LITHIUM-ION SUPPLY CHAIN CONSIDERATIONS

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CIRCULAR ECONOMY

MATERIALS KEPT IN USE DON'T NEED TO BE MINED

The smallest loops generally have the lowest resource demand

MINERAL RESOURCES DON'T GET USED UP

The earth is a closed system; they just get concentrated or diluted

As mineral deposits get leaner, we can mine urban waste.

	Natural Resources	Spent Batteries
One ton of battery-grade cobalt can come from:	 **300 TONS** OF ORE	 **5-15 TONS** OF SPENT LITHIUM-ION BATTERIES
One ton of battery-grade lithium can come from:	 **250 TONS** OF ORE  **750 TONS** BRINE	 **28 TONS** OF LITHIUM-ION BATTERIES

CIRCULAR ECONOMY CONCEPT HAS ISSUES

There are hundreds of definitions

- Basic idea: Close loops while minimizing something. What? That is a very hard question that is being discussed.
- But not all materials are scarce. Some are even renewable.
- Getting stuff back may have worse impacts. (LCA is a key tool!)
- Growth requires new material.
- Technology change will disrupt circles.

KEY REPORT RAISES QUESTIONS

- Concept works if there is no growth, technological change, or dispersive use
- In the utopian extreme, primary industries not needed
  - Unless everything recycled to basic standardized raw materials* at production site
- Recycling may not be lowest resource-use option
  - Abundant materials
  - Renewable materials
- What are the right metrics for evaluating options?
  - Circularity? No.
  - Energy use? No.
  - Jobs? No.
  - Resource depletion? GHG?
  -

**Do not wear clothing woven of two kinds of material.* (Leviticus 19:19).

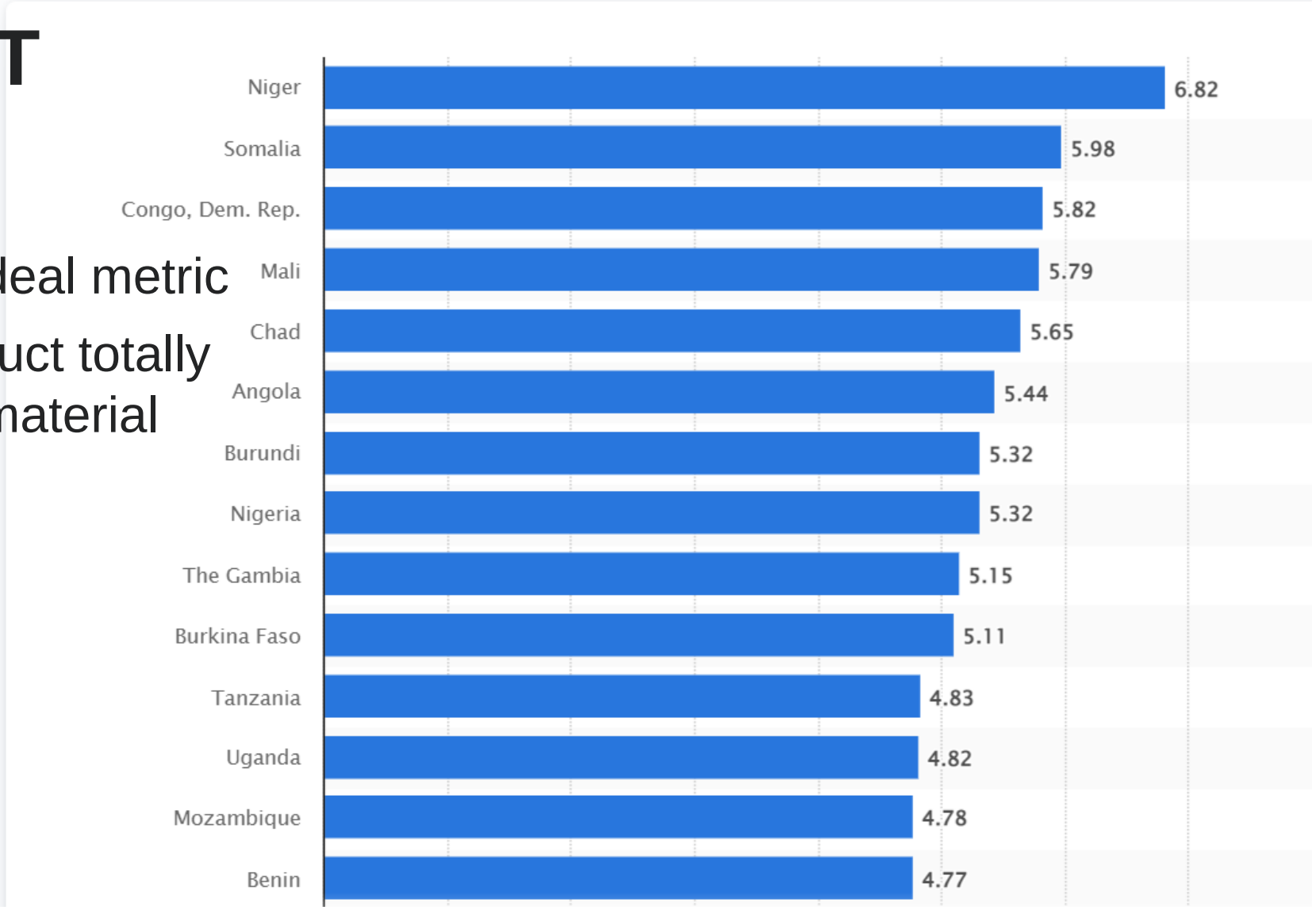
EXAMPLES OF PROPOSED METRICS

From Department of Commerce Foundation in 2022

- Amount recovered
- Carbon footprint
- Cost saving per use
- Estimated impact offset
- kWh produced
- Payback time
- Percent materials composition
- Percent recovered
- Percent recyclable
- Progress toward goal
- Return on investment

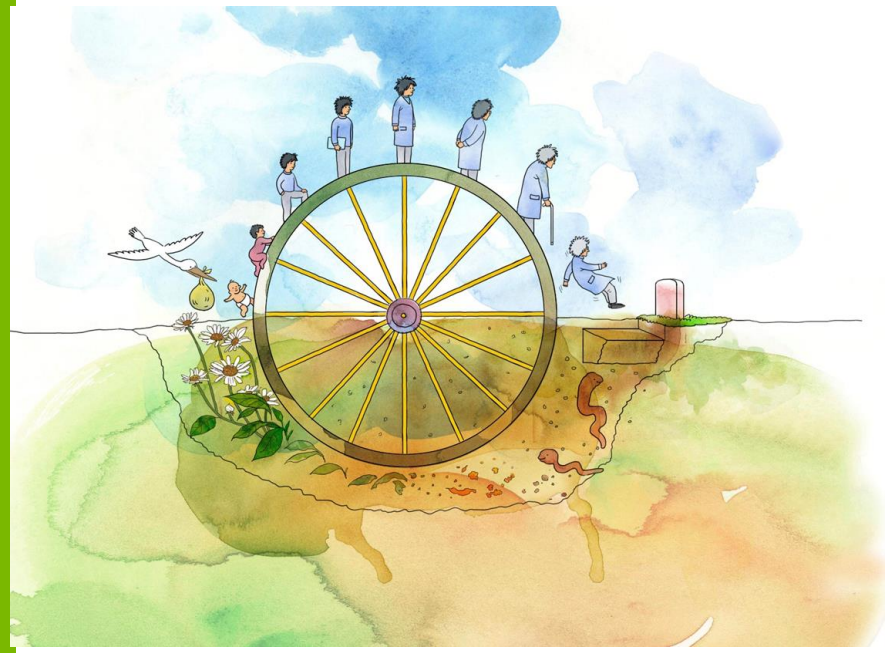
GROWTH IS NOT SUSTAINABLE

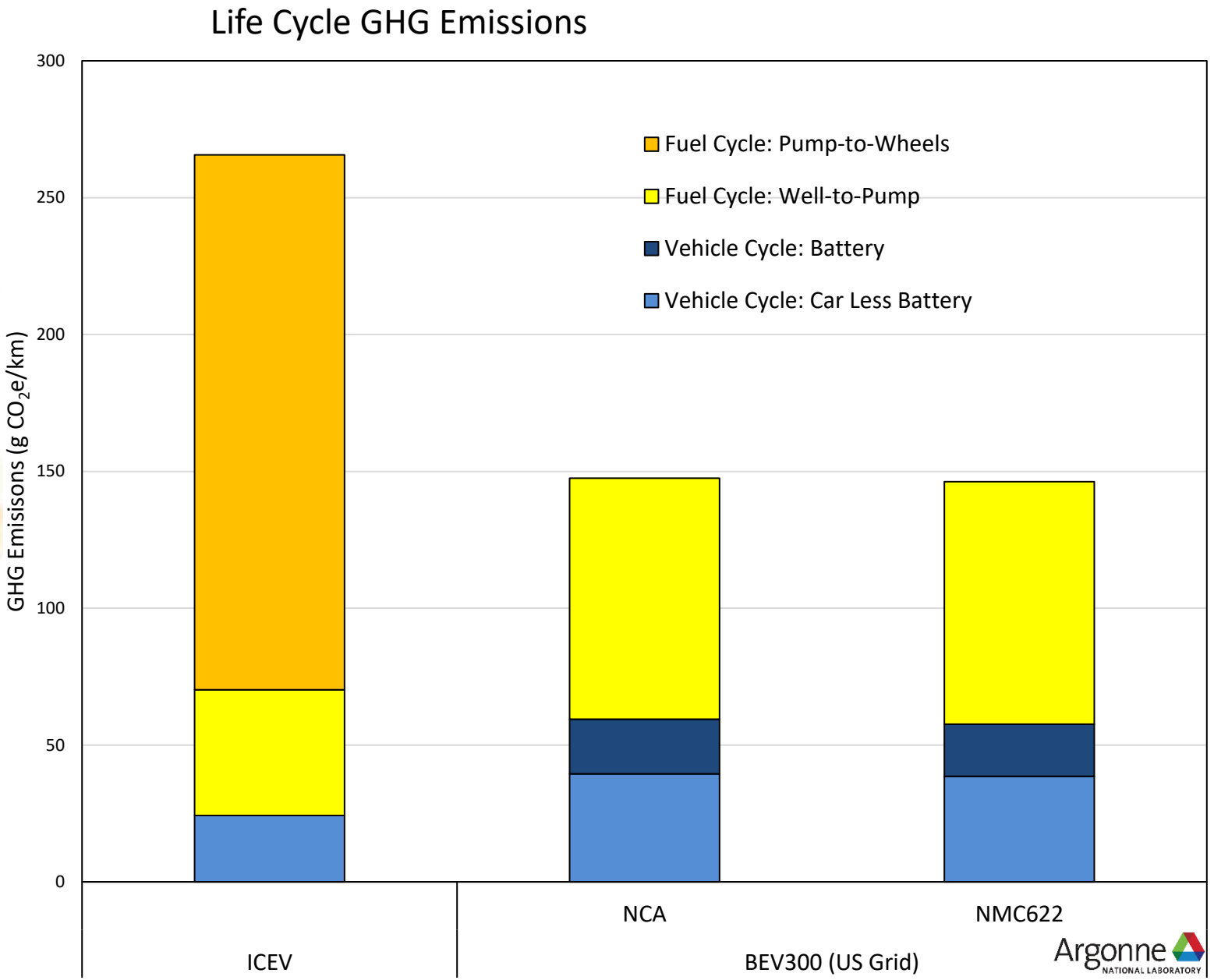
- Circularity may not be an ideal metric
- We could make every product totally circular and still have raw material supply issues



WHAT IS THE PROBLEM?

SHIFT TO EVS REDUCES LIFE CYCLE GHG EMISSIONS





GOALS WERE TO REDUCE CO_2 AND ELIMINATE OIL IMPORTS

But we are again reliant on imports -- of Li-ion battery materials

- The focus is on materials that have become critical due to rapid growth
  - Cobalt
  - Nickel
  - Lithium
- An expert panel evaluated likelihood of acquiring needed material
  - Probable
  - Possible
  - **Improbable**
  - Impossible

> Several Li-Bridge participants anticipate a worldwide shortfall in supplies of critical minerals and energy materials within a four-to-twelve-year time frame (before new foreign and domestic sources of supply can be brought online).
>
> Li-Bridge Report, February 2023

BUILDING RESILIENT SUPPLY CHAINS, REVITALIZING AMERICAN MANUFACTURING, AND FOSTERING BROAD-BASED GROWTH

100-Day Reviews under
Executive Order 14017

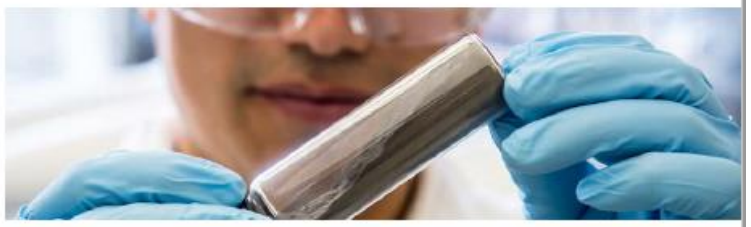
June 2021

A Report by
The White House

Including Reviews by
Department of Commerce
Department of Energy
Department of Defense
Department of Health and Human Services

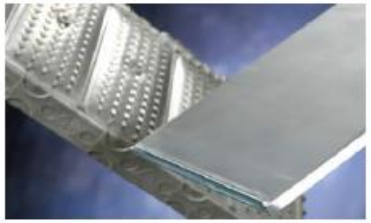
THE WHITE HOUSE
WASHINGTON

FCAB
FEDERAL CONSORTIUM FOR ADVANCED BATTERIES



EXECUTIVE SUMMARY

NATIONAL BLUEPRINT FOR LITHIUM BATTERIES 2021–2030



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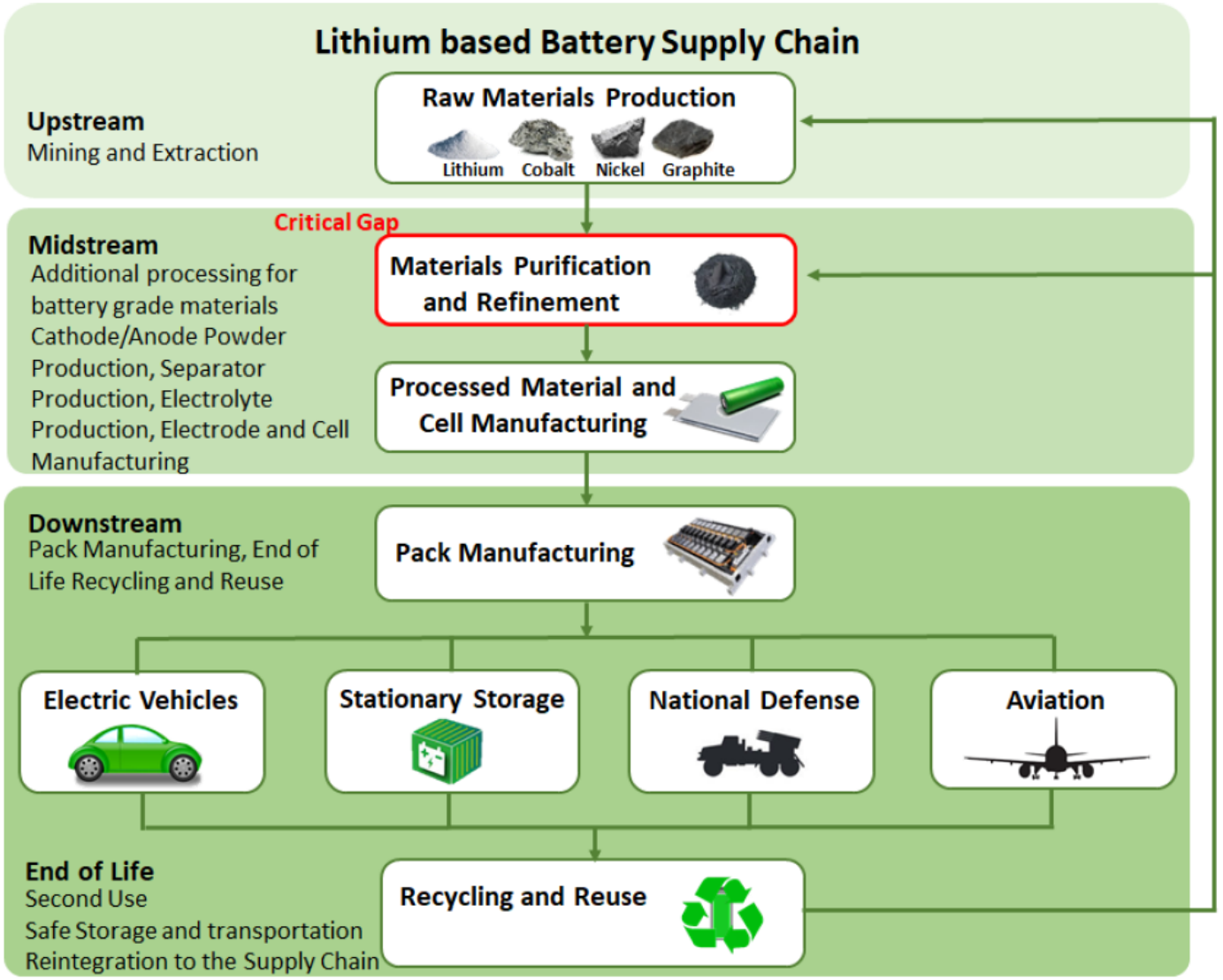


Source: DOE Vehicle Technologies Office (VTO)

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

US RESERVES ARE INSUFFICIENT

About 10 million cars are produced annually

If all US production were EVs with 100 kWh NMC811 batteries, domestic reserves couldn't even supply 1 year's cathode.

Table 1. Potential for use of U.S. reserves [1, 2]

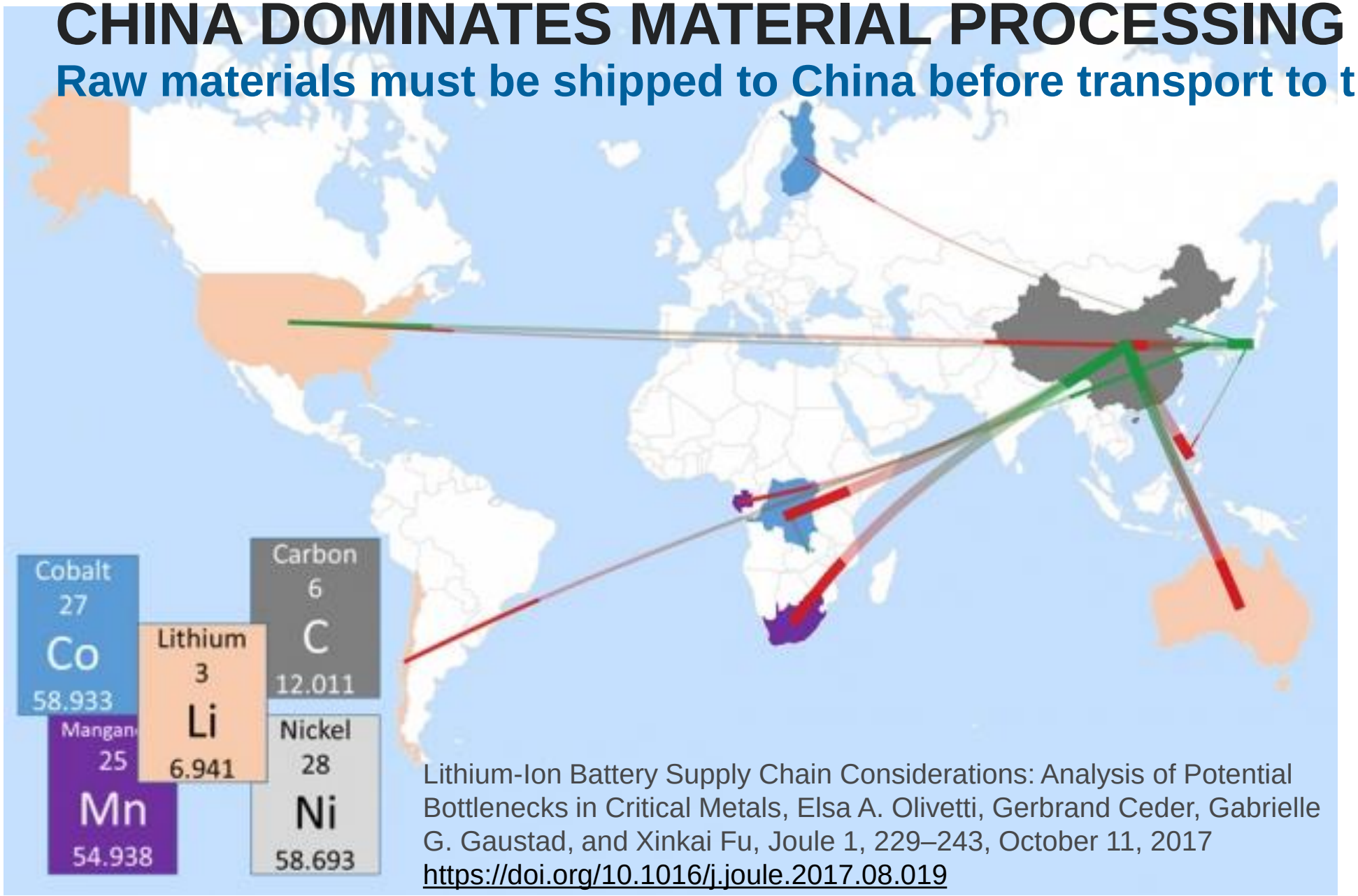
Element	kg/car @100 kWh	U.S. reserves (kT)	World reserves (kT)	Number for U.S. (million)	Number for world (billion)
Cobalt	15.4	69	8,300	4.5	0.54
Nickel	46.3	370	>100,000	8.0	2.2
Lithium	9.4	1,000	26,000	107	2.8

WHAT IS WRONG WITH GLOBAL SUPPLY CHAINS?

- They may be disrupted by
  - War
  - Pandemic
  - Political bargaining
- Disruption
  - Delays production
  - Causes product shortages
  - Costs money
  - Damages national security
- Transportation is
  - Expensive
  - Time-consuming
  - Produces emissions

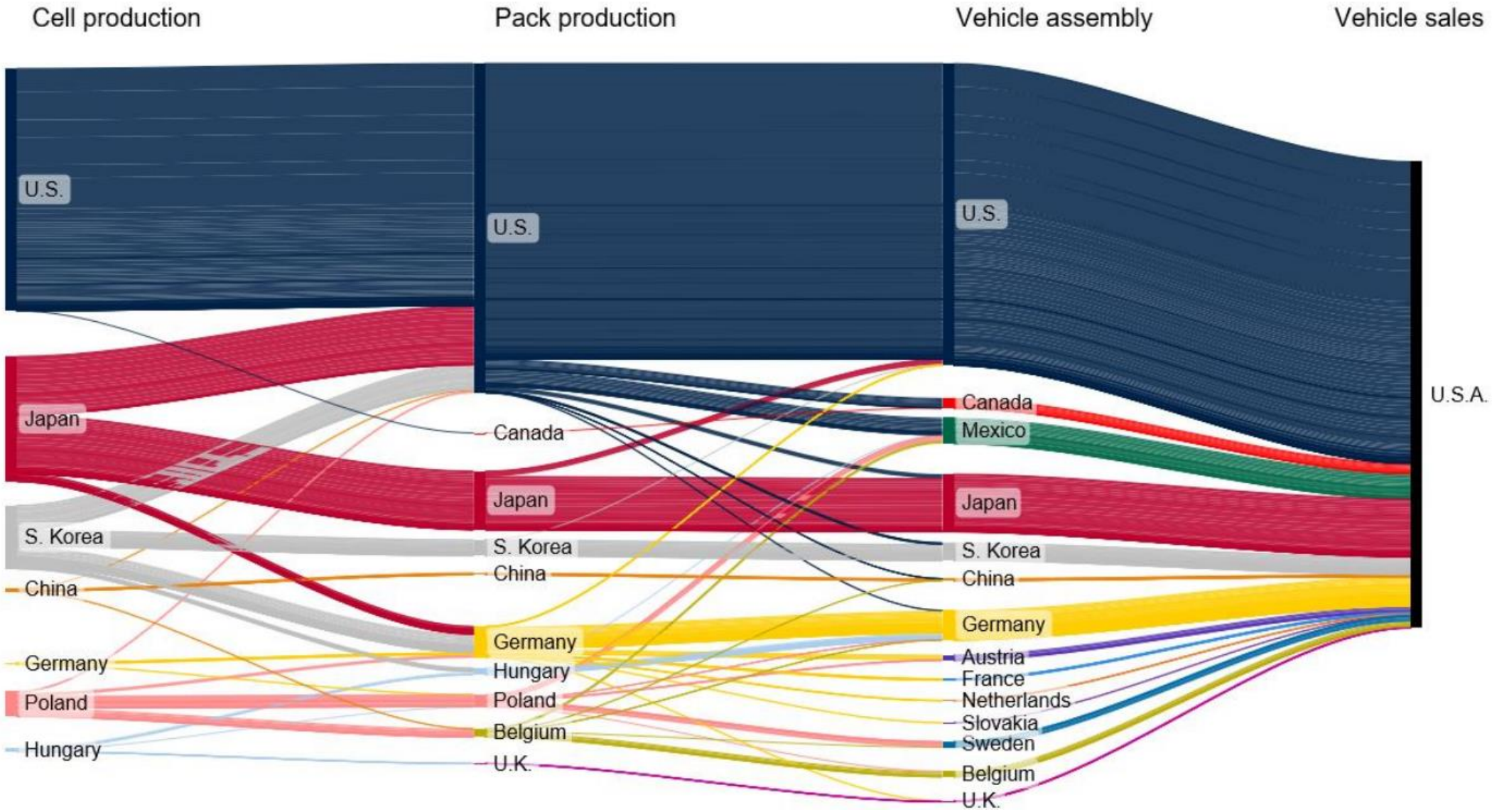
CHINA DOMINATES MATERIAL PROCESSING

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



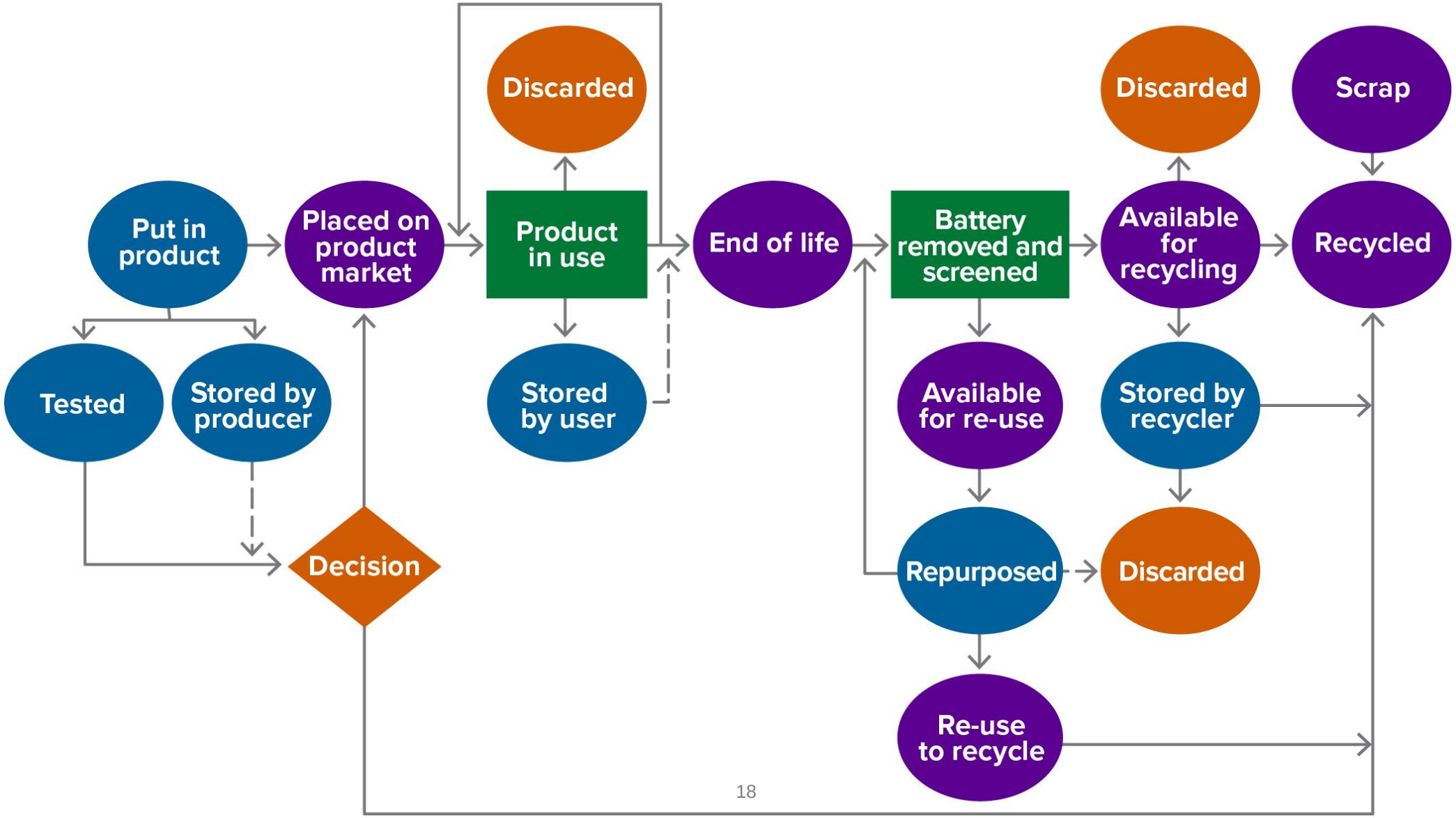
Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Elsa A. Olivetti, Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu, Joule 1, 229–243, October 11, 2017 https://doi.org/10.1016/j.joule.2017.08.019

US DOES PRODUCE CELLS, PACKS, VEHICLES



BATTERIES HAVE A COMPLEX LIFECYCLE

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



HOW TO CLOSE THE BATTERY LIFECYCLE LOOP

BATTERY DESIGN IS VARIED

- Battery pack size and shape differ from model to model.
  - Many types of closures are used
  - Enclosure designs and materials vary
- Modules vary in size, shape, number of cells
  - Adhesives or restraints hold cells in place
  - Cooling systems and electrical connections vary
- Cells can be cylindrical, prismatic, or pouch
  - Size and shape vary
  - Different cathode chemistries are used

- **This variety hinders repair and recycling**

REVISED DESIGNS COULD ENABLE DISASSEMBLY

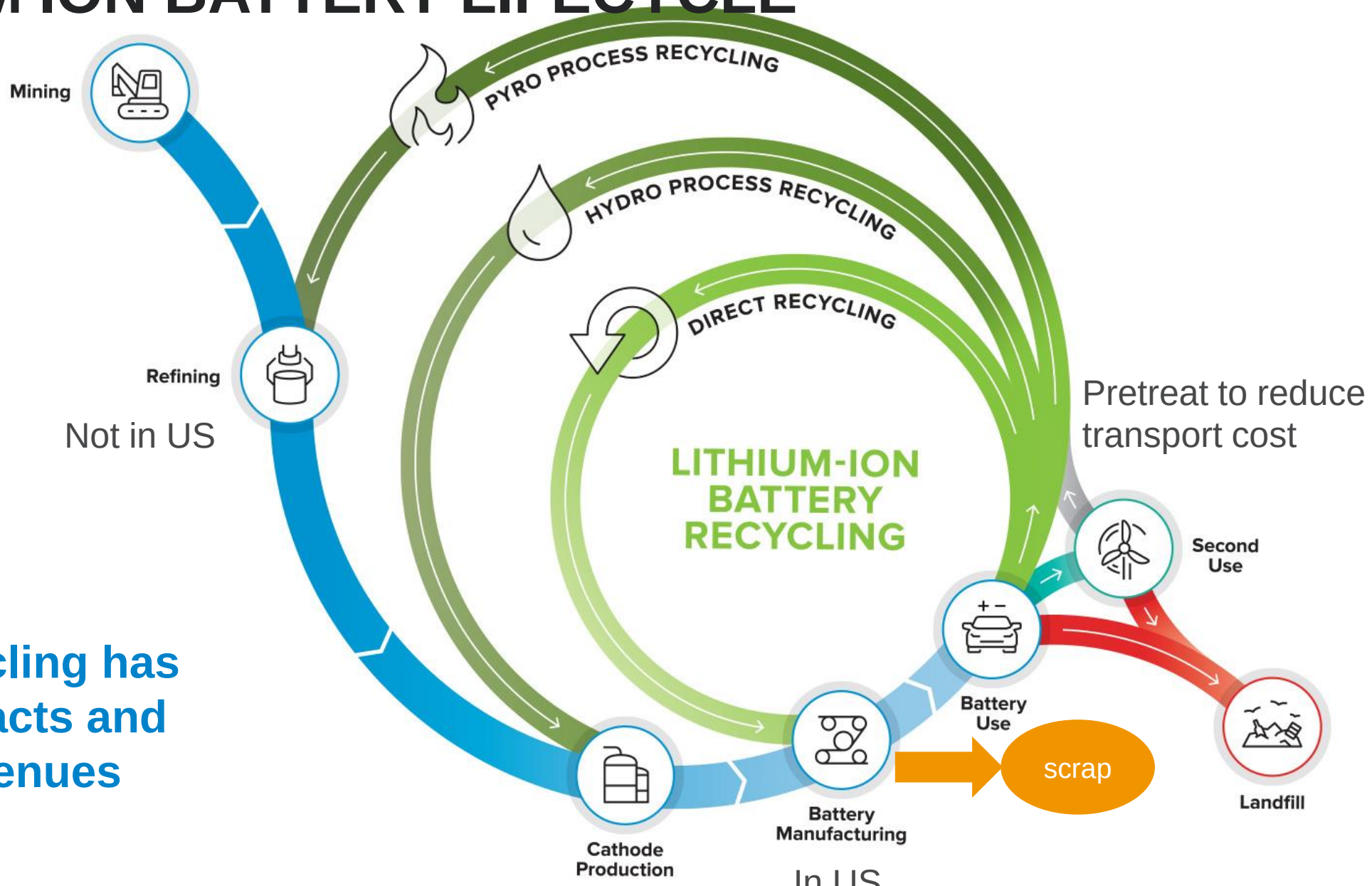
Design for repair, reuse, and recycling could reduce costs

- Uniformity and standardization would enable **robotic disassembly**
  - Make varied packs from standard modules
  - Limit cell form factors; use larger cells (Blade design)
- Limiting material choices would reduce separation steps needed
- Reversible joining would enable disassembly but might raise manufacturing cost
  - Adhesives and binders that can be dissolved
  - Thermoplastics not thermosets
  - Nuts and bolts instead of welds
- Simpler structure is easier to take apart
  - Integrate pack with vehicle structure: a help or hindrance?
- Innovation is needed at the cell level

SHREDDING A BATTERY IS LIKE PUTTING A VICTORIA SPONGE CAKE IN A BLENDER AND TRYING TO SEPARATE THE CREAM BACK OUT

Disassembly would enable easier recovery of valuable products

LITHIUM ION BATTERY LIFECYCLE



Not in US

Pretreat to reduce transport cost

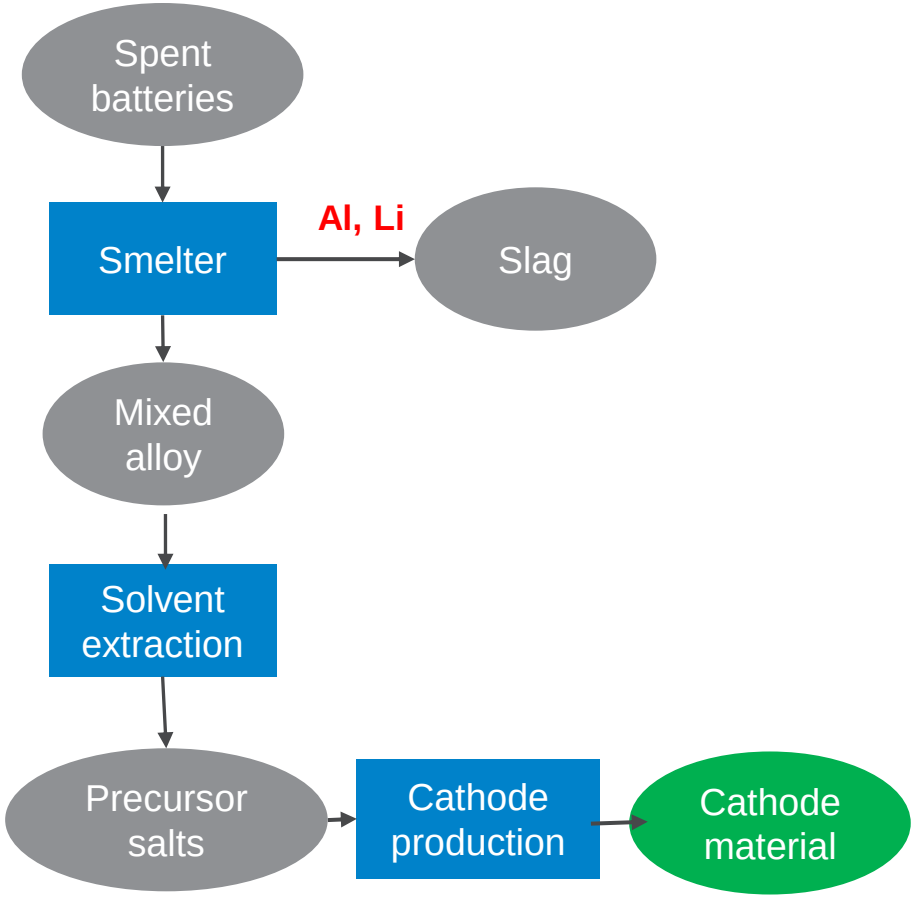
Direct recycling has lowest impacts and highest revenues

In US

Not in US

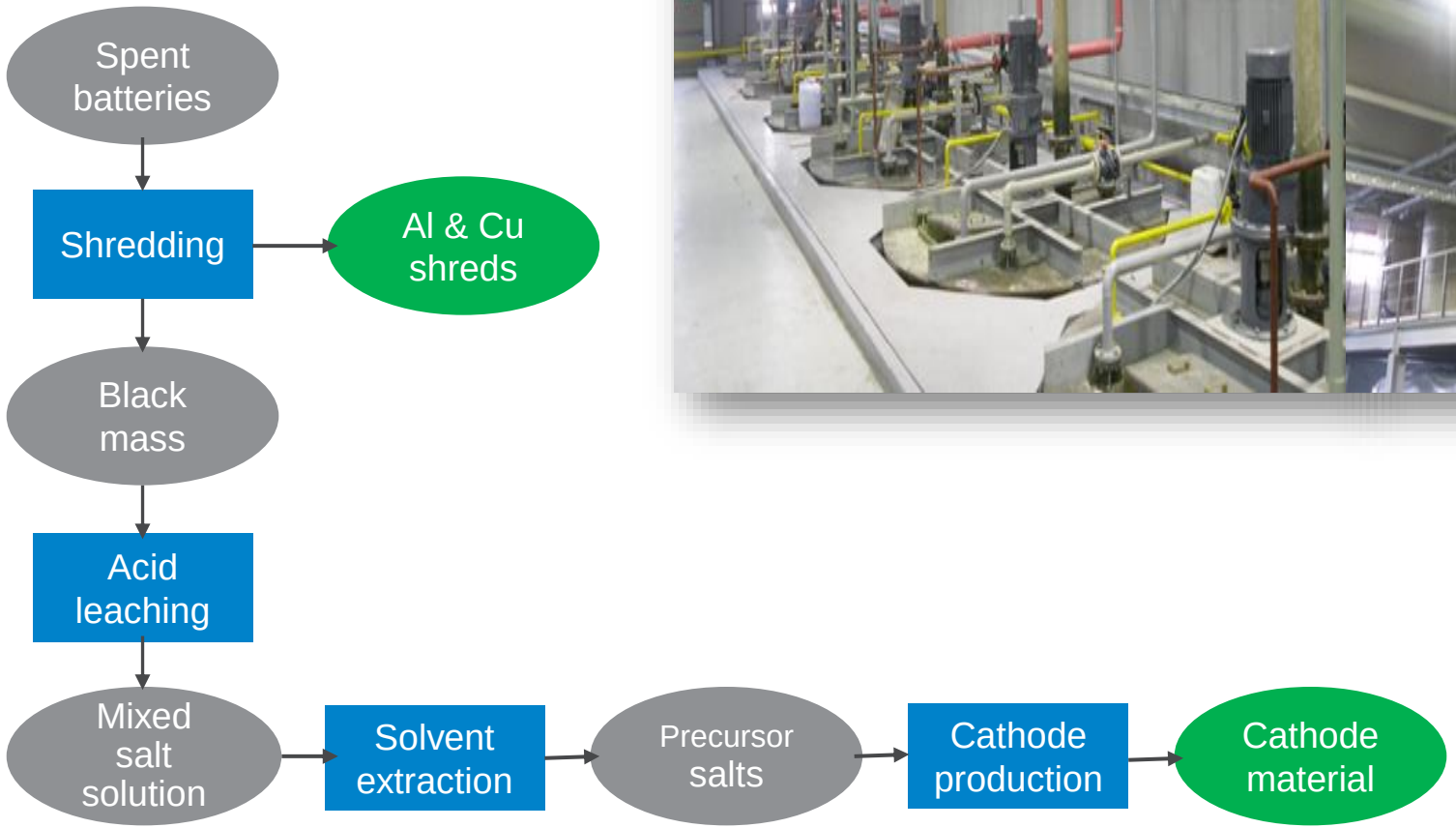
PYROMETALLURGICAL PROCESSING IS HIGH TEMPERATURE AND LARGE SCALE

Umicore pilot plant is designed to process 7,000 tonnes per year



HYDROMETALLURGY

Materials are dissolved in acid and components are separated



Courtesy of SMCC

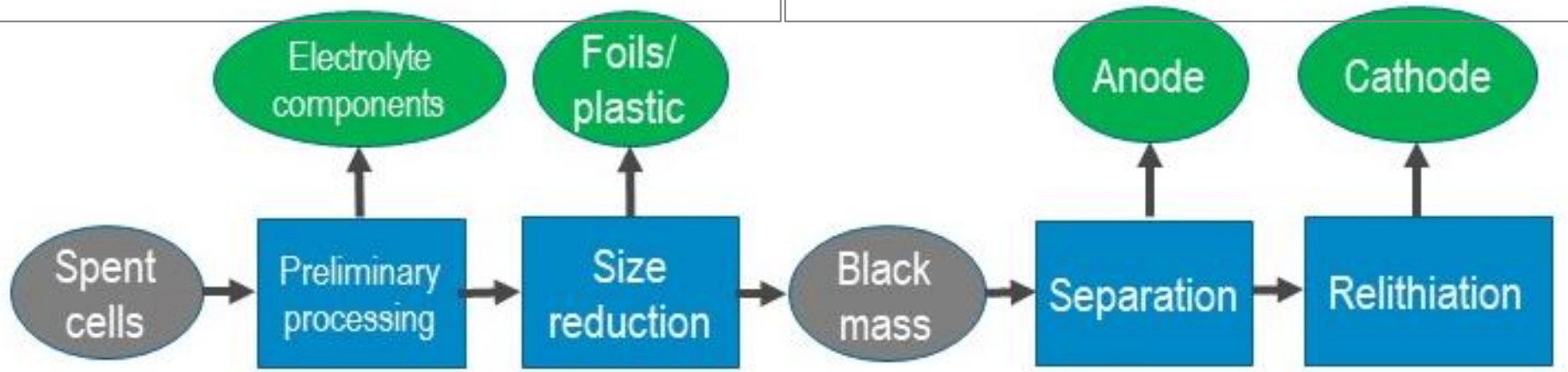
DIRECT RECYCLING is the recovery, regeneration, and reuse of battery components directly without breaking down the chemical structure.

BENEFITS

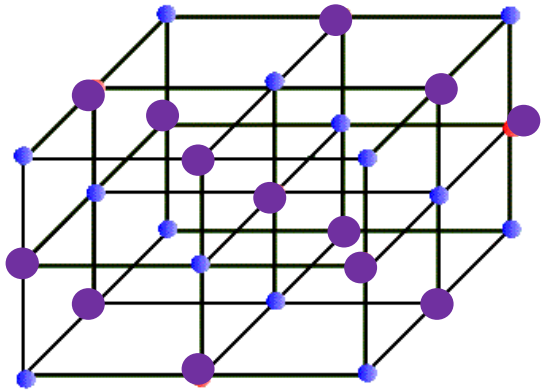
- **Retains valuable chemical structure**
- Enables economic recovery of more materials
- Could be used now for manufacturing scrap
- Low temperature, low energy
- Avoids most impacts of virgin material production

CHALLENGES

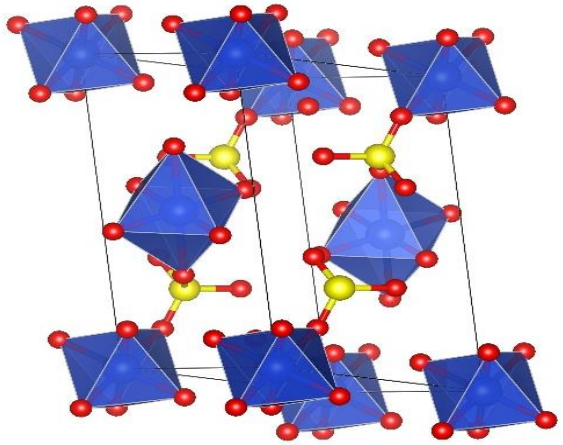
- Separating multiple cathode chemistry particles
- Product may be obsolete formulation
- Degradation may limit repeats
- Buyer must be assured of quality
- Not demonstrated on industrial scale



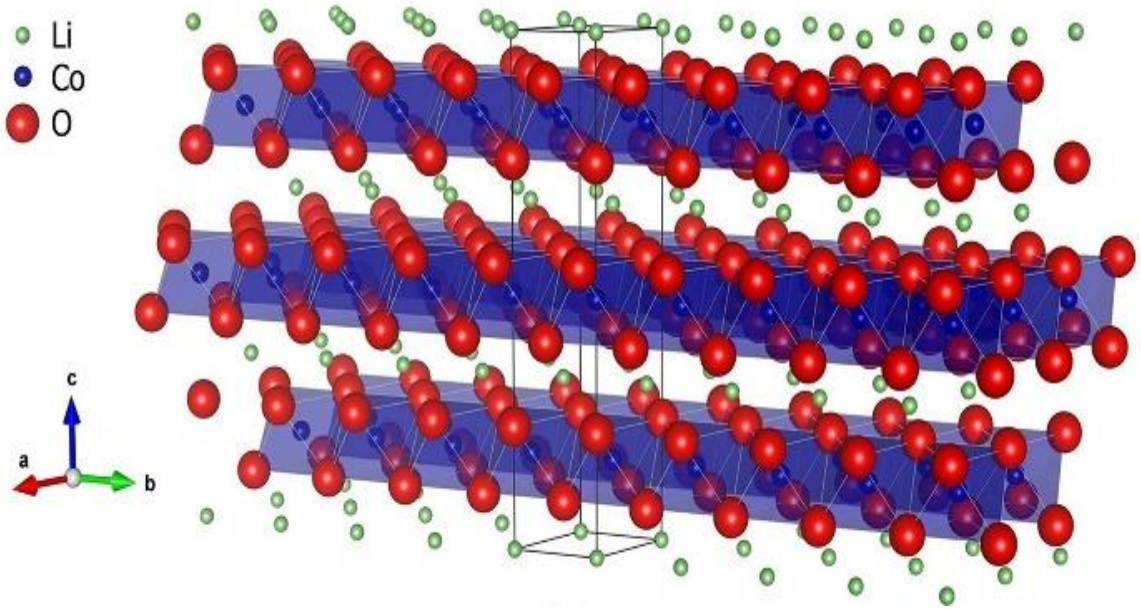
DIRECT RECYCLING RECOVERS HIGHLY STRUCTURED MATERIAL



Cobalt has a simple cubic structure; nickel impurities can substitute



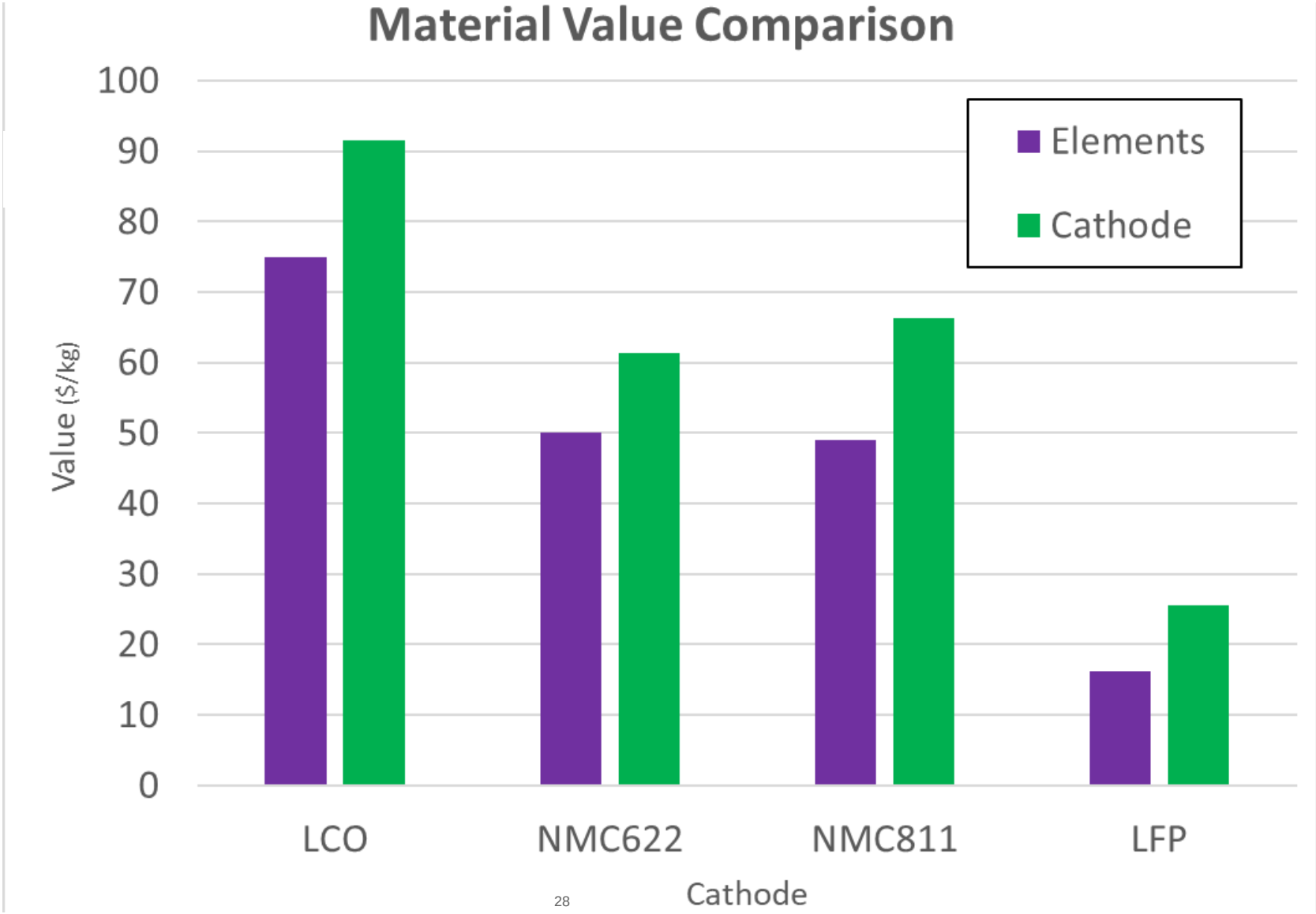
Cobalt sulfate is octahedral



LCO has an ordered layered structure

CATHODE VIABILITY IS KEY TO ECONOMICS

Cathode materials are valuable, even if constituent elements aren't

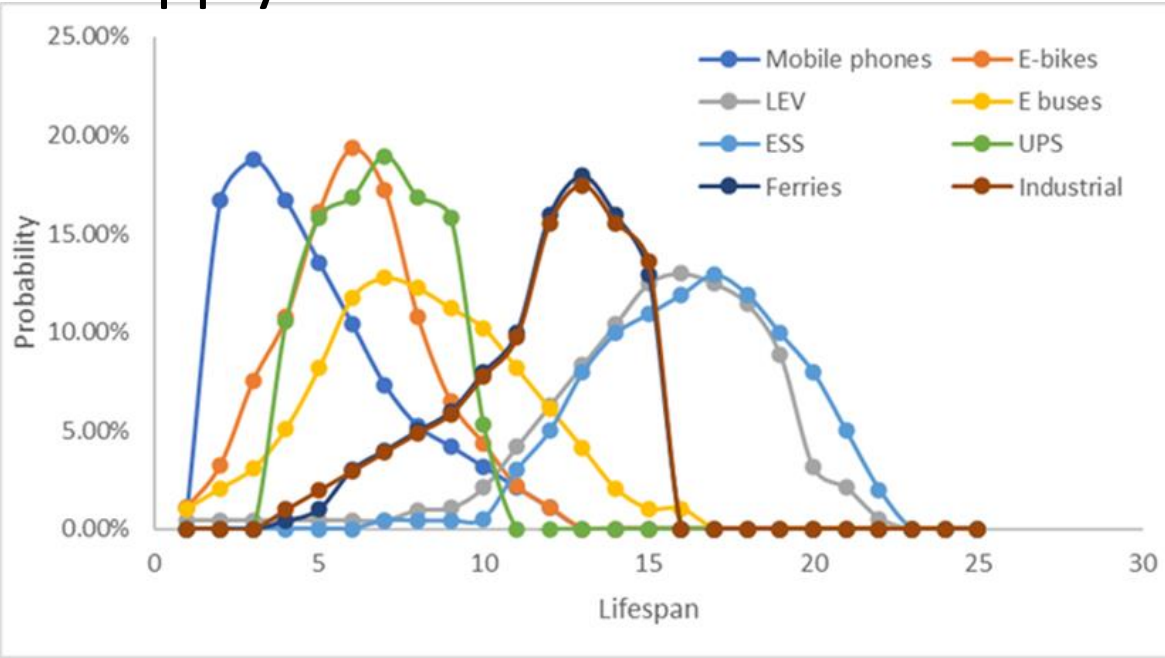


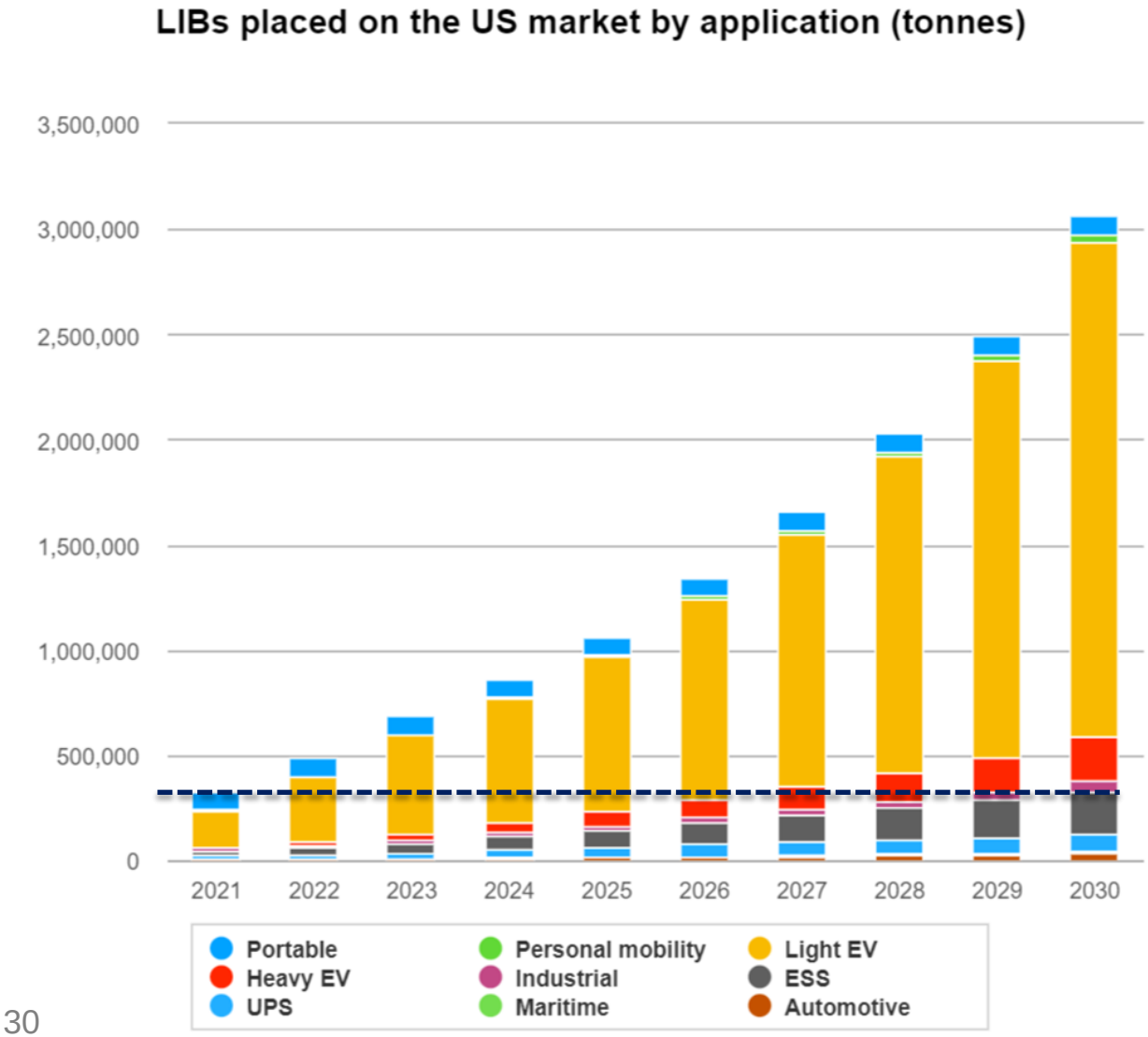
HOW MUCH RELIEF CAN RECYCLING PROVIDE?

EFFECT OF RAPID GROWTH PLUS LONG LIFE

All of the material from one lifetime ago is small fraction of current demand

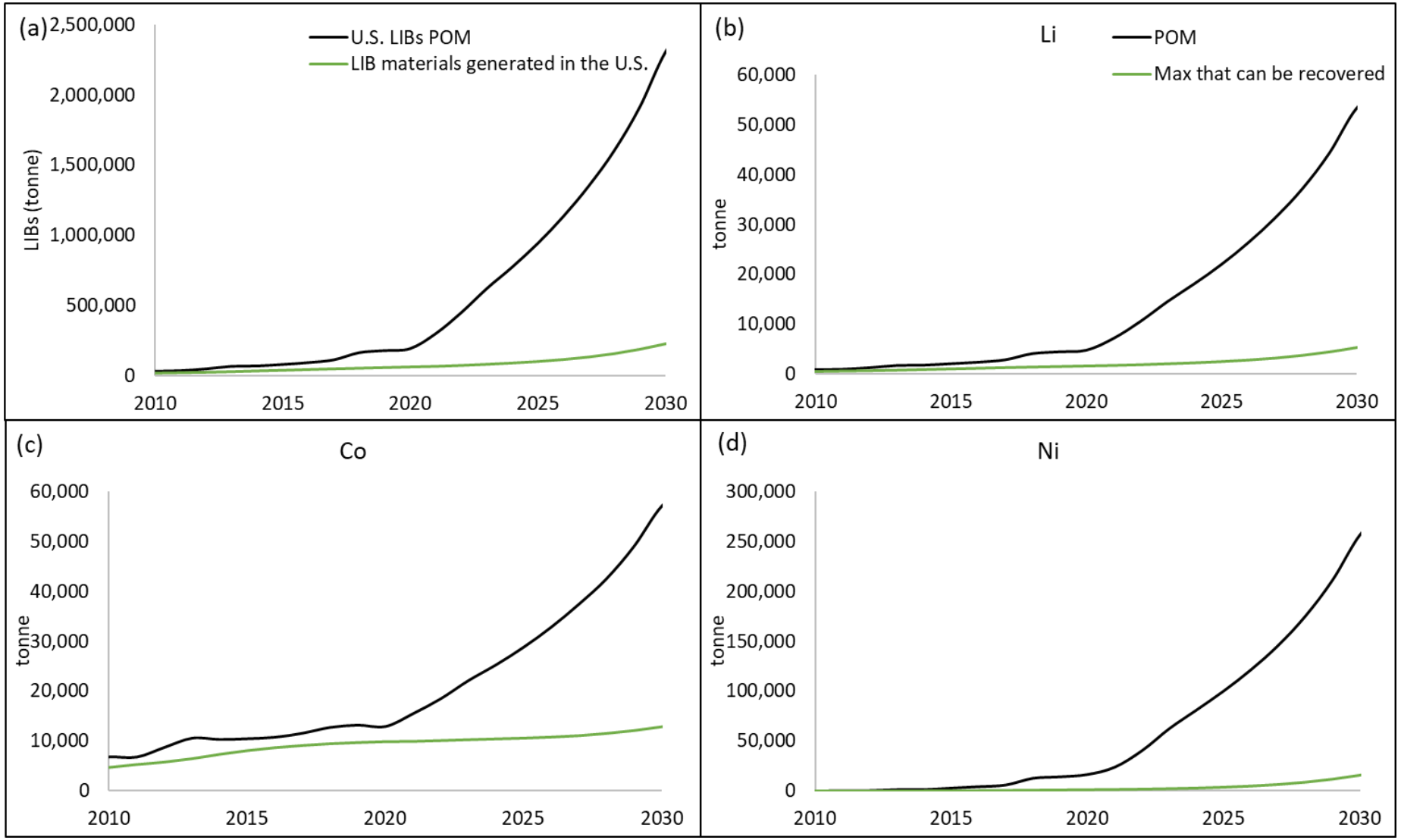
- 2030 demand = 3,064,247 T
- 2020 demand = 233,354 T
- Assume product life is 10 years
- Then 2020 material could supply **7.6%** of 2030 demand





RECYCLING COULD REDUCE DEMAND FOR MATERIALS

Recycling all generated could supply 10% of 2030 US demand, more later



WHAT IS THE RECYCLING RATE FOR LIBS?

Data available for 2019 from Circular Energy Storage (London)

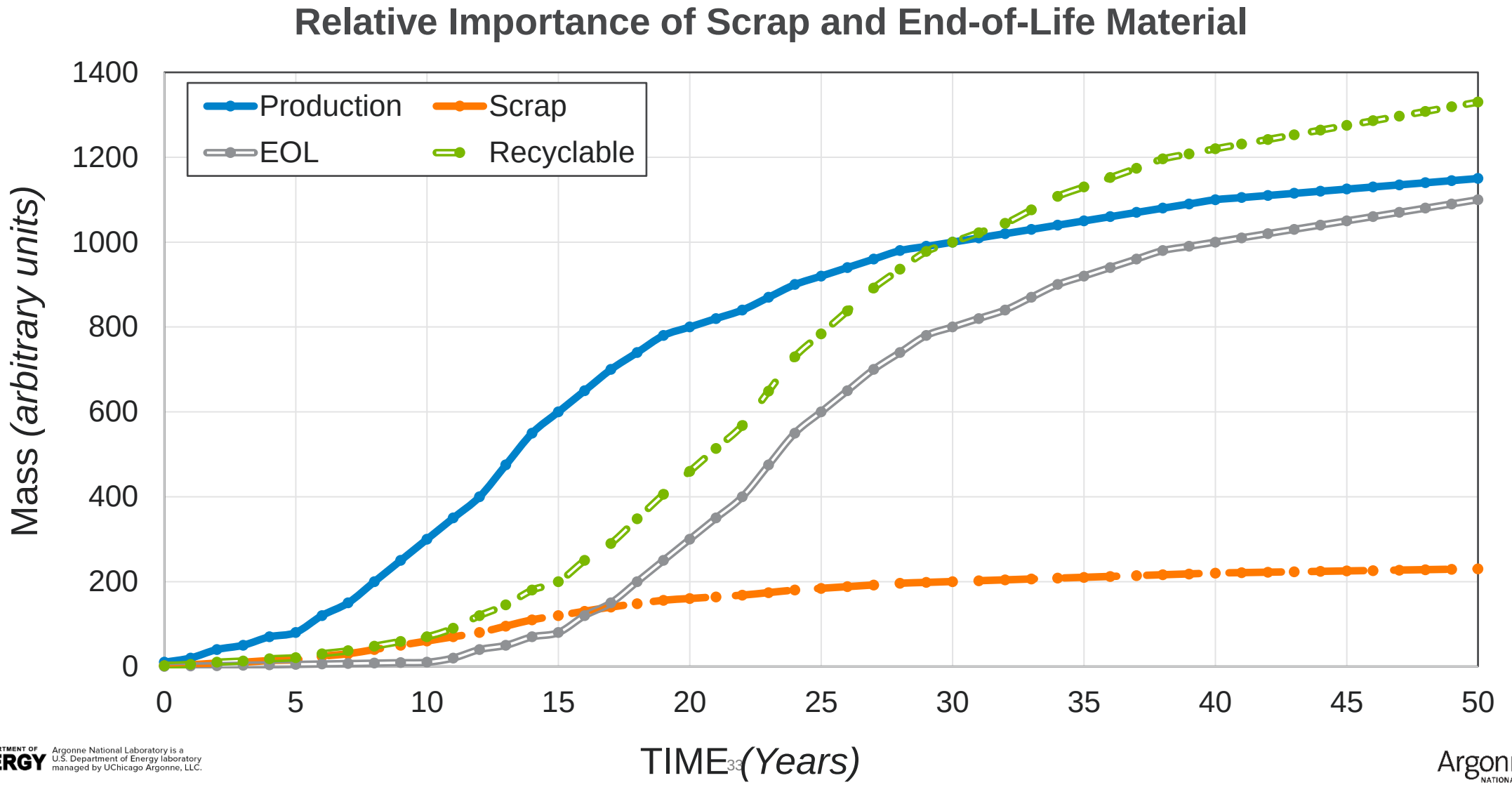
- Quantity generated based on lifetime distributions for batteries placed on market in US previously: 62 kT
- Quantity recycled in the US: 5.7 kT
  - Percent of generated that is recycled in US: 9.5%
- Quantity exported to China and recycled there: 27 kT
  - Percent of generated that is recycled in China: 44%
- **Total percent recycled of LIBs generated in US in 2019: 54%**
- Global generation: 332 kT
- Global recycled: 196 kT
- **Global percent recycled of LIBs generated in 2019: 59%**

CAVEAT! Material recycled is very hard to estimate

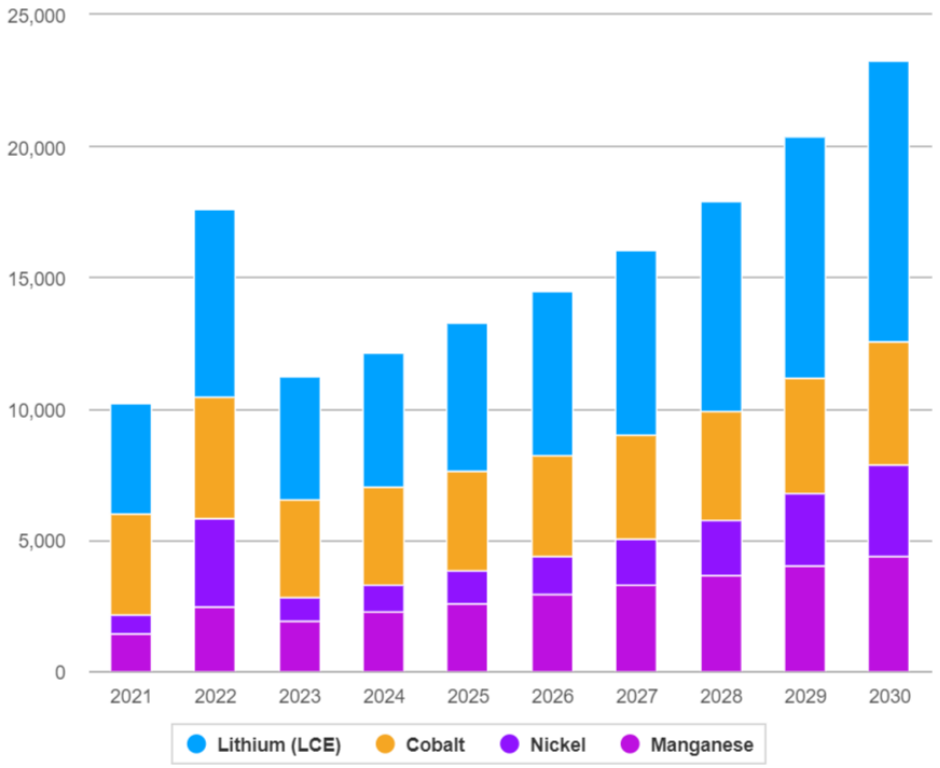
- Recycling capacity is known but not fully utilized
- Material intended for recycling may be stored or reused
- Multiple processing steps may cause miscounting
- Discards unknown

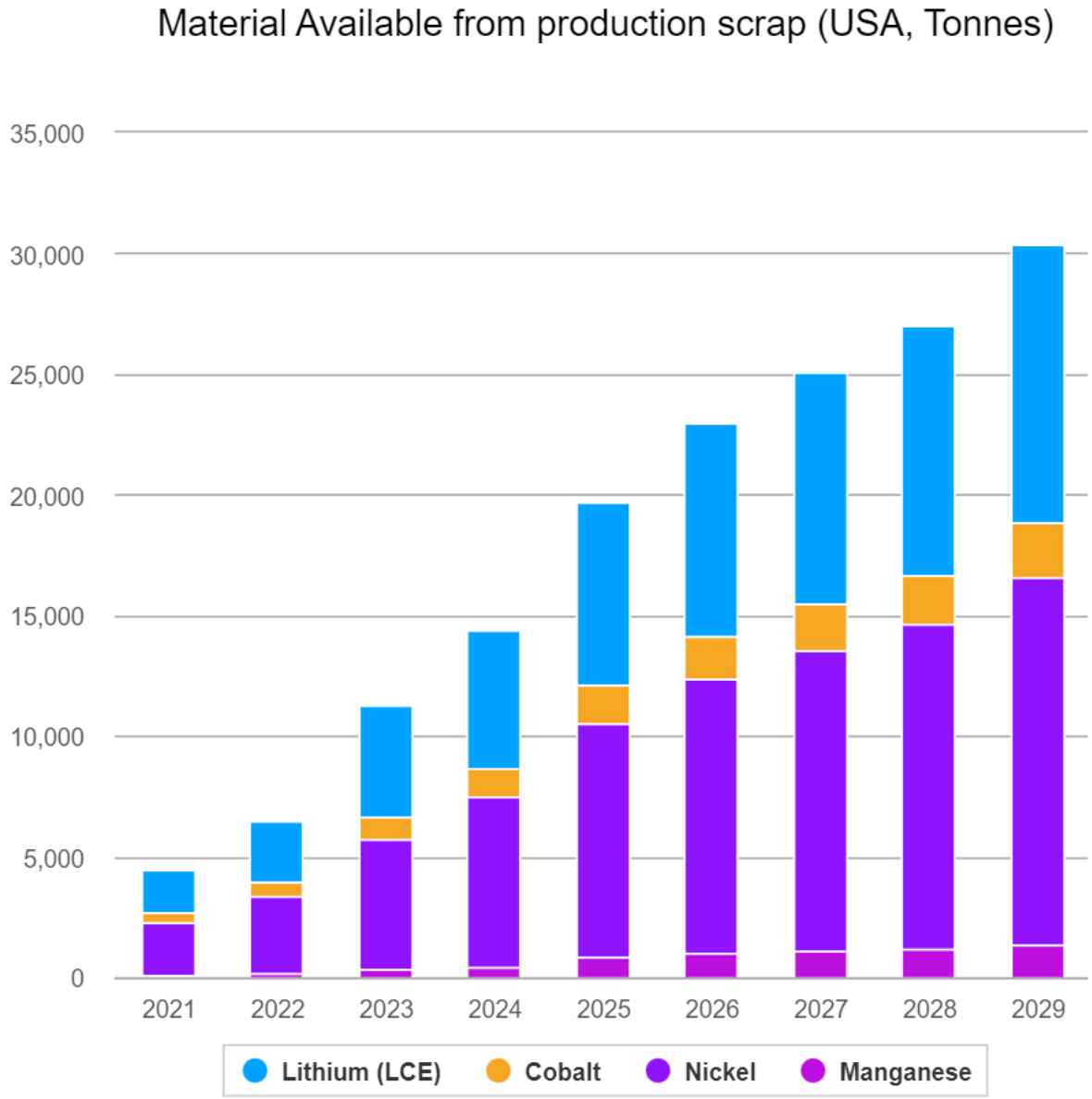
EOL MATERIAL MEETS DEMAND WHEN GROWTH STOPS

Scrap does not contribute to net material supply



MATERIAL AVAILABLE FROM EOL AND SCRAP IN US





WHY UPCYCLING MIGHT BE HARD

Upcycling could convert obsolete cathode to latest design

- Lithium ions flow during cell operation
  - Ions flow between crystal layers
  - Relithiation easily restores lost Li^+
- Upcycling seeks to add or substitute atoms in tightly bound crystal layer
  - Conversion of NMC111 to NMC622 adds 2 atoms for every 3
  - That requires significant bond disruption
- Upcycling enables use of excess obsolete cathode
  - But NMC111 may retain enough demand to absorb all the recovered material

RECYCLING IS IMPORTANT IN THE LONG TERM

- Many LIBs are already being recycled
  - Over 50% of batteries from North America get recycled
  - But much of the material is processed overseas
- US recycling capacity is coming online
  - Some plants will need to ship material overseas
- Scrap is an important feed for the growing recycling industry
- **Additional sources of material are still needed**

ALTERNATIVE MATERIALS

MIGHT OTHER PATHS BE MORE PROMISING?

Consider less scarce domestic materials (and more efficient batteries)

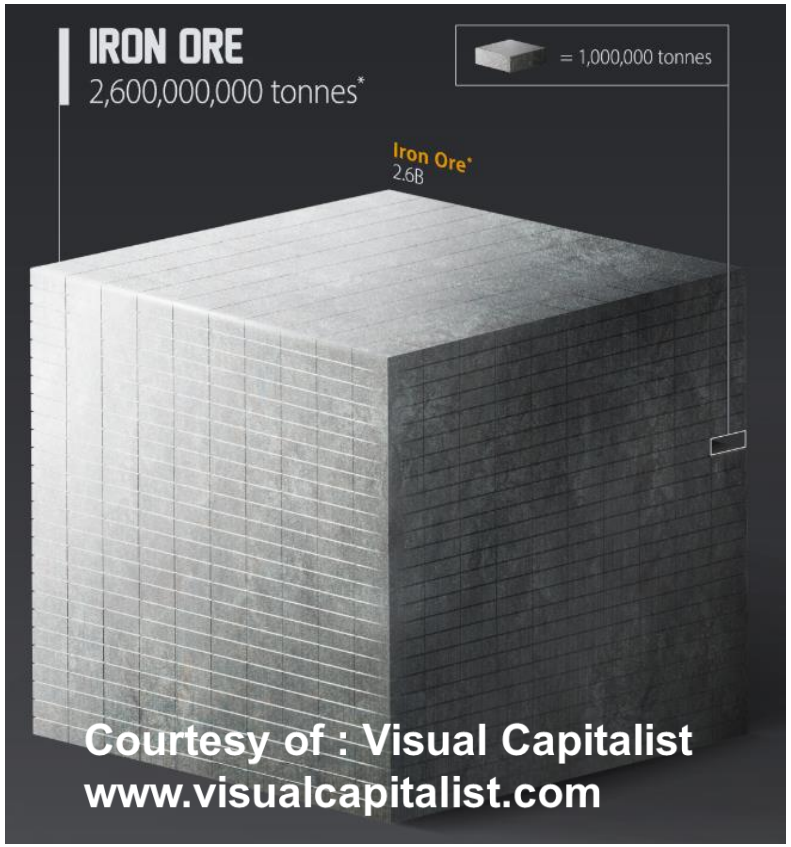
- Phosphorus and iron
- Manganese
- Sodium
- Sulfur
- Lithium metal
  - Solid electrolyte materials?
    - Zirconium
    - Yttrium
    - Indium
    - Lanthanum
- Copper
- Air!

Consider trying to leapfrog instead of playing catch-up.

PHOSPHORUS AND IRON ARE ABUNDANT IN US

US has a head start for producing lithium iron phosphate (LFP)

- LFP plants planned in St. Louis (ICL) and Quebec (First Phosphate)
- US has onshore:
  - Phosphate rock
  - Chemical grade phosphoric acid capacity
    - Might require expansion
  - Unlimited iron supply and refining capacity
  - Sufficient lithium for a few years
  - Resources for a complete domestic supply chain
- About 110 kg Fe and 70 kg P (including electrolyte salt) needed per car
  - Tighter constraint is P (~2 million T/y mined in US)
  - Enough for ~30 million cars annually



IRON SUPPLY WILL NOT BE AN ISSUE

Courtesy of : Visual Capitalist
www.visualcapitalist.com

MANGANESE IS ABUNDANT GLOBALLY

Several Mn-based cathodes are under consideration

- US reserves are poor
  - Ore containing 20% or more Mn not mined domestically since 1970.
  - Last USGS estimate 230 MT (enough for 34B 100 kWh batteries)
  - Too expensive to mine in US
- Ore and ferromanganese are imported from Gabon (67%), South Africa (19%), Mexico (12%)
  - Mn content ranges from 35-54% for Mn and from 74-95% for ferromanganese
  - Reserve 1.5 BT, resources larger

SODIUM SUPPLY IS NOT AN ISSUE

Sodium-ion batteries could relieve the lithium supply crunch

- US produces 42 million T/y salt (NaCl)
  - 94% from Kansas, Louisiana, Michigan, New York, Ohio, Texas, and Utah
  - 39% used by chemical industry
- Potential for extraction from seawater is practically unlimited

SULFUR IS A WASTE PRODUCT

From petroleum refining and copper smelting

- The incentive for recycling Li-S batteries could be low
  - Depends on Li price and whether any valuable structure can be recovered
- 2022 production 8 million T
  - 1.6 MT exported
  - 1.9 MT imported
- Main use is as sulfuric acid
  - Phosphoric acid is produced from phosphate rock and sulfuric acid
  - So S is needed for LFP as well as Li-S
- And don’t forget about Li-air!

ALTERNATIVE ANODES: LI METAL

Rapid expansion could enable US to be a long-term leader as market grows

- Additional Li metal capacity will be needed
- US is a player in this arena
- US does have Li reserves
  - Can supply our own needs, but cost uncertain
  - Geothermal brine coproduction lab call issued
- 100's of 1000's of tons may be needed, vs. current 5000 T (Li^0) market*
  - Larger demand if solid state batteries succeed
- Need better technology, on large scale
- **US has potential to get ahead of the curve on Li metal**
  - Can control our entire Li metal supply chain

	2020 BG Li Metal Capacity	2050 BG Li Metal Demand
US	**0.55**	**--**
World	**2.5**	**1,000**

Units: 1000 metric tons

* Half of Li metal is battery grade

ALTERNATIVE WAYS TO SUPPLY TRANSPORT

WHATEVER PATH WE TAKE, USING LESS EASES THE WAY

Technology options can enable sufficient range with less material

- Plug-in hybrid vehicles (smaller battery)
  - Range-extended EV is less complex than dual propulsion system PHEV
  - Supplementary fuel can be biofuel
- In-road charging
- *Battery swapping*
- Modular or hybrid battery design for flexibility
  - Easily available add-ons or vehicle rentals
- Car or ride sharing
- Mass transit with last-mile options

WRAP-UP

WAYS TO MINIMIZE IMPORTED MATERIAL DEMAND AND POTENTIAL DISRUPTIONS

While maintaining a high standard of living

- Change systems for supplying needed mobility services
- Reduce material required for product manufacture
- Use domestic materials and process locally
- Use more abundant materials
- Extend product lifetimes
- Reuse/recycle products and their constituent materials

Thank you!

Jingyi Zhang
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