



**THE LINDY EFFECT IN
HYDROMETALLURGY.**

PROOF.

Old Chemistry.
New Batteries.



WHY SOME PROCESSES ENDURE.

Century-Old Methods, Modern Battery Applications

When we think of something that's been around for centuries, we intuitively trust that it will continue to endure.

This notion is captured by the Lindy Effect, which dictates that the longer a technology or technique has been in use, the more likely it is to remain relevant.

The Lindy Effect explains why certain processes such as hydrometallurgy, which is the science of extracting metals from ores or recycled materials with water-based chemistry, still dominate today's industry.

By examining the roots and resilience of these methods, we can draw lessons from every stage of the modern battery value chain, from mining raw materials, to manufacturing cells, to recycling spent batteries.

The Foundations of Hydrometallurgy

Hydrometallurgy's story begins in the sixteenth century when Georgius Agricola (1494- 1555) described how to leach copper ores in vats and how to use nitric acid to separate silver from gold.

These techniques foreshadowed modern bioleaching. These early experiments demonstrated that dissolving metals in aqueous solutions allowed for purer and higher-quality products.

Fast forward to the nineteenth century, Michael Faraday's seminal work on electrolysis led to copper electrefining, which, by 1869, was patented by Elkington.

This leaching and electrolysis approach consumed relatively modest reagents, operated under mild conditions, and produced copper of exceptional purity.



The most established technologies are continuing to establish because they are commercially valid technologies.

Dr. Sebastian Leaper (CEO),
Dr. Ahmed Abdelkarim (CTO),
Watercycle Technologies



WHY HYDROMETALLURGICAL PROCESSES REFUSE TO FADE.

Over the ensuing decades, refinements focused on energy efficiency and cathode design, but the fundamental reaction, dissolving impure copper and plating out pure copper, remains essentially unchanged.

The traditional method reliably scales from small pilot operations to massive refineries, and exemplifies a Lindy-proof process; its long history and predictable economics make it unlikely to be eliminated.

Cyanidation and the Power of Proven Chemistry

Shortly after, in 1883, the MacArthur-Forrest cyanidation process revolutionized the extraction of gold and silver. By leaching crushed ores with dilute alkaline cyanide solutions, they achieved high precious-metal recoveries at ambient temperature.

Subsequent zinc precipitation freed gold and silver from solution in a straightforward, low-cost method. Within twenty years of its invention, global gold production had roughly doubled thanks to cyanidation.

More than a century later, modern refiners have tweaked how they destroy residual cyanide and manage tailings, but the core flow remains largely the same.

Its ongoing success stems from inexpensive reagents, well-understood chemistry, and predictable scale-up, all fulfilling the Lindy Effect's criteria for durability.

The Bayer Process: 130 Years of Continuity

A third keystone of classic hydrometallurgy is the Bayer process for refining alumina (aluminum oxide) from bauxite, developed between 1888 and 1892.

In this method, bauxite is digested with hot sodium hydroxide under pressure, dissolving aluminum-bearing minerals while leaving iron oxides and other impurities behind.

By carefully seeding the clear liquor with alumina hydrate, refineries precipitate nearly pure alumina.



THE LINDY EFFECT IN HYDROMETALLURGY.

Though energy consumption and red mud waste have been reduced through engineering improvements, the essential leaching-and-precipitation chemistry remains fundamentally the same 130 years later.

Since aluminum production underpins countless industries, Bayer's long-term success underscores how a well-balanced, technically sound, and economically viable chemistry becomes, in effect, the god of longevity.

What Makes a Process Lindy-Proof?

What attributes unite these "classic" hydrometallurgical processes?

First, they rely on inexpensive, widely available reagents, sulfuric acid, sodium hydroxide, cyanide, or simple organic acids, rather than exotic or custom-made chemicals.

Second, they operate at moderate temperatures and pressures, avoiding the need for specialized high-pressure vessels or extreme conditions.

Finally, refining a few hundred kilograms of ore in the lab follows the same fundamental reactions as processing thousands of tons in a large plant.

These characteristics create a positive feedback loop because the process is reliable, it attracts investment.

That investment then helps make small but steady improvements in areas like energy use, waste reduction, and automation. Over time, this strengthens the process's economic value.

According to the Lindy Effect, the longer a method has been used successfully, the more likely it is to keep working, so if it's lasted 150 years already, it's likely to last another 150.



THE BENEFITS OF INNOVATION.

Why Promising Chemistries Struggle to Scale

In contrast, academic laboratories continually explore innovative chemistries, with promises of greener or more selective metal recovery.

However, these alternatives often do not perform when faced with real-world demands.

Exotica like ionic liquids may excel at separating specific metals in bench-scale tests, but their high viscosity, sensitivity to moisture, and uncertain regeneration pathways can make large-scale use prohibitively complex and costly.

Similarly, replacing sulfuric acid with citric acid for leaching might sound environmentally friendly, yet manufacturing citric acid in bulk consumes sulfuric acid and lime, generates gypsum byproducts, and requires significant water and energy resources.

In practice, the end result is seldom more sustainable or less expensive than the tried-and-true approach.



When New Technologies Earn Their Place

However, we should not dismiss innovation altogether. Under the right combination of economic drivers, regulatory pressures, and entrepreneurial risk-taking, novel methods can become Lindy-proof.

A celebrated case is the first Leach–Solvent Extraction–Electrowinning (L–SX–EW) copper plant at the Bluebird Mine in Arizona, opened in 1968. Its owner, Maxie Anderson, chose solvent extraction to treat heap-leached oxide ore instead of the conventional scrap-iron cementation method.



The result was around 6,000 tons of cathode copper per year, proving that hydrometallurgical recovery could compete economically.

Within a decade, large producers worldwide adopted L–SX–EW, and today it accounts for nearly 18 percent of global primary copper production.

WHAT THE LINDY EFFECT MEANS FOR BATTERIES.

Mining and Refining

If we shift focus to the modern battery industry, the Lindy Effect's lessons apply at every stage, from raw-material extraction to cell assembly to recycling.

First, consider mining and refining for new batteries. Lithium, cobalt, nickel, manganese, and graphite still originate largely from traditional mines.

In nickel laterite deposits, for example, simpler operations use sulfuric acid leaching to dissolve nickel and cobalt, followed by solvent extraction, which are the same foundational steps honed in copper and nickel industries since the mid-20th century.

Although researchers explore novel solvents for cobalt or innovative pyrometallurgical routes for lithium, mining companies typically stick to hydrometallurgical flowsheets that have proved reliable. After all, global battery makers demand consistent, high-purity precursors, and bankable processes minimize supply-chain risk.

Battery-Precursor Production

Next, in battery-precursor production, manufacturers rely on multi-stage purification steps that resemble those used for decades to produce cobalt sulfate or lithium carbonate.

Sulfuric acid leaching, followed by solvent extraction, precipitation, and recrystallization, remains the backbone.

When a plant needs to upgrade its cathode materials, engineers tweak pH, adjust extractant ratios, or refine temperature profiles, but they rarely replace the underlying unit operations wholesale.

Thanks to their long track record, investors view the capital costs and operating parameters as predictable, in stark contrast to novel proprietary chemistries that promise better selectivity but lack real-world data.

Cell Assembly

At the cell-assembly level, while there are fewer direct hydrometallurgical steps, the importance of supply-chain stability and material purity resonates with the same Lindy logic.

Manufacturers need stable, consistent precursor salts and stable electrolyte formulations. Any radical change must demonstrate not only performance gains but also long-term supply reliability, compatibility with existing coating and calendaring machines, and manageable safety profiles.



CIRCULAR ECONOMY IN BATTERY PLANTS.



Partnerships are key to success for a startup company who want to take on the world, and trying to do too much on your own is very risky. The founder's team should have the same passion, vision, and motivation.

Dr. Sebastian Leaper (CEO),
Dr. Ahmed Abdelkarim (CTO),
Watercycle Technologies



Because conventional carbonate-based electrolytes and coating processes have decades of industrial use, they enjoy Lindy-proven trust, even as researchers tout new high-voltage salts or novel fluorinated solvents.

Battery Recycling

Finally, at the recycling stage, we return to a more obvious hydrometallurgical setting. Used lithium-ion batteries produce something like a "black mass," a tangle of shredded cathode and anode materials.

Established processes dissolve this black mass in sulfuric or hydrochloric acid, use solvent extraction to separate cobalt, nickel, manganese, and copper, and then precipitate each metal as a sulfate, hydroxide, or carbonate.

While academic labs explore deep-eutectic solvents or bioleaching, commercial plants generally stick to acid leaching paired with familiar extractants. The same unit operations have endured in copper, nickel, and cobalt recovery for generations.

Investors and plant operators understand the costs of acid, know how to regenerate it, and can predict waste streams, confirming the Lindy effect.

Circularity Without Reinventing the Process

Beyond recycling, battery plants increasingly embrace renewable energy integration and circular economy principles.

For instance, acid regeneration and heat recovery loops are now being adapted to gigafactories. By leveraging off-peak renewable electricity for heating reactors or running solvent recovery units, battery facilities reduce both operating expenses and carbon footprints.

In regions with surplus solar or wind power, running leach-tank heaters during midday when prices drop makes economic sense, just as metal refiners have done for years.

Similarly, closing water loops by recycling process water and recovering co-products like graphite from anodes or aluminum from current collectors mirrors mining's shift toward zero-liquid-discharge plants.

WHAT ENDURES AND WHY.



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The recycling market is not crowded. Many companies are doing recycling, but none of them make commercial success. There's no refinery in the U.S. at all. Every recycling company is selling black mass, bypassing repair. There's no middle string. Everybody has feedstock but they don't have the technology.

Dr. Haixia Casey Deng (Founder, CEO),
Xera Energy

In summary, the Lindy Effect reminds us that durability stems from proven economics. Hydrometallurgy's classic processes have survived because they balanced technical feasibility with cost-effectiveness.

In the battery industry, from sourcing ores to producing precursors, assembling cells, and recycling spent packs, those same attributes favor methods rooted in established hydrometallurgical wisdom.

Of course, innovation must continue. New battery chemistries, novel mining technologies, and advanced recycling schemes will emerge.

But when these innovations align with century-old, well-understood unit operations, rather than attempting to reinvent them entirely, they stand the greatest chance of becoming Lindy-proof, supporting a resilient and sustainable battery ecosystem for decades to come.

THE BENEFITS OF INNOVATION.



If we want to start reaping the rewards of innovation, we need to start now. Even when times get tough, people really need to stick to the mission, stick to their mission, and make sure that their technology sees the light of day.

Nick Grundish (VP of Battery Technology), EnergyX

PROOF. Intelligence

The reason these processes have lasted is fairly simple. People know how to make them work.

After decades of operating history, the chemistry is understood, the equipment is familiar and the economics are easier to model. Engineers know what can go wrong. Operators know how to keep plants stable. Suppliers know what the process needs. Investors have enough precedent to understand what they are backing.

That is very important in battery materials just as much as it does in traditional mining and refining. New technologies will continue to emerge, and some will prove genuinely better. But going from a promising result to a process that can run reliably at commercial scale is a different challenge altogether. It takes technical depth, process discipline and people who have seen enough plants, pilots and scale-up programs to know where problems usually appear.

For hiring, that experience carries a premium.

Companies commercializing new extraction, refining and recycling technologies still need metallurgists, process engineers, plant leaders and technical operators who understand the established unit operations underneath them.

The strongest teams tend to combine people willing to develop something new with people who know why older processes have lasted.

That is what the Lindy Effect looks like in practice.

Industrial processes endure because they are repeatable, economical and understood. The same is true of the teams behind them. Refine the hiring connection

We've built a platform to solve growing pains for scaling companies across materials, minerals and mining.

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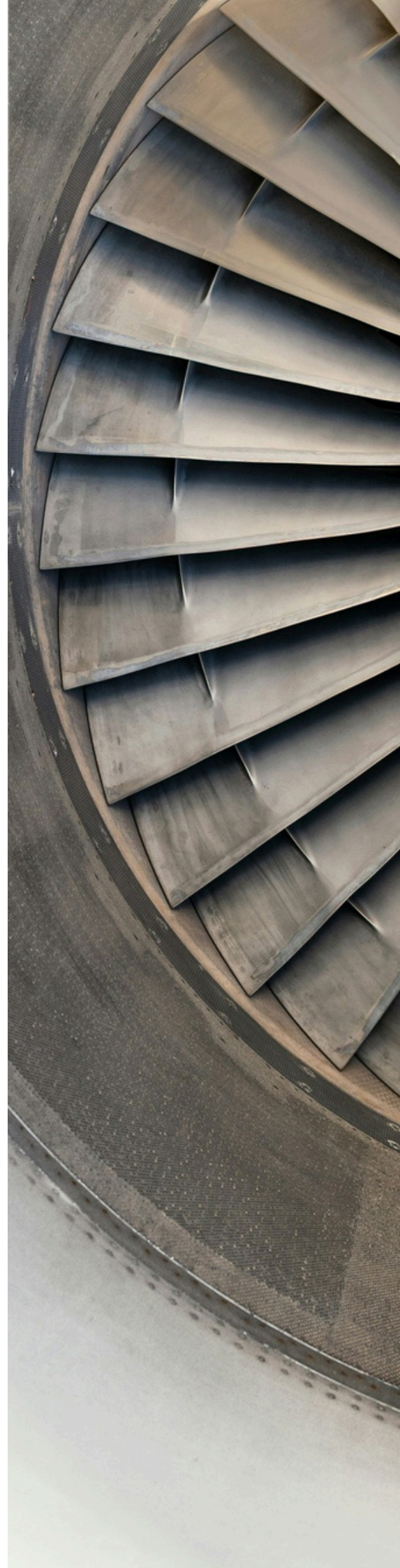
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16 Huckletree,
The Express Building,
9 Great Ancoats St,
Manchester, England,
M4 5AD

