Union of Concerned Scientists

Reuse and Recycling of Lithium-ion Batteries for Motor Vehicles

Background Information
for the California
Lithium-ion Battery
Recycling Advisory Group

Dr. Hanjiro Ambrose – Jan 27th, 2020

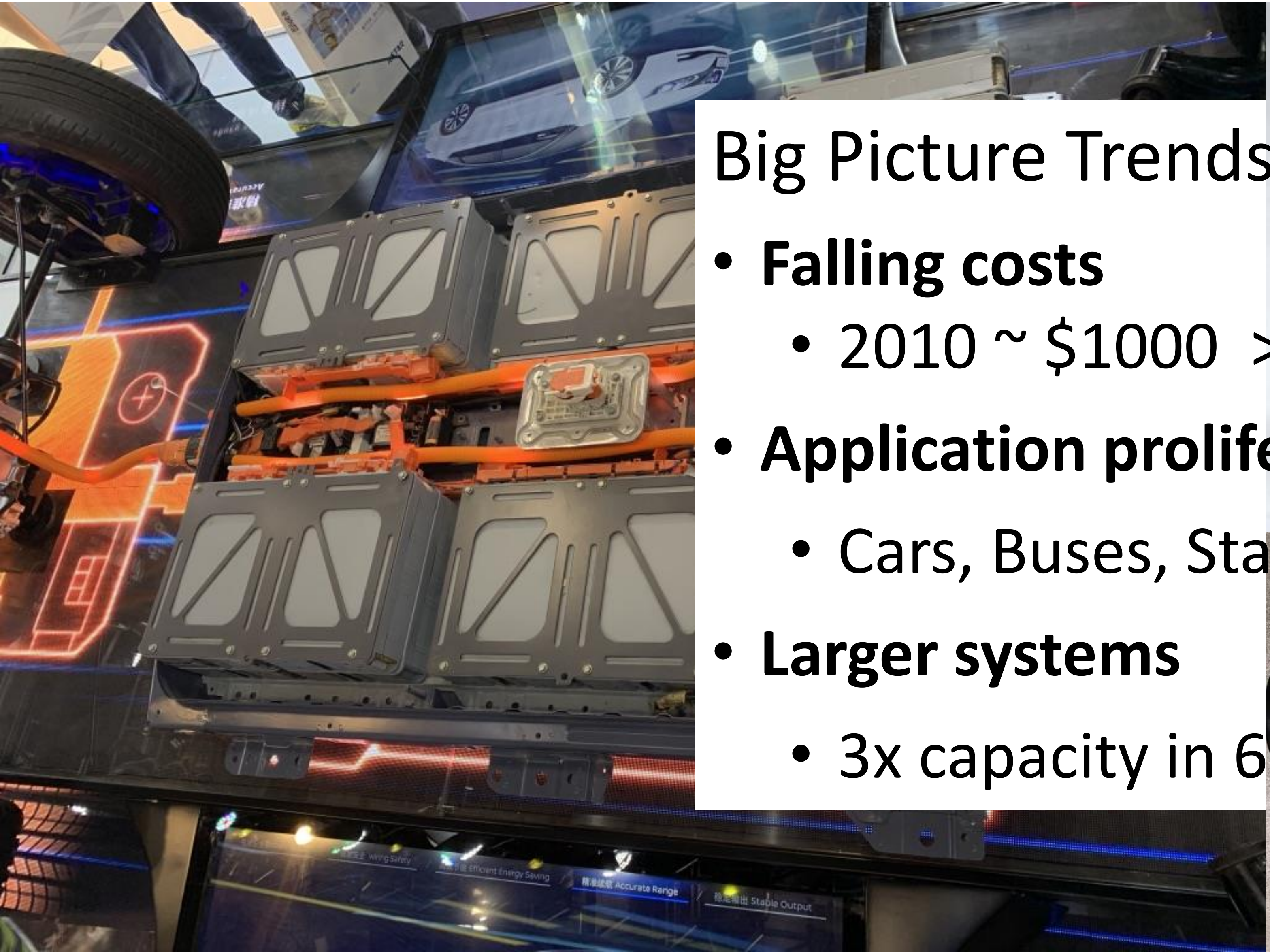
Outline

1. **Technology**: Chemistry, lifetime, and deployment
2. **Materials**: Composition, resources, supply
3. **Recycling**: Material recovery, design, logistics
4. **Reuse**: Testing, repurposing, second-life applications
5. **Conclusions**

Key Points

- Large scale retirements of electric vehicle (EV) batteries will begin to occur within the next 5 to 10 years (~3.5 to 30 GWh of battery retirements)
- Logistics, infrastructure, and knowledge sharing are key barriers for end-of-life (EOL) management
- Global value chains for electronic wastes, battery materials, and used vehicles pose further jurisdictional and equity challenges
- Mineral resources unlikely to limit battery manufacturing over the medium term, but recycling is critical in the long term
- Low-value of recovered materials could be a barrier to capital/investment required to ramp recycling infrastructure
- Battery reuse is promising, but there are policy, technical and market barriers

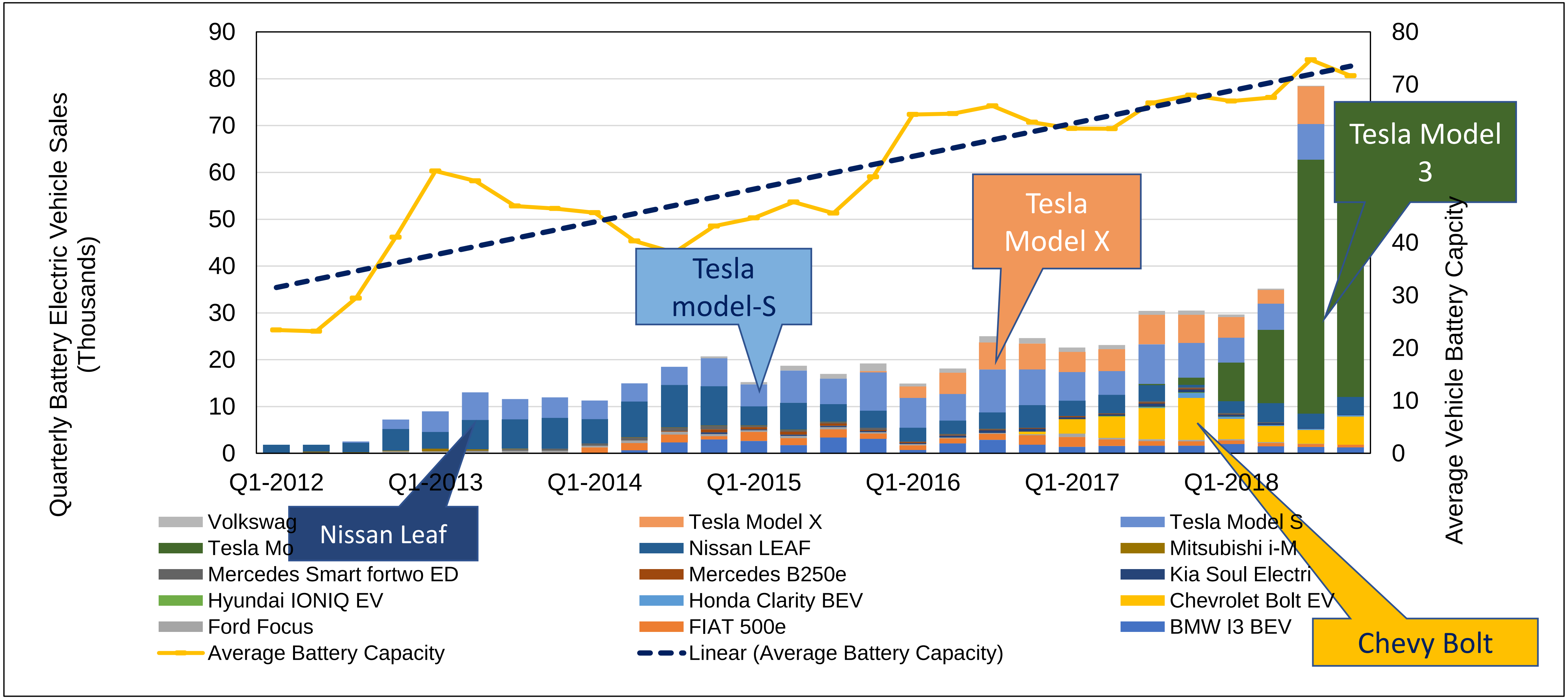
Lithium Ion Batteries (LIBs)



Big Picture Trends:

- **Falling costs**
  - 2010 ~ $1000 >>> 2020 ~$150
- **Application proliferation**
  - Cars, Buses, Stationary, Trucks, Scooters
- **Larger systems**
  - 3x capacity in 6 years

Deployment Trends



Tesla model-S

Tesla Model X

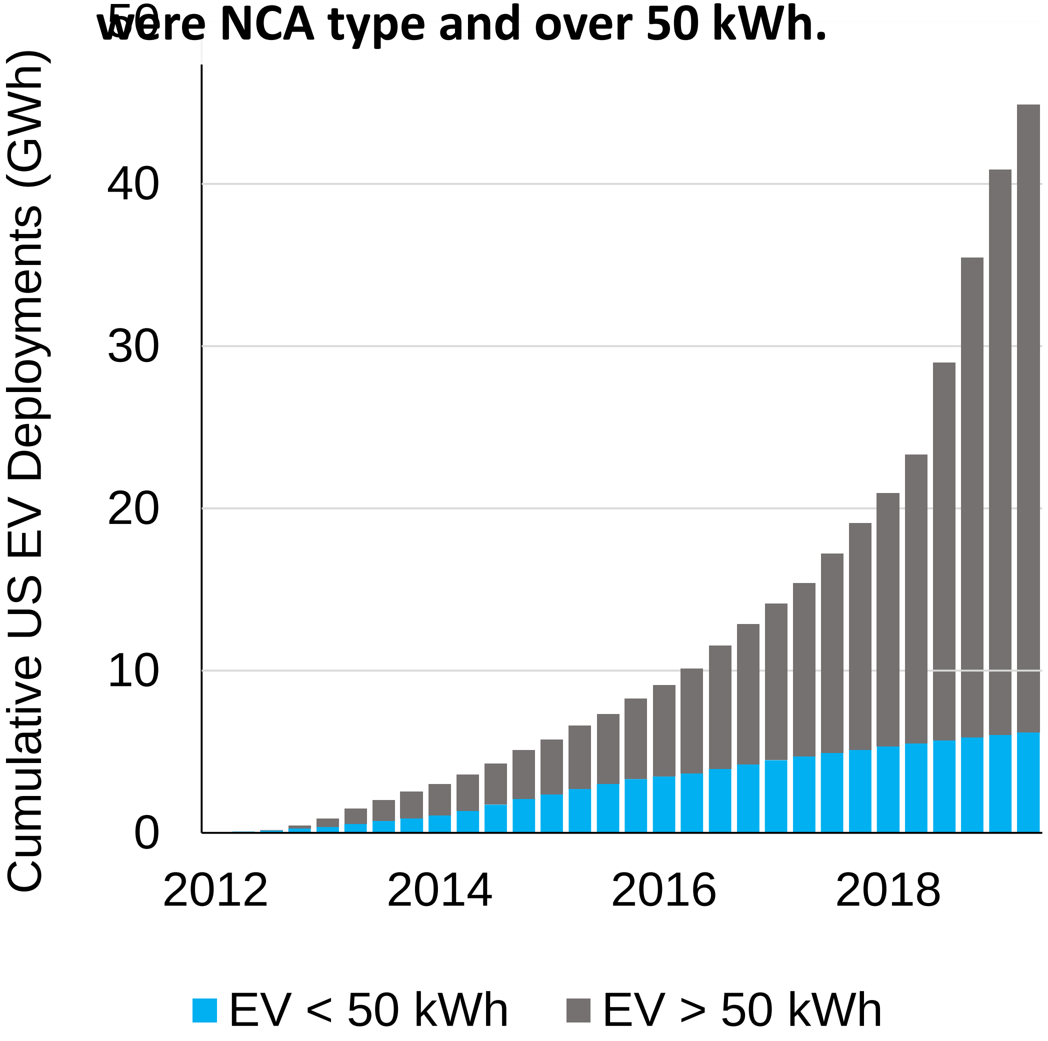
Tesla Model 3

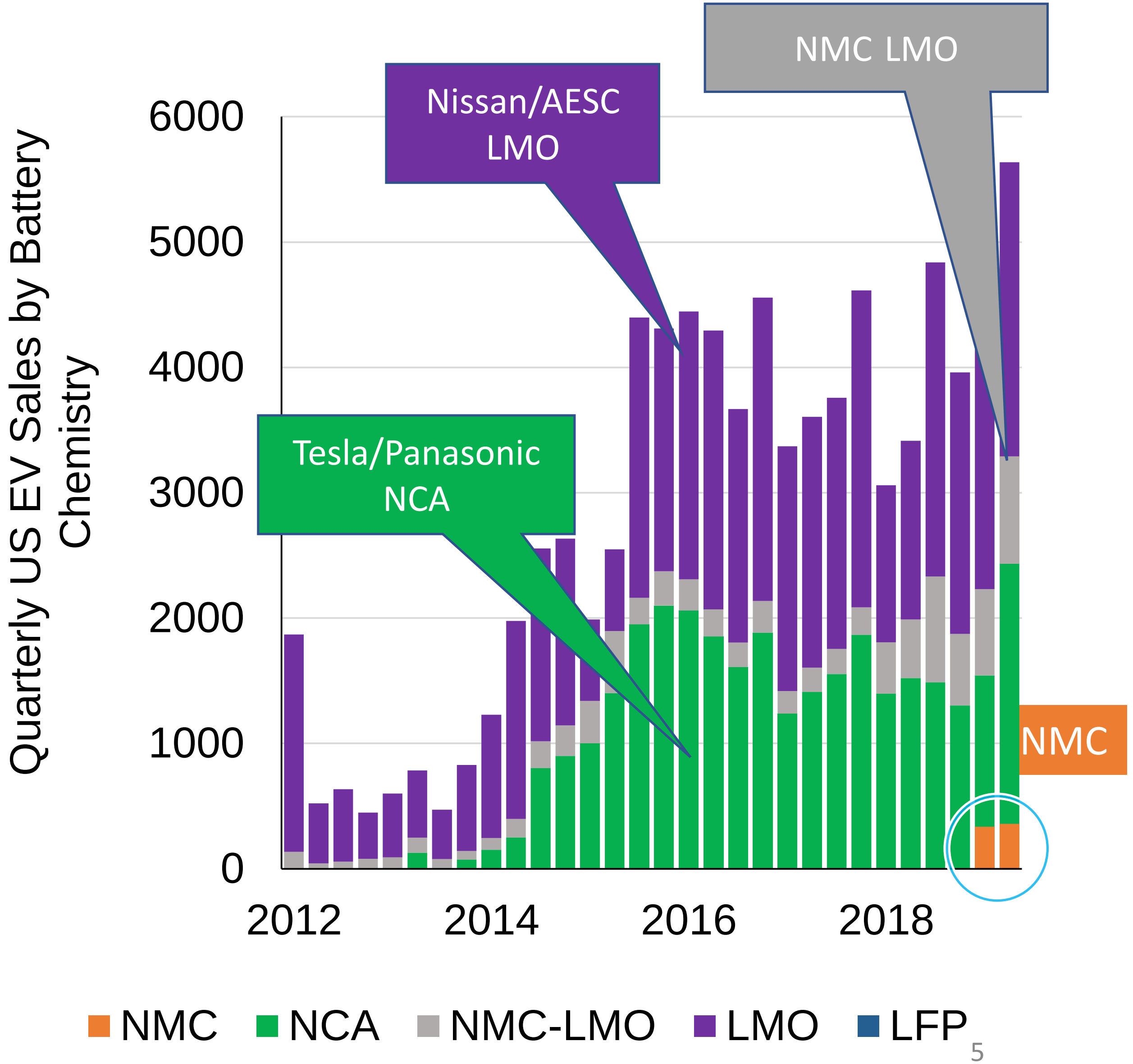
Nissan Leaf

Chevy Bolt

Deployment Trends

In 2019, ~90% of EV batteries deployed were NCA type and over 50 kWh.



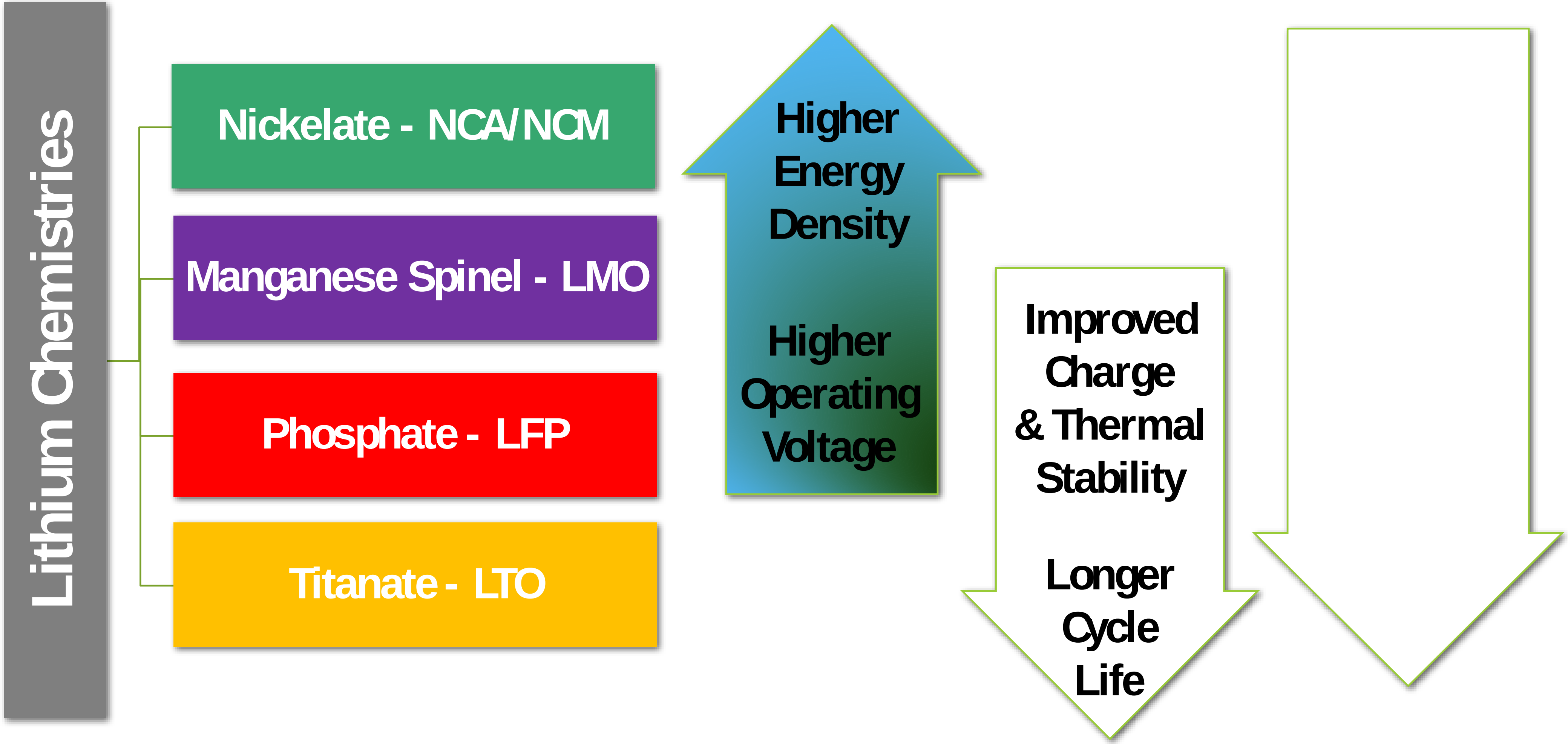

Nissan/AESC LMO

NMC LMO

Tesla/Panasonic NCA

NMC

Cathode Chemistry



Lithium Chemistries

Nickelate - NCA/NCM

Manganese Spinel - LMO

Phosphate - LFP

Titanate - LTO

Higher Energy Density

Higher Operating Voltage

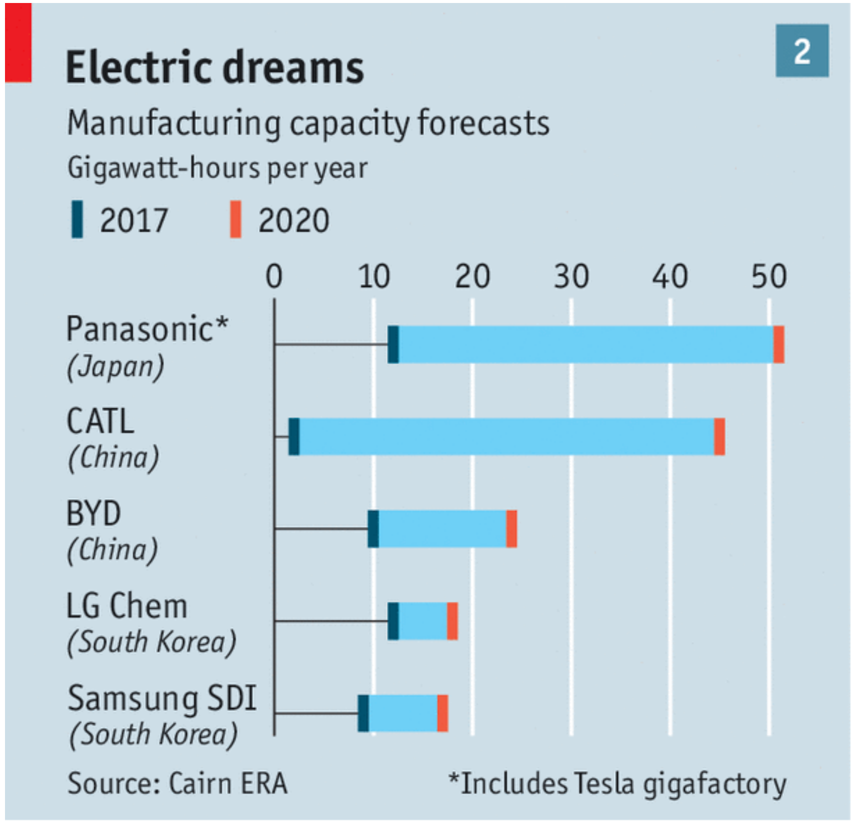
Improved Charge & Thermal Stability

Longer Cycle Life

Source: H. Ambrose, A. Kendall, Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility. Transportation Research Part D: Transport and Environment 47, 182 194 (2016).

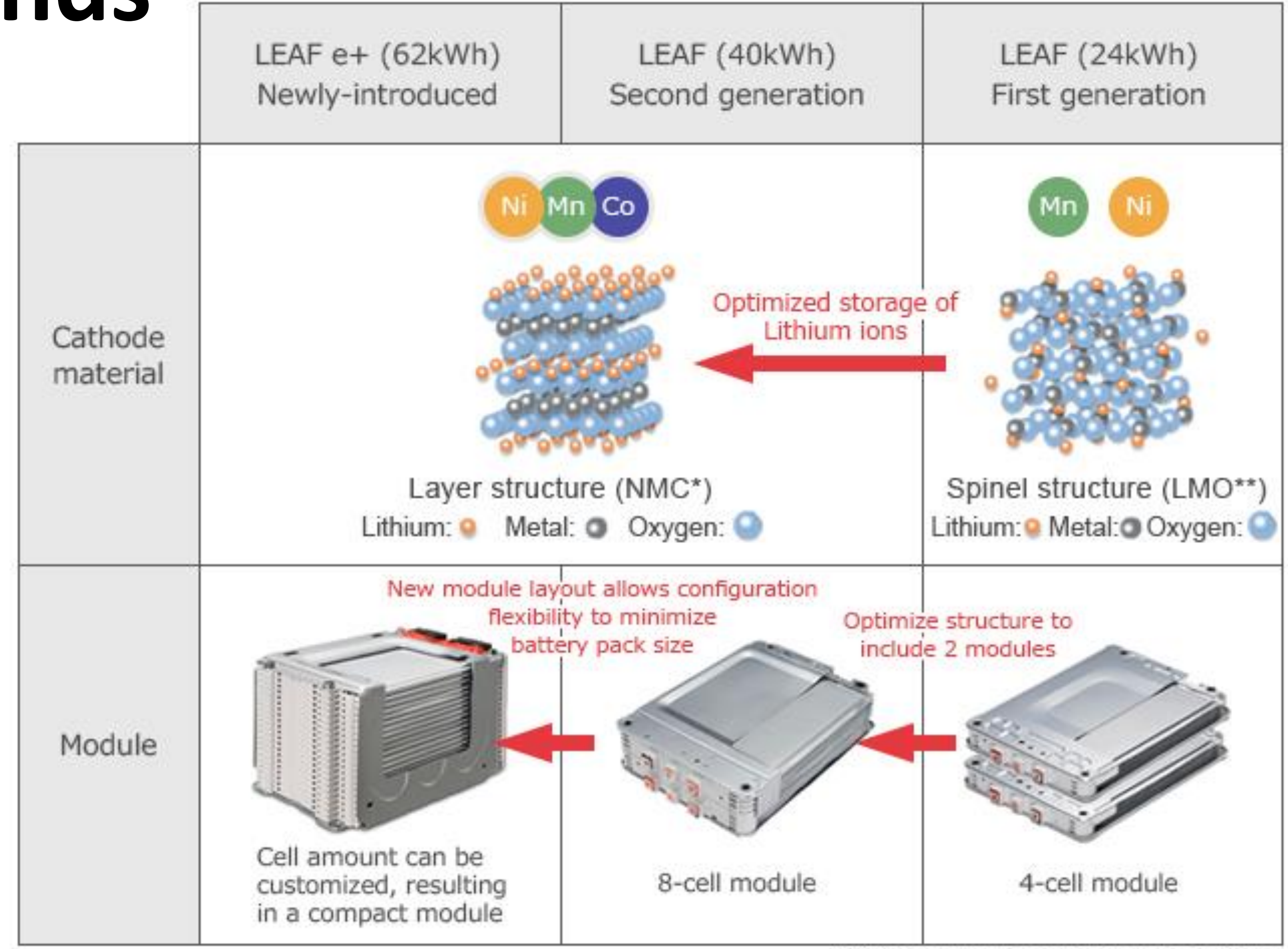
Deployment Trends

Nissan Leaf Gen 1 vs. Gen 2 ->



Economist.com

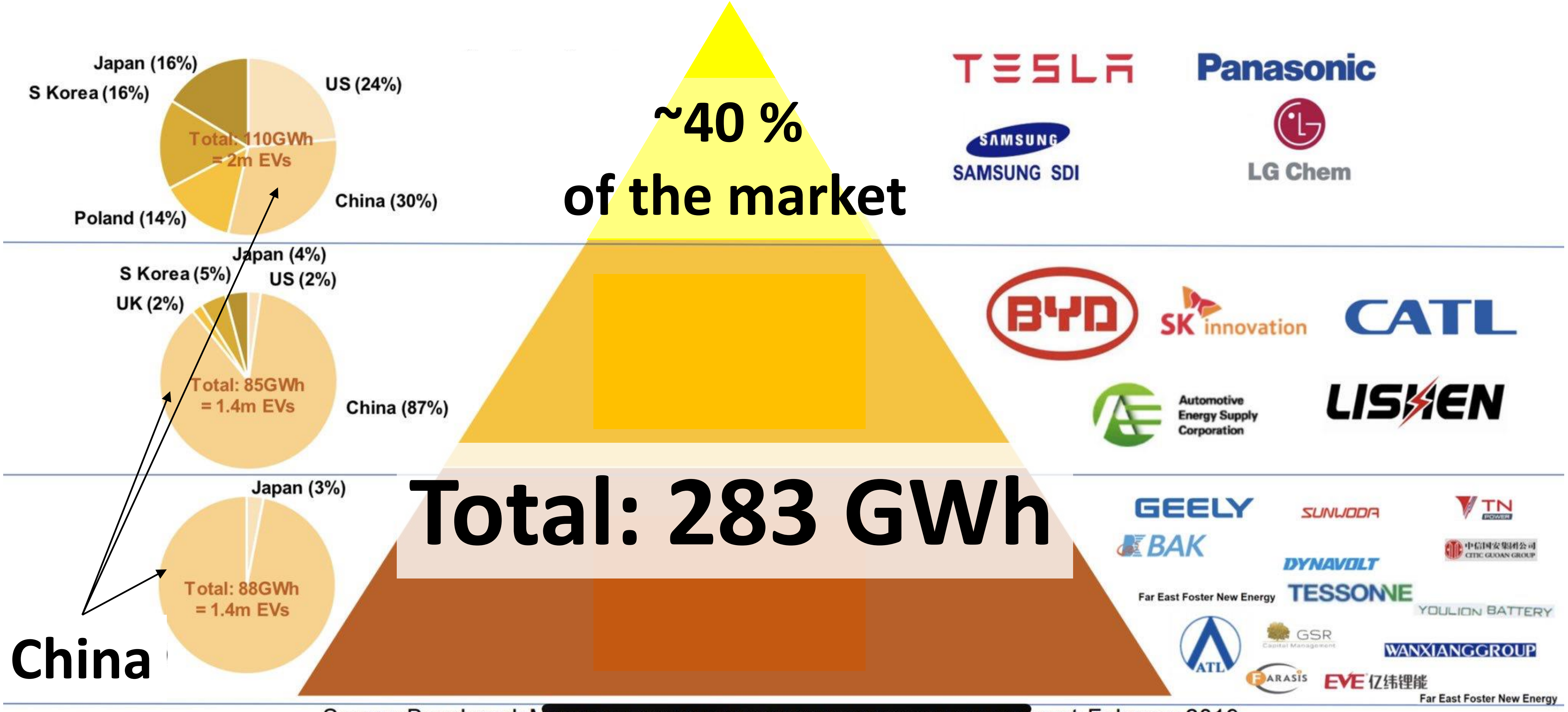
https://www.economist.com/briefing/2017/08/12/after-electric-cars-what-more-will-it-take-for-batteries-to-change-the-face-of-energy



*Lithium Nickel Cobalt Manganese Oxide
**Lithium Manganese Oxide

https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/li_ion_ev.html

Global LIB Production in 2018



~40 %
of the market

Total: 283 GWh

China

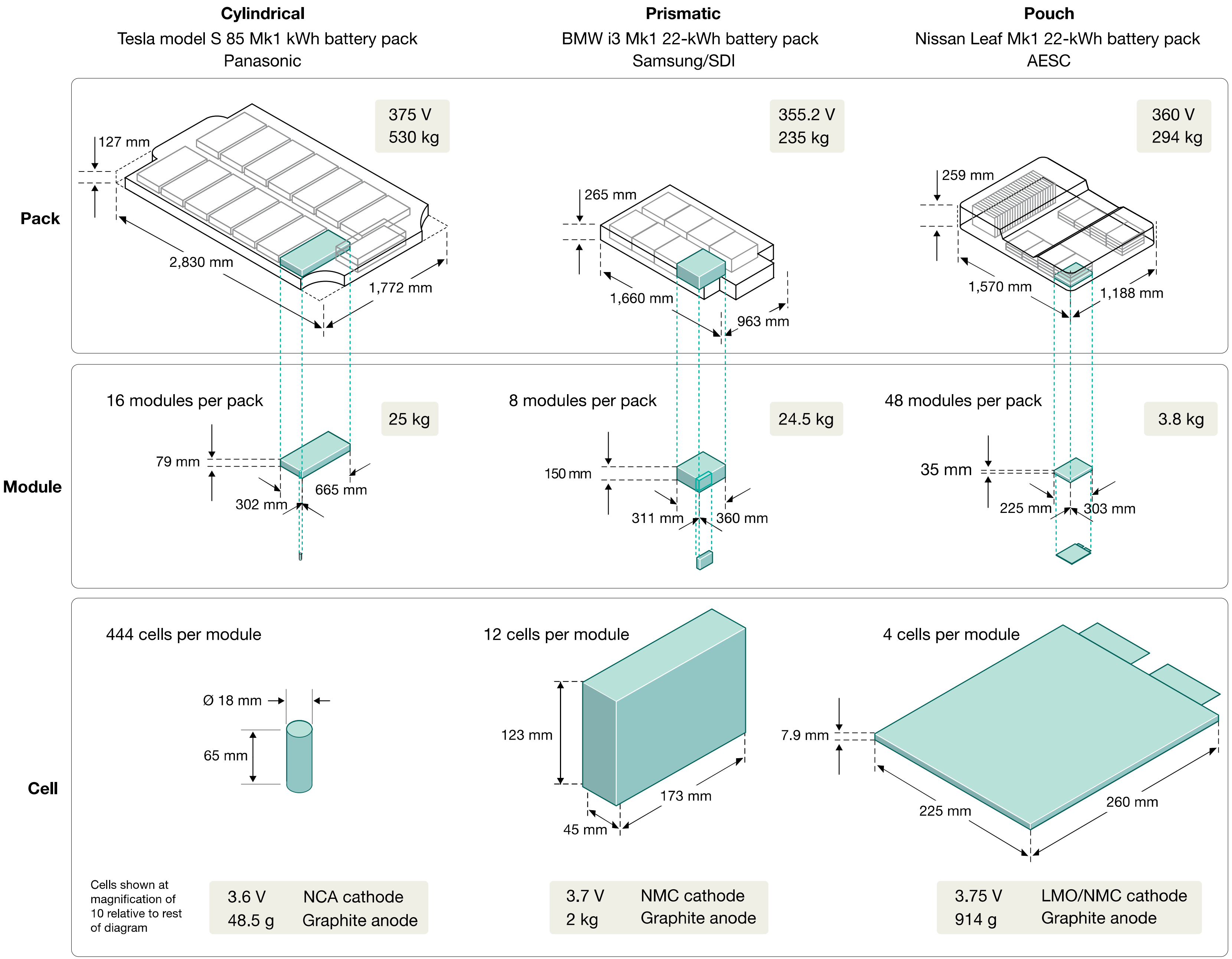
Source: Benchmark Minerals' Lithium Ion Battery Megafactory Assessment, February 2019

Original Graphic: Simon Moores via Twitter, Retrieved from: https://twitter.com/sdmoores/status/1164852499796373504

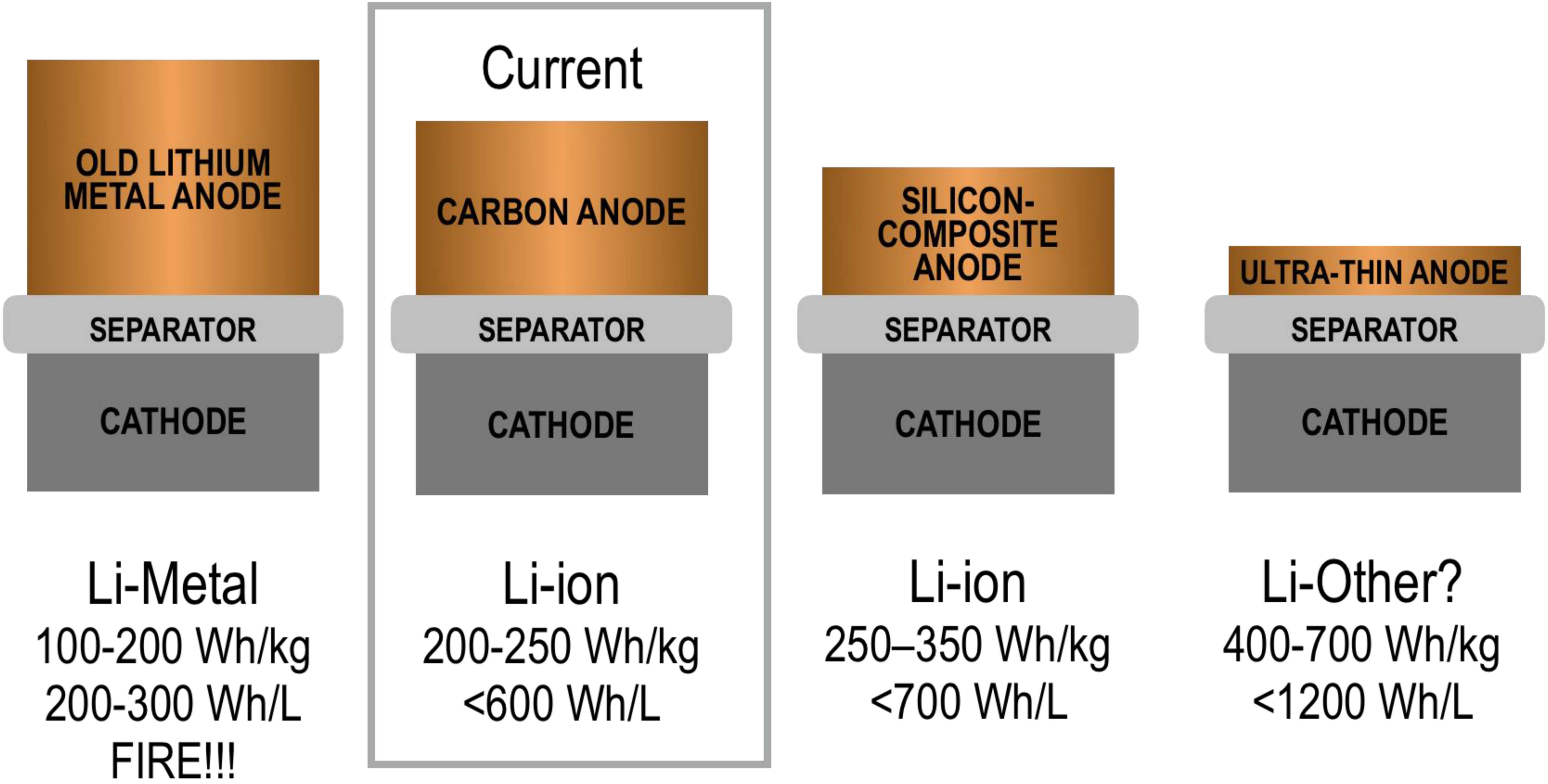
LIB Design

- A variety of cell and pack architectures are employed in EVs
- Limited similarities with LIBs for consumer electronics

https://www.richtek.com/battery-management/en/designing-liion.html



Harper, Gavin, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, Allan Walton et al. "Recycling lithium-ion batteries from electric vehicles." *Nature* 575, no. 7781 (2019): 75-86.



Li-Metal
100-200 Wh/kg
200-300 Wh/L
FIRE!!!

Li-ion
200-250 Wh/kg
<600 Wh/L

Li-ion
250–350 Wh/kg
<700 Wh/L

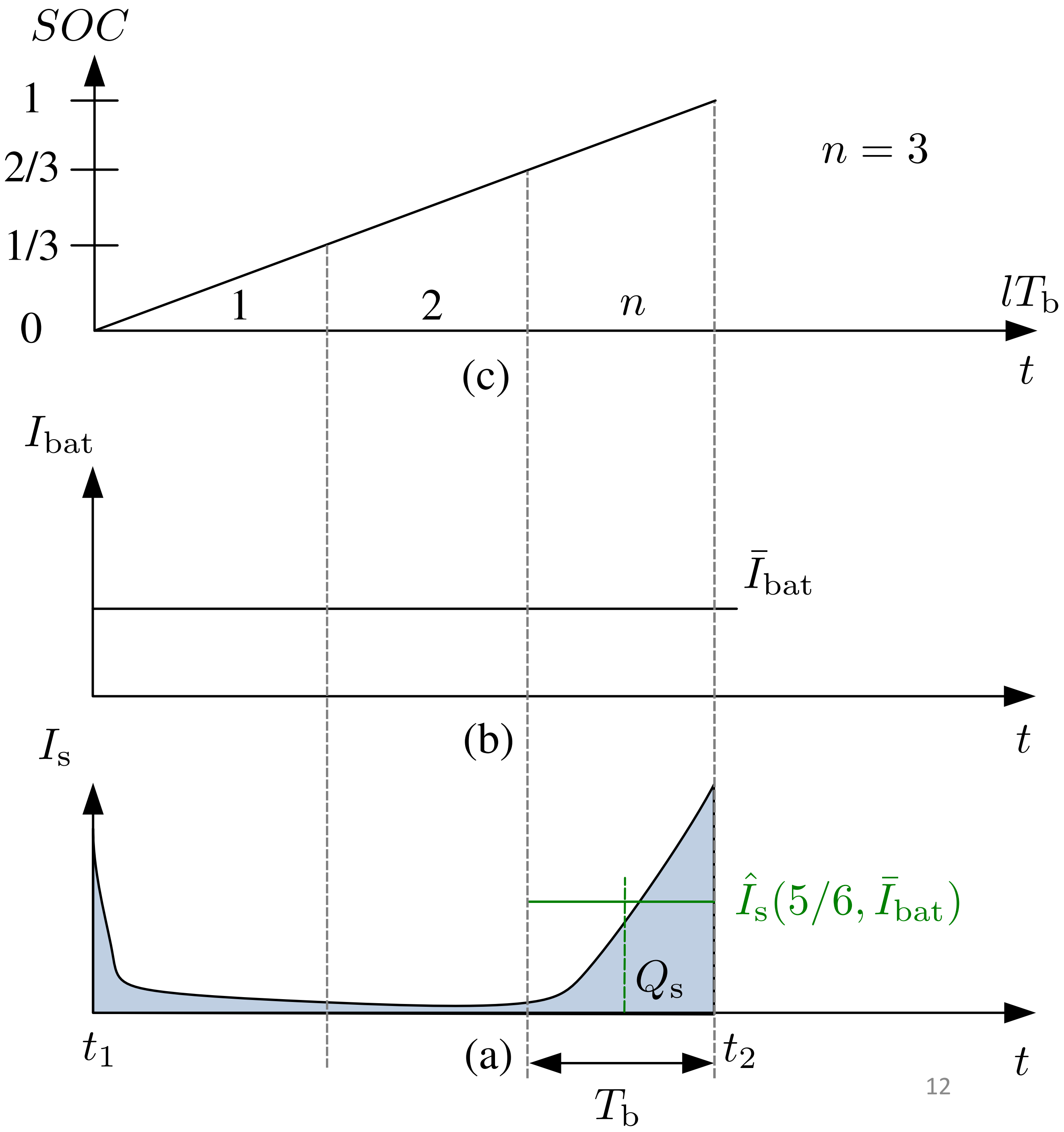
Li-Other?
400-700 Wh/kg
<1200 Wh/L

Key factors affecting battery lifetime (i.e. battery degradation)

- Cycling
- Depth of discharge
- Charge/discharge rate
- Temperature
- Time

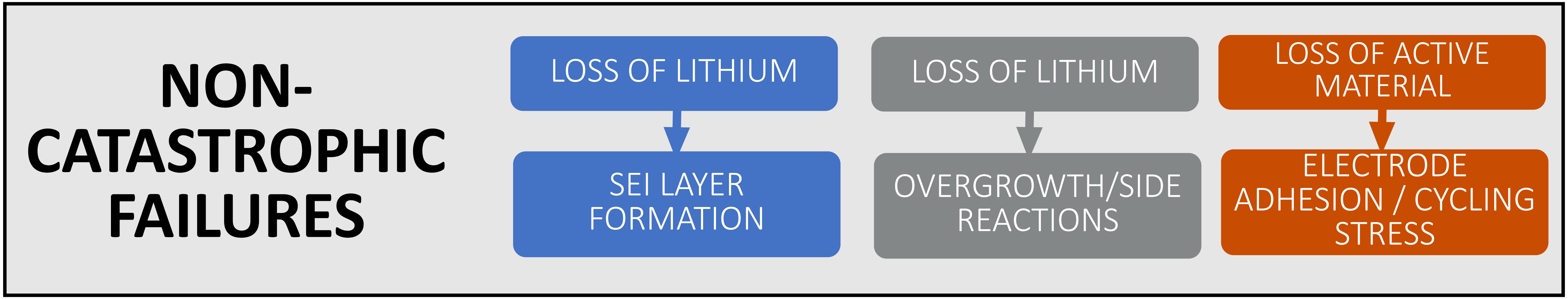
Battery Lifetime

- **Further improvements in the useful life of batteries are likely**
- **Oversizing could be a reliable strategy for increasing cycle life**
- **Lifetime has implications for both capital investments and secondary applications**



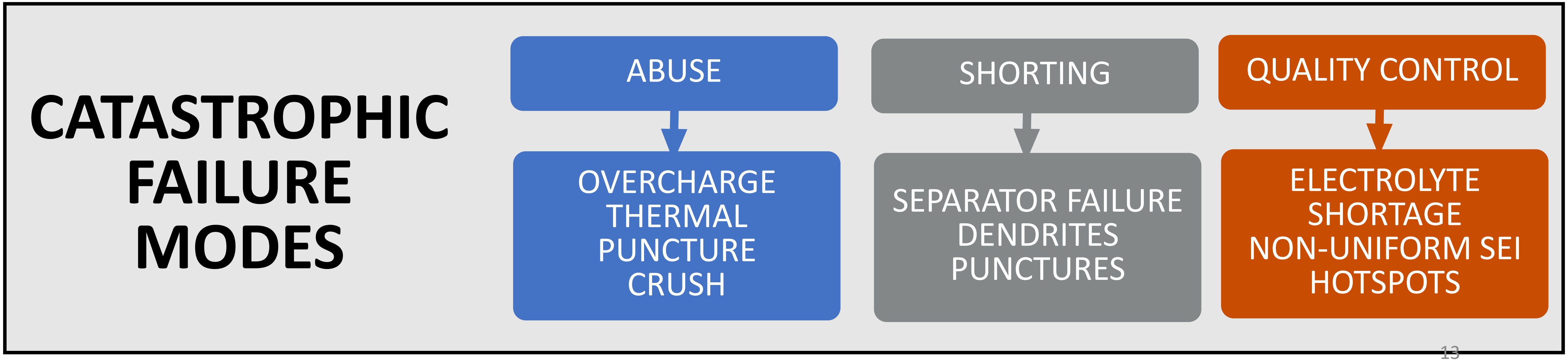
Fortenbacher, P., Mathieu, J. L., & Andersson, G. (2014, August). Modeling, identification, and optimal control of batteries for power system applications. In Power Systems Computation Conference (PSCC), 2014 (pp. 1-7). IEEE.

Battery Lifetime



NON-CATASTROPHIC FAILURES

- LOSS OF LITHIUM
  - SEI LAYER FORMATION
- LOSS OF LITHIUM
  - OVERGROWTH/SIDE REACTIONS
- LOSS OF ACTIVE MATERIAL
  - ELECTRODE ADHESION / CYCLING STRESS



CATASTROPHIC FAILURE MODES

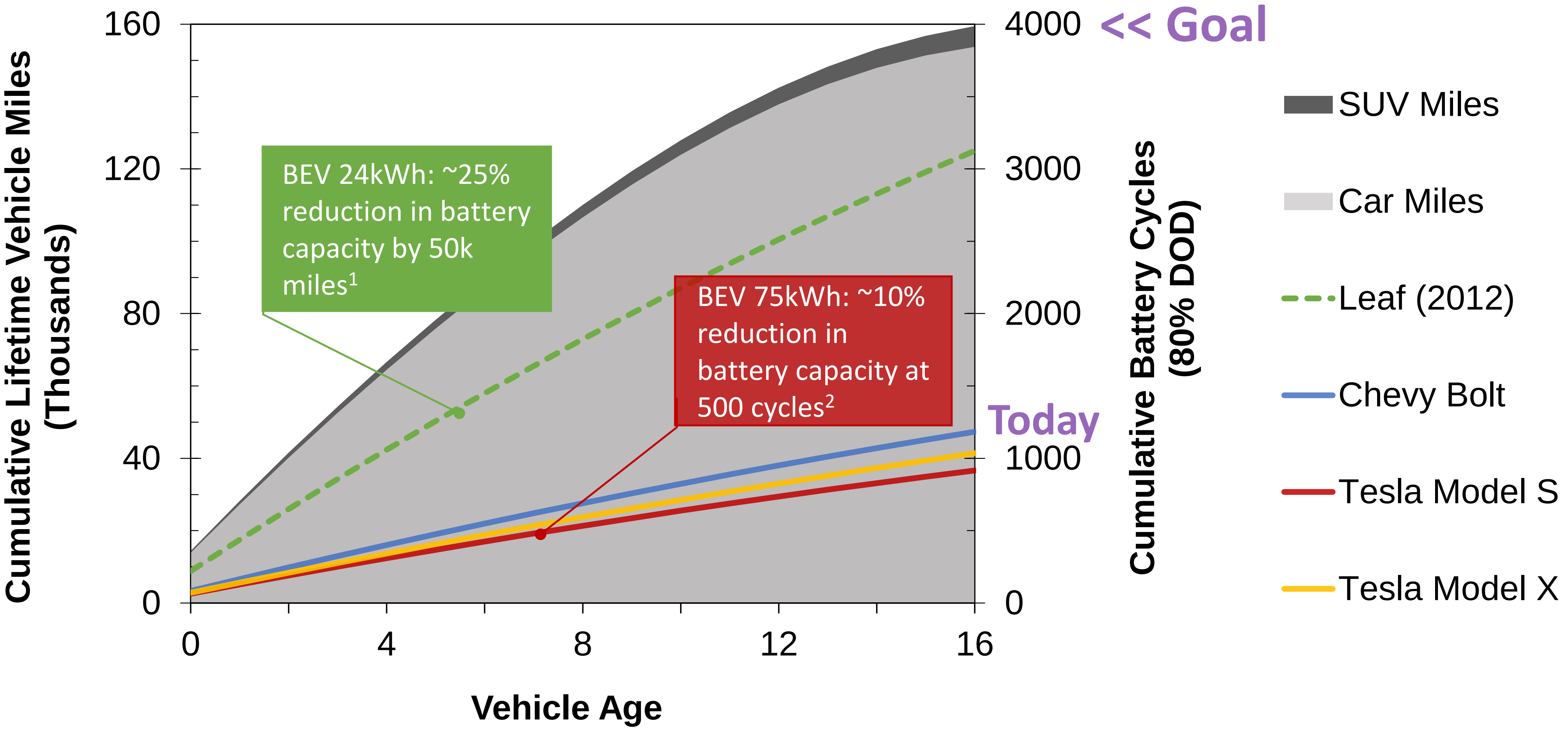
- ABUSE
  - OVERCHARGE
  - THERMAL
  - PUNCTURE
  - CRUSH
- SHORTING
  - SEPARATOR FAILURE
  - DENDRITES
  - PUNCTURES
- QUALITY CONTROL
  - ELECTROLYTE SHORTAGE
  - NON-UNIFORM SEI
  - HOTSPOTS

Battery Lifetime

NON-CATASTROPHIC FAILURES

CATASTROPHIC FAILURE MODES

Battery Lifetime is Improving



BEV 24kWh: ~25% reduction in battery capacity by 50k miles[1]

BEV 75kWh: ~10% reduction in battery capacity at 500 cycles[2]

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[1] Shirk, M. and J. Wishart (2015). Effects of Electric Vehicle Fast Charging on Battery Life and Vehicle Performance, SAE Technical Paper.

[2] Lambert, F. (2018). Tesla battery degradation at less than 10% after over 160,000 miles, according to latest data. electrek.

Materials

Goro Nickel Mine, 2009
https://commons.wikimedia.org/wiki/File:Goro mine_tailings dam.jpg

https://www.theguardian.com/global development/commentisfree/2019/dec/16/i saw the unbearable grief inflicted on families by cobalt mining i pray for change

https://www.albemarle.com/businesses/lithium

Short-term vs. Long-term Constraints

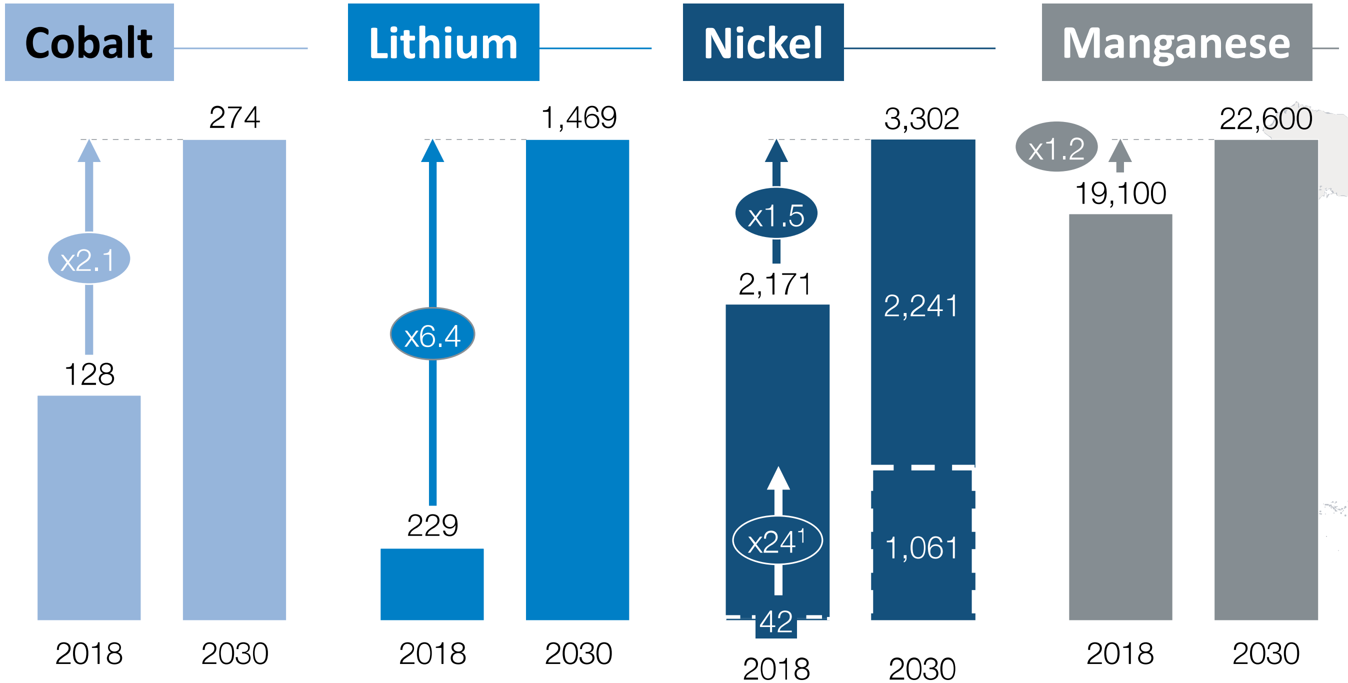
- **Potential for >1 billion 40 kWh batteries given current mineral reserves and LIB electrode technologies[1]**
- **Lithium and cobalt are the closest lithospheric constraints (depending on technology development!)**
- **Currently, there is a global ramp-up in production of battery materials**
- **But, mineral reserves are geographically concentrated which could create supply risks**

[1] Wadia, C., Albertus, P., & Srinivasan, V. (2011). Resource constraints on the battery energy storage potential for grid and transportation applications. *Journal of Power Sources, 196*, 1593-1598. doi:10.1016/j.jpowsour.2010.08.056

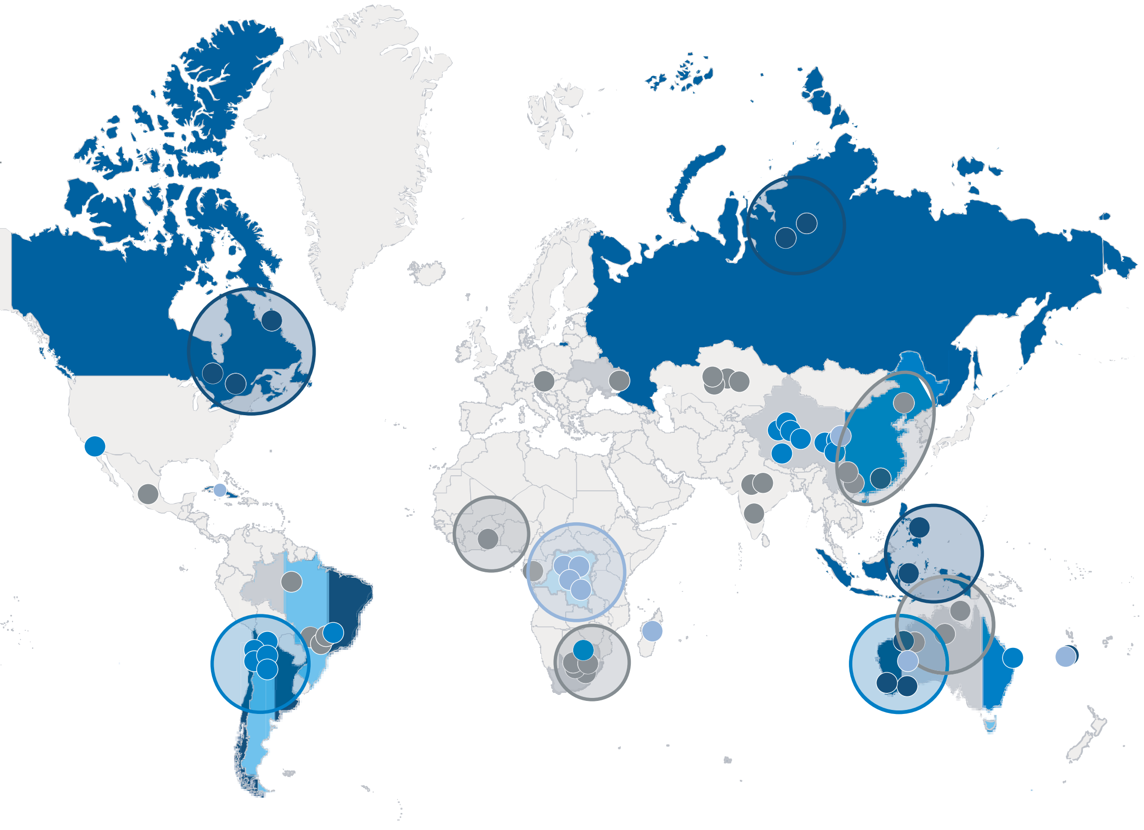
Supply Risks

Major mining sites of Cobalt, Lithium, Nickel, and Manganese

Raw Material Demand in kt/year



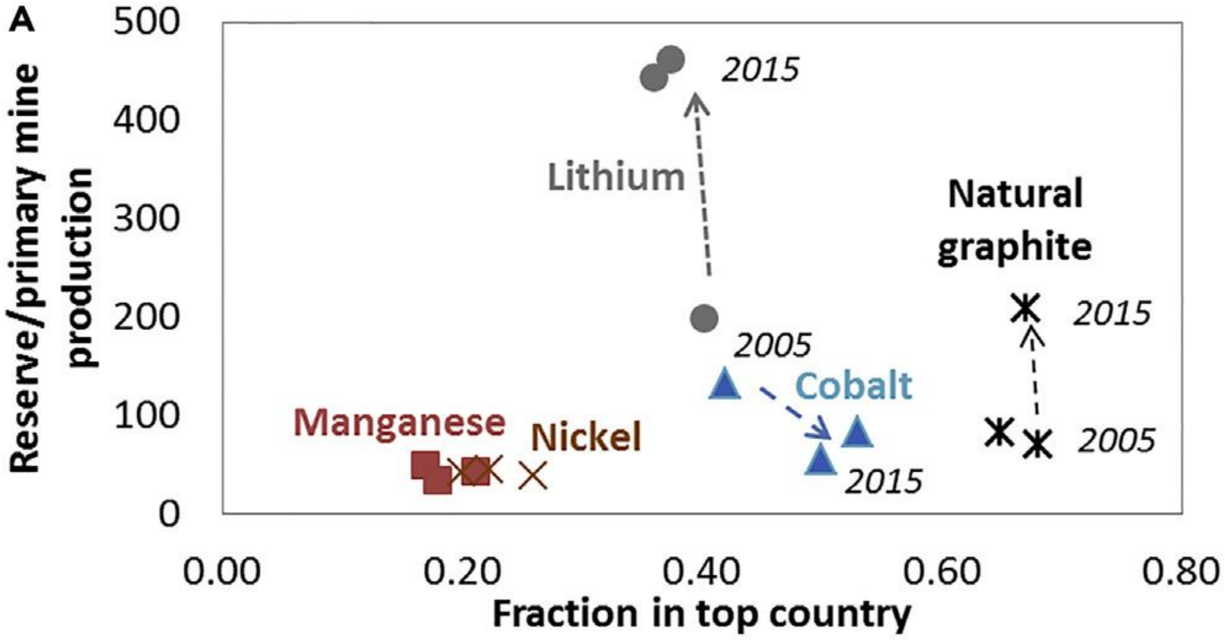
¹ Demand for class 1 nickel for batteries



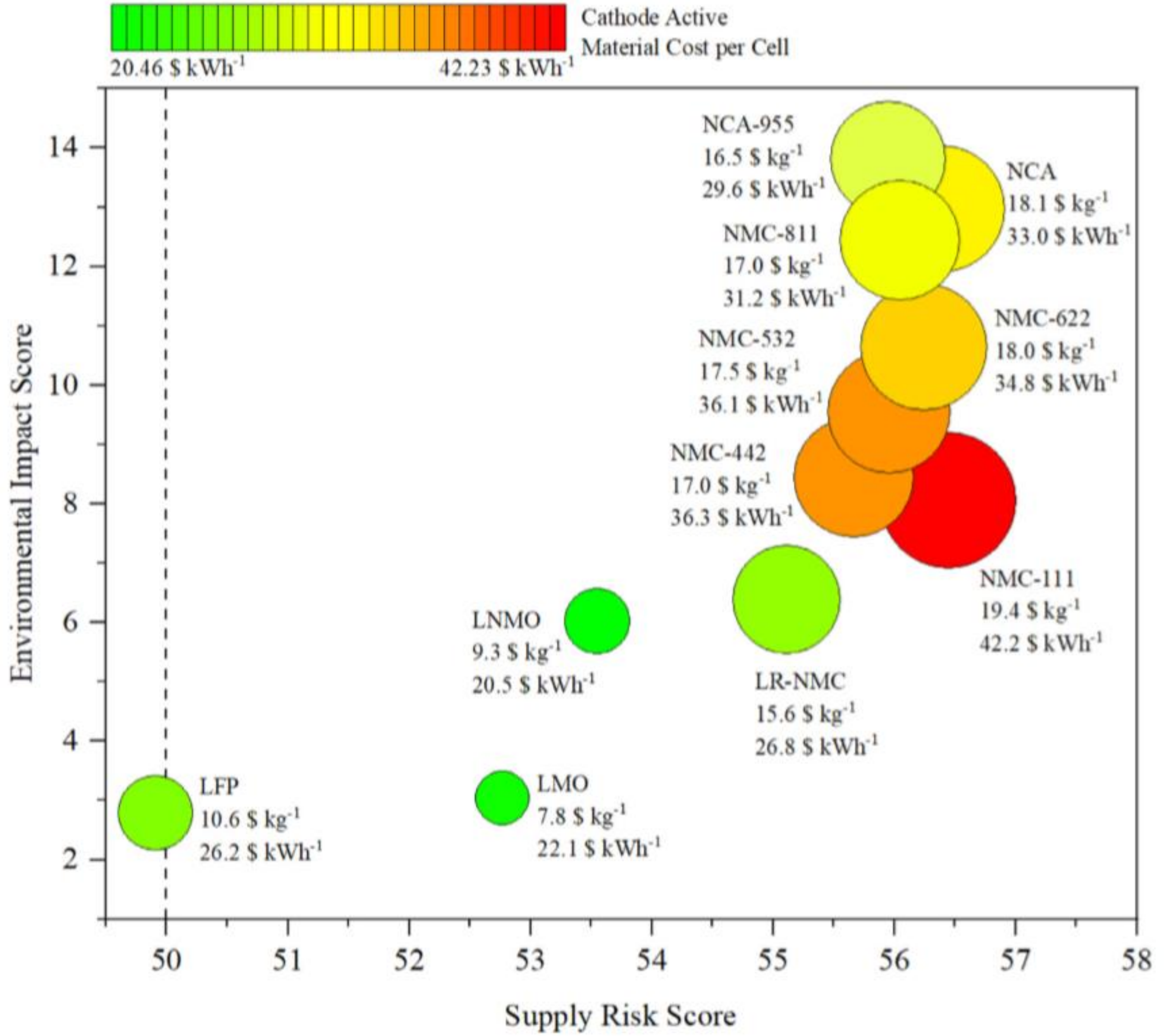
Global Battery Alliance, (2020). Retrieved from: http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

Supply Risks

- **Mineral reserves can increase with demand**
- **Cobalt is likely the main risk, as reserves are highly concentrated**



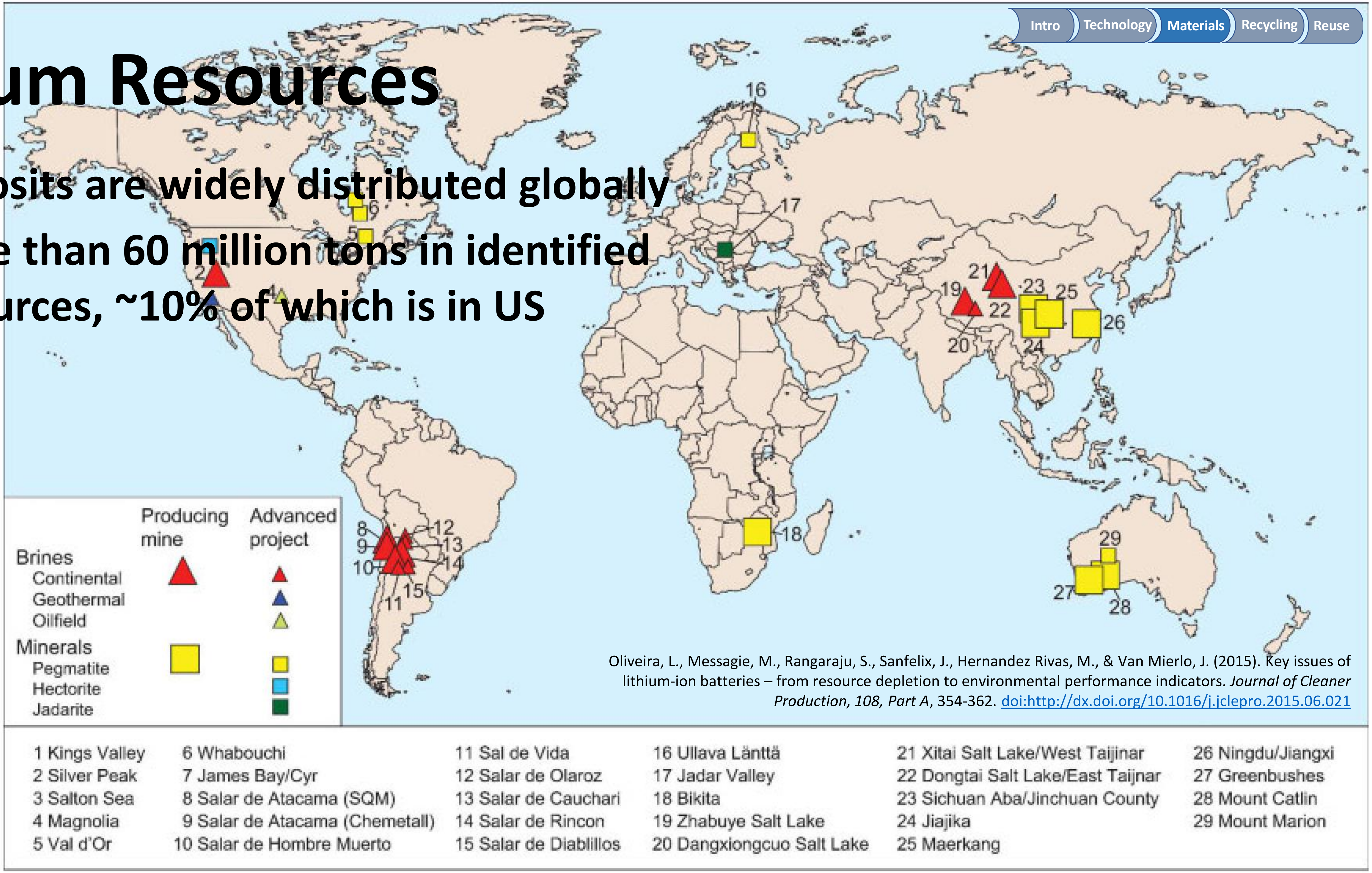
Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule, 1*(2), 229-243.



Wentker, M., Greenwood, M., Asaba, M. C., & Leker, J. (2019). A raw material criticality and environmental impact assessment of state-of-the-art and post-lithium-ion cathode technologies. *Journal of Energy Storage*, *26*, 101022.

Lithium Resources

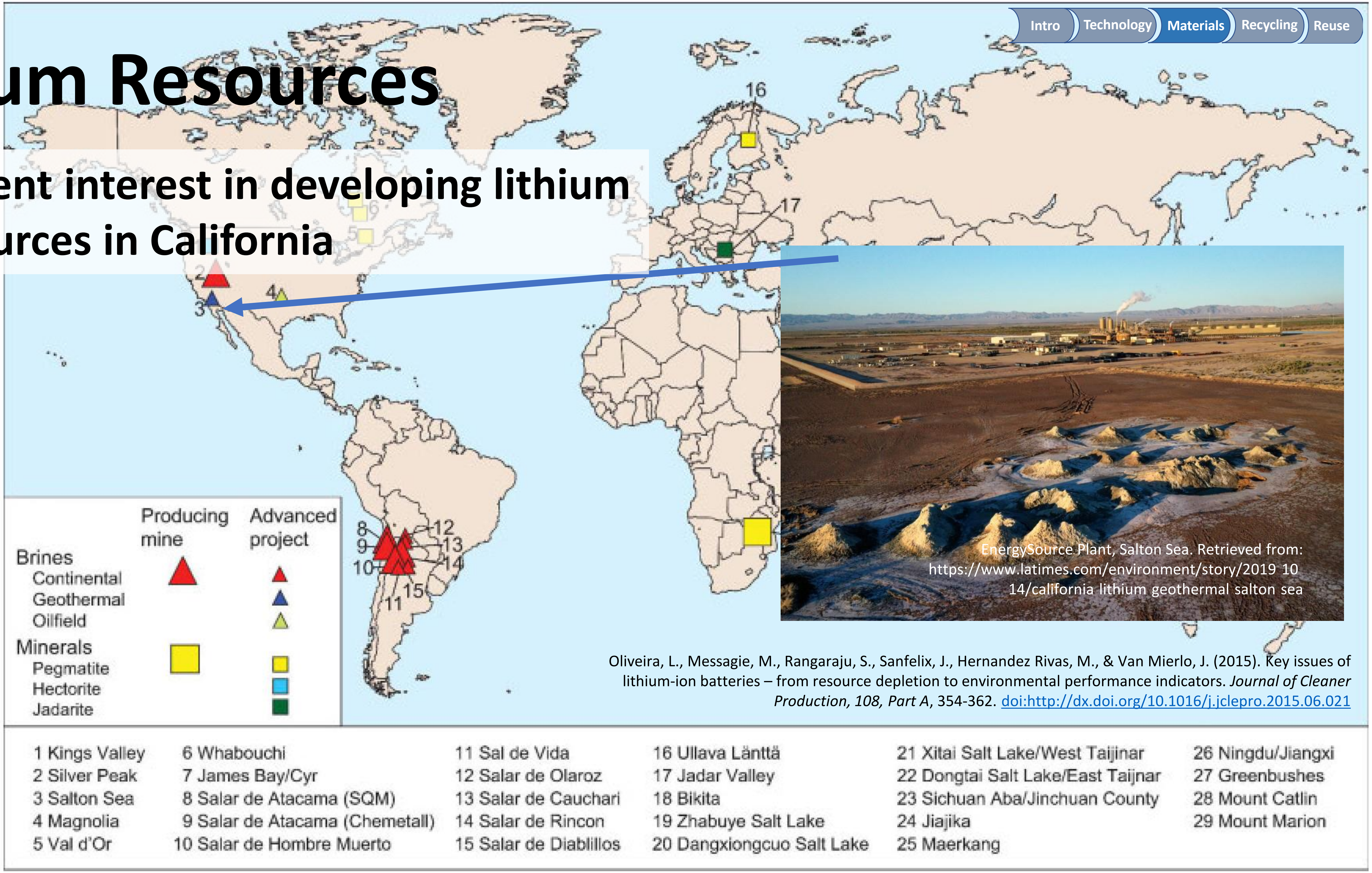
- Deposits are widely distributed globally
- More than 60 million tons in identified resources, ~10% of which is in US



Oliveira, L., Messagie, M., Rangaraju, S., Sanfelix, J., Hernandez Rivas, M., & Van Mierlo, J. (2015). Key issues of lithium-ion batteries – from resource depletion to environmental performance indicators. *Journal of Cleaner Production, 108, Part A*, 354-362. doi:http://dx.doi.org/10.1016/j.jclepro.2015.06.021

Lithium Resources

- **Current interest in developing lithium resources in California**



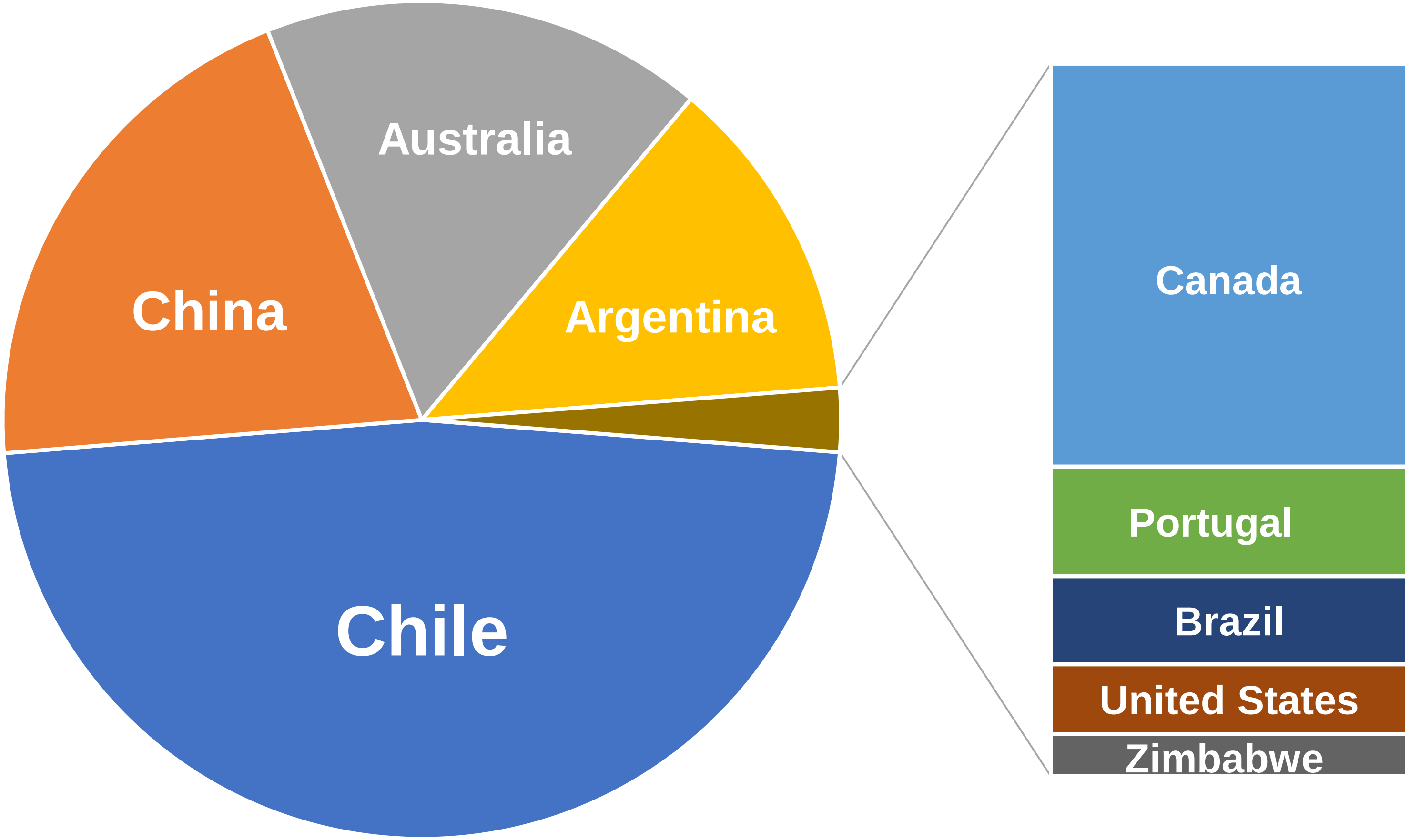
EnergySource Plant, Salton Sea. Retrieved from: https://www.latimes.com/environment/story/2019 10 14/california lithium geothermal salton sea

Oliveira, L., Messagie, M., Rangaraju, S., Sanfelix, J., Hernandez Rivas, M., & Van Mierlo, J. (2015). Key issues of lithium-ion batteries – from resource depletion to environmental performance indicators. *Journal of Cleaner Production, 108, Part A*, 354-362. doi:http://dx.doi.org/10.1016/j.jclepro.2015.06.021

Lithium Reserves

- Current reserves are ~20% of global resources.
- Major producing regions for 2018 were Australia (60%) and Chile (19%).
- In 2018, the static reserve ratio for lithium was 167 years.

World Lithium Reserves in 2018 (Source: USGS)



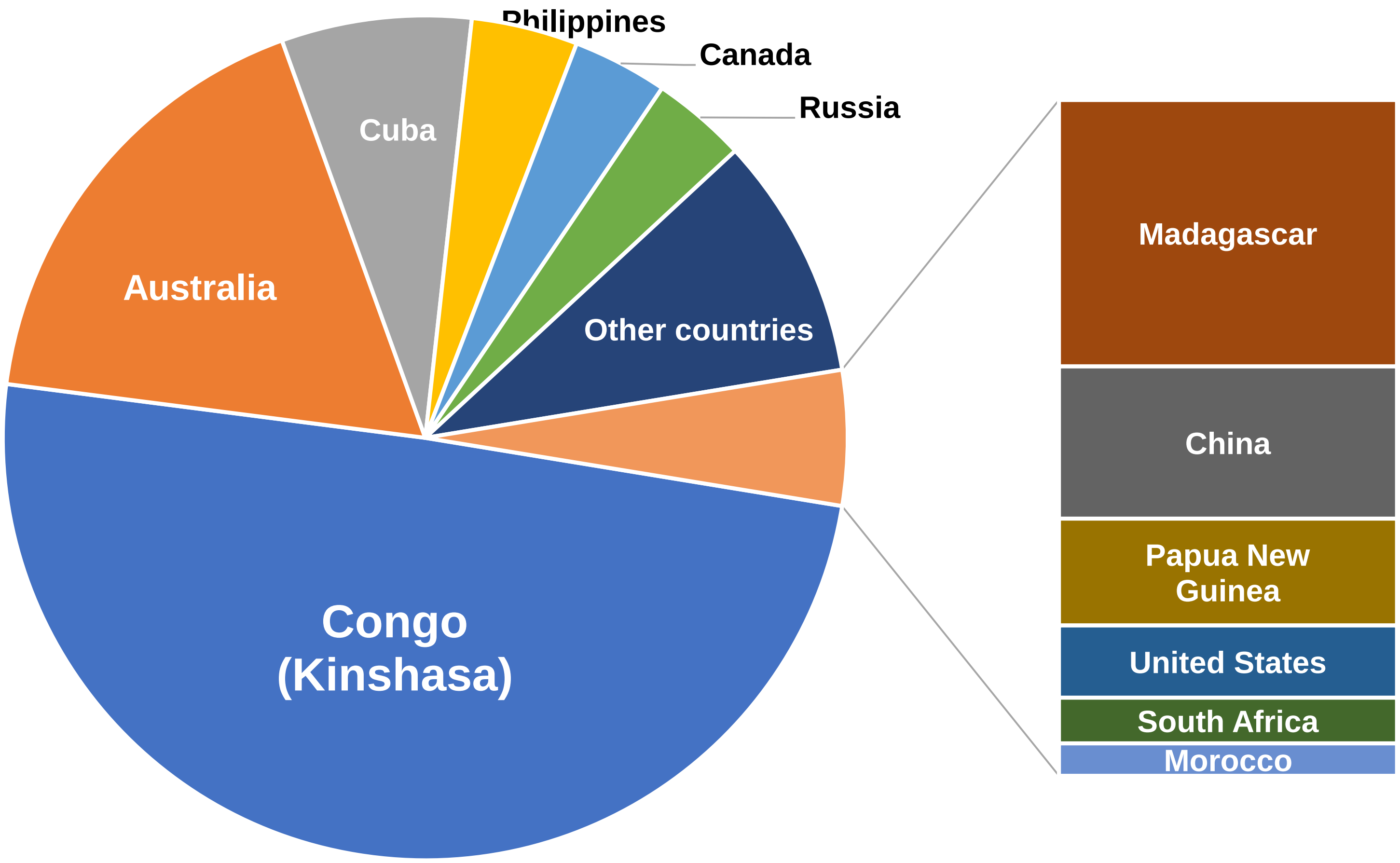
Total: 14 million tons

Jaskula, B. W. (2019). Mineral commodity summaries - Lithium. *US Geological Survey (USGS)*. Retrieved from https://prd-wret.s3-us-west-2.amazonaws.com /assets/palladium/production/atoms/files/mcs-2019-lithi.pdf

Cobalt Reserves

- Current cobalt reserves are ~28% of global resources.
- Major producing region is the DRC/Congo (64%), followed by Russia (4%).
- In 2018, the static reserve ratio for lithium was 49 years.

World Cobalt Reserves in 2018 (Source: USGS)

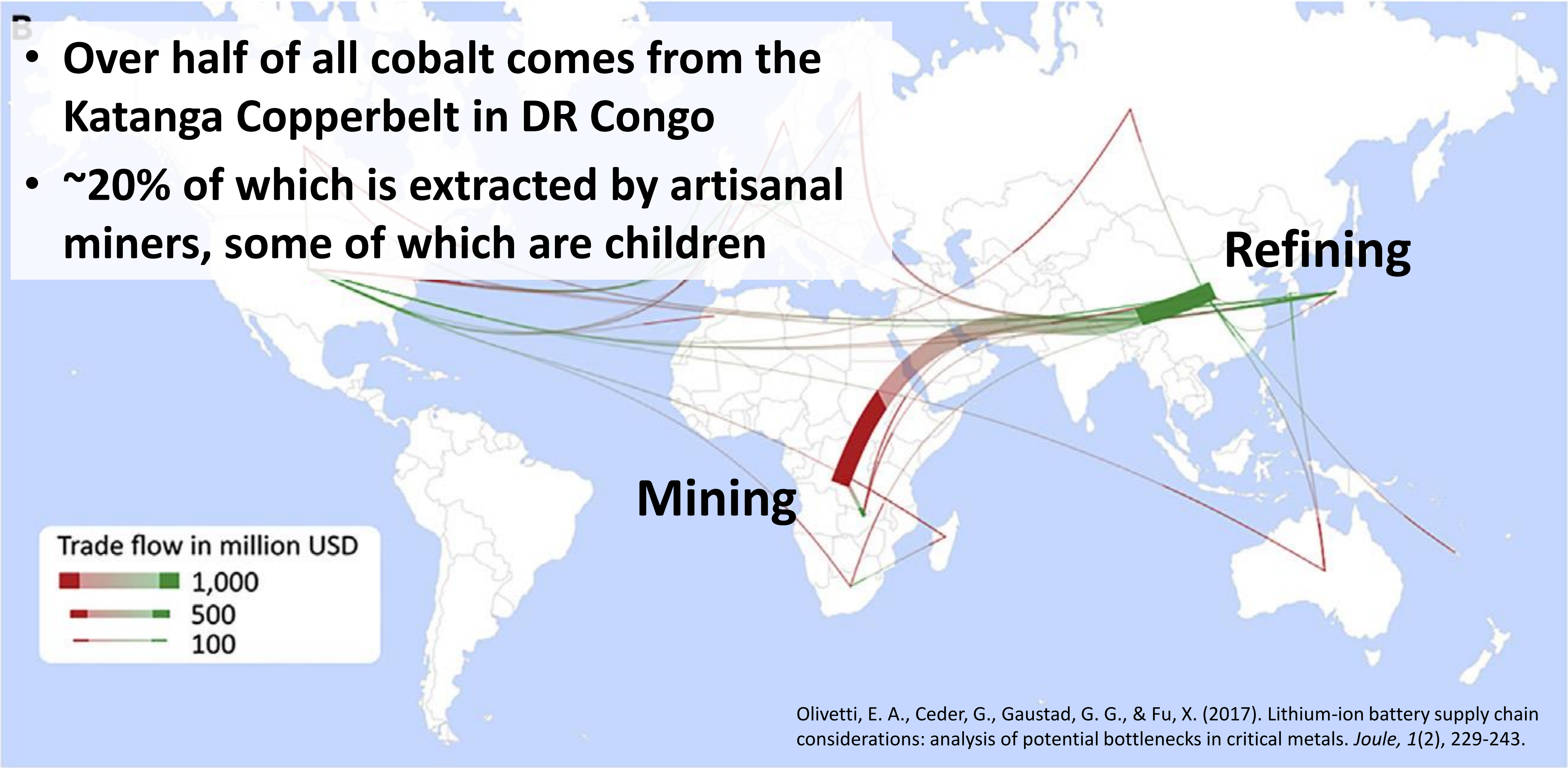


Total: 6.9 million tons

Shedd, K. B. (2019). Mineral commodity summaries - Cobalt. *US Geological Survey (USGS)*. Retrieved from https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2019-lithi.pdf

Cobalt Trade Flows 2015

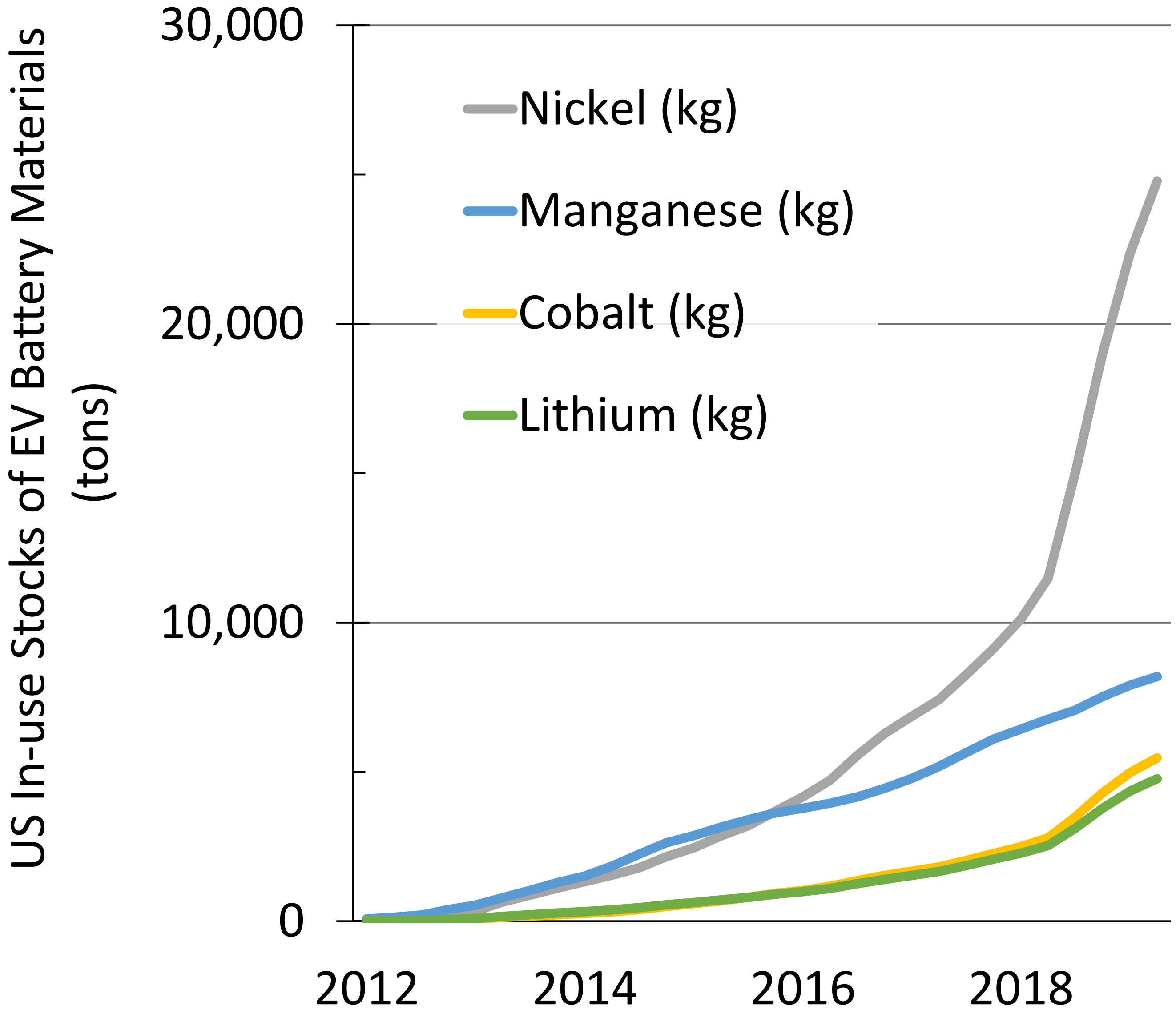
- Over half of all cobalt comes from the Katanga Copperbelt in DR Congo
- ~20% of which is extracted by artisanal miners, some of which are children



Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule, 1*(2), 229-243.

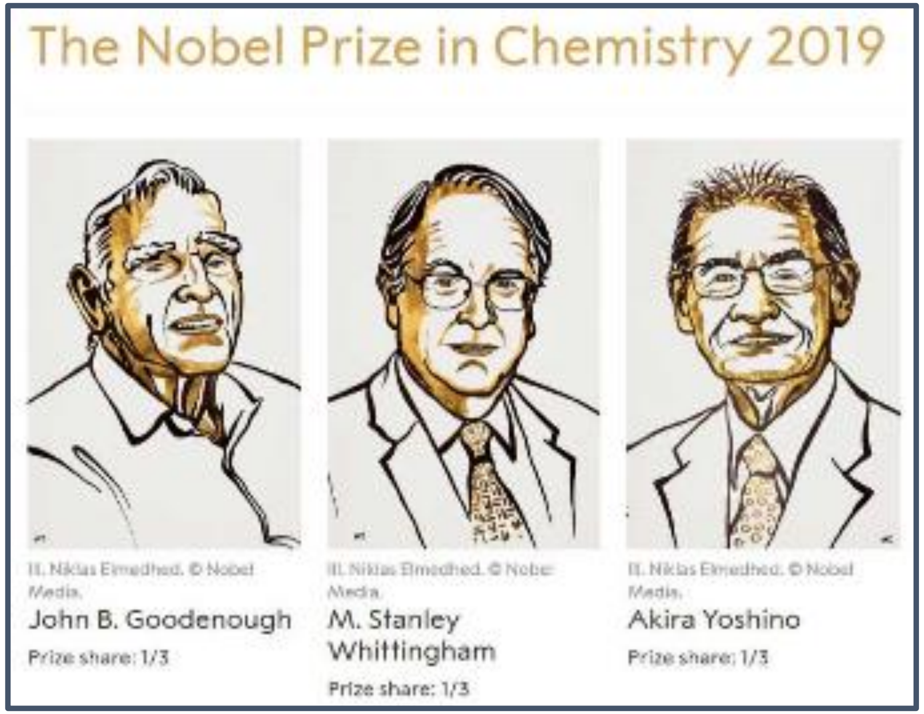
In-use Stocks

- Domestic resources include in-use stocks of materials.
- A move to low and no cobalt cathodes, combined with development of recycling, could help to reduce demand for primary production of cobalt.



Ambrose, H., Dunn, J., Kendall, A. (In Development) "In-use stocks of critical materials for batteries and implications for future supply."

Nobel Prize Winner Says ***Battery Recycling*** Key to Meeting Electric Car Demand



The Nobel Prize in Chemistry 2019

Ill. Niklas Elmedhed. © Nobel Media.
John B. Goodenough
Prize share: 1/3

Ill. Niklas Elmedhed. © Nobel Media.
M. Stanley Whittingham
Prize share: 1/3

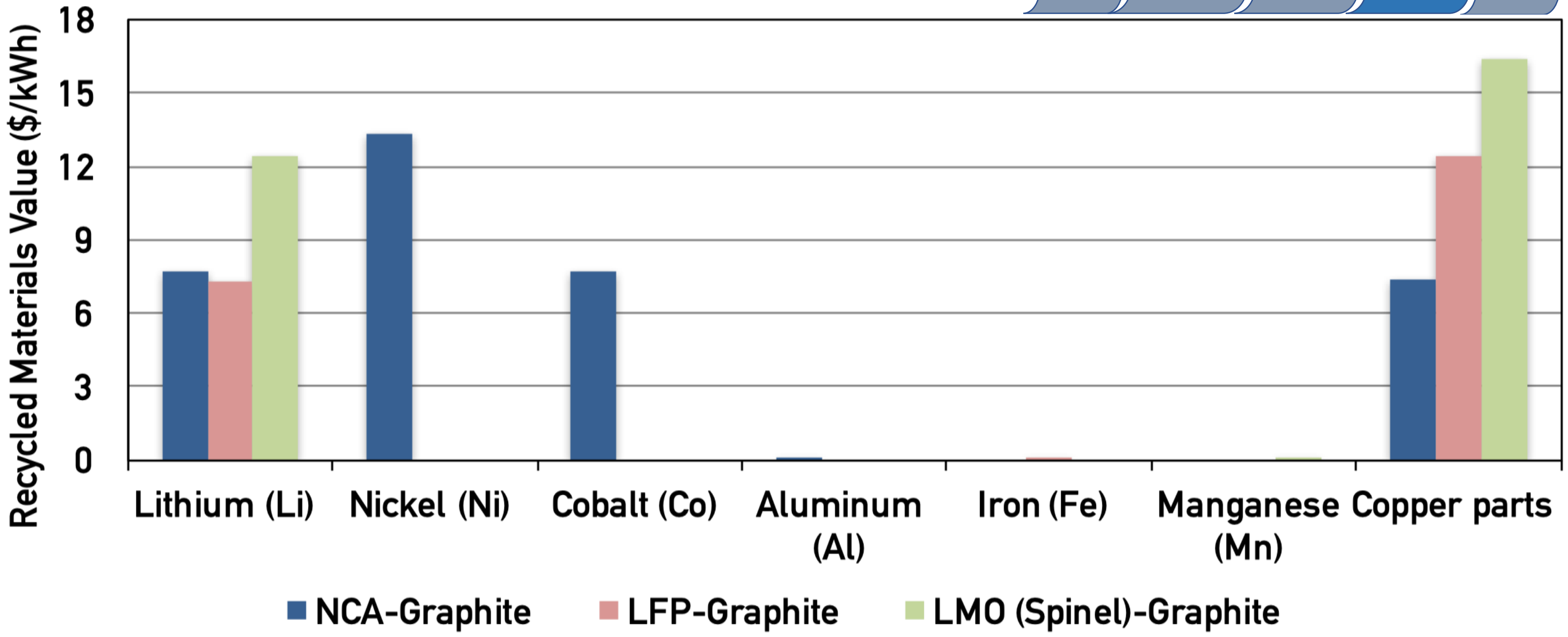
Ill. Niklas Elmedhed. © Nobel Media.
Akira Yoshino
Prize share: 1/3

- The 2019 Nobel Prize in Chemistry was awarded to John Goodenough, M. Stanley Whittingham, and Akira Yoshino "for the development of lithium-ion batteries."
- ***"The point is whether EV batteries can be recycled," said Akira Yoshino.***
- The world's transition to battery power… is set to boost demand for commodities from copper to nickel and cobalt. But there's also concerns that miners won't be able to expand raw material supply fast enough, and any shortfall will offer bigger opportunities for recycling."

https://www.bloomberg.com/news/articles/2019-10-10/nobel-prize-winner-says-battery-recycling-key-to-secure-supply

Recovery Value

- The value of recovered materials may be insufficient to motivate the costs of collection or recycling infrastructure.
- Could be compounded by a move away from cobalt cathode compounds.

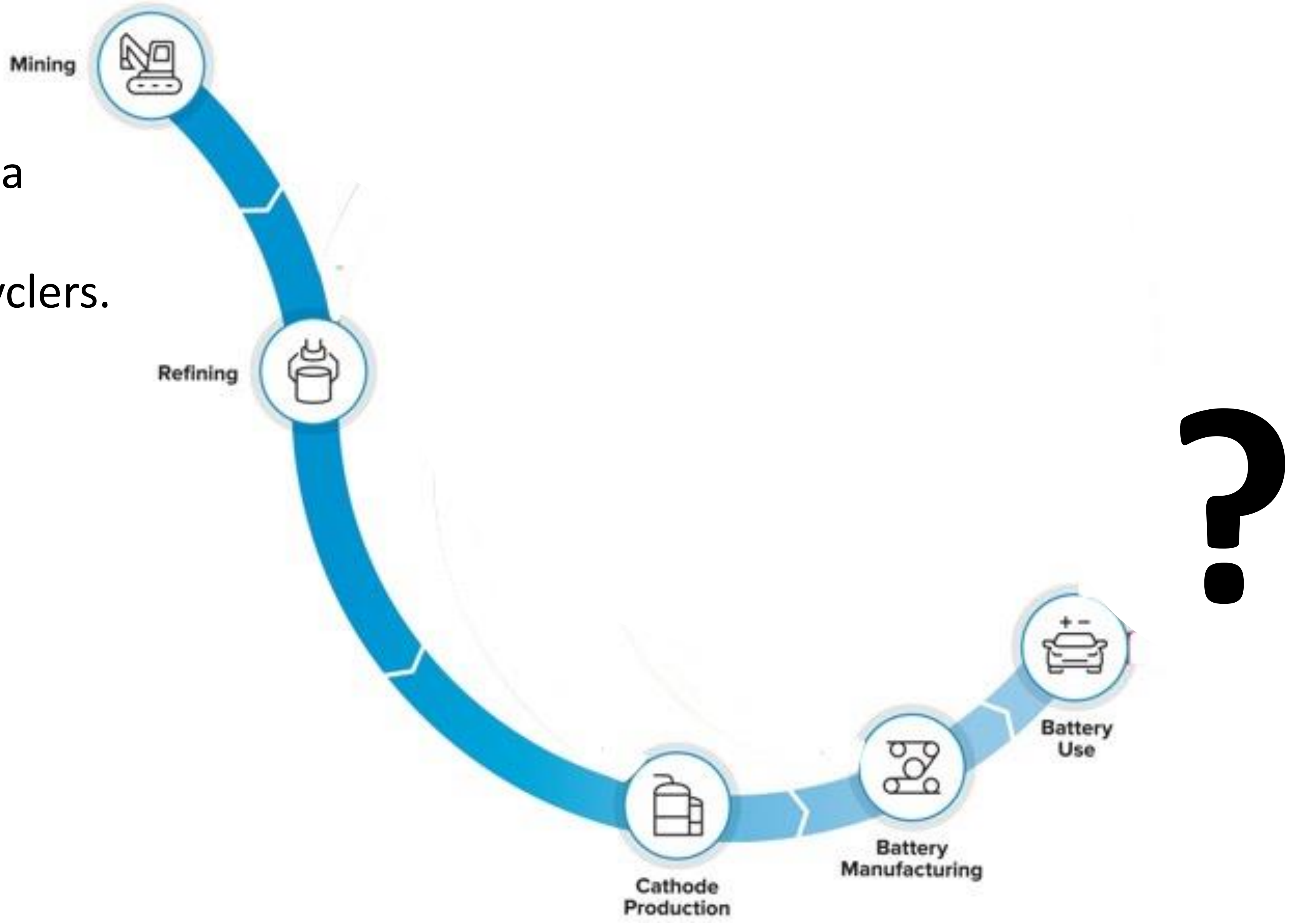


Retired EV Battery: Economic Analysis Averages		
	Minimum Cost ($/kWh)	Maximum Cost ($/kWh)
Secondary Purchase Cost	$10.00	$100.00
Collection, Testing, Repackaging	$18.00	$140.00
Shipment to Recycling Market	$1.70	$11.26
Recycling	$16.79	$74.29
Sale of Raw Material	$19.60	$36.15

Ambrose, H., Gershenson, D., Gershenson, A., & Kammen, D. (2014). Driving rural energy access: a second-life application for electric-vehicle batteries. *Environmental Research Letters,* 9(9), 094004.

Pathways

- There are currently a small number of commercial LIB recyclers.
- Pyrometallurgical processes are most common.



Original Image: https://recellcenter.org/publications/

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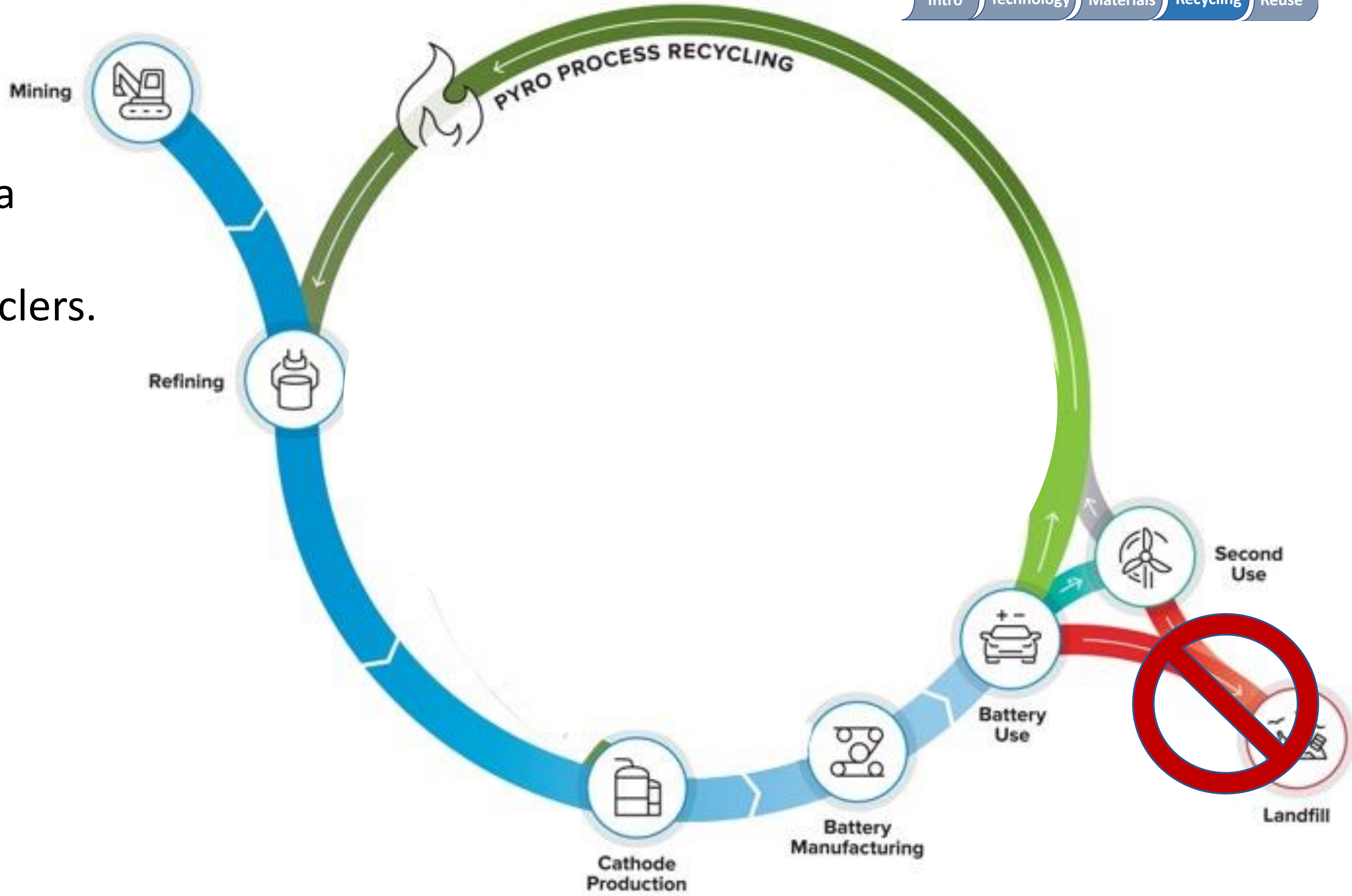

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Pathways

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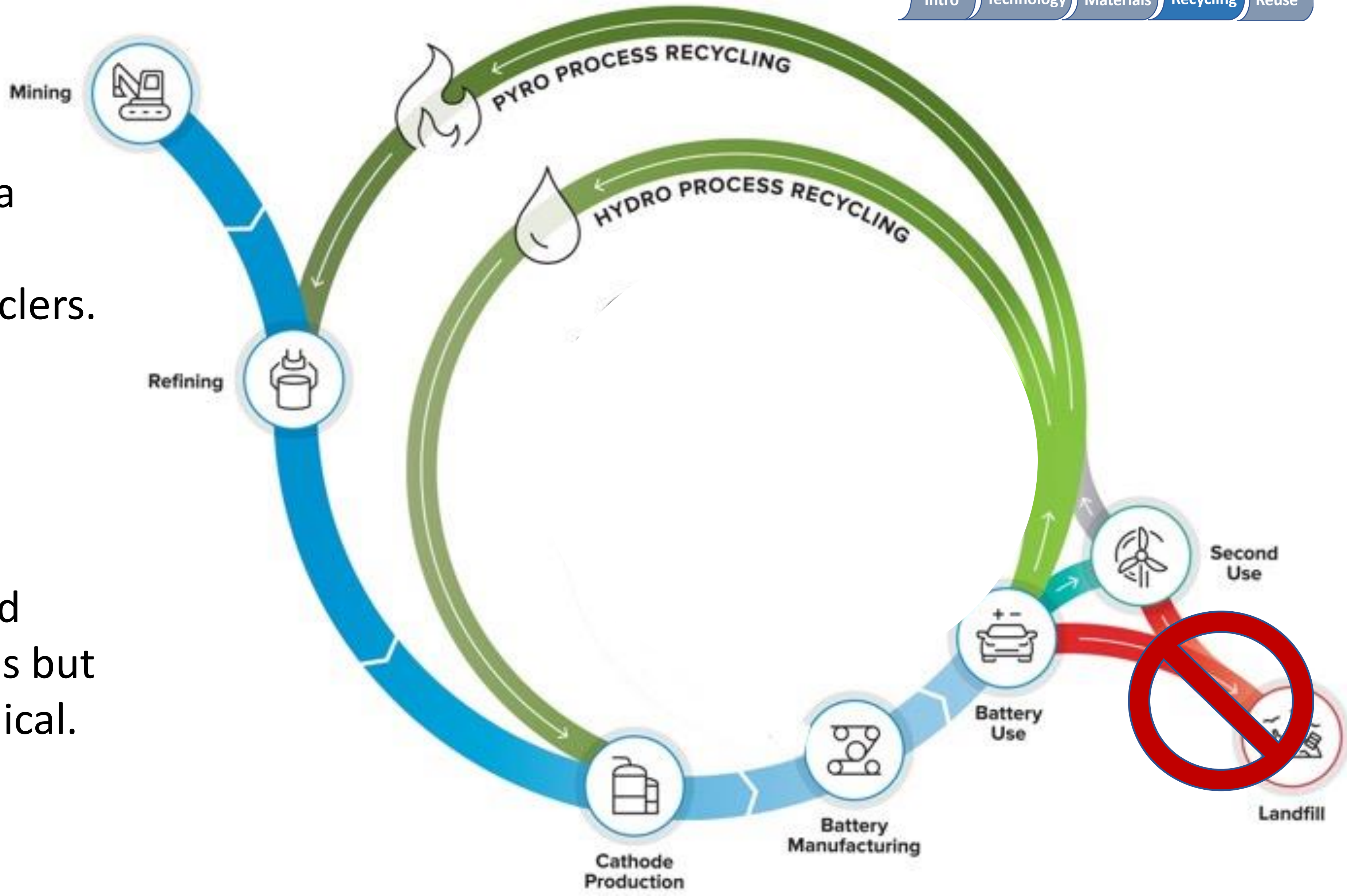
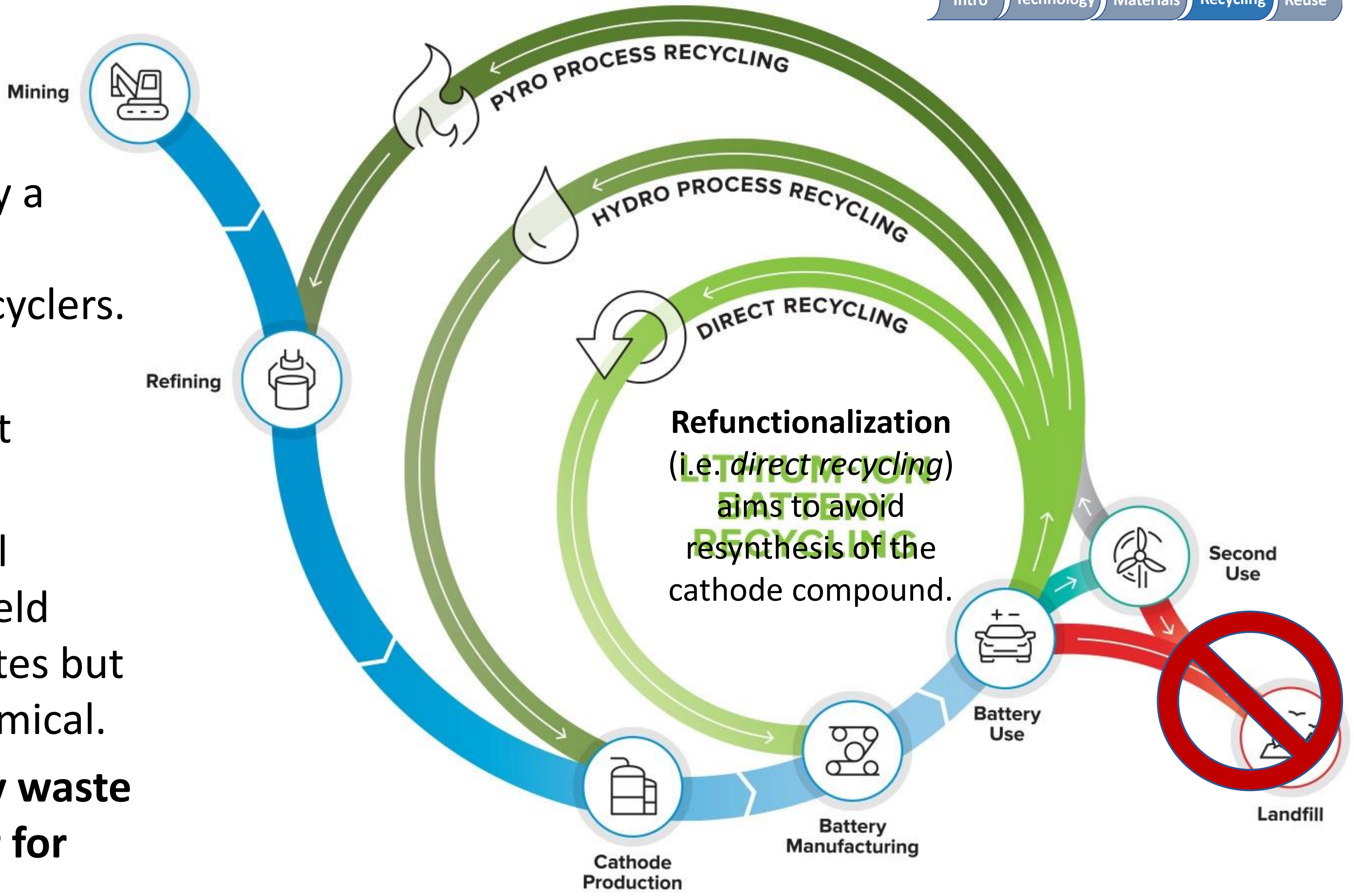
- Pyrometallurgical processes are most common.
- Hydrometallurgical processes could yield higher recovery rates but may be less economical.



Original Image: ttps://recellcenter.org/publications/

Pathways

- There are currently a small number of commercial LIB recyclers.
- Pyrometallurgical processes are most common.
- Hydrometallurgical processes could yield higher recovery rates but may be less economical.
- **A mixed chemistry waste stream is a barrier for battery recycling.**



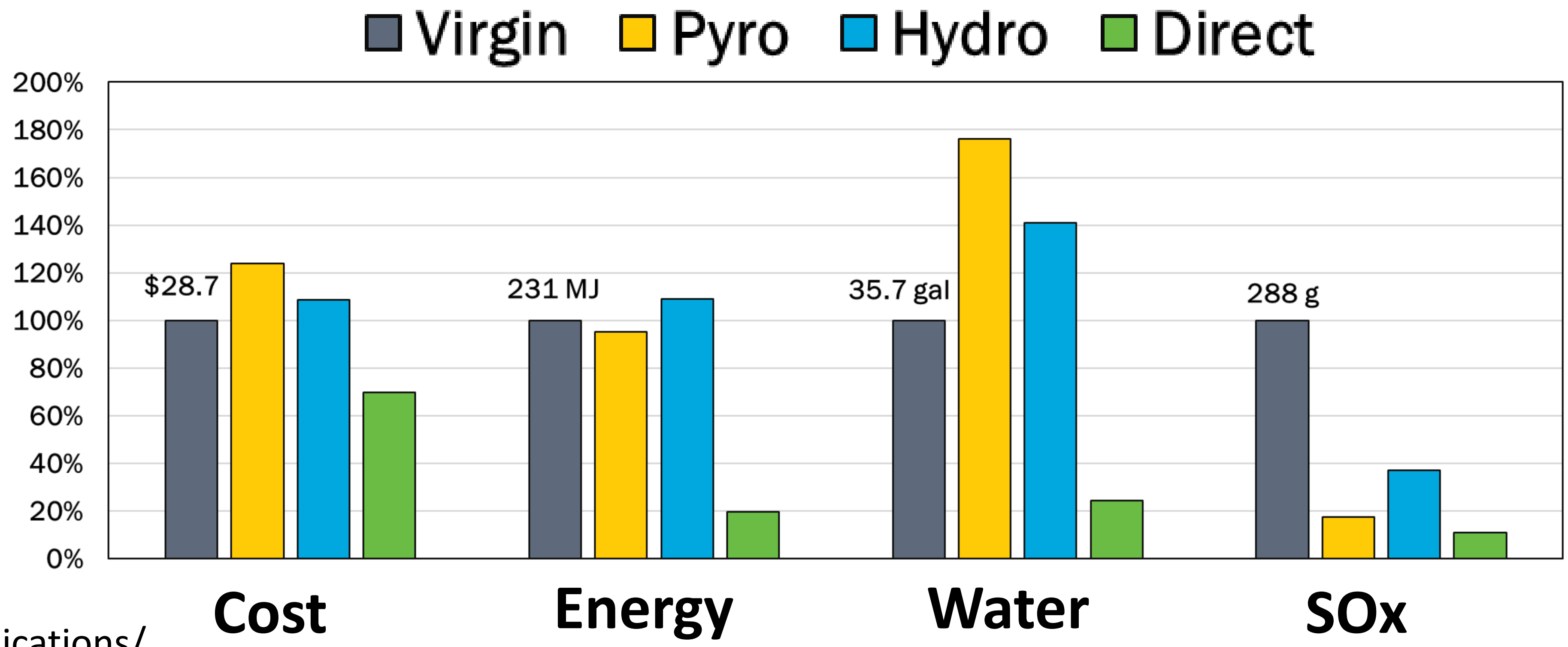
Refunctionalization (i.e. *direct recycling*) aims to avoid resynthesis of the cathode compound.

Original Image: ttps://recellcenter.org/publications/

Recovery Costs and Impacts

- Primary costs of pyrometallurgical processes are energy input and exhaust gas after treatment
- DOE supported research on direct cathode recycling suggests environmental and economic advantages

Costs and Impacts of 1 Kg NMC111 from Primary or Recycled Materials



https://recellcenter.org/publications/

Design for Recycling, Remanufacturing, and Reuse

- Integrated design
  - Collaboration of experts to identify EoL constraints
  - Modularity, standardized interfaces (housing), and design for disassembly
  - Ease of disassembling, cleaning, testing, and reassembling
- Barriers
  - Economic feasibility
  - Standardization of modules
  - Open access data
  - Reverse logistics

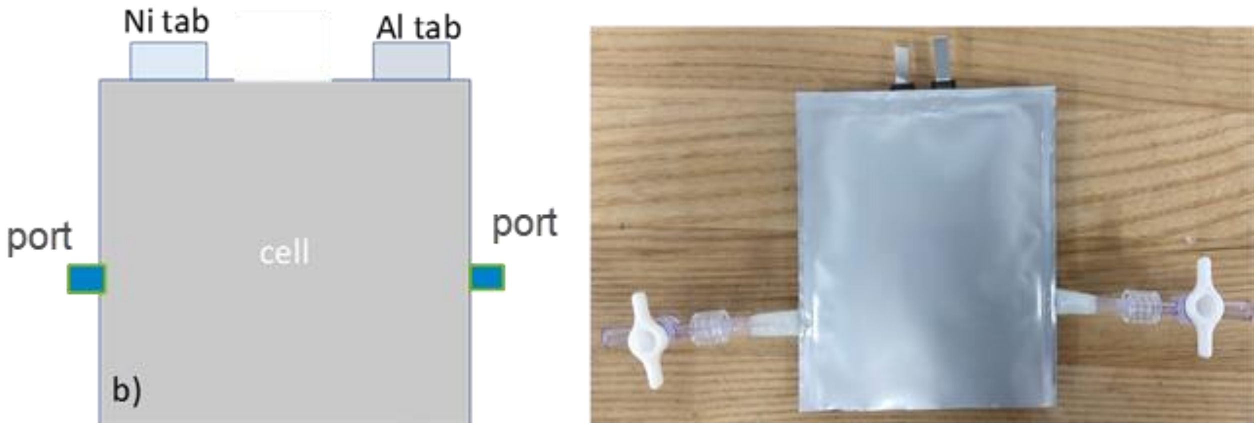
Design for Recycling, Remanufacturing, and Reuse

Example: Electrode and electrolyte flush

- New cell design - Joint project of Argonne and Oakridge National Laboratories
- Enabling cell flushing for rejuvenation

Potential Impact:

- Reduced cost of recycling
- Overall cost reduction
- Reduced number of cells reaching end of life
- Extended cell life for primary- or second-use applications



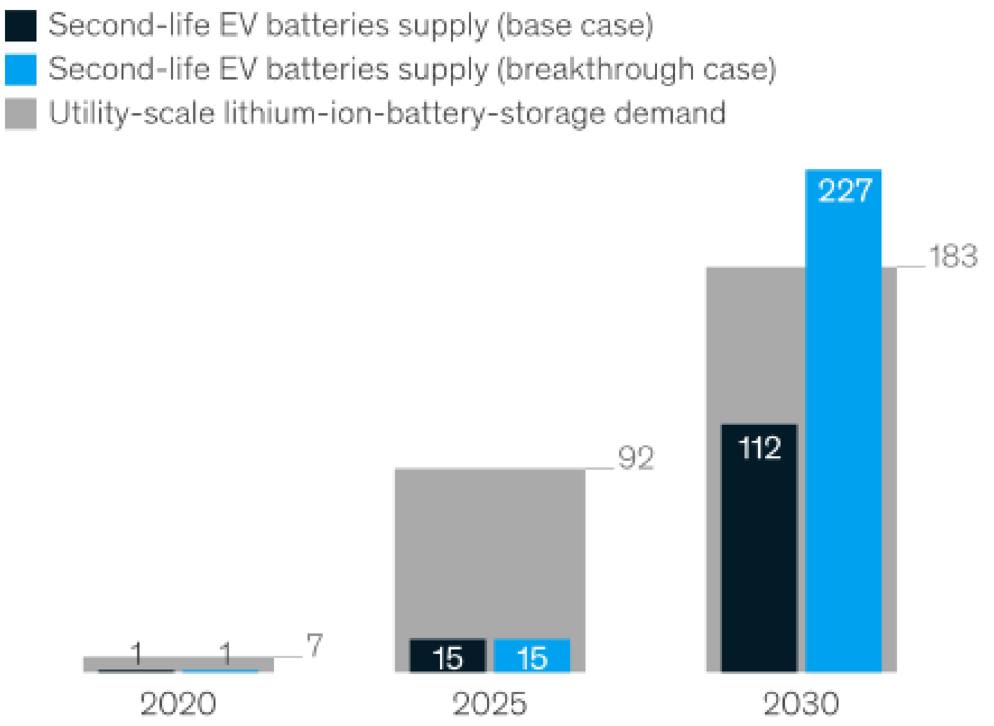
Initial design that will be used to determine pressures and flows needed to “rinse” cells

Gaines, L. (2020). Presentation at Transportation Research Board Conference, Workshop on Battery Recycling.

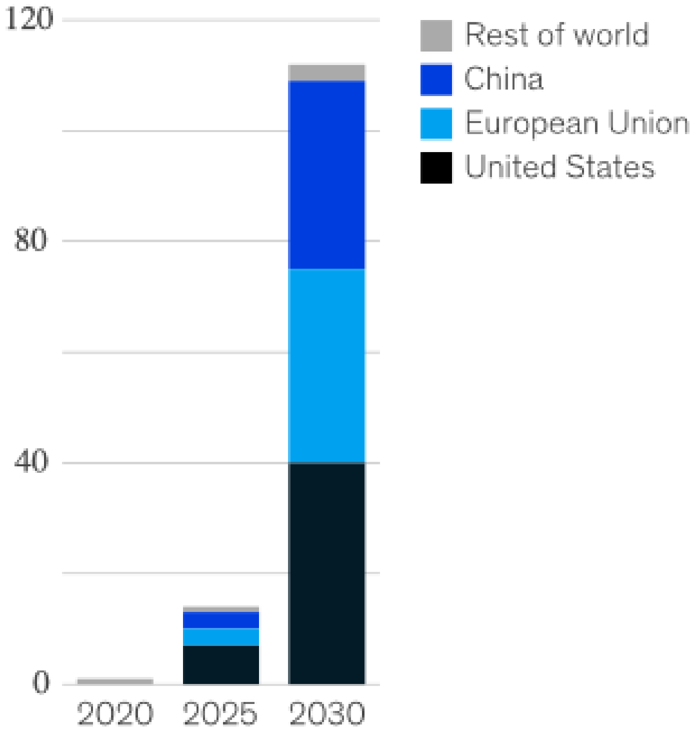
Battery Reuse

Second-life lithium-ion battery supply could surpass 200 gigawatt-hours per year by 2030.

Utility-scale lithium-ion battery demand and second-life EV[1] battery supply,[2] gigawatt-hours/year (GWh/y)



Second-life EV battery supply by geography (base case[2]), GWh/y



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[1] Electric vehicle.
[2] Only for batteries from passenger cars.

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

Battery Reuse

Key Questions:

- Data, testing, and repurposing costs
- Reliability and performance
- Competition

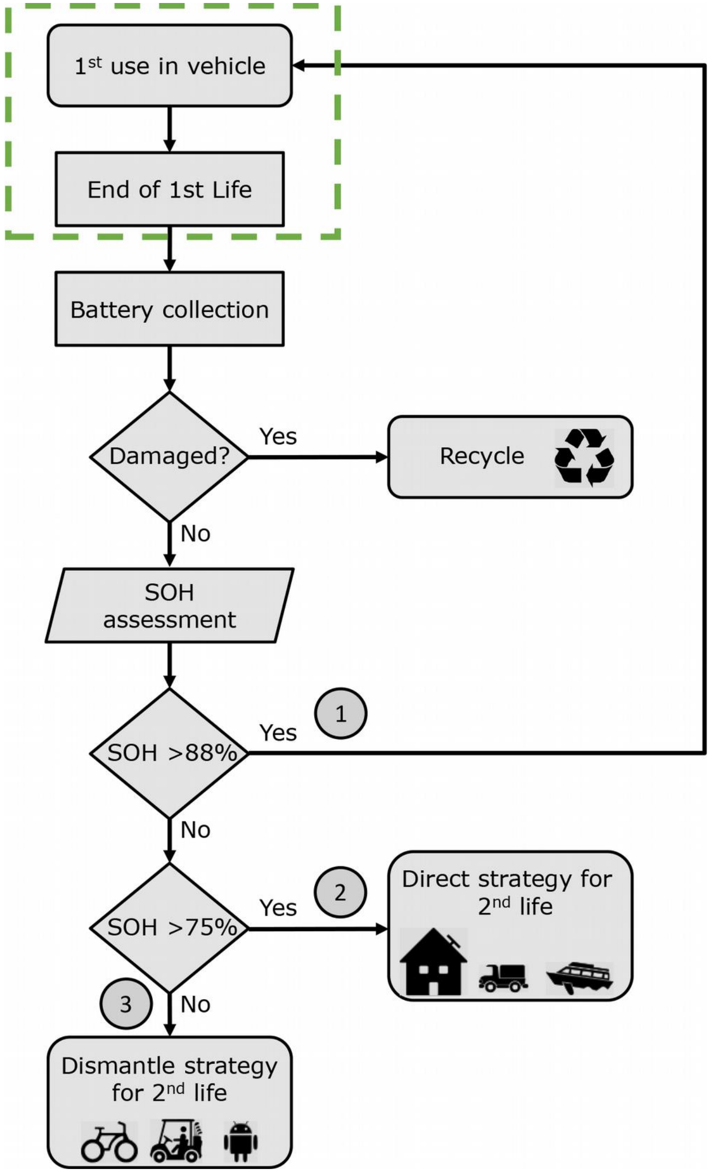
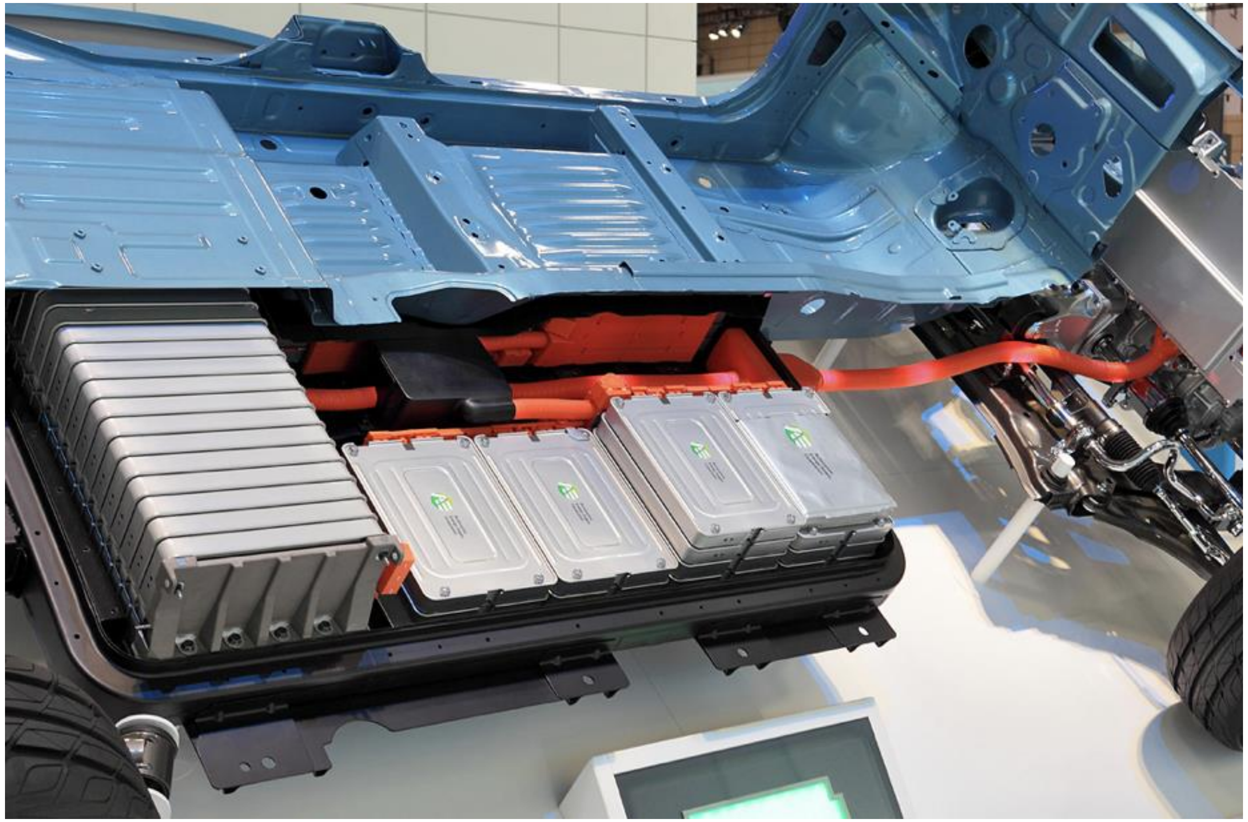


Figure 2. Decision making flow diagram for batteries at the end of its 1st life on EVs

Casals, L. C., García, B. A., & Cremades, L. V. (2017). Electric vehicle battery reuse: Preparing for a second life. *Journal of Industrial Engineering and Management*, *10*(2), 266-285.

Lead Battery Recycling: A Good Example?



https://circuitdigest.com/tutorial/lead-acid-battery-working-construction-and-charging-discharging

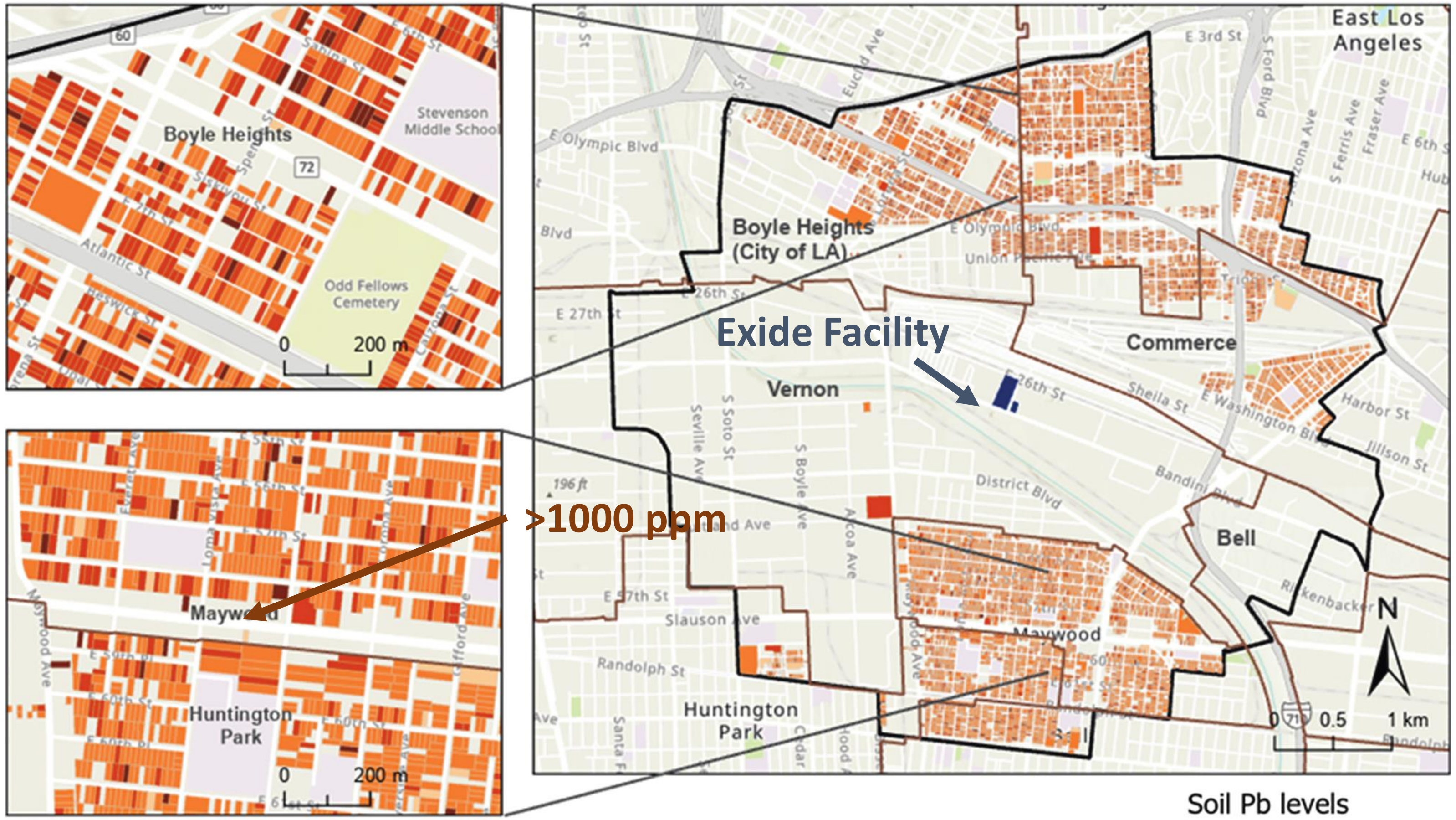
https://en.wikipedia.org/wiki/Electric_vehicle_battery

Yes and no…

- In 2018, ~70% of lead consumed in the US came from secondary (recycled sources).
- ~27 million spent lead acid batteries were exported to low and middle income countries
- There as many as 30 thousand sites for informal lead acid battery recycling globally.

Ericson, B., et al. (2016). The global burden of lead toxicity attributable to informal used lead-acid battery sites. *Annals of global health*, *82*(5), 686-699.

United States Geological Survey. Lead statistics and information. http://minerals.usgs.gov/minerals/pubs/commodity/lead/

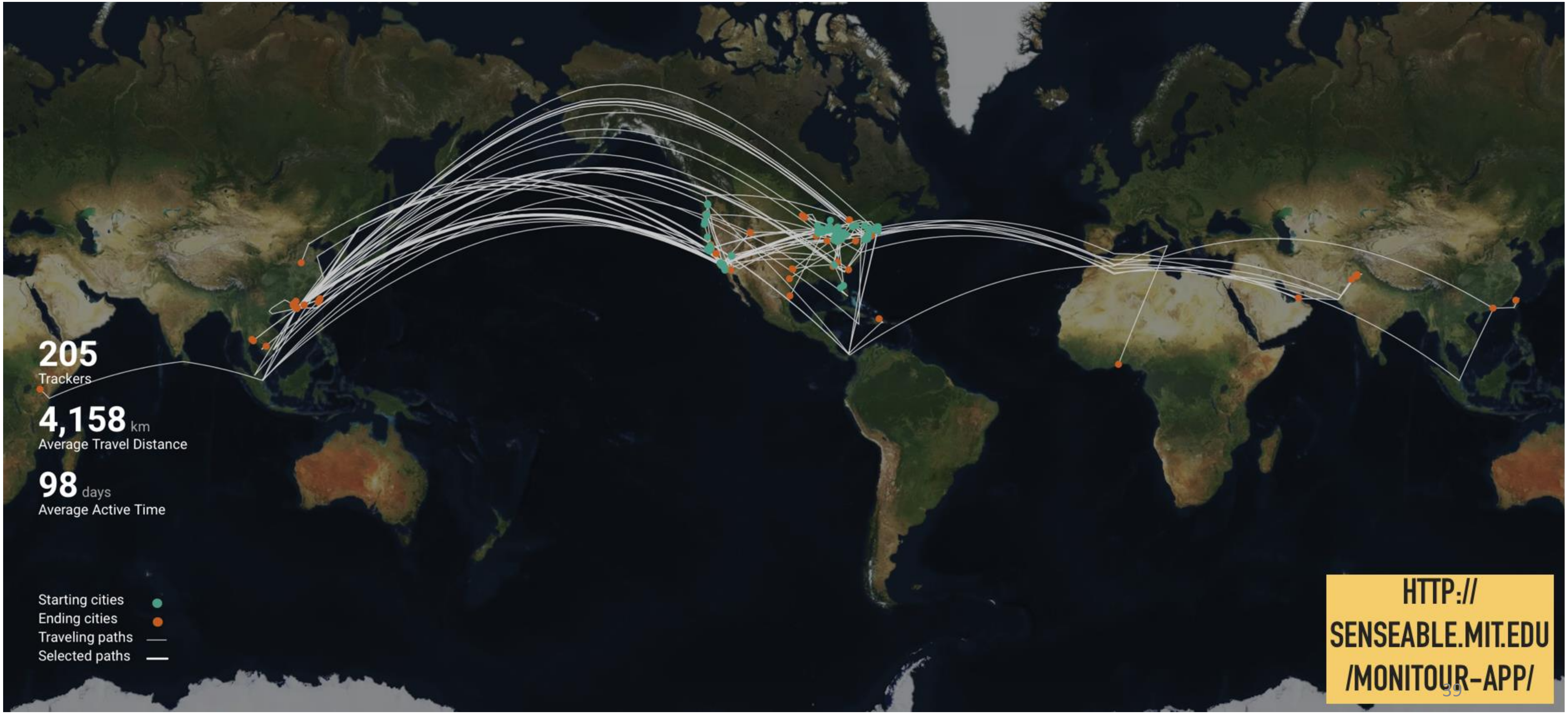


>1000 ppm

- Lead soil contamination is a legacy issue for the South Coast Basin
- Over 25% of properties surveyed around Exide battery recycling facility exceeded clean-up threshold (400 ppm lead in soil).

Wu, A. M., & Johnston, J. (2019). Assessing Spatial Characteristics of Soil Lead Contamination in the Residential Neighborhoods Near the Exide Battery Smelter. *Case Studies in the Environment*.

Global value chains for e-waste



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