Life Cycle Assessment of Lithium-ion Batteries

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Learning Objectives

» After this lecture, you should understand the following topics:

- Life cycle assessment (LCA); what it is and how people use it
- What the key materials in EV batteries are, how they are produced, and the social and environmental impacts
- Reuse and recycling options for EV batteries
- Solutions to make EVs more sustainable from a life cycle perspective

What is life cycle assessment?

- Evaluation of the environmental and economic burdens caused by a material, product, process, or service throughout its life span.
- Includes materials and energy to create the product, and waste and emissions generated during the process and use
- Can be used to compare alternative products and production pathways, or to identify hotspots in a system

Life cycle phases

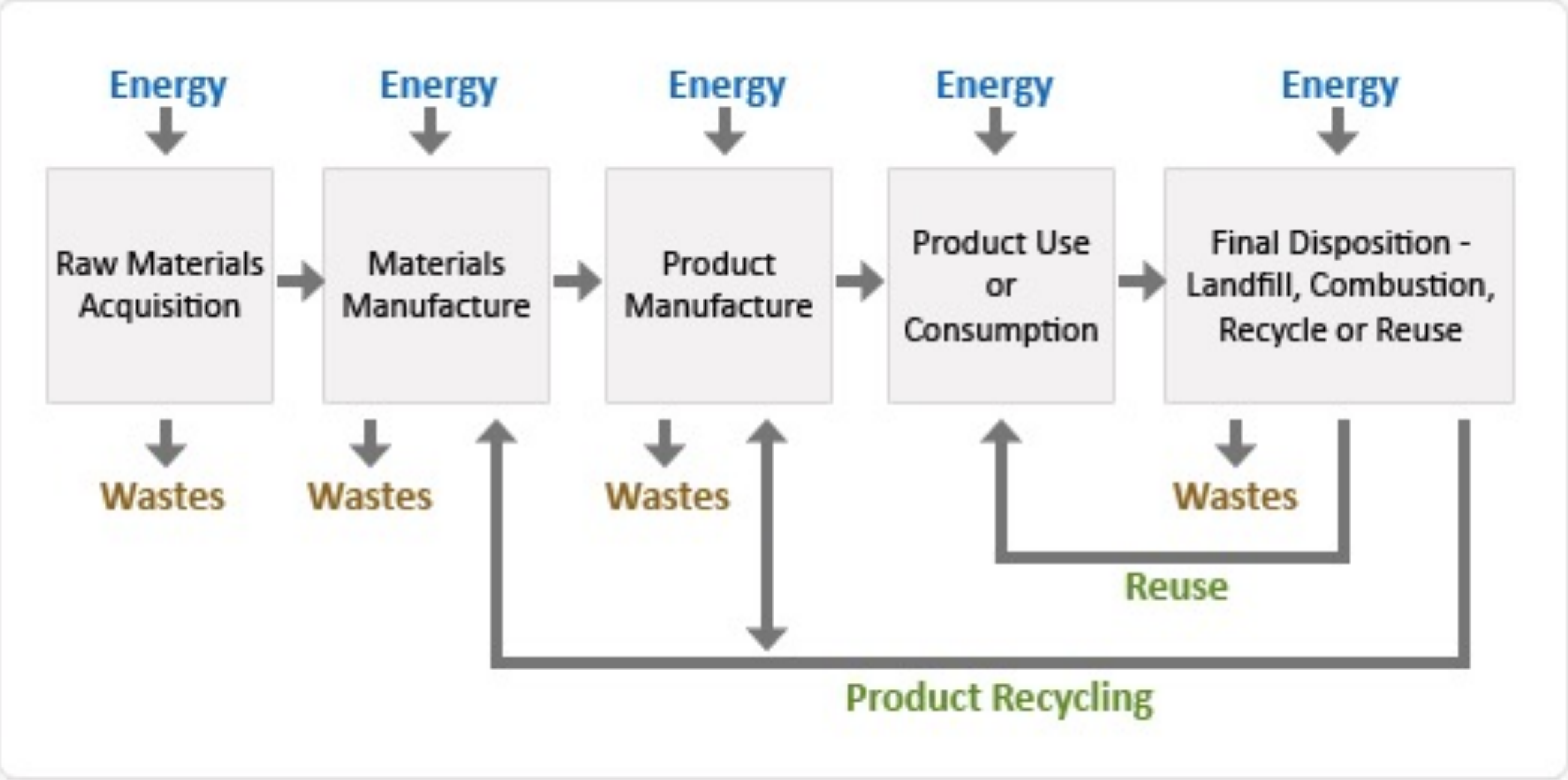


Image from Franklin & Associates

Context: Local impacts of oil extraction

» Contamination of land, water, air

» Negative impacts on public health for people who live near drilling and refining

» Environmental damage renders previous ways-of-life impossible (farming, fishing)

» Conflict

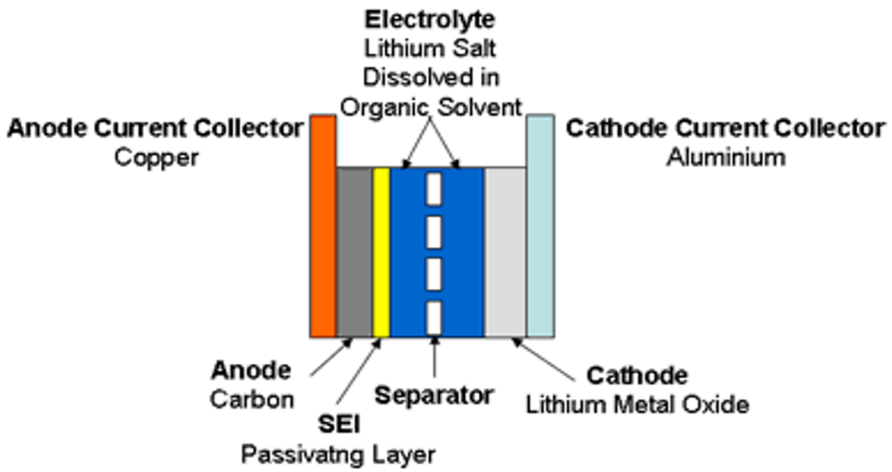
» See:

- Chevron refinery in Richmond
- Displacement of Isle de Jean Charles, Grand Caillou/Dulac, and Pointe-au-Chien Indian Tribes in Louisiana
- Oil spills in the Niger River Delta

LCA for Electric Vehicles

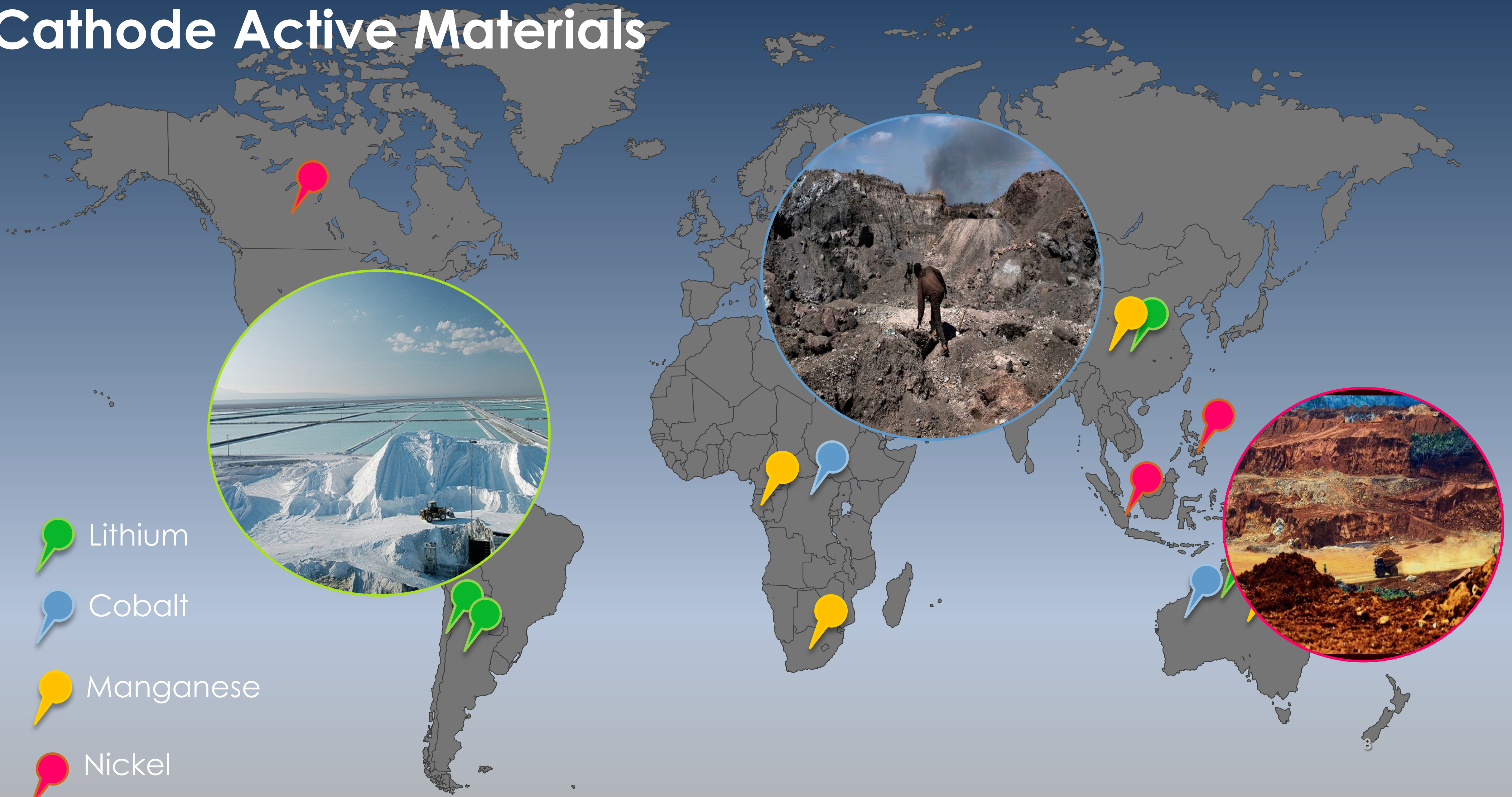
Introduction to Li-ion batteries (LIBs)

» Used in consumer electronics, electric vehicles, and energy storage applications



Ellingsen et al. (2013). Life Cycle Assessment of a Lithium-Ion B
Vehicle Pack. Journal of Industrial Ecology. 18. 10.1111/jiec.12072.

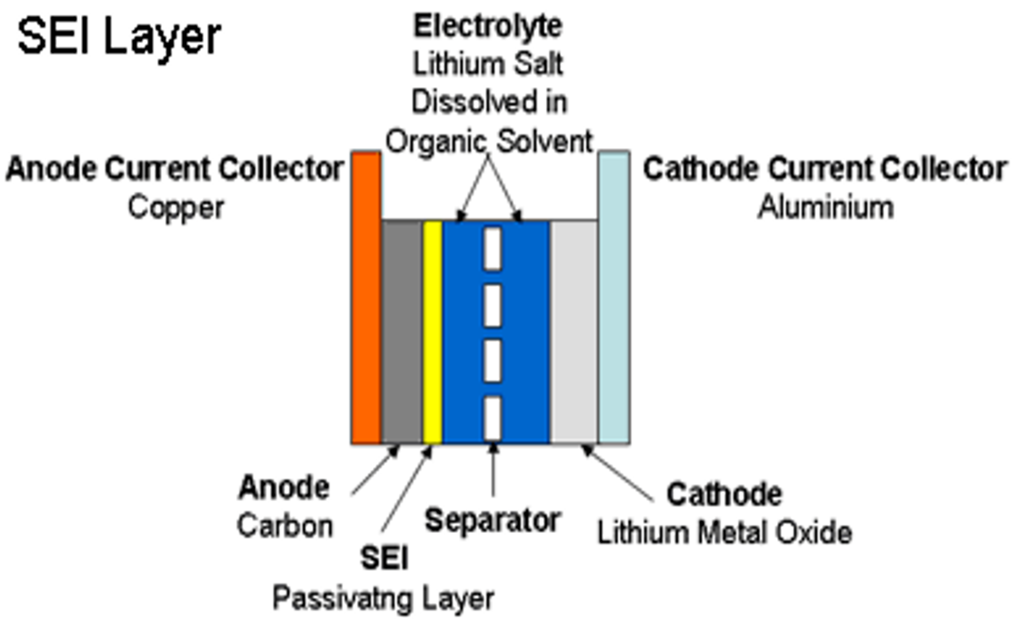
Cathode Active Materials



Sources: Gaines & Nelson (2009), US Geological Survey

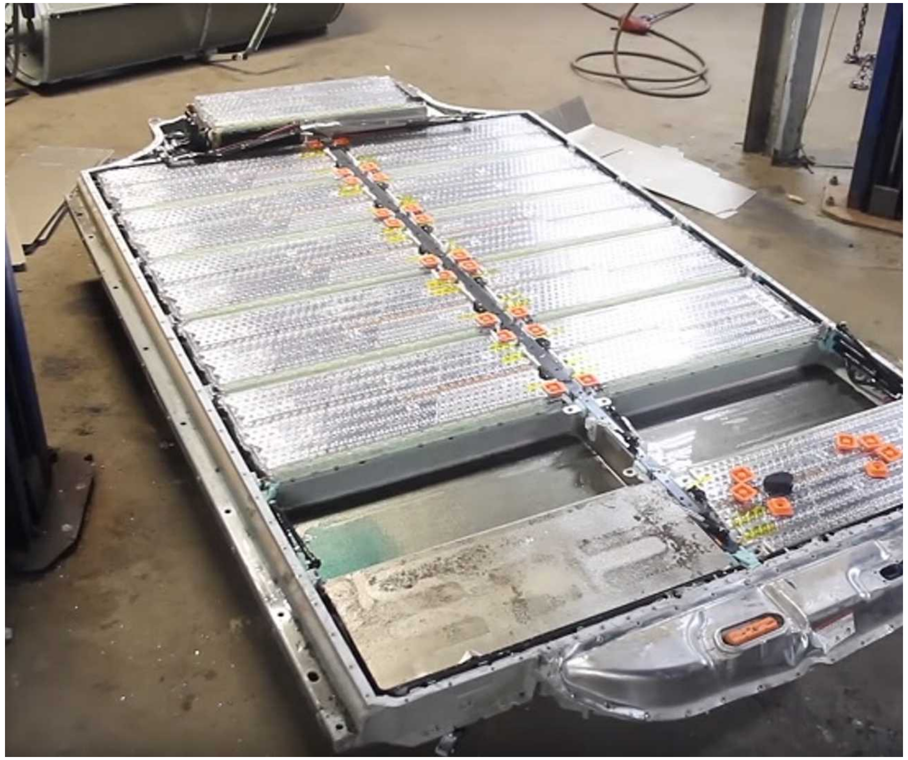
Other Materials

- Graphite (anode)
- Copper (cathode)
- Aluminum (battery pack and vehicle)
- Binder material for cathode and anode
- Electrolyte
- Solvents for cathode slurry preparation



Cathode and Cell Production

- Cathode powder is produced using co-precipitation (42.6 MJ of heat per kg of NMC 111) and calcination (25.2 MJ of electricity per kg)
- Cell production consists of slurry preparation, electrode production, cell assembly, cell conditioning
- Energy required for drying, humidity control
- Impact per-battery depends on facility throughput

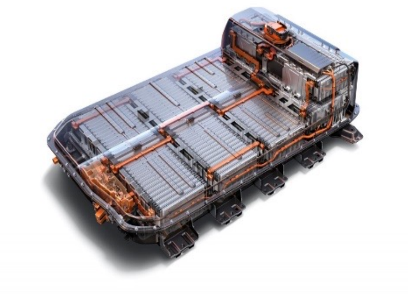


Use

- In-use (i.e., while actively driving) emissions are zero → air quality benefits
- GHG emissions from use phase depend on energy source
  - Benefit estimated to be 12% compared to gasoline if vehicle is fueled using electricity from natural gas
  - Emissions are increased if fueled by coal (Hawkins et al., 2013)
- Life cycle impacts depend on vehicle and battery lifespan
  - Global warming benefits are estimated to be 27-29%% better compared to a gasoline vehicle assuming a 200,000 km lifetime
  - Reduces to 9-14% assuming a 100,000 km lifetime

End-of-life

Discarded Li-ion battery



- 80% of original charge capacity
- Typically occurs after 8-10 years

Reuse Opportunity

- Applications as stationary storage, EV charging stations
- Extends usable life by 7-10 years

Landfill or stockpile

- Concerns about heavy metals, fire

Recycling Process

- Potential to recover valuable raw materials

1. 2017 Chevrolet Volt battery; 2. UCD Winery Microgrid Project;

Reuse

- Batteries can be reused in a vehicle or as stationary storage
- Repurposed batteries can be used to store excess solar energy and provide backup power
- There are several startups in California and elsewhere in the United States, as well as in Europe, China, and Japan

Recycling

Collection and transportation

↓ Battery pack or module

Mechanical separation and pre-treatment → Copper, aluminum, plastics, iron

↓ Black mass (cathode and anode materials)

Hydrometallurgical processing

↓ Metal sulfates (e.g., $CoSO_4$, $MnSO_4$, $NiSO_4$)

Cathode and battery production

Images from Li-Cycle

Recycling

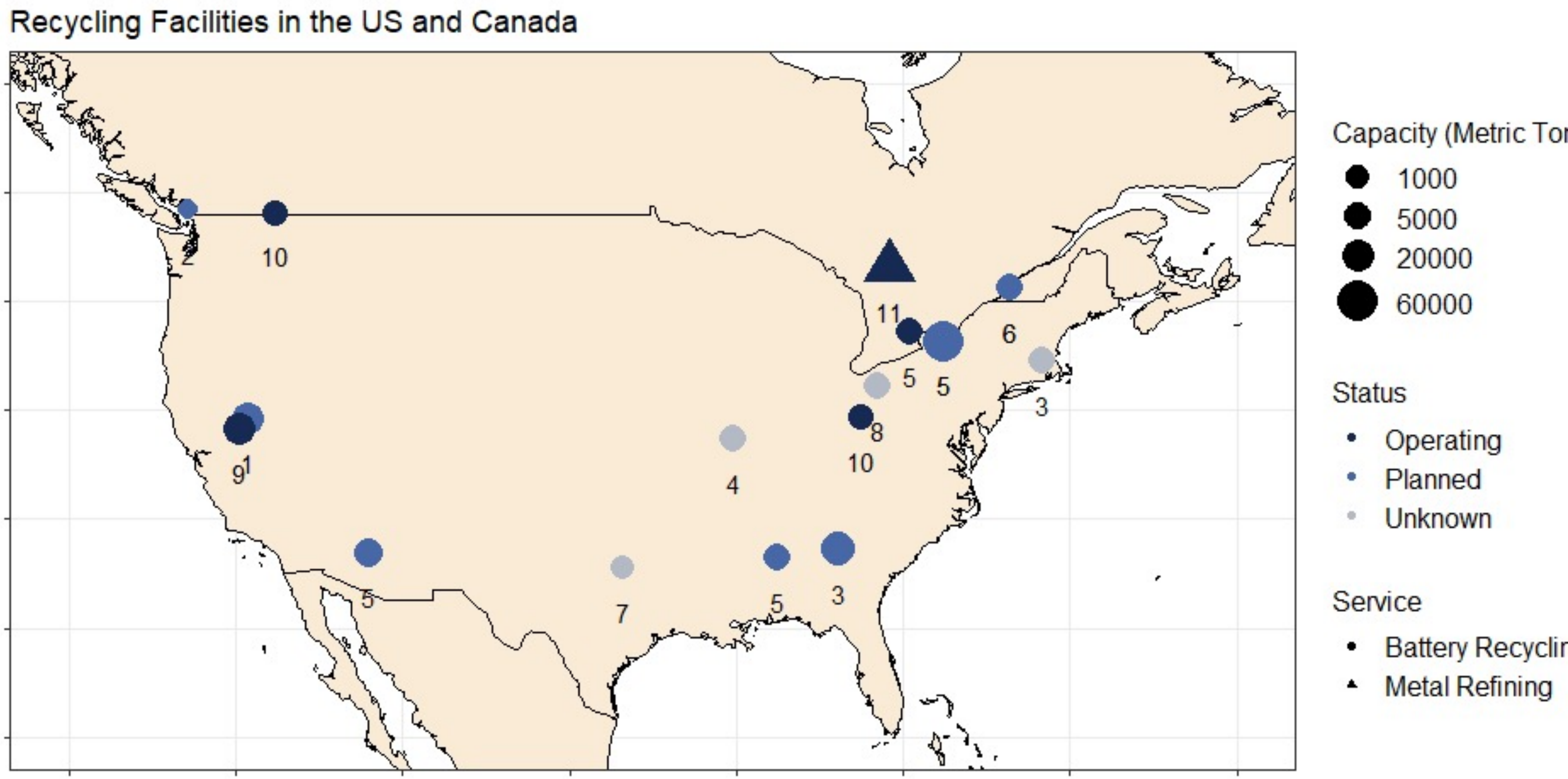
- Most companies in North America will use hydrometallurgical recycling process, claim to recover 90-95% of materials
- Economics of recycling are dictated by material value, processing cost, and transportation cost
- Lithium has not historically been recovered commercially
- Recovered material must be exported
- Majority of recycling to date has taken place in China and Korea

Outputs of shredding process: Copper, aluminum, plastics, iron

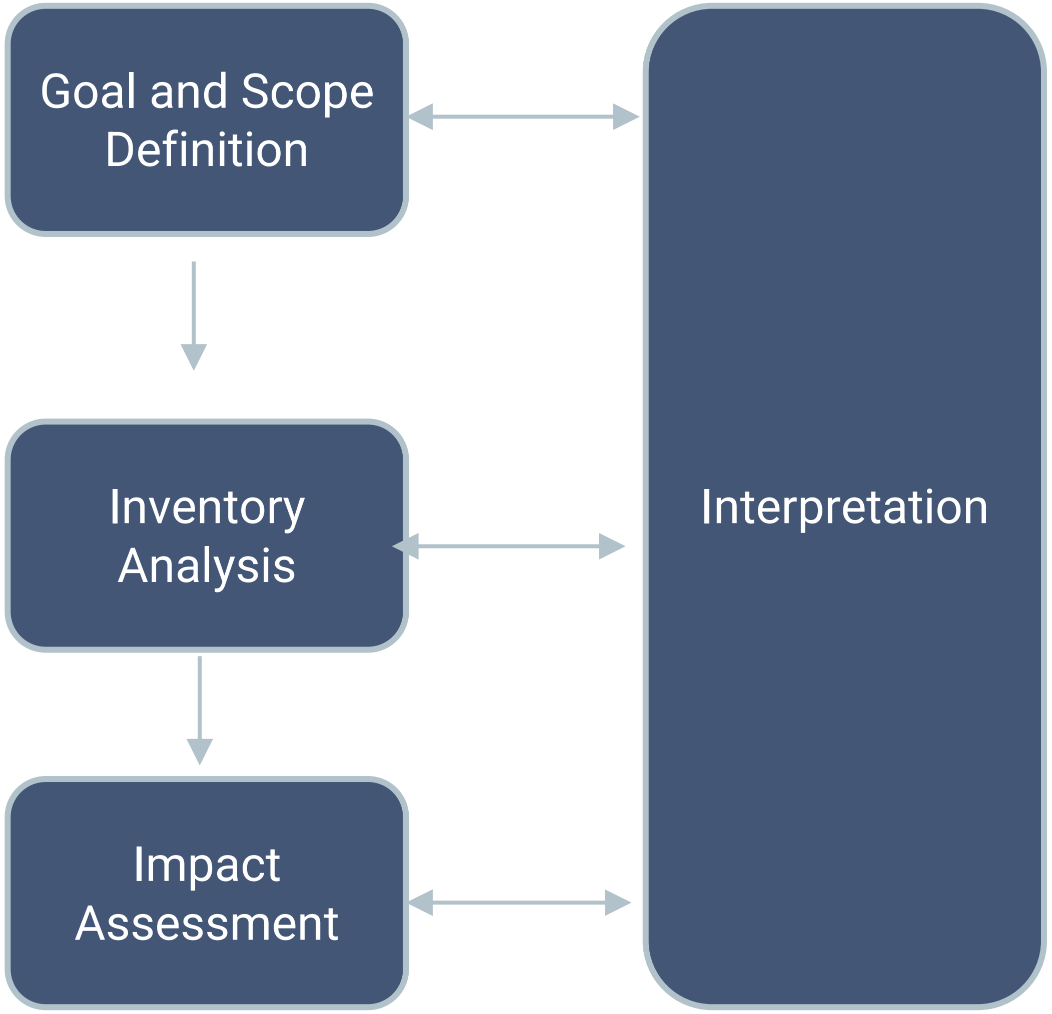
Image of "black mass" from Li-Cycle®

Recycling

1. American Battery Technologies
2. American Manganese
3. Acend Elements
4. Interco
5. Li-Cycle
6. Lithion
7. Lithion
8. Princeton NuEnergy
9. Recycling Coordinators
10. Redwood Materials
11. Retriev Technologies
12. Glencore



LCA steps


Goal and Scope Definition
Inventory Analysis
Impact Assessment
Interpretation

Goal and Scope

- » What product (or products) are you studying?
- » What is the functional unit?
- » What is the system boundary?
- » What is the purpose of your analysis?
- » Who is the intended audience?

- » Electric vehicle examples:
  - Cradle-to-gate of LIB production
  - Cradle-to-grave of EV

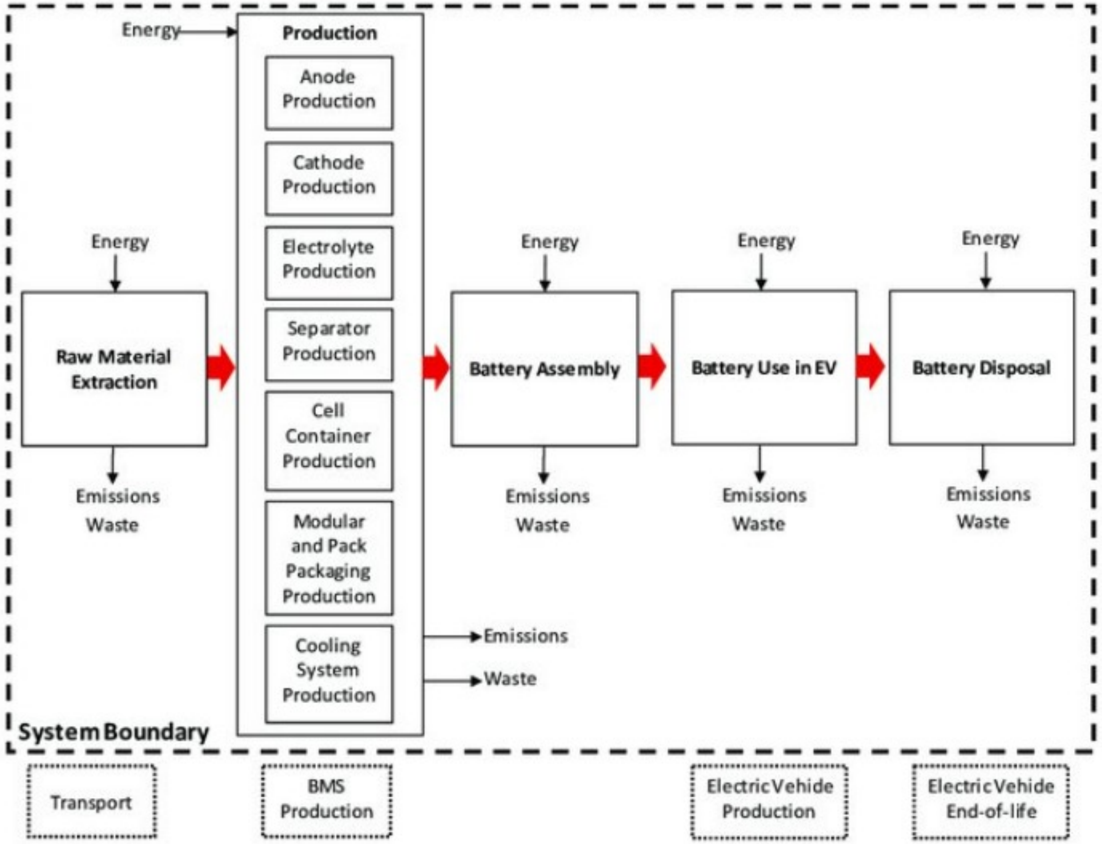
Inventory Analysis

- "Accounting" stage; purpose is to track inputs and outputs from system
- Create bill of materials and process flow diagram
  - What components are part of the product you are studying?
  - What are the processes used to make them?
  - What are the material and energy outputs at each step?
- Life cycle inventory (LCI) is the quantification of relevant inputs and outputs for a given product system

Inventory Analysis examples

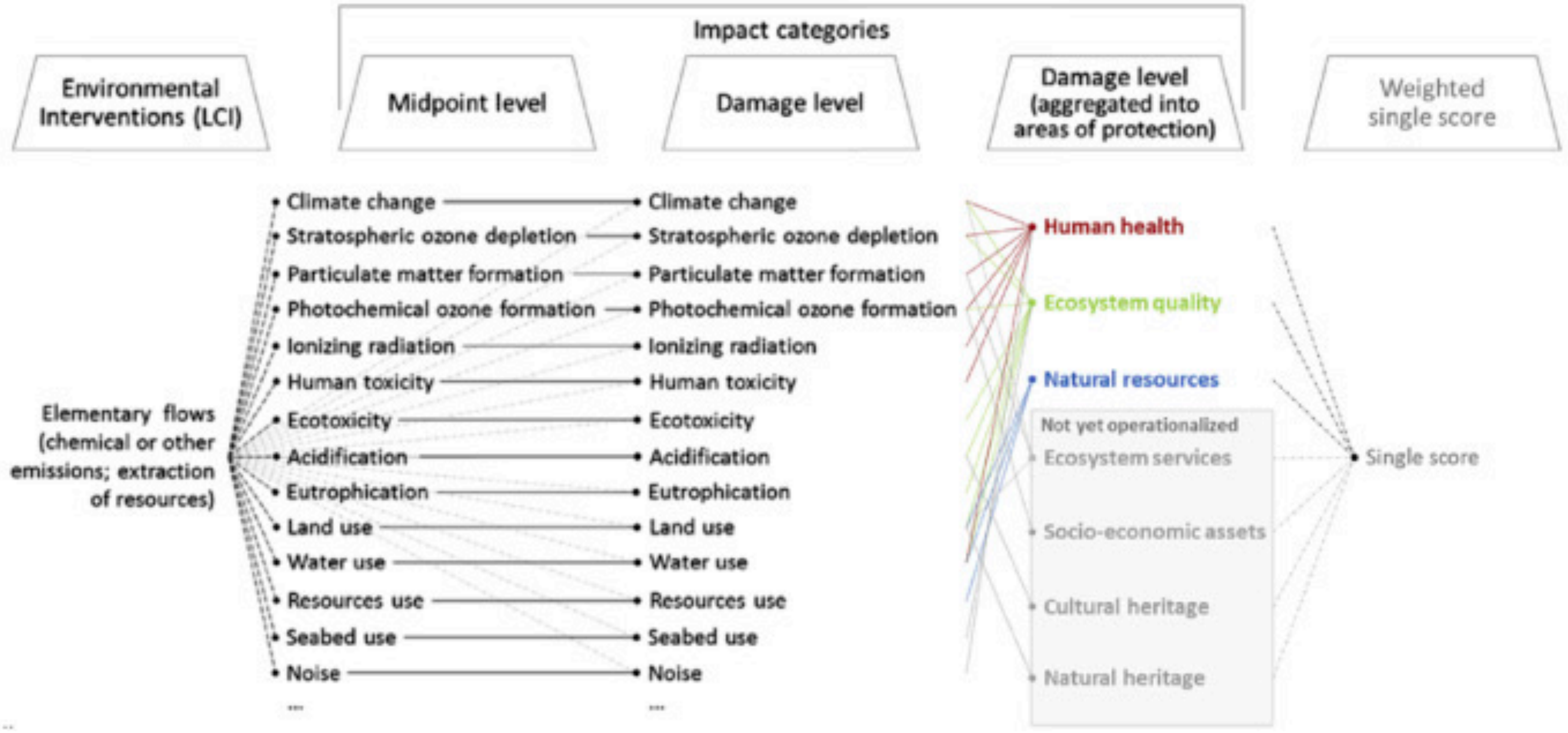
	Majeau-Bettez et al. (NMC442)	Ellingsen et al.* (NMC111)	GREET2018 (NMC111)
Calcination			
Material inputs (kg/kg NMC)			
$NMC(OH)_2$	0.95	0.95	0.95
LiOH	0.25	0.25	
Li_2CO_3			0.38
Energy inputs (MJ/kg NMC)			
Heat	0.55	0.55	
Electricity			25.2
Co-precipitation			
Material inputs (kg/kg $NMC(OH)_2$)			
$NiSO_4$	0.68	0.57	0.56
$MnSO_4$	0.66	0.55	0.55
$CoSO_4$	0.34	0.57	0.56
NaOH	0.88	0.88	0.89
NH_4OH			0.12
Energy inputs (MJ/kg $NMC(OH)_2$)			
Heat			42.6

*Adapted from the LCI for $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ (NMC442) production reported by Majeau-Bettez et al.



Left: LCI from Dai et al., 2019; Right: System Boundary from Casals et al., 2019

Impact Assessment



Source: Verones et al. (2017).

Impact Assessment

Type of impact	Climate change	Air emissions	Water	Local ecology	Public health
LCA impact categories	Energy use, GHG emissions	Particulate matter formation, SOx/NOx emissions	Water use, aquatic ecotoxicity	Acidification, eutrophication, land use, terrestrial ecotoxicity	Human toxicity

Example: Dai et al., 2019

» Scope

- Cradle-to-gate analysis of a 23.5 kWh NMC 111 battery
- Functional unit= 1 kWh
- Impacts: Total energy use, greenhouse gas emissions, SOx, NOx, PM 10 emissions, water consumption

» Findings:

- Active cathode material, aluminum, energy use for cell production are major contributors to energy and environmental impact

System Boundary (Dai et al., 2019)

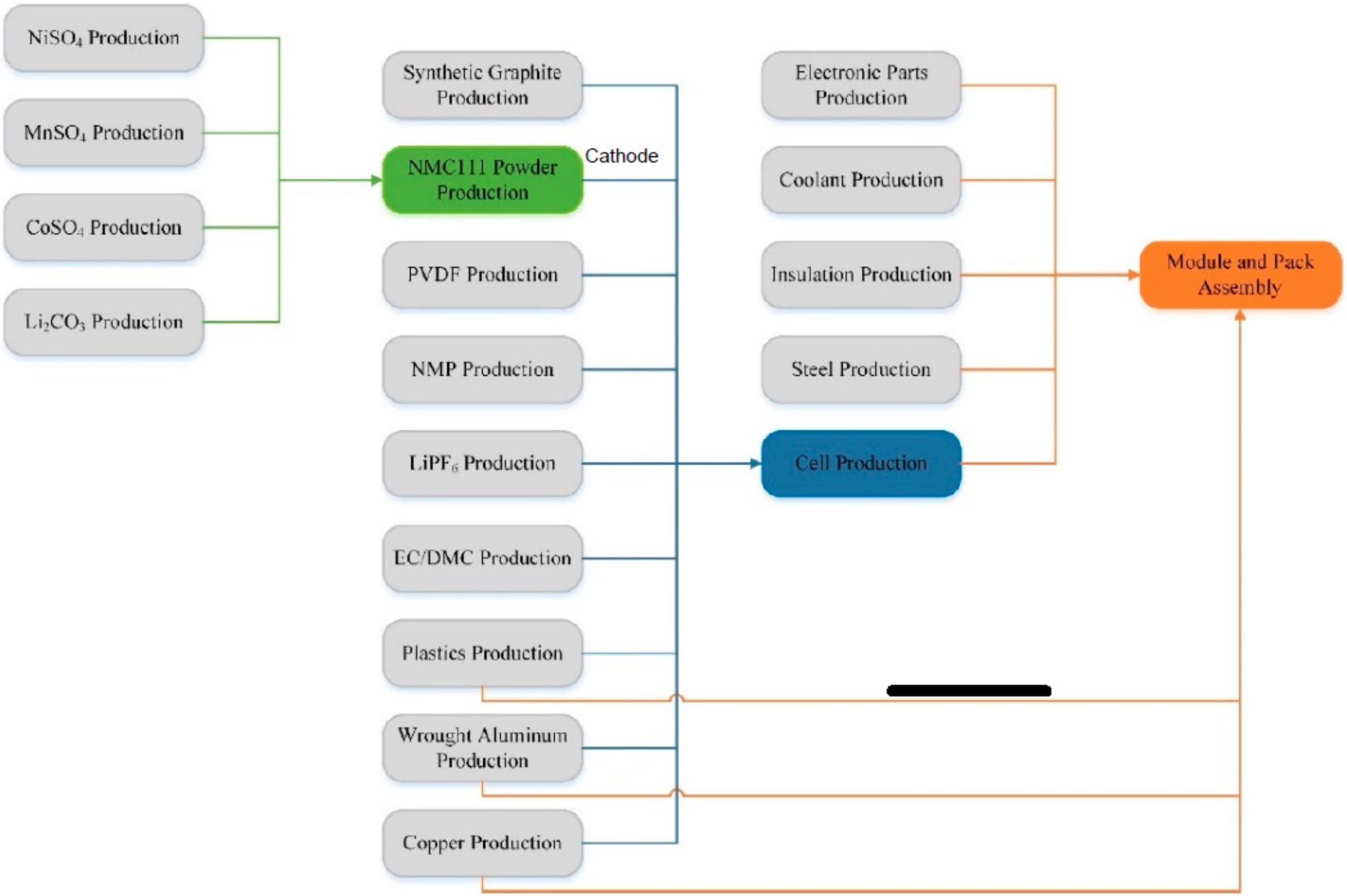


Figure 1. Cradle-to-gate system boundary of $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111) battery production.

Results

- **NMC 111 powder** is the most significant contributor to energy use and environmental burden
  - 36.4% of total energy use
  - 39.1% of GHG emissions
  - 63.5% of SOx emissions
  - 31.7% of water consumption

- **Aluminum** and **cell production** are also substantial contributors
  - **Aluminum** content responsible for 50.8% of water consumption, 18% of total energy use
  - **Cell production** represents 19.2% of total energy use

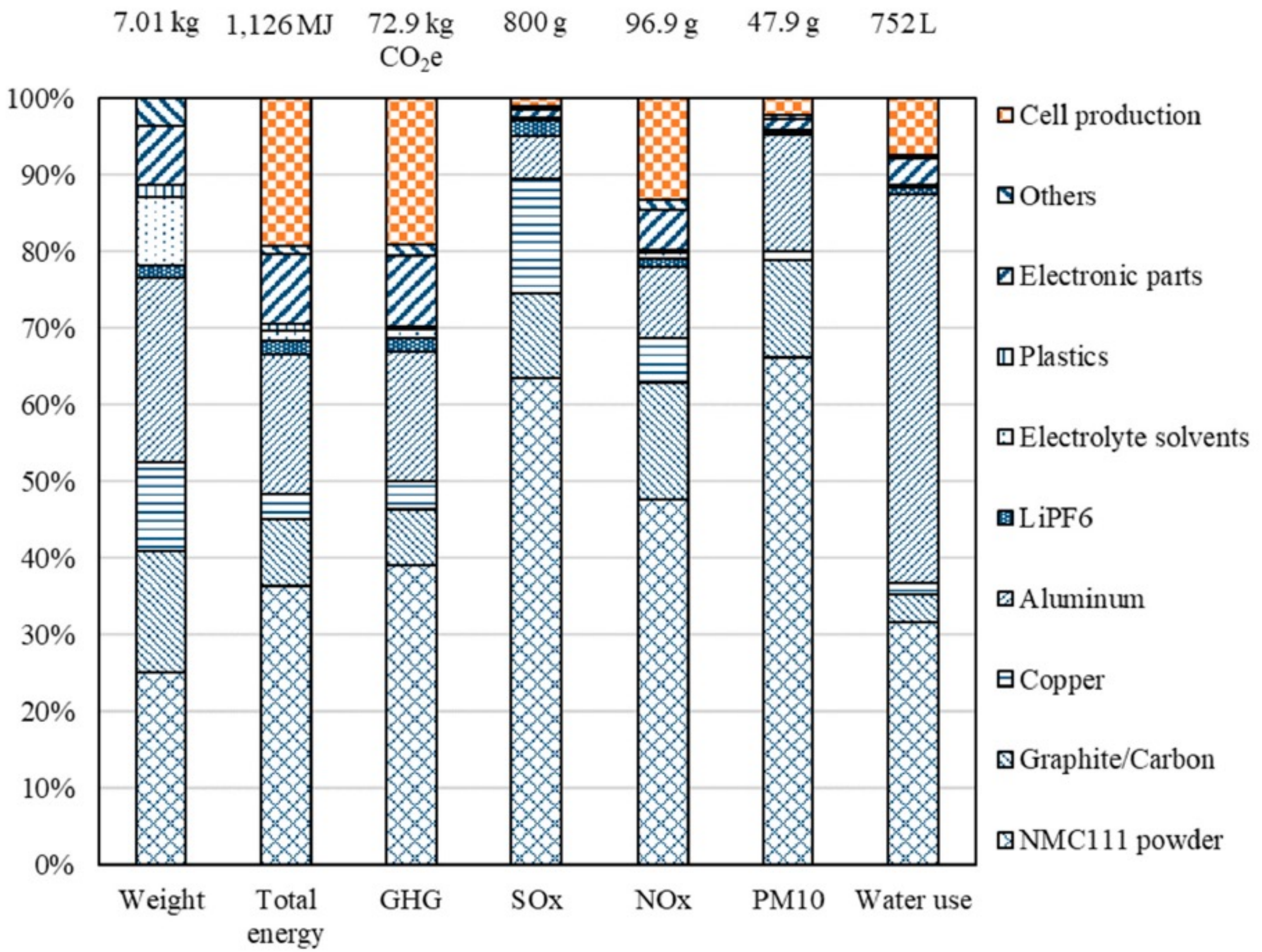


Figure 2. Cradle-to-gate impact breakdowns and bill of materials (BOM) of 1 kWh NMC111 battery. Blue denotes material inputs; orange denotes energy inputs for cell production.

Factors affecting life cycle impact

- Geographic region
  - What environmental protection measures are in place in material-producing region? Are emissions captured?
  - What is the electricity mix where the battery is produced?
  - What is the electricity mix where the car is driven?
- Facility throughput
- Shipping distance

Recycling in LCA

- How do you capture the impact of reuse or recycling in an LCA?
  - Estimate impact of battery recycling process and calculate the avoided impact from producing raw materials

- Factors that influence the benefits of recycling
  - Recycling process (pyro- vs. hydrometallurgy)
  - Outputs of process
  - Battery chemistry
  - Location
  - Which impacts are studied

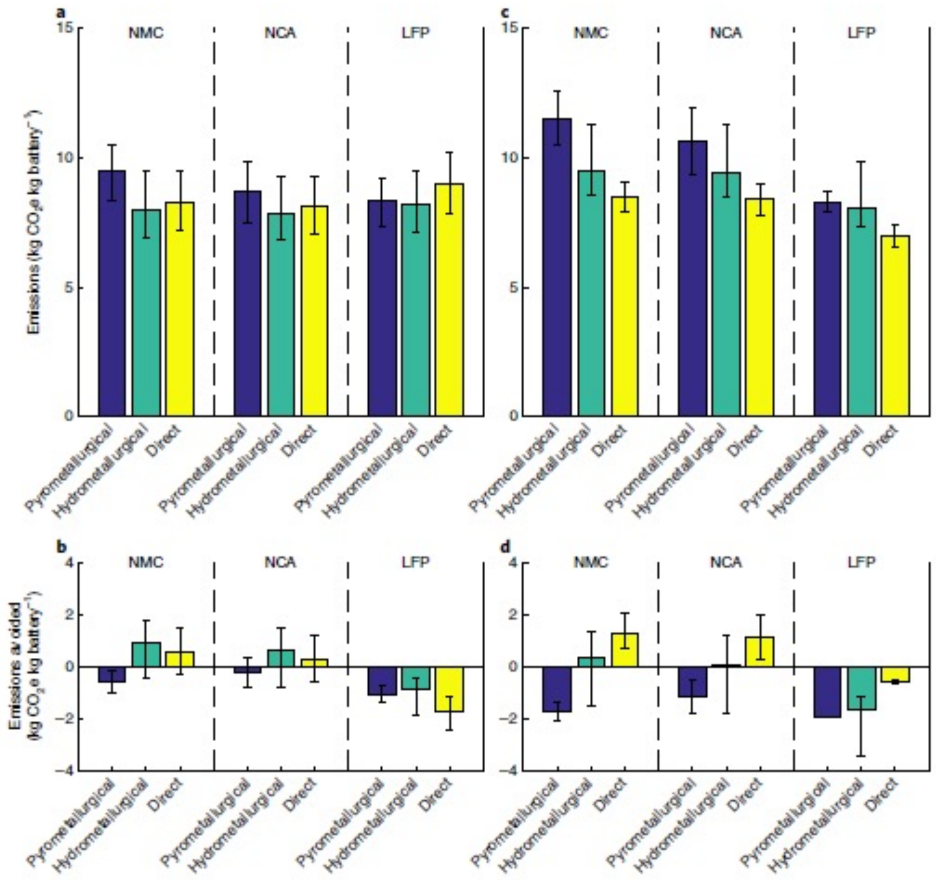
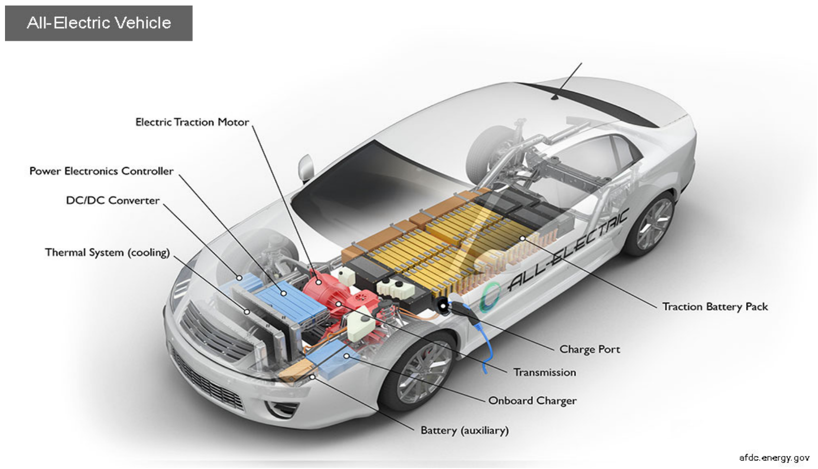


Fig. 3 | Battery recycling emissions. **a–d**, Medians and 95% confidence intervals for CO_2e emissions per kg less the CO_2e offsets from recovered material (**a**,**c**), and net CO_2e emissions avoided by using each recycling process (**b**,**d**) for cylindrical (**a**,**b**) and pouch battery manufacturing and recycling processe (**c**,**d**). All processes use US average electricity grid data.

Conclusion: ICE vs. EV

- Lighter production phase impacts (vehicle is lighter)
- High use phase impacts
- Overall higher global warming potential

- Impacts depend on geographic region
- More challenging end-of-life
- Lower GHG emissions, higher toxicity



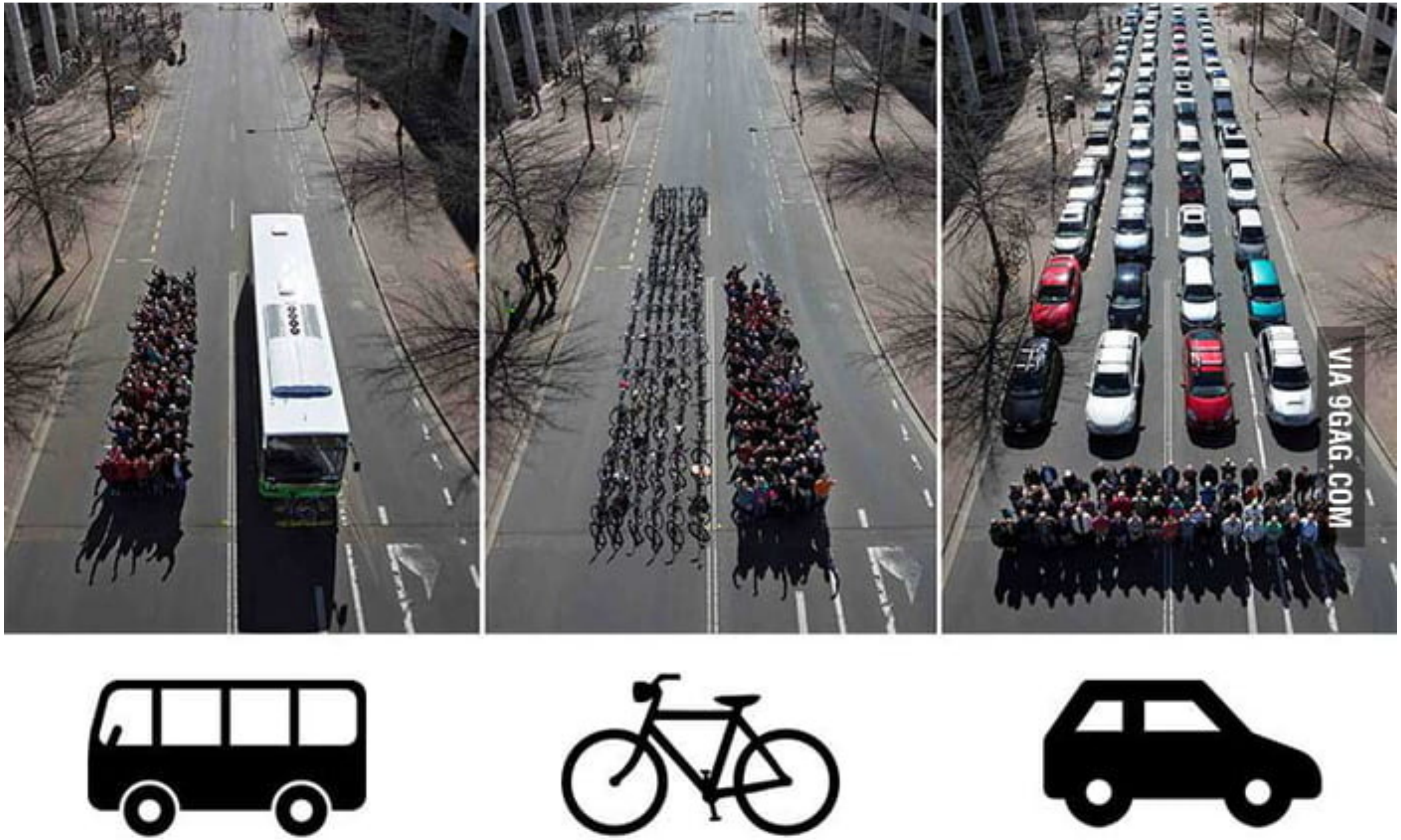
Source: Hawkins et al. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53–64

Supply-side solutions

- » Increase transparency in the supply chain through tracking
  - E.g., Global Battery Passport
- » Practice free, prior, and informed consent in material extraction developments
- » Require materials to be sourced from specific regions or using specific environmental mitigation measures

Other solutions

- Reduce demand



Questions?

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Selected References

- Casals, Lluc Canals, B. Amante García, and Camille Canal. 2019. “Second Life Batteries Lifespan: Rest of Useful Life and Environmental Analysis.” *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2018.11.046.
- Ciez, Rebecca E., and J. F. Whitacre. 2019. “Examining Different Recycling Processes for Lithium-Ion Batteries.” *Nature Sustainability* 2 (2): 148–56.
- Dai, Qiang, Jarod C. Kelly, Linda Gaines, and Michael Wang. 2019. “Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications.” *Batteries* 5 (2): 48.
- Dunn, Jennifer B., Christine James, Linda Gaines, Kevin Gallagher, Qiang Dai, and Jarod C. Kelly. 2015. “Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries.” Argonne National Laboratory . https://anl.app.box.com/s/afw5c0u7w43rr5gyfys4r1zjfmyw5q14