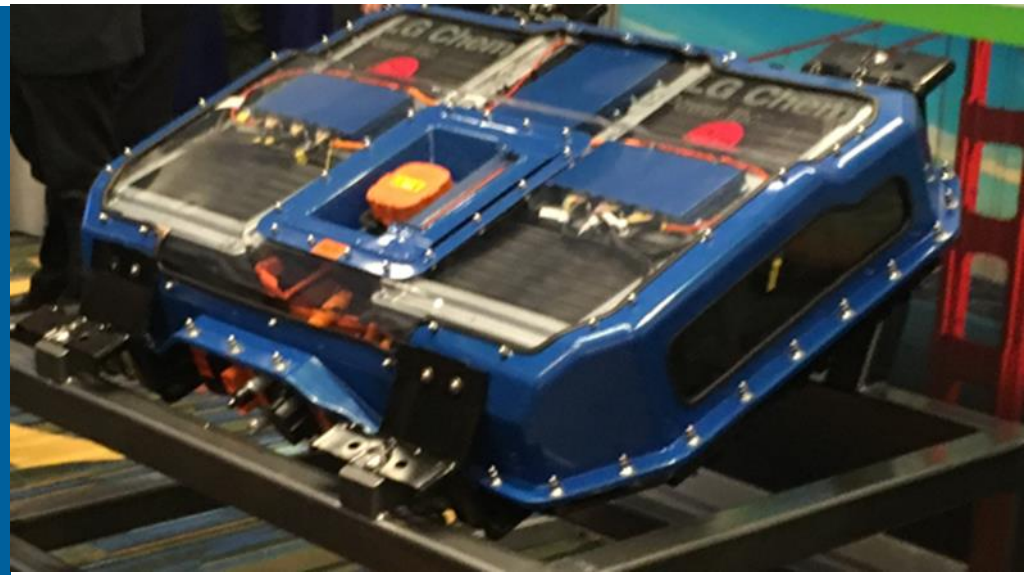
LITHIUM ION BATTERY LIFECYCLE OVERVIEW



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Sustainable Fleet Conference

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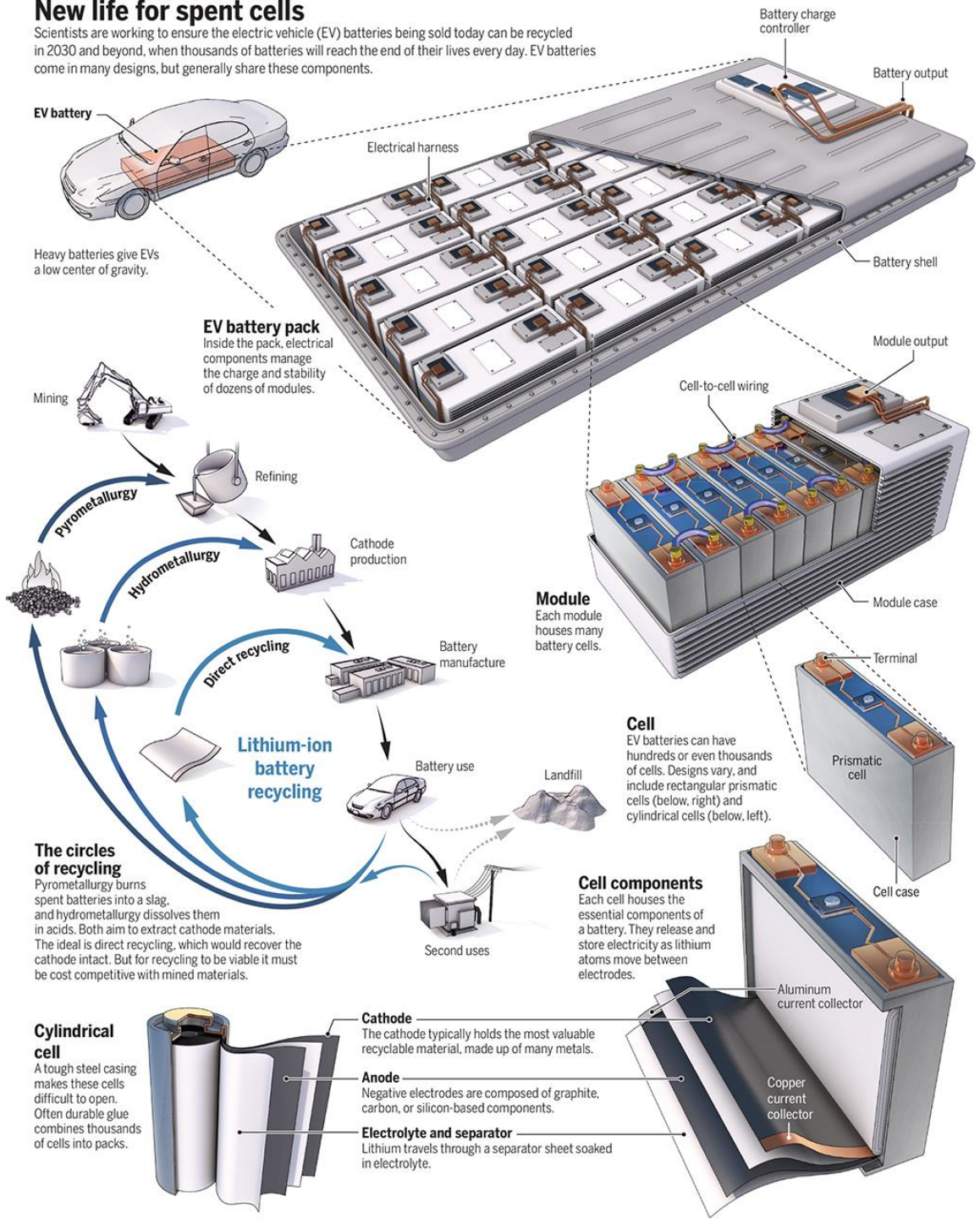
WE CAN PROVIDE SERVICES USING LESS SCARCE MATERIAL

Projected material demand is not sustainable

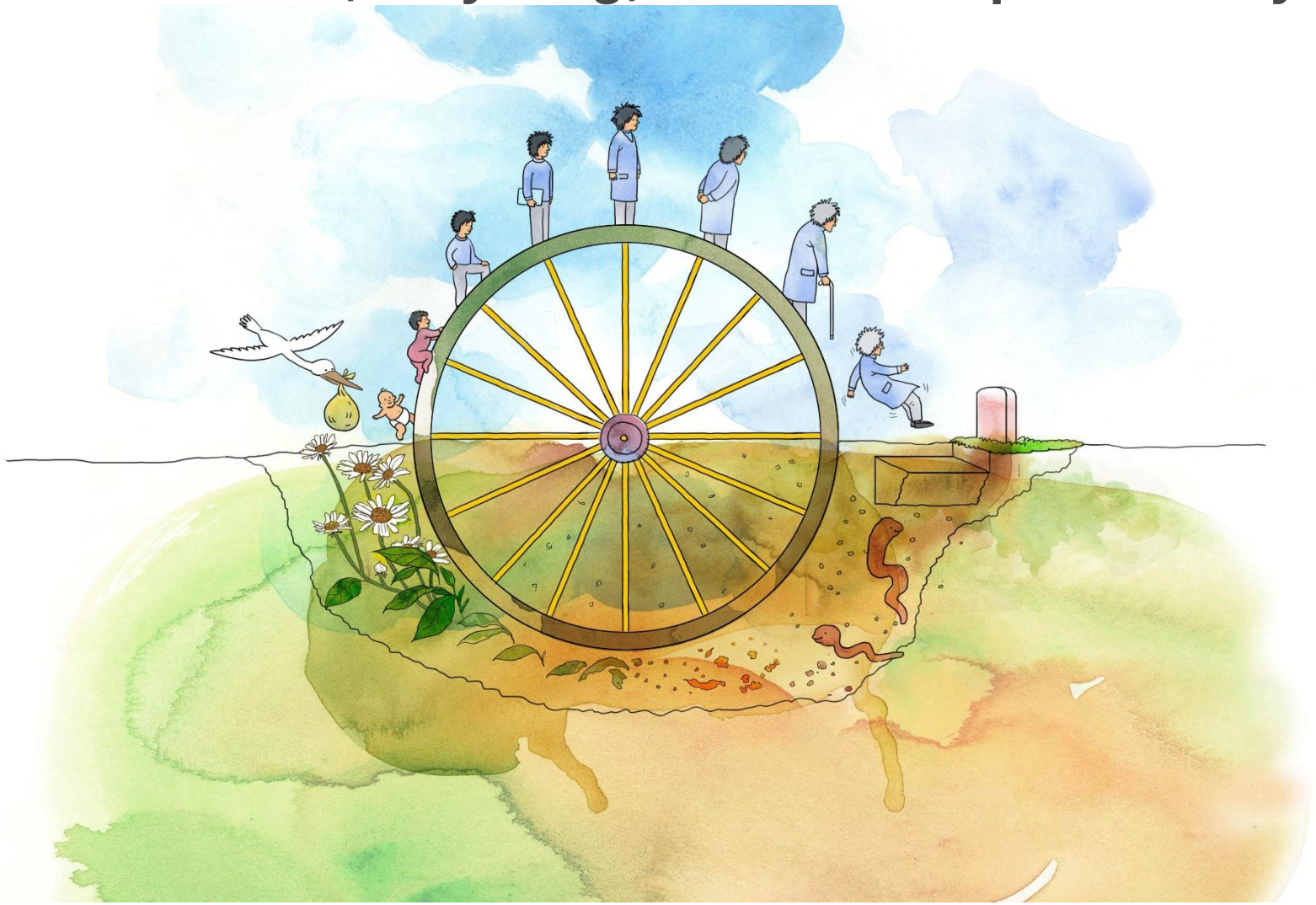
- Use smaller battery (bigger isn't always better!)
  - Plug-in hybrid
  - In-road charging (the ultimate fast charge!)
  - Battery swapping
  - Rent extra modules for long trip
- Develop more energy-dense batteries, novel designs
  - Solid-state
  - Anode-free
- Use more abundant materials
- Provide mobility with fewer personal vehicles
  - Mass transit with last-mile options
  - Car- or ride-sharing
- Reuse and recycling (circular economy)

FIGURE FROM SCIENCE



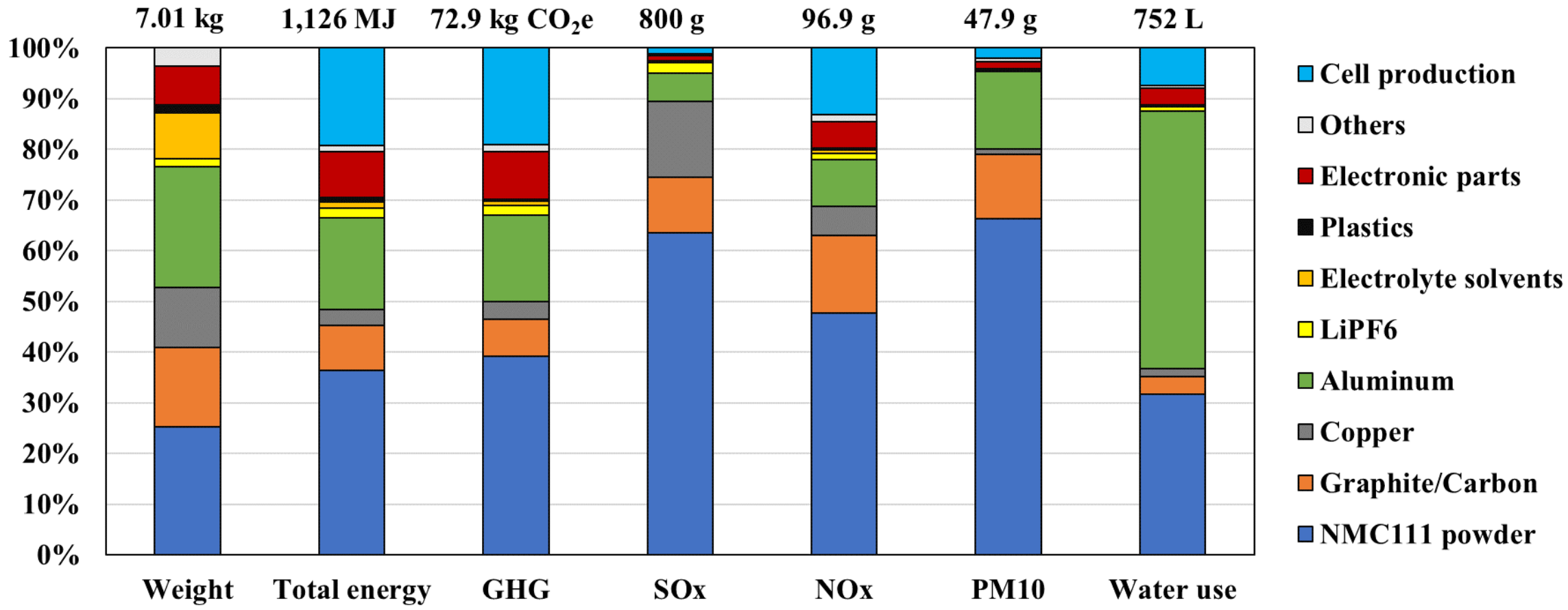
LIFECYCLE ANALYSIS EVALUATES PROCESS IMPACTS

of a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal if any.



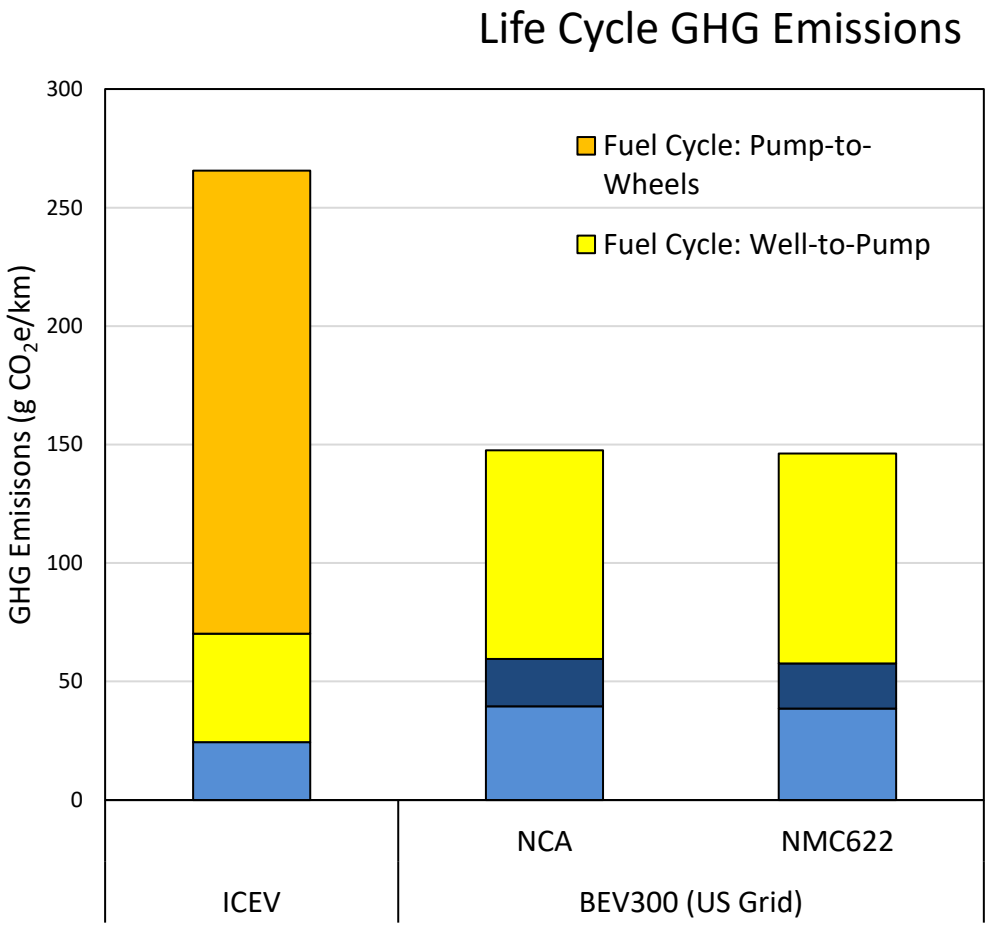
CRADLE-TO-GATE ENVIRONMENTAL IMPACTS: 1KWH NMC111 CELLS

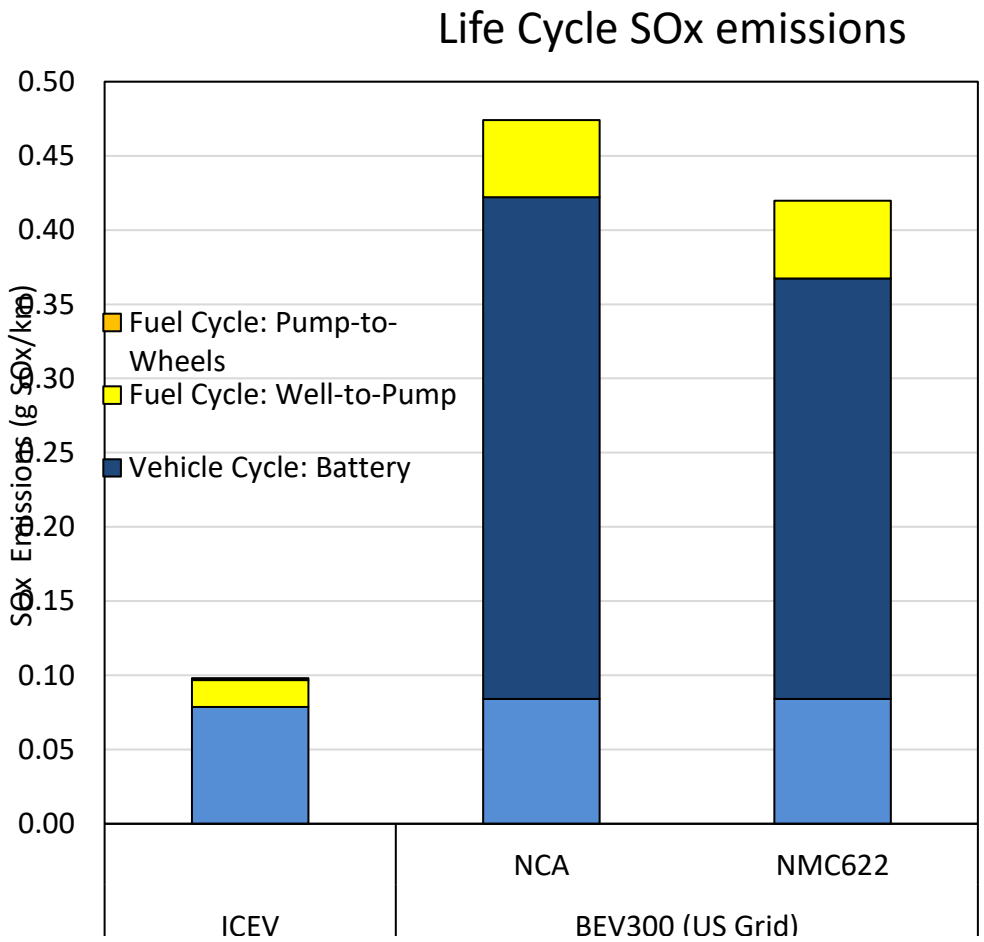
Cathode, production energy, and aluminum are notable contributors



BATTERY CONTRIBUTES LITTLE TO LIFETIME GHG

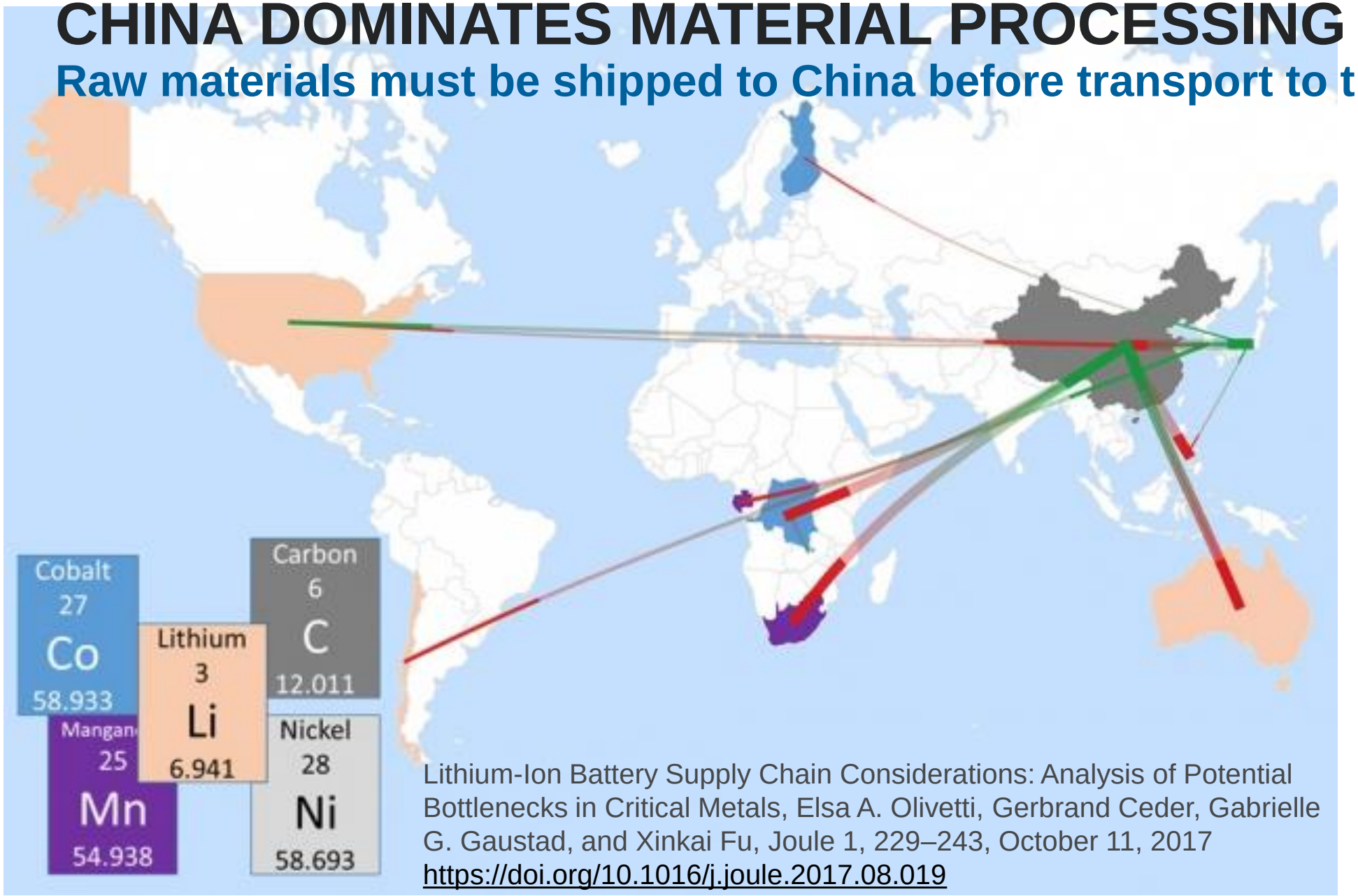
But significantly to SOx emissions





CHINA DOMINATES MATERIAL PROCESSING

Raw materials must be shipped to China before transport to the US



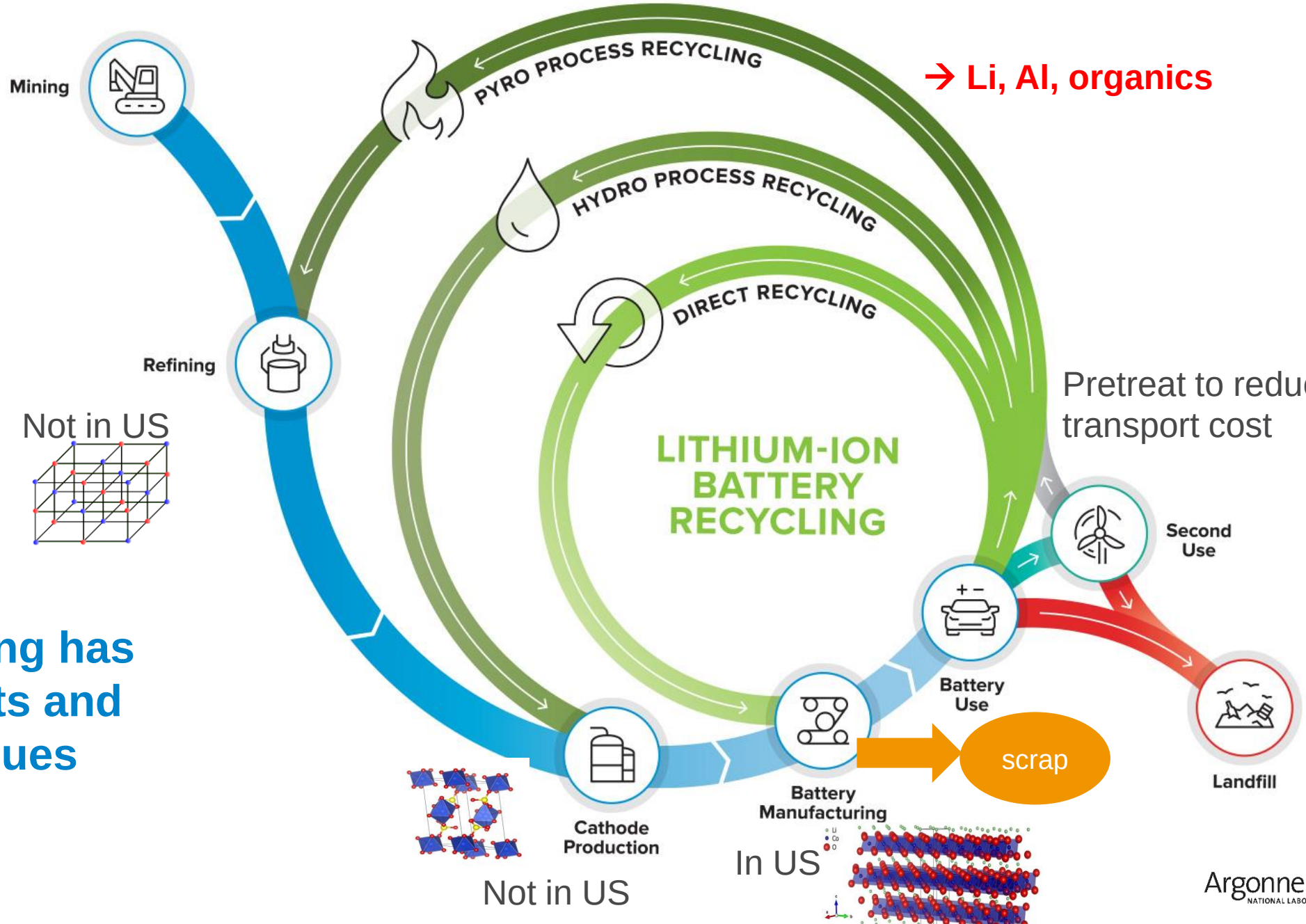
Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Elsa A. Olivetti, Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu, Joule 1, 229–243, October 11, 2017 https://doi.org/10.1016/j.joule.2017.08.019

RECYCLED MATERIALS MIGHT ALSO NEED TRANSPORTING

Increased recycling can decrease the need for new raw material extraction and production. Different recycling processes reintroduce that material at different stages of the supply chain. A more robust domestic recycling industry will be most effective at securing material supply chains if paired with growth at various stages of manufacturing. Without a footprint in the earlier stages of manufacturing (including materials processing, as well as electrode, cell, and pack manufacturing), intermediate recycled products will be exported to markets/countries that have these capabilities.

White House, BUILDING RESILIENT SUPPLY CHAINS, REVITALIZING AMERICAN MANUFACTURING, AND FOSTERING BROAD-BASED GROWTH 100-Day Reviews under Executive Order 14017 (June 2021) https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf?utm_source=sfmc%E2%80%8B&utm_medium=email%E2%80%8B&utm_campaign=20210610_Global_Manufacturing_Economic_Update_June_Members

LITHIUM ION BATTERY LIFECYCLE



→ Li, Al, organics

Pretreat to reduce transport cost

Not in US

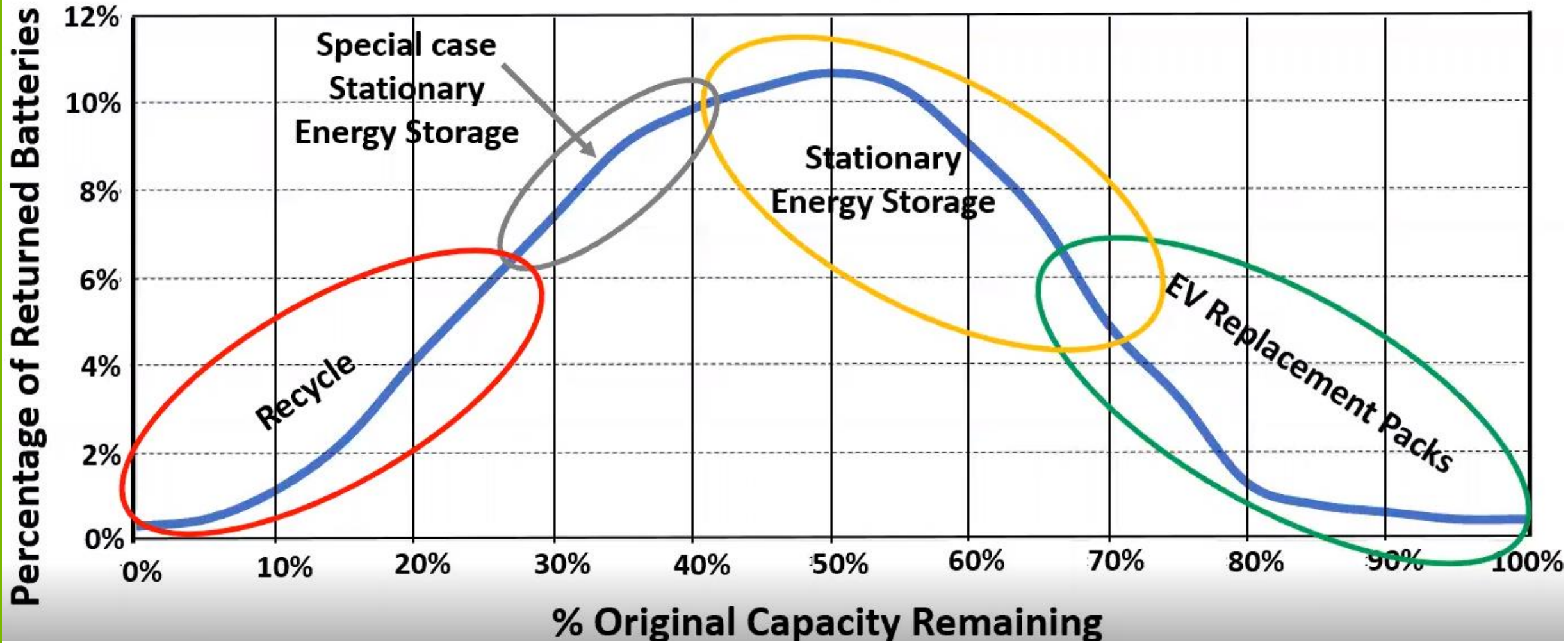
Direct recycling has lowest impacts and highest revenues

Not in US

In US

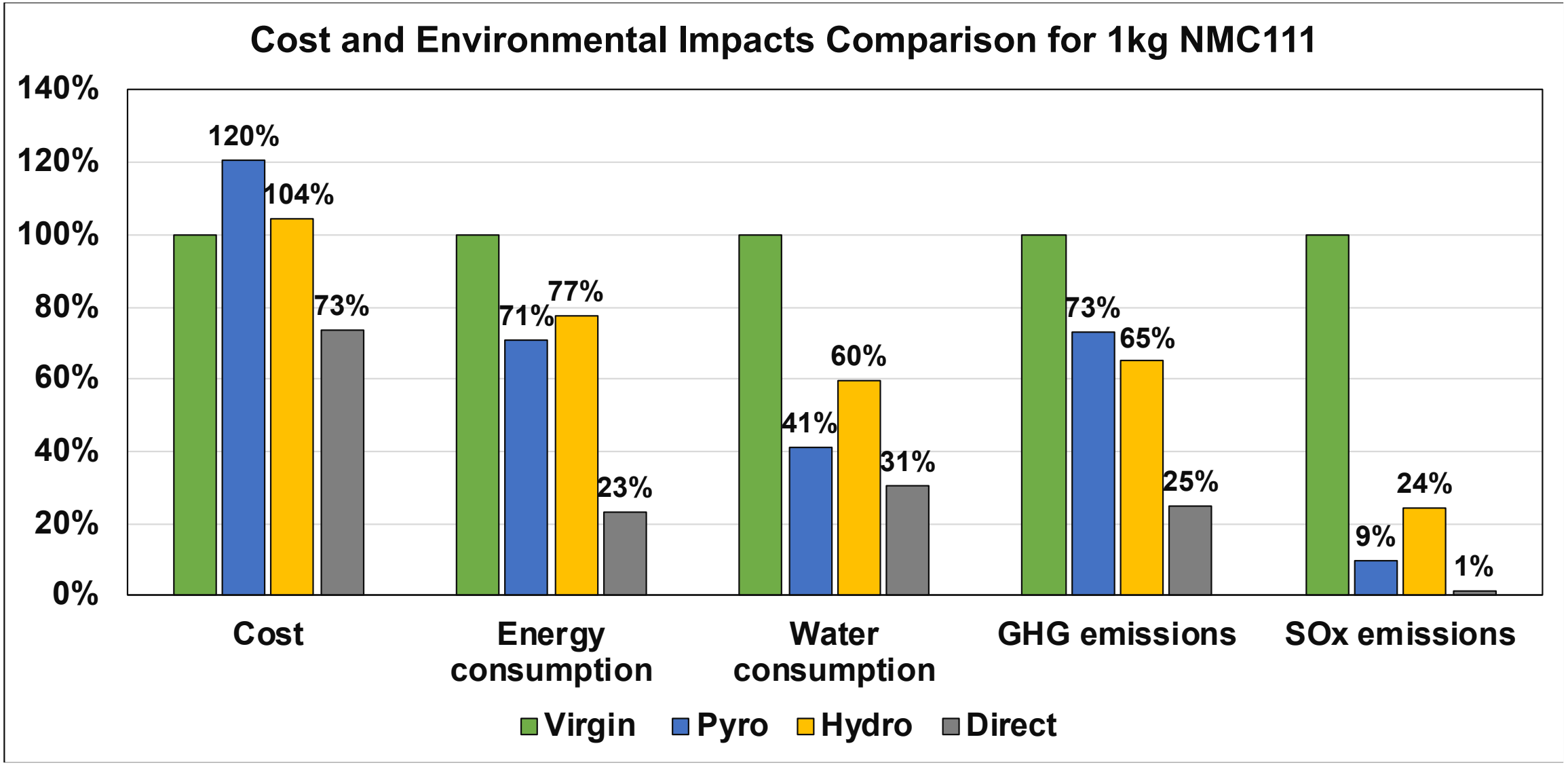
USING BATTERIES AGAIN REDUCES IMPACTS

Eventually, they will need to be recycled



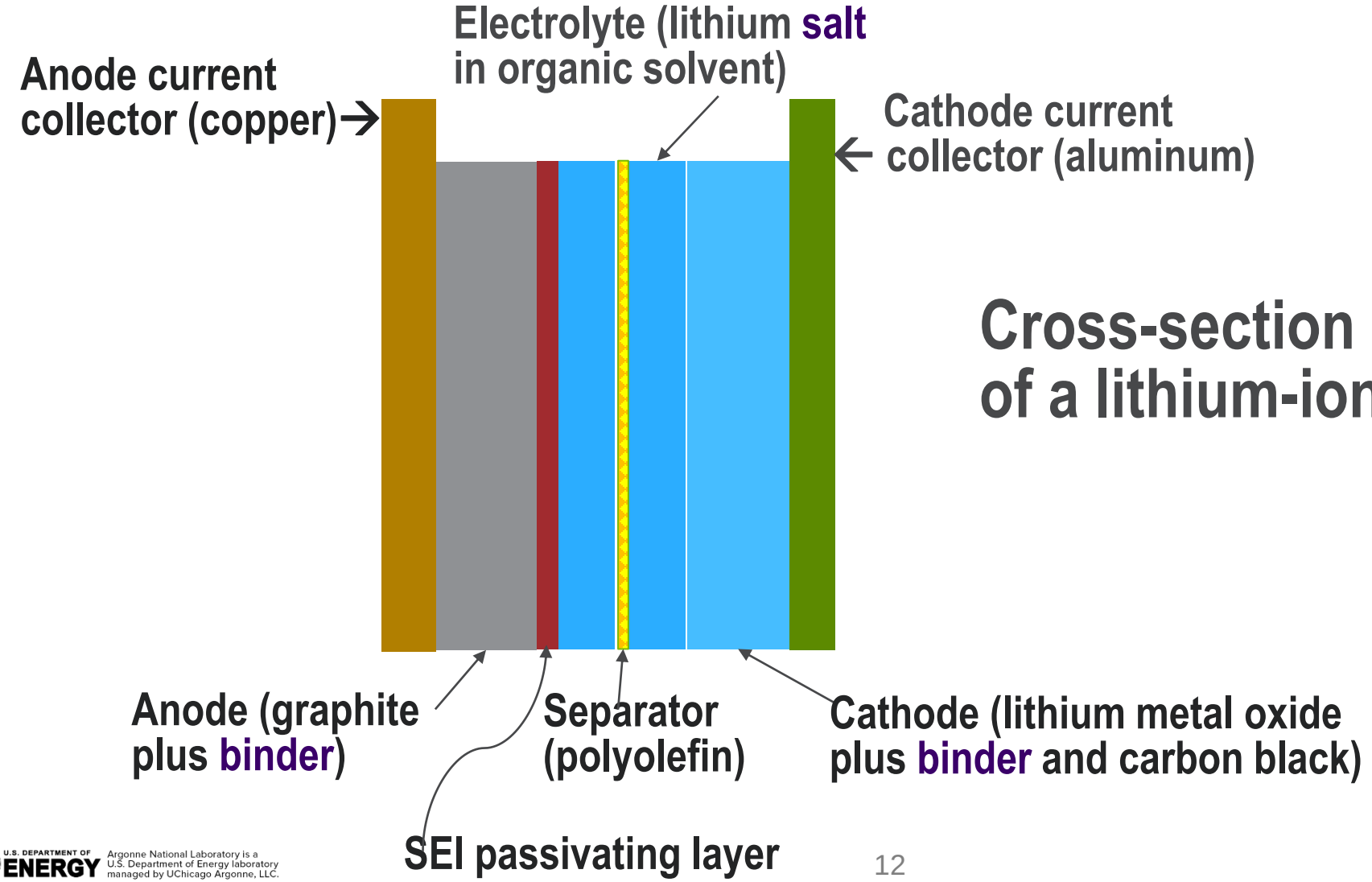
Source: Steve Tolen

DIRECT RECYCLING HAS LOWEST IMPACTS



PROCESSING REQUIRES MANY SEPARATIONS

Commercial technologies lose some of the materials



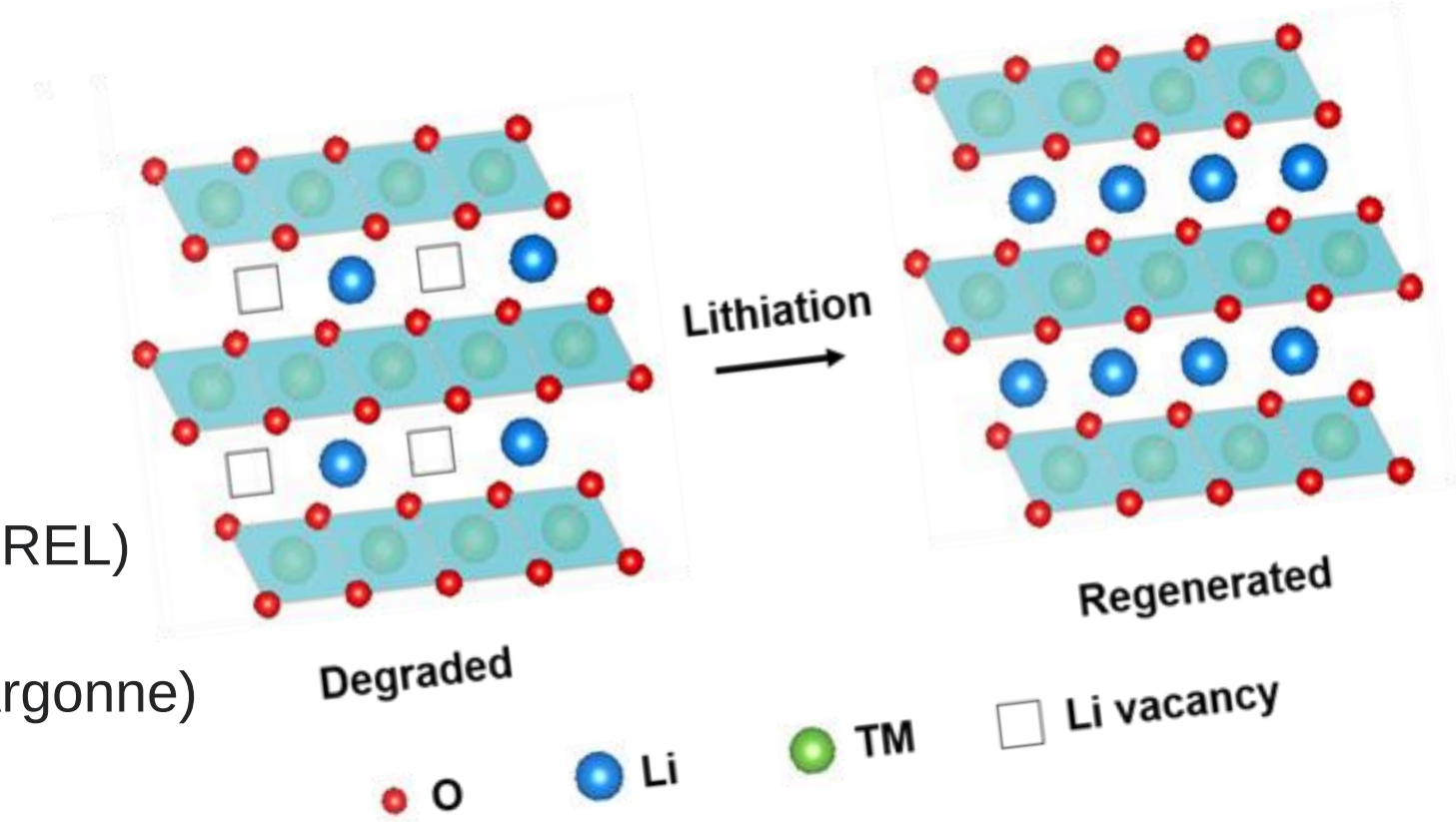
Cross-section of one layer of a lithium-ion cell

DIRECT RECYCLING UPGRADES CATHODE

Product must be as good as new… or better

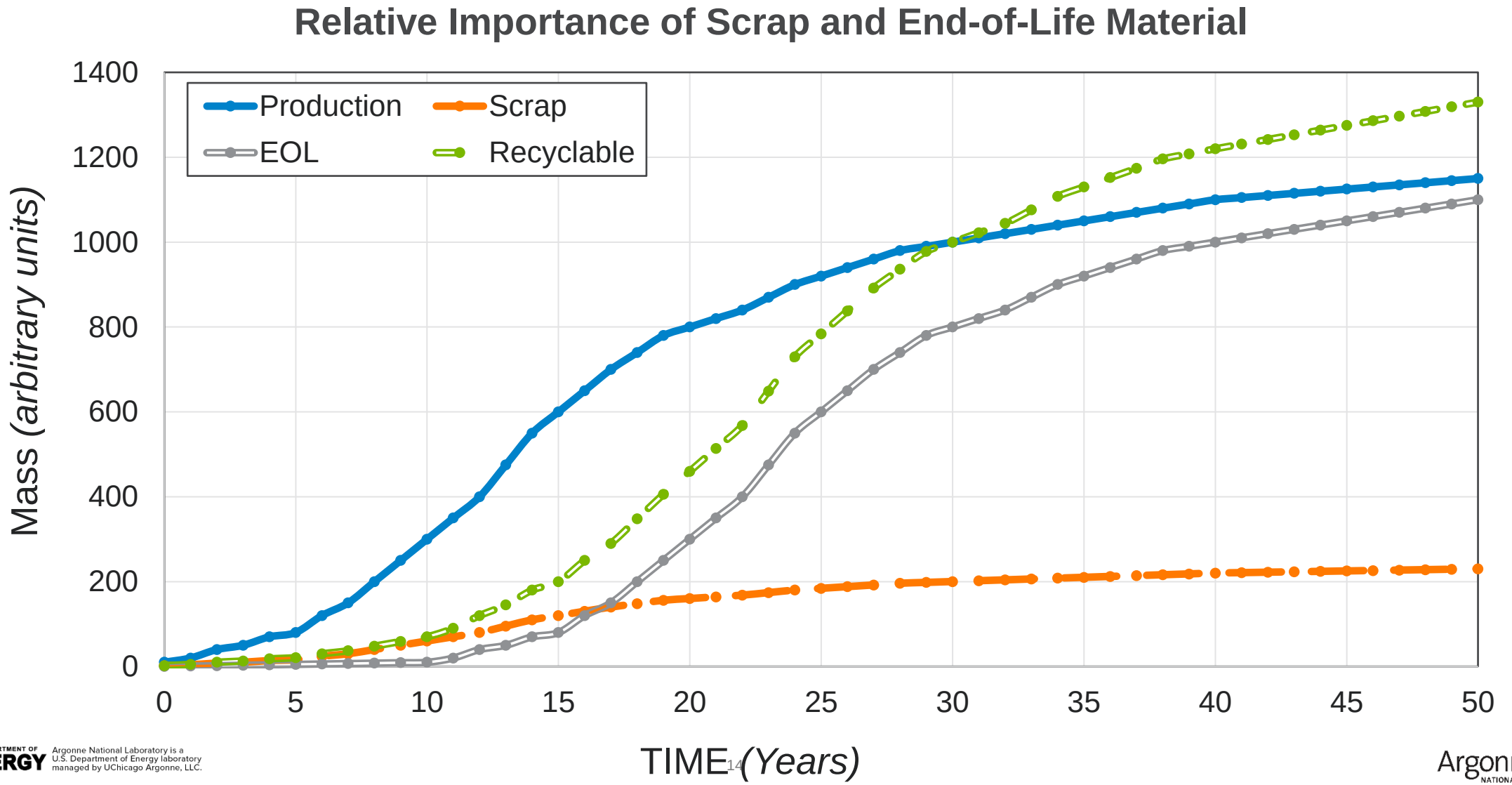
Several phenomena contribute to the gradual drop in lithium-ion battery performance, including surface degradation, cathode instability, reactivity with organic electrolyte components, and surface films. These phenomena need to be reversed and performance restored.

- **Relithiation**
  - Electrochemical (NREL)
  - Solid State (Argonne)
  - Hydrothermal (UCSD)
  - Ionothermal (ORNL)
  - Redox Mediated NREL)
  - Roll to Roll Processing (NREL)
- **Upcycling**
  - Compositional Change (Argonne)



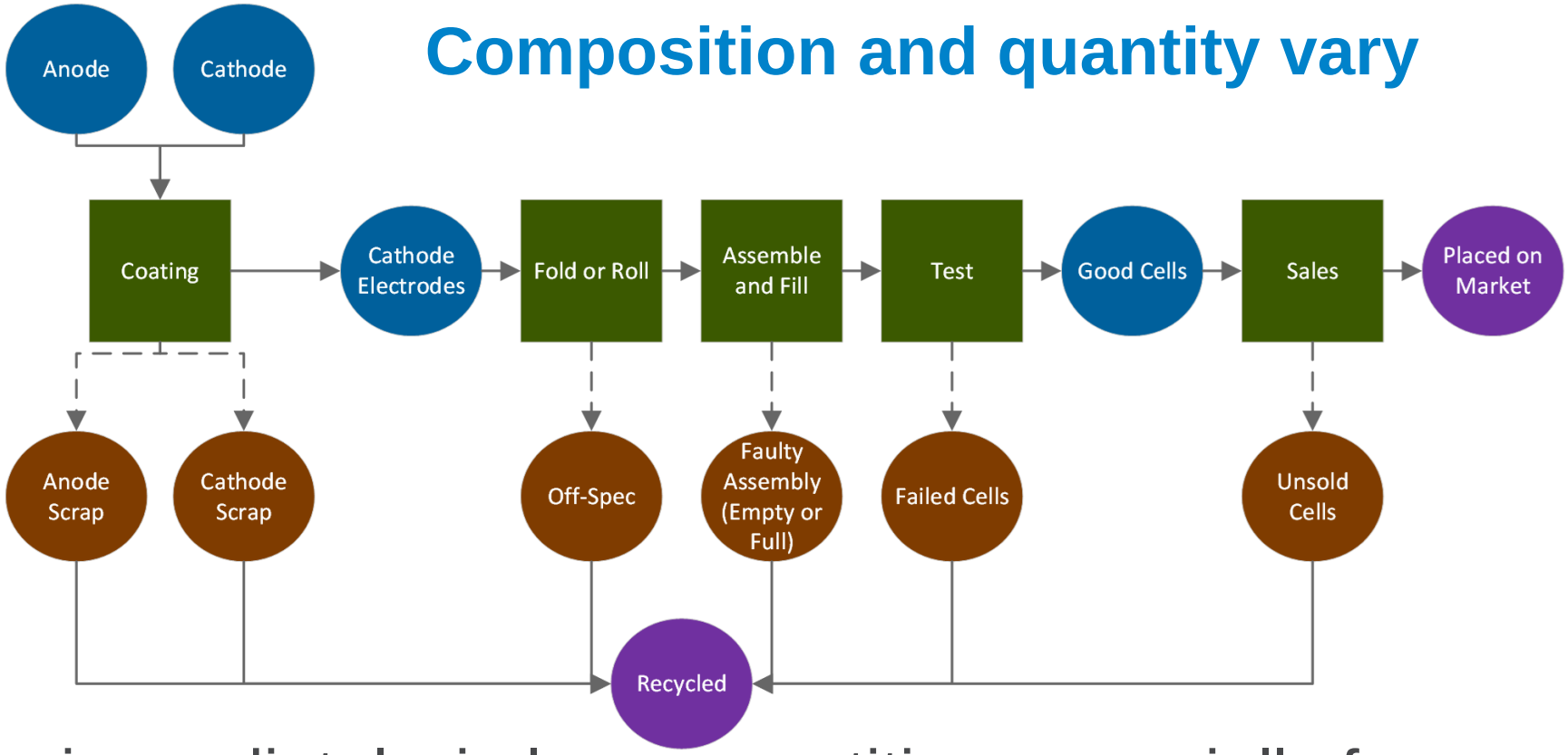
EOL MATERIAL MEETS DEMAND WHEN GROWTH STOPS

Scrap dominates available material during growth period



THERE IS SCRAP ALL ALONG MANUFACTURING PROCESS

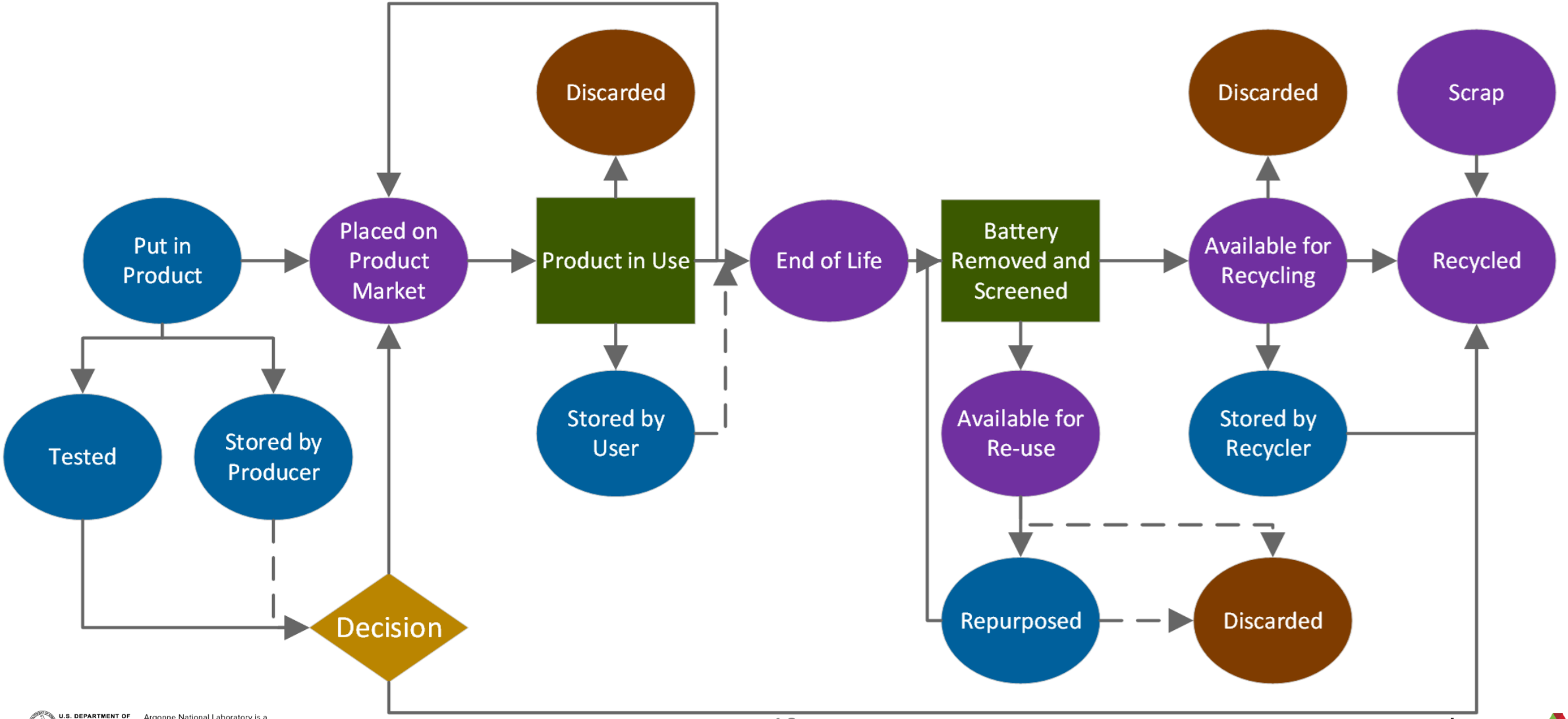
Composition and quantity vary



- Available immediately, in large quantities, especially from new plants
- Material is new and uncycled; composition is known
- Can go back into manufacturing process with minimal treatment
- Often exported, processed with end-of-life material

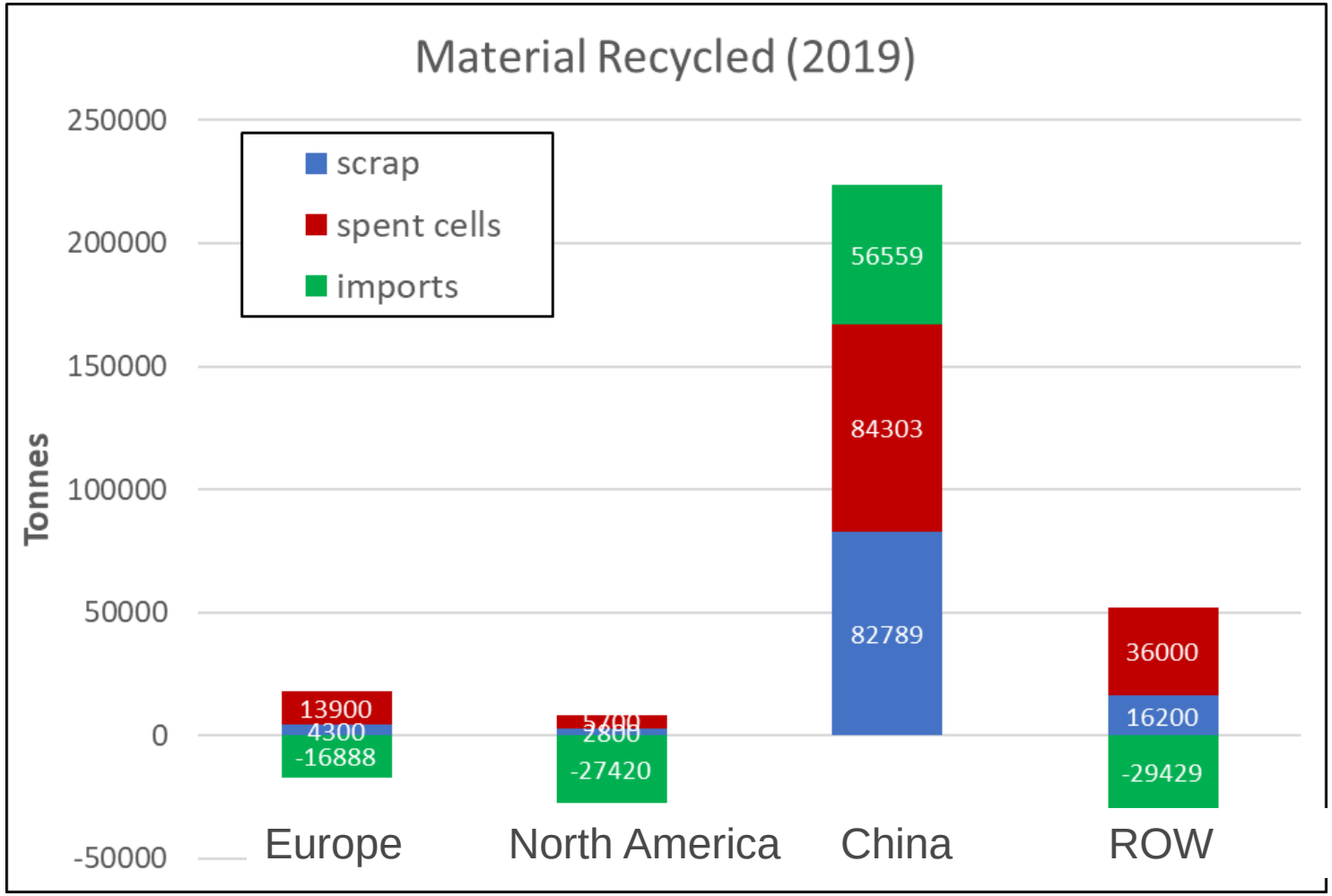
BATTERIES HAVE VARIED ROUTES TO RECYCLING

Batteries (and scrap) can also be exported or discarded along the way



HOW MUCH IS RECYCLED? WHERE?

Over 300kT of batteries and scrap were recycled in China in 2019

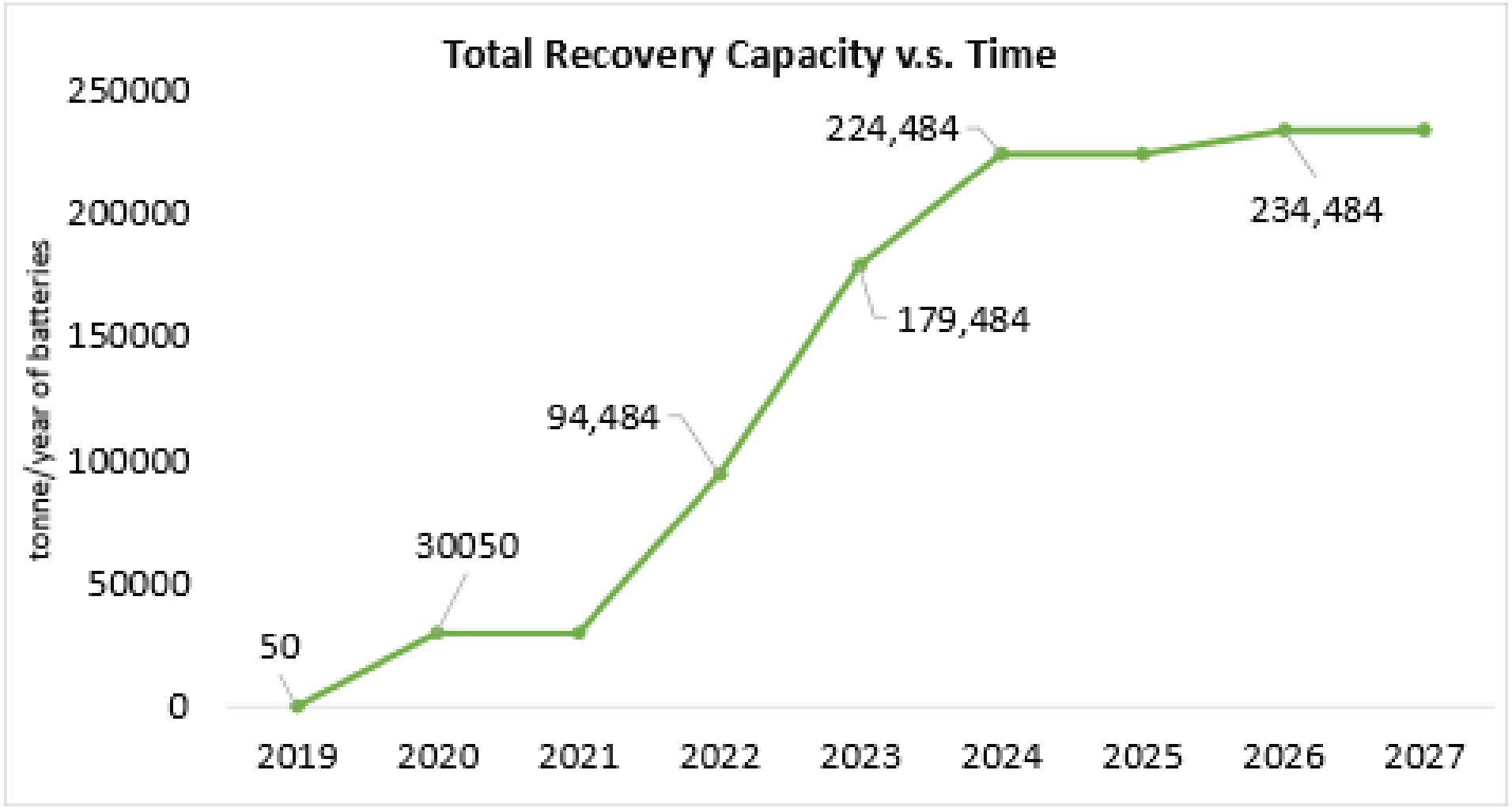


Negative values reflect material exported to China for recycling.

Source: The lithium-ion battery life cycle report 2021, Circular Energy Storage, London

NA RECOVERY CAPACITY IS GROWING RAPIDLY

Some recyclers have announced processing to cathode



Credit: Jessica Sun, summer intern

Thank you!
US Department of Energy, Vehicle Technologies Office
Industrial sponsor
Circular Energy Storage