Levegő Munkacsoport

CLEAN AIR ACTION GROUP

INTERNSHIP REPORT

Electric Vehicles in a Circular Economy Perspective

Reduce, Reuse and Recycle Strategies for EV Batteries

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Table o

1. Introduction

Electric mobility is expanding faster than almost any other technology in the energy transition. Around 58 million electric vehicles were on the road worldwide by the end of 2024, and that number is expected to reach 250 million within six years (International Energy Agency, 2025). This growth is widely presented as an environmental success, and in terms of tailpipe emissions it is. Yet every electric vehicle carries a battery, and every battery eventually reaches the end of its useful life in the vehicle. The scale of what follows is only now becoming visible: the volume of retired battery capacity available for reuse is projected to reach roughly 96 GWh by 2030 and to exceed 12,000 GWh by 2050 (Tankou et al., 2023).

This creates two problems at once.

The first is a problem of scarcity. Lithium-ion batteries depend on raw materials whose long-term availability is limited, chiefly lithium, nickel, cobalt, and manganese in the cathode, along with graphite. Their supply is also highly concentrated: 78.4 percent of lithium originates in Australia and Chile, 72.1 percent of cobalt in the Democratic Republic of Congo, and more than 60 percent of graphite production takes place in China, leaving these essential materials effectively monopolised by a handful of countries (Shen et al., 2025). Demand is meanwhile rising faster than supply can follow. By 2040 the projected demand for lithium, cobalt, and nickel for electric vehicle batteries is expected to exceed current global production, in some scenarios by as much as eight times (Maisel et al., 2023). There are other battery technologies but since lithium-ion batteries are currently most widespread, this study is limited to the assessment of lithium-ion batteries.

The second is a problem of waste. Extracting these elements demands considerable energy and frequently causes lasting environmental damage, pollution, and serious social and health consequences for the communities living near the mines (Nazim & Elavarasan, 2026). Discarding batteries at the end of their vehicle life compounds this: landfilling emits between 67 and 286 kilograms of CO_2 per kilogram of battery, by a wide margin the worst outcome available (Das et al., 2026). A linear model, in which materials are extracted, used once, and thrown away, is therefore untenable at the volumes now approaching.

The circular economy offers a framework for at least partially resolving both problems simultaneously, and its most established formulation is the 3R hierarchy: reduce, reuse, recycle. Reduce concerns the design and manufacturing stage, lowering the quantity of critical materials and energy embedded in each battery. Reuse extends the service life of a battery that is no longer suitable for driving but retains 70 to 80 percent of its original capacity, giving it a second life in less demanding stationary applications. Recycle recovers the valuable materials once no useful capacity remains, returning them to the supply chain rather than to landfill. Each stage delays the point at which new material must be extracted.

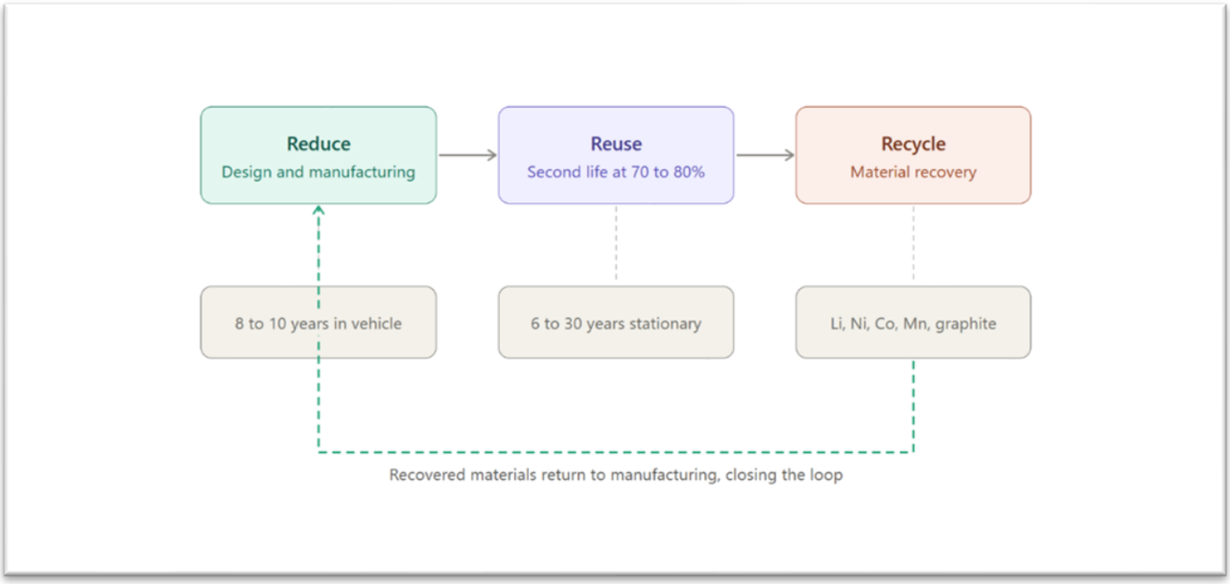

Figure 1. The 3R framework applied to the electric vehicle battery life cycle. *Author's own elaboration.*

The potential is substantial. Second-life storage systems can reduce investment costs by up to 25 percent compared with new batteries while supporting decarbonisation and adding flexibility to the power system (Nováková et al., 2023), and the recycling potential for lithium and nickel has been estimated at more than half the projected raw material demand for electric vehicle batteries in 2040, with the potential for cobalt exceeding demand altogether (Maisel et al., 2023).

Yet this potential remains largely unrealised. Less than 5 percent of the lithium-ion batteries produced are currently recycled (Das et al., 2026), and large-scale second-life deployment is still constrained by safety concerns, uncertain economics, and an incomplete regulatory framework. The gap between what the 3R model makes possible and what is happening in practice is the central concern of this report.

This report examines how the 3R principles apply to electric vehicle batteries, and where the obstacles to applying them lie. Section 2 addresses reduce, Section 3 reuse, and Section 4 recycle. Each section sets out the technologies and strategies available, the quantitative evidence for their economic and environmental performance, and the technical, economic, and regulatory challenges that currently limit their adoption.

2. Reduce

Reduce strategies for EV batteries operate on multiple fronts: extending product lifetime, incorporating a higher share of recycled content in manufacturing, improving energy and power density, enhancing cycle stability, and lowering both fabrication waste and the energy and carbon footprint of production (Helbig & Hillenbrand, 2024).

2.1 Design-based reduction

2.1.1 Design for disassembly and modularity

One of the clearest ways to apply the Reduce principle to EV batteries is through the physical design of the battery pack itself. Design for Disassembly (DfD) promotes strategies that allow components to be reused, repaired, and recovered rather than discarded, and is widely regarded as essential for achieving circularity in battery systems (Oka et al., 2026). At the heart of DfD is the principle of modular architecture: structuring a product so that individual components can be removed independently, without disrupting the rest of the assembly (Talens Peiró, Ardente, & Mathieux, 2017). This is not merely a design preference; it is increasingly a regulatory requirement, as the EU Batteries Regulation now mandates that certain battery packs and their cells be readily removable and replaceable (European Commission, 2023).

This logic connects directly to a broader principle within the Reduce strategy: extending the lifetime of a product is one of the most effective ways to lower overall material demand (Helbig & Hillenbrand, 2024). For EV batteries, this means designing not just for how the battery performs when new, but for how long it can remain useful. One framework that puts this into practice evaluates battery pack design across three complementary dimensions: how easily it can be manufactured, how well it can support a second life once its first use ends, and how easily its materials can eventually be recovered for recycling (Gonçalves et al., 2025). Within this approach, modularity again plays a central role, allowing the pack to be built from interchangeable modules that are easy to assemble, disassemble, repair, and adapt to different needs. Design choices guided by this logic can produce real environmental gains even at a small component level: replacing conventional steel with graphite in a battery's thermal pads, for instance, was found to lower emissions without compromising performance (Gonçalves et al., 2025).

At the same time, designing for disassembly is not a cost-free improvement. Empirical evidence from Oka et al. (2026), who compared a sealed battery housing with no disassembly potential against two alternative designs built specifically for disassembly, shows that both alternatives came with a manufacturing-stage penalty, up to 19% higher resource depletion for the most material-intensive of the two. This is largely because battery cells make up roughly 75% of a pack's total weight, so any additional structural material needed to enable disassembly adds a real, measurable burden before the battery is ever repaired. However, this upfront cost was consistently outweighed once a repair scenario was factored in: by retaining and reusing the cells after housing damage, rather than discarding the entire pack, the two disassembly-oriented designs reduced overall environmental impact by 24 to 48% compared to full replacement. The two designs needed different minimum shares of reused cells to break even on this trade-off, 8% for one design and 27% for the other, showing that not all disassembly-oriented designs are equally efficient. This was echoed in disassembly time itself, which ranged from roughly 73 to 83 seconds depending on the fastening method used, confirming that the specific design choices made, not simply the decision to allow disassembly in principle, ultimately determine how effective a design-based reduction strategy turns out to be (Oka et al., 2026).

2.1.2 Cell-to-pack design efficiency

Beyond enabling disassembly, material reduction can also be pursued through how densely a battery pack is packaged, independent of how easily it can later be taken apart. Longitudinal data on battery-electric vehicles show that specific energy at the cell level has historically improved faster than at the full system level, indicating that a meaningful share of potential efficiency gains is lost once cells are integrated into modules and packs (Löbberding et al., 2020), as shown in Figure 2

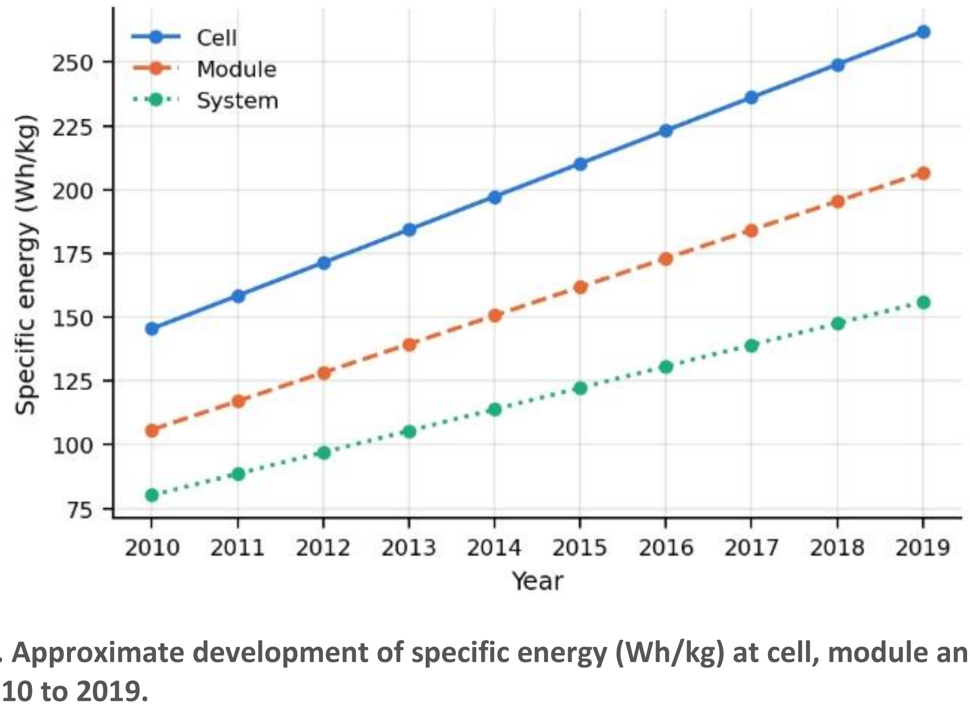

Figure 2. Approximate development of specific energy (Wh/kg) at cell, module and system level, 2010 to 2019.

Note: illustrative reconstruction based on the linear trend equations reported in Figure 2 of Löbberding et al. (2020). It approximates the overall trend rather than reproducing the original scatter plot.

Addressing this gap, cell-to-pack design approaches integrate battery cells directly into the pack, bypassing the intermediate module structure used in conventional designs. Empirical modelling of this approach shows that removing module housings alone can reduce the number of pack components by up to 40%, while the most integrated configuration reduced total pack volume to 79.93% of a conventional design, roughly 20% in savings, even as volumetric energy density increased from 246.9 to 308.8 kWh/l, meaning more energy stored using less material overall (Pampel, Pischinger, & Teuber, 2021), as summarised in Table 1. As with disassembly-oriented design, this gain is not without cost: because structural stiffness and thermal shielding are normally provided at module level, highly integrated cell-to-pack designs must reproduce these functions at the pack level instead, meaning that volume savings achieved at the module level do not always translate efficiently into the final system (Pampel, Pischinger, & Teuber, 2021).

Table 1. Pack volume and volumetric energy density across cell-to-pack conversion degrees

Parameter	Basic concept	Degree 1	Degree 2	Degree 3	Degree 4
Battery pack volume (%)	100.0	90.85	84.79	81.93	79.93
Volumetric energy density (kWh/l)	246.9	271.7	291.2	301.4	308.8

Source: Pampel, Pischinger, & Teuber (2021).

2.2 Reducing critical raw materials

While design-level interventions address how a battery pack is built, an equally important dimension of Reduce concerns what the battery is built from, specifically the critical raw materials used in the cell itself. Critical raw materials refer to elements such as cobalt, lithium, and nickel that are classified as strategically important due to their high risk of supply shortage, making battery manufacturing structurally dependent on continued mineral extraction (da Silva Vasconcelos et al., 2025).

NCA and NMC cathodes remain dominant in high-performance EVs, but their long-term viability is constrained by cobalt dependence, structural fragility, and cost (Hammed et al., 2025). In response, the industry is shifting toward cobalt-free and ultra-high-nickel cathodes, aiming to balance energy capacity, safety, and ethical sourcing (Hammed et al., 2025). This trend is independently corroborated by Manthiram (2020), who confirms that increasing nickel content while lowering or eliminating cobalt in NMC cathodes has become an increasingly prominent industry strategy.

Reducing critical raw materials in lithium-ion batteries is not a straightforward, linear process; it instead requires balancing several competing factors, including supply risk, toxicity, cost, and performance. Shifting from cobalt to nickel-based chemistries, for instance, addresses some of these concerns while simultaneously introducing new ones, which is precisely where targeted micro-doping strategies become relevant as a means of achieving this balance (Stephens et al., 2025).

Cobalt's problems stem from several combined factors: it is classified as a critical mineral by the European Union due to its high economic vulnerability, global supply risk, and low substitutability; it is significantly more expensive than other transition metals; and more than half of global production originates from the Democratic Republic of Congo, where an estimated 15 to 20% is extracted through small-scale artisanal mining, raising serious ethical concerns alongside local water, food, and wildlife contamination (Stephens et al., 2025). These combined pressures pushed the industry to gradually raise nickel content instead, moving from NMC111 through NMC622 and NMC811 to NMC955, since nickel is cheaper, more abundant, and carries lower supply risk than cobalt (Stephens et al., 2025). This shift, however, introduces its own hidden costs: nickel is in fact more toxic than cobalt, and manufacturing high-nickel cathodes requires specialised dry-atmosphere processing and additional heat treatment, both of which raise production costs (Stephens et al., 2025).

Table 2. Toxicity comparison, cobalt versus nickel

Material	LD50 (mg/kg)	Interpretation
Nickel sulfate hexahydrate	362	Lower value means higher toxicity
Cobalt sulfate heptahydrate	582	Nickel is more toxic than cobalt

Source: Stephens et al. (2025), citing Murdock et al. LD50 is the dose that kills half of a test population; the smaller the number, the more toxic. Nickel, the very substitute intended to reduce cobalt dependence, is in fact more toxic than cobalt itself.

Table 3. Supply risk of commercial cathode types.

Cathode	Supply risk (EU)	Supply risk (China)
LCO (full cobalt)	1.82	3.63 (highest)
NMC111	1.04	1.87
NMC622	0.79	1.62
NMC811	0.61	1.43
NMC955	0.52	1.34
LNO (full nickel)	0.44	1.25 (lowest)

Source: Stephens et al. (2025). As nickel content rises and cobalt content falls, supply risk decreases steadily, confirming the industry rationale for moving away from cobalt.

A more balanced alternative lies in micro-doping: adding very small quantities, on the order of 0.01 to 0.05 mol, of selected elements to the cathode to improve structural stability and performance, though each candidate dopant carries its own trade-offs in cost, availability, and toxicity (Stephens et al., 2025). Among the dopants examined, sulfate offered the best overall balance, providing a modest but meaningful performance improvement while keeping both cost and toxicity low, with only a slight increase in supply risk; notably, it was the only dopant found to actually lower the cathode material's overall price rather than raise it (Stephens et al., 2025).

Table 4. Dopant trade-offs

Dopant	Performance	Price	Supply risk	Verdict
Niobium (Nb)	Improves capacity and retention	Rises	Rises	Promising but costly
Tungsten (W)	Improves capacity and retention	Rises	Rises	Promising but costly
Zirconium (Zr)	Excellent capacity and retention	Rises sharply	Rises slightly	Promising, very costly
Sulfate (S)	Modest, meaningful gain	Falls	Rises very slightly	Best balance

Source: Stephens et al. (2025). Expensive dopants deliver good performance but raise both cost and supply risk. Sulfate alone achieves a practical balance across all three criteria.

Table 5. Raw material prices and toxicity of candidate dopants

Element	Price ($/kg)	Toxicity LD50 (mg/kg)
Sulfate (ammonium sulfate)	0.15 (cheapest)	2000 (low toxicity)
Nickelو	3.6	362
Lithium (carbonate)	10.6	525
Zirconium (nitrate)	27.9	2290
Molybdenum	37.5	2689
Tungsten (oxide)	79.2	2000
Niobium	180 (most expensive)	non-toxic

Source: Stephens et al. (2025). Sulfate is by far the cheapest dopant option with low toxicity, explaining its selection as the optimal candidate.

2.3 Alternative chemistries

Beyond reformulating nickel-cobalt cathodes, a parallel strategy for reducing critical material dependence is to shift toward an entirely more abundant chemistry: lithium iron phosphate (LFP). LFP's global market share rose from 28% to 40% between 2021 and 2023, with an even sharper increase in China, from 52% to 67% over the same period (Stephens et al., 2025). This growth is driven by two clear advantages: LFP is markedly cheaper, at approximately $48.5/kWh compared with $62.4/kWh for NMC, and it is substantially safer thermally, with thermal propagation in NMC811 occurring roughly five times faster than in LFP (Stephens et al., 2025).

The urgency of these strategies is underscored by projected demand: by 2040, demand for lithium, nickel, cobalt, and graphite is expected to increase by six to thirteen times relative to current levels (Stephens et al., 2025), making the reduction of critical raw material dependence a strategic necessity rather than solely an environmental consideration.

Taken together, these findings indicate that reducing critical raw material dependence in EV batteries does not follow a single path, but instead involves a series of trade-offs between supply risk, toxicity, cost, and performance: cobalt reduction through higher nickel content lowers supply risk but raises toxicity and manufacturing cost; micro-doping, particularly with low-cost sulfate, offers a practical route to balance these competing factors; and shifting entirely to LFP offers a more abundant and thermally safer alternative, albeit with its own performance trade-offs.

2.4 Cleaner manufacturing

Manufacturing offers a further avenue for reduction, independent of battery chemistry or design. Producing a 28-kWh lithium-ion battery generates approximately 2.7 to 3.0 tons of CO2-equivalent emissions, with cathode production representing the dominant contributor (Hao et al., as cited in Jin et al., 2024). Conventional wet electrode manufacturing relies on N-methyl-2-pyrrolidone (NMP), a toxic solvent requiring energy-intensive drying and recovery processes; eliminating this step through dry electrode processing has been identified as one of several technologies that could collectively reduce energy consumption per unit of processed electrode area by 42.5% to 57% by 2040 if fully industrialised (Degen, Winter, Bendig, & Tübke, 2023).

2.5 Lifespan extension

Extending battery lifespan is itself a form of material reduction: a battery that remains functional for longer needs to be replaced less frequently, which directly lowers the demand for new critical raw materials, manufacturing energy, and end-of-life waste (Sinha, Lehman, & Bharadwaj, 2026). Battery aging can be attributed to three underlying degradation modes: loss of lithium inventory, in which cyclable lithium ions are progressively consumed; loss of active material, in which the electrodes' capacity to store lithium gradually diminishes; and conductivity loss, in which rising internal resistance reduces the battery's power output (Sinha et al., 2026).

The rate at which these degradation modes progress is strongly influenced by how a battery is operated. State of charge has a measurable effect on calendar life: cycling a lithium-ion battery between 30% and 50% state of charge was found to extend its useful life to approximately six years, compared to only two years when the same battery was cycled between 60% and 80% state of charge (Ecker et al., 2012). Temperature is similarly influential, though its impact varies by chemistry: raising storage temperature from 25°C to 42.5°C increased capacity fade in NMC batteries by a factor of six, while the same temperature increase affected LFP batteries far less severely, accelerating fade by only 1.3 times (Spitthoff, Shearing, & Burheim, 2021). Current rate and depth of discharge add further influence: higher charging and discharging currents generally shorten battery life, and batteries subjected to shallow, regular cycling have been shown to last roughly three times longer than those subjected to the deep discharge cycles typical of vehicle-to-grid applications (Sinha et al., 2026). Table 6 summarises these operating factors and their documented effects.

Table 6. Operating factors influencing lithium-ion battery lifespan.

Factor	Effect on lifespan	Documented finding	Source
State of charge (SOC)	Extreme SOC ranges accelerate degradation	Cycling between 30 and 50% SOC extended calendar life to about 6 years, versus only about 2 years at 60 to 80% SOC	Ecker et al. (2012)
Temperature	High temperature strongly accelerates aging; effect is chemistry-dependent	Raising storage temperature from 25°C to 42.5°C increased NMC capacity fade sixfold; the same change increased LFP fade by only 1.3 times	Spitthoff et al. (2021)
Current rate (C-rate)	Higher current shortens life; charging is generally more detrimental than discharging	Higher discharge C-rate reduces cycle count; internal resistance rises most sharply at 10C to 15C	Sinha et al. (2026)
Depth of discharge (DOD)	Deep discharge cycles shorten life	A PHEV under regular use lasted approximately three times longer than one subjected to deep vehicle-to-grid discharge cycles	Sinha et al. (2026), citing Bishop et al. (2013)

Note: rows citing Sinha, Lehman, & Bharadwaj (2026) reflect findings that could not be independently verified against their original primary source at the time of writing and should be treated as secondary citations.

Beyond how a battery is used, how it is charged can independently extend its life, often substantially. Health-aware charging schemes compared against standard constant-current charging show considerable gains: positive pulse current charging, which introduces brief rest periods between charging pulses, was shown to extend battery life by up to 81.6% (Huang et al., 2023). Other advanced schemes reported in the literature include bi-directional pulse current charging, which adds a short reverse-current pulse to the rest phase, and multi-stage constant current charging, which reduces current progressively as charge accumulates; both have been reported to extend life substantially relative to conventional charging, in one case by as much as 128.6% (Sinha et al., 2026). These results indicate that adjusting the charging strategy alone, without any change to the battery's physical design or chemistry, can substantially extend its usable life, making it one of the most cost-effective levers available for reducing material demand.

Finally, this logic connects lifespan extension to a broader materials perspective: because lithium itself is a finite resource under increasing demand, sodium-ion chemistry has been identified as a promising longer-term alternative, owing to sodium's natural abundance and low cost, although current limitations in energy density and cycle life remain barriers to its widespread adoption (Sinha et al., 2026).

3. Reuse

In the context of electric vehicle batteries, reuse, also referred to as the second-life approach, means giving a retired battery a new purpose rather than discarding or recycling it immediately. When a battery's capacity declines to roughly 70 to 80% of its original value, it can no longer meet the performance standards required for vehicle operation and is therefore withdrawn from automotive use. Nevertheless, such batteries still retain considerable residual energy and material value, making them well-suited for less demanding stationary applications, such as energy storage. Repurposing these decommissioned batteries extends their service life, reduces lifecycle costs, and supports the circular economy by minimising waste and the extraction of new resources (Nazim & Elavarasan, 2026).

3.1 Battery lifetime: first-hand use and second life

An EV battery is typically warranted for eight to ten years of first-hand automotive use. It is then retired once its capacity falls to around 70 to 80 percent of its original value, at which point it no longer meets the demands of traction, even though most of its usable capacity remains (Gu et al., 2024; Canals Casals et al., 2019a).

How long that remaining capacity lasts in a second life depends heavily on the application. Modelling of four stationary uses found lifespans ranging from roughly 30 years in support of fast EV charging, down to about 6 years in area regulation grid services, where cycling is far more intensive. The same study found that second-life applications paired with renewable generation, such as self-consumption,??? deliver clearer environmental benefits than grid-oriented ones (Canals Casals et al., 2019a). Only after this second life is the battery finally recycled, so that its valuable materials can be recovered.

The applications of second-life batteries can be classified according to their position relative to the electricity meter. Front-of-the-meter (FTM) applications are connected on the grid side and provide services to the wider electricity network, whereas behind-the-meter (BTM) applications are located on the consumer's side and serve a specific user. Within these categories, applications can be further described as power services, which require a fast response over short durations, or energy services, which require large storage capacity over longer periods.

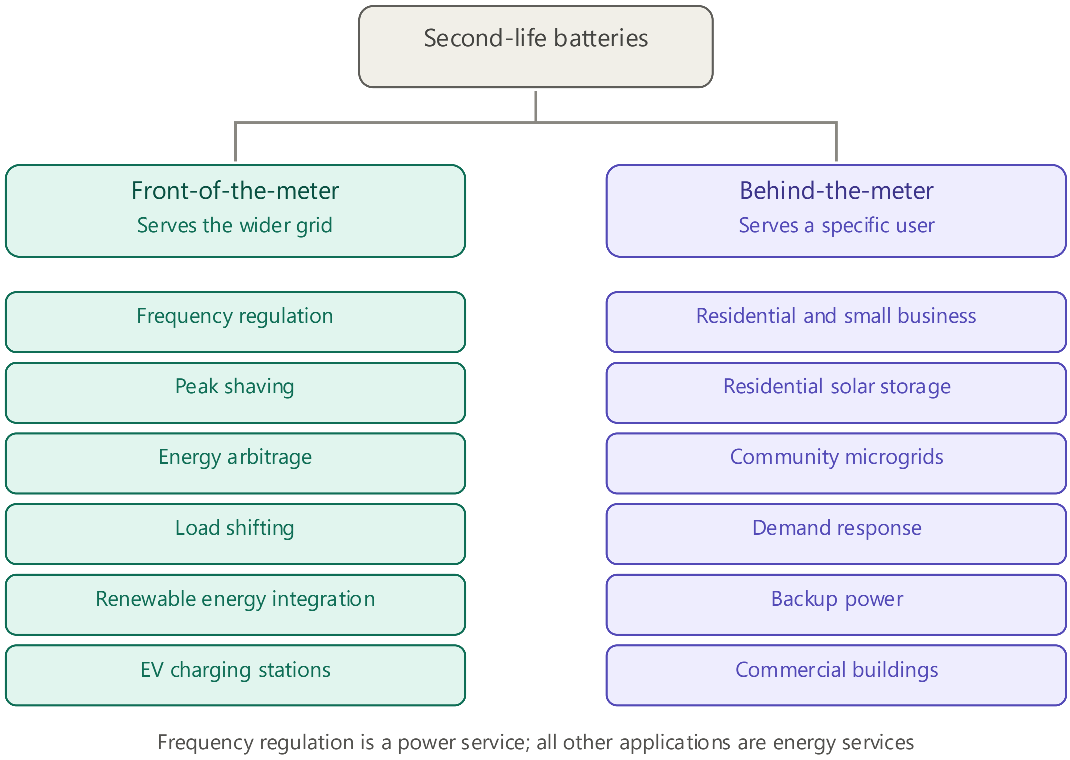

Figure 3. Classification of second-life battery applications into front-of-the-meter and behind-the-meter, and into power and energy services.
Author's own elaboration.

3.2 Front-of-the-Meter (FTM) applications

Frequency regulation

In grid applications, frequency regulation is regarded as one of the most technically demanding and beneficial services provided by stationary lithium-ion battery systems (SLBs). It requires very fast response times, high performance capabilities, and considerable power ratings, typically exceeding 1 MW. These systems usually operate with a power-to-energy ratio of approximately 1:1, making them suitable for meeting the rapid power adjustments required for frequency regulation (Hesse et al., 2017). SLBs are particularly effective in reducing short-term mismatches between electricity generation and demand, thereby supporting grid frequency stability. The economic feasibility of lithium-ion batteries for frequency regulation applications became evident as early as 2010 to 2011, when battery systems with ratings of 8 MW/2 MWh and subsequently 16 MW were deployed in New York City to provide grid support (Kim et al., 2017). Frequency regulation is classified as a power service because it requires rapid response and high power capability but only a low energy capacity (Huang et al., 2025).

Peak shaving

Peak shaving is a strategy in which a battery is charged when electricity is inexpensive and demand is low, then discharged during periods when demand and prices reach their highest levels (Lee et al., 2021). For commercial and industrial consumers, this approach carries significant financial value. Their electricity bills typically combine two components: an energy-usage charge based on total monthly consumption, and a separate maximum demand charge tied to the single highest level of power drawn during the billing period.??? This demand charge alone can represent between 30% and 70% of a consumer's total bill (McLaren et al., 2017), so lowering those brief peaks translates into meaningful savings. Although new storage systems are often too costly to justify for this purpose, second-life batteries provide an economically viable alternative, costing roughly a third, about 31.71%, of a new system (Lee et al., 2021). Peak shaving is classified as an energy service because it requires large storage capacity and long discharge durations rather than fast power bursts (Huang et al., 2025).

Energy arbitrage

Energy arbitrage is one of the most financially attractive applications for second-life batteries. It works by charging the battery when electricity prices are low, during off-peak periods, and discharging it when prices rise. Although this service has traditionally relied on conventional battery storage, the high upfront cost of new systems has limited its profitability (Grimaldi et al., 2024). Second-life batteries address this barrier by serving as a far cheaper storage option. Techno-economic assessments suggest that utility-scale arbitrage using second-life batteries is economically viable, potentially extending project lifetimes beyond 16 years while cutting costs by more than 80% compared with newly installed systems (Gu et al., 2024). Because arbitrage relies on charging and discharging over extended periods to exploit price differences, it can be classified as an energy service, prioritising large storage capacity over rapid power response.

Load shifting

Load shifting moves energy consumption from peak periods to off-peak periods rather than reducing peak demand itself. Beyond reducing electricity costs, it delays upgrades to transmission and distribution infrastructure while improving the utilisation of existing grid assets (Yang et al., 2022). A practical example of this approach is provided by a case study conducted on communication base stations in China, which require a stable and continuous electricity supply to support mobile communication networks. The researchers compared three scenarios: a conventional system relying entirely on the electricity grid without energy storage; a load-shifting system using refurbished second-life lithium-ion batteries, charged during off-peak hours and discharged during peak hours; and an equivalent load-shifting system using new lithium-ion batteries. The environmental and economic performance of these scenarios was assessed using Life Cycle Assessment and Net Present Value respectively. Based on a communication base station with a 2.16 kW load, eight hours of daily load shifting, and a 10-year project lifetime, the study found that the second-life battery system reduced life-cycle costs by 17.6% compared with the conventional system. However, because the repurposed batteries had a lower round-trip efficiency, 88% compared with 92% for new batteries, their environmental performance was almost identical to that of the conventional system. Furthermore, the economic viability of the proposed system depended largely on the electricity price difference between peak and off-peak periods (Yang et al., 2022). Given its long discharge duration of eight hours daily, load shifting can be classified as an energy service, since it prioritises large storage capacity over rapid power response.

Renewable energy integration

At the utility scale, second-life batteries support the integration of intermittent renewable sources such as solar and wind. By storing surplus energy during periods of high generation and releasing it during low production or peak demand, they help stabilise the grid and improve the reliability of renewable supply. A comparative study of utility-level applications found that second-life batteries reduced the levelised cost of electricity by 12 to 57 percent and life-cycle carbon emissions by 7 to 31 percent compared with new batteries (Kamath et al., 2020). A techno-economic study of a utility-scale solar-plus-storage project further showed that, with appropriate charge limits, second-life batteries can extend project life beyond sixteen years and remain profitable when priced below 60 percent of a new battery (Mathews et al., 2020).

EV charging stations

Charging infrastructure also benefits from second-life batteries, particularly when combined with solar systems to store surplus energy and reduce reliance on the grid. A techno-economic study found that second-life batteries become financially attractive for charging stations when their cost is 40 percent or less of a new battery (Gautam et al., 2025). In a separate study of an electric bus charging station, integrating second-life battery storage with a day-ahead scheduling strategy reduced operational costs by 11 percent while easing peak demand on the distribution network (Wei et al., 2025).

Table 7. Comparison of second-life battery energy applications

Application	Trigger	Timescale	Beneficiary
Energy arbitrage	Electricity price	Hours	Battery trader / operator
Load shifting	Grid demand / peak hours	Daily cycle	Grid operator
Renewable integration	Solar/wind generation level	Daily to seasonal	Utility / renewable producer
EV charging stations	Vehicle arrival / charging need	Minutes to hours	Charging station operator

Note: All four applications share the same core mechanism — charging when conditions are favourable and discharging when conditions change. They differ not in mechanism but in what triggers the charge/discharge decision, over what timescale, and who ultimately benefits. Author's own elaboration

3.3 Behind-the-Meter (BTM) applications

Behind-the-meter applications place the battery on the consumer's side of the meter, serving a specific user rather than the wider grid. Across all of these applications, second-life batteries function primarily as energy services, since they prioritise large storage capacity delivered over extended periods rather than fast, short-duration power output.

Residential and small-business storage

Behind the meter, second-life batteries can serve as stationary storage for consumers such as small businesses. A study of two real cases in Spain, a furniture factory and a hotel, found that economic viability depends strongly on battery price and ageing. In the smaller case, the system saved 1,924 euros per year with a return on investment shorter than the battery's lifespan, making it viable, whereas the larger case was not profitable due to its oversized and costlier system. The study also found energy arbitrage more profitable than peak shaving, and noted that viability improves significantly when batteries participate in secondary electricity markets (Rallo et al., 2020).

Residential solar storage

At the residential level, second-life batteries paired with rooftop solar systems allow households to store their own solar energy for later use, increasing self-consumption and lowering electricity bills. Compared with rooftop PV alone, adding second-life batteries has been shown to reduce the levelised cost of electricity by 15 to 25 percent and life-cycle carbon emissions by 22 to 51 percent, making them attractive for residential consumers (Kamath et al., 2020). Their economic appeal is reinforced by their low cost: examining used EV batteries repurposed as home storage in a near-zero energy building with rooftop PV, Biskupski (2025) found that such a system can carry an initial cost three to four times lower than a newly purchased PV battery system, while offering two to four times the capacity for the same price.

One of the tested configurations delivered stable output comparable to a brand-new system, confirming the suitability of second-life batteries for residential use and supporting the reintroduction of batteries into the circular economy (Biskupski, 2025).

Community microgrids

Beyond individual buildings, second-life batteries can serve as shared storage in community microgrids, allowing groups of prosumers to manage the renewable energy they generate locally. A feasibility study found that shared second-life storage can achieve high self-consumption of renewable energy even without any financial incentives. Compared with new batteries, it increased financial savings by up to 8 percent and lowered carbon emissions, reducing CO_2 by as much as 23.5 percent in the most favourable case. The study further linked wider adoption to carbon pricing and government incentive schemes, underlining the role of policy in making second-life storage economically viable (Terkes et al., 2023)

Demand response

In demand response programmes, second-life batteries allow buildings to adjust their electricity use to support grid balancing in exchange for financial rewards. A study of European electricity markets found that reusing EV batteries in buildings extends their lifespan by around 40 percent, but that residential use alone may not be the most profitable option. However, when these batteries participate in secondary electricity markets through an aggregator, combining demand response with normal building use, the business case becomes attractive while causing relatively little additional battery ageing (Canals Casals et al., 2019b).

Backup power

Another valuable role for second-life batteries is backup or uninterruptible power supply, providing reliable electricity for critical loads such as hospitals, data centres, residential buildings, and microgrids. Their main advantages in this role include high capacity, reliability, and cost-effectiveness. In the event of power deficits or grid faults, they enhance supply reliability and ensure that essential equipment continues to operate (Song et al., 2024).

Commercial buildings

In commercial settings, second-life batteries are increasingly deployed in buildings where electricity bills combine both energy and demand charges. A study validated on a real system operating for twelve months found that using second-life batteries with an intelligent control strategy reduced electricity costs by 28.6 percent compared with operating without storage. The system achieved a five-year payback period and a low annual battery degradation of just 1.20 percent, demonstrating that second-life batteries are practically viable for commercial energy management while supporting the circular economy (Cao et al., 2025).

3.4 A note on overlapping applications

It is important to note that the classification of applications into front-of-the-meter and behind-the-meter is not always rigid. Some applications can occur on either side of the meter depending on their scale and purpose. For example, renewable energy integration and peak shaving can operate at the utility level to support the grid, or at a smaller scale to serve a single household or business. In this review, each application has been placed under the category in which it is most commonly deployed, while recognising that these boundaries can overlap in practice.

3.5 Challenges

3.5.1 Safety and thermal runaway

The most significant barrier to the large-scale deployment of second-life batteries is uncertainty about their safety. A retired pack rarely arrives with a documented history of how it was driven, charged, or stored, which makes its true condition and reliability difficult to establish (Azizighalehsari et al., 2024).

The hazard that matters most is thermal runaway. Once internal reactions begin generating more heat than the cell can dissipate, temperature climbs, the reactions accelerate, and the cycle feeds itself until fire or explosion follows. Mechanical damage, electrical misuse, and excessive heat can all set this chain in motion (Chen et al., 2021). Used packs are especially vulnerable. Demanding operating conditions push temperatures up quickly, eroding capacity, raising internal resistance, and cutting efficiency. Worse, the cells inside a pack do not age at the same rate, so a handful of weak cells may overheat and drag the whole module into failure. Warning signals appear before the event: the casing warms, voltage drops abruptly, smoke escapes, and the shell begins to swell (Song et al., 2024).

One finding deserves particular attention, because it undermines a common assumption. Screening cells by their remaining capacity does not, on its own, establish that they are safe. Zhang et al. (2024) compared cells that had been aged in different ways and found that those cycled in cold conditions began releasing heat at a markedly lower temperature and slipped into runaway far sooner, even though every cell in the comparison registered a similar state of health. Two cells can therefore look identical on a capacity test and behave very differently under thermal stress, depending entirely on what they endured in their first life. Safe reuse consequently depends on understanding how a battery degraded, not merely how much capacity it has lost. Among the measures proposed to manage this risk are improved structural design, real-time identification of cell parameters, more capable battery management systems, and control strategies driven by artificial intelligence that can anticipate a failure before it occurs (Song et al., 2024).

3.5.2 Cell inhomogeneity

A second challenge concerns the differences that develop between individual cells within a pack. Cell inhomogeneity in second-life batteries appears mainly in three parameters: capacity, voltage, and internal resistance. Because cells no longer share the same state of charge, the depth to which each is charged and discharged varies. Cells with smaller capacity reach full charge before the others, which exposes them to a risk of overcharging, while inconsistencies in resistance produce further differences in voltage and current across the pack (Song et al., 2024).

Several mechanisms drive this divergence. When cells are connected in parallel they share a common terminal voltage, yet differences in their parameters, structure, and connections still produce an imbalance; sustained over time, this imbalance alters the real capacity and state of health of individual cells and accelerates the divergence between them (Piombo et al., 2021). Ageing also raises cell impedance, which lowers charging and discharging efficiency and increases energy losses, and these impedance differences widen as the battery ages (Roy & Khan, 2020). Because cells differ in capacity, resistance, and electrochemical behaviour, the rate at which they absorb and release energy is uneven, leading to an unequal distribution of energy within the pack and, in some cells, excessive discharge (Yang & Zhang, 2024). Long-term cycling, meaning the repeated charge and discharge a battery undergoes across thousands of cycles in normal use, also degrades the electrode materials themselves, further widening the gap in capacity and resistance between cells and weakening the overall safety of the pack (Song et al., 2024).

Solutions

Two families of balancing strategies address cell inhomogeneity. Active balancing regulates and redistributes power between cells using power conversion devices, transferring charge from stronger cells to weaker ones. It offers high balancing efficiency, fast operation, and good energy utilisation, but the technology is complex, costly, and difficult to implement, since it requires transformers, power switches, and driver circuitry. Passive balancing instead relies on resistive discharge, releasing the excess electricity from higher-voltage cells as heat and giving the remaining cells more time to charge. It is a well-proven, low-cost, and highly reliable approach, but its balancing efficiency and energy utilisation are low, and it generates considerable heat (Song et al., 2024).

Comparative studies suggest that neither approach is optimal on its own. Active balancing has been shown to slow battery ageing, reducing the end-of-discharge voltage difference more than fivefold, increasing discharge capacity by 3.1 percent, and extending service life by 7.7 percent. For second-life applications specifically, a bilevel equaliser, which combines active and passive balancing, has been found to be considerably more efficient and cost-effective than either strategy used alone (Song et al., 2024).

3.5.3 Compatibility

Compatibility determines whether a retired pack can actually serve the role it is assigned. Chemistry is the first constraint: LFP, NMC, and NCA cells behave very differently in terms of energy density, power density, cycle life, and thermal stability, and finding a chemistry that genuinely suits the intended application is not straightforward. A poor match produces disappointing performance, complicates the management of the pack, and can create safety risks. Voltage and capacity must also line up with the target system, since a mismatch on either front leads to inefficient energy transfer and, again, to hazards. For the same reason, packs grouped together should have aged to a broadly similar degree, so that their performance and operating behaviour remain comparable (Patel et al., 2024).

Solutions

Progress here depends largely on smarter management. A new generation of battery management systems is being developed with far stronger diagnostic and monitoring capabilities: these can track degradation as it unfolds, detect load imbalance across the packs, and flag faults before they become safety-critical. As confidence in such systems grows, repurposed packs can be pushed further, carrying heavier loads with narrower safety margins before being declared spent. Alongside this, intelligent storage controls that adapt to what a used battery can realistically deliver, adjusting charge and discharge rates and managing heat, help extend its working life. Underpinning all of it is the need for a structured process, from selection and testing through sorting, repurposing, validation, and documentation, which allows second-life projects to meet legal standards while supporting a more sustainable energy system (Patel et al., 2024).

3.5.4 Data security and protection

The operating data of an EV battery are continuously recorded and stored by its management system, which over the years accumulates a substantial database covering manufacturers, consumers, and operators alike. Much of that information touches on consumer privacy and commercial confidentiality, and if it is misused, the security of a second-life storage system can be compromised (Song et al., 2024; Kampker et al., 2023). Three risks stand out. Charging and discharging behaviour could be deliberately manipulated by malicious actors, destabilising the grid and, in the worst case, triggering widespread outages. Personal information such as travel patterns, driving habits, and home addresses could be exploited. And parameters like cycle count and state of health represent commercial secrets: if competitors obtain them illegally, product technology can be reverse-engineered and intellectual property violated. Conventional battery management systems were never designed to detect or defend against these threats in a second-life context, which makes advanced data protection strategies essential (Song et al., 2024).

Notably, data security is not a marginal concern. In a systematic review of the barriers facing second-life battery systems, it is grouped with stakeholder management under other barriers, yet the authors stress that its importance is no lower than that of the more frequently discussed obstacles (Kampker et al., 2023).

Solutions

Several strategies have been developed to protect this data. A digital passport assigns each second-life battery a unique identity, recording its factory origin, usage history, and key parameters. Smart metering secures the channel through which data travels between the battery and the user, while Internet of Things technologies encrypt the data itself and protect the databases in which it is stored. Each approach has its own strengths and weaknesses, and what is now urgently needed is compatibility and standardisation across these different methods, without which second-life storage systems will struggle to move into widespread practical use (Song et al., 2024).

Regulation is beginning to provide that structure. The European Union's Battery Regulation, adopted in July 2023, introduces a digital battery passport: a dynamic record that follows a battery through its entire life, from production to end-of-life management, making the value chain transparent and traceable. Accessed through a QR code, the passport is maintained by the operator who places the battery on the market, and when a battery is repurposed for a second life a new passport is issued. Crucially, the regulation resolves the tension between transparency and confidentiality by tiering access: general information is public, while sensitive data such as composition, dismantling technique, and safety measures is reserved for the European Commission, notified bodies, and parties with a legitimate interest. From February 2027 the passport becomes mandatory for all electric vehicle and industrial batteries (Soavi et al., 2026).

4. Recycle

After a battery has served its automotive life and, where possible, a second life in stationary storage, recycling becomes the final stage. At this point the pack no longer holds enough usable capacity for any application, and its value lies entirely in the materials it still contains.

Lithium-ion batteries depend on cathode raw materials, chiefly lithium, nickel, cobalt, manganese, and graphite, that are being depleted at a significant rate. Their supply is also highly concentrated. According to 2022 data from the United States Geological Survey, 78.4 percent of lithium resources originate in Australia and Chile, 72.1 percent of cobalt is produced in the Democratic Republic of Congo, roughly a third of manganese is controlled by South Africa, over half of nickel minerals are extracted in Indonesia, and China accounts for more than 60 percent of world graphite production. These essential materials are therefore effectively monopolised by a handful of countries (Shen et al., 2025). Extracting them also demands considerable energy and frequently causes lasting environmental damage, pollution, and serious social and health consequences for the communities living near the mines (Nazim & Elavarasan, 2026).

The pressure on these supplies is set to intensify. By 2040 the projected demand for lithium, cobalt, and nickel for electric vehicle batteries is expected to exceed current global production, in some scenarios by as much as eight times (Maisel et al., 2023).

Recycling offers a substantial part of the answer. Recovering valuable metals from spent batteries reduces dependence on primary extraction, lessens environmental impact, and improves the overall sustainability of the battery industry (Nazim & Elavarasan, 2026). The scale of that contribution is significant: the recycling potential for lithium and nickel has been estimated at more than half the raw material demand for EV batteries in 2040, while for cobalt the recycling potential exceeds projected demand altogether (Maisel et al., 2023).

4.1 Recycling routes

Pyrometallurgy

Pyrometallurgy is the most established of the three routes and the most forgiving in what it accepts. Because it does not require batteries to be sorted or reduced in size beforehand, different chemistries can be fed into the furnace together, and lithium-ion cells can even be processed alongside Ni-MH batteries as a single mixture. Pretreatment therefore becomes optional. The material is pyrolysed, the metals are reduced, the resulting gases are incinerated, and the output is a metal alloy, all at smelting temperatures approaching 1500 degrees Celsius. Recovery of the high-value metals is efficient, exceeding 90 percent for cobalt and nickel.

Its weaknesses, however, are considerable. The process is highly energy-intensive and releases toxic gases, and further steps are needed afterwards to separate the individual metals out of the alloy, which pushes processing costs up. Recovery is also selective rather than complete: the method captures cobalt and nickel from the cathode and copper from the anode current collector, while lithium and manganese are generally lost in the slag and the electrolyte and plastics are vaporised at high temperature. Historically the route stayed profitable because traditional cells contained a great deal of cobalt, but as the industry shifts toward low-cobalt chemistries, its long-term economic viability is increasingly in question (Das et al., 2026). In quantitative terms, pyrometallurgy has been estimated at 3.4 dollars per kilogram and 18.4 megajoules per kilogram (Xu et al., 2020).

Hydrometallurgy

Hydrometallurgy works in aqueous solution and proceeds in two stages: leaching, then metal separation. In the leaching stage, pretreated material is exposed to acids together with reducing agents, dissolving the solid metals into soluble ions. Both inorganic acids, such as sulphuric, hydrochloric, and nitric acid, and organic ones, such as citric, tartaric, and oxalic acid, are commonly used. Once dissolved, the metal ions are separated selectively by chemical precipitation, solvent extraction, ion exchange, or electrodeposition. The whole process runs below 100 degrees Celsius and can extract the key metals at efficiencies above 95 percent.

Compared with smelting, this route consumes less energy, emits less, recovers a far wider range of components, and yields products of higher purity. The trade-offs lie elsewhere. Batteries must be sorted first, which raises storage requirements and cost. Separating metals with similar chemical behaviour, such as cobalt, nickel, manganese, iron, and copper, remains technically demanding. And the process consumes chemicals and water while generating wastewater that has to be treated, all of which adds to the overall bill. It is also less economically attractive for chemistries low in cobalt or nickel, such as LFP (Das et al., 2026). Its reported figures are 2.4 dollars per kilogram, but the highest energy demand of the three routes at 30.6 megajoules per kilogram (Xu et al., 2020).

Direct recycling

Direct recycling takes a fundamentally different approach: rather than breaking the cathode down into its constituent metals, it recovers the active material with its original chemical structure intact. The battery is disassembled, its components are separated physically using techniques such as magnetic separation and controlled thermal treatment that avoid degrading the active material, and the material is then purified and repaired through hydrothermal treatment, solid-phase processing, electrochemical techniques, or chemical re-lithiation. The result is a regenerated cathode that retains between 80 and 100 percent of its original performance, obtained with roughly 40 percent less energy than the alternatives, and with a substantial reduction in emissions and secondary pollutants (Das et al., 2026). The quantitative advantage is striking: 2.1 dollars per kilogram, 3.5 megajoules per kilogram, and 0.7 kilograms of CO_2 per kilogram, the lowest figures across all three categories (Xu et al., 2020).

The obstacles are practical rather than conceptual. Sorting and identifying mixed chemistries coming from different manufacturers is difficult, since even small variations in composition and design affect the quality of the reconditioned material. Spent cathodes and anodes do not degrade uniformly, which makes consistent performance after regeneration hard to guarantee. Residual binders, electrolytes, and impurities frequently compromise the purity and safety of the regenerated material. And the absence of standardised disassembly and diagnostic techniques, combined with limited automation, restricts industrial adoption. For these reasons the method remains largely confined to laboratory scale and is currently applied mainly to electrode scrap of known chemistry. Even so, it is widely regarded as the most promising pathway toward an energy-efficient, low-emission, closed-loop recycling system (Das et al., 2026).

4.2 Comparison of the three routes

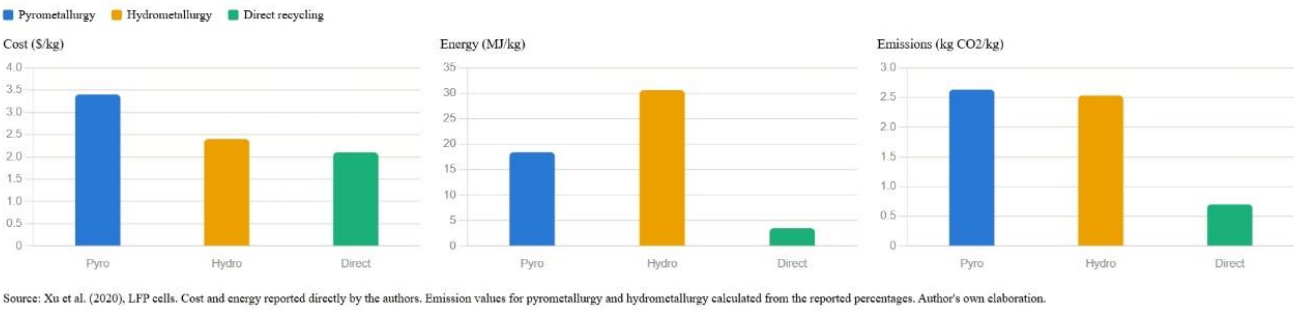

Figure 3. Comparison of recycling routes by cost, energy use, and greenhouse gas emissions.
Source: Xu et al. (2020), LFP cells. Author's own elaboration.

Table 8. Comparison of pyrometallurgical, hydrometallurgical, and direct recycling routes

Criterion	Pyrometallurgy	Hydrometallurgy	Direct recycling
Principle	Smelting (~1500 °C)	Acid leaching (<100°C)	Structure-preserving recovery
Pre-sorting required	No	Yes	Yes, rigorous
Cost ($/kg)	3.4	2.4	2.1
Energy (MJ/kg)	18.4	30.6	3.5
Emissions (kg CO_2/kg)	2.63*	2.53*	0.7
Water use (gal/kg)	1.4 to 27.5	6.6 to 12.6	4.2 to 6.8
Water pollution	Medium	Low	Minimal
Main chemicals	Limestone, sand, coke	H_2SO_4, HCl, H_2O_2	LiOH, citric acid
Recovery (theoretical)	>90% (Co, Ni only)	>95% (most components)	80 to 100% of performance
Materials lost	Lithium, manganese, graphite	Fewer losses	Minimal
Maturity	Industrial	Industrial	Laboratory scale

*Cost and energy from Xu et al. (2020), based on LFP cells. Emission values marked * were calculated from the percentages reported by the authors: direct recycling emits 26.6% and 27.7% of the emissions from pyrometallurgy and hydrometallurgy respectively. Water use, water pollution, chemicals, and recovery rates from Das et al. (2026).*

As Table 8 and Figure 3 show, the pattern across the three routes is unambiguous. Direct regeneration consumes 3.5 megajoules per kilogram, which the authors report as only 19 percent of the energy required by pyrometallurgy and 11 percent of that required by hydrometallurgy. Its greenhouse gas emissions of 0.7 kilograms per kilogram represent roughly 27 percent of the emissions of either conventional route. Its cost falls to 2.1 dollars per kilogram, against 3.4 for pyrometallurgy and 2.4 for hydrometallurgy. The saving comes principally from a better operational design and considerably less chemical use during processing (Xu et al., 2020). Direct recycling also preserves the cathode structure rather than destroying it, which is what allows 80 to 100 percent of the original performance to be retained, and it produces only minimal water pollution, against low for hydrometallurgy and medium for pyrometallurgy (Das et al., 2026).

The economics are decisive in a way the aggregate figures obscure. Direct recycling generates a potential profit of 1.04 dollars per kilogram of spent cells processed, whereas the revenue from recovered materials in the two conventional routes cannot cover their high costs, owing to expensive equipment, heavy material inputs, and high energy consumption. This, rather than any technical obstacle, is the principal reason the industry does not currently recycle LFP cells at all (Xu et al., 2020).

The comparison between the two established routes is less clear-cut. Pyrometallurgy operates on unsorted, mixed feedstock and demands no pretreatment, but it consumes substantial energy, releases toxic gases, and loses lithium, manganese, and graphite entirely. Hydrometallurgy recovers a far broader range of materials at higher purity and operates at much lower temperatures, yet carries the highest energy figure of the three and generates wastewater requiring treatment. Its economics also weaken for low-cobalt chemistries such as LFP (Das et al., 2026).

Placing these figures in context sharpens the case further. Manufacturing a battery from virgin materials costs 22.7 to 23 dollars per kilogram, consumes 152.9 to 163.8 megajoules, and emits 11.3 to 19.8 kilograms of CO_2, while carrying a very high water pollution burden from mining. Every recycling route therefore represents a substantial improvement over manufacturing from virgin materials; the question is not whether to recycle but which route to scale.

The decisive qualification concerns maturity. Pyrometallurgy and hydrometallurgy are deployed industrially today; direct recycling is not. Its advantages are measured largely under laboratory or modelled conditions, and scaling it up depends on solving problems that are practical rather than theoretical: reliable sorting of mixed chemistries, consistent regeneration despite uneven degradation, contamination from residual binders and electrolytes, and the absence of standardised disassembly and diagnostic procedures (Das et al., 2026). Direct recycling therefore represents the most promising destination rather than the current state of the industry, and realising its potential depends less on further chemistry than on standardisation, automation, and the traceability of what enters the recycling stream.

4.3 Challenges

The gap between potential and practice

The most striking problem in battery recycling is not technical capability but the distance between what is possible and what actually happens. Under laboratory and pilot conditions, pyrometallurgy recovers over 90 percent of cobalt and nickel, hydrometallurgy exceeds 95 percent for most components, and direct recycling retains 80 to 100 percent of original cathode performance. In practice, however, less than 5 percent of the lithium-ion batteries produced are currently recycled (Das et al., 2026). The overwhelming majority of the material discussed in the preceding sections is therefore never recovered at all, regardless of which route is theoretically best.

This gap matters because the value at stake is not hypothetical. As shown earlier, the recycling potential for lithium and nickel has been estimated at more than half the projected raw material demand for EV batteries in 2040, and for cobalt it exceeds demand altogether (Maisel et al., 2023). A recovery rate below 5 percent means that this potential remains almost entirely unrealised.

Economic barriers

Recycling has to pay for itself, and on current terms it often does not. In hydrometallurgy, raw materials account for 72.3 percent of total cost, and the expenses for labour, equipment, electricity, and water are considerable in their own right, given the complexity of the operating procedures and the use of strong acid (Rezaei et al., 2025). This leaves little margin once the recovered metals are sold. The problem is compounded by the direction the industry is taking. Pyrometallurgy remained profitable historically because traditional cells contained a great deal of cobalt; as manufacturers shift toward low-cobalt chemistries, the economic case for smelting weakens considerably. Hydrometallurgy faces the same pressure from a different angle, since it is less cost-effective for chemistries low in cobalt or nickel, such as LFP (Das et al., 2026). In other words, the batteries entering the waste stream are becoming progressively less valuable to recover precisely as their volume grows.

The wider business case is equally fragile. Because each retired battery must be assessed individually for its remaining condition, investment costs vary from one batch to the next, and a generally valid business model is difficult to calculate (Kampker et al., 2023). Recycling therefore struggles to attract investment on purely commercial grounds, which is one reason the recovery rate remains as low as it is.

Technical and logistical barriers

Before any recycling route can be applied, the battery has to be collected, transported, assessed, and dismantled, and it is at these earlier stages that much of the difficulty lies. The challenge most frequently identified in the literature is the sheer diversity of end-of-life batteries: cell chemistry, system architecture, user behaviour, operating conditions, operating strategy, and the timing of market exit all vary, producing a waste stream that is inherently unpredictable (Kampker et al., 2023).

That variability directly undermines the most promising route. Direct recycling depends on knowing what is being processed, yet sorting and identifying mixed chemistries from different manufacturers remains difficult, since even small variations in composition and design affect the quality of the regenerated material. Spent cathodes and anodes degrade unevenly, making consistent performance after regeneration hard to guarantee, and residual binders, electrolytes, and impurities frequently compromise the purity and safety of the recovered material. Underlying all of this is the absence of standardised disassembly and diagnostic techniques, which, combined with limited automation, keeps the method confined largely to laboratory scale and to electrode scrap of known chemistry (Das et al., 2026).

Regulatory barriers and the emerging framework

Recycling on the scale required will not emerge from market forces alone, and the regulatory framework has until recently been a barrier in itself. The European Union has moved to address this. Regulation (EU) 2023/1542, adopted in July 2023, rests on three pillars: standardising the rules that apply to all market participants, closing the gaps in collection and recycling that hold back the circular economy, and prioritising sustainability and safety across the battery life cycle. It also extends the categories covered to include EV batteries and light means of transport such as e-bikes and e-scooters (Soavi et al., 2026).

Several of its provisions bear directly on the problems described above. Carbon footprint reporting became mandatory for industrial, light means of transport, and EV batteries in 2025, with maximum thresholds enforced from 2027. Due diligence obligations require manufacturers to identify and address social risks throughout their supply chains, in line with OECD guidance, which speaks to the mining conditions noted at the start of this section. Most significantly for recycling, the digital battery passport becomes mandatory for all EV, light means of transport, and industrial batteries by February 2027, making the value chain transparent and traceable and giving recyclers access to information about what they are receiving (Soavi et al., 2026). Since the central technical obstacle is not knowing the chemistry, history, and condition of an incoming battery, traceability of this kind addresses the sorting problem at its root rather than downstream.

The challenges of repeated recycling

Recycling processes do not ensure complete recovery of the original battery materials. Even for high-cobalt cathodes, conventional recycling processes recover only around 70% of the cathode's original value, and this figure drops notably for less cobalt-rich chemistries (Harper et al., 2019). Moreover, direct recycling processes require the lithium content to be replenished to compensate for losses due to material degradation, indicating that recovered material rarely matches the quality of the original (Harper et al., 2019). This pattern is consistent with the broader phenomenon of downcycling, formally defined as the reduction in quality of materials reprocessed from waste relative to their original quality, expressed thermodynamically, functionally, and economically (Helbig et al., 2022). Because no current recycling route recovers battery materials at their original purity or structure, and each additional recycling cycle requires further energy and material inputs, repeated recycling is expected to progressively compound these losses over time, reinforcing the priority given to reduce and reuse strategies ahead of recycling in the 3R hierarchy.

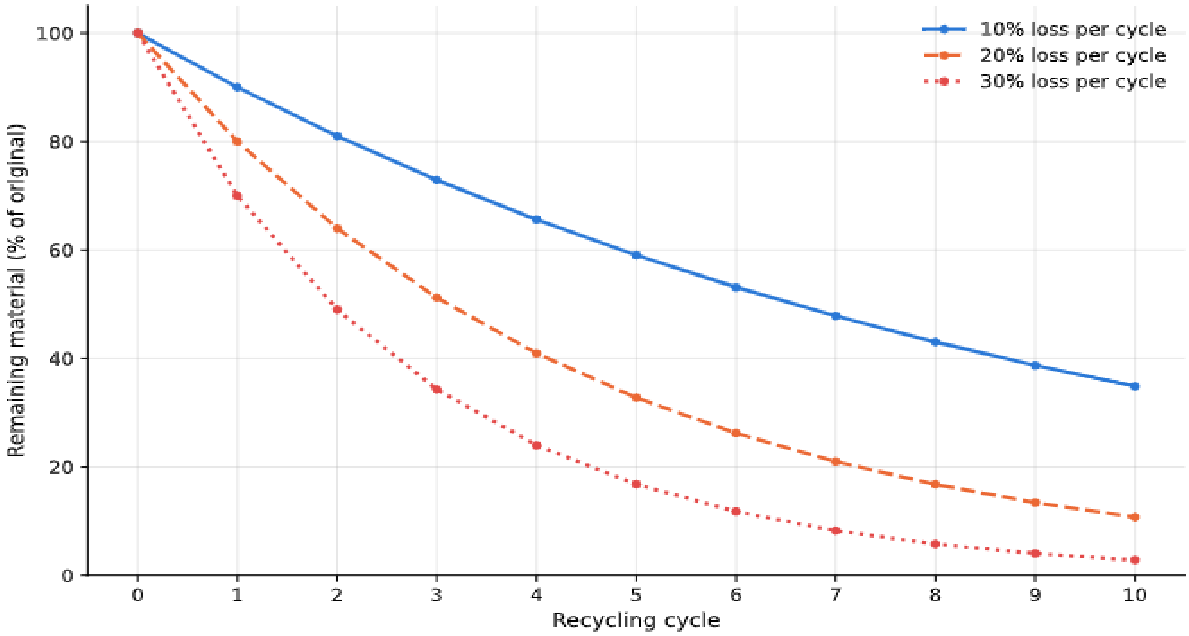

Figure 4. Illustrative material loss across repeated recycling cycles.
Note: scenarios are illustrative, based on the general principle of downcycling (Helbig et al., 2022) and compounding losses across successive purification stages of approximately 30 percent per stage (Condorchem, 2025). Actual multi-generation decline rates for EV battery materials have not yet been empirically established in the literature. Author's own elaboration.

5. Conclusion

The transition to electric mobility has solved one problem and created another. Removing tailpipe emissions from transport is a genuine environmental gain, but it has bound the sector to a supply chain of critical materials that is geographically concentrated, environmentally costly to extract, and heading toward a demand that will outstrip current production within fifteen years. The batteries now entering the market will eventually leave it, and the volume approaching over the coming decades is large enough that how they are handled will determine whether electrification remains sustainable in the long term.

The 3R hierarchy addresses this at three different points in the battery's life, and the evidence examined in this report suggests that each stage carries a advantages and disadvantages, some of which are distinct and others are common.

Reduce operates before the battery exists, at the level of material selection, cell design, and manufacturing. It is the least visible of the three stages, and often the most efficient, because material that is never used requires neither reuse nor recovery.

Reuse operates at the point where the battery leaves the vehicle at 70 to 80 percent of its original capacity. The evidence here is the most immediately practical of the three. Across twelve applications on both sides of the electricity meter, from frequency regulation on the grid to solar storage in a single household, second-life batteries deliver measurable economic and environmental benefits: costs reduced by up to 28.6 percent in commercial buildings, carbon emissions lowered by 22 to 51 percent in residential solar systems, and initial investment three to four times lower than a comparable new system. Reuse extends the working life of a battery by roughly 40 percent, and in favourable applications by considerably more, delaying the moment at which new material must be extracted.

Recycle operates at the end, and the comparison between the available routes is unambiguous. Direct regeneration outperforms both established industrial routes on cost, energy, and emissions simultaneously, at 2.1 dollars, 3.5 megajoules, and 0.7 kilograms of CO_2 per kilogram, while preserving 80 to 100 percent of the cathode's original performance. Set against manufacturing from virgin materials, or against landfilling at 67 to 286 kilograms of CO_2 per kilogram, any recycling route represents a substantial improvement.

What emerges across all three stages, however, is that there are binding constraints. Second-life deployment is held back by the absence of documented usage histories, by the difficulty of assessing safety when capacity screening alone proves insufficient, and by the heterogeneity of packs drawn from different manufacturers. Recycling is held back by economics that no longer favour recovery as cobalt content falls, and by a waste stream so diverse that the most promising route, direct regeneration, cannot yet be applied at scale.

The result is that less than 5 percent of lithium-ion batteries are currently recycled, while the recycling potential for lithium and nickel alone could meet more than half of projected demand in 2040.

Moving closer to a circular economy in battery manufacturing and use requires standardised interfaces and diagnostic procedures, collection and sorting infrastructure capable of handling a diverse waste stream, and above all traceability: knowing the chemistry, history, and condition of a battery before deciding what to do with it. Regulation has begun to supply this. The European Union's Battery Regulation makes a digital battery passport mandatory for all electric vehicle and industrial batteries from February 2027, requiring a transparent record that follows each battery from production to end-of-life, and issuing a new passport when a battery is repurposed. Whether the circular potential of electric vehicle batteries is realised will depend less on further advances in battery chemistry than on whether such frameworks are implemented, harmonised, and enforced.

However, an insurmountable obstacle will always exist. The recycling of batteries consumes huge quantity of energy, water and other natural resources, exerting substantial pressure on the environment. Furthermore, as 100% recycling is impossible, as time goes by, less and less materials will remain to be recycled. Thus, the only solution is to reduce our consumption.

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