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# Technology needs for realizing a circular battery supply chain

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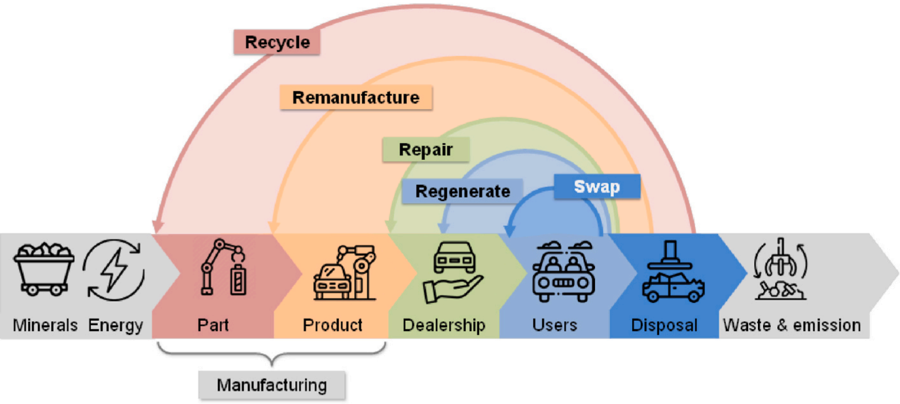
## HIGHLIGHTS

- This position paper explains how there is more to circularity than recycling.
- Strategies to prolong cell life and rejuvenate battery materials *in situ* are discussed.
- Reversible manufacturing methods can facilitate repair, reuse, and remanufacture.
- Autonomous robotic disassembly of battery packs using AI is essential to circularity.
- Metrics quantifying the value proposition of a circular battery supply chain are presented.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The growing use of batteries for energy storage will eventually result in significant waste. While recycling is currently the main option for managing this waste, existing methods are energy intensive, emit pollution, produce waste, and recover a fraction of the battery mass. The shift to cheaper battery chemistries makes recycling less economically viable as fewer high-value metals can be recovered. A circular economy approach offers a better solution by focusing on designing and manufacturing batteries with their entire lifecycle in mind. These strategies emphasize the need for material selection, design, and manufacturing approaches that can maintain battery performance for as long as possible. They should also facilitate disassembly to enable rework, repair, reuse, remanufacture, and recycling at the end of life. This perspective piece identifies technology needed to achieve a circular battery supply chain. Particular attention is given to material regeneration, innovative cell designs, modular pack designs, reversible manufacturing methods, and AI-enabled autonomous robotic disassembly to facilitate repair, remanufacture, and recycling; and advanced cell-level sensing methods to prolong battery life. These innovations could create new business opportunities and reduce the demand for new materials while lowering energy need and lifetime costs, and thereby maximize the environmental benefits of electrification.

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## 1. Introduction

The world is witnessing the beginning of the electric vehicle (EV) revolution. Today, about 3 % of all vehicles on the road globally are electric. This number is expected to reach 28 % by 2030 and 58 % by 2040 [1]. The EV revolution is fueled by a combination of (i) consumer demand for cleaner vehicles, (ii) fluctuations and uncertainties in the price of gasoline, (iii) reduction in the price of EVs, (iv) emerging legislation that may limit or even prohibit the sale of internal combustion engine (ICE) vehicles, and (v) financial incentives to purchase EVs in the form of rebates and tax credits. The EV revolution has been made possible by significant and rapid reductions in the price of battery packs, from about $1300/kWh in 2010 to around $130/kWh in 2023 [1]. This reduction in price has been achieved through economies of scale, improved manufacturing processes, and the introduction of new battery chemistries that reduce or eliminate the requirement for costly critical minerals, particularly cobalt [2]. These new and cheaper chemistries, such as lithium iron phosphate (LFP), are gaining market share and prices for battery packs are projected to fall below $80/kWh by 2030 [1, 3].

The electrification of light-duty vehicles and, possibly, of other modes of transportation will help decarbonize the transportation sector, which accounted for 29 % of total U.S. greenhouse gas emissions (GHG) in 2021 [4]. Replacing ICE vehicles with EVs will improve air quality in cities around the world, where more than 60 % of the global population live today. Note, however, that producing an EV emits 2–3 times more GHGs compared to producing an ICE vehicle. The EV revolution may also strengthen the energy independence and security of countries with limited oil reserves, provided robust supply chains are developed that mitigate the geographic constraints associated with accessing the critical mineral resources needed to build EVs and with deploying renewable energy capacity (e.g., wind and solar photovoltaic) to achieve a carbon-free grid.

Current battery pack manufacturing practices have been established along a linear economic model of “take, make, use, and dispose” with negligible consideration for battery end of life (EOL). Disposing of batteries, regardless of chemistry, is challenging because spent batteries pose a significant fire hazard and may leak toxic chemicals into the environment. Today, lithium-ion batteries (LIBs) from consumer electronics are responsible for two thirds of the fires at landfills and materials recovery facilities (MRF) in the United States, mostly due to cell puncture and subsequent exposure of reactive components to the atmosphere during trash handling [5]. These fires are very challenging for first responders to extinguish and can last for days or weeks, due to the presence of methane from decomposition of organic waste in landfills. These fires produce toxic smoke and often require the closure of MRFs for extended periods of time as well as the evacuation of communities surrounding landfills [5]. Thus, the anticipated increase in the number of EVs on the road will be accompanied by a significant increase in toxic and flammable battery waste that must be taken care of, albeit with a 10–20-year time lag depending on conditions of use.

Recycling is typically put forth as the solution of choice for managing battery waste. However, conventional battery recycling methods such as pyrometallurgy and hydrometallurgy are energy-intensive, emit significant quantities of GHGs, and produce large volumes of waste disposed of in landfills [6]. Recycling processes currently focus on separation and extraction of the most valuable critical minerals (cobalt, nickel, copper). However, as new and less expensive battery chemistries are introduced, the economics of recycling become more challenging as fewer high-value metals can be recovered. In addition, EV battery recycling may not be viable in the absence of regulations such as extended producer responsibility and/or financial incentives.

Herein, we suggest a more holistic approach to battery supply chain that integrates the principles of circularity. The U.S. Environmental Protection Agency (EPA) defines a circular economy as “*an economy that uses system-level approaches and involves industrial processes and economic activities that are restorative or regenerative by design. A circular economy reduces material use, redesigns materials, products, and services to be less resource intensive, and recaptures “waste” as a resource to manufacture new materials/products.*” [7] Unfortunately, the term “circularity” has often been used interchangeably with “recycling”, but this simplification does not encompass complementary approaches. The concept of circularity promotes the idea that manufactured goods and materials should be maintained at their highest level of performance for as long as possible. Current battery recycling methods shred entire battery packs or modules and thus destroy the manufacturing value of all components within, including cells that have not reached their end of life [8]. To create a circular battery supply chain, new technologies must be developed and deployed. Such technologies will extend the life of battery components and materials, better maintain manufacturing value, and reduce the volume of spent battery waste sent to landfills.

This perspective piece aims to provide a vision for achieving a circular battery supply chain. It starts by recognizing that recycling is not the primary and only pathway to closing the supply chain. Instead, recycling should be considered as a process of last resort. Emphasis can be placed on alternative strategies and transformational technological solutions to prolong the useful life of battery cells and packs and maintain materials at their highest level of performance for as long as possible. This paper also discusses the new business models and opportunities that such a paradigm shift can offer in terms of new products

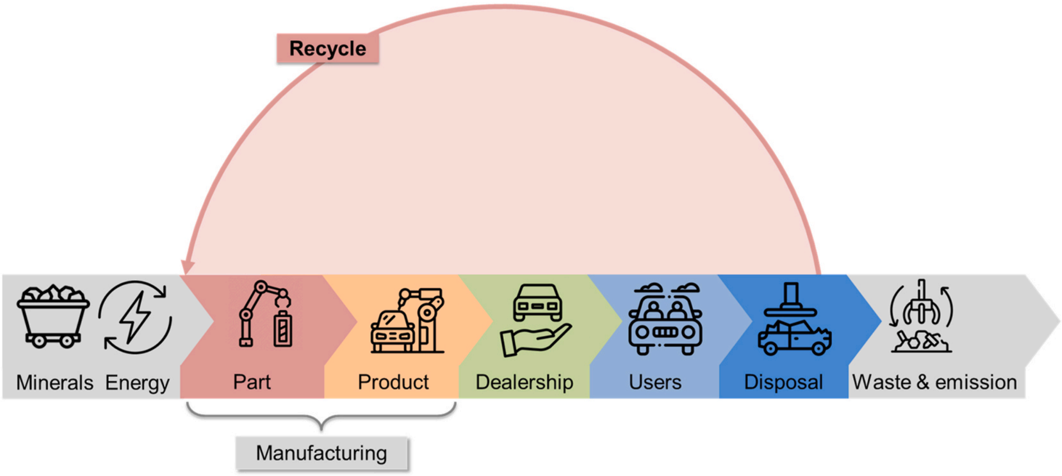

**Fig. 1.** Schematic of the current EV supply chain and how circularity is achieved through recycling only.

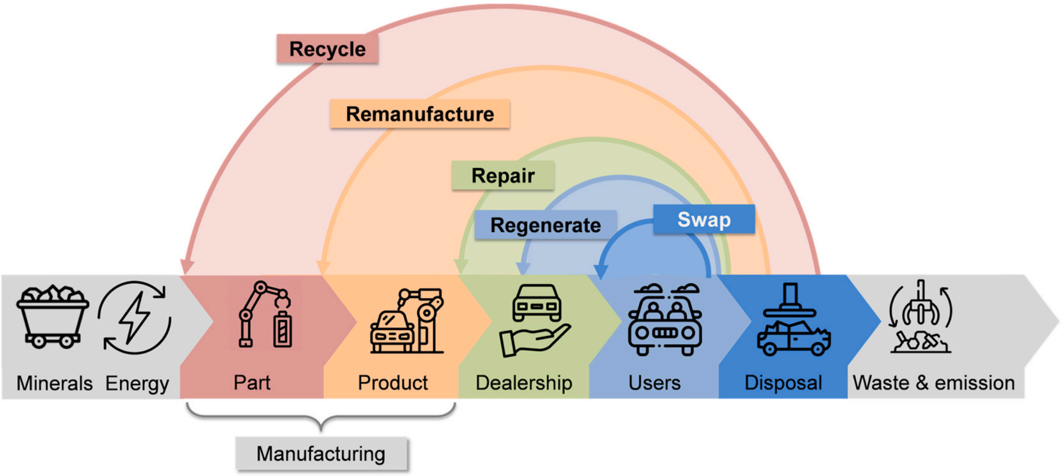

**Fig. 2.** Schematic of a circular EV battery supply chain achieved through comprehensive strategies including swapping, regeneration, repair, remanufacture, and recycling. Here, recycling is considered as a process of last resort.

and services as well as sources of revenue and cost reductions. Finally, we critically review promising technologies and define technological needs to enable circularity strategies including (i) battery swapping, (ii) materials and methods for cell regeneration, and (iii) design and manufacturing methods to enable rework, repair, reuse, and remanufacture of battery cells and packs. These different approaches will facilitate recycling by reducing the associated cost, energy demand, and carbon footprint. Overall, these technologies will enable the optimization of battery life cycle and the recovery of not only critical minerals but also manufacturing value from spent battery components. Designing batteries with EOL in mind and adopting circular supply chain strategies will lower the net-energy burden and net carbon footprint associated with batteries, reduce demand for pristine materials, and enable a more resilient, local supply chain. Such innovations are necessary to maximize the environmental benefits promised by vehicle electrification.

## 2. New business opportunities in a circular battery supply chain

### 2.1. Current linear EV battery supply chain

Fig. 1 shows the current, mostly linear, EV supply chain and the associated activities and actors, including mineral extraction and refining, cell and pack manufacturing, EV assembly, dealerships, owners, dismantlers, and waste management. To close the supply of critical minerals, the current supply chain relies on recycling. Within this mostly linear model, each participant is insular and aims to optimize its business operations and maximize profit within a specific segment of the supply chain. For example, automotive original equipment manufacturers (OEMs) and their suppliers optimize their operations for producing and selling the largest number of vehicles.

As previously stated, the market demand for EVs is increasing. Since batteries often represent around 50 % of EV price, OEMs are under considerable pressure to minimize costs above all else to remain competitive. Battery material selections and battery cell and pack designs have so far focused on performance and safety, as well as efficient and cost-effective manufacturability. Unfortunately, little consideration has been given to selecting battery materials or designing and manufacturing cells and packs with battery EOL in mind. At the same time, an overreliance on the development and deployment of recycling strategies as a primary solution by third parties has contributed to a dearth of practical waste management solutions. Indeed, the profitability of recycling EV batteries is uncertain as battery cells and packs become cheaper thanks to the use of more abundant and less expensive materials.

Most car OEMs sell EVs through dealerships, which then sell vehicles to individual car owners or corporations. In fact, many states in the United States prohibit the direct sale of cars by their manufacturers and require that cars be sold via dealerships [9]. Today, important revenue streams for dealerships include interest payments and insurance on car loans and fees associated with the service and repair of vehicles throughout their life [10,11]. However, newer EV-only manufacturers (e.g., Tesla, Rivian, Lucid Motor) have introduced a direct sales model which keeps dealerships outside the value chain and challenges the current ICE model. Moreover, ICE vehicles require significant maintenance including oil and filter changes, tire rotations, and various repairs due to their numerous moving parts. In 2023, EVs accounted for 18 % of all new vehicle sales globally (~9.5 % in the US) [12]. This fraction is expected to reach 36 % by 2030 (50 % in the U.S.) [10]. In addition, some countries and states have banned the sale of ICE cars after 2035. The fact that EVs require less maintenance than ICE cars will reduce the aftermarket revenues of dealerships. The rising share of EV sales will require dealerships to train personnel for the sale and servicing of EVs and invest in new equipment. Overall, the EV revolution will impose significant strain on dealerships and may pose an existential threat to existing ICE-based business models [13].

Currently, all roads of the EV battery supply chain pass through China. More than 75 % of EV battery cells produced globally are made in China [14]. Nearly all EV battery chemistries rely on lithium, graphite, copper, and to varying extents, cobalt, nickel, and manganese. China produces more than 60 % of the world's graphite and controls the dominant share of global lithium, nickel, and cobalt processing capacity [15]. Similarly, 80 % of global battery recycling capacity is located in China. The U.S. and E.U. have both recently launched major initiatives to jump start their domestic EV battery supply chains and reduce their dependence on imports. For example, the 2022 Inflation Reduction Act, passed in the U.S., supports the development of technologies to produce critical minerals and the deployment of domestic battery manufacturing and recycling [16].

### 2.2. A future circular EV battery supply chain

Fig. 2 illustrates the different approaches that can be developed to achieve a circular EV battery supply chain including swapping, regeneration, repair, and remanufacture. Here, recycling is considered a process of last resort. The multiple strategies presented involve a variety of actors and contrast with the current recycling-focused view of circularity, illustrated in Fig. 1.

Creating a circular supply chain focuses on optimizing the full vehicle life cycle. Thus, the focus must shift from maximizing production and sales within an ownership model to meeting customers' mobility

**Table 1**
Critical mineral content of a 60-kWh battery pack with different chemistries [20].

| Critical mineral | Battery material mass (kg) | | | |
|---|---|---|---|---|
| | NMC622<br>Ni (60 %), Mn (20 %), Co (20 %) | NMC811<br>Ni (80 %), Mn (10 %), Co (10 %) | NCA<br>Nickel cobalt aluminum oxide | LFP<br>Lithium iron phosphate |
| Lithium | 6 | 5 | 6 | 6 |
| Cobalt | 11 | 5 | 2 | 0 |
| Nickel | 32 | 39 | 43 | 0 |
| Manganese | 10 | 5 | 0 | 0 |
| Graphite | 50 | 45 | 44 | 66 |
| Aluminum | 33 | 30 | 30 | 44 |
| Copper | 19 | 20 | 17 | 26 |
| Steel | 19 | 20 | 17 | 26 |
| Iron | 0 | 0 | 0 | 41 |

needs and access in the form of (i) leasing, as it exists today, (ii) vehicle-on-demand (e.g., Zipcar®), and (iii) mobility-on-demand via robotaxis, for example [17]. These different business models can obviously coexist but will require increasing collaboration and transparency among different actors, while costs and revenues will be distributed across the supply chain.

A circular supply chain can offer new revenue streams and business opportunities by providing services to maximize EVs' lifetime performance through (1) enhancing regular predictive maintenance to prolong the life of batteries, (2) regenerating, repairing, and remanufacturing battery cells, modules, and/or packs, (3) improving the reuse and recovery of EOL parts and materials, and (4) minimizing carbon footprint and maximizing resource efficiency.

A circular supply chain also offers opportunities to reduce production and operating cost by (i) improving the quality and stability of recycled critical mineral supply chains through cell regeneration, reuse, and recycling, (ii) facilitating rework, reuse, repair, and remanufacturing of battery packs through modular designs, reversible manufacturing materials and methods, and (iii) reducing asset costs per unit amount of energy delivered owing to the retention of the embedded manufacturing value of batteries, their prolonged lifetime, and the extended use of EVs. This approach could provide EV dealerships with new sustainable business models. Additionally, making disassembly easier can offer business opportunities for second use of battery modules or packs to power less demanding mobility solutions (e.g., electric scooters) and/or for energy storage solutions for EV charging stations, for example.

Finally, automotive OEMs are the best positioned to coordinate the shift to a circular supply chain since they already play a significant role and are accountable for the end of life of EVs in countries where extended producer responsibility is enforced (e.g., China, Europe). Alternatively, mobility companies with large fleets of electric robotaxis and significant purchasing power could also become the coordinators of a circular supply chain.

## 3. State of the art of battery technologies

### 3.1. Battery chemistries

Lithium-ion batteries (LIBs) currently dominate the EV market because they have the highest energy and power densities available, and therefore, enable the largest EV ranges. Among LIBs, some of the highest energy densities and cyclabilities can be achieved using lithium nickel manganese cobalt oxide, $LiNi_xMn_yCo_zO_2$ (or NMC with $x + y + z = 1$), as the cathode active material (CAM). The anode is typically made of graphite, which is increasingly mixed with silicon, while the electrolyte is typically lithium hexafluorophosphate ($LiPF_6$) salt dissolved in organic solvent. Mixtures of ethylene carbonate (EC) and dimethyl carbonate (DMC) are commonly used as solvents. However, the supply of cobalt and nickel is limited and insufficient to meet expected increases in demand [18]. The prices of these minerals have also featured strong temporal fluctuations in recent years. Cobalt is particularly expensive, which has led the industry to reduce the amount of cobalt in the material chemistry from NMC 111 (33 % Ni, 33 % Mn, 33 % Co) to NMC 811 (80 % Ni, 10 % Mn, 10 % Co). Further cost reductions have been achieved with $LiFePO_4$ (LFP) cathodes, which contain neither nickel nor cobalt. LFP batteries are also safer and have a longer lifetime and cyclability than NMC batteries under the same conditions [19]. Table 1 summarizes the mass of critical minerals in a 60-kWh battery pack for NMC 622, NMC 811, nickel cobalt aluminum oxide $LiNi_xCo_yAl_zO_2$ (NCA), and LFP. It illustrates the historical trend towards minimizing the use of cobalt and nickel to address limited supply, fluctuating prices, and high battery cell costs.

The market share of LFP batteries has steadily increased in recent years, even though LFP batteries have half the energy density of NMC batteries (90–160 Wh/kg vs. 250–300 Wh/kg). NMC batteries still dominate the market at present, but LFP batteries accounted for 28 % of all EV batteries sold in 2022 and are projected to have the largest market share by 2028 [21]. The lower cost and lower energy density of LFP batteries makes them well-suited for entry-level vehicles. However, the fact that consumers in the U.S. prefer larger vehicles and demand longer range, could cause an ever-larger volume of low energy density of LFP batteries with limited recycling value, as discussed later in this section.

### 3.2. Cell manufacturing

Prior to cell manufacturing, critical minerals, such as cobalt, nickel, lithium, copper, and graphite, must be mined. These minerals are then refined and purified to make electrode slurries consisting of (i) active materials, in the form of nanoparticles, (ii) carbon black to increase the electrical conductivity, and (iii) binders [e.g., polyvinylidene difluoride (PVDF) or carboxymethyl cellulose (CMC)] in a solvent to hold the slurry's constituents together and attach the electrodes to the current collector. CAM slurries are deposited on a thin current collector foil made of aluminum. Similarly, the anode is made from slurries of graphite particles deposited on copper foil. Then, the electrodes are dried to remove any trace of solvent. A separator (typically a microporous film of polyethylene and polypropylene) is placed between the anode and cathode to electrically insulate them while allowing for ion transport. Finally, the multilayer sheets are cut, rolled or folded, connected to outside terminals, and eventually packaged into cells of different shape factors, such as pouch, prismatic, or cylindrical. The cells are then filled with electrolyte and sealed. Finally, cells are subjected to formation cycle at low C-rate, to create and stabilize the protective layer of solid electrolyte interphase (SEI) at the anode and of cathode-electrolyte interphase (CEI) at the cathode. Overall, the battery manufacturing process consumes critical minerals, polymers, organic solvents, and energy. The electrode drying process is particularly energy intensive [22] and the formation cycle is time consuming and often a bottleneck due to limited cycling resources.

### 3.3. Battery pack manufacturing

Once individual cells are fabricated, they are often welded together onto a busbar to form modules. Depending on the cell shape factor and battery pack design, modules consist of few to dozens, or even hundreds, of cells. The modules are then assembled into a battery pack with adhesives, pressure pads, and sealants, which ensure good electrical connections, reliability, and safety under the harsh road conditions including high or low temperatures, vibrations, and shocks. The pack also contains thermal management fluid to control temperature and thermally interface materials between cells and modules to reduce the risks of fire propagation due to thermal runaway from one cell to its immediate neighbors. New cell-to-pack battery designs do not use modules but instead integrate individual cells directly into packs.

Similarly, cell-to-chassis designs consist of integrating cells with the vehicle body to provide structural strength while reducing overall vehicle weight, and thus, improving efficiency. This design may require more and different adhesives to compensate for the mechanical rigidity lost by the removal of the busbar.

### 3.4. Battery degradation mechanisms

Battery degradation is a complicated process that may proceed through different chemical, mechanical, and/or thermal pathways depending on the selection of electrode materials, electrolyte compositions, cell designs, and cycling conditions [23]. First, loss of active lithium inventory is arguably the most common cause of degradation as lithium ions ($Li^+$) no longer participate in reversible redox reactions [21]. It is caused by several mechanisms including solid electrolyte interphase (SEI) formation at the anode. Rapid charging of conventional LIBs in cold temperatures can also result in undesired lithium plating and dendrite formation at the graphite anode due to sluggish lithium intercalation and phase transitions. In addition, the cathode degrades through dissolution of the cathode materials in the electrolyte, structural changes due to $Li^+$ intercalation, and cracking of redox active particles [21]. Moreover, the electrolyte degrades at voltages exceeding the electrochemical stability window (ESW) resulting in gas formation and increased pressure in the cell. The ESW depends on the electrolyte and narrows with increasing temperatures. In addition, the mechanical properties of the binder (e.g., PVDF) change over time resulting in increased resistive losses caused by the degradation of the adhesion to the current collector and/or the active material particles [24]. In addition, not only high or low temperatures can cause cell degradation [25,26] but also temperature differences across the cell and even between electrodes can trigger and accelerate different degradation mechanisms [27].

### 3.5. Battery recycling

Most recycling processes start with discharging the spent battery pack to allow for safe handling. This electrical energy can be stored to partially power the recycling process. Then, the pack is manually disassembled, and modules are extracted and shredded to produce so-called "black mass." Shredding of the entire battery pack submerged in a dielectric fluid has also been deployed but the resulting black mass contains more plastic, which may lower the purity of the recovered critical minerals [22]. Shredding of modules is justified by recyclers' incentive to maximize the processing rate and by the diversity of battery form factors, chemistries, and EOL conditions recycling processes must take in. In addition, the fact that cells are welded together to busbars to form modules makes the recovery of individual cells difficult and time-consuming. Unfortunately, shredding mixes the different cell components (i.e., anode, cathode, current collectors, separator, electrolyte). Therefore, shredding increases the cost of recovery by decreasing the purity of the constituent materials and making the separation of valuable materials more difficult.

Two recycling processes have been deployed at industrial scale namely the pyrometallurgical and hydrometallurgical processes. The pyrometallurgical process consists of smelting black mass. It consumes a significant amount of energy to operate at temperatures above 1000 °C and emits large quantities of GHGs and toxic fumes (e.g., HF from the decomposition of PVDF binder and $LiPF_6$), which require expensive gas treatment [30]. In addition, the pyrometallurgical process leaves lithium and aluminum in the slag making them difficult and expensive to recover. The hydrometallurgical recycling process consists of performing a pre-treatment of the black mass and leaching the valuable metals from different streams using various acids [28]. This is followed by solvent separation and purification using solvent extraction, chemical precipitation, and electrochemical deposition. This process operates at near room temperature but consumes energy and chemicals. It results not only in GHG emissions but also in the production of toxic sludge that requires treatment [29]. Pyrometallurgical and hydrometallurgical processes can recover 90–95 % of more expensive elements like Co, Ni, and Cu contained in spent batteries [30,31]. The hydrometallurgical process can also recover Li in the form of lithium carbonate ($Li_2CO_3$), albeit at an additional cost [27]. However, these two main recycling processes recover only the cathode material. The lower value anode, separator, and electrolyte are typically calcined, dissolved, or disposed of and not recycled. Both hydrometallurgical and pyrometallurgical recycling processes only recover about 30 % of the total mass of spent batteries (see Table 1).

Progress in so-called direct recycling [32] has also been made but the process remains a subject of investigation currently tested at pilot scale [30]. Direct recycling consists of a series of less energy intensive processes including dissolution, solvent extraction, foam flotation, and magnetic separation. In direct recycling, foils of Cu and Al current collectors are delaminated and separated from the electrodes while the nanoparticles of graphite from the anode and of CAM from the cathode are separated and recovered. The PVDF binder and the carbon black can also be recovered using solvent extraction [33]. Direct recycling is less energy intensive and has a smaller carbon footprint than pyrometallurgical and hydrometallurgical processes [30]. Nonetheless, direct recycling also requires shredding and thus destruction of the manufacturing value of different battery pack components. Finally, the recovered materials (e.g., graphite, PVDF) may still be more expensive and lower quality than their pristine counterparts, limiting the utility of this approach.

Furthermore, as the fraction of Co in the CAM is reduced to decrease battery price on the front end, the economic viability of battery recycling may become increasingly challenging on the back end [34,35]. The recovery of Co and Ni from NMC batteries is what currently makes the recycling process economically viable. Since LFP batteries contain neither Co nor Ni, recycling LFP batteries may not be profitable, even after recovering Li [29,30]. An additional concern is that battery recycling recovers active materials of a chemistry that may be in lesser demand by the time the batteries reach their EOL [29]. Note that while LFP cells are gaining EV market share and may be quite durable, the volume of NMC production is still forecast to increase as the entire battery market grows. In addition, collection and transport of spent batteries account for a significant fraction ($\sim$20–40 %) of total recycling cost [36]. In fact, in the U.S., spent LIBs are considered Class 9 miscellaneous dangerous hazardous waste and need to be packaged and handled with special precautions, which further adds to transportation costs [29].

Today, a large fraction of the feedstock for battery recycling facilities comes from production scrap [37]. This can be attributed to production defects in cells and the limited ability to rework defective battery packs on the production line. In fact, up to 30 % of the production volume for a new gigafactory must be discarded in the first months of operation [38]. Generation of production scrap can be reduced with better quality control and precise automation of battery production [35]. Moreover, a steady supply of spent batteries is necessary to feed recycling facilities. Reduced EV production and/or delays in EV adoption and battery replacement beyond the 8-10-year warrantee may expose the recycling industry to overcapacity until 2035, when more spent EV batteries are expected to come from consumers, decreasing reliance on production scrap [39].

In countries without extended producer responsibility, there is no guarantee that spent EVs will be recycled as the cost may be prohibitive for dismantlers [28]. In addition, a large fraction of vehicles sold in the U.S. may end their life abroad, mostly in Latin America, as observed for ICE cars [40]. For individual owners, EV batteries are typically under warrantee for the first 8–10 years, or 100,000–150,000 miles, depending on the car manufacturer and EV model. Replacing the battery pack represents a major cost to vehicle owners. Owners may prefer to adapt the use of their EVs to reduced range and overall performance instead of replacing their battery thus delaying recycling [37,41].

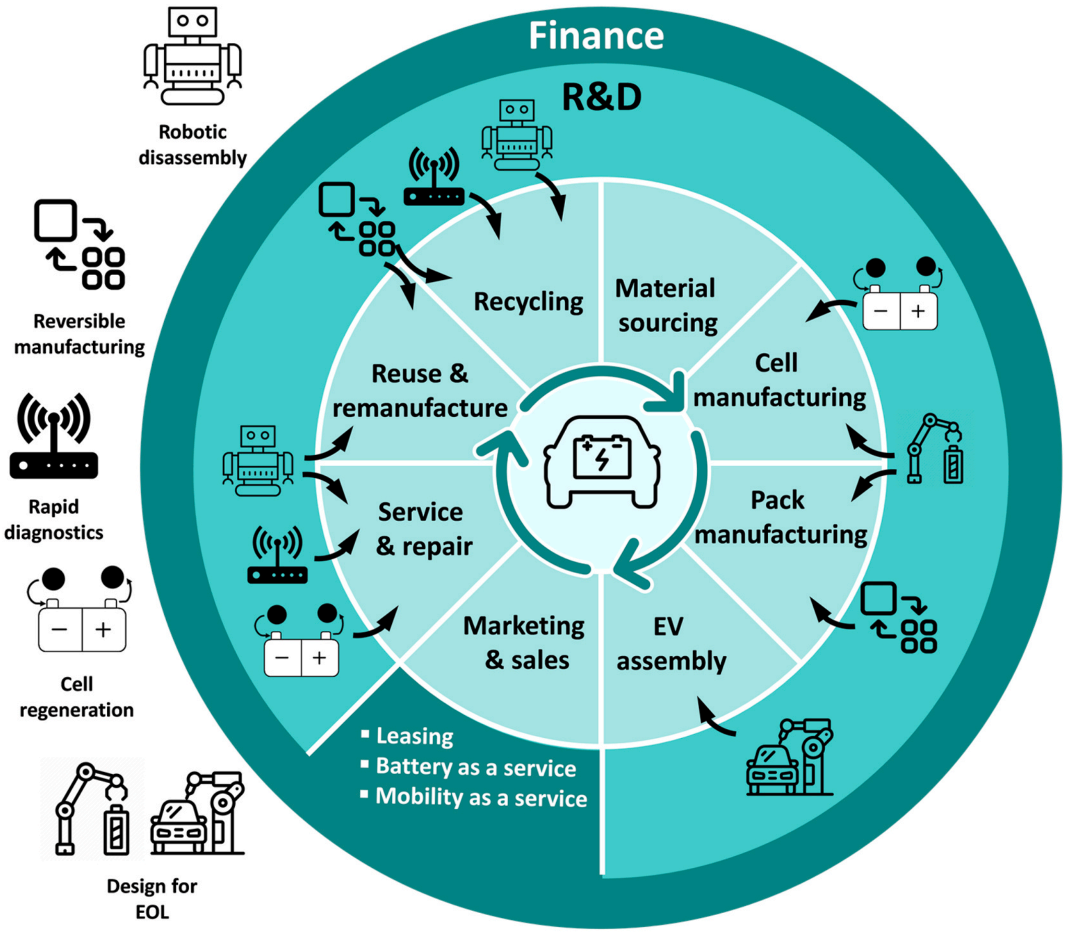

**Fig. 3.** Illustration of the research and development needs and financial strategies that can be deployed along a circular EV battery supply chain.

Overall, recycling of batteries faces many challenges including (i) the large energy demand and carbon footprint of existing recycling processes, (ii) the significant amount of landfilled materials, (iii) the limited initial feedstock of spent batteries, (iv) the cost of transporting spent batteries, and (v) the cost of manual disassembly. Therefore, recycling should be viewed as a process of last resort in a circular supply chain. Regeneration, reuse, repair, and remanufacturing are preferable to recycling because they prolong the life of battery packs and their components and preserve manufacturing value. Only after these different options have been exhausted should batteries and the critical materials they contain be returned to the supply chain through recycling.

### 3.6. Lessons learned from lead-acid battery supply chain

The supply chain for commercial lead-acid batteries used in ICE vehicles is frequently highlighted as an example of a successful circular supply chain achieved solely through recycling [42]. First, 99 % of lead-acid batteries are recycled in the U.S [43]. This is due, in part, to an efficient and incentivized recovery strategy. Second, lead-acid batteries use an aqueous electrolyte and electrodes in the form of millimeter thick lead (Pb) and lead oxide ($PbO_2$) plates. The simple design and chemical composition enable facile separation of electrodes, electrolyte, and plastic casing for recycling [44]. However, lead-acid battery recycling is an energy intensive process that includes comminution, melt-processing and extrusion of plastics, and smelting of lead-containing components [45]. The practice also raises major concerns over environmental contamination and human exposure to toxic lead.

Effective methods exist for regenerating degraded lead-acid batteries. During discharge, lead sulfate ($PbSO_4$) crystals may form on the Pb electrode surface. Upon deep discharge, or if the battery is left discharged for a long time, a hard and thick layer of $PbSO_4$ can grow and significantly reduce battery performance. Several methods have been shown to regenerate Pb electrodes by reversing $PbSO_4$ formation. For example, pulse conditioning consists of imposing a high voltage pulse which electrochemically reverses the $PbSO_4$ formation reactions without causing excessive heating. Alternatively, adding chemicals to the sulfuric acid electrolyte can help remove the $PbSO_4$ layer and restore battery performance.

The supply chain model for lead-acid batteries is difficult to reproduce for LIB packs for several reasons. First, LIBs use flammable, reactive, and hazardous organic electrolytes instead of water. LIBs also exhibit greater architectural and compositional complexity (e.g., use of thin film electrodes) and have a significantly higher energy content. Despite these differences, EV batteries may be able to emulate some of the following lead-acid battery design features to promote circularity: (i) the ability to swap one battery pack for another; (ii) the ability to prolong battery life by regenerating electrode materials *in situ* (e.g., pulse conditioning, chemical treatment) and/or by replenishing the electrolyte; (iii) the simplicity of the materials chemistry, design, and manufacturing which makes batteries easy to disassemble and facilitate repair, remanufacture, and recycling; (iv) the standardization of battery chemistry and form factor; and (v) the incentives and logistics deployed for the recovery of spent batteries and the sales and distribution of new ones.

## 4. Technology needs for a circular EV battery supply chain

A major shift in conventional thinking and operation is required to realize a circular EV battery supply chain with innovations and practices that consider EOL while recognizing the need for recycling as a process of last resort. The following sections briefly discuss examples of materials, designs, and manufacturing strategies that may contribute to the development of a circular EV battery supply chain. The topics highlighted in the following sections are illustrative examples of relevant technologies. Fig. 3 depicts the vision of the circular battery supply chain that may be achieved through the innovative technologies and business models discussed in the next sections.

### 4.1. *Battery swapping*

Battery swapping consists of replacing an EV battery, as needed, with a fully charged battery [46]. Swapping is most viable within a battery service model, where consumers purchase access to a network of swapping stations alongside purchasing an EV. Battery swapping for four-wheel electric vehicles is actively used and expanding in China where swapping is performed at automated battery swapping stations and typically takes only 5–10 min by substituting battery packs from the underside of vehicles.

Swapping offers many practical and financial advantages to EV buyers and owners. First, swapping is optional as swappable batteries can be recharged just like any other EV battery. This flexibility is particularly attractive for managing fleets of heavily used vehicles. Second, battery swapping is convenient to EV owners if the battery has degraded over time and needs to be replaced without requiring major and costly disassembly to access the faulty or spent battery. In addition, during the 10–20-year lifespan of EV batteries, some owners may want to swap their existing batteries for new ones that are safer and/or have improved performance. Third, battery swapping results in a reduction in the purchase price of EVs by as much as $10,000/vehicle, as the swappable battery is leased instead of owned. Finally, old batteries can be swapped for new ones to increase the resale value of EVs. Currently, the resale value of second-hand EVs is around 40 % of the initial purchase price compared to 50–70 % for ICE vehicles. This difference is attributed to buyers' concerns about the overall state of health (SOH) and remaining useful life (RUL) of the used EV batteries, particularly if the warrantee has expired.

From a circularity standpoint, battery swapping has the advantage of prolonging the life of LIBs by enabling scheduled maintenance and slow charging under reasonable temperatures and currents to reduce material degradation and loss of lithium inventory to ensure lasting performance and safety, as previously discussed. In addition, battery swapping enables centralized battery charging during grid off-peak hours when electricity is cheaper. It also offers new business opportunities as the swapping stations can contribute to grid storage infrastructure using bidirectional battery storage. Finally, swapping could contribute to streamlining and reducing the cost associated with collection and transport of spent batteries.

Despite its obvious advantages, battery as a service is a new business model that has attracted little interest in North America, unlike in Asia. This is often attributed to concerns over long term reliability and safety of swappable EV batteries. Car manufacturers also may wish to avoid the use of third-party batteries that may compromise the safety and reliability of their vehicles, and thus, their brand reputation. Another argument against battery swapping is the cost to own and maintain a large stock of spare and often disparate EV batteries for EVs of different types and ages. Overall, resistance to battery swapping may be attributed to business concerns as much to technical concerns. Standardization of the battery outer dimensions across a brand, or across the entire industry, could address some of these concerns. One must also recognize that battery packs in excess of 100 MWh, such as those used in some SUVs and trucks, also contributes to the resistance to swapping in North America. Such large batteries are considerably heavier than those used in the types of smaller EVs popular in Asia and Europe, and thus, are harder to robotically swap. Electrifying large vehicles may make sense from a business point of view to meet consumer demand but may be counterproductive when considering the environmental costs associated with procuring the large quantity of necessary critical minerals required and the desire to provide access to affordable EVs for the greatest number of people globally to rapidly decarbonize the transportation sector.

### 4.2. *Prolonging battery life*

All batteries degrade, as previously discussed. Conceivably, strategies capable of efficiently and cost-effectively limiting degradation mechanisms and/or regenerating battery materials and electrodes to their beginning of life (BOL) performance are promising options for extending the service life of individual battery cells in support of circularity. Such techniques can be performed *ex situ* or *in situ*, although the latter is more desirable from a practical point of view and from a circularity perspective.

***Strategies to limit cell degradation and prolong life.*** One strategy to prolong the life of batteries is to adjust the charging/discharging protocol including the cutoff voltage and potential window or the state of charge (SOC) and depth of discharge. Then, however, battery life is often prolonged at the expense of cell energy density [21,47]. Reducing the C-rate during one or multiple discharging and/or charging step(s) can also limit degradation but at the expense of cell power density and/or charging time.

Other approaches have been explored including (i) using coating graphite and cathode particles and/or optimizing the electrolyte as ways to control SEI and CEI formation; (ii) finding new anode materials to avoid complications associated with the use of graphite, and (iii) using anode-free cells when Li is plated or stripped from the bare Cu current collector. However, these approaches may face other challenges including higher cost, different degradation mechanisms, and/or costly and time-consuming R&D efforts.

Real-time model-based control strategies have also been developed to optimize the variable current imposed during the cycling period. The approach was shown to increase the cycle life of 16 A h NMC/graphite cells by 100 % compared with standard 2C charging and 5C discharging [48].

Ensuring appropriate and uniform temperature and/or stress within each cell is arguably a simpler approach to limiting cell degradation. In practice, unfortunately, achieving uniform temperature within each cell across the battery pack, to ensure slow and uniform degradation among cells, is challenging. This is particularly true during transient operations and more importantly during fast charging when heat generation can be significant. This is made even more difficult as the cell shape factors become larger and as packs are designed to maximize the cell to pack mass ratio. Applying an optimum and uniform external pressure on the cell has also been shown to prolong the life of cells [49,50]. Cell thickness and stress fluctuate during cycling due to reversible intercalation-induced volumetric expansion of the electrode materials combined with an irreversible increase over time caused by SEI formation, Li plating, particle cracking, and/or gas formation [47,51]. On the one hand, excessive pressure can enhance chemical degradation and limit kinetics and mass transfer. On the other hand, unconstrained cells can suffer from electrode delamination. As an example, Wünsch et al. [52] showed that optimum bracing of large NMC622/graphite pouch cells using spring tension can achieve 80 % more cycles than similar unbraced pouch cells. While many battery packs use compression pads between cells, the level and uniformity of mechanical stress is not typically optimized. Further optimization and even pressure distribution may prolong cell lifetimes and limit uneven aging among cells.

Finally, innovative strategies have been recently proposed to reduce degradation during charging and/or discharging. For example, subjecting cells to surface acoustic waves during charging and/or discharging has been shown to enhance Li diffusion and reduce/disrupt Li plating as well as SEI and dendrite formation, thus prolonging the life of individual cells [53,54]. These effects can be particularly significant at low temperatures [55].

***Ex situ* Material regeneration.** *Ex situ* regeneration consists of performing electro-chemical treatment (e.g., relithiation) on particles of active materials recovered through direct recycling [56]. Then, new electrodes and cells can be manufactured using the recycled active materials with new binder, carbon black, and electrolyte. Regeneration of CAM recovered in the form of particles from direct recycling has been demonstrated using hydrothermal relithiation in high ionic strength aqueous solvents [57,58]. The process takes a few hours, and the cost of the resulting regenerated CAM is 5–10 times lower than that of CAM obtained from mining or from pyrometallurgical and hydrometallurgical recycling. Similarly, graphite powder recovered from direct recycling of spent battery anodes can be rejuvenated by heating it up to 2300 °C with a simple flash of light [59,60]. Electrodes made with the regenerated graphite were shown to perform as well as pristine graphite [56]. Unfortunately, despite its benefits, *ex situ* regeneration requires shredding of battery cells or packs, thus destroying their manufacturing value.

***In situ* regeneration.** *In situ* cell-level regeneration is more desirable than *ex situ* regeneration because it preserves the manufacturing value of individual cells. The ability to easily regenerate battery cells could also open the battery material space to new battery systems.

An earlier attempt at remediating the loss of lithium inventory consisted of carefully opening the cell, immersing it in fresh electrolyte, and cycling it against an external Li metal electrode to replenish the cell with fresh lithium ions [61]. This approach provides valuable proof-of-concept but is impractical to implement on a large volume of cells. Alternatively, injecting fresh electrolyte into the cells after a certain number of cycles can compensate for the loss of lithium inventory. Similar procedures can be performed in cells with liquefied gas electrolyte [62]. Alternatively, flushing the cell with supercritical $CO_2$ can dissolve the SEI and the electrolyte before replenishing the cell with fresh electrolyte [63,64]. These *in situ* regeneration methods require easy access to the interior of the cells, which could be achieved by integrating a valve or injection port in the cell design. Then, larger shape factor and cylindrical cells would be more amenable to regeneration in terms of both practicality and cost.

The addition of a third Li-rich electrode or of a Li metal strip in electrical contact with an electrode inside the cell during fabrication has also been successfully demonstrated on different lithium-ion cell chemistries and shape factors [65–68]. Here, the additional electrode and Li metal strip act as a lithium reservoir that can release lithium ions electrochemically on demand [62,63] or passively over time [64,65] to compensate for the loss of lithium inventory. Lithium release and transport through the cell could be enhanced with increasing temperature, for example [62].

More recently, Ogihara et al. [69] proposed a method of regenerating the cathode in spent NMC batteries suffering from capacity fade due to loss of lithium inventory. The process relies on injecting a solution of $Li^+$ and naphthalene radical anions into a spent cell to induce a reduction reaction at the cathode that effectively regenerates the cathode. The regeneration mechanism depends on the solvent environment and on the careful control of the applied potential at the electrode-electrolyte interface. The authors successfully demonstrated their method on a 4 A h spent commercial NMC/graphite cell and regenerated it to >98 % of its original capacity. The use of naphthalene, as opposed to a more expensive arene, suggests that large volumes of batteries may be economically regenerated using this approach.

To date, limited investigative effort has been dedicated to *in situ* regeneration approaches, which also necessitate innovations in cell design depending on the battery chemistry and on the regenerative methods used. Arguably, cell regeneration would be most valuable for electrode materials that degrade more rapidly than others, including mixed metal oxides of nickel, manganese, cobalt, or aluminum (e.g., NMC or NCA) conventionally used in LIBs. Importantly, safety of the redesigned cells during fabrication, operation, and regeneration must be maintained according to current industry standards. Finally, *in situ* regeneration of the cells could be performed directly onboard EVs using the battery management system (BMS), at a specialized facility, or at dealerships. Such a service could provide a source of revenue for the dealership and a substitute to the activities lost by replacing ICE with electric vehicles.

### 4.3. Reversible manufacturing™

Battery pack repair and remanufacture promote circularity of the EV battery supply chain through replacement of defective and/or deteriorated components. Within aging, defective, or spent battery packs there may exist individual salvageable battery cells, modules, and components which could potentially be economically recovered, reused, or recycled, and in all cases, removed from the waste stream. Reincorporating these salvaged components into new, refurbished, or remanufactured battery packs preserves their embedded manufacturing value. Battery repair and remanufacturing may be more intrusive, time consuming, and expensive compared to *in situ* battery regeneration but could still be performed by qualified technical staff in specialized facilities or dealership service departments. This approach would benefit from a holistic design of EVs and battery packs and a judicious selection of materials and manufacturing methods, which would promote safe and convenient disassembly to access components that are more prone to failure earlier in life (e.g., the BMS or cooling pumps). Simple, rapid, and safe disassembly procedures could facilitate rework of defective battery packs during production, and thereby reduce the quantity of scrap generated. Streamlined disassembly could also enable the replacement of aging battery pack components as a preventative measure and/or to improve performance.

The following subsections discuss representative technical approaches to realize so-called “reversible manufacturing” which refers to the ability to “unmanufacture” battery packs as rapidly or easily as they were manufactured. In this case, the word “reversible” takes on its full thermodynamic meaning in that the goal is to minimize entropy generation during the entire lifecycle of the battery pack.

**Design for reversible assembly.** Existing battery packs that were not originally designed with EOL in mind require arduous and time-consuming disassembly processes during recycling [22]. By contrast, sustainable designs would enable individual cells, BMS, thermal management components, etc., to be easily isolated, serviced, reused, replaced, and upgraded. Then, only defective cells and deteriorated components that have reached their EOL would require recycling, instead of shredding entire modules or packs. This will result in a recycling stream consisting of only spent cells which would yield black mass with a higher concentration of critical materials and therefore higher recycling value per unit mass. Moreover, a modular design would make this solution highly scalable.

As an example, the battery pack design by Aceleron Energy based on compression technology without permanently bonded components [70]. Rather, electrical connections between cells and conduction plates are achieved by compression provided by a system of fasteners holding the pack together. This design presents the advantages of being modular and scalable. Fasteners should be designed to ensure that they do not loosen up over time due to vibrations or fatigue, resulting potentially in excessive resistive losses at the connections and potential overheating of the pack. Similar efforts in designing easy to disassemble modular battery packs would be beneficial to achieving a circular EV battery supply chain.

**High strength debondable adhesives.** Some pack designs rely on adhesives to ensure the safe and reliable operation of EV batteries by making sure that cells, modules, and other critical pack components can withstand mechanical vibrations and shocks. Development of high strength (1–10 MPa), debondable adhesives with equivalent performance to conventional adhesives used in commercial battery packs would simplify disassembly, rework, while the adhesives could potentially be reused [71–75]. In principle, stimuli-responsive adhesives that respond to heat, solvent, light at selected wavelengths, ultrasound, and/or electric or magnetic fields, may be leveraged to achieve clean and controlled debonding of battery pack adhesives. However, restrictions must apply to ensure that cells do not encounter debonding conditions during normal use. For example, heating the adhesive above a certain temperature for debonding could damage the cells (e.g., boiling of the electrolyte) and/or induce unintended thermal runaway during repair. Moreover, the benefits of debondable adhesives can be fully leveraged if the pack is designed in such a way that the surface area used for adhesives is minimized. Finally, more radical approaches would be to eliminate the use of adhesives altogether through adhesive-free battery pack designs and/or the use of metal-to-polymer joining/disjoining techniques [76].

**Reversible welding and joining techniques.** Battery pack manufacturing may use different joining techniques including but not limited to mechanical fastening, laser welding, resistance spot welding, pulsed arc welding, ultrasonic welding, and/or ultrasonic wedge bonding [77]. Welding is employed in battery packs primarily due to its long-term durability, mechanical strength, and low interfacial electrical resistance. Effective and scalable strategies for reversible welding or more generally reversible joining of cells, modules, and other battery pack components would facilitate recovery of individual cells. Battery pack designs that circumvent the requirement for permanent joining, either partially or entirely, would be especially advantageous for separating battery packs into individual components. For example, compression technology could reduce the number of permanently bonded components with a battery pack, as previously discussed [67].

Overall, sustainable designs, innovative materials, and reversible manufacturing techniques can enable the safe and rapid manual disassembly of batteries for repair, reuse, remanufacture, and recycling. A complementary or alternative approach to manual disassembly could rely on autonomous robotic disassembly of battery packs.

### 4.4. *Robotic disassembly*

Currently, disassembly of battery packs into individual modules is performed manually and typically takes several hours due to complex, irreversible designs and manufacturing, including welded parts and the use of permanent adhesives that are difficult to remove [78]. The current slow and complex disassembly process hinders the adoption of circularity practices and contributes significantly to the cost of EV battery recycling [6]. The increasing voltage of EV battery packs (400 V–800 V) is also a major safety concern, complicating manual disassembly even when performed by highly trained technicians. Therefore, robotic disassembly of battery packs may be a promising option to increase safety and throughput while simultaneously reducing the cost of repair, reuse, remanufacturing, and recycling; thereby enabling scalable solutions capable of handling the projected future growth of spent EV battery volumes.

One of the main challenges to the development of robotic disassembly is the wide variety of battery pack designs and manufacturing methods among EV models. Designs and manufacturing methods evolve over time, even for the same EV models. Additionally, battery packs may have various degrees of potential degradation during use (e.g., corrosion, cell expansion). Moreover, the use of traditional robots with preprogrammed motions (commonly used for automation on the production line) would be limited to handling batteries of a specific design and manufacturer. To address this challenge, standardization of battery pack design has been suggested [22] but is unlikely to occur in the early and competitive stages of the EV revolution. Therefore, robotic disassembly should be performed autonomously so as to select, evaluate, and adapt unmanufacturing processes to each and all EV battery packs on the disassembly line.

The autonomous robotic system should be able to manipulate precisely objects with various shapes, weights, and mechanical properties (e.g., cells, screws, pads) and perform tasks such as (un)screwing, cutting, pulling, and torquing. Thus, it should utilize computer vision hardware and algorithms as well as tactile and force-sensing capabilities to ensure that battery packs and their constituents are handled safely. Such autonomous robotic disassembly systems should also be able to learn from their own experiences, from those of other robots, or from simulations, videos, and/or other media. Strategies may also need to be developed to coordinate the disassembly of battery packs cooperatively between robots and humans. This vision could be achieved by leveraging recent advances in artificial intelligence and machine learning, for example.

Furthermore, inspection of battery packs to determine geometric parameters, aging conditions, and potential defects that could compromise safety may be necessary prior to attempting robotic disassembly. External inspection can be performed by visible or multispectral cameras. In addition, X-ray computed tomography scans of the entire battery pack and individual cells offer a non-destructive testing method to retrieve non-invasively the pack design and to detect defects in cells and modules such as gas formation, electrolyte losses, weld defects, electrode delamination, particle cracking, and mechanical damages. For all inspection modalities, automatic defect recognition could be enabled by artificial intelligence and machine learning methods. This information, combined with that of other characterization methods, could then be used to inform the robotic disassembly process.

Finally, it may be necessary to modify the design, material choices, and manufacturing methods used to produce battery packs to enable practical implementation of inspection methods and to facilitate autonomous robotic disassembly.

### 4.5. *Rapid diagnostic of the state of health and recertification*

Quantifying the SOH and RUL of individual cells or modules continuously during operation within the battery pack, at specific times during repair, and/or at EOL, is critical for deciding whether cells should be regenerated, reused/repurposed, or recycled [79,80]. Such determinations must be made rapidly and reliably and be capable of diagnosing a wide variety of commercial battery cell chemistries and form factors. Relying on traditional electrochemical methods that require several hours to charge and discharge cells at slow rates is impractical, especially considering the anticipated future volume of spent EV batteries. Several rapid diagnostic techniques have been explored including, but not limited to, electrochemical impedance spectroscopy and ultrasound techniques [81] both combined with physics-based models, data-driven models, and/or artificial intelligence [76,77,82]. Such SOH, RUL, and other diagnostics performed during normal EV operation could be used to inform the BMS in performing restorative measures to prolong the life of individual cells, thus achieving circularity objectives [83]. Unfortunately, some of these models and data analysis methods can be computer-intensive and time-consuming and may not be able to run on onboard computers. They would require data transfer from the vehicles to the Cloud through the public telecommunication network (e.g., 5G), for example. Such a scenario, however, raises major concerns in terms of owner privacy, intellectual property for the car OEMs and their suppliers, cybersecurity, and liability. Therefore, it is desirable that all data analysis be performed onboard the EV with data download possible for accredited partners. In fact, data sharing of cycling history, SOH, and RUL among participants of the supply chain including car OEM, dealerships, repair shops, and battery recyclers during the lifetime of the battery packs and at the end of life would be essential to perform preventative maintenance and to maximize the energy delivered during the pack lifetime and the use of critical minerals. This information could also help improve the battery pack design, manufacturing, and management as well as increase the resale value of EVs, and facilitate risk assessment for insurance companies. To the best of our knowledge, however, discussions of BMS data management and sharing agreements are still at an early stage.

### 4.6. Remanufacturing

Remanufacturing of a battery pack consists of rebuilding the pack for its original purpose with the same (or superior) specifications using a combination of reused, repaired, and new cells and components. Kampker et al. [8] confirmed experimentally the simulation results of Mathew et al. [84] indicating that the life of battery packs can be prolonged by replacing, at some time intervals, the cells that may have degraded below the performance and safety standards of EV batteries. In other words, many of the cells in a used battery pack could be reused if the individual deteriorated cells could be safely, quickly, and cost effectively identified, removed, and replaced. The authors argue that cell-level disassembly is the optimal depth of disassembly needed to maximize material and energy efficiencies of the EV battery supply chain. Unfortunately, cell-level disassembly needed is not available to date. Remanufacture would be made easier by the rapid determination of each cell's SOH and RUL and by the disassembly of packs to recover individual cells, which could be made possible with designs that incorporate end of life considerations as well as reversible manufacturing methods and joining techniques.

### 4.7. Repurposing or second use

Repurposing or second use of EV batteries aims to extend the life of batteries to applications other than the original EVs they were designed for. For example, modules from an EV can be used for smaller EVs (e.g., scooters) or for stationary energy storage, either for EV charging stations or for grid storage. Complete battery packs could even be used for electricity grid storage albeit with new power electronics to enable bidirectional interfacing. Second use is beneficial in that it extends the useful life of EV batteries and delays the global need for critical minerals. However, it does not contribute to circularity *per se* as spent batteries are still ultimately disposed of according to current standard practices. In an ideal circular supply chain, little to no material is disposed of. Additionally, second use applications are typically only employed when a lower level of battery performance can be tolerated. A key tenet of circularity is maintaining materials in circulation at their highest level of performance. Moreover, manufacturers and insurance companies may also be hesitant to provide warrantees and insurance for new products that use repurposed batteries due to uncertainty regarding batteries' remaining lifetime and safety. These concerns should be addressed through experience and the development of best practice. Battery repurposing would benefit from standardization of battery chemistry, cell shape factor, and/or module geometry.

### 4.8. Standardization

Some level of standardization among EV batteries is highly desirable for optimizing a circular supply chain, as previously discussed for LIBs. Currently, automotive OEMs use various cell shape factors and chemistries and very different module and pack designs and manufacturing methods. Standardization of pack, module, and/or cell designs would facilitate automated disassembly of battery packs for repair, reuse, remanufacture, and recycling. However, at this time, automotive OEMs and cell manufacturers typically consider standardization a constraint that could inhibit innovation and limit their perceived competitive advantage. The desire to control the value chain may also motivate opposition to standardization, as is observed in many other consumer products.

Standardization of cell chemistry is arguably the most challenging to achieve as it is what defines the performance and safety of EVs. However, a common cell chemistry would enable the development and optimization of recycling processes to maximize recovery of critical materials. Even with battery standardization, one can argue that competitive advantage can still be gained from other features of the EV such as, the powertrain, style, comfort, reliability, and safety. These criteria have always been important to car buyers and owners of ICE cars. Performance differentiation, another important criterion for some customers, can be achieved not only through chemistry but also through compact battery pack design and/or efficient thermal management, while retaining a high level of standardization. The industry may agree over time on what can be standardized as best practice including chemistry, cell voltage, shape factor, and/or performance. Like in many other consumer products, there is no reason why such standardization cannot take place over time as the industry matures, consolidation takes place, and competitive advantages arise from non-battery aspects of EVs.

### 4.9. Metrics

Energy and power densities as well as cycle life of cells and battery packs are currently the metrics of choice in the selection of battery chemistry to satisfy consumer demand for long driving range, acceleration, reliability, lifespan, and safety. Cost per kWh of energy stored in the cell or battery pack is another important metric to ensure cost-effective EV battery production and widespread consumer adoption, thus enabling electrification and decarbonization of the transportation sector. While these metrics are meaningful, they were developed intrinsically in the context of a mostly linear supply chain and an EV ownership model.

A circular EV battery supply chain aims to reduce the use of pristine materials, the energy consumption, GHG emissions, and waste generated over the entire EV battery lifespan. Therefore, new metrics and analytical tools need to be developed to capture the benefits of a circular EV battery supply chain. Here, we propose considering the following metrics when assessing technologies that aim to create a circular EV battery supply chain.

- Overall energy delivered by unit mass of a cell during its lifetime (in kWh/kg). Note this metric considers all functional materials, components, and packaging. Typically, the current state of the art cells can deliver less than 500 kWh/kg over their lifetime. A circular supply chain with life prolonging measures and regeneration methods could achieve more than 1000 kWh/kg corresponding to more than 1.4 million miles traveled for an average electric vehicle operating at 0.32 kWh/mile with a battery pack mass of 450 kg.
- Overall cost of energy stored during a cell's lifetime. Currently, we estimate this cost at \$0.04–0.07/kWh depending on the cell chemistry, but circularity approaches could achieve \$0.01–0.02/kWh if life is prolonged by a factor 2–3 and/or regeneration can be performed cost-effectively.
- Total mass of critical materials (Co, Ni, Li, Mn, Cu, graphite) consumed per unit of energy delivered by a cell during its lifetime (in kg/kWh). This metric should be as small as possible to minimize production cost and secure material supplies.
- Total GHG emissions over a cell's lifetime from cradle to grave. Currently, cell lifetime GHG emissions are 25–30 kg $CO_2$/kWh delivered over the cell lifetime [85]. A circular supply chain could reduce this amount by a factor of 2.

The above metrics indirectly account for the ability to prolong the useful life, repair, reuse, and remanufacture of EV batteries. These metrics can also be used in technoeconomic analyses to identify potential new sources of revenue from new business models associated with a circular supply chain. These can also help maximize the use of vehicle fleets and transition from an ownership to an access-to-mobility model.

## 5. Conclusion

This perspective piece articulates why new technology is needed to create circular EV supply chains and presents innovative strategies to practically and economically achieving circularity at commercially

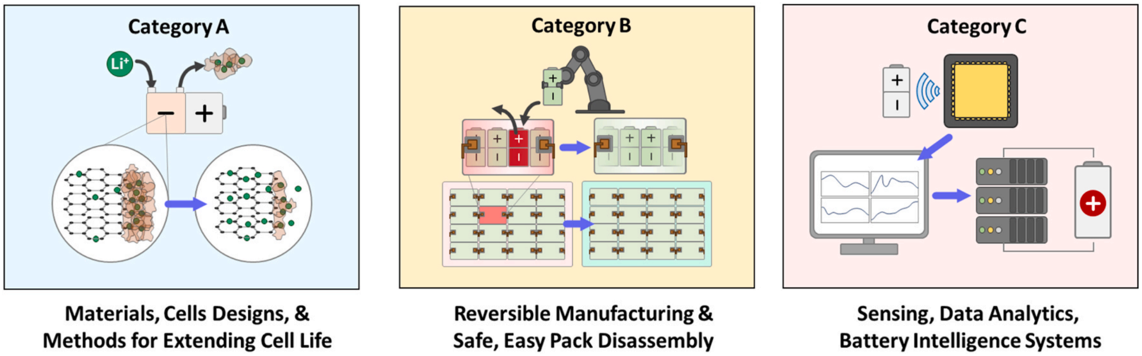

**Fig. 4.** Illustration of the three technical categories of the CIRCULAR program.

relevant scales. These innovations can be grouped into three main R&D thrusts, illustrated in Fig. 4. Category A focuses on the cell level and includes needed innovations in battery materials, cell designs, regeneration methods, and corresponding manufacturing techniques to prolong battery service life including, but not limited to (i) methods and apparatuses to limit degradation of cell performance; (ii) battery materials amenable to *in situ* regeneration; (iii) regeneration methods and/or operations to cost-effectively restore cells to BOL performance and safety; and (iv) cell designs that enable implementation of regeneration methods at scale. Category B focuses on the pack level and encompasses innovations needed in battery pack designs, materials, and reversible manufacturing methods as well as fast and safe disassembly techniques to recover manufacturing value of cells and pack components including, but not limited to (a) battery pack designs and reversible manufacturing techniques to facilitate battery pack disassembly to the cell-level; (b) materials and methods to enable reversible manufacturing such as debondable adhesives or other reversible joining methods; and (c) autonomous robotic disassembly of battery packs. Category C focuses on cell-level sensing, data analytics, and battery intelligence systems for circularity and safety. Innovations needed in this category include (1) sensing methods for rapid SOH and RUL determination of individual cells during operation and/or at EOL; (2) seamless and cost-effective integration of sensors during cell and pack manufacturing; (3) data analytics and battery intelligence systems to enable predictive maintenance and/or to extend the service life of cells, modules, and packs; (4) data-driven guidance to determine the fate of individual cells, i.e., regeneration, repair, reuse, or recycling; and (5) advanced diagnostic tools and techniques to identify damaged and potentially hazardous cells. Finally, technoeconomic, lifecycle, and circularity analysis tools and metrics capable of quantifying the impact of new technologies to both justify their adoption of these technologies and inform new business models and opportunities should be developed.

The proposed vision offers a diverse array of solutions that could be adopted separately, in combination with others, at different times according to the technology development, and at different stages along the battery supply chain. It is expected that introducing new materials and sensing methods, leveraging cell-level life-prolonging strategies, envisioning innovative cell and pack designs, and adopting new reversible manufacturing methods will be challenging for industry, since implementation will likely lower yield and increase capital expenses, at least initially. Despite short-term economic barriers, there is an immediate and critical need to accelerate development of enabling technologies and solutions to catalyze the transition from a linear to a circular supply chain for domestic EV batteries. Chemistry-agnostic technologies are particularly relevant given the current and future diversity of EV battery chemistries envisioned.

## CRediT authorship contribution statement

**Laurent Pilon:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Julia E. Greenwald:** Formal analysis, Investigation, Visualization, Writing – review & editing. **Sean Vail:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Ray Duthu:** Data curation, Formal analysis, Resources, Writing – review & editing. **Jacob Tidwell:** Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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