Innovations in Lithium-ion Battery Recycling: Fewer Emissions, Less Energy Use, and Lower Cost

June 14, 2021

Dr. Chao Yan
chaoy@princeton.edu
chao_yan@pnecycle.com

TESLA

“…costs associated with large-scale battery material recovery and recycling will be far lower than purchasing and transporting new materials to put into cells.”

Argonne NATIONAL LABORATORY

“…the problem is, the batteries that have come to their end of life are not cost effectively recycled right now.”

FORTUNE

“…the fate of the many millions of used lithium-ion batteries that power electric vehicles will become an urgent environmental issue.”

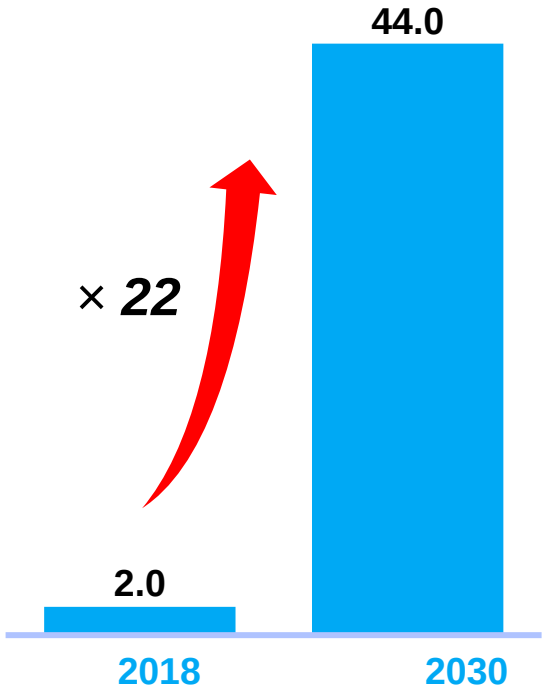
Executive summary

- **Electric vehicle sales are expected to grow rapidly**
- As a result, the **total demand for battery raw materials is expected to increase sharply** (Cobalt, Nickel and Lithium)
- The Li-ion **battery waste** generated by end-of-life electric vehicles and appliances is expected to **grow from 100 kt in 2018 to 1M tons by 2030**
- **Closing the loop through battery recycling** is expected to be an important factor to balance supply and demand for these battery raw materials, de-risk the value chain and reduce the environmental impact
- The **economics of battery recycling** are supported by cobalt and to a lesser extent nickel, meaning there are strong differences depending on the cathode chemistry:
  - Using current economics, recycling companies can profitably recover cobalt and nickel from consumer electronics (**LCO/NMC111**)
  - In contrast with this, recyclers charge a ‘recycling fee’ to recycle low-cobalt EV batteries (**NMC622/NCA**)
  - Recyclers cannot recover significant material value from **LMO/LFP**
- **Princeton NuEnergy (PNE) developed innovative technology to recycle lithium-ion batteries**

The rapid growth in electric vehicles will generate huge amounts of Li-ion battery wastes

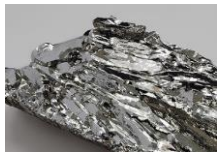
PRINCETON NUENERGY

Electric vehicle sales[1] (base case)
Million units



After recycle each vehicle, we could save:

8.4 kilograms of lithium



52 kilograms of nickel

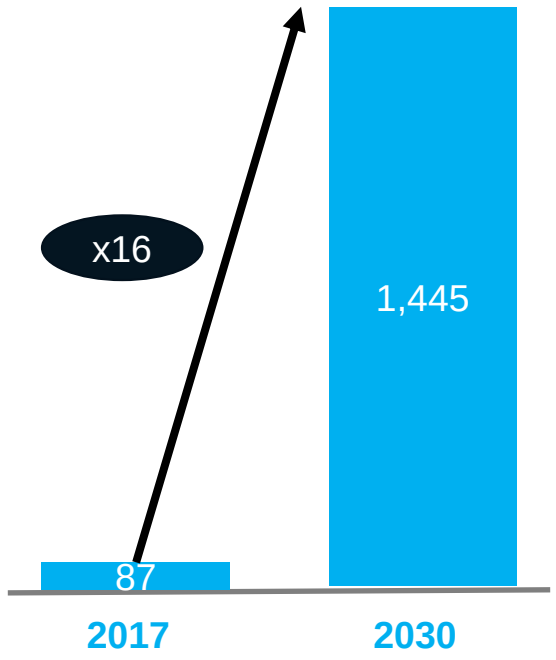
6.6 kilograms of cobalt

The demand for these raw materials is expected sharply increasing in the future

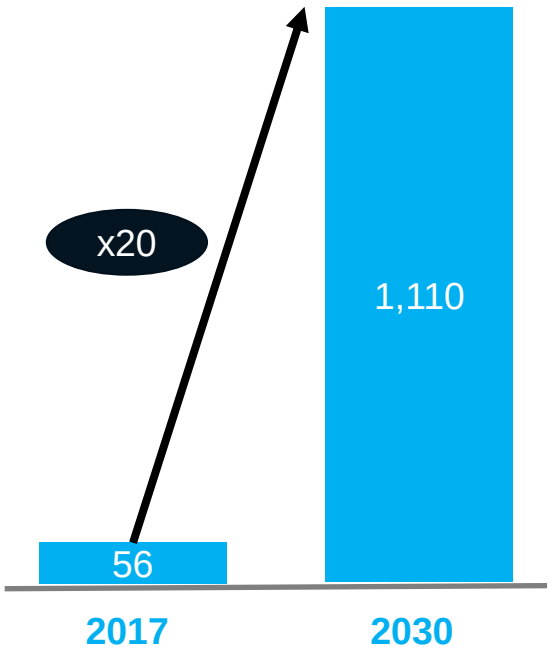
PRINCETON NUENERGY

Li, Ni, Co demand from 2018 – 2030 (batteries)

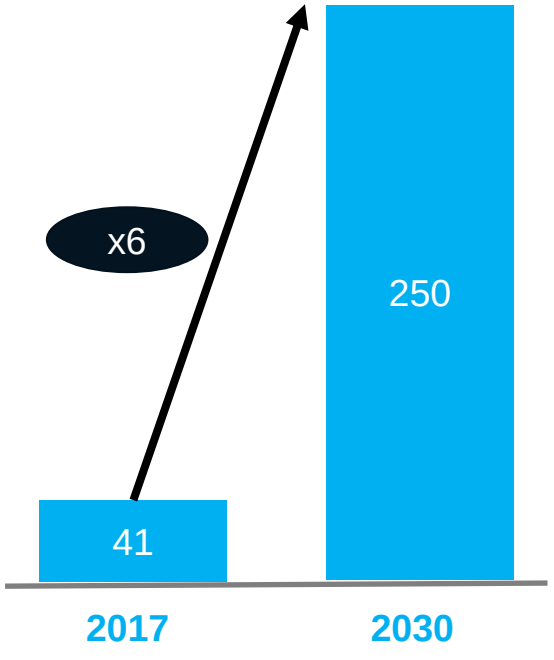
Lithium, kiloton



Nickel, kiloton



Cobalt, kiloton



A service fee is required from OEMs to recycle EV batteries due to the lower cobalt content

EV batteries

- In most cases, the value of the recovered metals from EV batteries is **not sufficient to compensate the recycling costs**
- **Battery recyclers will therefore request a service fee** from car OEMs in order to recycle the EV battery
- Some OEMs arrange '**cobalt leasing**' terms with the recyclers to limit supply chain risk and reduce the environmental impact of their batteries
- **Collection rates are high (>90%)** as car OEMs recuperate end-of-life cars in order to comply with the producer responsibility for battery recycling

Consumer electronics batteries

- In most cases, the value of the recovered metals from consumer electronics batteries is **sufficient to compensate the recycling costs**
- **Battery recyclers are therefore willing to pay** the battery collection schemes a fee for consumer electronic batteries
- **Collection is the bottleneck** – current collection rates for Li-ion batteries in United State is < 5% despite sensibilization efforts by the battery collection schemes and governments

Where we can get used Li-ion batteries: the suppliers?

PRINCETON NUENERGY

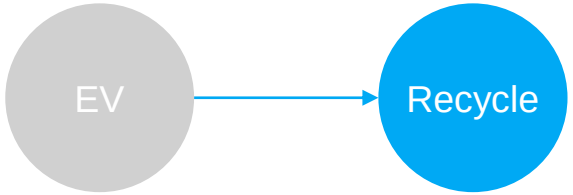
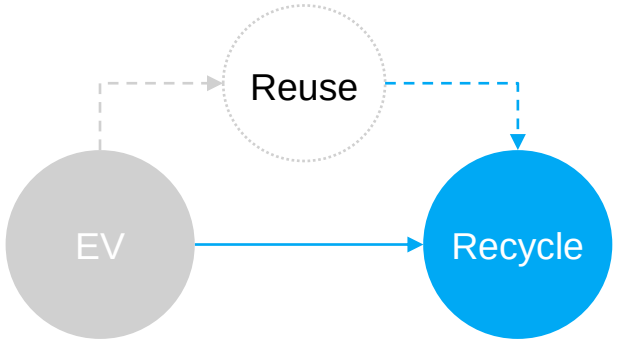
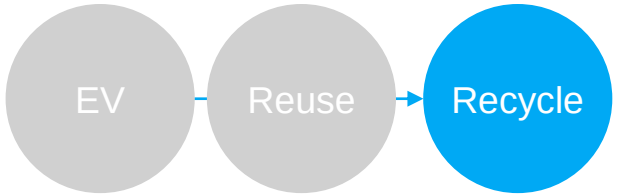
		Small consumer electronics	Electric mobility & storage
Applications		Cell phones, MP3, camera's Portable computers Electric bikes, skates, hoverboards Drones Other (e-sigarettes, headphones,…)	Electric cars Electric busses Electric trucks Electric scooters Electric storage
Collection efficiency		5-10%	> 90%
End-of-life volume	2018	~40 kt	~40 kt
	2030	~100 kt	~800 kt
Dismantling required?		No	Yes
Material value		Medium/High (LCO/NMC/NCA)	Low/Medium (NMC/NCA/LMO/LFP)

The battery chemistry determine the recycle options

PRINCETON NUENERGY

High raw material value

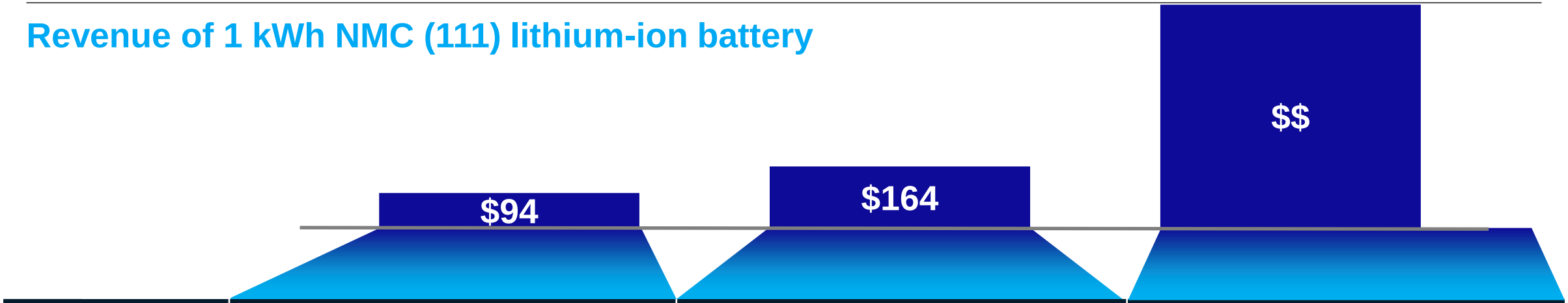
Low raw material value

Chemistry	End of life flow	Comment
LCO NMC111		Even in countries with no collection obligation such as the U.S., companies have started collecting Li-ion batteries from consumer electronics (e.g. smartphones, laptops) as recyclers are willing to pay up to a 1,000 USD per ton for these batteries
NMC622 NMC811 NCA		OEMs pay service fee for NMC and a much higher fee for LFP to recyclers so that business is viable for recyclers. Cobalt content is the key factor.
LMO LFP		LFP and LMO are fundamentally not economic in raw material recovery regardless of scale due to low raw material value. Most people are exploring 2nd life use

Three types of recycling processes can currently be employed

PRINCETON NUENERGY

Revenue of 1 kWh NMC (111) lithium-ion battery



	Pyrometallurgical	Hydrometallurgical	Direct Recycling Process
Description	Melting and reducing the battery materials to obtain metals	In-solution chemistry to isolate component chemical compounds	**Direct regeneration of cathode & anode materials**
Pros	Can take more than one battery chemistry at the same time and simplified logistics	Recycled products with high purity; Process is flexible	**Preserve chemistry and direct regeneration; Simple and green procedures; High profitability**
Cons	High energy consumption; Easy to trap elements in the slag	Need to treat large amount of waste hot water, acids, and solvents	**Recover the original materials**
Suitability	Suitable for chemistry with high cobalt and/or high nickel content (e.g., NMC, NCA)	Suitable for chemistry with high cobalt and/or high nickel content (e.g., NMC, NCA)	**Suitable for any chemistry**

Challenges of current lithium-ion battery recycle technologies

PRINCETON NUENERGY

High recycle cost

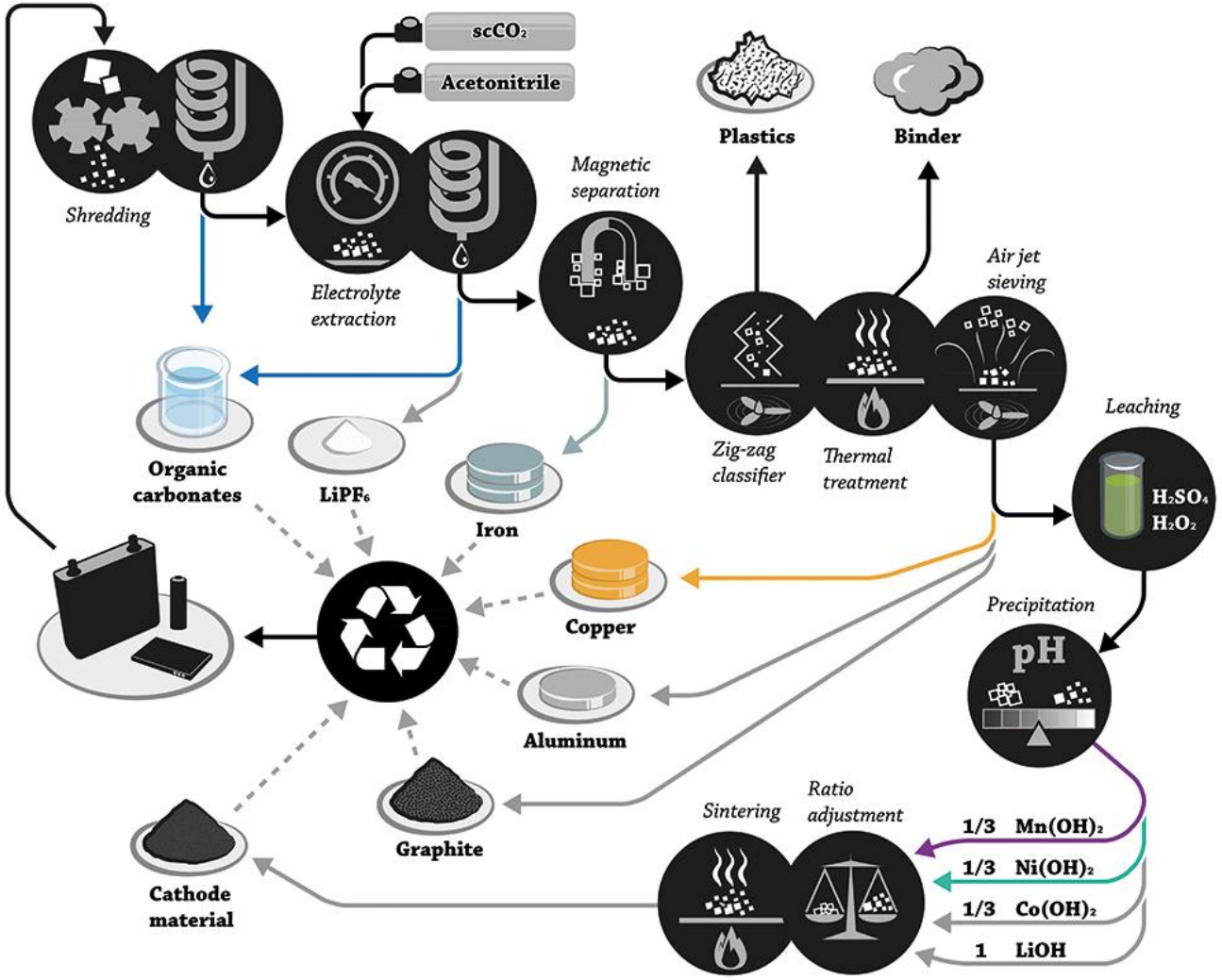
- ✓ The value of the recovered materials is not sufficient to compensate the recycling costs

High pollution and chemical usages

- ✓ Huge waste is generated from current technologies

Complicate recycle process

- ✓ Current technologies require complicate wet chemistry or high temperature processes



Major recycling players

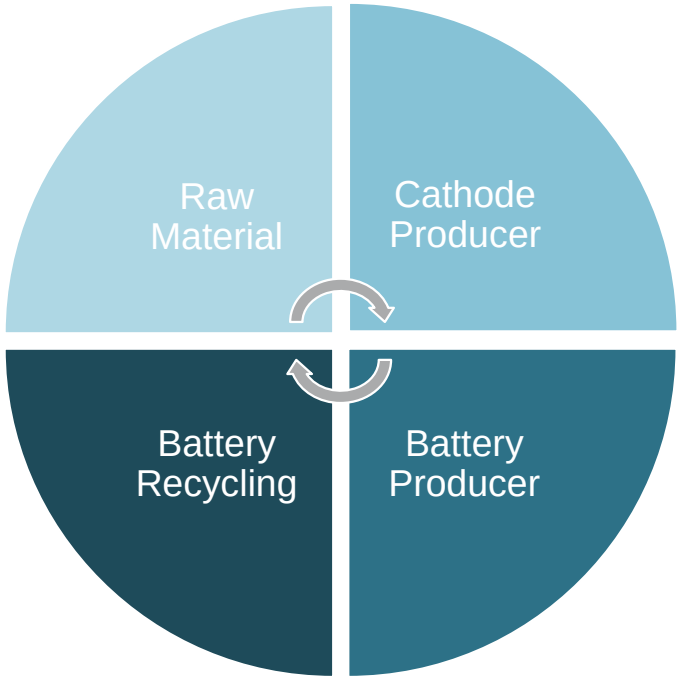
Li, Co mining company

Mining companies expand into battery recycling as **scrap battery is new source of metal**

Independent battery recycling player

Recycling providers get **raw material from scrap battery**, i.e., reduce reliance on mines

Independent recycling providers are **moving to supply cathode precursor/material** recently



Cathode producer

Cathode players integrate recycling business to **secure raw material supply**

Battery producer

Driven by **regulation** requirement and needs to **guarantee raw material supply,** battery suppliers active expand into battery recycling market

What is Direct Recycling Technology?

Comparison with current recycling process

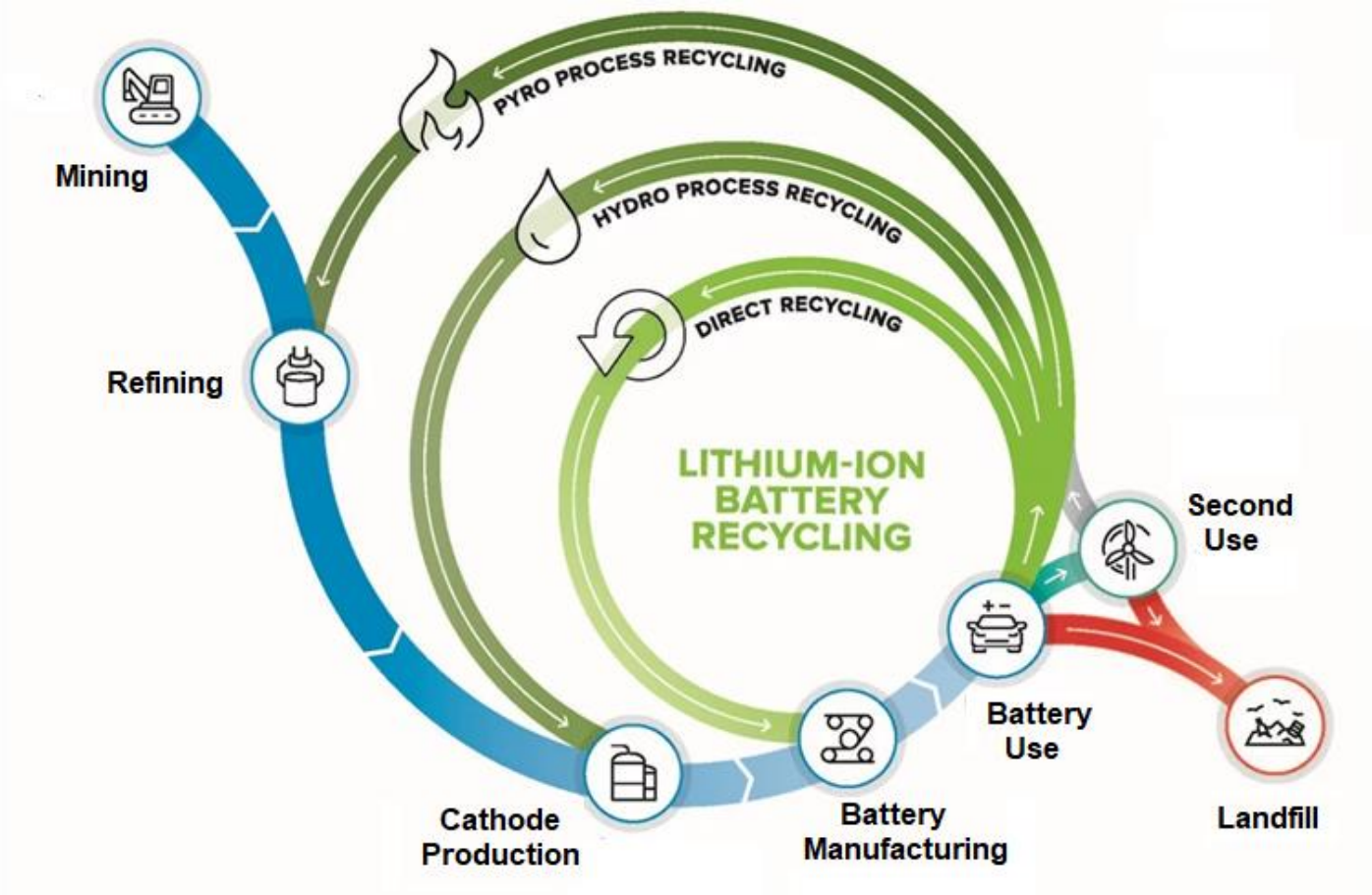
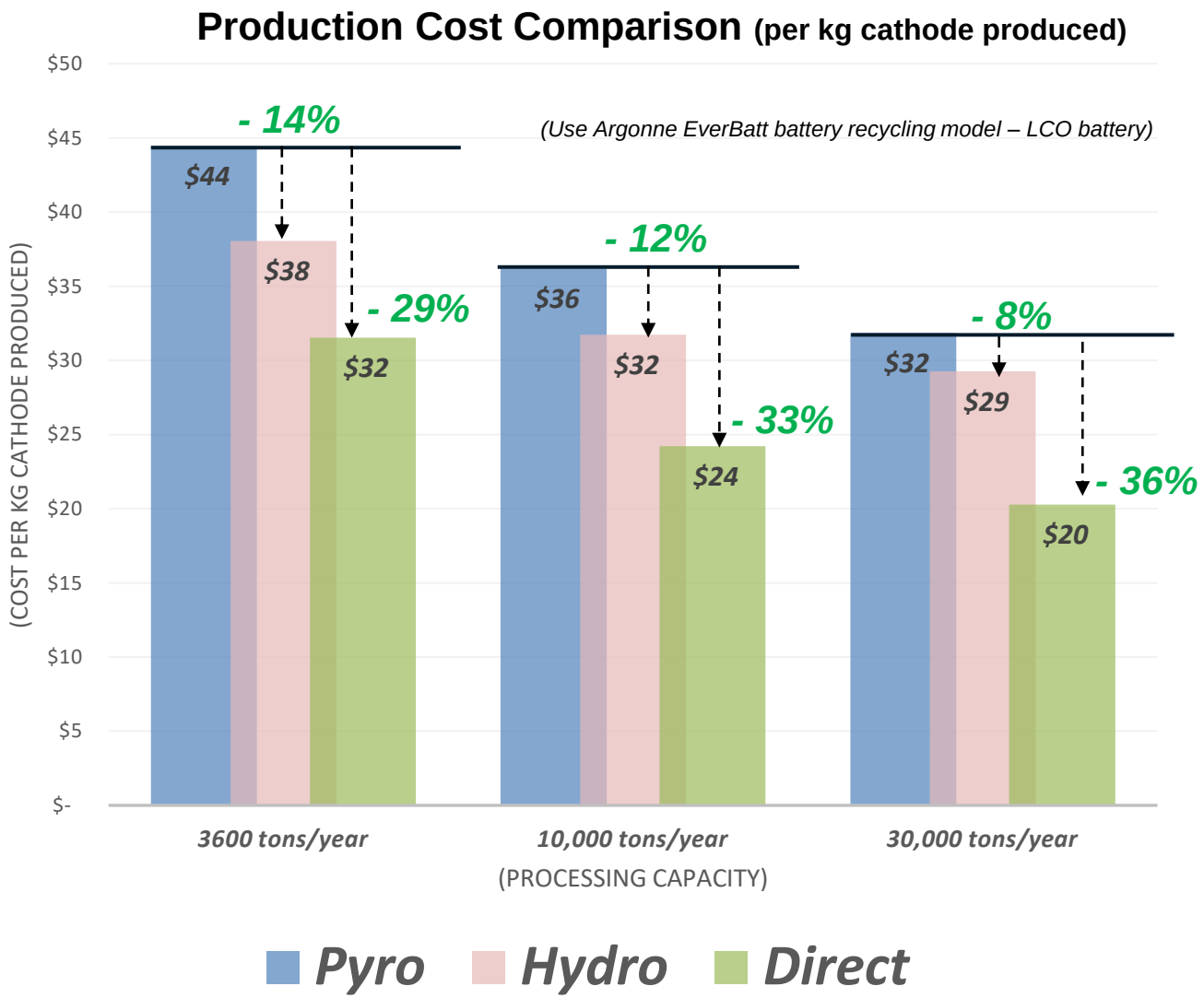


Image by Argonne National Laboratory

- **Skip refining and production processes**
- **Significantly reduce the industry cost**

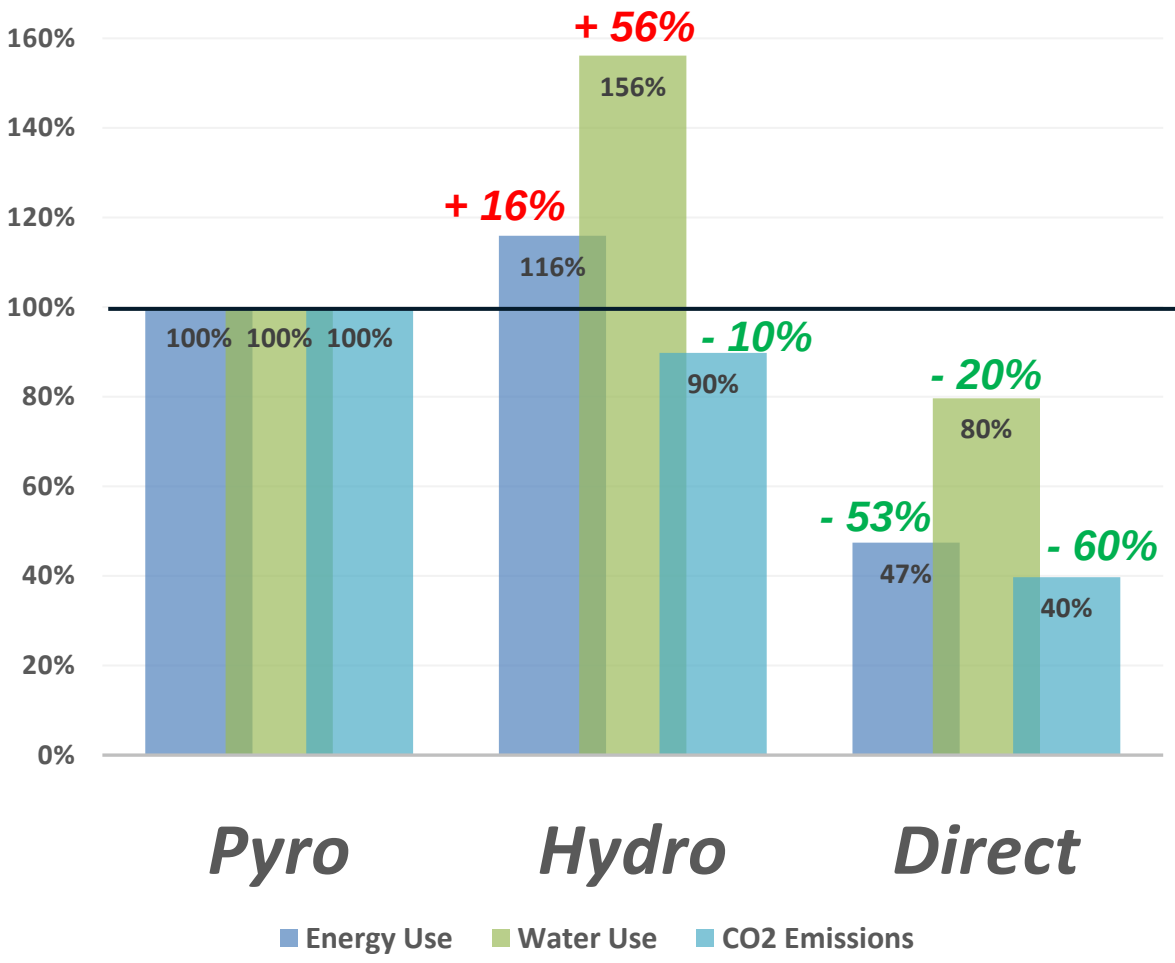
Direct Recycling – Business Values



- Apple to Apple compared three different scales of processing capacity (3.6K, 10K and 30K tons/year) between Pyro, Hydro and Direct Recycling
- Calculated the total ***End-to-End Cost to produce 1 kg cathode materials*** (from battery collection, transportation, disassembly, recycle and cathode generation)
- Direct Recycling Technology can reduce ~ **35%** total cost to produce and sale the same cathode materials

Direct Recycling – Environmental Value

Energy & Water & CO2 Emission



Use Pyro Recycling as **Benchmark**, apple to apple compared Hydro & Direct Recycling Methods

Compared with Pyro, Direct Recycling can

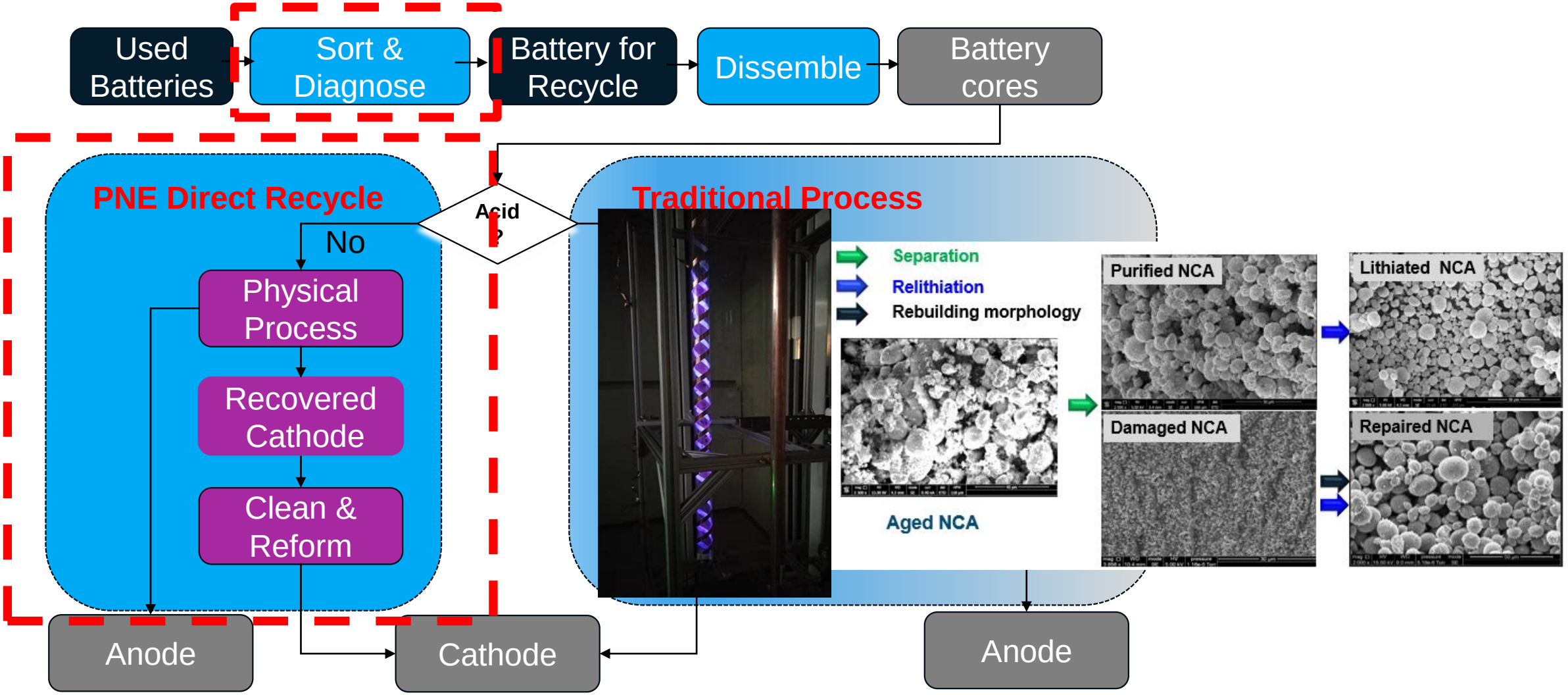
- Reduce ***53% Energy use***
- Reduce ***20% Water use***
- Reduce ***60% CO2 Emission***

Compared with Hydro, Direct Recycling can

- Reduce ***69% Energy use***
- Reduce ***76% Water use***
- Reduce ***50% CO2 Emission***

(Use Argonne EverBatt battery recycling model – LCO, annual capacity 30K tons)

PNE Direct Plasma Recycling Technology



Executive summary

- **Electric vehicle sales are expected to grow rapidly**
- As a result, the **total demand for battery raw materials is expected to increase sharply** (Cobalt, Nickel and Lithium)
- The Li-ion **battery waste** generated by end-of-life electric vehicles and appliances is expected to **grow from ~100 kt in 2018 to ~1,000 kt by 2030**
- **Closing the loop through battery recycling** is expected to be an important factor to balance supply and demand for these battery raw materials, de-risk the value chain and reduce the environmental impact
- The **economics of battery recycling** are supported by cobalt and to a lesser extent nickel, meaning there are strong differences depending on the cathode chemistry:
  - Using current economics, recycling companies can profitably recover cobalt and nickel from consumer electronics (**LCO/NMC111**)
  - In contrast with this, recyclers charge a ‘recycling fee’ to recycle low-cobalt EV batteries (**NMC622/NCA**)
  - Recyclers cannot recover significant material value from **LMO/LFP**
- **Princeton NuEnergy developed innovative technology to recycle lithium ion batteries**

Thank you.

chao_yan@pnecycle.com

www.pnecycle.com