LITHIUM-ION BATTERY MATERIAL CONSIDERATIONS

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GREEN DRIVES
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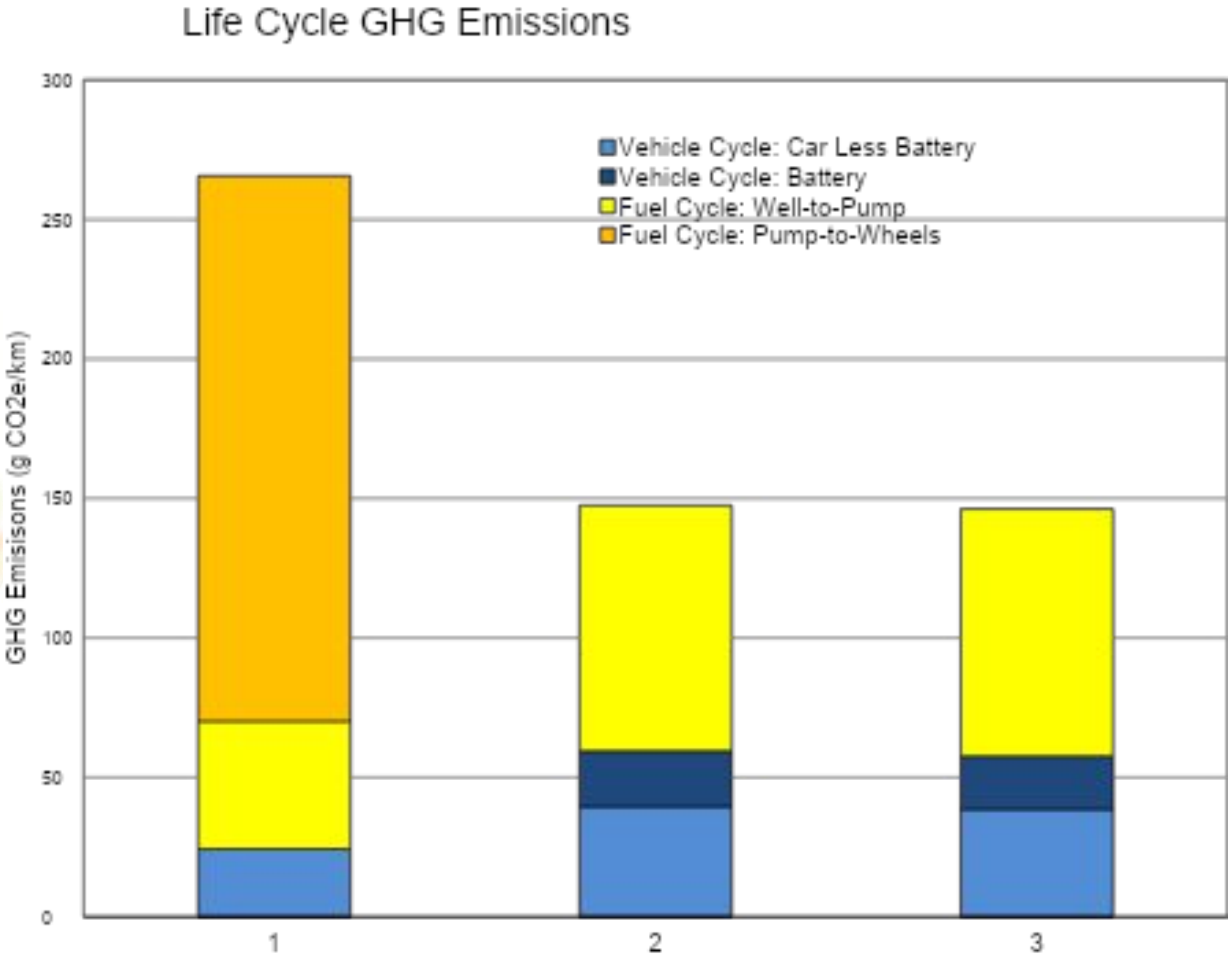
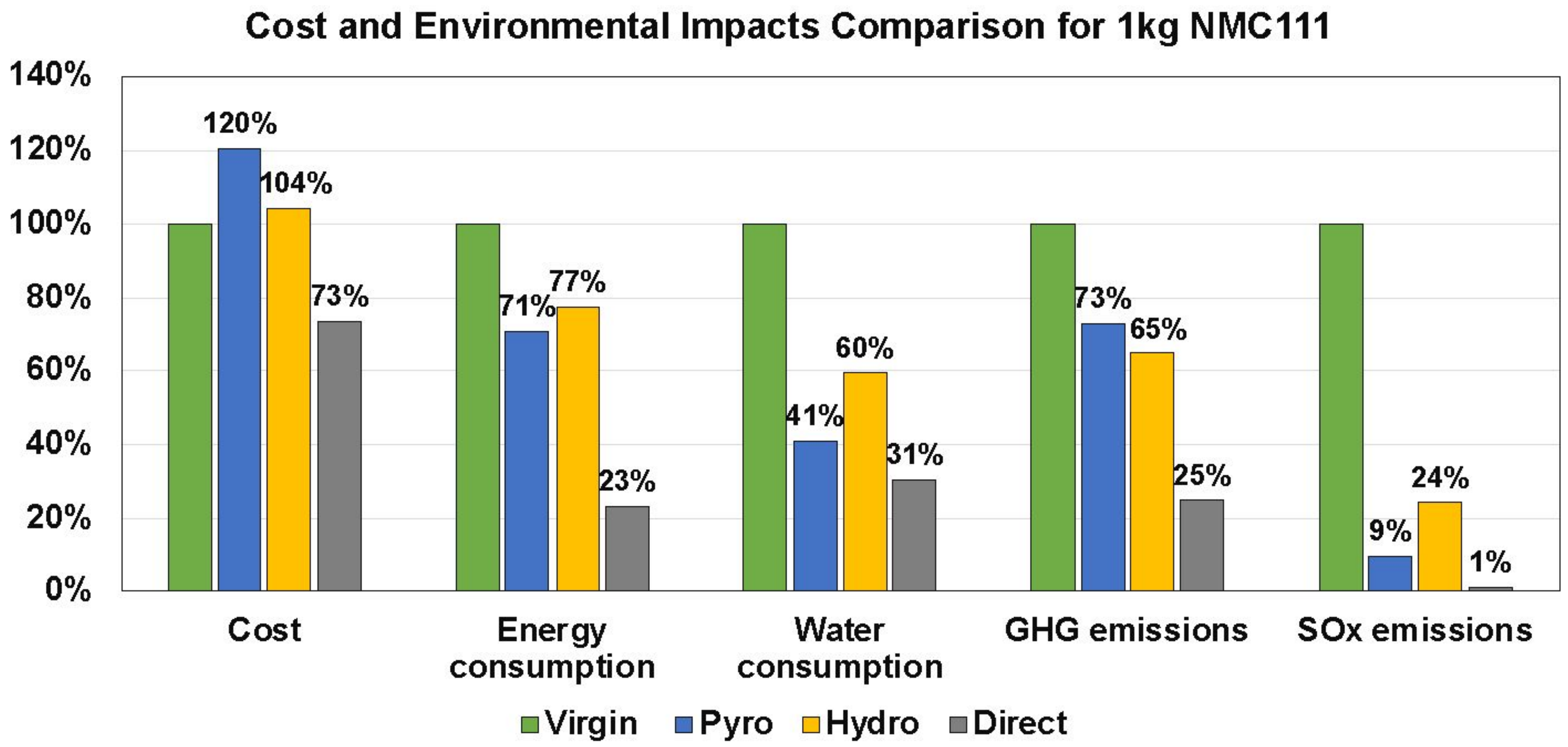
EV USE REDUCES LIFETIME GHG EMISSIONS

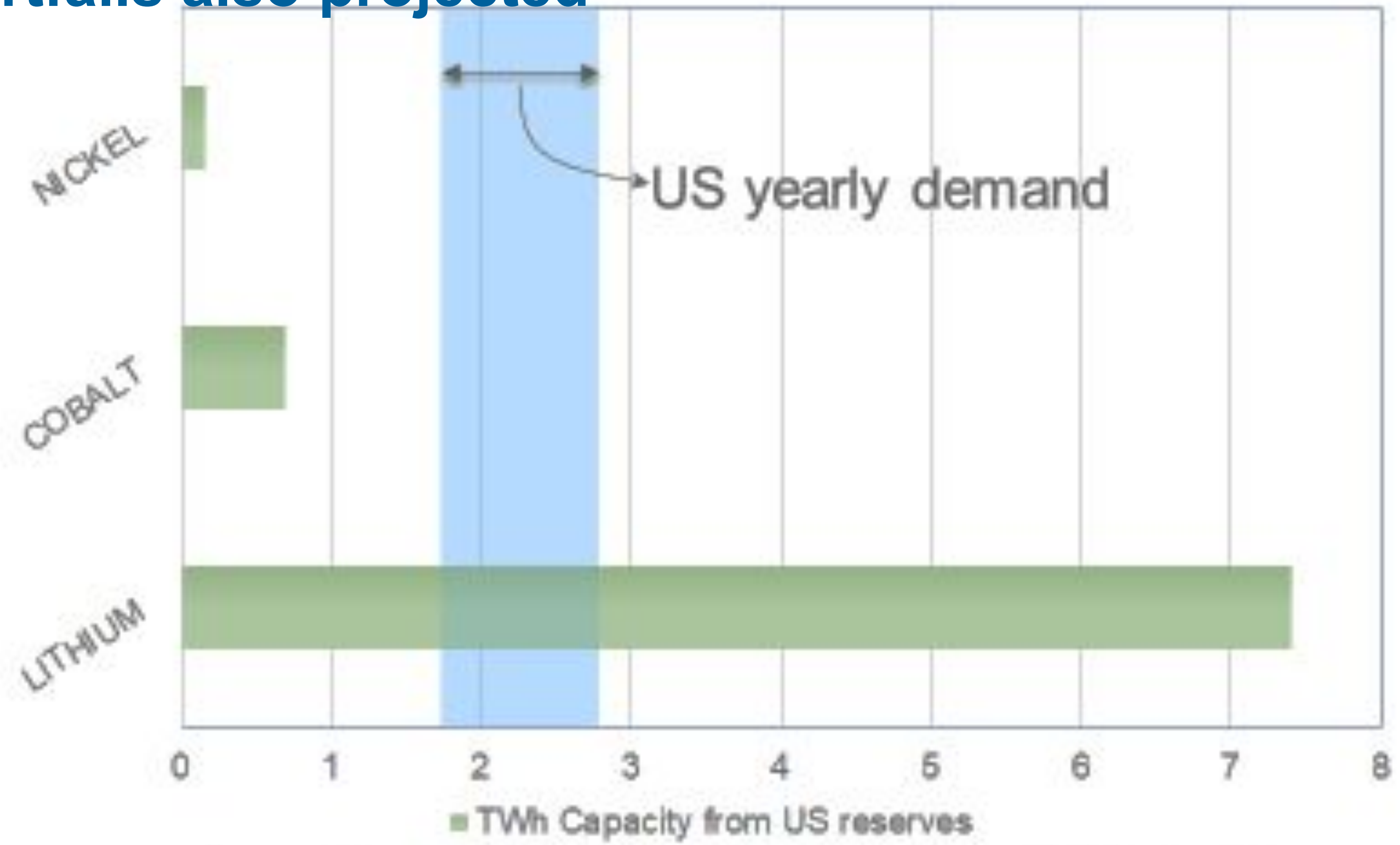


RECYCLING REDUCES BATTERY IMPACTS



US RESERVES ARE INSUFFICIENT

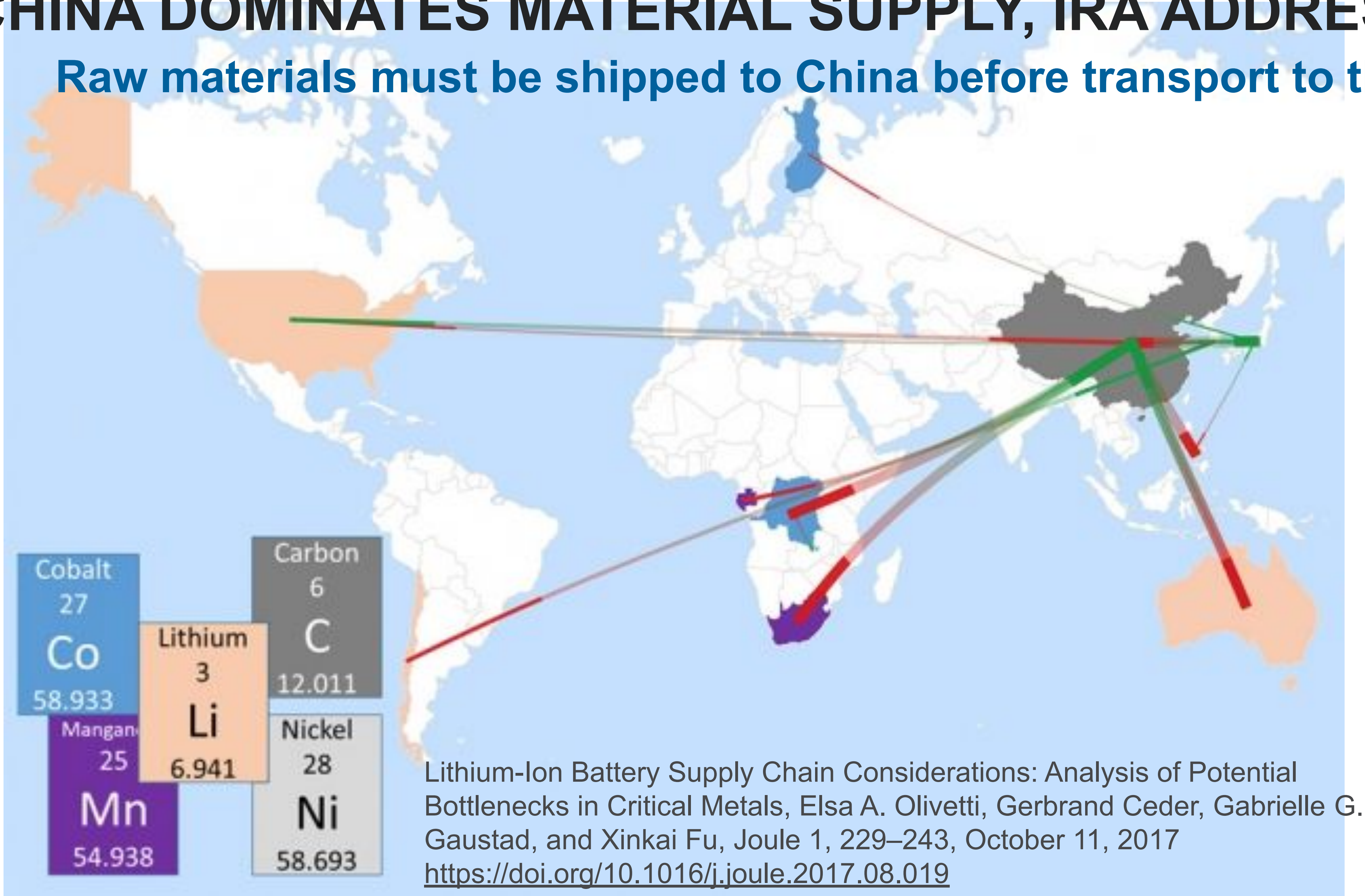
Global shortfalls also projected



Source: Argonne National Laboratory derived from USGS mineral commodities summaries (2021) and simulations using BatPaC 4.0 for Li-ion batteries with $LiNi_{0.4}Mn_{0.1}Co_{0.1}O_2$ cathode.

CHINA DOMINATES MATERIAL SUPPLY, IRA ADDRESSING

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

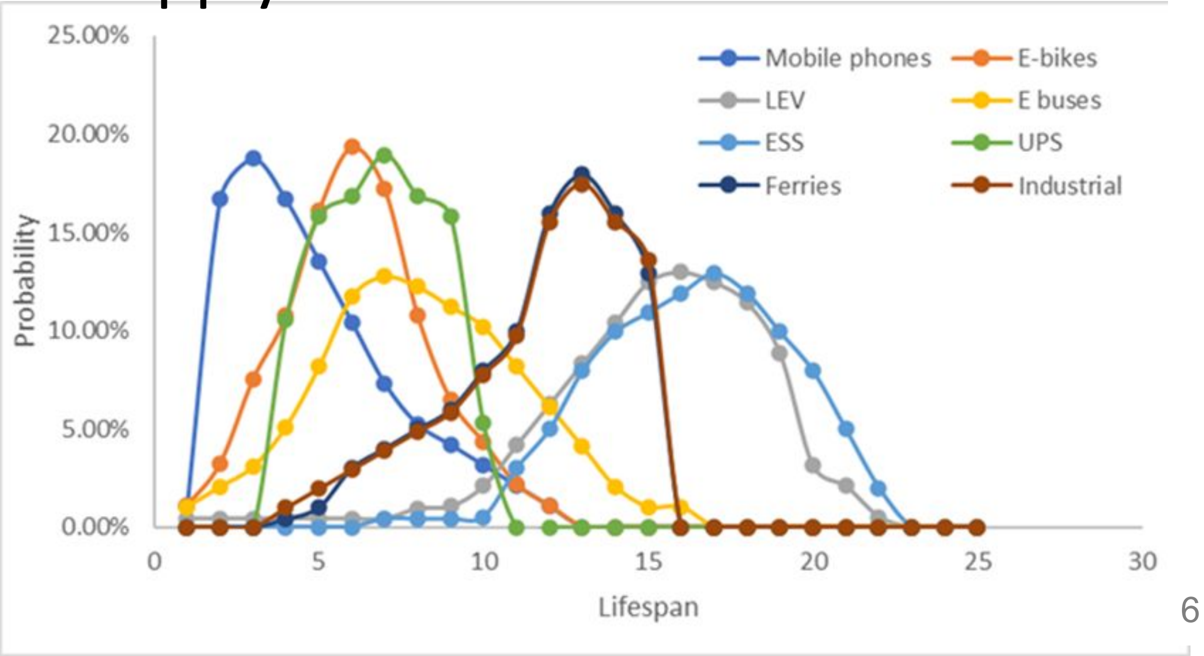


Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Elsa A. Olivetti, Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu, Joule 1, 229–243, October 11, 2017
https://doi.org/10.1016/j.joule.2017.08.019

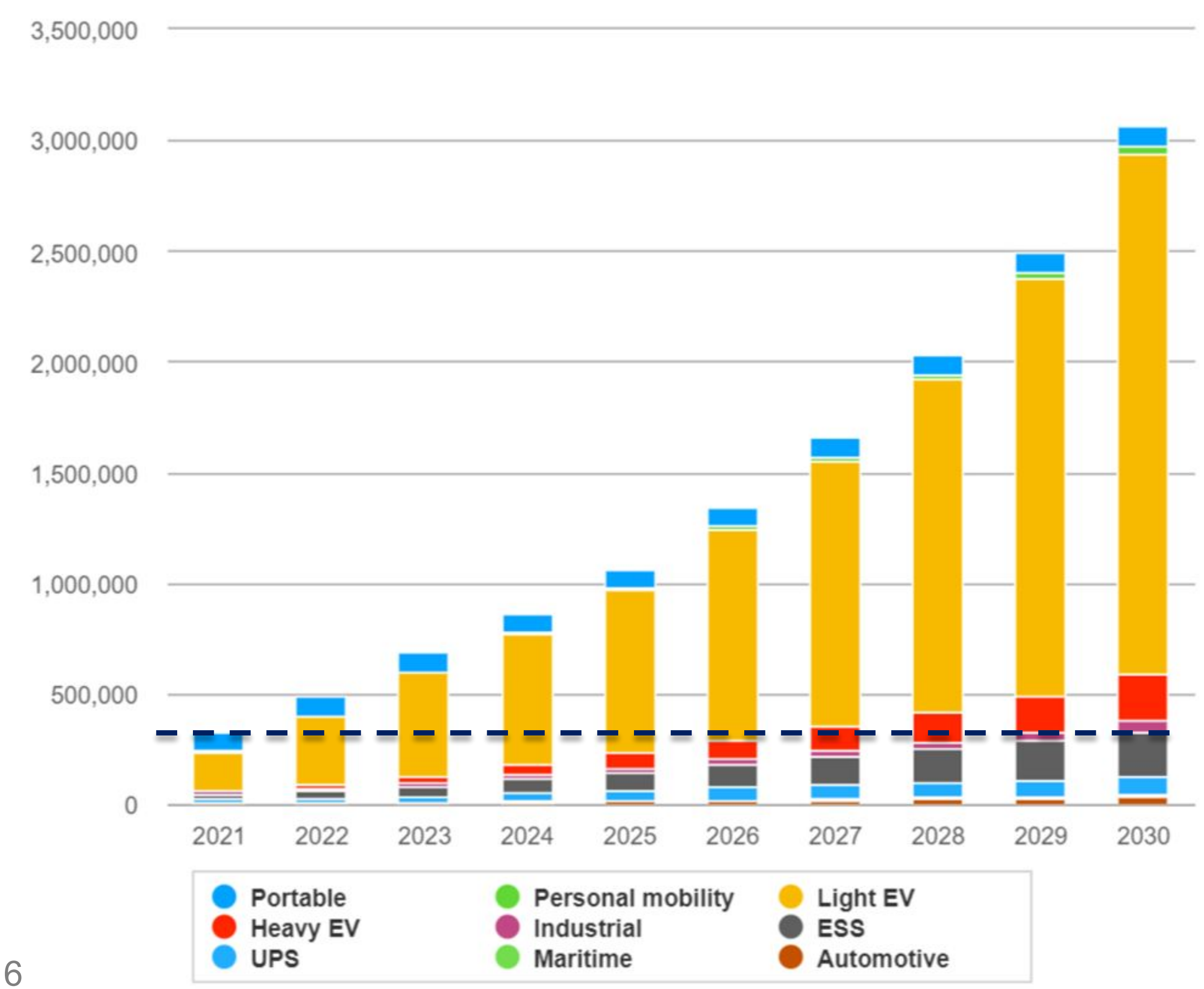
RAPID GROWTH PLUS LONG LIFE LIMIT SUPPLY FROM RECYCLING

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

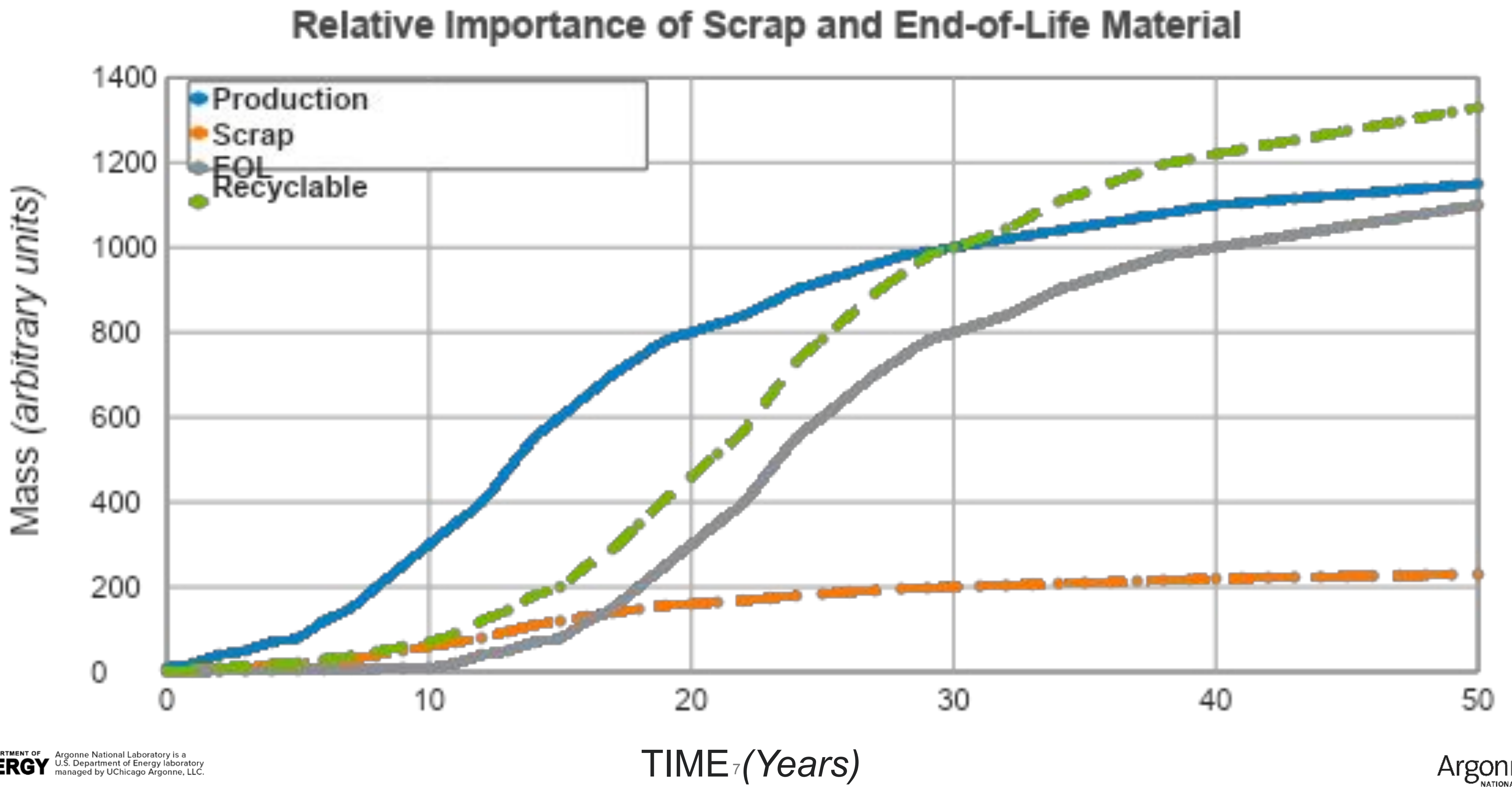


LIBs placed on the US market by application (tonnes)



EOL MATERIAL MEETS DEMAND WHEN GROWTH STOPS

Recovered material lags during growth period



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%**

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

- Global generation: 332 kT
- Global recycled: 196 kT
- **Global percent recycled of LIBs generated in 2019: 59%**

MIGHT OTHER PATHS BE MORE PROMISING?

Consider less scarce domestic materials (and more efficient batteries)

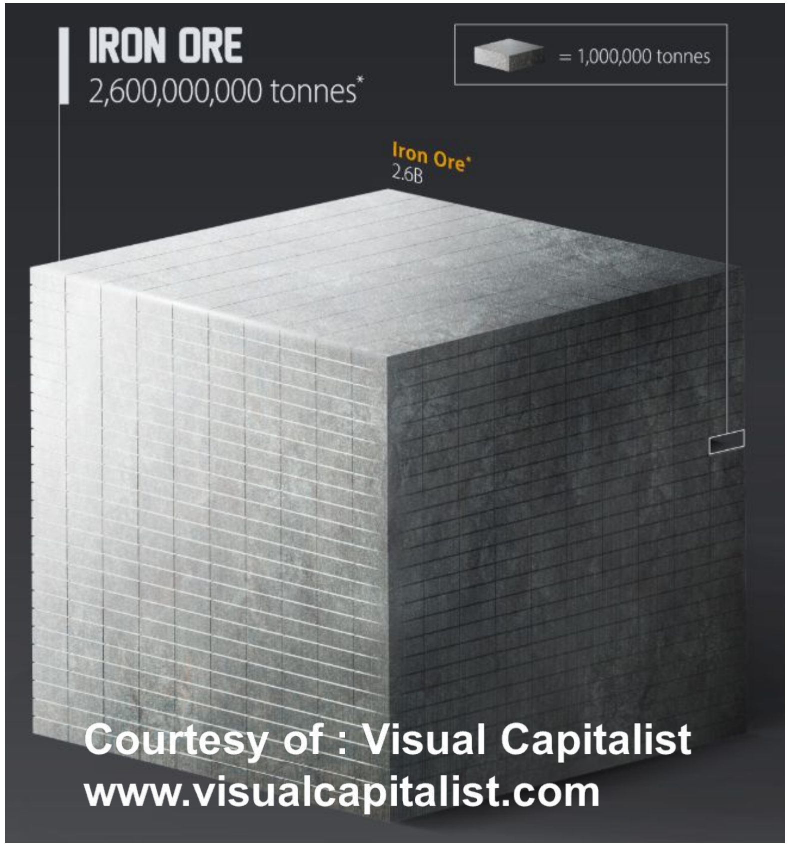
- Phosphorus and iron
- Manganese
- Sodium
- Sulfur
- Silicon
- Lithium metal
  - Solid electrolyte materials?
    - Zirconium
    - Yttrium
    - Indium
    - Lanthanum
- Air!

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



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!

SILICON IS 2ND MOST ABUNDANT ELEMENT

- Si anode could enable smaller batteries
  - Small quantities mixed in now
  - More would enable aviation
- Cracking problem may be solved

WHAT WOULD BE NEEDED FOR SOLID-STATE BATTERIES?

Anode and electrolyte are different

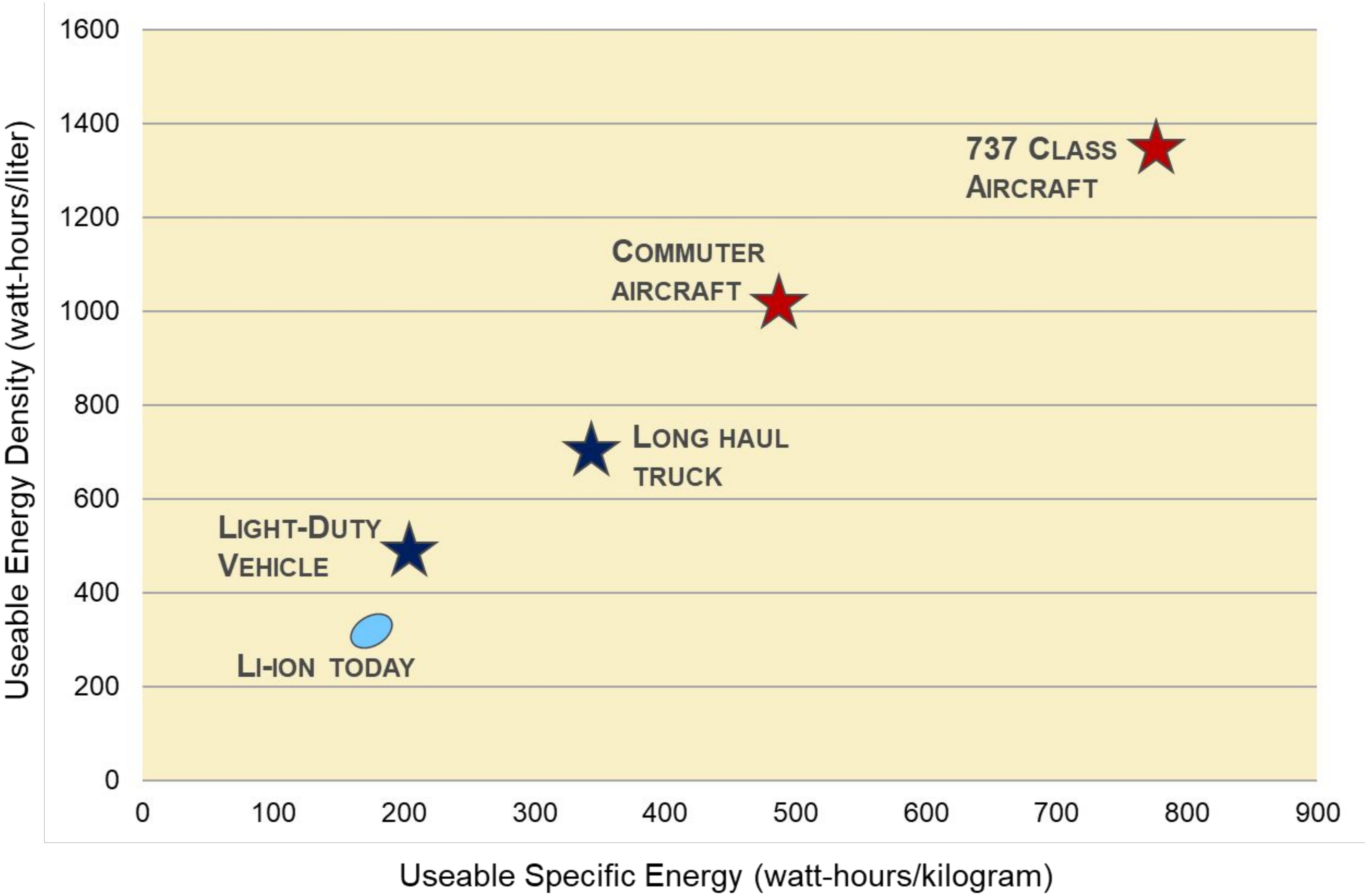
- Lithium metal needed for the anode
  - US is a player in this arena
  - US does have Li reserves
- SSB expert identifies 3 major contenders for solid electrolyte
  - Li argyrodites (Li_6PS_5Cl, Li_6PS_5Br)
  - Li garnets ($Li_7La_3Zr_2O_{12}$ with either Ta, Al, or Ga dopants)
    - Dopants only needed in trace quantities
  - Li halides (Li_3YCl_6, Li_3AlF_6, Li_3InCl_6, etc.)
    - Halide elements not scarce
- *Would recycling be difficult?*

Elements to look at:
Zirconium
Indium
Yttrium
Lanthanum

ENERGY STORAGE FOR HEAVY-DUTY TRANSPORTATION REQUIRES NEW CHEMISTRIES

Potential alternatives to Li-ion batteries?

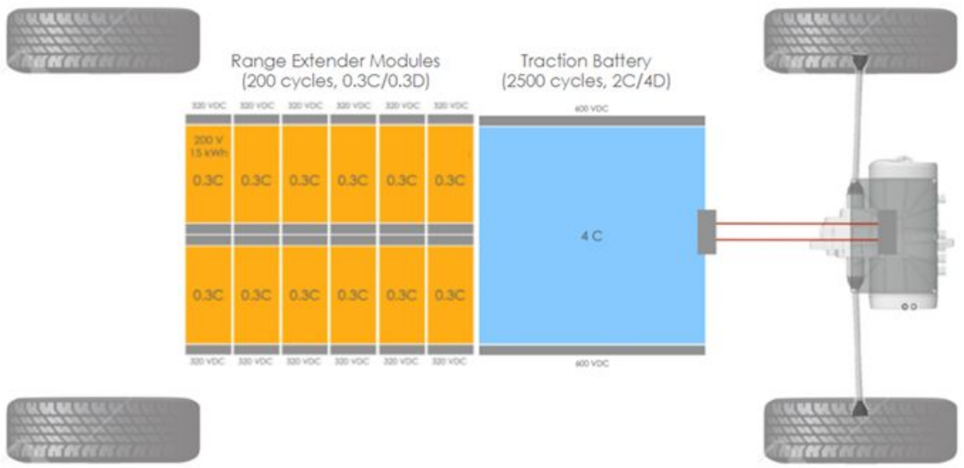
- Solid-state batteries
- High-energy cathodes
- Liquid fuels



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



CONCLUSIONS

- EV use reduces transport impacts
- Recycling will be important in the long term
  - Over 50% of batteries from North America get recycled
  - But much of the material is processed overseas
- Scrap is an important feed for the growing recycling industry
- Additional sources of material are still needed
- Alternate materials and more efficient use could ease supply issues

Thank you!

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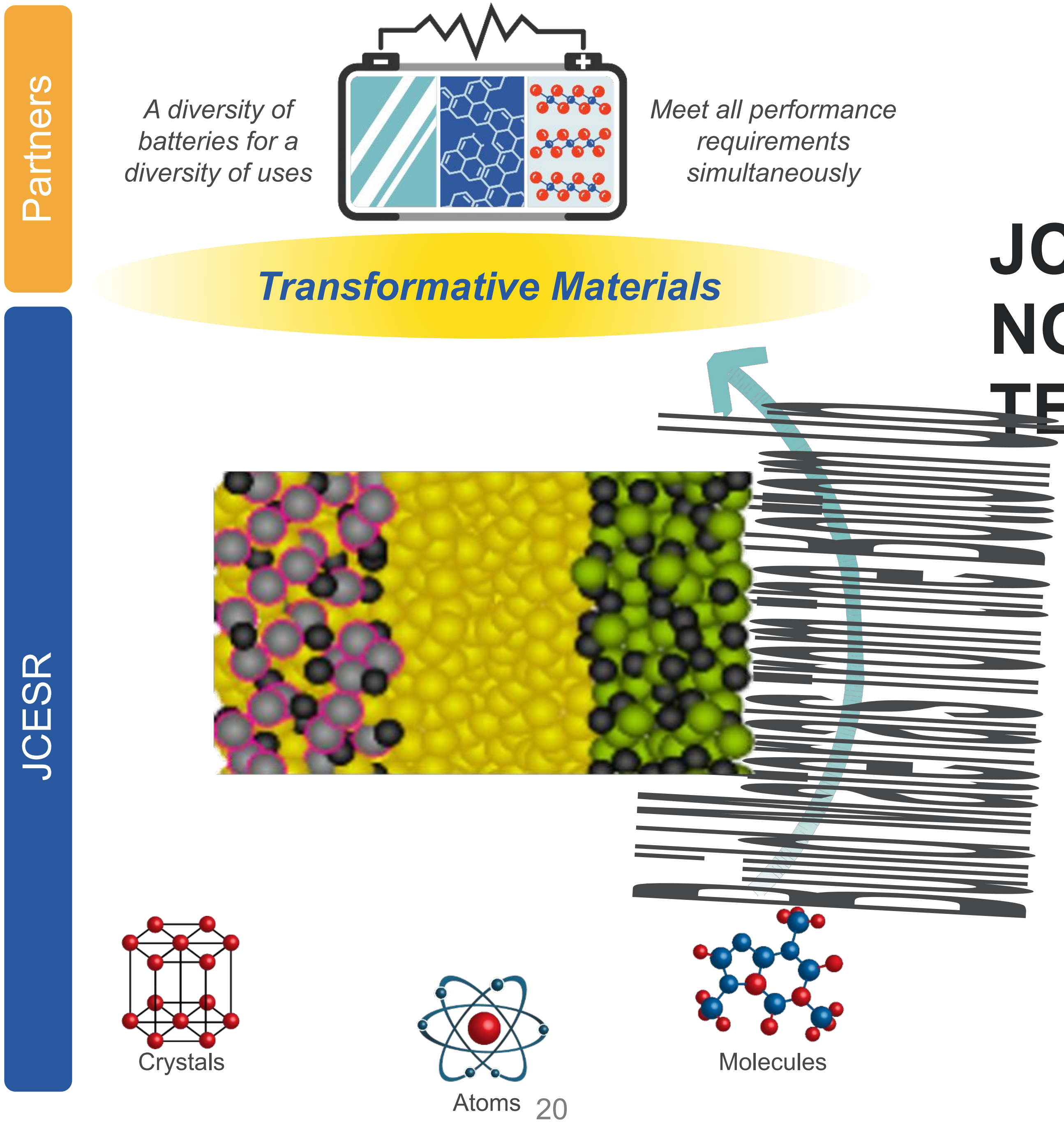
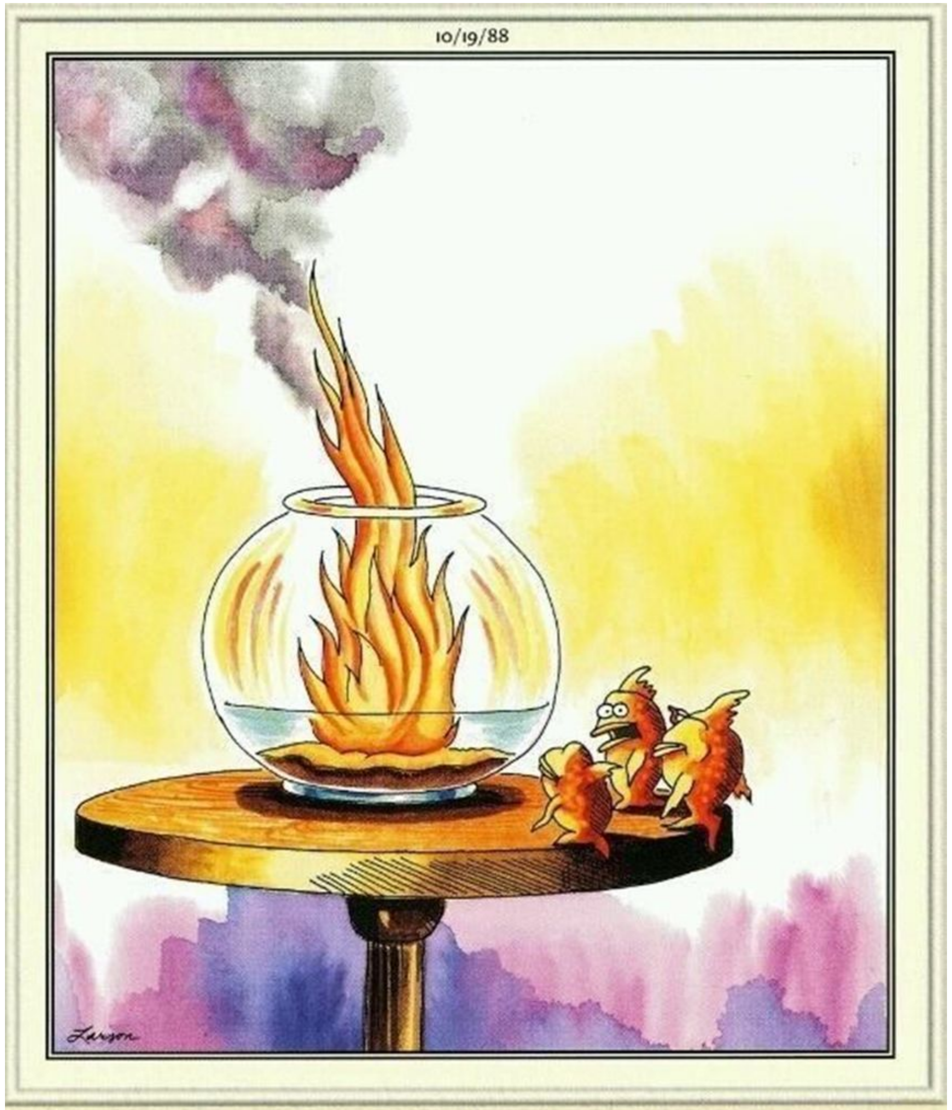
JCESR SEEKS NOVEL TECHNOLOGY



GOALS WERE TO REDUCE CO_2 AND ELIMINATE OIL IMPORTS

But we are again (still?) reliant on imports

- The focus has been on materials that have now become critical
  - Cobalt
  - Nickel
  - Lithium
  - Graphite



"Well, thank God we all made it out in time. ... 'Course, now we're equally screwed."