WE START WITH YES.

COMPARE AND CONTRAST: PB-ACID AND LI-ION BATTERIES

LINDA GAINES AND QIANG DAI

Energy Systems Division
Argonne National Laboratory
lgaines@anl.gov, qdai@anl.gov

AABC
June 22, 2017

SOME BASIC DIFFERENCES BETWEEN BATTERY TYPES

LEAD-ACID

- Invented 1859 by Gaston Plante
- ~85% of market MWh in 2015
- Major use is vehicle SLI
  - Also used for forklifts, back-up
  - Use for start-stop is growth area
- Materials and design standardized
- Recycling rate nearly 100%
- Lower price

LITHIUM-ION

- Commercialized 1991 by Sony
- ~15% of world MWh in 2015*
- Rapid growth 2005-2015*
  - 22%/y on MWh basis
  - 15% on $ basis
- Used for electronics, **propulsion,** SLI
- Materials and designs evolving
- Recycling rate under 10%
- **Higher energy density**
- Lower self-discharge rate

Vehicle	Range mi (km)	Seats	Battery kWh	Battery mass lb (kg)	Vehicle mass lb (kg)	Battery % of mass
GM Impact (Gen 2)	100 (161)	2	18.7	1310 (594)	3086 (1400)	42.4
Tesla Model S	265 (426)	5	85	1323 (600)	4647 (2108)	28.6
Chevrolet Bolt	238 (381)	5	60	960 (435)	3580 (1620)	26.8

*The Rechargeable Battery Market and Market Trends 2015-2025 (33rd International Battery Seminar and Exhibit, 3/21/16)

Periodic Table of Elements

A Resource for Elementary, Middle School, and High School Students

Group / Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.94	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.79
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.96	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	*	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.38	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	**	104 Rf (267)	105 Db (268)	106 Sg (269)	107 Bh (270)	108 Hs (277)	109 Mt (278)	110 Ds (281)	111 Rg (282)	112 Cn (285)	113 Nh (286)	114 Fl (289)	115 Mc (289)	116 Lv (293)	117 Ts (294)	118 Og (294)

Lanthanide Series*	57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series**	89 Ac (227)	90 Th 232	91 Pa 231	92 U 238	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

- Alkali metals
- Alkaline earth metals
- Transition metals
- Post-transition metals
- Metalloid
- Lanthanides
- Actinides
- Nonmetals
- Halogens
- Noble gases

Source: http://periodic.lanl.gov/index.shtml

LI-ION BATTERIES DEPEND ON IMPORTED RAW MATERIALS

Material	Atomic Weight	Price/lb ($)	% US imports	US Reserves (kT)	World Resource (MT)	Main sources	Notes
Lead	207.2	0.90	33	5,000	>2,000	China, US, Australia	
Lithium	6.9	18 (based on 3.40 Li_2CO_3)	~100?	38	40	Chile, Argentina	
Cobalt	58.9	12	74	21	25	Congo, Australia	
Nickel	58.7	4	30	160	130	Philippines Russia, Canada	
Graphite (Carbon)	12.0	0.60-0.80	100	--	800	China, India	Can produce synthetic graphite

LIFECYCLE ANALYSIS EVALUATES PROCESS IMPACTS

of a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal if any.

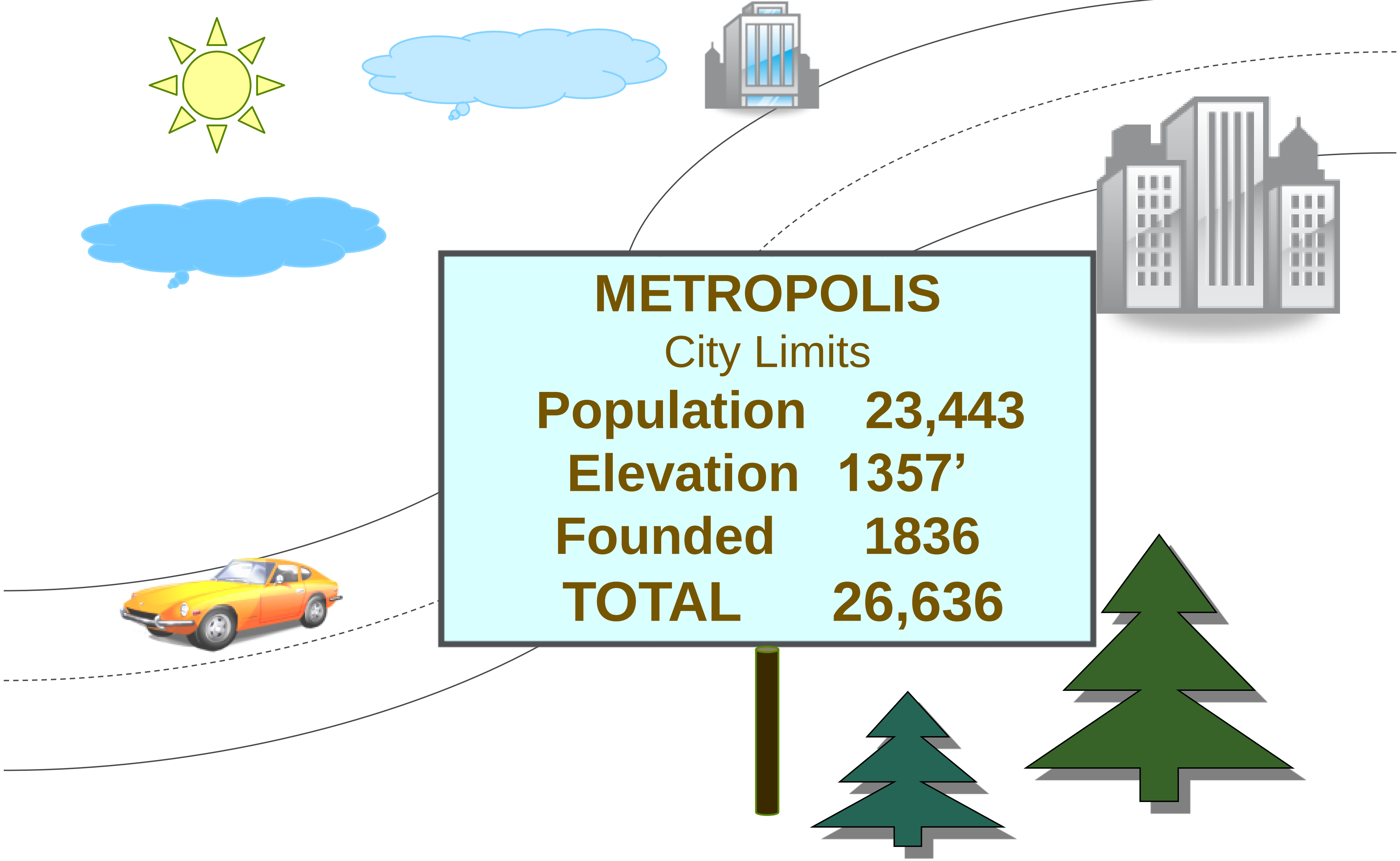
Argonne NATIONAL LABORATORY

ON A PER-KG BASIS, LEAD HAS LOW IMPACTS

But there are more kgs of it used!

Name\Impact	Total Eco-Cost €/kg	Human Health €/kg	Resource depletion €/kg	Carbon footprint €/kg
Aluminum (primary)	3.97	0.06	1.96	1.26
Aluminum (secondary)	0.28	0.00	0.01	0.25
Cobalt	45.65	0.01	43.80	1.04
Copper (primary)	3.08	0.00	2.44	0.43
Copper (secondary)	0.34	0.00	0.01	0.30
Lead (primary)	1.71	0.05	1.04	0.25
Lead (secondary)	0.12	0.00	0.01	0.10
Lithium	106.04	0.03	103.00	2.48
Nickel (primary)	14.92	0.11	9.02	4.33
Nickel (secondary)	0.34	0.00	0.01	0.30

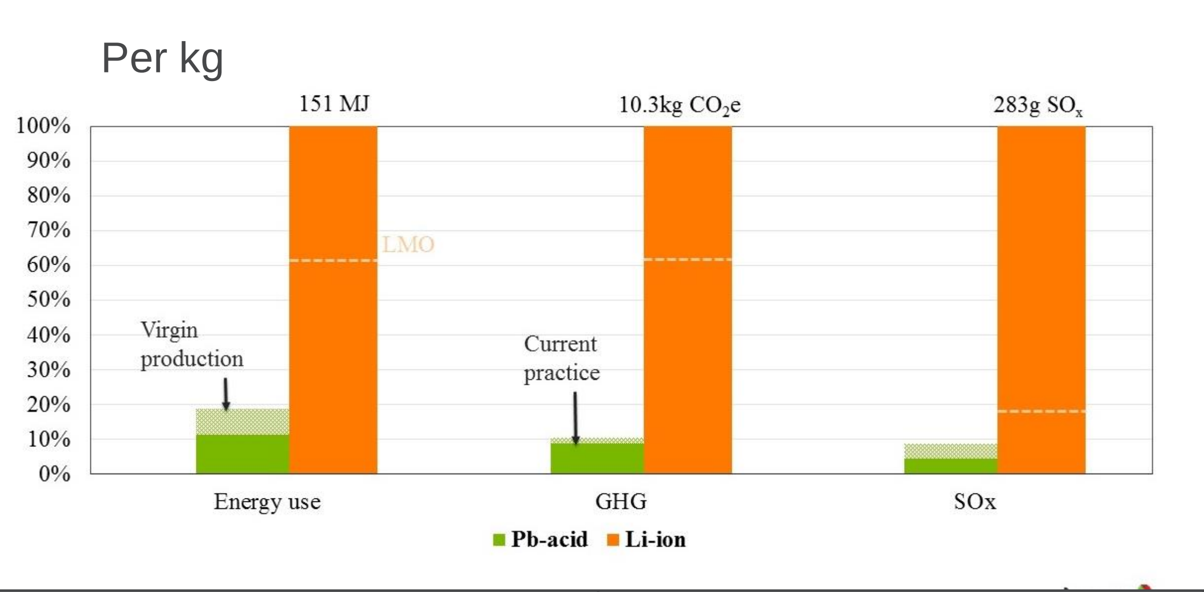
Data from Idematapp 2016 (http://ecocostsvalue.com/EVR/model/theory/subject/5-data.html)

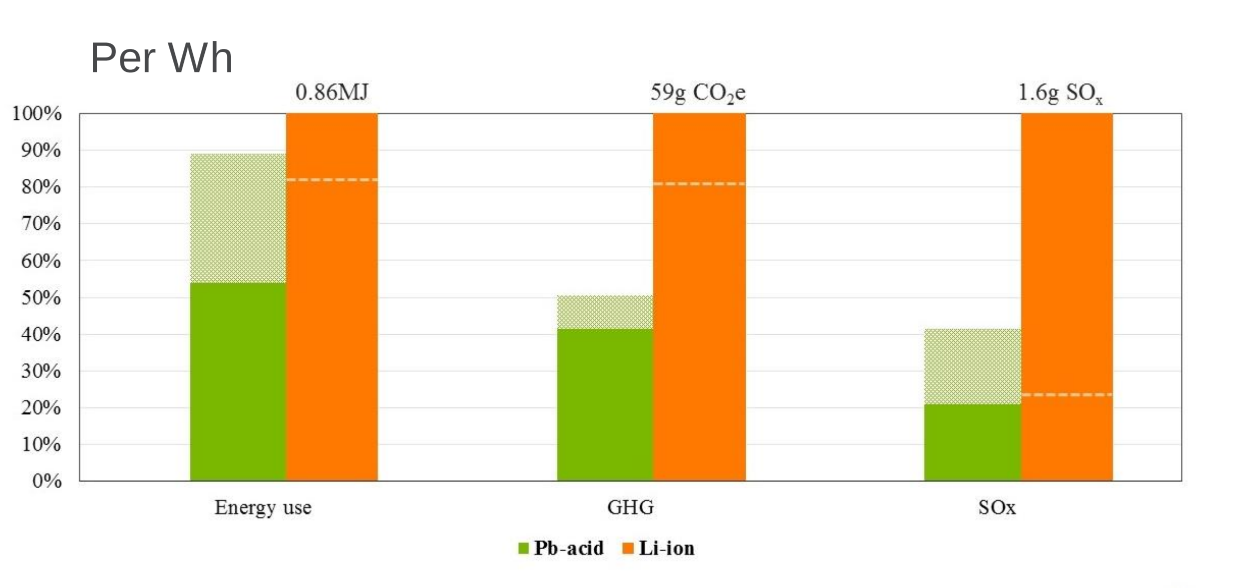


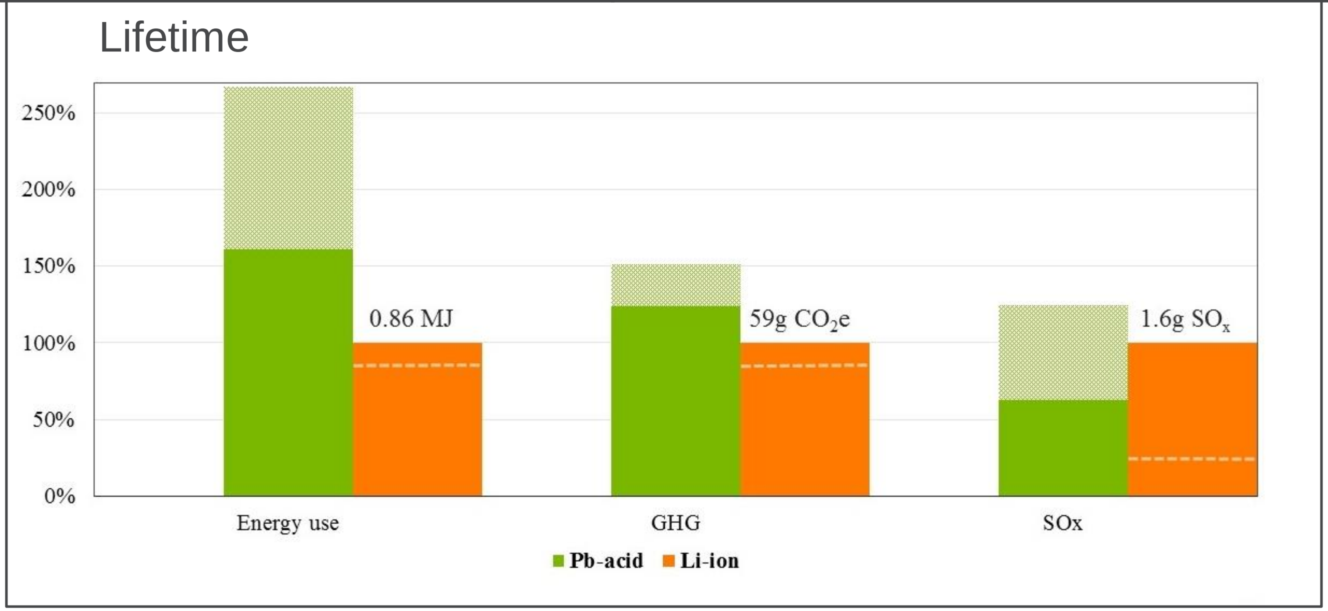
THERE IS NO CORRECT WAY TO AGGREGATE IMPACTS INTO A SINGLE “SCORE.”

PB-ACID AND LI-ION ENERGY USE AND EMISSIONS COMPARED

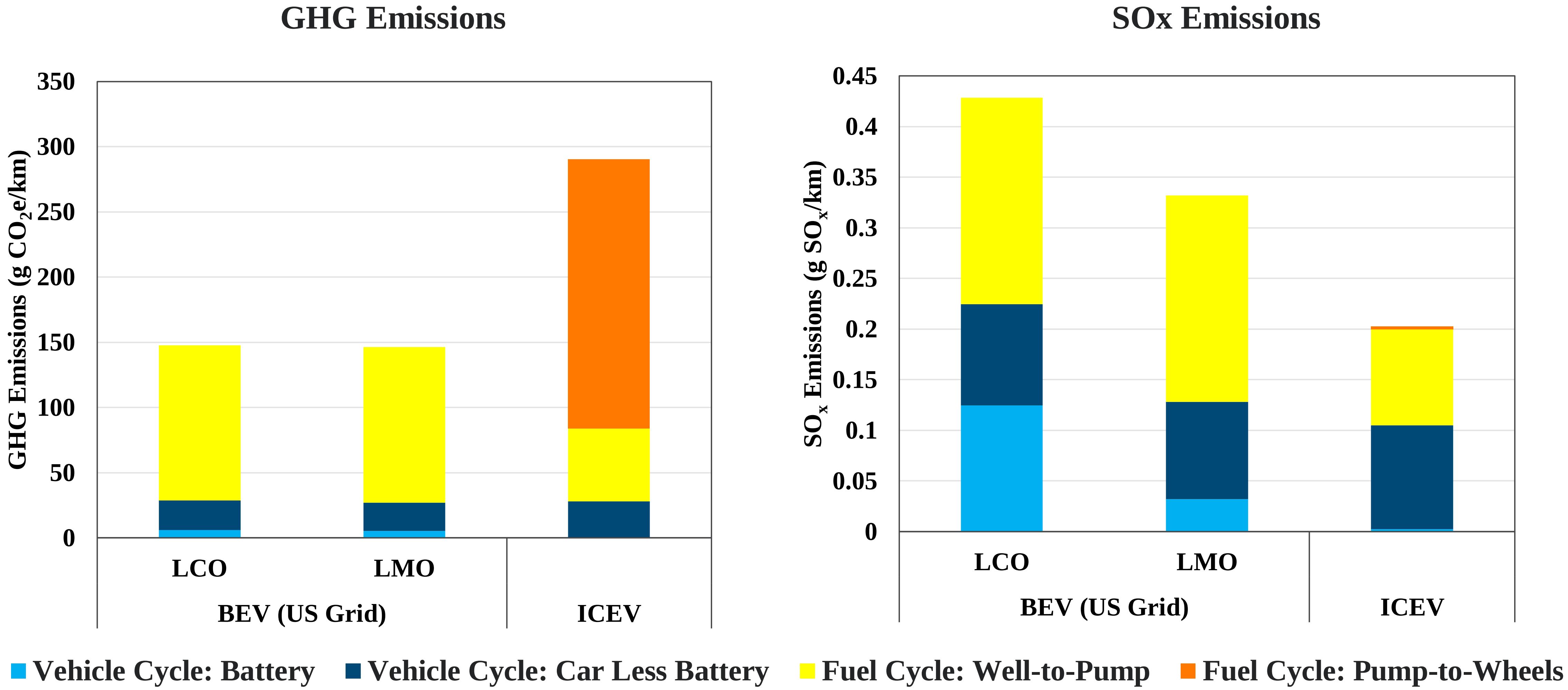
Energy, GHG, and SO_x emissions, per kg, per Wh, and over battery life





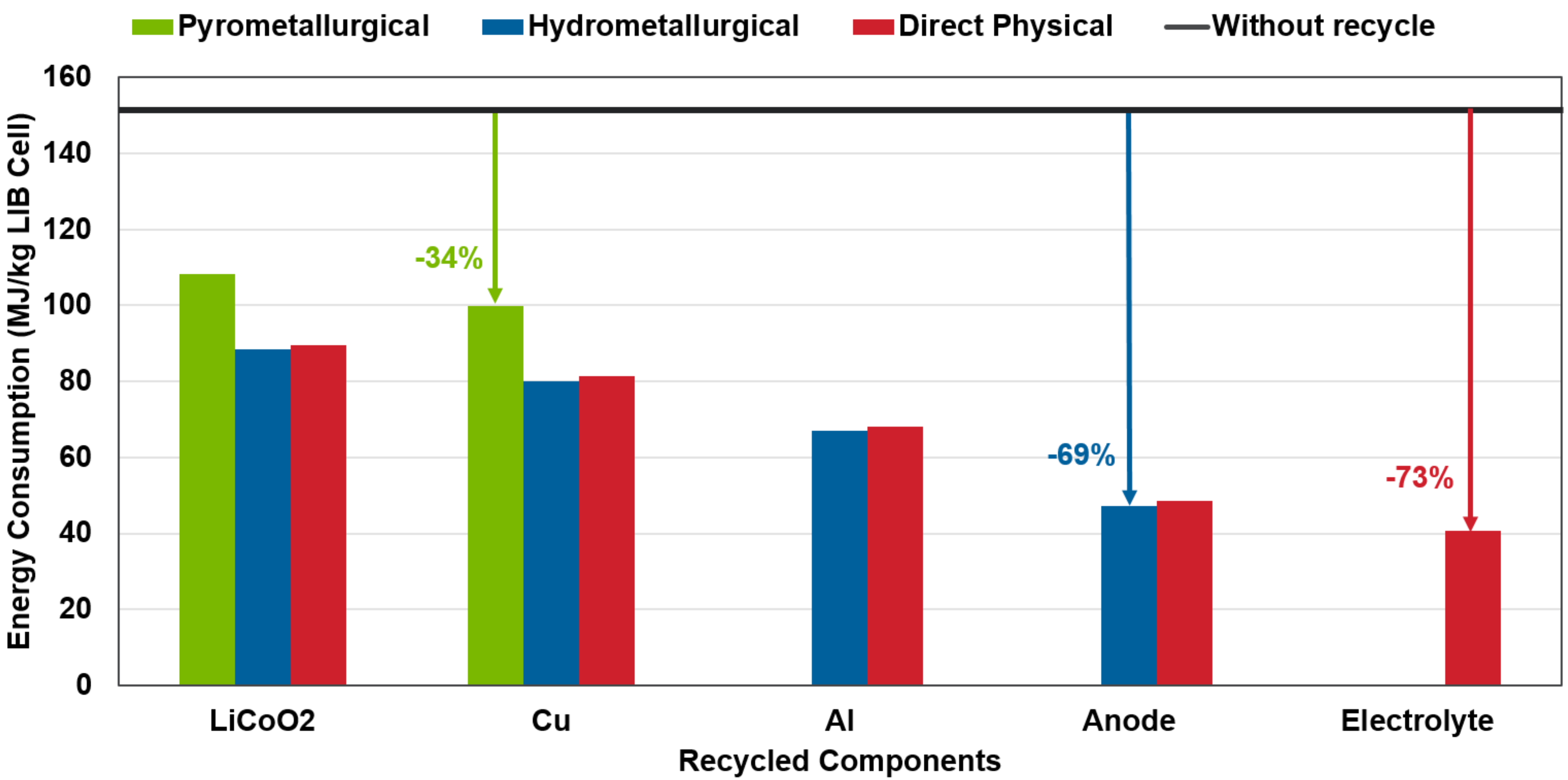


LI-ION BATTERY CONTRIBUTION TO LIFE-CYCLE GHG IS SMALL BUT SIGNIFICANT FOR SO_X EMISSIONS



RECYCLING MINIMIZES BATTERY IMPACTS

- Recycled materials take less energy to make
- Recycling reduces emissions burdens and material costs
- Recycling reduces demand for raw materials

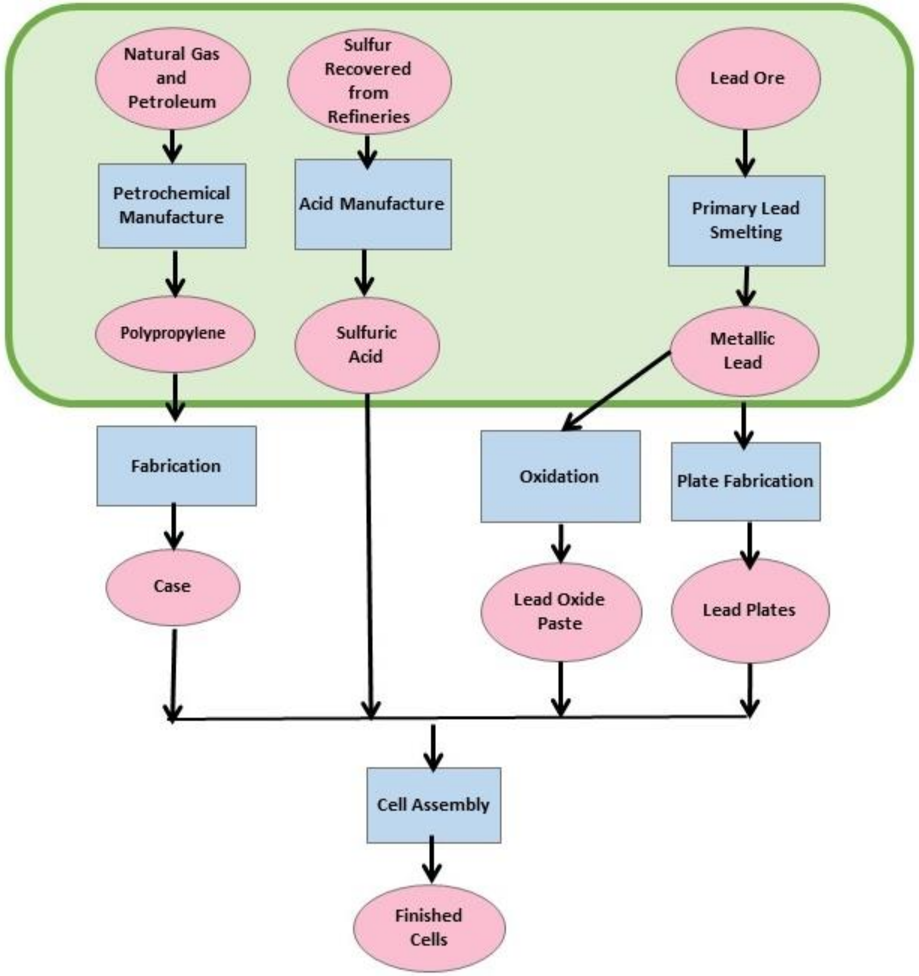


PB-ACID BATTERIES ARE RECYCLED PROFITABLY

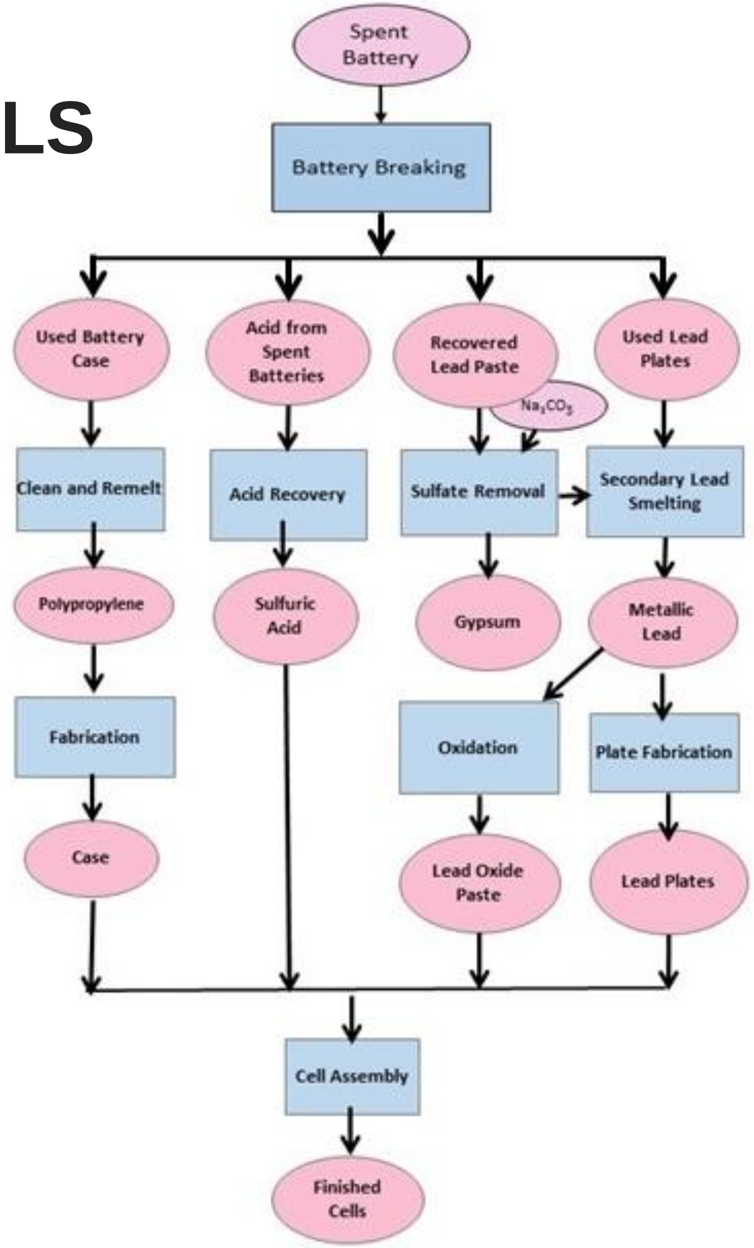
- ~98% of U.S. Pb-acid batteries are collected and recycled
  - Disposal is illegal
  - Dealers are required to collect when new ones purchased
  - They are paid to return them
  - Export is averted (but not prevented)
- Batteries are returned to manufacturer via back-haul
- Transport and processing are regulated to protect people and the environment
  - Lead and sulfur emissions are tightly regulated
- Single design and chemistry easily recycled
- The product is standardized and accepted in the marketplace

Argonne NATIONAL LABORATORY

LEAD-ACID RECYCLING DISPLACES ALL PRIMARY MATERIALS

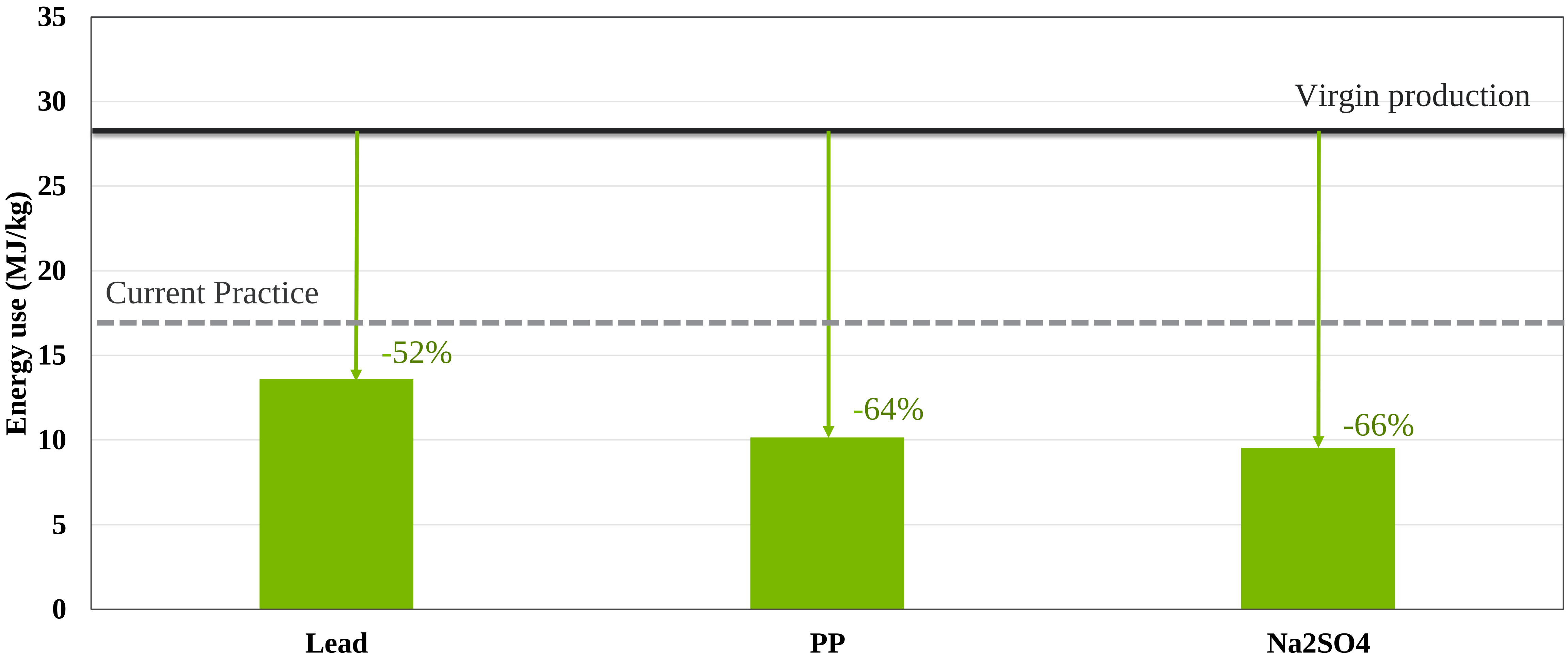


Virgin Cell Production



Recycled Cell Production

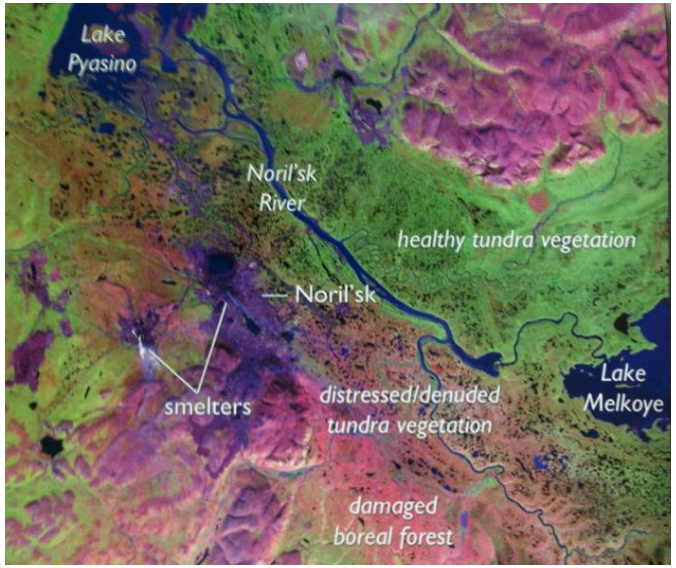
BENEFITS OF SPENT LEAD ACID BATTERY RECYCLING: ENERGY USE



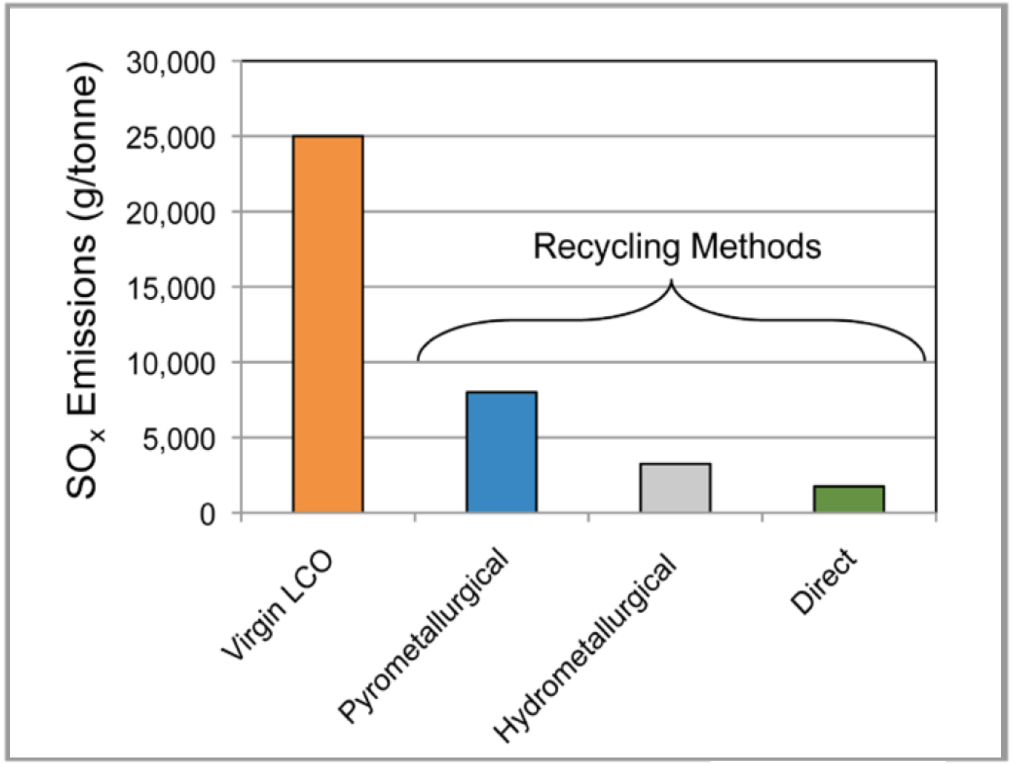
LEAD RECYCLING REQUIRES SULFUR CONTROLS

Li-ion recycling avoids sulfur emission concerns

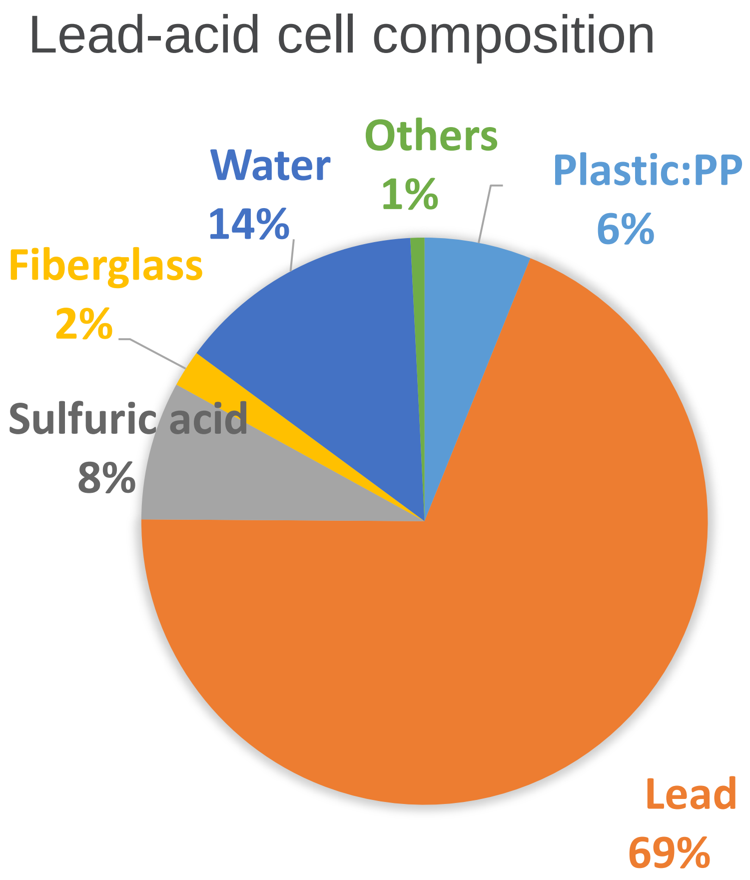
- Production of metals from sulfide ores requires extensive emission controls
- Primary lead, cobalt, nickel, and copper are all smelted from sulfide ores
- Lead-acid batteries use sulfuric acid as electrolyte
- Lead sulfate deposits on both electrodes and converts to stable configuration
- Sulfur must be recaptured in secondary lead processing
- No sulfur-containing components in Li-ion batteries

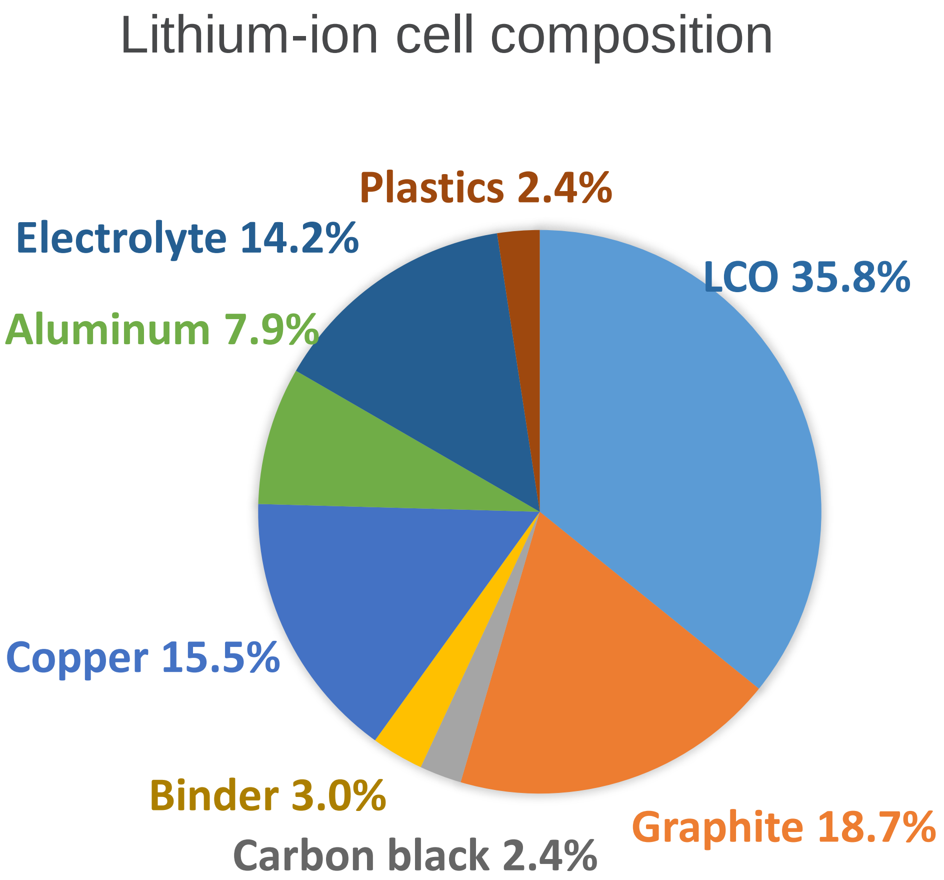


Source: NASA poster NW 2011-10-093-GSFC



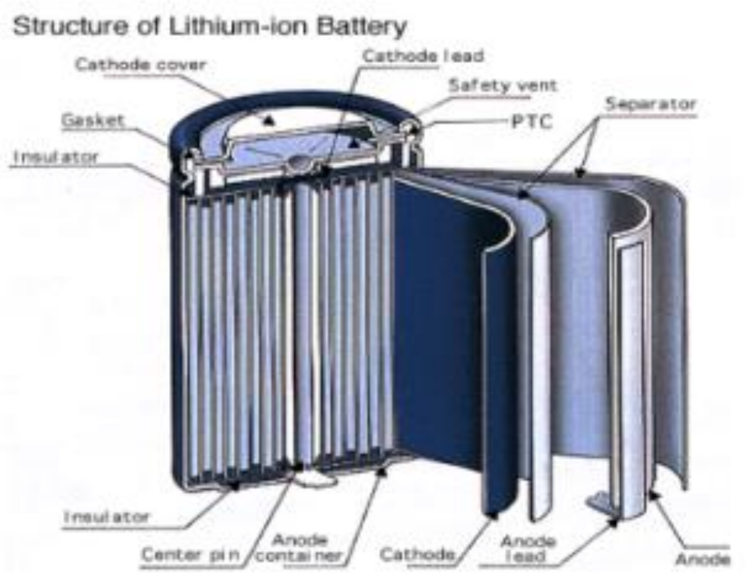
LITHIUM-ION CELLS ARE MORE COMPLICATED THAN LEAD-ACID

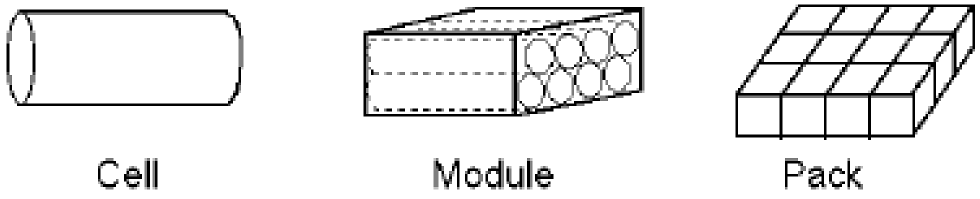




LCO= lithium cobalt oxide; PP = polypropylene

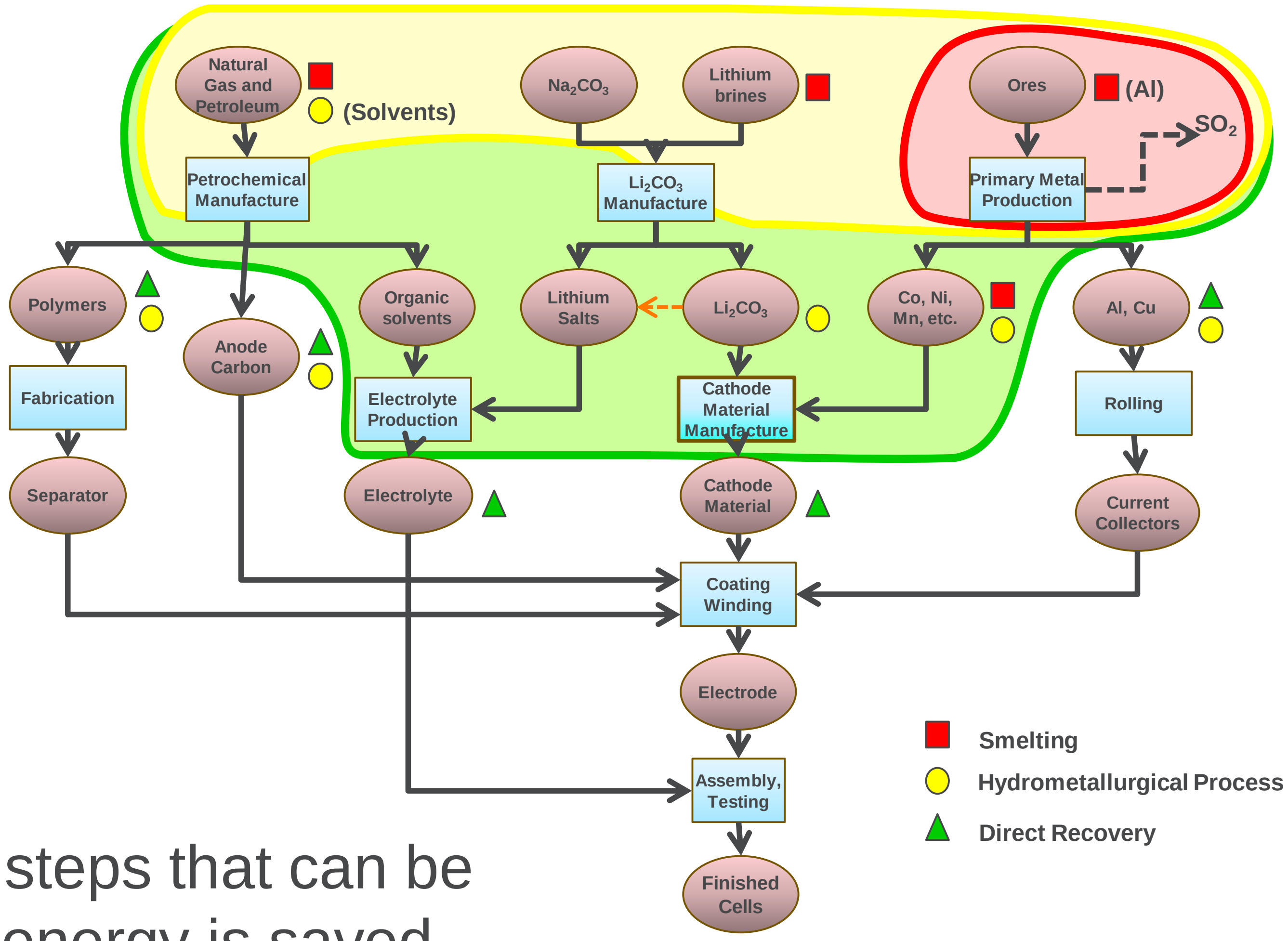
AN AUTOMOTIVE LI-ION BATTERY PACK IS A COMPLEX SYSTEM





Source: L. Gaines and R. Cuenca, *Costs of Lithium-Ion Batteries for Vehicles*, Report ANL/ESD-42 (2000)

LI-ION RECYCLING PROCESSES DISPLACE MATERIALS AT DIFFERENT PRODUCTION STAGES



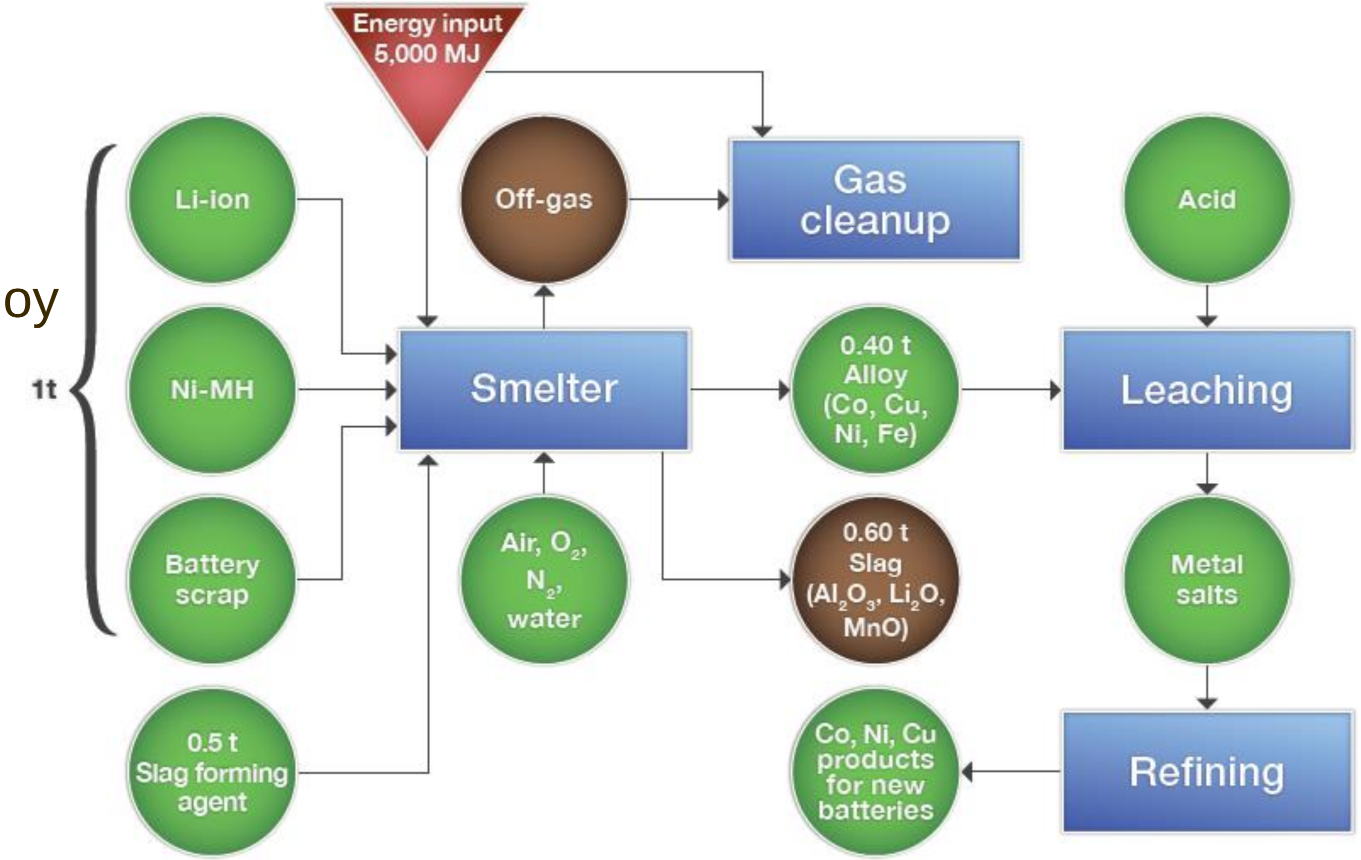
The more process steps that can be avoided, the more energy is saved.

Argonne NATIONAL LABORATORY

SMELTING AVOIDS SOME ORE PROCESSING

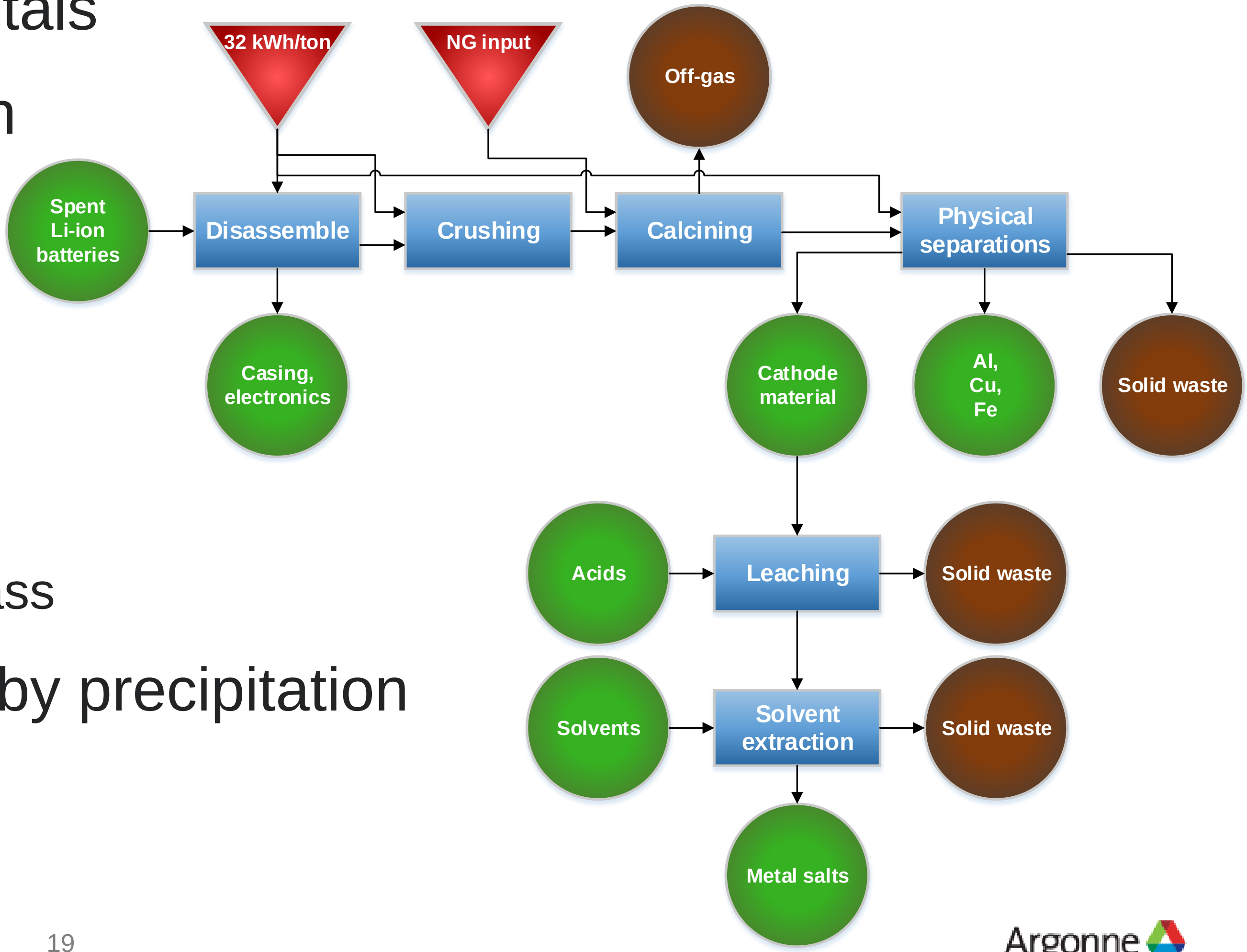
Leaching is required to recover metals

- High-temperature required
- Organics are burned at high-T
- Valuable metals are recovered
  - Co, Ni, Cu are leached from mixed alloy
  - Economics depends on them
  - Not available from new chemistries
- Li, Al go to slag
- Flexible process input
- Requires high volume
- Extensive and expensive gas treatment



HYDROMETALLURGY CAN RECOVER ALL METALS

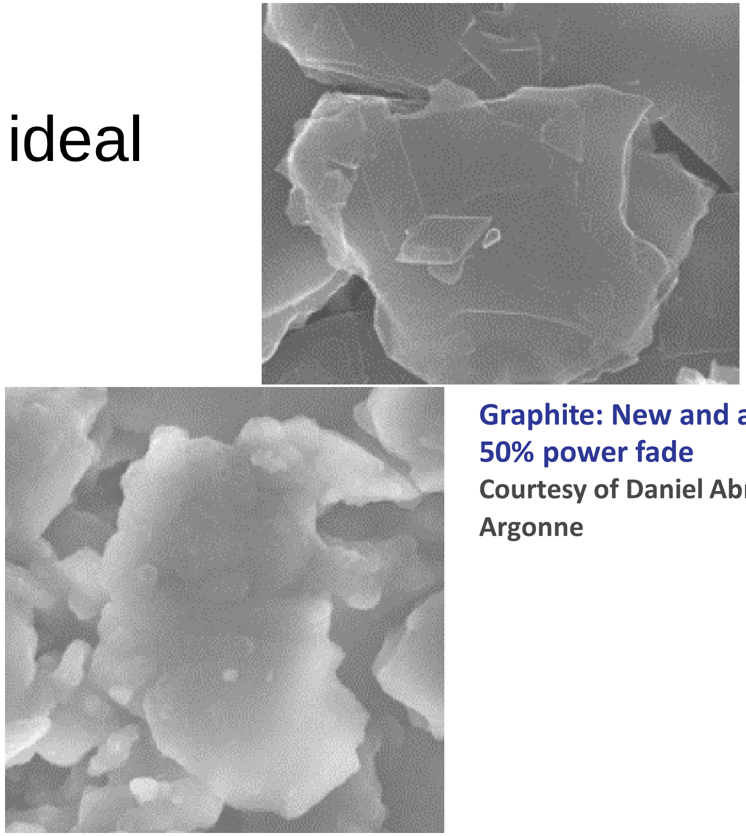
- Low temperature, low energy process
- Copper and aluminum are recovered by shredding
- Acid is used to leach out cathode metals
- Oxide/salt can be input for production of new cathode material
  - Mixture of input chemistries yields mixed oxide product
  - Novel idea: Add virgin oxides to match desired cathode product
  - Retriev omits acid and recovers black mass
- Lithium carbonate can be recovered by precipitation



Argonne NATIONAL LABORATORY

RECOVERY OF BATTERY-GRADE MATERIALS AVOIDS IMPACTS OF VIRGIN MATERIAL PRODUCTION

- Direct recycling demonstrated for several chemistries
  - Demonstrated on bench scale only
  - Combination of physical processes
- Components are separated to retain valuable material structure
- Does not require large volume
- Requires uniform feed so prompt scrap ideal
- Low-temperature, low energy process
- Product may be degraded or obsolete
- Willing purchaser needed

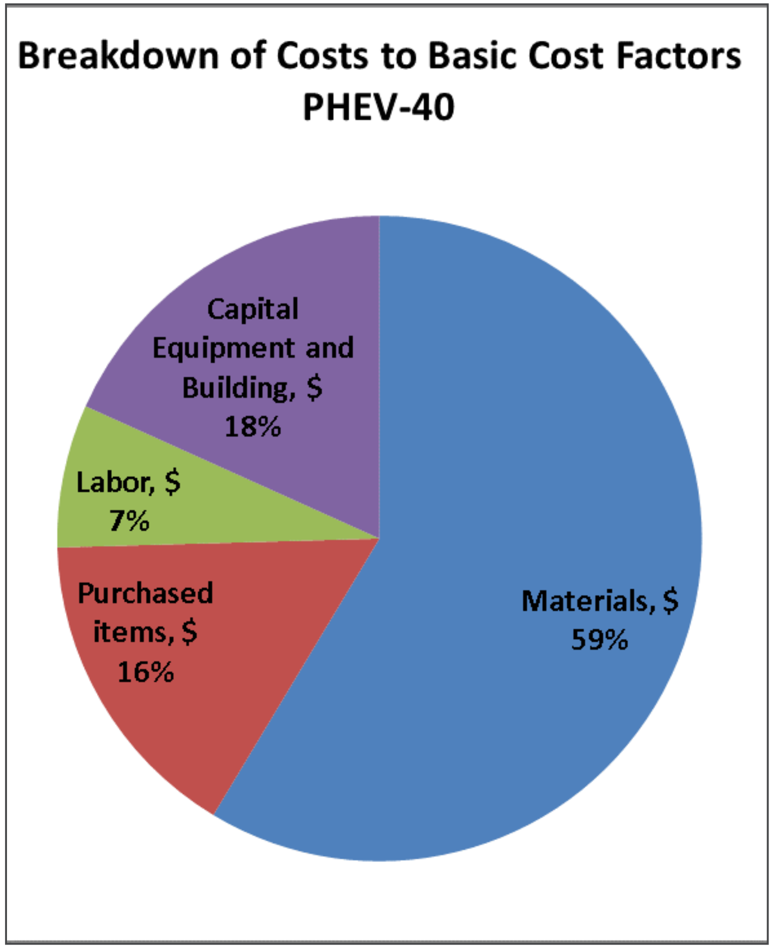


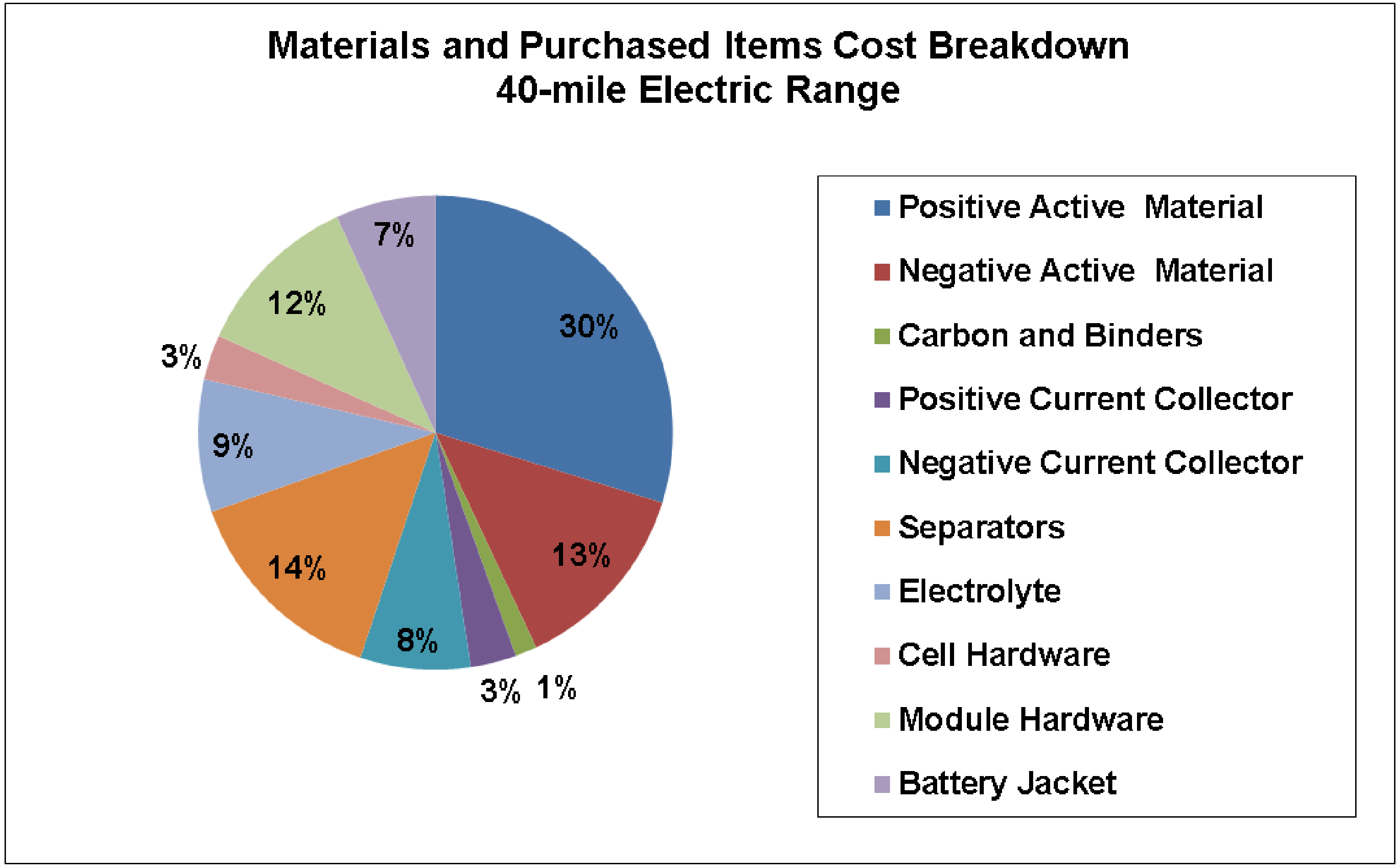
Graphite: New and after 50% power fade

Courtesy of Daniel Abraham, Argonne

MATERIALS DOMINATE LI-ION BATTERY COST

Cathode is by far the largest contributor to recover



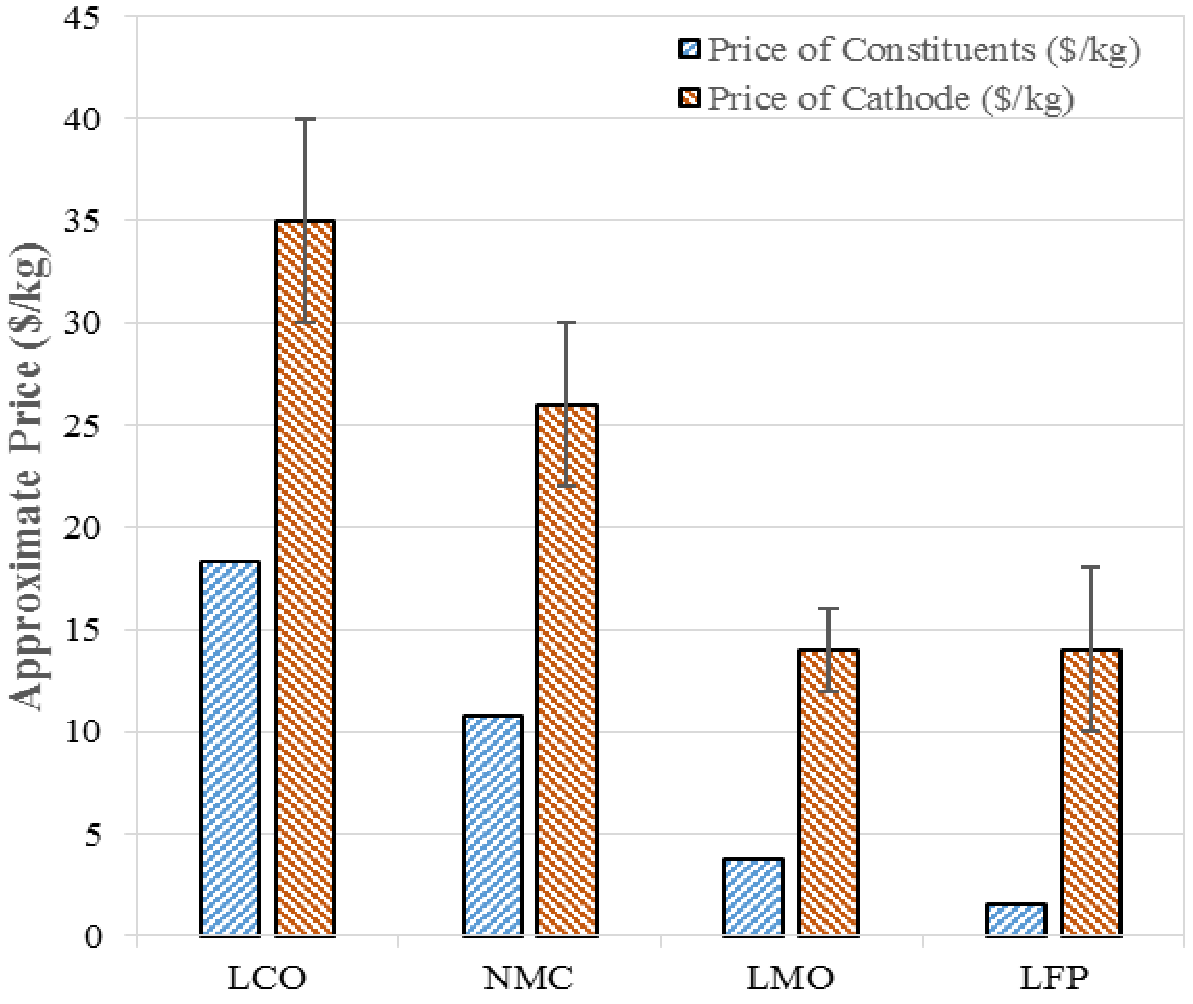


Source: K. Gallagher, Argonne, *Cost of batteries for energy storage today, in the future, and origin of cost goals: a description of cost analysis tools* (11/3/2015)

Argonne NATIONAL LABORATORY

CATHODE VIABILITY IS KEY TO ECONOMICS
FOR CATHODES WITH LOW ELEMENTAL VALUES

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



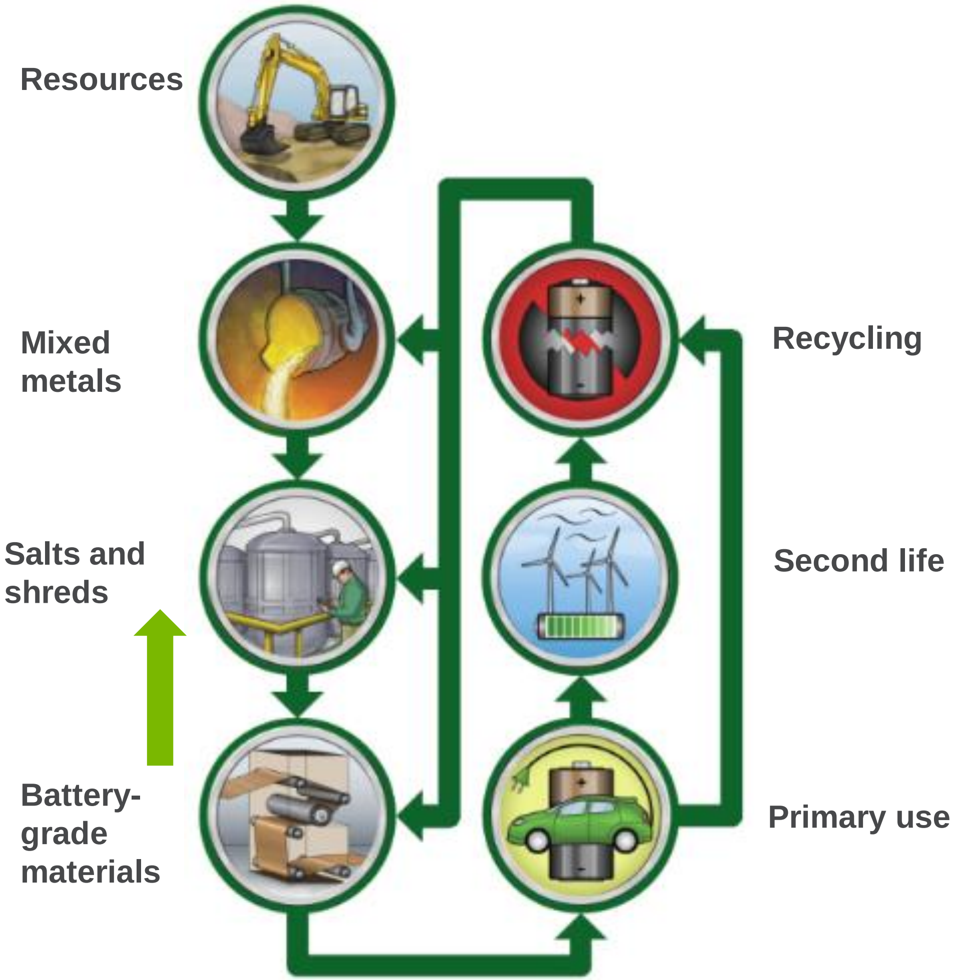
Argonne NATIONAL LABORATORY

CHALLENGES TO LI-ION RECYCLING CAN BE ADDRESSED BY R&D

Challenge	R&D needed to address
Long-term performance of some recycled materials is not proven	Long-term testing
There is no standard chemistry or design	Convergence of chemistries and designs Flexible processes Design for recycling Automation
There are no regulations, so restrictive ones could be imposed	Fashioning regulations that will protect health and safety without hindering recycling
Many of the constituents have low market value	Process development to recover multiple high-value materials
Low value of mixed streams, prevention of fires and explosions	Effective labeling and sorting

THANK YOU!

Dave Howell and Samm Gillard
DOE Vehicle Technologies Office



Lithium-Ion Battery Issues
IEA Workshop on Battery Recycling Hoboken, Belgium (September 26-27, 2011)
https://anl.app.box.com/s/ko9zpwi8ui0amvew4uxdzn80p6ndaptp