

Green Recycling of Electrochemical Batteries and Rejuvenation Technologies for Critical Materials: A Dual Perspective of Techno-Economic Analysis and Life Cycle Assessment

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Abstract. The global renewable energy sector has grown very fast. This growth has brought industry to a critical turning point. A large number of old batteries will soon need to be dealt with. They cause serious environmental problems, but they also offer a great chance to recover valuable resources. Moving to sustainable recycling and material recovery is no longer just a choice. It has become a must for the industry. This review gives a full analysis of current battery recycling methods. It tracks how technology has progressed from traditional water-based chemical methods to new green solvents and direct upcycling. These methods are looked at using both cost and technical analysis and environmental life cycle assessment. Through this, the arguments about whether they are commercially feasible and truly eco-friendly become clearer. Organic acids and new solvent systems can greatly lower environmental harm. But they also bring clear economic downsides, like higher spending on chemicals and longer processing time. On the other hand, direct upcycling appears to be a very hopeful option. It can cut the carbon footprint by 40% to 60%. Finally, these advanced closed-loop recycling systems must be integrated with proactive design for recycling ideas. That integration builds the foundation for a strong and green energy supply chain.

Keywords: Lithium-ion battery recycling, cost and technical analysis, environmental life cycle assessment, direct upcycling, design for recycling

1. Introduction

The global commitment to mitigating climate change and curbing dependence on fossil fuels has triggered unprecedented growth across the renewable energy industry [1]. Central to this transition are electrochemical storage devices—particularly lithium-ion systems—which now power everything from consumer vehicles to grid-scale utility applications [2]. However, this rapid industrial scale-up brings a massive wave of battery retirements. Projections indicate that by 2030, the cumulative volume of decommissioned batteries globally will reach a staggering 11 million tons [3]. Allowing this volume of electronic waste to accumulate unmanaged poses severe environmental

hazards; volatile organic electrolytes and heavy metal species can easily leach into soil and aquatic systems, while also introducing prominent fire and safety risks [4].

On the other hand, old battery packs are a very rich mine of lithium, cobalt, nickel, and manganese. Making green recycling and material recovery techniques is now a key job. People need these methods to keep the clean energy supply stable and to reach global carbon neutrality goals. But scaling up these complex recycling plants for business faces two main problems: Economic and technical side: Can the big money spent on building plants and buying chemicals produce recycled materials that can compete with cheap new ones? Environmental side: Do steps that use a lot of energy, heat treatments, or many chemicals offset the ecological benefits that hope for? In recent years, researchers and industry people have tried to solve these problems by moving from high-emission smelting ways to cleaner, low-impact recovery methods.

2. Environmentally friendly recycling technology paths

People are studying how to make the battery economy circular. Their work mainly looks at three different technology directions.

2.1. Environmental issues of traditional processes

Standard hydrometallurgical recycling relies heavily on strong inorganic mineral acids such as hydrochloric, sulfuric, and nitric acids. While highly efficient at extracting metals from the battery framework, these acids generate vast volumes of hazardous wastewater that demand costly energy-intensive treatment [5]. To mitigate this issue, modern greening strategies substitute these harsh substances with biodegradable, low-toxicity organic solutions—such as citric, malic, oxalic, and ascorbic acids—paired with reducing agents like hydrogen peroxide or glucose [6]. The carboxylic groups within these organic structures fulfill a dual purpose: they supply protons to break down the spent cathode while simultaneously acting as ligands that secure dissolved metal ions into stable complexes, preventing secondary pollution directly at the source.

2.2. Emerging solvent systems and bio-metallurgy

Moving beyond organic acids, deep eutectic solvents (DES) and ionic liquids represent a major paradigm shift in chemical separation technology [7]. A typical DES is prepared by combining a hydrogen bond acceptor (such as choline chloride) with a hydrogen bond donor (e.g., urea, glycerol, or oxalic acid) at designated molar proportions [8]. These green solvents work at mild temperatures, often below 100°C. Their inner structure is complex, and this gives them high selectivity and good results when metals are taken out. At the same time, biological methods make use of some acid-loving microbes, like *Acidithiobacillus ferrooxidans*. These bacteria naturally produce metabolic substances. Under normal room conditions, these substances can leach out important metals. The process leaves behind a very small environmental footprint.

2.3. Direct rejuvenation and upcycling

Rather than completely dissolving the cell structure, direct upcycling aims to repair degraded materials in-situ [9]. When the cathode works for many cycles, it builds up deficiencies, lithium vacancies, and phase transitions. This method fixes these problems directly. It uses ways like a solid-state relithiation process with heat and chemicals, a healing step in hot water, and deposition using electric current. After fixing, the crystal structures can work as well as before. They do not need to

be broken down completely and remade. The method is also good for the anode. Used graphite from it can be taken out, cleaned, and rebuilt into valuable silicon-carbon composite structures.

3. Dual-dimensional assessment of forward-looking recycling pathways

To break down the ongoing debates regarding industrial efficiency, cost-effectiveness, and real environmental returns, a systematic side-by-side comparison is essential [10]. This study looks at a typical industrial plant. The plant handles 10,000 tons of old battery packs every year. Table 1 puts together data that shows different technologies are very different in capital investments, costs, energy needs, and total carbon footprints.

3.1. Techno-economic analysis (TEA)

TEA is a useful tool. It can check whether a green recycling method can truly jump from a lab bench to a business that earns its own money. The traditional method of using mineral acid and water to recover metals gets low starting chemical costs. But it must pay a lot to manage environmental risks and treat wastewater. Those costs eat up 22% to 28% of the total operating expense. When factories change to leaching with organic acids, the wastewater treatment bills are cut by more than 60%. But the money saved is partly balanced out by the price of the organic acids themselves. Those acids cost 3 to 5 times more than industrial sulfuric acid. Also, organic acids react more slowly. Processing times get stretched 1.5 to 2 times longer, and total energy use goes up.

For deep eutectic solvents, a kind of green solvent, business success depends fully on how well the solvents can be recovered in a closed loop. A DES system must keep its recovery efficiency above 90% to 95%. Only then can the high costs be watered down to a level that works for business. Bio-metallurgy, which uses microbes to get metals, needs very little starting money and chemical costs. Its costs are about 30% of those of standard wet chemical methods. However, its use in industry is greatly slowed down by very slow reaction speed. It takes 7 to 21 days, while chemical leaching only needs 2 to 4 hours.

Direct upcycling, the method of direct repair and reuse, shows the best economic promise in TEA. It skips the breaking down and rebuilding of structures. This cuts total chemical reagent needs by 70% to 80%. When there is a steady supply of waste, direct upcycling operations can bring gross margins that are 18% to 30% higher than those from traditional smelting or wet chemical plants.

3.2. Life cycle assessment (LCA)

LCA gives us a strict quantitative framework to evaluate total ecological impacts, focusing heavily on greenhouse gas emissions [11]. The old high-temperature recycling method uses furnaces that run between 1100 and 1300 °C. It burns a large amount of fossil fuels. This causes a big carbon footprint. For each ton of cathode material that is recovered, 4.2 to 5.8 tons of CO₂ equivalent are released.

Leaching with organic acids and using microbes offer a clear improvement. They bring down the harm to water life and risks to human health by 75% to 85% when set against mineral acid standards. The microbe-based method actually achieves the lowest total greenhouse gas emissions. It falls below 0.8 tons of CO₂ equivalent for each ton of processed cathode.

Deep eutectic solvents come with a problem known as an "upstream environmental paradox". The extraction step itself runs cleanly, but making the DES parts needs a lot of energy in upstream

chemical production. If the recovery rate of the solvent at the end of the loop goes below 90%, its net carbon advantage across the life cycle quickly goes away.

Direct upcycling provides the strongest environmental advantage. Fixing cathode materials in this way gives a life cycle carbon footprint that is 40% to 60% lower than making brand-new materials from mined ores. It is also 50% lower than the footprint from high-temperature recycling.

Table 1. Comprehensive comparison of TEA and LCA indicators across different recycling pathways

Technology Pathway	Technical Maturity	Key Economic Bottlenecks (TEA)	Profitability / Cost Characteristics	Carbon Footprint (LCA, CO ₂ eq)	Main Environmental Benefits / Risks
Mineral Acid Hydrometallurgy	High	High waste treatment cost (22%-28% of OPEX)	Low basic operating costs	Moderate	High human health and freshwater toxicity
Pyrometallurgy	High	High energy consumption and material loss	High equipment investment (CAPEX)	4.2 - 5.8 t/t cathode	High indirect carbon emissions
Organic Acid Leaching	Medium	High reagent unit price and slow kinetics	Reagent costs increase by 15%-18%	Low	Ecotoxicity risks drop by 75%-85%
Deep Eutectic Solvents (DES)	Medium-Low	Highly dependent on high recycling rate (>90%)	Non-competitive at low recycling rates	Dependent on recycling efficiency	Upstream energy consumption paradox
Bio-metallurgy	Low	Extremely long leaching cycle (7 - 21 days)	CAPEX is only 30% of traditional hydrometallurgy	< 0.8 t/t cathode	Extremely low carbon emission and eco-friendly
Direct Upcycling and Regeneration	Medium	Dependent on stable input material streams	Gross margin is 18%-30% higher than traditional	40%-60% lower than pristine route	Short process chain and overwhelming emission reduction

4. Synergistic coupling pathways and source design optimization

The dual perspectives from TEA and LCA underscore a vital reality: no single recycling pathway serves as a flawless, standalone solution. Consequently, contemporary research and industrial designs are shifting toward integrated, multi-process configurations and modifications at the initial manufacturing stage.

4.1. Multi-process coupling construction

Recent pilot trials demonstrate that merging different techniques can form highly optimized hybrid systems. For instance, combining mechanical activation pretreatment with an eco-friendly DES leaching loop, followed by pyrometallurgical recovery to extract residual trace metals from the leftover slag, provides an incredibly balanced strategy [12]. This combined workflow lets operators get strong profits (reaching good results in cost analysis) while keeping the total environmental footprint well inside strict legal limits (reaching good results in environmental life cycle assesment).

4.2. Design for Recycling (DfR) and sensitivity check

To make the recycling of old batteries more efficient, the physical design of the battery must be improved when it is first made. When Design for Recycling ideas are used on packs and modules, people need to pick smart thermal glues that can be unstuck. Permanent mixed glues should be replaced with high-precision laser welding setups. Numbers from sensitivity checks show that moving to automatic or half-automatic taking-apart setups speeds up the processing flow by more than 3 times. The time needed for taking apart is cut by 70%. Also, this greatly lowers the cost of manual work and stops materials from mixing together in a bad way. Because of this, the net profit of the recycling loop goes up by 15% to 25%. When strong, mixed shredding that cannot tell materials apart is removed, unneeded sorting steps are also removed. This brings down the total life cycle energy use of the recycling plant by about 12%.

5. Conclusions

This paper has looked at the three main methods for green recycling and regeneration of old electrochemical batteries. They were checked against two sets of measures: Techno-economic analysis (TEA) and environmental life cycle assessment (LCA). The results prove that direct upcycling and direct upcycling is the way forward. Its simple method, high-value outputs, and big ability to cut carbon (40% to 60%) set up a very good balance between money and climate goals. To speed up the use of these systems in real industry, future study should focus on three main areas: Making multi-process coupling clear: Mixed recycling workflows need to be made better. This is done by direct upcycling and heat mismatches between different physical and chemical steps. The goal is to get the most resources without raising total energy use. Scaling up direct upcycling in factories: Direct upcycling methods must be able to handle the chemical and structural differences found in the real world. It must be sure that automatic relithiation and direct upcycling of defects give steady, high-quality materials across big industry batches. Making Design for Recycling (DfR) systems work better: Battery setups that can be taken apart and used again, and glues that can be unstuck, must move from labs to real factories. This will set up a closed-loop supply chain from making to the rebirth of materials.

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