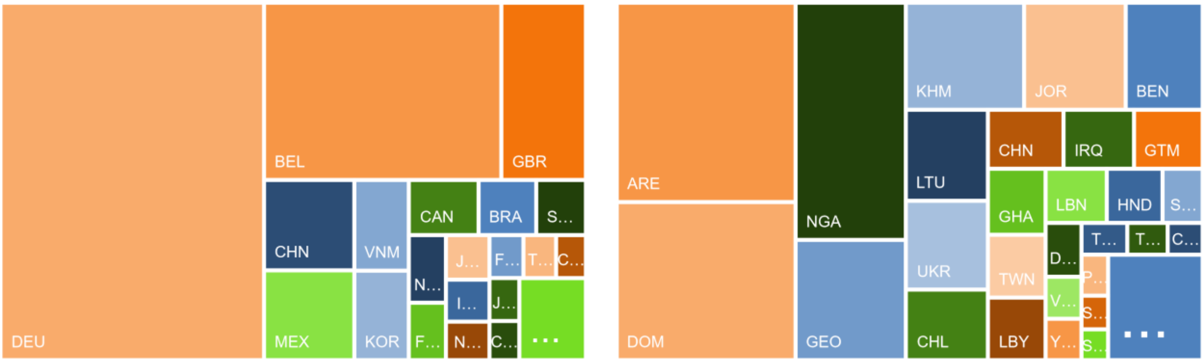
Figure 12. Japan's exports of new (left) and used (right) electric vehicles 2017-2020



Note: China includes Hong Kong (China). Japan's exports of new EVs totalled 361 752 vehicles in 2017-2020 and Japan's exports of used EVs totalled 32 533 vehicles in 2017-2020. EVs include plug-in spark-ignition hybrid and battery electric vehicles.
Source: International Trade Centre.

Unlike the EU and Japan, where exports of used EVs represent only a minor fraction compared to exports of new EVs, the United States exports more used plug-in hybrid electric vehicles (PHEVs)[17] than new ones. The difference between destinations for new and used vehicles is also even more striking for US exports. While the largest markets for new PHEVs are Germany, Belgium, the United Kingdom, China and Mexico, used PHEVs are sold mostly to the United Arab Emirates, Dominican Republic, Nigeria, Georgia and Cambodia (Figure 13).

Figure 13. US exports of new (left) and used (right) electric vehicles 2017-2020



Note: China includes Hong Kong (China). US exports of new EVs totalled 78 990 vehicles in 2017-2020 and US exports of used EVs totalled 294 758 vehicles in 2017-2020. EVs include plug-in spark-ignition hybrid and plug-in diesel hybrid vehicles.
Source: US Census.

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[17] There are four main types of EVs. The most common Hybrid electric vehicles (HEVs) combine a fuel-based engine and an electric motor with a larger battery; Plug-in hybrid electric vehicles (PHEVs) also combine fuel-based internal combustion engine (ICE) and an electric motor, but the latter is recharged via an external plug and can provide a more significant autonomy of about 20 to 30 miles. Battery electric vehicles (BEVs) are powered entirely by electricity via larger on-board batteries; mild hybrid electric vehicles (MHEVs) use a modest 48V battery and electric motor to increase the efficiency of their ICE and improve gas mileage.

4. Trade policies to promote the circular economy of LIB

Trade can play an important role in ensuring the economic viability and environmental relevance of circular economy solutions – particularly for LIBs. It becomes thus increasingly important to ensure that trade policies are designed and implemented so as to support that role, while remaining WTO consistent. Import- and export-related regulatory requirements – comprising permits, tax refund provisions, provisions that affect transparency and traceability, rules of origin and administrative procedures at the border, including with respect to safety and risk management – can significantly promote, or on the contrary hinder, circular economy solutions. In addition, prospects for circularity and extended product life will be shaped by other trade-related policies and the broader regulatory environment, such as harmonisation of standards, international certification, labelling and marking requirements; the regulation of supporting services; regulatory incentives, including through green public procurement or incentives for electric shared mobility; government support for various sources of energy and for EVs and related equipment and materials; or extended producer responsibility provisions.

4.1. Definitional issues. What is waste? What is hazardous?

The preliminary issue with respect to regulatory requirements affecting EoL LIBs is whether they would be classified as hazardous waste or not. If used EV batteries are classified as hazardous waste, this will not only raise particular know-how and safety demands on stockpiling and storage[18], but also will make transport more highly regulated and hence expensive (Harper et al., 2019[5]). This will also define how control procedures are enforced at the border. In particular, LIBs transported across national borders would be subject to notice, consent and tracking requirements to the extent they fall under the purview of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal ("the Basel Convention").[19] This question is particularly important with respect to LIBs intended for reuse, repurposing or remanufacturing.

Used LIBs would be considered "wastes" under the definition of Article 2 of the Basel Convention if they "are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law". Disposal operations include not only final disposal but also operations leading to the possibility of resource recovery, recycling, reclamation, direct re-use or alternative uses (Annex IV of the Basel Convention). While the classification of operations such as recovery of components or reclamations of materials from used LIBs or from black mass among the disposal operations listed in Annex IV is relatively straightforward, the re-use of EV batteries or battery components, including for EV upgrade or conversion, or their repurposing into stationary energy storage systems may raise definitional questions. Some guidance to help distinguish between waste and non-waste under the Convention was established under the Technical Guidelines series, including UNEP/CHW.14/7/Add.6/Rev.1,[20] which seeks to bring clarity concerning the status of whole used electrical and electronic equipment and components. However, the Guidelines acknowledge that the distinction between waste and non-waste may differ across countries and the definition ultimately lies in the hands of national authorities.

[18] Accidental fires already on the rise in metal-recovery facilities illustrate some of the safety concerns in stockpiling large amounts of LIB

[19] The provisions of the Basel Convention regulate the transboundary movements of hazardous and other waste and engage its Parties to ensure that such waste is managed and disposed of in an environmentally sound manner. Objects or substances subject to the Convention's provisions are determined on the basis of the complex interaction between the Convention's Article 2 (definition of 'waste' and 'disposal') and Annexes I (Categories of Wastes to be Controlled), II (Categories of Wastes Requiring Special Consideration), III (List of Hazardous Characteristics), IV (Disposal Operations), VIII and IX (Lists of Wastes Characterised as Hazardous).

[20] Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention, 20/06/2019. The guidelines do not cover materials resulting from the dismantling of the electrical and electronic equipment.

The OECD has also formulated general guidance for distinguishing waste from non-waste, including whether the product has an intended use, market demand and positive economic value; whether it can be considered part of a normal commercial cycle or utility chain; and whether further processing would be required for the material to be directly used in manufacturing operations or commercial applications (Yamaguchi, 2022[17]) (OECD, 2009[18]) (OECD, 1998[19]). On the basis of these criteria, LIBs dismantled to recuperate critical materials and black mass would in principle be considered as waste, while LIBs reused in stationary energy storage applications would probably not.

National definitions and approaches will differ among countries, although the implications of such differences on the stringency of controls may be limited, given the hazardous characteristics of LIBs (see below). For instance, regulatory frameworks for waste in Australia[21] or Brazil[22] consider end-of-life products or materials "waste" whether or not they are of value, or can be processed, recycled, re-used or recovered, whilst actively promoting their reuse and recycling. In Canada, the legislation establishes a distinction between waste, meant to "be disposed of", and recyclable material.[23] In Colombia[24] or Mexico[25] products or materials that cannot be reused for their original purpose are considered as waste. In China, EoL batteries would be classified as waste under the Identification Standard for Solid Waste, unless they are reused without further repair/reprocessing or after being repaired/reprocessed at the place where they were originally manufactured; or they are used for lab analysis or scientific research (WEF, White&Case, 2020[20]). In the context of the EU Waste Framework Directive (2008/98/EC) substances or objects that are commonly used for specific purposes; for which there is an existing market or demand; and whose use is lawful and will not lead to overall adverse environmental or human health impacts cease to be waste and are no longer subject to waste – in particular hazardous waste – regulation (Art.6). However, most of these criteria are subject to interpretation and do not provide sufficient clarity concerning objects such as LIBs headed for second life applications (Malinauskaite, Anguilano and Schmidt Rivera, 2021[21]) or black mass meant for material recovery.

Insufficient clarity about LIB status, or inconsistencies as to what that status would be under different jurisdictions can be problematic, not only in terms of traceability but also in terms of consistent implementation of applicable regulations across a LIB supply chain crossing borders. In many jurisdictions[26] the import and export of spent batteries is strictly regulated or even prohibited, yet estimates of waste and scrap flows point to spent batteries traded for reuse but ending in recycling streams (as previously mentioned).

While LIBs are not explicitly listed in Annexes I and VIII of the Basel Convention, LIB wastes would be deemed hazardous in accordance with Article 1 as conventional electrolytes for Lithium and Li-ion batteries fall under Annex I (categories of wastes to be controlled),[27] while their potential for combustion and explosion brings them under codes H4.1 (flammable solids) and H1 (explosive) of the Convention's Annex

[21] Recycling and Waste Reduction Act 2020, Art.15.

[22] Lei 12.305/2010, Art.3.

[23] Cross-border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations, Consolidation SOR/2021-25.

[24] Decree 4741 of 2005.

[25] Ley General del Equilibrio Ecológico y Protección al Ambiente, Art.3.

[26] For instance, under the EU Batteries Directive (Directive 2006/66/EC), it is illegal to landfill, incinerate or improperly dispose of spent batteries, which are required to undergo treatment and recycling (Art.12.1.b). Similar provisions are applied in China, which also imposes a total ban on the import of solid waste and the export for dumping, piling up or disposal purposes (Sun et al., 2021[42])

[27] They would fall under Y15(wastes of an explosive nature …), Y32 (inorganic fluorine compounds …), Y34 (acidic solutions or acids in solid forms), Y35 (basic solutions or acids in solid forms), Y41 (halogenated organic solvents) and Y42(organic solvents excluding halogenated solvents)

III (list of hazardous characteristics).[28] They would be comprised among list A[29] wastes in Annex VIII. On the other hand, some of the materials reclaimed through dismantling would rather fall under list B[30] and questions may be raised as to whether some types of black mass would qualify. In any event, national legislation regulating LIB waste as hazardous for purposes of import and export will trigger Basel controls under Article 1(1)(b), or, for countries that are not Parties to the Convention, have similar effects. For instance, discarded LIBs can meet both the US ignitability and reactivity[31] hazardous characteristics under regulations implementing the Resource Conservation and Recovery Act (RCRA).

In 2020, preliminary draft guidance on the development of an inventory of waste batteries containing lithium (UNEP/CHW/OEWG.12/INF/17) further considered the applicability of the Basel Convention to LIBs. However, the guidance mainly focusses on promoting information collection about LIBs considered waste at the national level –the amount of waste generated, its disposal and transboundary movement- so as to support related national reporting and environmentally sound management; not on defining LIB waste at a supranational level.

Further clarity at the global level regarding the status of LIBs aimed for reuse, repurposing, remanufacturing and recycling would be essential for promoting circular value chains for LIBs while preserving consistent and transparent management of related environmental, health and safety risks.

4.2. Transportation regulations, safety, labelling and marking requirements

Even if particular LIBs were not considered waste, their hazardous characteristics would still imply they are subject to specific management and transportation requirements to ensure their safe handling. Safety regulations[32] will entail high transportation costs, which are estimated to account for as much as half of the total disposal cost of EoL LIBs (Hill et al., 2019[16]). When LIBs are transported across borders, this added cost is aggravated by the lack of international agreements governing transportation, which burdens international supply chains with complexities and obstacles as battery transport needs to comply with rules in each jurisdiction ((Gaines, 2018[22]) and transport operators need extra training and certification requirements (Energy Storage Association 2020).

UN Model Regulations, originally developed by the UN Economic and Social Council (ECOSOC)'s Committee of Experts on the Transport of Dangerous Goods and regularly revised,[33] provide a model for a uniform development of national and international regulations on transport safety across various transportation modes.[34] This covers standards for the packaging used to transport LIBs; and hazard communication requirements, including labelling and marking of packages, and documentation and emergency response information required to accompany each shipment. LIBs meant for disposal and recycling must be clearly marked as such, and appropriately packed to prevent short circuits and

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[28] Under the OECD Decision, Appendix 1 (on categories of wastes to be controlled) and Appendix 2 (the list of hazardous characteristics) would similarly apply.

[29] List A wastes (Annex VIII of the Convention) are characterized as hazardous under Article 1. This would include A1170 (Unsorted waste batteries excluding mixtures of only list B batteries. Waste batteries not specified on list B containing Annex I constituents to an extent to render them hazardous); and A1180 (Waste electrical and electronic assemblies or scrap containing components such as accumulators & other batteries included on list A, …)

[30] List B wastes (Annex IX of the Convention) would not be considered hazardous unless they appear on Annex 1 (see footnote 9 above) and display an Annex III (hazardous) characteristic.

[31] Under US regulations reactivity is a hazardous characteristic comparable to Basel's H1. The United States has signed but not ratified the Basel Convention.

[32] For example, hermetic sealing and the packaging of LIBs with more expensive materials that can prevent short-circuiting or other damage complicate the recycling process (Energy Storage Association,, 2020[35]).

[33] The latest (19th) revised edition was published by the UNECE Secretariat in 2015.

[34] According to ICAO Technical Instructions and IATA Dangerous Goods Regulations, lithium batteries shipped for recycling or disposal are forbidden on air transport unless approved by the state of origin and the state of the operator.

overheating. The Basel convention also subjects Annex III wastes to labelling requirements providing information on hazards to human health and the environment.

However, the Model Regulations are not binding and applicable national and international regulations, even those inspired by them, are not completely consistent with each other. As an illustration, most European countries follow International Electrotechnical Commission (IEC) norms and regulations, which are mostly but not fully harmonized with UN regulations. Japan's regulations[35] for shipping lithium batteries are stricter than the IEC standards, while in Korea, the KC mark required for transport is similar to IEC 62133 except that it covers all LIB irrespective of their energy density value (Huo et al., 2017[23]). In the United States, where the US EPA recommends spent LIBs to be managed as hazardous waste under the universal waste provisions of US EPA regulations that are subject to PIC procedures for exports and imports[36], LIBs are also classified by the US Department of Transportation (DOT) as "Class 9 miscellaneous hazardous materials" and subject to hazardous material transportation regulations.[37] The same Class 9 classification applies in Australia, both for new and for waste LIBs.[38]

Across national (or even sub-federal) jurisdictions there may not only be differing safety, storage and transport requirements on dangerous goods, including complex permit requirements for import, export and transit, but also differing regulations and processes for the implementation of such requirements at the border; as well as multiple and differing tracking processes and platforms. Such regulatory divergence makes related information more difficult to obtain and justifies efforts to enhance transparency and traceability of consignments. The implementation of a "battery passport" currently under discussion (see below, Section 4.5) may help ensure compliance with applicable safety and sustainability requirements for battery transport, through data traceability.

Sunk costs in reverse logistics may be particularly problematic for the implementation of take-back schemes supporting extended producer responsibility requirements. The return of batteries from remote locations could add to the potential cost and economic risk in ways that would make reverse supply chains unsustainable, especially in the reuse and repurposing applications where used batteries compete with new 'designed for purpose' LIBs (Albertsen et al., 2021[24])

4.3. Administrative procedures at the border

Assuming that LIB meant for recovery or recycling operations are considered (hazardous) waste, administrative procedures at the border are defined by provisions of the Basel Convention[39], the OECD Decision on the Control of Transboundary Movements of Wastes Destined for Recovery Operations (OECD/LEGAL/0266) and applicable national regulations. As indicated above, if they are not considered waste, they would still be subject to specific management and transportation requirements to ensure their safe handling on account of their hazardous characteristics. International legal frameworks and national requirements governing controls and procedures at the border would also apply in either case.

The Basel Convention calls for reducing the transboundary movements of hazardous waste to the minimum consistent with their environmentally sound and efficient management (Art.4.2.d), but acknowledges the use in recycling or recovery operations in the importing country as a potentially valid reason for allowing their export (Art.4.9.b). The Convention also requires Parties not to permit their

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[35] Electrical Appliance and Material Safety Act ("DENAN") of April 2001.

[36] A US EPA statement (https://www.epa.gov/recycle/used-lithium-ion-batteries) affirms that many spent LIBs are likely to be hazardous waste for being reactive or ignitable and recommends that they be managed as hazardous waste under the universal waste provisions of US EPA regulations (FN See Code of Federal Regulations 40 CFR Part 273). Universal waste regulations require complying with PIC procedures implemented in the hazardous waste provisions of US EPA regulations (See 40 CFR Part 262 Subpart H) for exports and imports.

[37] For instance, Code of Federal Regulations (49 CFR Parts 173.185 and 173.159.

[38] Which, as hazardous wastes will require a permit to be exported from Australia.

[39] An amendment to increase controls, including the implementation of PIC procedures, for the transboundary movement of e-waste, adopted by the Parties to the Basel Convention in 2022, enters into force in January 2025.

movement to countries that have prohibited hazardous waste imports (Art.4.1.b), or to and from non-Parties (Art.4.5).[40]

Since December 2019, the "Ban Amendment"[41] prohibits the movement of hazardous wastes destined for resource recovery, recycling, reclamation, direct re-use or alternative uses, from OECD and EU countries and Liechtenstein to other countries. While the Ban Amendment does not apply between two Parties that have not ratified it, ratification by one of the two Parties is enough to subject a waste movement to the prohibition of Art.4.1.b. Several Basel Parties had incorporated the Amendment into their national legislation even prior to its entry into force.[42] China, the major destination of LIB for recovery and recycling operations, is among the Parties that have ratified the Ban Amendment formally removing consent for waste imports from OECD and EU countries; however, contrary to lead-acid, nickel-cadmium and mercury oxide chemistries the status of LIB meant for reuse is as yet unclear under applicable national regulation.

Outside these standing prohibitions, the Basel Convention subjects transboundary movements of hazardous waste to "prior informed consent" (PIC) procedures, whereby such movements are only allowed if there is prior agreement between import, export and transit countries. The OECD Decision applies similar PIC procedures to waste subject to "amber control procedures".

Under the PIC procedures, exporters need to notify and obtain consent from the competent authorities (normally environmental protection agencies) of import, export and transit countries before a shipment is made, and shipments made without consent are illegal (Basel Art.4.1.c and Art.6). Notification and consent may concern either individual transboundary movements, or multiple shipments with the same physical and chemical characteristics to the same facility. Under the OECD Decision, it is also possible to obtain pre-consent by the importing country for the movement of certain types of wastes to specific recovery facilities (section D(2) of the OECD Decision). Under both instruments, countries have the discretion to introduce additional national requirements aimed at better protecting the environment, including additional trade controls or additional waste categories to be controlled under these frameworks.

The exchange of information is central to PIC procedures, so as to ensure not only the compatibility of the movements with environmentally sound management of the waste, but also to provide tools for efficiently handling any issues that may arise. It covers among other things the reason for the export, the exporter's details, the intended disposal site and methods of disposal, means of transport and insurance information. The persons in charge of transporting or disposing of the wastes must be authorised to perform such operations and the consignments must be packaged, labelled, and transported in conformity with relevant international rules and standards.[43]

In addition to potential uncertainty regarding applicable requirements for movements of LIB meant for reuse or recycling, the important delays in obtaining consent for individual or multiple shipments may create significant disincentives for reuse, recovery or recycling operations across borders. A wider use of pre-consent for the movement to specific facilities and the gradual replacement of paper-based PIC procedures with electronic approaches to the notification and movement documents would greatly facilitate legitimate movements without compromising required controls.[44]

[40] However, Art.11 provides the possibility of waste movements to and from non-Parties on the basis of bilateral, multilateral or regional agreements or arrangements with provisions that "*are not less environmentally sound than"* the Convention's.

[41] Decision II/12 of the Conference of Parties to the Basel Convention, adopted in March 1994 (UNEP/CHW.2/30) and entered into force on 5 December 2019.

[42] For example, the European Union, in the Waste Shipment Regulation (Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, OJ L 190)

[43] A number of countries have also introduced specific labelling requirements at the national level, such as China's labelling requirement concerning the lithium content and risks of Li-ion batteries applicable to the batteries' transportation.

[44] Work on electronic approaches is currently underway under the Committee Administering the Mechanism for Promoting Implementation and Compliance (ICC) of the Basel Convention.

As regards controls at the border, a Manual for Customs Officers (Secretariat of the Basel, Rotterdam and Stockhold Conventions, 2014[25]) highlights the importance of risk assessment, the use of intelligence and risk profiles in efficiently controlling shipments and targeting potentially suspicious ones. All three facilitating approaches -broadening pre-consent, dematerialising the required documentation and promoting risk assessment- can draw interesting insights from the provisions of the WTO Trade Facilitation Agreement on authorised operators, the use of information technology in formalities and documentation requirements, and risk management.

4.4. Rules of origin

Rules of origin (RoOs) can be a significant policy factor hindering or facilitating the trade of electric vehicles and their tariff treatment in particular between FTA partners. As the embedded battery accounts for a significant percentage of the final value of an electric vehicle – around 35 to 45% – where the battery is sourced may determine the origin of the vehicle itself depending on the stringency of applicable RoOs and on whether origin is defined on the basis of value addition or other criteria.[45] The same goes for some of the critical materials contained in the battery. Although indirectly, RoOs can thus affect the circular value chains for LIBs.

In addition to the application of tariffs, in particular to determine eligibility for preferential treatment under applicable free trade agreements (FTAs) and to implement measures and instruments of commercial policy such as anti-dumping duties and safeguard measures,[46] RoOs may affect the implementation of tax incentives to promote the uptake of technologies for the green transition. For instance, the Inflation Reduction Act adopted by the United States in 2022 conditions refundable income tax credits for qualifying plug-in EVs[47] on the use of a progressively increasing percentage, from 40-50% before 2024 to 80-100% by 2028, of "originating"[48] critical minerals or of components, such as batteries. RoOs may also affect the implementation of proposed regulations about minimum levels of recycled content in new batteries, such as those promoted by the European Parliament in the context of the revision of the Batteries Directive.

On the other hand, RoOs may be designed in a way that promotes circularity, as shown by the provisions incorporated in the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP)[49] or the USMCA[50] allowing recovered materials to count as originating from a country if they are incorporated into a remanufactured good. Suggestions in the literature hint at incorporating similar provisions for recycled materials in future RTAs (Kommerscollegium, 2020[26]).

[45] For products that are not "wholly obtained" (i.e. grown, manufactured or assembled) in a country, the origin – or national source of a product, affecting the duties and trade measures that may be applied on the product at the border – is determined by the place of its last "substantial transformation". Different national systems use different criteria to define substantial transformation, including the value-added rule (the value of non-originating components does not exceed a given percentage of the product's price); the change of tariff classification (the transformation of non-originating components into the resulting product has resulted in a shift of HS classification code); combinations thereof, or other criteria, such as the use of specific production operations, the exclusive use of originating materials, etc.

[46] See WTO | Rules of origin - Technical Information

[47] Inflation Reduction Act, Part 4--Clean Vehicles, Sec. 13401 and following. The Act provides credit of USD 3 750 for any vehicle meeting certain critical minerals requirements and USD 3 750 for vehicles meeting certain battery component requirements, for a maximum allowable credit of USD 7 500 per vehicle.

[48] Originating materials have to be extracted or processed in the United States or in a country with which the United States has an FTA in effect, or recycled in North America. Originating components have to be manufactured or assembled in North America.

[49] CPTPP, Chapter 3, article 3.4 "…a recovered material derived in the territory of one or more of the Parties is treated as originating when it is used in the production of, and incorporated into, a remanufactured good".

[50] USMCA Art.4.4.

4.5. Standards and certification

The ability to enforce standards across borders in a way that does not stifle innovation is also important in the current environment. Complexities associated with non-standardized battery system design, lack of quality and performance guarantees, and inconsistent procedures around the LIB globally can generate important barriers to LIB reuse and recycling. Harmonisation of standards for LIB design can support repurposing, repair and recovery of materials by promoting expertise for the batteries' state of health diagnosis; expanding the network of qualified service providers able to service used LIBs and support second life solutions; and facilitate disassembly and module exchange. Battery construction that allows for standardized tooling and servicing and for swift dismantling may lower the cost of collection, transport and handling for repurposing and recycling by up to 50% (World Economic Forum, 2019[13]). Ensuring the technical readiness of LIBs and their compatibility with power market regulations can help promote the adoption of vehicle-to-grid (V2G) applications across countries. Likewise, the capacity to test, refurbish and certify LIBs for performance and safety can greatly promote market trust for second life LIBs.

However, the pursuit of innovation and first mover advantage may provide LIB producers and automotive companies with limited encouragement to harmonise design or optimize it for repair and refurbishment absent outside incentives. Regulation calling for recovery-, reuse-, and recycling-friendly design is increasingly a part of circular economy strategies around the world, though applying these requirements on EVs would call for more information on EV longevity and pack failure rates to better assess repair and refurbishment needs. Different countries are progressing down different pathways to address immediate challenges. In the EU for instance, Directive 2000/53/EC on EoL vehicles require that vehicles should be designed in a way that they can be easily recovered, reused, and recycled. The recycling of LIBs is also encouraged by the EU Battery Directive 2006/66/EC[51].

Collaboration with the private sector and support to improve recycling processes and enhance material recovery rates is another path. The ReCell Center, a collaboration of industry, academia and national laboratories under the auspices of the US Department of Energy, aims to support the development of technologies to improve battery design and recycling, including direct recycling processes that would not require breaking battery structure down to constituent elements (ReCell, n.d.[27]). A series of partnership projects signed by the European Commission, national authorities and European manufacturers under the Important Projects of Common European Interest (IPCEI) initiative,[52] aim to develop safe and innovative methods for the collection, dismantling, reuse and recycling of EV batteries.

Current regulations on batteries do not generally address second life issues, nor distinguish between various recovery streams. For instance, the recent evaluation of the EU Batteries Directive[53] in support of the proposed Batteries Regulation estimated that current provisions did not support re-use approaches, nor did they fully reflect the importance of resource efficiency and circular economy in material recovery, lacking strong information and traceability requirements and potentially leading to downcycling. While most LIBs are still serving their first life in most of their current applications worldwide,[54] the need for standards and regulations to ensure compatibility between first life design and characteristics and the safety and performance requirements for second-life usage is now pressing.

While labelling of LIB shipments to inform about the shipment's hazards is a widespread and well enforced requirement (see above), labels providing information about the make-up and composition of LIBs to reinforce traceability are only starting to pick up steam. Such labels could provide valuable support in distributing batteries among reuse, repurposing or recycling circuits in the most environmentally

[51] The EU Batteries regulation proposed in December 2020 is centred around sustainability and circularity, including a framework that will facilitate the repurposing of batteries from electric vehicles so that they can have a second life.

[52] IPCEIs aim to "bring together knowledge, expertise, financial resources and economic actors throughout the Union, so as to overcome important market or systemic failures and societal challenges which could not otherwise be addressed." They are meant to support large-scale projects and are funded by state aid.

[53] EC (2019), Commission staff working document on the evaluation of the directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.

[54] In 2019, reuse of LIBs in Europe had not yet reached 100 MWh of installed capacity and were just beyond an installed capacity of 10 MWh in the United States (Melin, 2019[41]).

sustainable and economically and logistically efficient way, provided they ensure suitable protection of proprietary information.

A possible path in that direction would be the adoption of battery passports, as currently developed by the Global Battery Alliance (GBA)[55] to include digital IDs for batteries, a global reporting framework, a quality seal for batteries, and a digital platform to exchange data. A battery passport is meant as a unique digital identification linked to the physical product, including embedded static and dynamic data (f.i. about the material composition, environmental and social footprints, origin, health, and chain of custody of the battery)[56] and which can be made available as needed for the duration of the lifetime of the product until it (or its components) reach end of life and are recycled. In addition to its recognition by relevant authorities as a medium for obtaining and exchanging the information needed for applicable controls, standard setting bodies would need to elaborate appropriate interoperability solutions for authenticating data against a set of common standards in alignment with government requirements for sustainability, and responsibility, as well as data disclosure.

4.6. Government incentives to promote LIB circularity

Government incentives to promote circular LIB value chains include low carbon fuel standards and associated financial penalties, targets for banning ICE vehicle sales, and targets for the collection of EV batteries and for the recovery of critical materials.

Low carbon fuel standards and associated financial incentives introduced by a number of countries are significant upstream catalysts in increasing the demand for electric vehicles and EV batteries. Policies to restrain ICE vehicle circulation in urban centres and targets for banning ICE vehicle sales in the medium term further compound this effect.

In December 2021, US EPA revised its vehicle emissions rules to a much more ambitious level, estimating that they will result in a 17% increase of new EV or PHEV circulation in the United States by 2026.[57] In the European Union, proposed CO2 emission performance standards for new cars aim at a 55% reduction by 2030 and 100% by 2035 compared to 2021 levels (Council of the EU, 2022[28]). The reduction targets will apply to car manufacturers' fleets, so that high-emission models would have to be offset with sales of low-emission or zero-emission vehicles, such as electric vehicles. Financial penalties will apply in cases of non-compliance with the manufacturers' obligations. These negative incentives, coupled with the requirements set in the revised Clean Vehicles Directive[58] to ensure a minimum percentage of low and zero-emission fleets in the aggregate public procurement of Member States, are meant to boost the demand and further deployment of low and zero-emission vehicles powered through EV batteries. In China, Hainan was the first province to announce official phased-in sales targets by sector[59] in the Clean Energy Vehicle Development Plan adopted in 2019.

[55] The GBA (www.globalbattery.org) is a public-private collaboration platform founded in 2017 at the WEF and operating independently since 2021. The GBA brings together international organizations, NGOs, industry actors, academics and multiple governments, and aims to help establish a sustainable and responsible battery value chain by 2030.

[56] The EU new proposed regulatory framework for batteries, meant to replace the 2006 Batteries Directive, would also require automotive and industrial batteries to indicate the material content, quantity of each material and its origin and be labelled with the name of the manufacturer, date of manufacture, presence of hazardous substances and other information that facilitates recycling or reuse.

[57] https://www.reuters.com/business/autos-transportation/us-epa-propose-new-tougher-vehicle-emissions-rules-by-march-2022-06-21/.

[58] EU Directive 2019/1161 of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles https://eur-lex.europa.eu/eli/dir/2019/1161/oj.

[59] Specifically government fleets, buses, taxis, urban freight, sanitation, rental services, tour coaches, intercity coaches, and private cars. Hainan's Clean Energy Vehicle Development Plan (2019-2030) https://theicct.org/sites/default/files/publications/Hainan_Clean_Energy__Vehicle_Dev_20190426.pdf.

Many European cities, including Oslo, Paris, Rome, Amsterdam, London and Brussels, have implemented measures to prohibit ICE vehicles from entering or driving in certain city areas, partly in response to EU air quality standards. Typical regulatory measures include urban vehicle access regulations such as car-free city centers, congestion charges, low emission zones (LEZs) or outright bans of diesel or ICE vehicles access to the city after a certain date (Wappelhorst, 2020[29]). An increasing number of local and national governments intend to phase out ICE vehicles altogether, using various financial and fiscal incentives, active extensions of fast-charging networks, outright banning registration of new ICE vehicles after a certain date with possible exemptions for people living in remote areas[60]. Norway has set the most ambitious target of an ICE phase out already in 2025,[61] while Denmark set a 2030 target to stop sales of ICE cars and a 2035 goal to bar new PHEVs.[62] British Columbia was the first jurisdiction worldwide to legislate in 2019 a 100% zero-emission vehicle sales target, phasing it in progressively between 2025 and 2040.[63]

Targets for the collection and recycling rates for EoL EV batteries provide parallel incentives at the other end of the batteries' lifecycle. The proposed new EU Battery Regulation sets both objectives for minimum recycled content in new batteries (12% for cobalt, 4% for lithium and 4% for nickel by 2030 and 20%, 10% and 12% respectively by 2035) and mandatory recovery rates from EoL batteries (65% of LIBs by 2025). A number of EU Members also set national targets for EoL batteries collection rates in their national legislation. In the United States where there is currently no specific legislation at federal level mandating or promoting the recycling, reuse and repurposing of batteries, the States of California, Minnesota and New York have enacted relevant legislation.[64] California's Lithium-Ion Car Battery Recycling Advisory Group currently works to develop policy recommendations for achieving as close to 100% as possible of LIB reuse or recycling.

In parallel, the US Department of Energy (DOE), has announced plans to invest USD 20.5 million in LIB recycling, with the aim of boosting capture rates from less than 5% currently to 90% and furthering the policy goals of Executive Order 13817 of 2017 to "ensure secure and reliable supplies of critical minerals", including by means of "developing critical minerals recycling and reprocessing technologies".

4.7. Extended producer responsibility

Extended producer responsibility (EPR) is defined as "a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product and especially to take-back, recycling and final disposal of the product" (Lindhqvist, 2000[30]) It is a significant component of circular economy strategies in many countries. However, while most markets have some form of regulation requiring the recycling or remanufacturing of consumer electronics or of automobiles in general, EV-battery-specific requirements or delineations of responsibility between the producer and the consumer are less common. Even where the burden of organising and paying for the collection and recycling of waste batteries is clearly laid on battery producers, vehicle manufacturers or importers,[65] the possibility to discharge this obligation through collective take-back systems have been criticised for failing to provide information and incentives

[60] Iceland's 2019 Climate Action Plan.

[61] Norway's 2017 Transport Plan aims for sales of passenger cars and light vans to be zero-emissions from 2025 onward, subject to "improvements in technological maturity in a way that zero-emission vehicles will be competitive in relation to conventional vehicles.

[62] Denmark's 2018 Climate and Air Plan.

[63] British Columbia, Zero-Emission Vehicles Act https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/zev_act_regulations_intentions_paper-1-final_-_updated_29oct2019.pdf.

[64] California Rechargeable Battery Recycling Act of 2006; Minnesota Rechargeable Battery and Products Law of 1994; New York Rechargeable Battery Recycling Act of 2010.

[65] Such as in Art. 3(6) of Directive 2006/66/EC (Battery Directive).

to influence the waste management costs and effectiveness at the level of individual LIB or EV producers (Albertsen et al., 2021[24]).

Under the EU Battery Directive, OEMs must bear the costs of collecting, treating and recycling EV batteries in relation to private, non-commercial vehicles. EU Members' national legislation further clarifies this approach; for instance Germany's Batteries Act (BattG) requires OEMs to register and obtain approval for their take-back systems with a Used Electronic Devices Register. OEMs may discharge of their producer responsibility obligations through dealers networks recuperating batteries returned voluntarily by the consumers (as is the case for Volkswagen); pursuing a battery leasing strategy that maintains battery ownership with the OEM and ensures return (as for Renault); or the creation of OEM central hubs to concentrate processing and optimise reverse logistics in view of the growing volume of returning LIBs (as is the GRS Batterien Foundation[66]). However, OEMs generally engage with recyclers, who shoulder the applicable mandatory recycling target by weight and sell the reclaimed secondary materials on the market.[67] There is no involvement or tracing by the automotive OEM other than the payment of a fee to cover the difference between the costs of the operation and the revenues generated by the sale of the secondary raw materials. The proposed EU Battery Regulation meant to replace the Battery Directive introduces a more stringent requirement concerning EPR for the collection, transport, preparation for repurposing and remanufacturing, treatment and recycling, and on reporting about those to competent authorities.

In China, the responsibility for recycling EV batteries and ensuring their proper second-life utilization or their disposal lies with car manufacturers. A number of automobile manufacturers, such as NIO, discharge this responsibility by retaining ownership over the entire battery life via battery swapping or battery-as-a-service schemes. The Interim Measures for the Management of Recycling and Utilisation of Power Batteries of New Energy Vehicles, issued by the Ministry of Industry and Information Technology in 2018, require automobile manufacturers to establish battery recycling channels and recycling service outlets which are responsible for collecting used power storage batteries.

In Australia, following the 2019 National Waste Policy Action Plan,[68] the Battery Stewardship Council proposed a stewardship scheme for batteries in line with the provisions of the Australian Product Stewardship Act[69] and approved in 2020 by the Australian Competition and Consumer Commission (ACCC). Aiming to assist the recycling industry by providing more certainty for their investments, the scheme will charge a levy on battery imports and offer to recyclers a rebate per kg for collection, sorting & processing upon EoL. The scheme is being implemented across Australia utilising support from the federal government, while further financial support to develop the recycling industry, including for batteries was announced at the subnational level by New South Wales, South Australia, Queensland and Victoria as part of their COVID-19 economic recovery policies (Zhao et al., 2021[31]). Larger battery systems such as EV batteries and residential energy storage systems are meant to be included in the scheme during its second phase of development.

66 Established in 2009 in Hamburg, GRS Batterien Foundation received its approval as a producer's own take-back system in 2020.

67 A notable exception involves Umicore and Audi, which established a strategic research cooperation for closed-loop recycling, recovering 90% of the cobalt and nickel from LIB modules (Audi MediaInfo, 2019[43]).

68 The Action Plan called for the establishment of a Product Stewardship Investment Fund to accelerate work on new industry-led recycling schemes for batteries among other waste, and for the development of a common approach to restrict the disposal of priority products and materials in landfill, starting with lithium-ion batteries, materials collected for the purpose of recycling, and e-waste.

69 The Act, enacted in 2011, establishes the shared responsibility for managing wastes and their impact throughout the life cycle of a product. It allows for product stewardship arrangements in the form of a) voluntary, industry-led and funded schemes; b) co-regulatory stewardship, where the government sets the minimum outcomes and operational requirements, while industry develops and administers how they are achieved; c) mandatory product stewardship, imposing legal requirements and the way to achieve them (none in place to date under the Act). Depending on their voluntary or mandatory character, these arrangements can, or have to be accredited by the Australian Government.

While much attention in R&D and laboratories goes to the metals extraction process, it might be advisable for the first steps of the recycling process – retrieving and conveying the batteries – to receive as much attention from policymakers since the efficiency and profitability of recycling is not only linked to the efficiency of metal extraction but also to EV-LIB collection rates, which are currently quite low (Hettesheimer et al., 2019[32]) (World Bank, 2020[33]). [70] The lack of regulation creates uncertainties for manufacturers, second-life-battery companies, and potential customers. It also gives rise to regional differences regarding whether recycling or reuse is the dominant pathway (McKinsey, 2019[34]) and affects the way second-life or EoL LIB can cross borders.

5. Conclusions

The LIB recycling market is still in its infancy. Its development is being propelled by the boom of the electric vehicle industry, which is exponentially increasing the production of LIB and ultimately the generation of LIB waste. LIB recycling will help meet the demand for reliable sources of materials for LIB production and contribute to decoupling LIB production from the mining of virgin materials. Dumping LIB waste in landfills would create environmental and health risks and waste limited resources. Consequently, the development of LIB recycling and reuse markets has become an integral part of strategies for the electric vehicle industry.

LIB recycling is an area of active innovation and research. Many applications are still at the laboratory stage and the market is relatively fragmented with many small players focussing on specific stages of the recycling process. Yet, there are already signs of consolidation as several established LIB producers are integrating battery recyclers into their supply chain.

The current global recycling capacity is estimated to greatly exceed the current supply of waste LIB. However, this spare capacity is entirely driven by China where LIB recycling has been supported by government policies. In other markets, on the other hand, LIB recycling is currently underdeveloped. International trade in LIB waste has therefore been essential for LIB recycling.

The global distribution of recycling capacity for LIBs is likely to become less uneven as new LIB recycling facilities are being built in Europe and the United States. International trade in LIB waste may therefore become more regional, but it will still remain essential for making LIB recycling viable. The reason is that the material extraction stages of the LIB recycling process currently require scale, which in many economies would not be achievable through reliance on solely domestic LIB waste streams. Moreover, many LIB will come to the end of their life in smaller, developing, and emerging economies where they are often sold as part of second-hand electric vehicles. Due to the lack of the necessary infrastructure, these economies are likely to rely on recycling capacities in larger or more developed markets while volumes grow.

A number of national and international regulatory requirements applying to the cross-border movement of EoL LIBs, as well as policies designed and implemented to promote reuse, repurposing, remanufacturing and recycling can significantly promote, or on the contrary hinder, circular economy solutions.

- Further clarity at the international level with respect to the status in various configurations of EoL LIBs as a waste might encourage reuse, repurposing, remanufacturing and material recovery from LIBs thanks to smoother, less onerous circular value chains, while preserving the consistency and efficiency of health and safety controls regarding handling, transportation and disposal.

[70] Absence of LIB recycling within Europe was claimed to be due to low volume streams of EoL LIBs (only 5% of total LIB waste collected for recycling in 2019). According to the Consortium for Battery Innovation similar low streams in North America make it likely that materials recovered from LIB would have to be exported to other countries, such as China, where significant recycling infrastructure exists. On the contrary, in countries with early EV adoption like Norway collection targets for electric passenger car batteries come close to 90% (Dahllöf, Romare and Wu, 2019[36]).

- Improving consistency of transport and storage safety regulations would further remove disincentives for cross-border LIB circular value chains and facilitate the traceability of consignments. The implementation of a “battery passport” as currently discussed by various jurisdictions might be a way forward in further enhancing traceability and supporting a smoother operation of EPR schemes.
- A wider use of pre-consent for the movement to specific facilities and of risk assessment to better target controls would allow to reduce delays in obtaining consent and in clearing shipments at the border, thus considerably reducing sunk costs in reverse value chains for LIBs. The digitalization of PIC procedures would also greatly facilitate legitimate movements without compromising required controls.
- Harmonisation of standards for LIB design can support repurposing, repair and recovery of materials by promoting expertise for the batteries’ state of health diagnosis; expanding the network of qualified service providers able to service used LIBs and support second life solutions; facilitating disassembly and modules’ exchange. The capacity to test, refurbish and certify LIBs for performance and safety can greatly promote market trust for second life LIBs.
- Regulatory targets for the collection and recycling rates for EoL EV batteries will provide incentives for more efficient reverse supply chains but would need to be coupled with well-functioning stewardship and take-back schemes operated jointly with the private sector.

References

Adrian, K. et al. (2021), “An Overview of Parameter and Cost for Battery Electric Vehicles”, *World Electric Vehicle Journal*, Vol. 12/1. [3]

Agarwal, S. and M. Rosina (2020), “Lithium-Ion Battery Recycling Market and Technology Trends 2020”, *Market & Technology Report. Yole Développement*, https://s3.i-micronews.com/uploads/2020/07/YDR20092_Li-ion_Battery_Recycling_Trends_2020_flyer. [15]

Albertsen, L. et al. (2021), “Circular business models for electric vehicle lithium-ion batteries: An analysis of current practices of vehicle manufacturers and policies in the EU”, *Resources, Conservation & Recycling*, Vol. 172, https://doi.org/10.1016/j.resconrec.2021.105658. [24]

Audi MediaInfo (2019), *Battery recycling: Audi and Umicore start closed loop for cobalt and nickel*, https://www.umicore.com/storage/main/1217-audi-umicore-english.pdf. [43]

Chen, T. et al. (2020), “Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems”, *Transactions of Tianjin University*, Vol. 26, pp. 208-217, https://link.springer.com/article/10.1007/s12209-020-00236-w. [39]

Circular Energy Storage (2021), *The Lithium-Ion Battery Life Cycle Report*. [8]

Council of the EU (2022), *First ’Fit for 55’ proposal agreed: the EU strenghtens targets for CO2 emissions for new cars and vans*, https://doi.org/www.consilium.europa.eu/en/press/press-releases/2022/10/27/first-fit-for-55-proposal-agreed-the-eu-strenghtens-targets-for-co2-emissions-for-new-cars-and-vans/. [28]

Crompton, P. (2016), *Closed Loop Lithium Battery Recycling Still Not Economical*, https://www.bestmag.co.uk/content/closed-loop-lithium-battery-recycling-still-not-economical. [10]

Dahllöf, L., M. Romare and A. Wu (2019), *Mapping of Lithium-Ion Batteries for Vehicles; A Study of Their Fate in the Nordic Countries*, http://norden.diva-portal.org/smash/get/diva2:1364968/FULLTEXT01. [36]

de Sa, P. and J. Korinek (2021), “Resource efficiency, the circular economy, sustainable materials management and trade in metals and minerals”, *OECD Trade Policy Papers*, No. 245, OECD Publishing, Paris, https://dx.doi.org/10.1787/69abc1bd-en. [9]

DOE (2019), *Vehicle Technologies Office’s Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries*, https://www.energy.gov/sites/prod/files/2019/07/f64/112306-battery-recycling-brochure-June-2019%202-web150.pdf. [38]

Energy Storage Association, (2020), *End-of-Life Management of Lithium-Ion Energy Storage Systems*, https://energystorage.org/wp/wp-content/uploads/2020/04/ESA-End-of-Life-White-Paper-CRI.pdf. [35]

Gaines, L. (2018), “Lithium-ion battery recycling processes: Research towards a sustainable course”, https://doi.org/10.1016/j.susmat.2018.e00068. [22]

Harper, G. et al. (2019), “Recycling Lithium-Ion Batteries from Electric Vehicles”, *Nature*, Vol. 575, pp. 75-86, https://www.nature.com/articles/s415. [5]

Hettesheimer, T. et al. (2019), *Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1; Technologies – For Ecodesign and Energy Labelling*, https://ecodesignbatteries.eu/sites/ecodesignbatteries.eu/files/attachments/2019_08_16_Task%204_Technologies_final.pdf. [32]

Hill, N. et al. (2019), *Circular Economy Perspectives for the Management of Batteries Used in Electric Vehicles; Final Report for the European Commission, Joint Research Centre*, https://doi.org/10.2760/537140. [16]

Huo, H. et al. (2017), "Safety requirements for Transportation of Lithium Batteries", *Energies*, Vol. 10, https://doi.org/doi:10.3390/en10060793. [23]

IEA (2022), *Electric vehicles - Technology deep dive*, https://www.iea.org/reports/electric-vehicles. [2]

International Energy Agency (2021), *Electric Vehicles*, https://www.iea.org/reports/electric-vehicles. [1]

Kelleher Environmental (2019), *Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries*, https://www.api.org/-/media/Files/Oil-and-Natural-Gas/Fuels/Kelleher%20Final%20EV%20Battery%20Reuse%20and%20Recycling%20Report%20to%20API%2018Sept2019%20edits%2018Dec2019.pdf. [14]

Kommerscollegium (2020), *Rules of Origin for the 21st Century*, https://www.kommerskollegium.se/globalassets/publikationer/rapporter/2020/rules-of-origin-in-the-21st-century.pdf. [26]

Lindhqvist, T. (2000), *Extended producer responsibility in cleaner production: Policy principle to promote environmental improvements of product systems.*, https://lup.lub.lu.se/search/ws/files/4433708/1002025.pdf. [30]

Lohani, A. (2020), "Recycling Li-Ion Batteries: Opportunities and Challenges", *Observer Research Foundation*, https://www.orfonline.org/expert-speak/recycling-liion-batteries-opportunities-challenges-68409/. [7]

Malinauskaite, J., L. Anguilano and X. Schmidt Rivera (2021), "Circular waste management of electric vehicle batteries: Legal and technical perspectives from the EU and the UK post Brexit", *International Journal of Thermofluids*, Vol. 10, https://doi.org/10.1016/j.ijft.2021.100078. [21]

McKinsey (2021), *Why the automotive future is electric*. [40]

McKinsey (2019), *Second-life EV batteries: The newest value pool in energy storage*, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage#. [34]

Melin, H. (2019), *The lithium-ion battery end-of-life market-a baseline study*, https://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf. [41]

Mossali, E. et al. (2020), "Lithium-Ion Batteries towards Circular Economy: A Literature Review of Opportunities and Issues of Recycling Treatments", *Journal of Environmental Management*, Vol. 264, https://www.sciencedirect.com/science/article/pii/S0301479720304345. [12]

OECD (2009), *Guidance Manual for the Implementation of Council Decision C(2001)107/FINAL, as amended, on the Control of Transboundary Movements of Wastes Destined for Recovery Operations*, https://dx.doi.org/10.1787/9789264060753-en. [18]

OECD (1998), *Final Guidance Document for Distinguishing Waste from Non-Waste*, https://doi.org/ENV/EPOC/WMP(98)1/REV1. [19]

Pagliaro, M. and F. Meneguzzo (2019), “Lithium battery reusing and recycling: A circular economy insight”, *Heliyon*, Vol. 5/6, https://doi.org/10.1016/j.heliyon.2019.e01866. [11]

ReCell (2020), *Fourth Quarter Progress Report 2020*, https://recellcenter.org/2020/12/02/recell-advanced-battery-recycling-center-fourth-quarter-progress-report-2020. [37]

ReCell (n.d.), *Direct Cathode Recycling*, https://recellcenter.org/research/direct-cathode-recycling/. [27]

Secretariat of the Basel, Rotterdam and Stockhold Conventions (2014), *Manual for Customs Officers on Hazardous Chemicals and Wastes under the Basel, Rotterdam and Stockholm Conventions*, http://www.basel.int/Implementation/Publications/TrainingManuals/tabid/2363/Default.aspx. [25]

Sun, S. et al. (2021), “Management status of waste lithium-ion batteries in China and complete closed-circuit recycling process”, *Science of the Total Environment*, Vol. 776, https://doi.org/10.1016/j.scitoenv.2021.145913. [42]

United States Geological Survey (2021), *Cobalt*, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cobalt.pdf. [4]

Wappelhorst, S. (2020), *The end of the road ? An overview of combustion-engine car phase-out announcements across Europe*, https://theicct.org/sites/default/files/publications/Combustion-engine-phase-out-briefing-may11.2020.pdf. [29]

WEF, White&Case (2020), *Comparative Analysis of Legal Frameworks*, https://www3.weforum.org/docs/WEF_Annex_Comparative_Analysis_of_Legal_Frameworks_2020.pdf. [20]

World Bank (2020), *Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery Energy Storage Systems*, https://faraday.ac.uk/wp-content/uploads/2020/10/Reuse. [33]

World Economic Forum (2019), *A Vision for a Sustainable Battery Value Chain in 2030; Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation*, https://pacecircular.org/sites/default/files/2020-01/A%20Vision%20for%20a%20Sustainable%20Battery%20Value%20Chain%20in%202030%20-%20Global%20Battery%20Alliance_0.pdf. [13]

Xu, C. et al. (2020), “Future Material Demand for Automotive Lithium-Based Batteries”, *Communications Materials*, Vol. 1/99, pp. 1-10. [6]

Yamaguchi, S. (2022), *Securing reverse supply chains for a resource efficient and circular economy*, https://doi.org/10.1787/6ab6bb39-en. [17]

Zhao, Y. et al. (2021), *Australian landscape for lithium-ion battery recycling and reuse in 2020 - Current status, gap analysis and industry perspectives, CSIRO*, https://fbicrc.com.au/wp-content/uploads/2021/03/CSIRO-Report-Australian-landscape-for-lithium-ion-battery-recycling-and-reuse-in-2020.pdf. [31]

Annex A.

Table A.1. The number of patent applications by applicant and their country of origin

Applicant	Applications	Country
Sumitomo Metal Mining	17	Japan
SK Innovation	16	Korea
JX Nippon Mining & Metal	15	Japan
LG Chem	15	Korea
LG Energy Solution	13	Korea
Basf	12	Germany
Guangdong Bangpu Recycling Technology	10	China
Dowa Eco-System	8	Japan
Commissariat à l'Energie Atomique et aux Energies Alternatives	5	France
Panasonic	5	Japan
Umicore	5	Belgium
CATL	4	China
Chinese Academy of Sciences	4	China
Denso	4	Japan
Lilac Solutions	4	United States
University of California	4	United States
Urban Mining Company, Nmr 360	4	United States
APB	3	Japan
Dongwoo Fine Chem	3	Korea
Ecopro Innovation	3	Korea
Kawasaki Heavy Industries	3	Japan
Zhongke Process (Beijing) Technology	3	China
Bromine Compounds	2	Israel
Duesenfeld	2	Germany
Eco Home	2	Norway
Guangdong Haozhi Technology	2	China
Honda Motor Industry	2	Japan
Hulico	2	United States
Hunan Jinyuan New Materials	2	China
Li Industries	2	United States
Li-Cycle	2	Canada
Mitsubishi Electric Corporation	2	Japan
Montanuniversität Leoben	2	Germany
Northvolt	2	Sweden
Nemaska Lithium	2	Canada
Sasakura Engineering	2	Japan
Subaru	2	Japan
Virginia Tech	2	United States
Worcester Polytechnic Institute	2	United States
XProEM	2	Canada

Note: The number of Patent Cooperation Treaty (PCT) patent applications with priority date between 2017 and 2020 related to LIB recycling. Applicants with at least two applications.
Source: OECD calculations based on Google Patents.

Methodology to collect data on patent applications related to LIB recycling

We use the Google Patents database, which contains the universe of patent applications submitted to the World Intellectual Property Organization (WIPO). Each search result can be downloaded in a csv format including the patent ID, the name of the applicant, the priority date, and the patent title. The current international patent classification does not have specific codes for the recycling or reuse of lithium ion batteries. We therefore used a full text search of key words combined with selected Cooperative Patent Classification (CPC) codes (Table A.2). The selection of CPC codes and their combinations is based on two sources: (1) a dataset from Circular Energy Storage that lists patent applications related to LIB recycling; (2) a broad Google Patents pre-search based on key words 'lithium ion recycling', 'lithium ion recovery' and 'lithium ion waste', which was then manually filtered considering the first 200 most relevant (as determined by Google) results.

All searches were limited to international patent applications submitted to WIPO under the Patent Cooperation Treaty (PCT) with priority date from 1 January 2017 (in the Google Patent search language: 'country:WO after:priority:20170101'). Patent application quality and value are highly heterogeneous. Limiting the dataset to applications submitted to WIPO helps to some extent solve this issue. International patent applications are costlier than domestic ones and therefore it is expected that applicants go through the process only for inventions that they consider of high value. Priority date is the date closest to the actual invention.

The results of the search still contain many patents that are not relevant to LIB recycling. Besides obviously irrelevant patents, we make sure to keep only inventions that relate to lithium-ion batteries (as opposed to other types) and, if concerning lithium recovery, that relate to extraction of lithium from battery recycling streams (as opposed to other sources). We proceed in two steps. First, we use a Stata code to exclude patent applications that include in their title the words "lead", "brine", "bitumen", "clay", "aqueous", "calcium", "ore" or "sulfide". Then, we check the abstract and description of the remaining patents to make sure that they are relevant. During this process, we also determine the stage of reycling/reuse to which the patent relates. A few patents relate to both pre-processing and material recovery, in which case we assign them to material recovery. For the reuse category, we exclude patents related to the monitoring of battery health during its usage.

Table A.2. CPC codes and key words used in the Google Patents search

CPC codes	Key words	Areas covered
H01M10/54	((lithium) OR (li-ion))	Reclaiming serviceable parts of waste accumulators
Y02W30/84	((lithium) OR (li-ion))	Recycling of batteries or fuel cells
H01M10/4242 AND H01M10/052		Regeneration of electrolyte in accumulators AND Li-accumulators
H01M10/4242 AND Y02E60/10	((lithium) OR (li-ion))	Regeneration of electrolyte in accumulators AND Technologies enabling energy storage using batteries
G01R31/36	((lithium) OR (li-ion)) AND (reuse)	Arrangements for testing, measuring or monitoring the electrical condition of accumulators or electric batteries, e.g. capacity or state of charge
G01R31/392	((lithium) OR (li-ion)) AND (reuse)	Determining battery ageing or deterioration, e.g. state of health
Y02W30/84	((lithium) OR (li-ion)) AND (reuse)	Climate change mitigation technologies related to solid waste management - recycling of batteries or fuel cells
Y02P10/20 AND C25C3/02	((lithium) OR (li-ion))	Recycling technologies related to metal processing AND Electrolytic production, recovery or refining of alkali or alkaline earth metals by electrolysis of melts
Y02P10/20 AND C22B26/12		Recycling technologies related to metal processing AND Obtaining lithium
Y02P10/20 AND C22B7/006	((lithium) OR (li-ion))	Recycling technologies related to metal processing AND Wet processes to produce non-ferrous metals and compounds thereof from scrap
Y02P10/20 AND C22B7/007	((lithium) OR (li-ion))	Recycling technologies related to metal processing AND Acid leaching to produce non-ferrous metals and compounds thereof from scrap
Y02P10/20 AND C22B23/02	((lithium) OR (li-ion))	Recycling technologies related to metal processing AND Obtaining nickel or cobalt by dry processes

Box A A.1. Heterogeneity in classifications of used plug-in electric vehicles in national trade statistics

United States

8703.60 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **both spark-ignition internal combustion** reciprocating piston engine **and electric motor** as motors for propulsion, capable of being charged by plugging to external source of electric power

– Of a cylinder capacity exceeding 1,500 cc but not exceeding 3,000 cc

  – Other than motor homes

    – New: 8703.60.0020, 8703.60.0030, 8703.60.0040

    – Used: 8703.60.0045

– Of a cylinder capacity exceeding 3,000 cc

  – Other than ambulances, hearses and prison vans, and motor homes

    – New: 8703.60.0060, 8703.60.0070, 8703.60.0080

    – Used: 8703.60.0090

8703.70 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **both compression-ignition internal combustion** piston engine (diesel or semi-diesel) **and electric motor** as motors for propulsion, capable of being charged by plugging to external source of electric power

– Of a cylinder capacity exceeding 1,500 cc but not exceeding 2,500 cc

– New: 8703.70.0030

– Used: 8703.70.0050

– Of a cylinder capacity exceeding 2,500 cc

– Other than ambulances, hearses and prison vans, and motor homes

– New: 8703.70.0070

– Used: 8703.70.0090

European Union

8703.60 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **both spark-ignition internal combustion** reciprocating piston engine **and electric motor** as motors for propulsion, capable of being charged by plugging to external source of electric power

– New: 8703.60.10

– Used: 8703.60.90

8703.80 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **only electric motor** for propulsion (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 870310)

– New: 8703.80.10

– Used: 8703.80.90

Japan

8703.60 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **both spark-ignition internal combustion** reciprocating piston engine **and electric motor** as motors for propulsion, capable of being charged by plugging to external source of electric power

– Used: 8703.60.100

– Other than used: 8703.60.900

8703.80 – Motor cars and other motor vehicles principally designed for the transport of <10 persons, incl. station wagons and racing cars, with **only electric motor** for propulsion (excl. vehicles for travelling on snow and other specially designed vehicles of subheading 870310)

– Used: 8703.80.100

– Other than used: 8703.80.900

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Comments are welcome and can be sent to tad.contact@oecd.org.