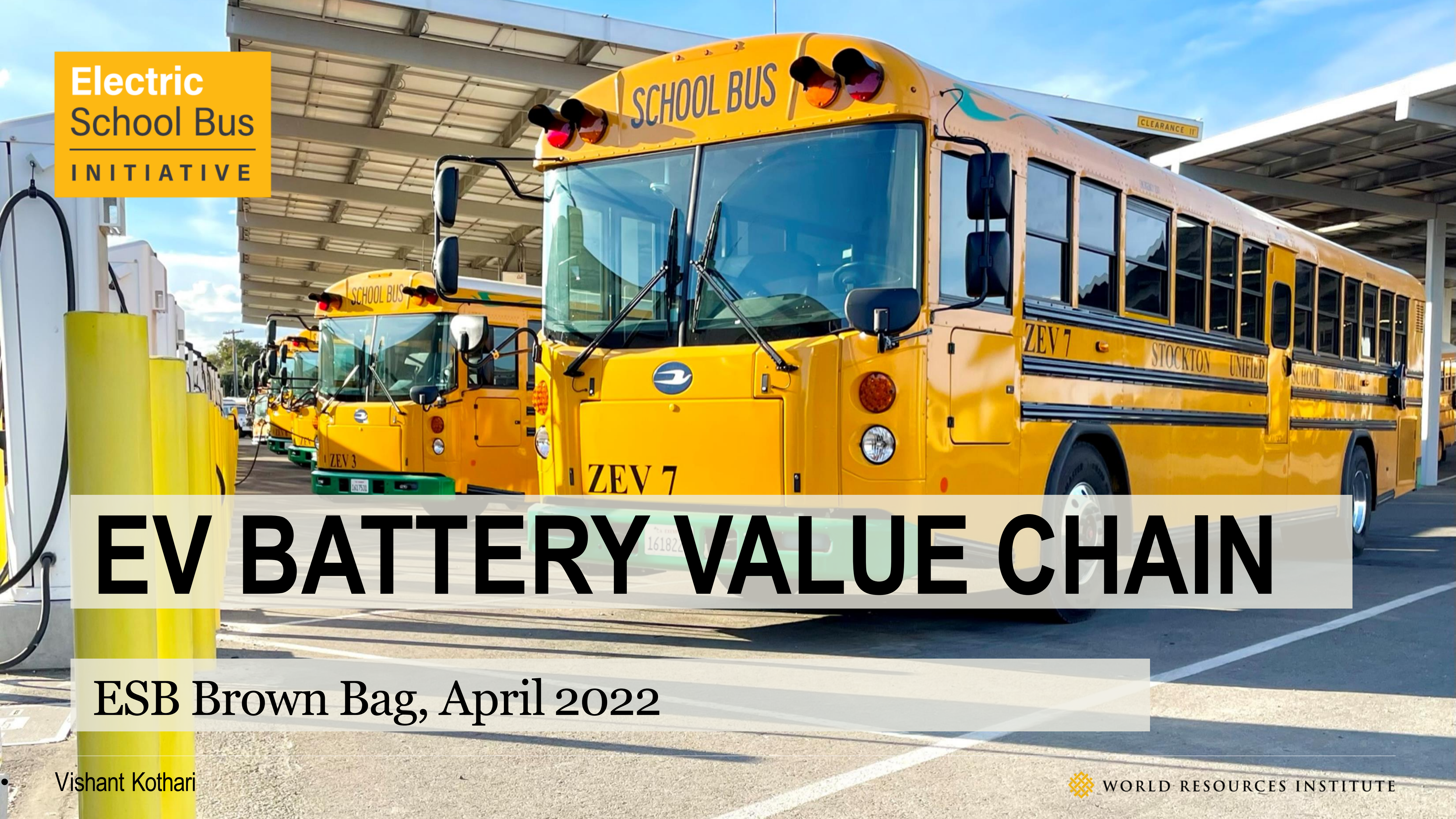
Electric School Bus INITIATIVE



EV BATTERY VALUE CHAIN

ESB Brown Bag, April 2022

• Vishant Kothari

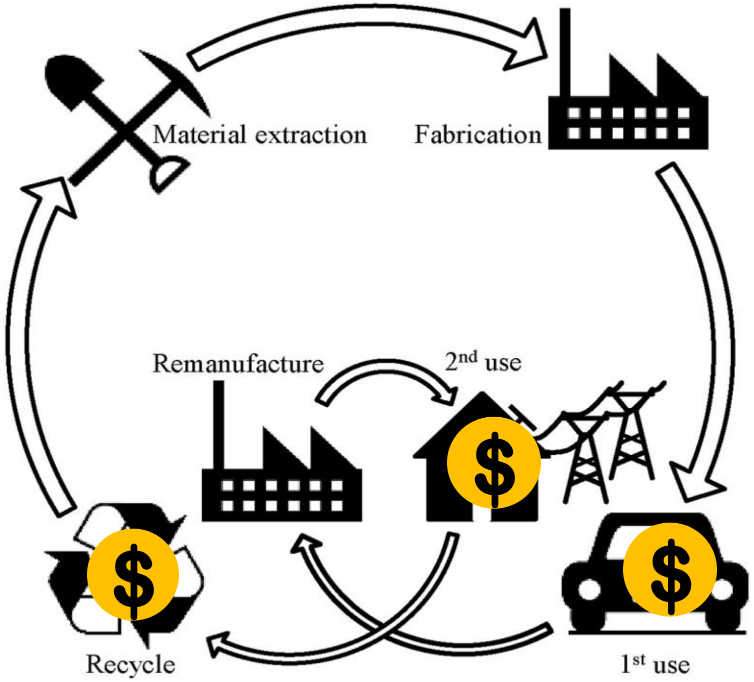
WORLD RESOURCES INSTITUTE

WHY SHOULD WE CARE?

1. **Batteries are necessary for addressing the climate challenge**
   - Up to 30% transport & power sector emissions reductions
   - Access to electricity to 600 million people
   - Create ~10 million jobs globally

2. **Batteries have a significant impact on vehicle (EV) price**
   - Batteries comprise 30-40% of ESB price
   - Light commercial EV batteries last 8-10 years during first life
   - Used EV batteries still possess 60-80% of their original capacity
   - Three-tiered value chain for batteries:
     - Vehicle > Second-Life > Recycle

3. **Batteries are primarily developed by mineral extraction**
   - Battery upstream and downstream practices can lead to adverse social, environmental, economic impacts.



Source: Casals, Garcia, & Canal 2018; Center for Sustainable Energy 2016; GBA

THIS PRESENTATION

EV battery value chain

- Baseline trends
- EV battery types
- Upstream – mining and processing
- Environmental impacts
- Social impacts
- Downstream – second life use and recycling

Potential role that WRI-ESB can play

Deep-dive into mining practices, challenges and issues

Industrial processing methods for minerals

Commodity price fluctuations and market economics

Global landscape of battery manufacturing

Batteries for energy security

LEARNING OBJECTIVES

1. Develop awareness on global battery trends
2. Understand how a battery works and what they are made of
3. Gain knowledge about battery manufacturing processes and stakeholders
4. Understand barriers and opportunities for second-life use and recycling

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EV BATTERY VALUE CHAIN

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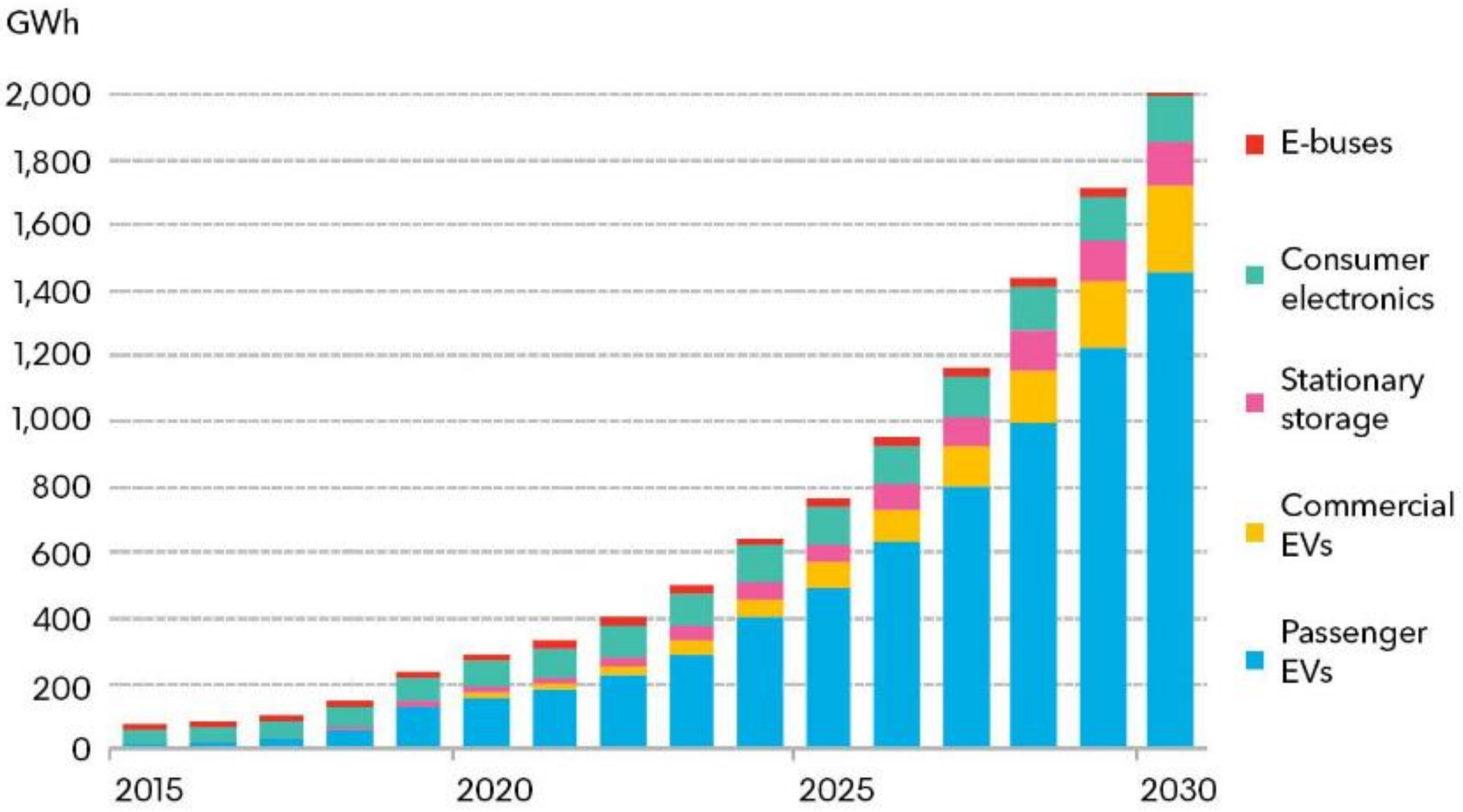
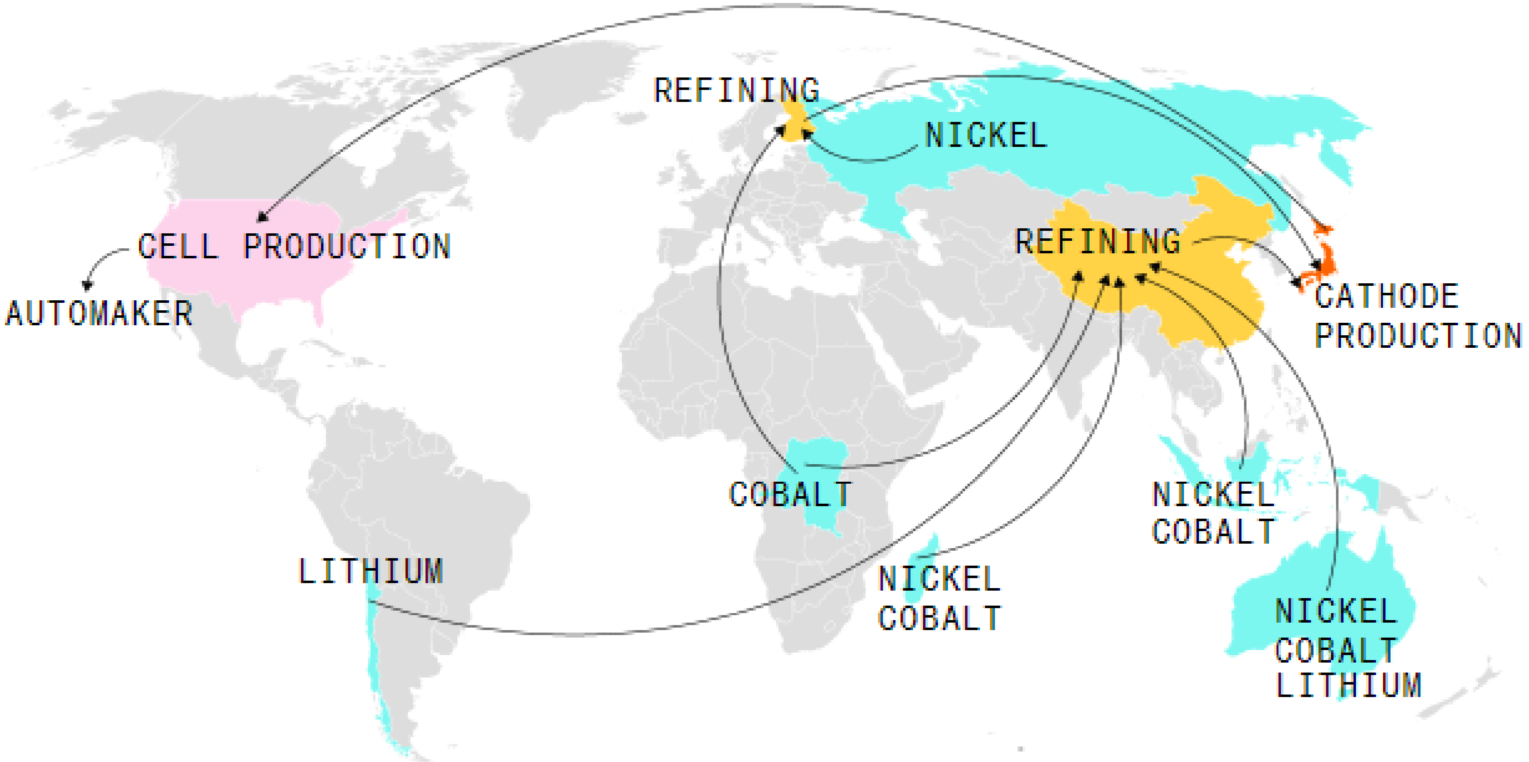
BASELINE

LI-ION EV BATTERY DEMAND IS INCREASING

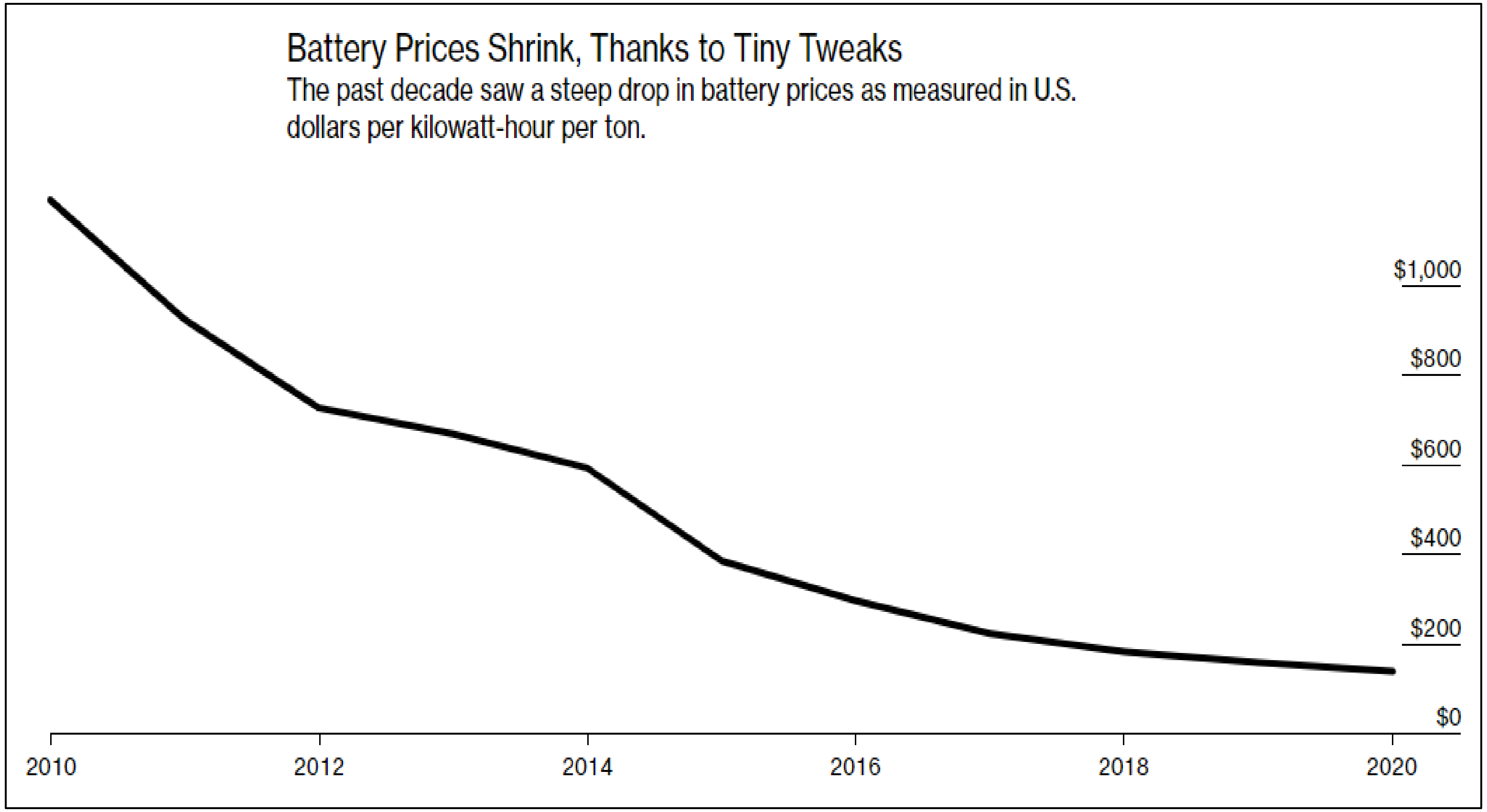


Sources: Data from Bloomberg

BATTERY MANUFACTURING IS DEPENDENT ON GLOBAL SUPPLY CHAINS



BATTERY PRICES ARE FALLING (GENERALLY)



World of Statistics
@stats_feed

Lithium price ($/tonne):

2022: $78,032
2021: $17,000
2020: $6,800
2019: $11,310
2018: $14,660
2017: $12,070
2016: $8,840
2015: $5,110
2014: $4,680
2013: $4,750
2012: $4,450

4.9x

3.8x

Source: Bloomberg

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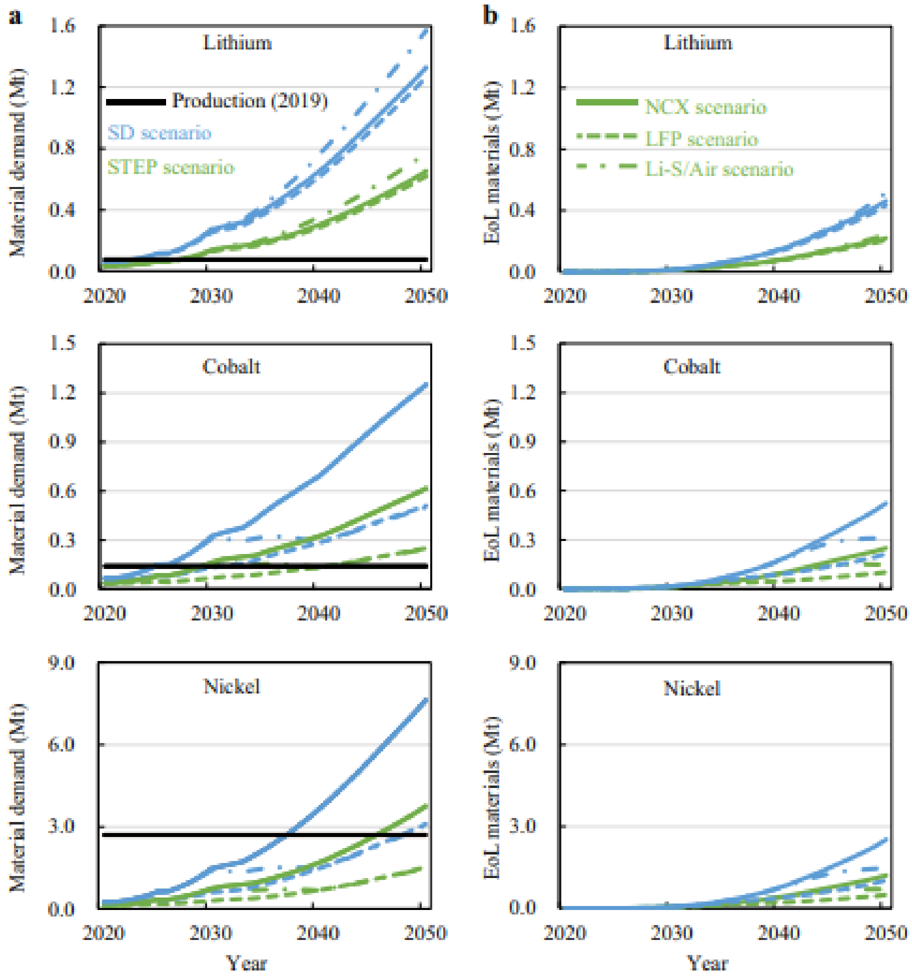
BATTERY RECYCLING AND SECOND-LIFE USE WILL BE NECESSARY



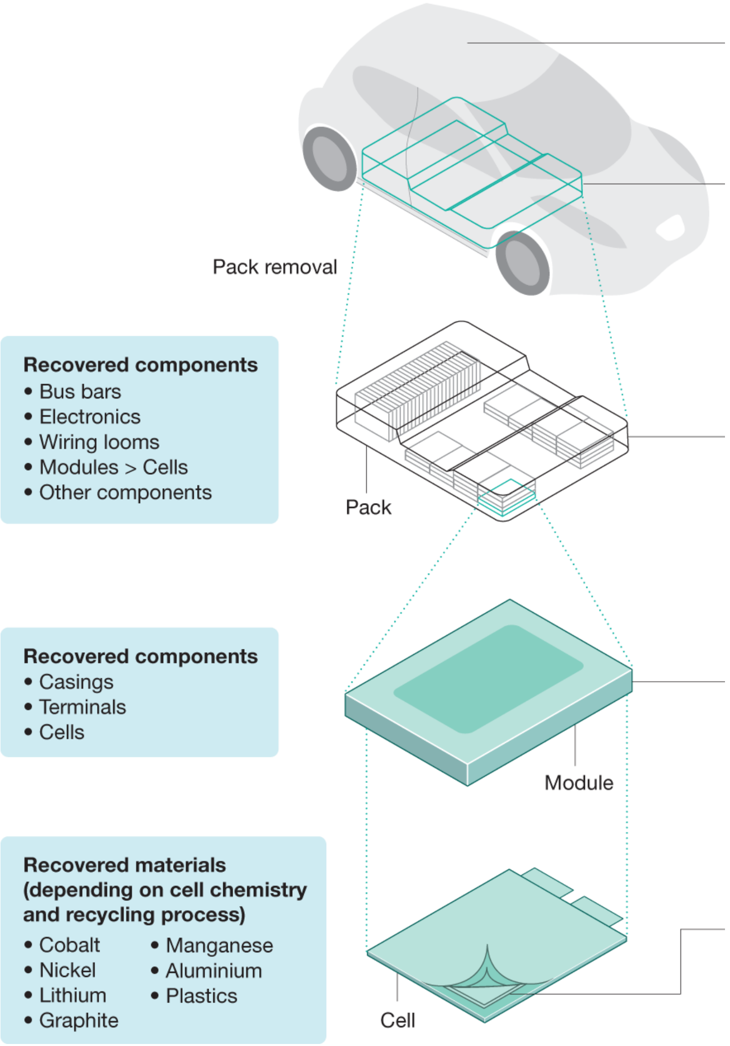
"Recycling electric vehicle batteries specifically **can reduce the need for new mining by between 25% and 55%** depending on the mineral by 2040.

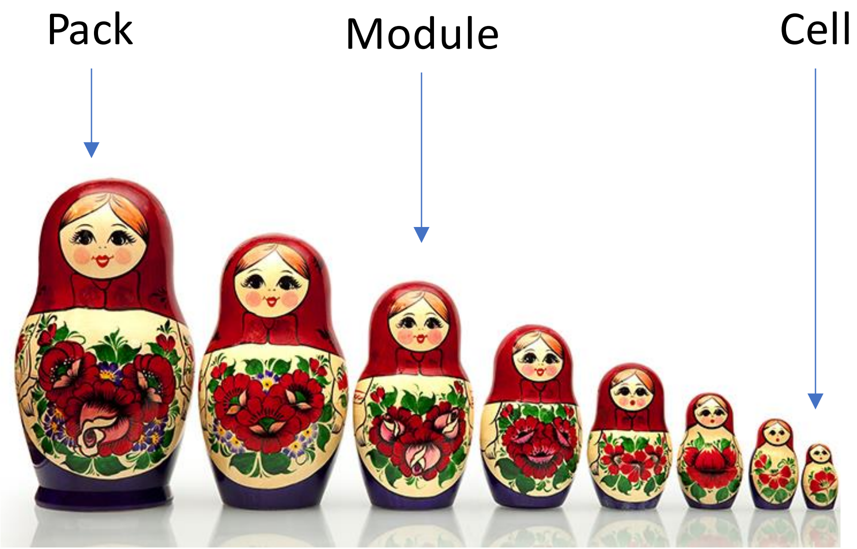
So, we need to be thinking not only about mining but about alternative sources for these minerals"

- Earthworks

Source: Nature; Podcast episode

EV BATTERIES ARE MADE OF SMALLER PARTS



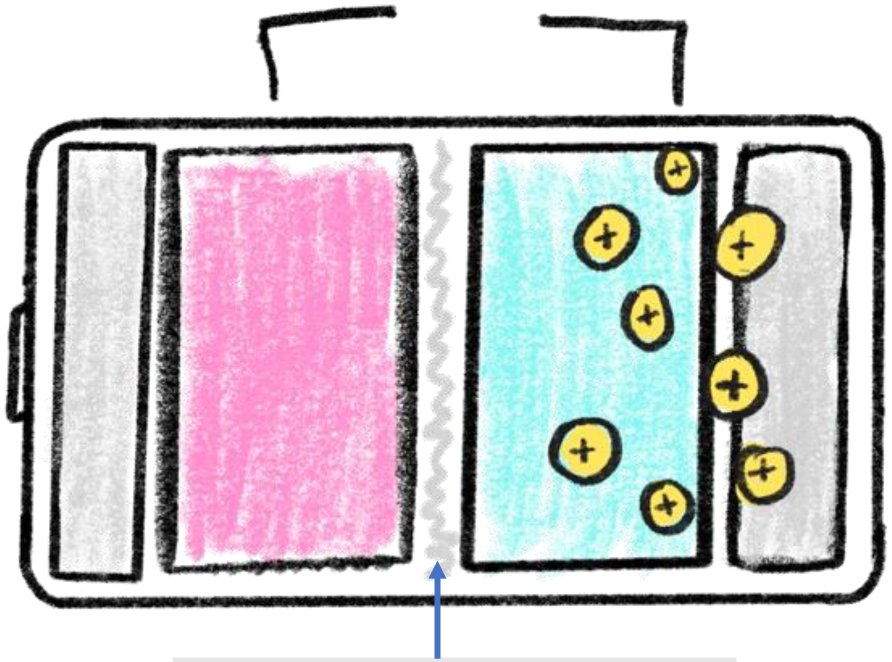


Source: Nature

HOW DOES AN EV BATTERY WORK?

When a battery is charged, ions flow from the cathode to the anode. When it's discharged, the ions reverse course.

CATHODE
- Li-Metal oxides
  - Nickel
  - Cobalt
  - Iron
  - Phosphorus
  - Manganese
- Primary recyclable material of the cell



ANODE
- Graphite, Zinc

SEPARATOR
- Prevents contact of the cathode and anode

ELECTROLYTE
- Help move Li-ions
- Traditionally in liquid-form (water, acids, alkalis)

Source: [Bloomberg](); [Univ of Washington]()

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CATHODES

COMMON CATHODES

Lithium-cobalt oxide (LCO)

Lithium-nickel-cobalt-aluminum (NCA)

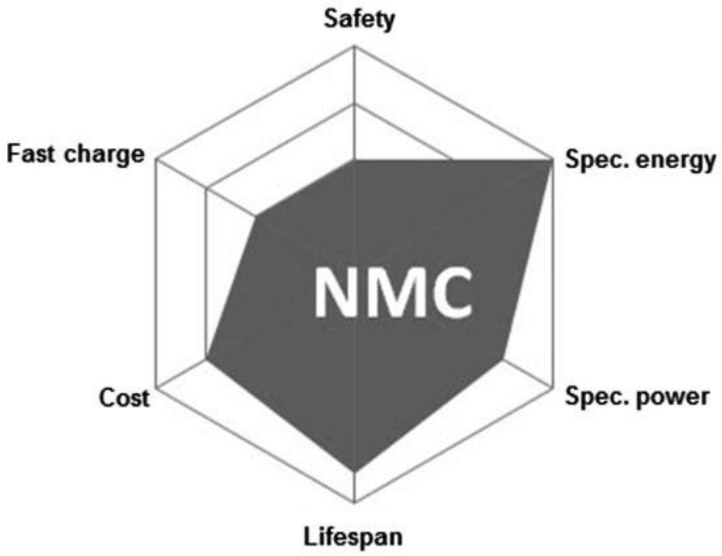
Lithium-nickel-manganese-cobalt (NMC)

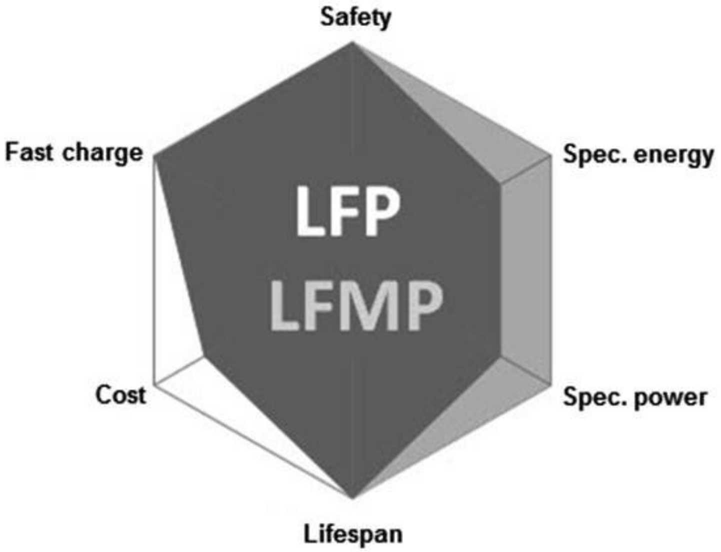
Lithium-manganese-spinel (LMO)

Lithium titanite (LTO)

Lithium-iron phosphate (LFP)

COMMON CATHODES





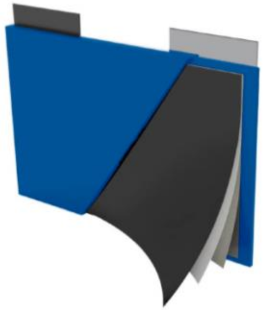
NMC (111, 622, 811) – Lithium nickel manganese cobalt oxide

- Three active ingredients are nickel, manganese and cobalt
  - Sometimes used in equal parts, but trend towards more nickel and less cobalt
- All NMCs still do not provide sufficient cycle length for e-buses
- **Preferred candidate for most EVs**
- **Economical, lowest self-heating rate, good performance**
- Used by the Tesla powerwall

- **Good electrochemical performance** with low resistance
- High current **rating and long cycle life, good thermal stability, enhanced safety and abuse-tolerant**
- Higher self-discharge than other li-ion batteries, causes balancing issues with ageing
  - Can be mitigated with high quality cells and/or control electronics – both of which increase the cost of the battery
- Excellent safety
- **Does not contain cobalt**

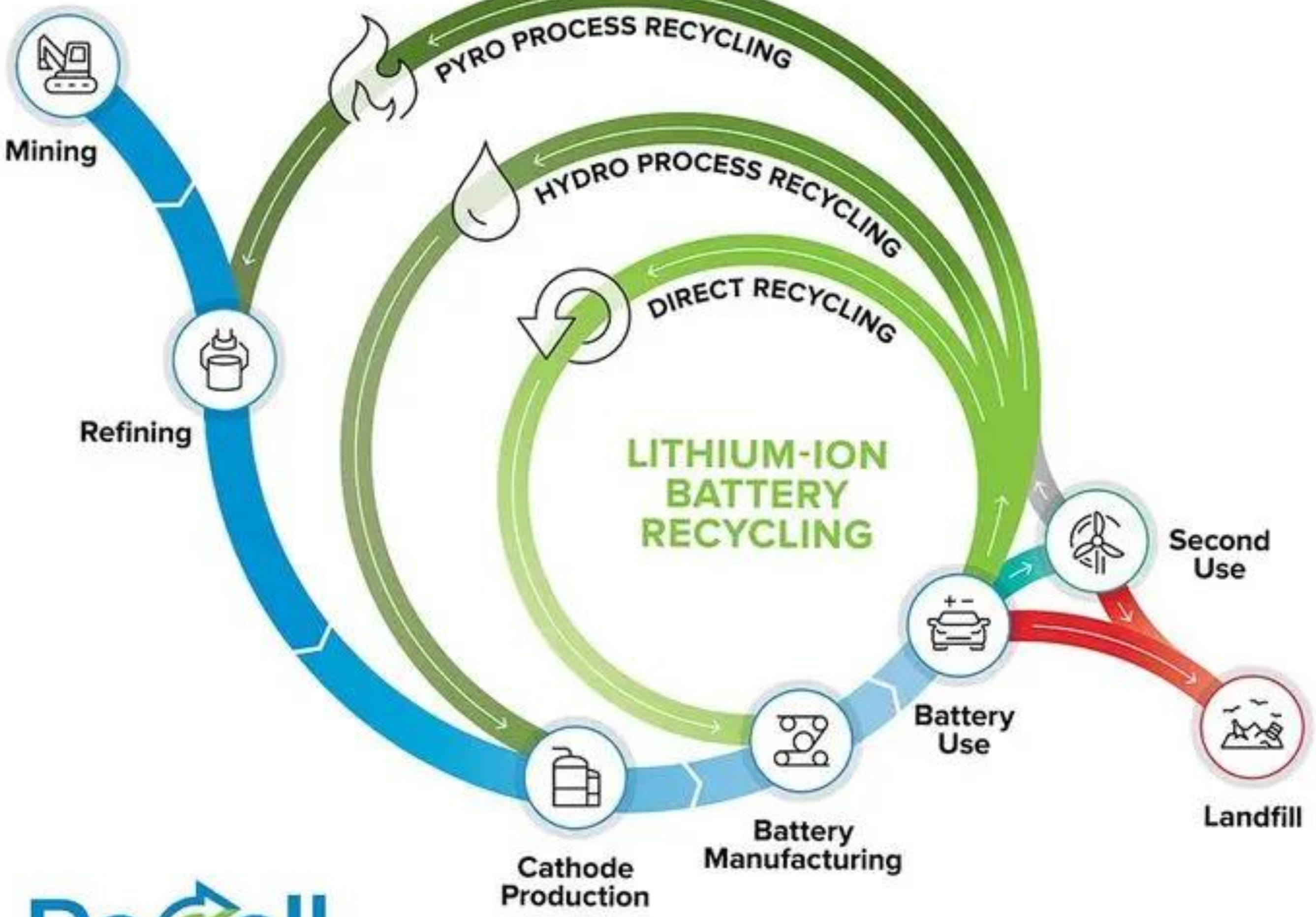
Source: Cathode comparison

COMMON CELL SHAPES

Cell Types	Image	Characteristics
Cylindrical		▪ Cell can tolerate a higher internal pressure without deformation ▪ Packaging density of cylindrical cells is low, easy thermal management ▪ Commonly found in medical instruments, laptops, e-bikes, and power tools, Tesla vehicles
Prismatic		▪ Edges can get deformed easily due to high stress cells ▪ Higher packaging density, challenging thermal management ▪ Commonly used in laptops, cell phones and most EV types
Pouch		▪ Uses flexible foil as packaging material that saves space, however designers must allocate space for swelling. ▪ Poor thermal management, high risk ▪ Used by EV OEMs, but fast changing.

Sources: Circuit; Battery University

LITHIUM-ION
BATTERY LIFECYCLE



ReCell
ADVANCED BATTERY RECYCLING

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

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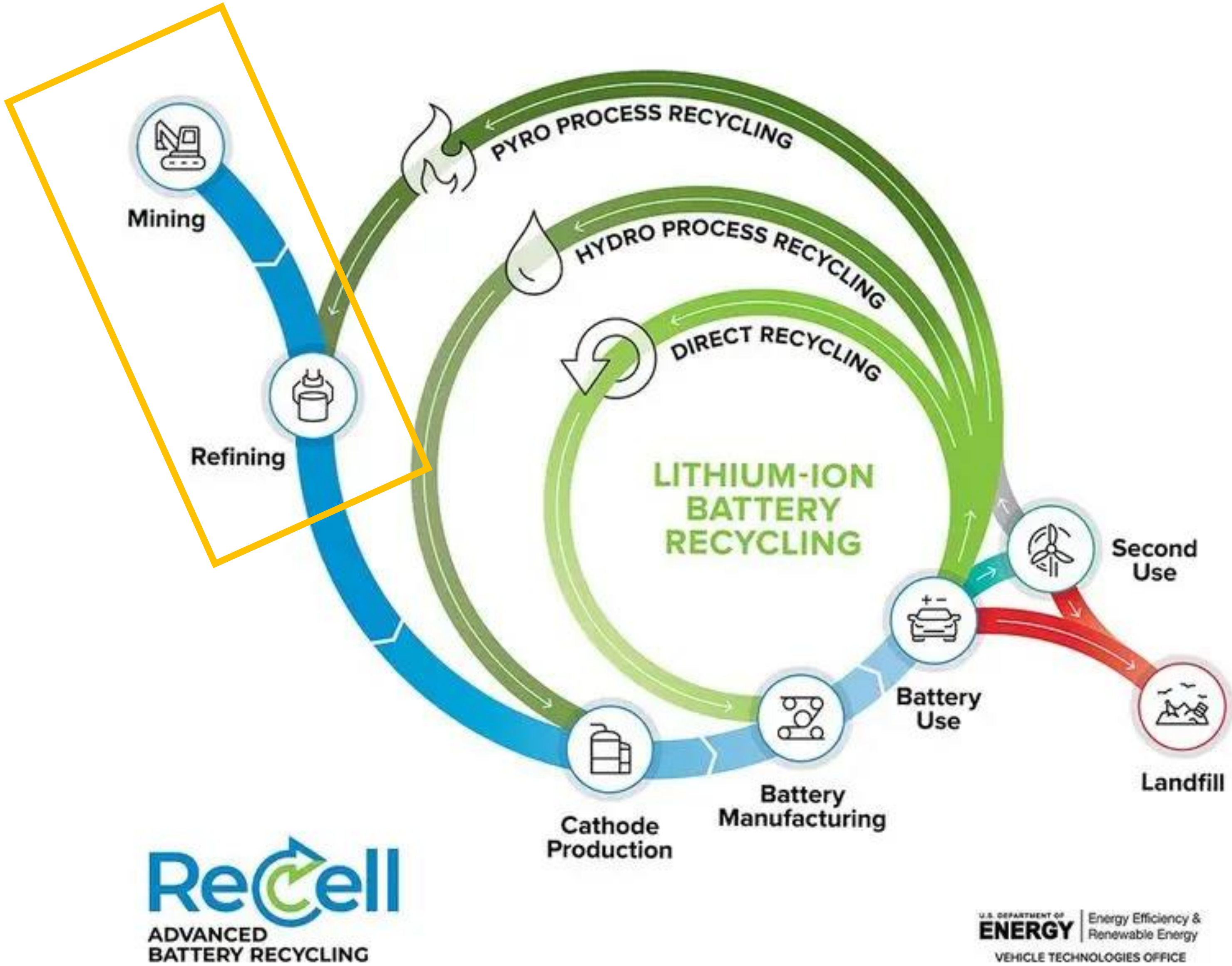
SUPPLY CHAIN: UPSTREAM

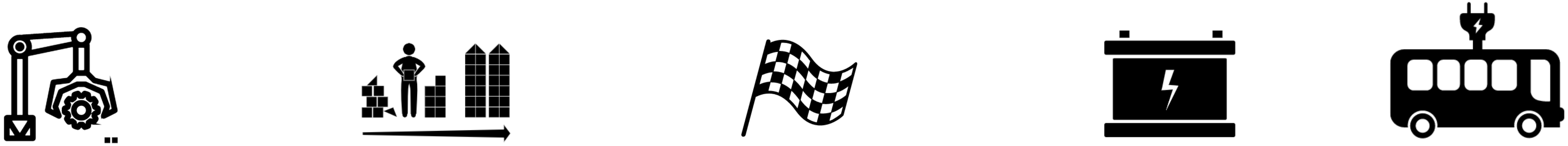
LITHIUM-ION
BATTERY LIFECYCLE



BATTERY MINERALS

Lithium	Nickel	Cobalt
Manganese	Iron	Phosphorus

LI-ION BATTERY CELL PRODUCTION PROCESS



Electrode Manufacturing → Cell Assembly → Cell Finishing → Pack Assembly → Vehicle

Process intensive across a global supply chain – data transparency is essential

Engaging siloed industries – mining and OEMs – will need coordination and regulation

Source: Aachen University; CalEPA report

LI-ION BATTERY CELL PRODUCTION PROCESS

Electrode Manufacturing → Cell Assembly → Cell Finishing → Pack Assembly → Vehicle

	Electrode Manufacturing	Cell Assembly	Cell Finishing	Pack Assembly	Vehicle
PROCESSES	• Mixing • Coating • Drying • Calendering • Slitting • Vacuum Drying	• Separation • Stacking • Packaging • Electrolyte filling • Winding • Packaging	• Roll Pressing • Formation • Degassing • Aging • EOL Testing	• Cell unpacking • Testing • Building modules • Modular assembly • Packing into packs	• Testing • Fitting • Certification • QA
STAKEHOLDERS	• Mining companies • Shipping companies • Cell manufacturers	• Cell manufacturers • Vehicle OEMs	• Cell manufacturers • Vehicle OEMs • Transport companies	• Pack suppliers • Vehicle OEMs • Transport companies	• Pack suppliers • OEMs

Source: Aachen University; CalEPA report

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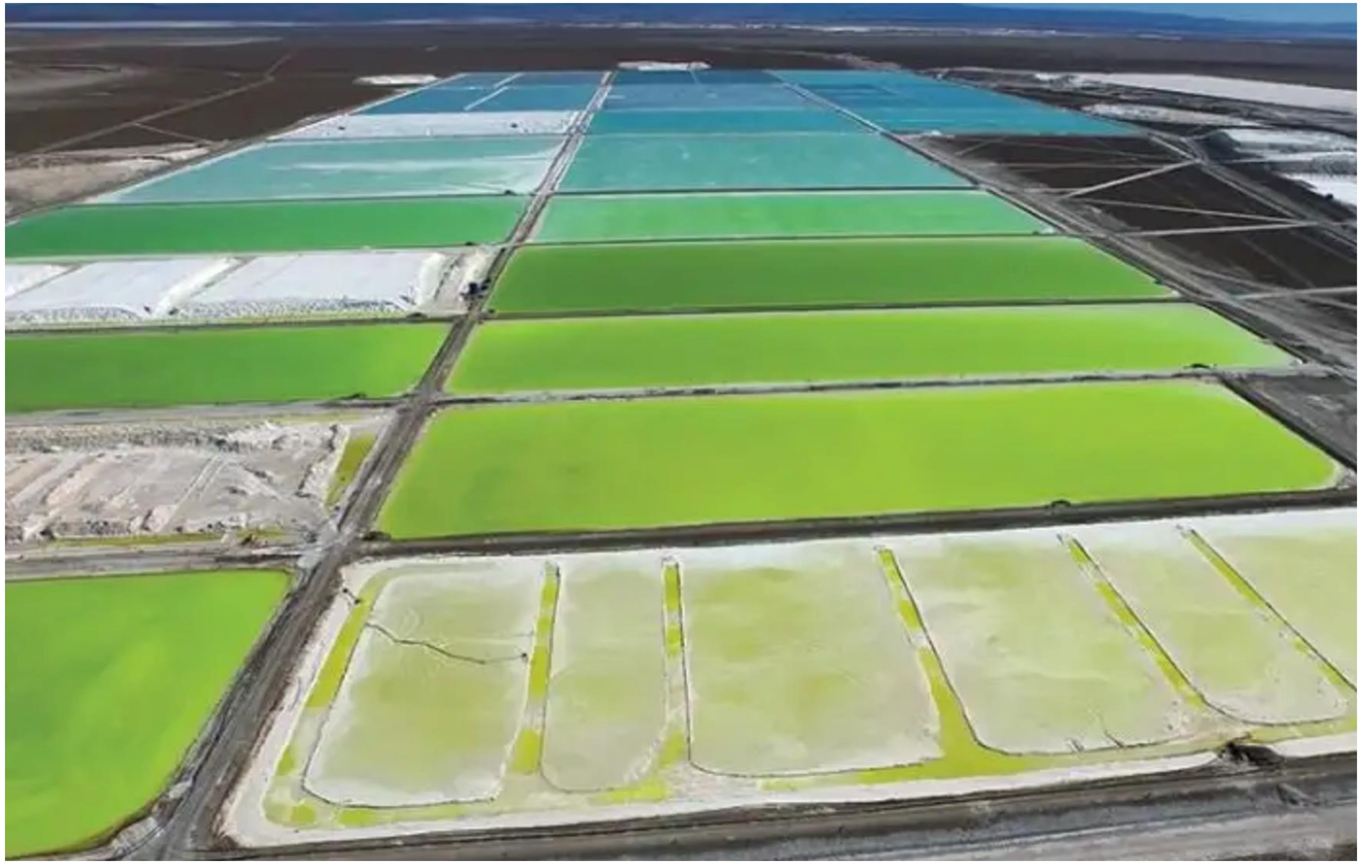
ENVIRONMENTAL IMPACTS - WATER

- Mining for the minerals used in batteries often leads to adverse environmental impacts including contamination and overuse of surface and groundwater, soil erosion, air pollution, and loss of biodiversity.

- **Brine pool lithium extraction:** More than half of the world's supply lies in underground pockets of water beneath the salt flats of the lithium triangle (Chile, Argentina, Bolivia) in South America, an already arid and drought-ridden region.
  - Up to half a million gallons of water are pumped from the ground and evaporated out to produce a ton of lithium in the lithium triangle.
  - Toxic chemicals such as hydrochloric acid leak from evaporation pools into water supply.



Sources: IER; GTM

ENVIRONMENTAL IMPACTS - WATER

- In other regions of the world, such as Australia, the world's largest lithium producer, **lithium** is extracted from **hard rock mining**.
  - Water is used at mine sites to grind and separate minerals from ore, wash and transport materials, control dust, and cool drilling machinery, as well as for froth flotation to concentrate lithium.
- At the **processing** stage (mainly in China), chemicals such as sulfuric acid and waste products end up in tailings ponds with the potential to leak into surface and groundwaters.
- Other key battery minerals such as **cobalt** also pose risks to freshwater resources.
  - **Acid mine drainage** often occurs at cobalt mines, particularly in the Democratic Republic of Congo, whereby sulfuric acid is generated when sulfur minerals present at the mine sites are exposed to air and water. The acidic water dissolves heavy metals from surrounding rock, leading to toxic concentrations of zinc, lead, arsenic, etc. and damaging rivers, streams and aquatic life.
- More research is needed to better quantify the water quantity- and quality-related risks that mining activities pose to freshwater resources.

Sources: IER; EPA; BGS; UNCTAD

SOCIAL IMPACTS FROM BATTERY MANUFACTURING ARE SIGNIFICANT

- Adverse impact on indigenous people in Chile, US and other mining locations.

- About 20% of cobalt sourced from Congo comes from artisanal mines, where some 40,000 children work in extremely dangerous conditions.

- Increasing the share of domestic battery manufacturing in the model from 25 percent (base model assumption) to 50 percent and then 75 percent in the net-zero scenario leads **to an additional 850,000 and 1.7 million jobs, respectively** (Devashree, 2022).

- Training and education will be essential to build the talent pool necessary
  - Ensuring worker safety while battery handling will be critical (as this is largely an informal sector).

- **Regulation and data transparency** will be essential in helping overcome adverse social impacts from battery mining.

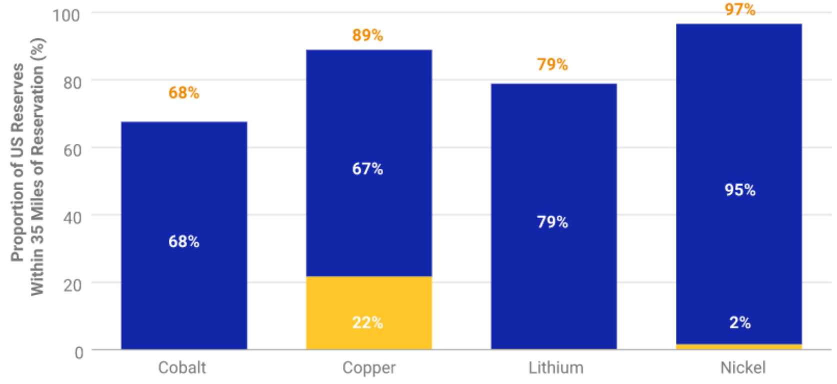
Sources: UNICAD; McKinsey

UPSTREAM REGULATIONS REFORM

- EPA could close the loophole where Clean Water Act allows mining waste to be dumped into streams, wetlands, and rivers.
- Congress could reform General Mining Law of 1872
  - USDA & DOI should strengthen regulations on mining on public lands
- Mandating IRMA (Initiative for Responsible Mining Assurance) for US companies & federal government.
- Possible upcoming battery circularity legislation.

Source: Earthworks

GLOBAL PICTURE



- Mining practices need to be reformed around the world
  - Impact on indigenous communities in areas, such as Chile
  - In the US, mining disproportionately harms indigenous people.
- Investments will need to reach early-mid stream to have a sizable impact
  - While upwards of $500bn has flowed into building the 285 gigafactories around the world – and $150bn last year alone – critical mineral mines and mid stream processing plants have not seen anywhere like this type of investment. (Benchmark Minerals)
- Regulations can drive meaningful change
  - EU Draft legislation for battery circularity has the support of battery manufacturers as well.

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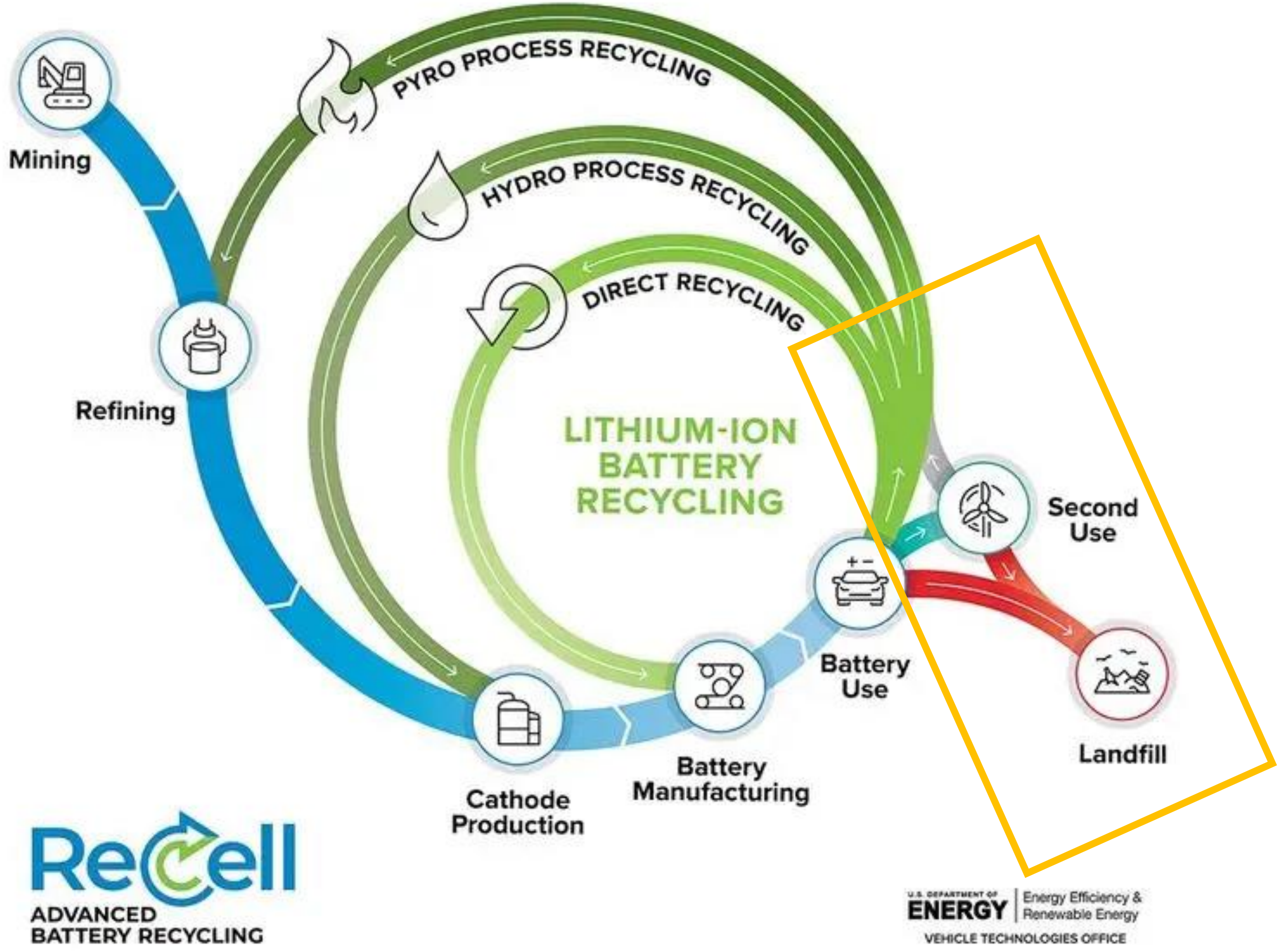
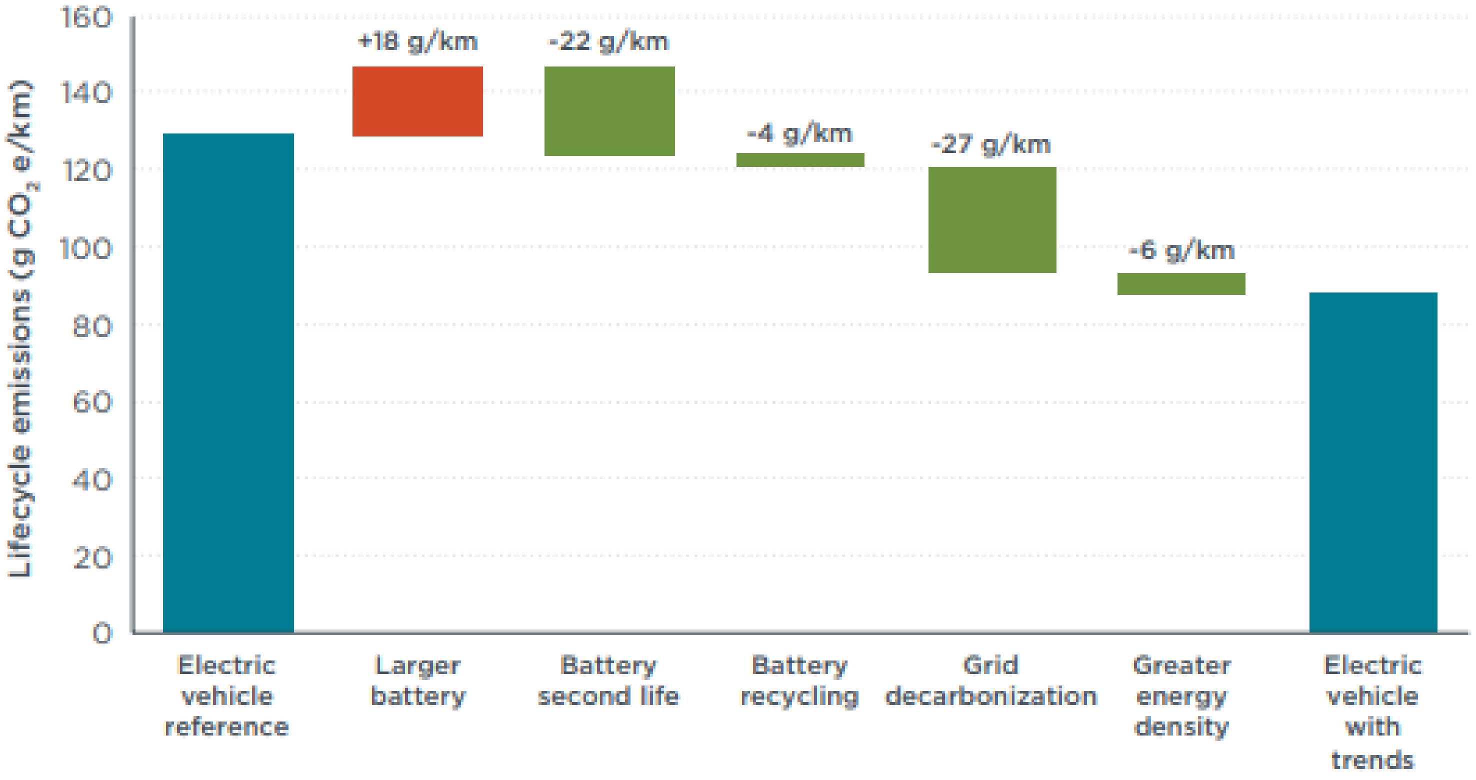
DOWNSTREAM: SECOND LIFE AND RECYCLING

LITHIUM-ION
BATTERY LIFECYCLE



LIFECYCLE EMISSIONS REDUCTION POTENTIAL



- The automotive battery capacity available for repurposing will grow by **560% by 2030.**
- Second life battery capacity could account for about **17% of all energy storage.**
- Recent **research identified 95% recyclability** for the cathode material.

Source: [ICCT, 2019]; [IEA]; [BNEF; Argonne]

SECOND-LIFE EV PRODUCTION PROCESS

Vehicle-Battery Separation → Transport → Testing & Grading → Remanufacture/ Refurbish → Second Life

Key considerations:

- Variable chemistries
- Battery Management Systems
- Battery health
- Safety
- Variable requirements for second use

Key stakeholders:

- Vehicle OEMs
- Fleet managers/owners
- Battery collectors and dismantlers
- Transportation provider
- Second-life battery producer and purchaser

Source: Authors interview notes

SECOND LIFE USE APPLICATIONS ARE PLENTIFUL

Provide low- to **zero-emission peaking services to electric utilities, reducing cost, use of fossil fuels and greenhouse gas emissions**

- Behind the meter (BTM) storage services
- Front-of-the-meter (FTM) storage services
- Telecommunications and data center back up
- EV charging for DCFC
- Low power EVs

Source: NREL; Argonne

BARRIERS AND OPPORTUNITIES TO SECOND-LIFE USE OF EV BATTERIES

BARRIERS

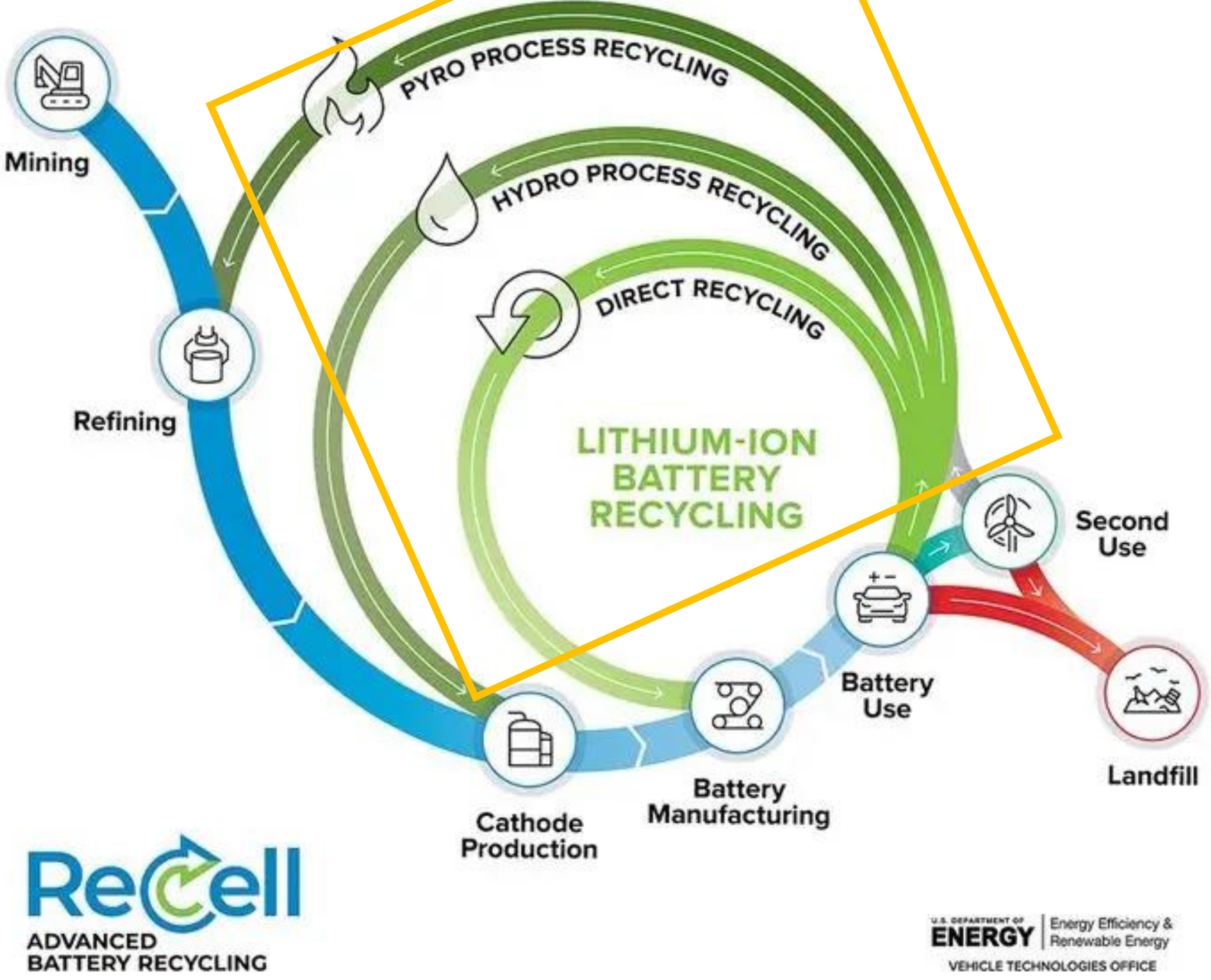
- Limited data across different battery pack designs
- Falling costs of batteries
- Second-life use standards for reliability, capacity, testing
- Non-existent or nascent regulation for EV batteries repurposing
- EV batteries are considered Class 9 hazardous materials, making its transportation challenging

OPPORTUNITIES

- Advantageous in the clean energy transition.
- Regulation to define second-life use, reliability, battery health standards, etc.
- Automakers under pressure to unlock value in used batteries. E.g. GM, VW.
- More use cases, commitments, start ups

Source: McKinsey; GTM

LITHIUM-ION
BATTERY LIFECYCLE



RECYCLING PROCESSES

Battery recycling has three general stages:

- **Pretreatment** primarily consists of mechanically shredding (to form 'black mass') and sorting plastic and metal materials.
- **Secondary treatment** involves separating the highest value materials in the cathode from the aluminum collector foil with a chemical solvent.
- The final step is **separating the cathode materials** through leaching chemicals ("hydrometallurgy"), electrolytic reactions, and/or heat treatment ("pyrometallurgy" or "smelting")

TYPES OF RECYCLING PROCESSES

Process	Characteristics
Direct Recycling	▪ Cathodes are generally heavier and sink, making separation between them hard (E.g. NMC v/s NMO). ▪ Uses a froth floatation concept, one cathode floats due to water repellent solution. ▪ Most environment friendly, least commercially viable currently
Hydro-metallurgical	▪ Black mass is treated with solvents. ▪ Process usually involves leaching and reduction - acid leaching and biological leaching according to the leaching method. ▪ Detrimental water impacts.
Pyro-metallurgical	▪ Batteries are reduced by preheating, pyrolysis and smelting, successively. ▪ Furnace temperatures go to 700 C in order to separate the plastic and metal alloys. ▪ Energy intensive process

Source: Argonne; Science

NET PROFITS FROM DIFFERENT CHEMISTRIES

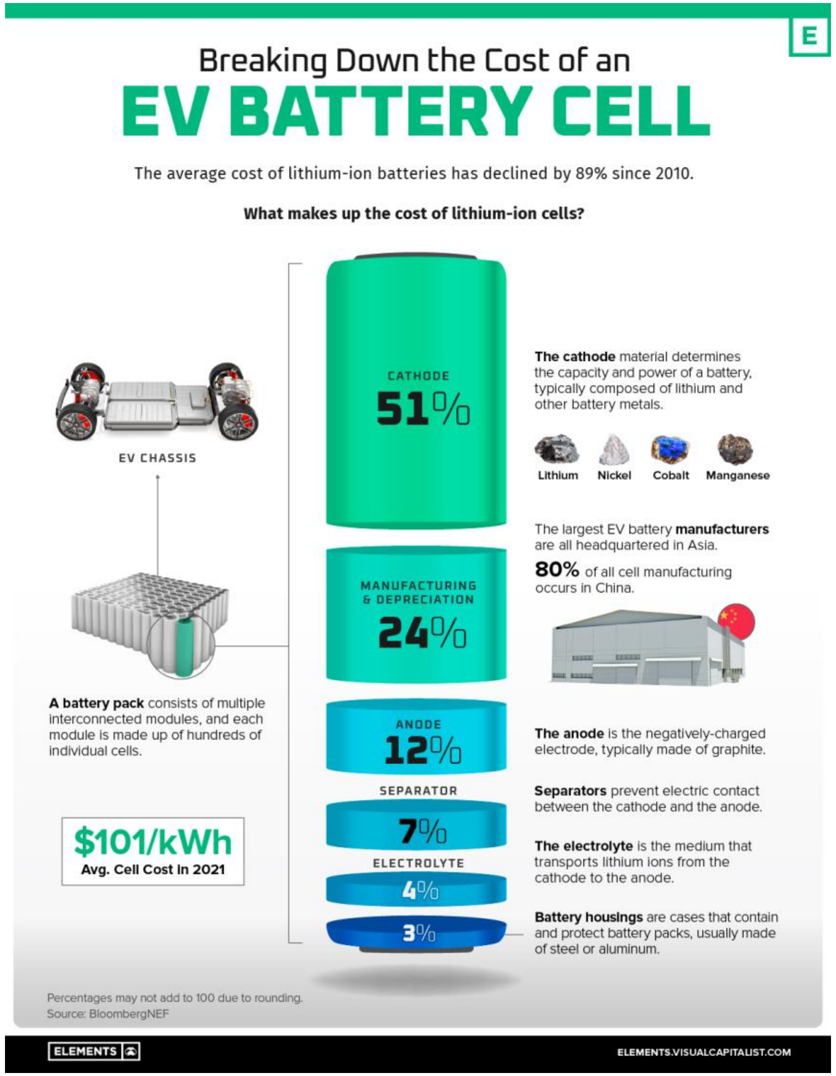
Cathode Chemistry	kg/kWh				$US/kWh
	Lithium	Cobalt	Nickel	Manganese	
LCO	0.113	0.959	0.000	0.000	**$76**
NCA	0.112	0.143	0.759	0.000	**$22**
NMC-111	0.139	0.394	0.392	0.367	**$38**
NMC-622	0.126	0.214	0.641	0.200	**$27**
NMC-811	**0.111**	**0.094**	**0.750**	**0.088**	**$19**

- Electric School Buses mainly have LFP, which has no cobalt, making the economics for recycling even more challenging.
- Govt mandates can help increase recycling volume when the economics are unfavorable.

Source: API

CHALLENGES WITH BATTERY RECYCLING

- Not designed for recycling
- Large fluctuations in the prices of raw battery materials
- Economically not viable with limited resources
  - Battery materials
  - Logistics
  - Process
- Limited data transparency leads to increased:
  - Labor costs
  - Risk
- Nascent regulation and market development



U.S. FEDERAL GOVERNMENT ROADMAP

Vision for the Lithium-Battery Supply Chain

By 2030, the United States and its partners will establish a secure battery materials and technology supply chain that supports long-term U.S. economic competitiveness and equitable job creation, enables decarbonization, advances social justice, and meets national security requirements.

Goals to Achieve Our Vision

- **Goal 1:** Secure access to raw and refined materials and discover alternatives for critical minerals for commercial and defense applications
- **Goal 2:** Support the growth of a U.S. materials-processing base able to meet domestic battery manufacturing demand
- **Goal 3:** Stimulate the U.S. electrode, cell, and pack manufacturing sectors
- **Goal 4:** Enable U.S. end-of-life reuse and critical materials recycling at scale and a full competitive value chain in the U.S.
- **Goal 5:** Maintain and advance U.S. battery technology leadership by strongly supporting scientific R&D, STEM education, and workforce development

BATTERY RECYCLING COMPANIES ARE ON IT, TOO

REDWOOD MATERIALS

Li-Cycle®

RETRIEV TECHNOLOGIES

Company	Location(s)	Current capacity (t/year)	Planned total capacity (t/year)
American Battery Technologies	Fernley, NV	-	20,000
American Manganese	Vancouver, BC	-	182.5
Ascend Elements	Worcester, MA; Novi, MI; Covington, GA	Unknown	30,000
Interco	Madison, IL	Unknown	Unknown
Li-cycle Corporation	Rochester, NY; Kingston, Ont; Phoenix, AZ; Tuscaloosa, AL	10,000	85,000
Lithion	Ajou, Quebec; Planned locations unknown	200	7,500
Princeton NuEnergy	Dallas, TX	-	Unknown
Recycling Coordinators	Akron, OH	Unknown	Unknown
Redwood Materials	Carson City, NV; Reno, NV	18,100	Unknown
Retriev Technologies	Lancaster, OH and Trail, BC	4,500	4500
Umicore Canada Inc.	Fort Saskatchewan, AB	Unknown	Unknown

Source: [CalEPA]

BARRIERS AND OPPORUNITIES TO RECYCLING EV BATTERIES

BARRIERS

- Limited data across different battery pack designs
- Falling costs of batteries
- Non-existent or nascent regulation for EV batteries recycling
- EV batteries are considered Class 9 hazardous materials, making its transportation challenging

OPPORTUNITIES

- New recycling processes can make it economical
- Regulation from China, EU (draft) stepping up battery recycling systems
- More use cases, commitments and start-ups help commercialize business models
- Limit mineral extraction
- Define standards, infrastructure build-out

Source: McKinsey; GTM

GOOD NEWS

BATTERIES

Breakthrough Research Makes Battery Recycling More Economical

How do we make battery recycling cost effective? Scientists at the ReCell Center have taken another step towards that goal.

By U.S. Department of Energy Published 10 hours ago 15 Comments

Mar 11, 2022 - 03:15 pm

EU Parliament agrees on position on battery regulation

Wave of investment just the beginning for EV battery recycling

Within the last month, four lithium-ion battery recyclers saw a collective $255 million worth of investment and another completed a merger.

Published Oct. 27, 2021

A Tesla Co-Founder Aims To Build an Entire U.S. Battery Industry

Redwood Materials, led by J.B. Straubel, is planning a massive new factory to move $25 billion of the battery supply chain from Asia to the U.S.

More than 95% of the core battery materials are recycled, according to Redwood.

Source: Clean Technica; Electrive; WasteDive

LEARNING OBJECTIVES

1. Develop awareness on global battery trends
2. Understand how a battery works and what they are made of
3. Gain knowledge about battery manufacturing processes and stakeholders
4. Understand barriers and opportunities for second-life use and recycling

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