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Lithium-ion batteries for energy and mobility: Ensuring the environmental sustainability of current plans

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Introduction

This paper, produced in the context of EPFL International Risk Governance Center's (IRGC) project about ensuring the environmental sustainability of emerging technology outcomes, presents concerns raised by policy and industry decisions to develop large-scale plans to produce electric batteries for the mobility and energy sectors without adequate large-scale plans being made upfront for recycling, reusing or disposing of them. Ultimately, this may contribute to aggravating certain environmental challenges.

The rapid improvements of lithium-ion batteries (LIBs) in terms of performance and lifetime over the past decade, combined with decreasing costs and increasing global demand, put this technology at the forefront of electrochemical energy storage markets. LIBs are everywhere: in consumer electronics, industrial machinery, home storage and electric vehicles (EV).

EVs are considered a key technology to decarbonise the transport sector and achieve the climate target defined in the Paris Agreement (International Energy Agency, 2021).

There were over 21 million EVs worldwide in June 2022 (BloombergNEF, 2022) but, by the end of the decade, this number could increase to more than 350 million (International Energy Agency, 2022). When those vehicles reach their end of life, there will be around 8.6 million tons of lithium-ion batteries per year (Ruiz Leotaud, 2021) that need to be disposed of, recycled, or reused in an economical and sustainable manner (Thompson et al., 2020). While the ease of collection and the vast quantities of electric car batteries that will reach end-of-life offers an excellent opportunity to create a more robust value chain, since recycled materials can decrease the pressure on mining, it also brings various technical and economic challenges. The different designs, different LIBs chemistries and the high voltage of EV batteries mean that safe dismantling remains complex, sometimes dangerous, and time-consuming.

Moreover, global decarbonisation will require the electrification of other sectors, i.e., the industrial, energy generation, commercial and residential sectors. Looking at the energy sector, greenhouse gas (GHG) emissions will be reduced by increasing the penetration of renewable energy sources. In countries like Germany, production from renewable sources will account for more than 50% of the electricity supply in 2030. Dealing with intermittent renewable energy sources will be facilitated by installing batteries that can balance production and consumption. Moreover, batteries can increase the flexibility of the grid by balancing short-term energy fluctuations, avoiding investment in upgrading the power transmission and distribution infrastructure, allowing a more decentralised energy system, and eventually bringing electricity to off-grid communities.

Looking at the scale of the market segment, the expected evolution of the technology and the resources needed to achieve them, the coordination between economic, environmental, social, and regulatory entities is essential to assure the sustainability of LIBs.

Currently, the percentage of LIBs that are recycled is uncertain but ranges from 15% (Gaines et al., 2021) to 50% (Maisch, 2019). As of late 2021, there are at least 32 established or planned facilities for LIB recycling with roughly 322,500 tons of recycling capacity (J. Z. Baum et al., 2022) but given the projection of LIBs deployment in the next years, additional recycling facilities will be needed.

The biggest challenges for LIBs recycling are (1) separating small cells from other e-waste and (2) coping with the currently low volumes of EV and other large-format batteries that make operating plants at scale not profitable. However, the current low recycling rate should not be considered the only bottleneck of the LIB value chain. Other challenges that should be considered are, for example, (1) the sourcing of critical materials for the conspicuous volumes needed in the EV market, especially considering the geopolitical conditions, (2) the importance of using the battery as long as possible (during the first and second life — the longer the use, the lower the material request for new battery systems as well as the lifetime emissions), (3) the necessity to improve dismantling and remanufacturing to increase the ratio of material that can be recycled and/or reused. All of these elements aim to build a business model that will allow for a sustainable and low-risk value chain around batteries by pivoting from the current linear trajectory of the value chain to creating a circular one. Globally, moving from a linear to circular economic model for LIBs "could result in a reduction of 34 Mt of greenhouse gas (GHG) emissions while creating an additional economic value of approximately US$35 billion" (World Economic Forum, 2019).

Table 1 | Some facts about the scale of LIB developments and needs for recycling and disposal, indicating the potential sheer size of the upcoming sustainability challenge

In June 2022, there were over 21 million EVs on the road globally, but by the end of the decade, this number could increase to 350 million.	(International Energy Agency, 2022; BloombergNEF, 2022)
Currently, the percentage of LIBs that are recycled is uncertain but ranges from 15% to 50%.	(Gaines et al., 2021) (Maisch, 2019)
Since 2010, the global manufacturing capacity of lithium-ion batteries has increased 33-fold, with the most significant increase in the automotive industry.	(Baker McKenzie, 2022)
The global battery demand is expected to increase 14-fold by 2030, and the European Union (EU) could account for 17% of that demand.	(European Parliament, 2022)
The expected supply increase for major raw materials in 2030, with respect to 2018 levels, is about 4 times for cobalt, 6 for lithium and 24 for class 1 nickel.	(World Economic Forum, 2019)
It is forecast that, in 2025, 27% of batteries from the automotive sector will have a second life in stationary applications, while the rest will be available for recycling.	(Curry, 2017)
By 2030 the total annual European LIB recycling market could reach about 130 GWh, equivalent to more than 700 kilotons of recycling capacity needed. This number is expected to increase three-fold by 2040 as more EV batteries reach the end of their life. Up to €555 million could be recovered by 2030 from the four critical materials (nickel, lithium, cobalt and graphite) from EV batteries. In 2040, these figures will increase up to €2.6 billion. Therefore, recycling, as opposed to extracting the raw material, may help reduce CO_2 emissions, with a net savings of over 1 million tons of CO_2-eq in 2040.	(Navarro et al., 2022) (Drabik & Rizos, 2018) (Dominish et al., 2021)
Moving from a linear to circular economic model for LIBs "could result in a reduction of 34 Mt of greenhouse gas (GHG) emissions while creating an additional economic value of approximately US$35 billion".	(World Economic Forum, 2019)

1.

Sustainability challenges and regulatory framework

Current LIBs pose environmental, economic, social, legal and even ethical challenges in the different stages of the value chain, starting from the production/manufacturing, passing through the use of these systems and down to the recycling/disposal.

The socio-environmental risks can be linked to the rapid growth of the volume of this technology on the market. Since 2010, the global manufacturing capacity of LIBs has increased 33-fold (Baker McKenzie, 2022), with the most significant increase in the automotive industry. As a result, the global battery demand is expected to increase 14-fold by 2030, and the EU could account for 17 % of that demand (European Parliament, 2022).

Given the segment's scale and strategic importance, different countries are issuing legislative proposals to create a regulatory framework to ensure sustainability along the entire value chain.

At the end of 2020, the EU created a proposal for a regulation on batteries and waste batteries that is oriented towards modernising EU battery legislation to ensure the sustainability and competitiveness of EU battery value chains (European Commission, 2020b). The proposal is part of the European Green Deal (European Commission, 2019), the new Circular Economy Action Plan (European Commission, 2020a) and the new industrial strategy (Berger et al., 2022; Global Battery Alliance, 2022). More precisely, the circular economy action plan identified batteries as one of the resource-intensive sectors with a high potential for circularity to be addressed as a matter of priority. Specifically, the Global Battery Alliance and the EU promote the Battery Passport.

This instrument can be used as a global solution to share the information and data of battery systems needed for recycling, which can prove responsibility and sustainability to consumers while enabling resource efficiency across the battery life cycle. The standardisation provided by the Passport could serve as an incentive and support industry marketing strategy, branding and reputation. Thus, the Battery Passport will not only enable transparency and standard setting but also support progress tracking of the entire industry over time.

In China, the world's largest lithium battery consumer market, the scale of the lithium battery industry reached 324 GWh in 2021, four times that of 2017. In the same year, the global LIB market reached 545 GWh and China accounted for more than half of the total. Moreover, by the end of 2021, China held 70% of the world's global total battery production capacity (Pandaily, 2022). At the same time, China is also leading the recycling market, with installed recycling facilities with up to 188,000 tonnes of battery recycling capacity (J. Z. Baum et al., 2022).

The first Chinese legislation about battery recycling, introduced in the mid-1990s, mainly focused on batteries containing mercury and cadmium. Only in 2018 was a regulation on EV end-of-life LIB management issued. Along with other successive and more recent guidelines, an overall policy framework for today's battery recycling industry in China was defined. The key elements of this policy framework are (1) encouragement of manufacturers to design batteries for easy disassembly; (2) obligation of manufacturers to provide the technical information necessary for end-of-life battery treatment; (3) promotion of cascaded application and second life of batteries; (4) responsibility of EV and battery producers for battery waste treatment; (5) responsibility of cascaded application companies, EV makers and battery producers for establishing waste battery collection outlets; (6) material recovery targets (Neumann et al., 2022). Despite the well-thought-out framework, current estimates indicate that only 30–40% of battery materials are recycled (Hampel, 2022).

As evident from the regulatory frameworks of the EU and China, taken as examples, progress in the sustainability of LIBs will not be effective if the challenges in a specific phase of their lifetime are addressed individually. Therefore, a systemic and holistic approach should be embraced to create feasible and genuinely sustainable solutions.

1.1 Risks during manufacturing

The sharp increase in battery production demand also requires the availability of certain raw materials for production to ramp up, which increases risks in the manufacturing process that can affect the availability, price and sustainability of the final product.

The materials used for batteries are numerous. Some are highly abundant (carbon), while others are scarce (cobalt) and concentrated in some geographical regions. The impact of mining minerals is inherently associated with social and environmental problems, and those mined for battery production are no exception, as has been well documented over the last years (Conde, 2017; González & de Haan, 2020; Kallitsis et al., 2022).

The expected supply increase for major raw materials in 2030, with respect to levels of 2018, is about 2 times for cobalt, 6 for lithium and 24 for class 1 nickel (World Economic Forum, 2019). Even if global reserves have been proven to exceed forecast demand (Buchert et al., 2018), lithium and cobalt mining sourcing is a well-known social, economic and environmental- challenge and a possible bottleneck for the LIB supply chain (Olivetti et al., 2017).

Mining battery raw materials like lithium, cobalt and nickel is labour-intensive, requires chemicals, uses energy coming from CO_2-emitting fossil fuels (for every tonne of mined lithium, 15 tonnes of CO_2 are emitted into the air (Crawford, 2022)), requires enormous amounts of water, and can leave contaminants and toxic waste behind. Lithium extraction from salt brines in South America (Chile, Argentina and Bolivia hold 75% of the world's lithium resources (González & de Haan, 2020)) comes with concerns of contamination of local water basins and salinisation of fresh water. Cobalt mining in the Democratic Republic of the Congo (accounting for 70% of the world's total production (González & de Haan, 2020)) has raised numerous issues related to human rights violations such as child labour and environmental damage.

Other risks might occur for other metals as well. For example, the Russian-Ukraine conflict disrupted the EU nickel market, as Russia is the biggest exporter of this metal to Europe (Jain, 2022).

Even if the critical materials can and will be recovered by recycling, the volume will not be enough to compensate for the rising demand expected in the coming years (Zeng et al., 2022).

Along with raw materials sourcing, some details of the manufacturing processes can be taken into consideration. Energy intensity and pollution must still be addressed depending on how and where the battery is manufactured. After mining, raw materials are subsequently refined and processed to produce active electrode materials as core components of battery cells. Asia Pacific accounted for 81% of the global manufacturing capacity of LIBs in 2020 (with 73% of the global capacity manufactured in China) (Baker McKenzie, 2022). Electricity used in the battery manufacturing process accounts for about half of the emissions associated with battery production, so increased use of renewable energy and more efficient power plants will lead to cleaner batteries. The expected drop of 30% in the average carbon intensity of global electricity production by 2030 will translate to a 17% reduction in the emissions related to battery production (Hall & Lutsey, 2018). However, coal is the primary energy source in China, the biggest battery producer.

Different solutions and propositions on how to act around these risks exist, including to:

1. Increase efficient use of raw materials, limit waste and increase quality during manufacturing.
2. Propose raw materials governance (Bechberger & Vorholt, 2021).
3. Increase the use of synthetic fabricated material (as is already the case for graphite) or secondary metals (as is the case for platinum) (World Economic Forum, 2019).
4. Suggest regulatory programmes for mining, for example dictating the maximum level of extraction (Buchert et al., 2018).
5. Request transparency and identification of what materials have been used and from where they have been mined.
6. Include ethical aspects — such as human rights abuses and environmental risks in the product identification of batteries (Amnesty, 2019).
7. Switch towards different use of chemistries and electrode designs. For example, lithium iron phosphate batteries (LFP) have gained popularity, and different battery manufacturers are increasing the proportion of battery production with electrodes that do not contain cobalt. Moreover, recent developments have demonstrated that this formulation can reach higher energy density and battery lifetime compared to the past, decreasing the gap with nickel manganese cobalt batteries (NMC) and thus allowing their implementation for mobility purposes (Zeng et al., 2022).
8. Demand high levels of vertical integration so that original equipment manufacturers (OEM) or battery manufacturers become increasingly involved in the supply chain up to the mining stage (Bernhart, 2022). Occupying critical control points along the supply chain can provide a strong competitive advantage and mitigate supply chain risk and abuse.
9. Encourage public and large companies with high purchasing power to request sustainable and responsible manufacturing conditions in producing EVs. At the same time, appropriate purchasing criteria can promote the necessary transparency in supply chains (Bernhart, 2022).
10. Manufacture with renewable energy and scale up manufacturing sites to reduce energy waste (this is already the case for the EU market).
11. Move toward flexible, innovative and versatile plants that can accommodate or enable a change in technology toward the new chemistries of the future, especially in the EU, where major manufacturing plants are currently being built (Claussnitzer, 2020).

The most effective recommendations that can mitigate the sustainability risks linked to the sheer size of the problem include a long-term supply strategy, responsible sourcing, safe and energy-efficient manufacturing processes, and technologies that will allow enhanced resource efficiency and lower the dependence on primary raw material sourcing.

1.2 Risks during using and reusing

Efficient battery use during their lifetime can contribute considerably to the sustainability of the technology, as it decreases the environmental burdens associated with the production of new systems as well as the disposal of used batteries. If the battery systems can be used as long as possible, the use of materials needed to build new systems can be avoided, and the emissions originating from the mining, manufacturing and disposal processes can be spread over a longer lifetime.

By minimising exposure to conditions that accelerate degradation, batteries can last longer. The critical conditions are related to three main variables that impact battery health: temperature, state of charge and current. The battery management system (BMS) records and monitors these variables in real-time. For example, extreme temperatures (both high and low) when using or storing LIBs should be avoided. Elevated temperatures, in particular, can accelerate the degradation of almost every battery component and lead to significant safety risks, including fire or explosion. Likewise, the time the battery spends at a low or high state of charge should be limited. Especially the low state of charge could bring the battery to an over-discharge state that can be dangerous and require the battery to be replaced. Additionally, since high current for both charge and discharge contributes to performance degradation, fast charging and intense use should be metered (Woody et al., 2020).

When batteries reach the end of their first life (meaning that they reached the end of their usefulness and can no longer operate at sufficient energy and/or power for the intended application), they can still hold 70—80% of their initial capacity. Because considerable value is embedded in manufactured LIBs, it is recommended that their use should be cascaded through a hierarchy of applications to optimise material use and life cycle impacts. For this reason, before batteries are recycled to recover critical energy materials, reusing batteries in secondary applications (provided the battery's cells are undamaged) is a promising strategy that will allow them to operate for several more years in a less demanding function. However, deciding if a battery should be recycled or reused is a trade-off problem that should be solved by identifying the value-maximising path between the two options.

Batteries used in EVs lose roughly 2.3% of their energy capacity annually, meaning a new 64 kWh battery might have 48.4 kWh of its original storage capacity after 12 years (Berman, 2019). According to various studies, cars run for a full twelve years in the EU. A battery with 48 kWh capacity is still a useful product with the possibility of having a second life, even if it is insufficient for use in an EV. Energy storage systems can use these batteries after the EV itself has reached the end of its life (Casals et al., 2017). These batteries can be used in residences, microgrids and as utility-scale storage. Reuse can double the useful lifetime of the batteries. After that, they can be recycled.

It is forecast that, in 2025, 27% of the batteries from the automotive sector will have a second life in stationary applications, while the rest will be available to be recycled (Curry, 2017). The European Commission (EC) DG Joint Research Centre listed the main barriers to determining the suitability of a battery to be used in a second-life application (Hill et al., 2019). It stated that "only with professional diagnostic equipment used by experts who have the knowledge on how to get the history out of the battery management system (BMS), can that advice or decision be taken" to unlock the second life market potential.

Concerning the battery's first life with regard to use in EVs, charging time and range availability still limit their large-scale adoption. People are not yet in favour of a means of transportation that cannot offer the same benefits as an internal combustion engine (ICE), such as refueling in a few minutes and being able to travel over a longer range before needing to refill. For this reason, fast charging (that can decrease battery lifetime), as well as swappable battery stations (Siddiqi & Edmondson, 2022) (exchange a battery with a charged one), are some of the proposed concepts for improving EV acceptance, along with increasingly powerful batteries. Especially the last two points might suggest that if the consumer mindset is not changed, higher numbers and larger-sized battery systems than those needed will be produced, affecting the sustainability potential of the technology.

Moreover, battery data should be tracked and made available during the battery's first life. By doing so, real-time operating strategies can be suggested to increase lifetime and avoid improper use that might lead to the inability to use the battery for a second life or even create safety hazards.

Avoiding adverse conditions should be of particular interest to users, as there are significant financial incentives to extend the battery lifetime, as the cost of LIBs can range from 5% to over 50% of a product's cost (University of Michigan, 2022).

Other challenges and risks linked to the use/reuse phase are associated with several factors, including a large number of battery pack designs with different sizes, chemistries and formats, missing regulatory schemes for data exchange, improper use of batteries, no guarantees on second life battery quality or performance, and the absence of an incentive scheme that will allow higher battery reuse.

Thus, despite the promise of circular economy solutions for end-of-first-life LIBs, many unknowns still limit widespread adoption, especially related to liability issues and regulatory voids (Babbitt, 2020).

Different solutions and propositions on how to act around these risks include to:

1. Allow easy interexchange of complete BMS data recorded during use. With the Battery Passport, the EC is already moving in this direction even if it is not yet indicated which essential data (for the use phase) need to be recorded and made available, leaving space for non-uniformity and obstacles due to intellectual or proprietary data.
2. Define which data should be recorded during operation to allow an understanding of the wide variation in the state of health (SoH) across an EV pack during its life and its possible exposure to temperature extremes, overcharging and/or charging at high currents, all of which can increase the potential for thermal runaway and safety concerns (Mrozik et al., 2021).
3. Put in place an incentive scheme for people to return their batteries to allow for reuse and circularity.
4. Define standards for testing used batteries and create a market of second-life batteries without safety risks and with acceptable performance.
5. Formulate liability schemes for second-life batteries.
6. Define a target for reuse since it is not yet part of the EU proposal (Nature, 2021).

The main strategies to guarantee the sustainability of the expected large-scale market should focus on the definition and adoption of data storage standards and open protocol for data transfer, system design and sensing.

1.3 Risks during recycling/remanufacturing

When direct reuse of a LIB system is not possible, recycling it is the best option as it closes the loop of the battery value chain. End-of-life LIB recycling could provide substantial economic benefits, as it reduces the need for new mineral extraction and can improve weaknesses in the supply chain.

According to some estimates, by 2030, the total annual European LIB recycling market will reach about 130 GWh (equivalent to more than 700 kilotons of recycling capacity needed), and this number is expected to increase three-fold by 2040 as more EV batteries reach the end of their life (Navarro et al., 2022). A study conducted by the Centre for European Policy Studies (CEPS) estimated that up to €555 million could be recovered by 2030 from the four critical materials (nickel, lithium, cobalt and graphite) from EV batteries (Drabik & Rizos, 2018). In 2040, these figures will increase up to €2.6 billion. Recycling has the potential to reduce primary annual demand compared to total demand in 2040 by approximately 25% for lithium, 35% for cobalt and nickel and 55% for copper (Dominish et al., 2021).

However, the recycling processes are still far from optimal. While battery researchers and manufacturers have focused on lowering costs and increasing battery longevity and charge capacity, recycling processes are hazardous and often inefficient.

Traditionally, LIBs are recycled by means of three techniques: pyrometallurgy, hydrometallurgy and a combination of both. The first, more common, is a heat-based extraction and purification process in which the batteries are shredded and burned before the metals are extracted. In hydrometallurgy, metals are extracted from ore through a process that involves the use of a leaching agent, separation of impurities and precipitation of the metal. Neither is ideal: pyrometallurgy is energy-intensive, while hydrometallurgy uses potentially harmful chemicals (HDI Global SE, 2021). With the combination of the two approaches, batteries are shredded, heated, and then processed with an aqueous solution. Still, much can be done to improve the recycling process, especially considering the different processes needed for the various battery chemistries and the rising number of batteries that will reach end-of-life.

The efficiency of the recycling process is also limited by the battery design and the collection rate. Recently, a study from the Centre for Research on Multinational Corporations (SOMO) pointed out that battery manufacturers are currently not designing LIBs to optimise recycling (González & de Haan, 2020). Packs are not easy to disassemble, and cells are not easy to separate for recycling. LIBs are compact, complex devices of different sizes and shapes. Large battery packs in electric vehicles may contain several thousand cells grouped in modules. The packs also include sensors, safety devices, welded connectors and circuitry that controls battery operation. These elements add complexity and costs to battery dismantling and recycling. According to the International Energy Agency (IEA), “increasing collection and sorting rates is a crucial starting point to scale up recycling. Government policies can play a major role in facilitating waste collection, thereby ensuring a sufficiently large waste stream to justify infrastructure investment” (van Halm, 2022).

For these reasons, the EC is working on modernising the battery recycling directive 2006/66/EC (2006). The objective of the directive is to achieve an average LIB recycling target of approximately 70% by 2030, with the aim to recover 70% of lithium and 95% of nickel, copper and cobalt in end-of-life batteries. The updated proposals in the amended Regulation (EU) No 2019/1020 (European Commission, 2020b) also contain goals for recycled materials that must be used in new cells. These figures are 4% for lithium and nickel and 12% for cobalt by 2030.

Considering the main outstanding issues around the recycling process, propositions for dealing with uncertainties and risks include to:

1. Design new batteries for recycling so that materials can be easily separated and the recovery percentage can be increased. One of the significant challenges in setting up a performant collection infrastructure lies in the heterogeneity of battery types available on the market. LIBs are used for a wide range of applications, resulting in a large variety of battery designs that differ with regard to their capacity, shape, size and chemical composition (Neumann et al., 2022).
2. Make sure that sufficient recycled materials will be recovered, which is difficult due to the significant percentage of batteries going to second-life uses. A possible solution to obtain recycled materials to produce new batteries is to use the waste (material scrap) from battery manufacturing that can become the main source of recycled material as well as the ideal starting point (Boukhalfa et al., 2022).
3. Prevent manufacturers from being secretive about the materials and concentrations used in the batteries they produce. If the composition is not known, recycling them properly is harder. In this perspective, the Battery Passport and correct labelling will clarify which materials are used in a battery and thus facilitate recycling. Moreover, LIB chemistry is constantly evolving, making it even more challenging for those in charge of the recycling process to foresee future technologies.
4. Improve the recycling process as it remains energy-intensive and polluting because battery binders do not allow for easy separation. Thus, water-based solvents should be investigated (both for performance and durability) to allow easy recycling (Li et al., 2020). Moreover, there is a need for new technologies for material recovery that are less energy-intensive, cheaper and reduce secondary pollution. Improving the recycling process should also consider optimising the recycled materials' quality to maintain the properties needed for manufacturing new cells.
5. Define standards to decide which batteries are to be recycled and which should be used for other purposes, to avoid recycling batteries that can still serve in a second use.
6. Define responsibilities for recycling battery systems at their end-of-life, as is done for portable electronics. Furthermore, illegal disposal and informal processing that leads to severe pollution must be prevented. This could be achieved through better collection schemes, expansions and improvements in the current recycling infrastructure, and posing legal obstacles to exporting second-hand EVs or LIBs (Mrozik et al., 2021).

All of the proposed solutions will help handle the expected rise in the volume of LIB to be recycled, but especially the first points (1 to 3) will help achieve current policy targets (for collection and material recycling rates) and allow the recycling process to be economically viable with the smaller volumes of LIB available today. However, developing the recycling capacity to meet the expected needs will require a clear policy framework with strong monitoring to prevent the growth of informal markets. It will also require heavy investments in recycling infrastructure.

2. Conclusion

Environmental, social and economic benefits are possible by expanding a sustainable battery value chain. However, this will not be possible without coordination and immediate action by policymakers, investors and companies in consultation with all stakeholders.

Sustainability risks for the LIB industry can arise in each stage of the battery lifetime, from production to recycling. Regulatory programmes have already addressed most of these risks, but there are still open points that need to be dealt with, especially considering the large volume of battery systems that will be created, used and recycled in the following years.

In Europe, as well as in other countries, the adopted strategy is grounded in circular economy principles that can guide the sustainable management of the rising volume of end-of-life LIBs via a hierarchy of recovery pathways: direct reuse of used LIBs in vehicle applications, followed by reuse in less demanding applications (such as stationary energy storage) and material recovery through recycling which reduces the burden of mining raw materials. Each of these reuse pathways offers the potential to minimise the magnitude and pace of LIB waste generation while simultaneously reducing the life cycle environmental impacts of energy and vehicle storage systems (Babbitt, 2020).

To reach this holistic approach and create a low-risk value chain around batteries, there is a need to create a circular business model not only for large but also for small/medium enterprises which are involved in the electrification of the vehicle fleet and faced with the task of offering solutions for their end-of-life batteries.

A concrete solution already in the EU regulatory plan that could enable a circular trajectory is the Battery Passport. The Passport would support data sharing on details such as materials chemistry, battery origin, the state of health of the battery, or the chain of custody. It could provide a powerful means to identify and track batteries throughout the life cycle and, hence, support the establishment of systems for life extension and end-of-life treatment (World Economic Forum, 2019). More specifically, the Battery Passport will allow for the reduction of sustainability risks listed above and reach the following targets: (1) the reduction and/or the sustainable procurement of critical metals, (2) the reduction of waste, (3) an efficient manufacturing and recycling process, (4) the exchange of data among key stakeholders to improve the economics of life extension through repair, refurbishment and recycling, and (5) the promotion of product design and technical development to facilitate disassembly for repurposing, repair and recovery of materials. More importantly, the new circular approach will offer storage solutions in an affordable, sustainable and more democratic way to keep pace with the expected electrification necessary for the decarbonisation of different sectors.

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