CEMAC
Clean Energy Manufacturing Analysis Center

Toward Greater Understanding of Upstream and Downstream Manufacturing Processes of Automotive Li-ion Batteries

Advanced Automotive Batteries Conference

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National Renewable Energy Laboratory

Agenda

I. Critical Materials for LIBs

II. LIB Raw Materials Supply Chain

III. Manufacturing Methods of LIB Materials

IV. Cost Analysis for LIB Materials Production

V. LIB Pack Assembly and Cost

VI. Conclusions

I Critical Materials for LIBs

Critical Materials for LIB

Materials used in Li-ion batteries have low to medium criticality ratings

- Study by Joint Research Center (JRC) in the European Commission on critical materials shows that several of the elements used in the manufacturing of lithium ion batteries (LIBs) are considered critical

Table 1: Criticality ratings of shortlisted raw materials

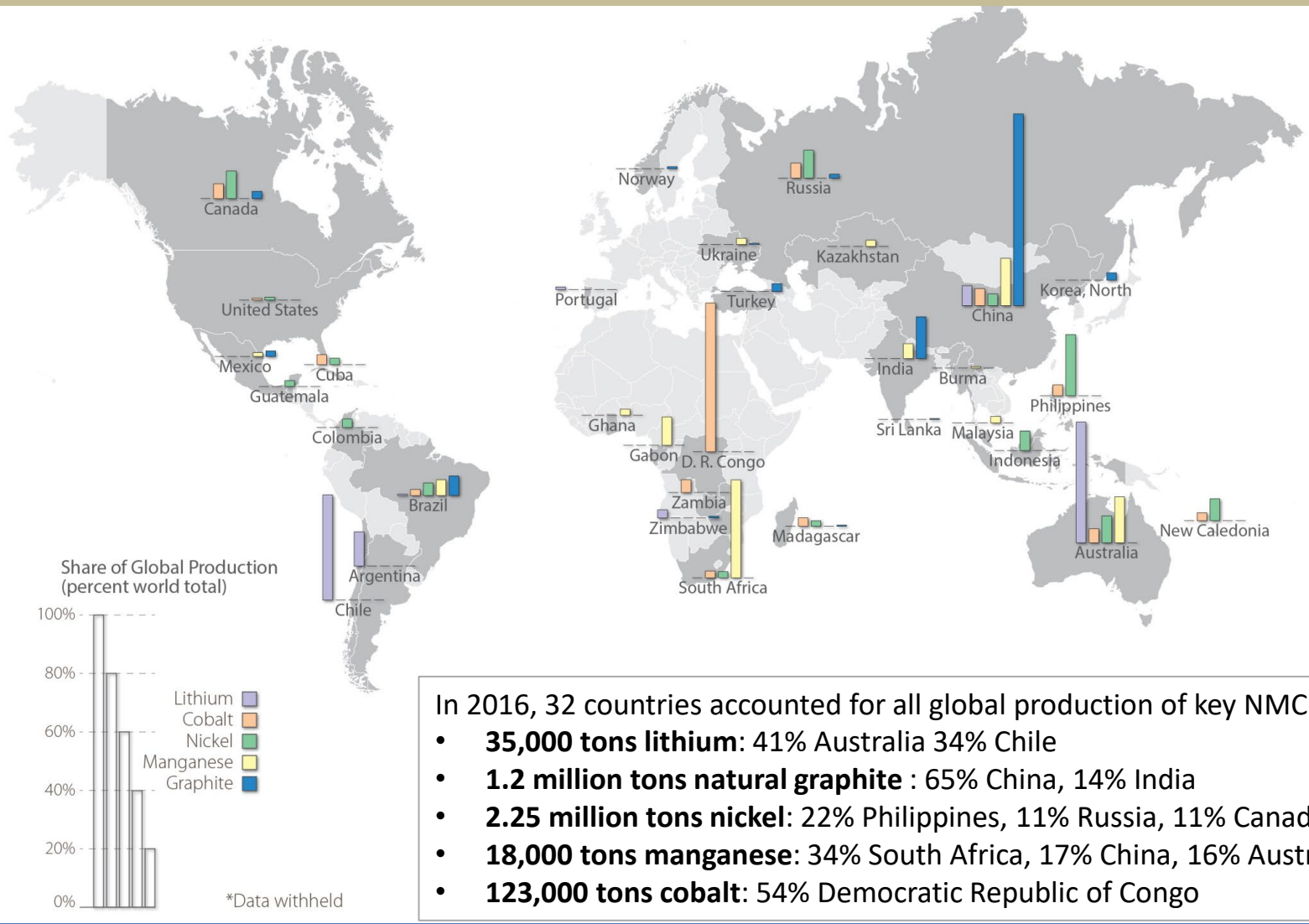
High	High-Medium	Medium	Medium-Low	Low
REE: Dy, Eu, Tb, Y	Graphite	REE: La, Ce, Sm, Gd	Lithium	Nickel
REE: Pr, Nd	Rhenium	Cobalt	Molybdenum	Lead
Gallium	Hafnium	Tantalum	Selenium	Gold
Tellurium	Germanium	Niobium	Silver	Cadmium
	Platinum	Vanadium		Copper
	Indium	Tin		
		Chromium		

Moss et al., 2013

II LIBs Raw Materials Supply Chain

LIB Supply Chain – Raw Materials

In 2016, 32 countries accounted for all global production of Li, Co, Ni, Mn and Graphite, with 50% of production of each element originating in one or two countries.

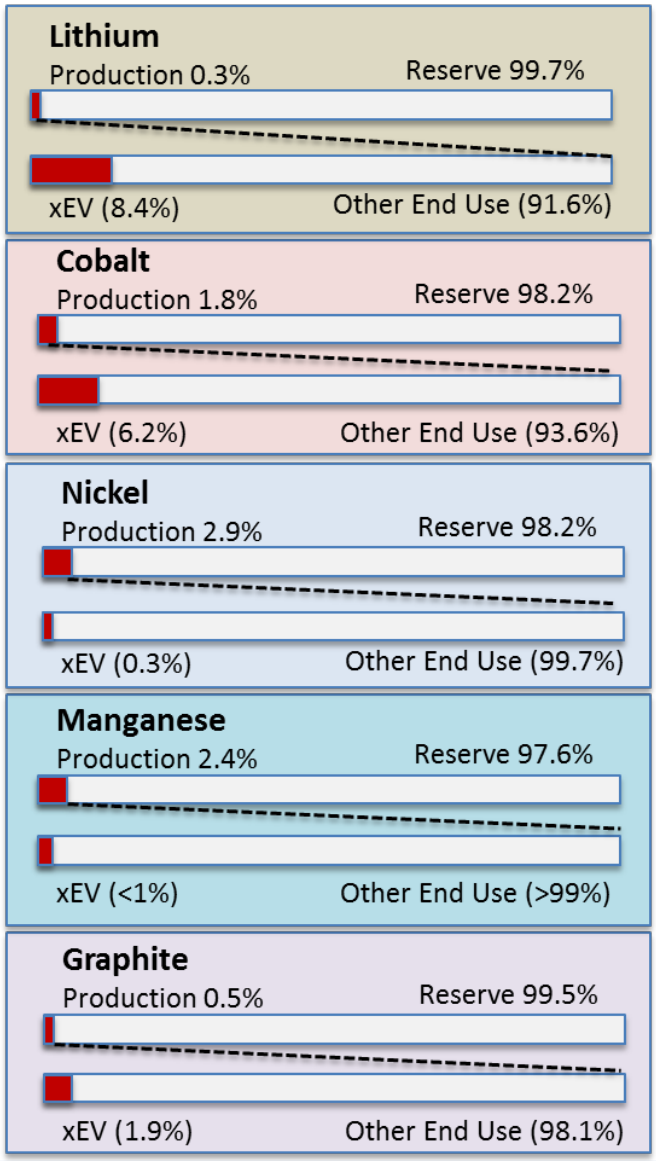


In 2016, 32 countries accounted for all global production of key NMC materials

- **35,000 tons lithium**: 41% Australia 34% Chile
- **1.2 million tons natural graphite** : 65% China, 14% India
- **2.25 million tons nickel**: 22% Philippines, 11% Russia, 11% Canada, 9% Australia
- **18,000 tons manganese**: 34% South Africa, 17% China, 16% Australia
- **123,000 tons cobalt**: 54% Democratic Republic of Congo

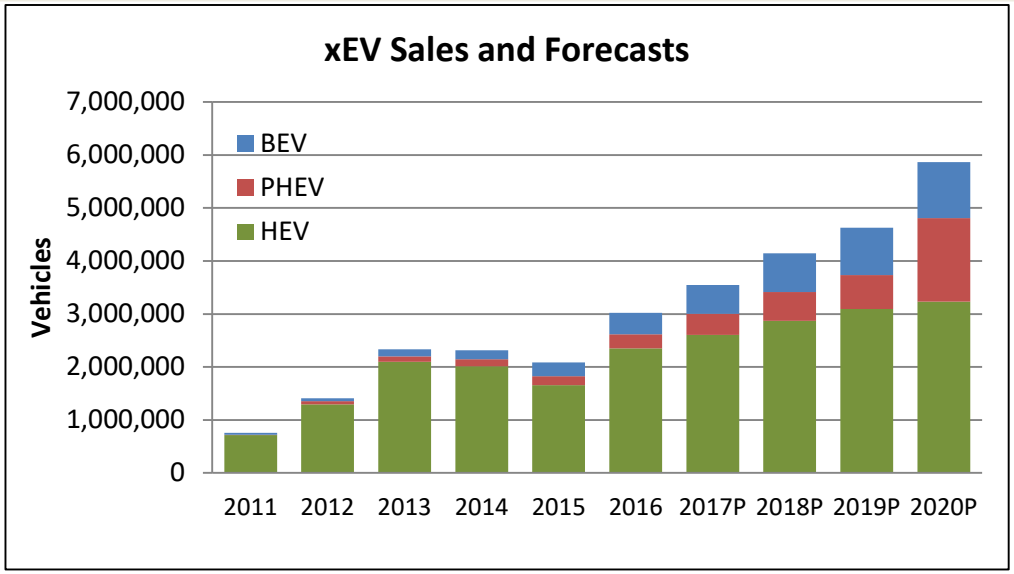
LIB Supply Chain – Raw Materials

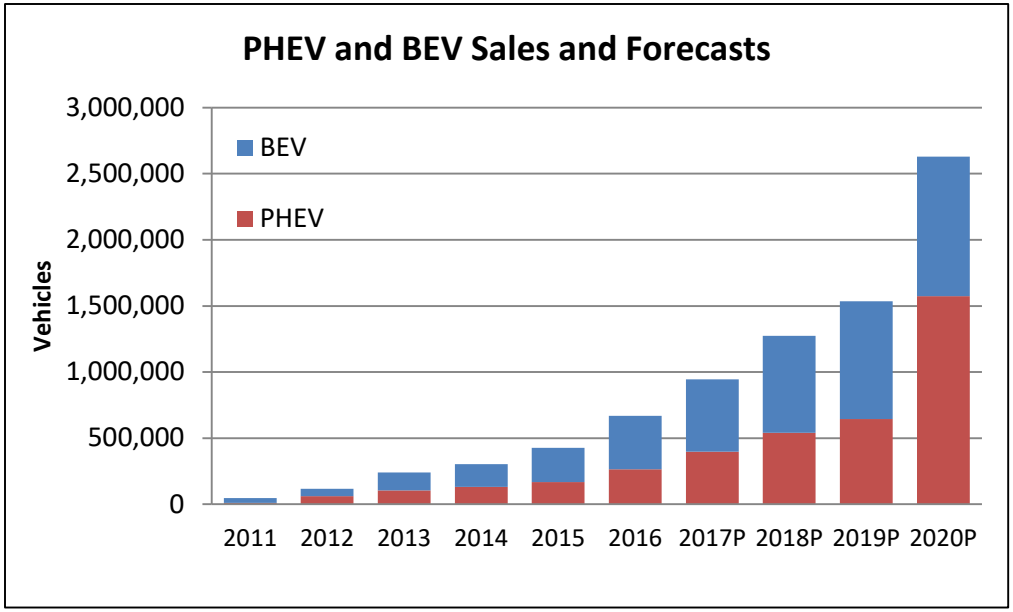
World Mine Production (2016)



- Elements critical for LIB manufacturing do not constitute the majority end use of any of these elements
- Based on estimated battery designs and 2016 EV sales figures, approximately 8% of lithium, 6% of cobalt, <1% of nickel, <1% of manganese, and 2% of graphite produced in 2016 were used for EV battery manufacturing
- Current reserves of these elements continue to change as known deposits are depleted, and as new ones are discovered. These reserves are also based on economically extractable resources – driven by markets and technology
- For all these elements, 2016 mining production represented less than 3% of estimated reserves.

BEV, PHEV Sales Steady - HEV Sales Slow

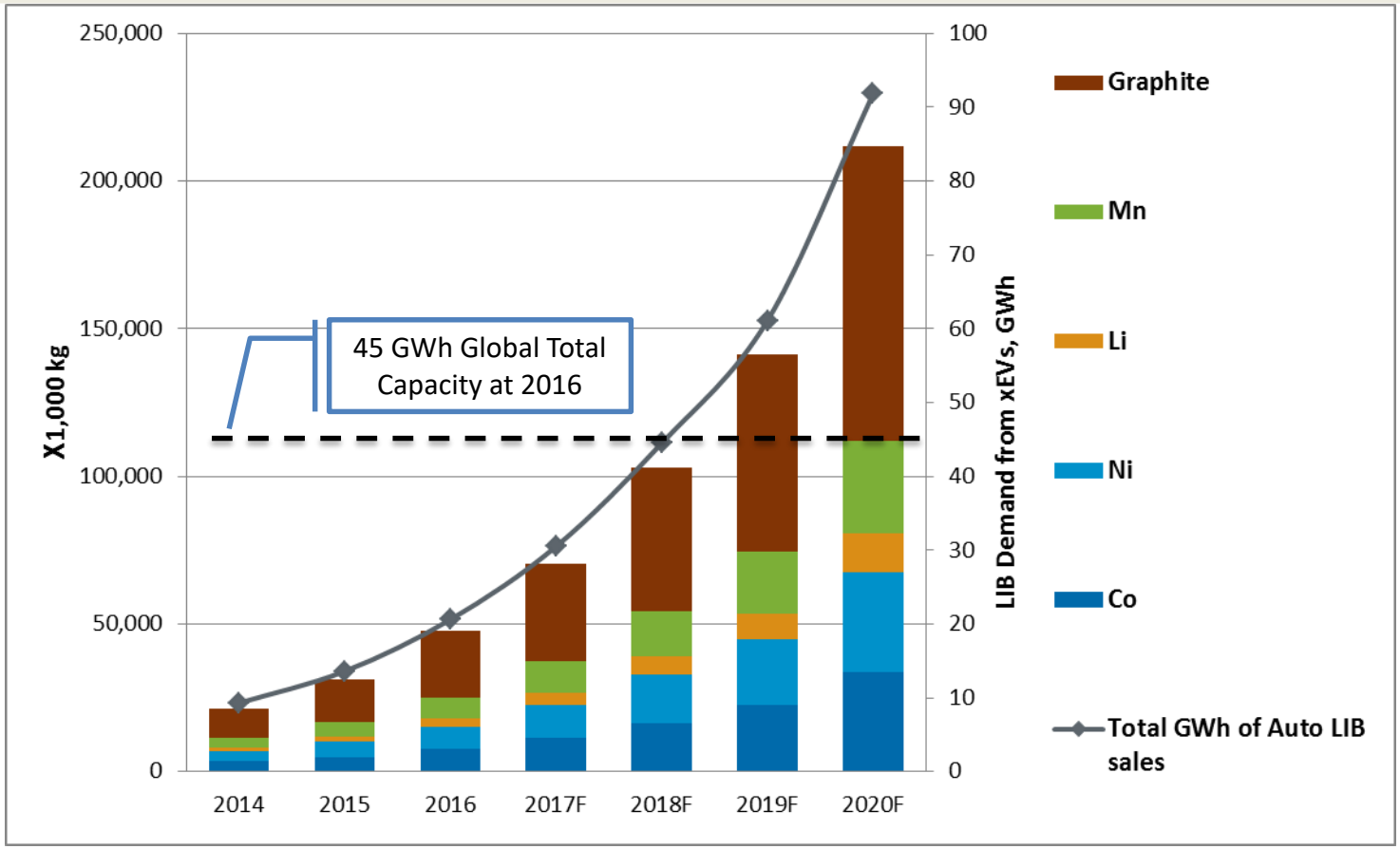




- **Total xEV sales grew rapidly 2012-2016 @ 17% CAGR**
- **Hybrid Electric Vehicles (HEVs)**
  - **50% CAGR 2011-2016**
  - **But, sales flat to declining 2013-2015**
  - **8% CAGR forecast 2017-2020**
- **Plug-in Hybrid Electric Vehicles (PHEVs)**
  - **34% CAGR 2011-2016**
  - **56% CAGR forecast 2017-2020**
- **Battery Electric Vehicles (BEVs)**
  - **44% CAGR 2011-2016**
  - **42% CAGR forecast 2017-2020**

Sources: BNEF 2016; Navigant 2015; Technavio 2015; Roland Berger 2015; International Energy Agency (IEA) 2015; NREL estimates

xEV LIB Demand vs. Materials



- **25% CAGR in LIB forecast from 2017-2020**
- **LIB demand estimates are driven by BEVs and PHEVs**
- **Assumed energy storage requirements: 1 kWh for HEVs; 10 kWh for PHEVs; 35 kWh for BEVs**
- **Total automotive Li-ion battery capacity is expected to exceed 90 GWh by 2020**
- **This requires more than 120 million kg of battery materials (Li, Co, Mn, Ni, and Gr) by 2020**

Sources: BNEF 2016; Navigant 2015; Technavio 2017; Roland Berger 2015; International Energy Agency (IEA) 2015; Oak Ridge National Laboratory (ORNL) 2015; NREL estimates

III Manufacturing Methods of LIB Materials

Methods of Powder Production

Mechanical methods:

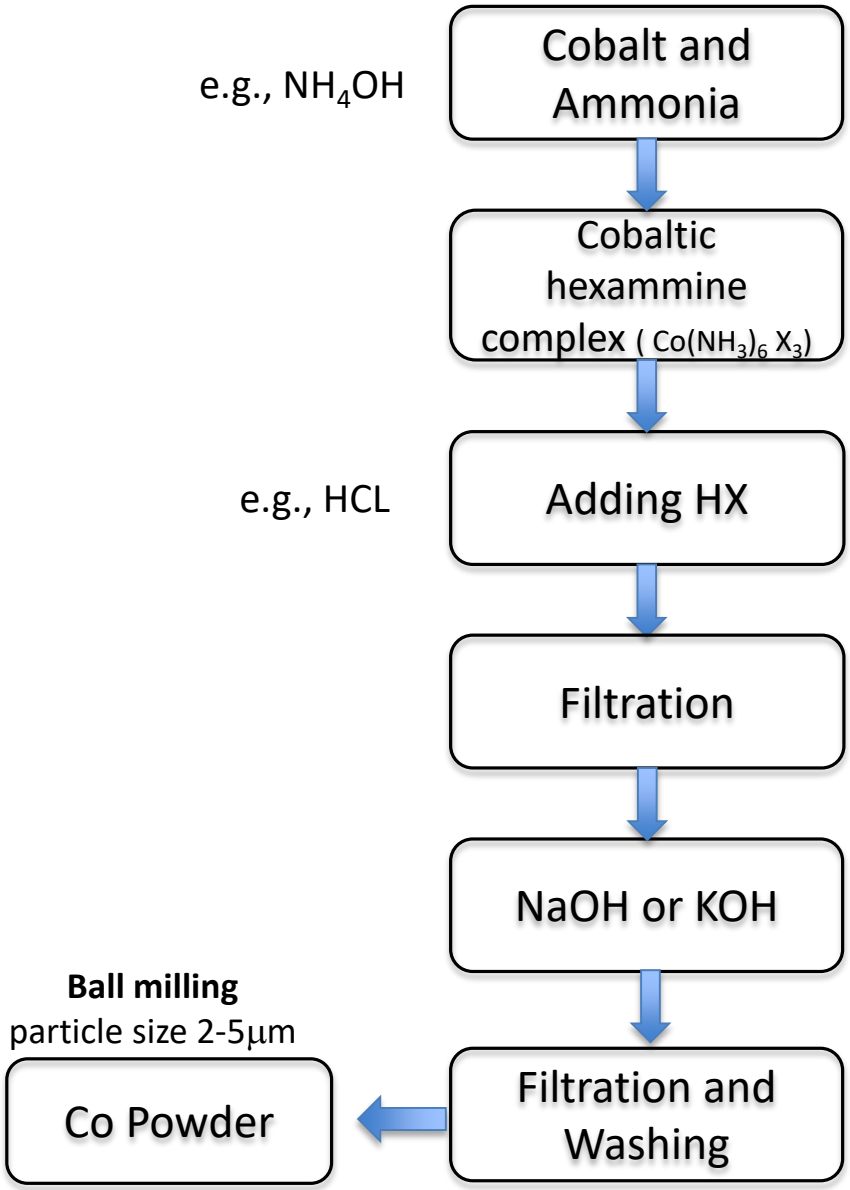
i) Chopping or Cutting
ii) Abrasion methods
iii) Machining methods
iv) Milling
v) Cold-stream Process

Chemical methods:

i) **Precipitation from solutions**
ii) Reduction of oxides
iii) Thermal decomposition of compounds
iv) Hydride decomposition
v) Thermit reaction
vi) Electro- chemical methods

✓ **Precipitation from solutions is one of the most economic and high yield processes**

Co Powder Preparation

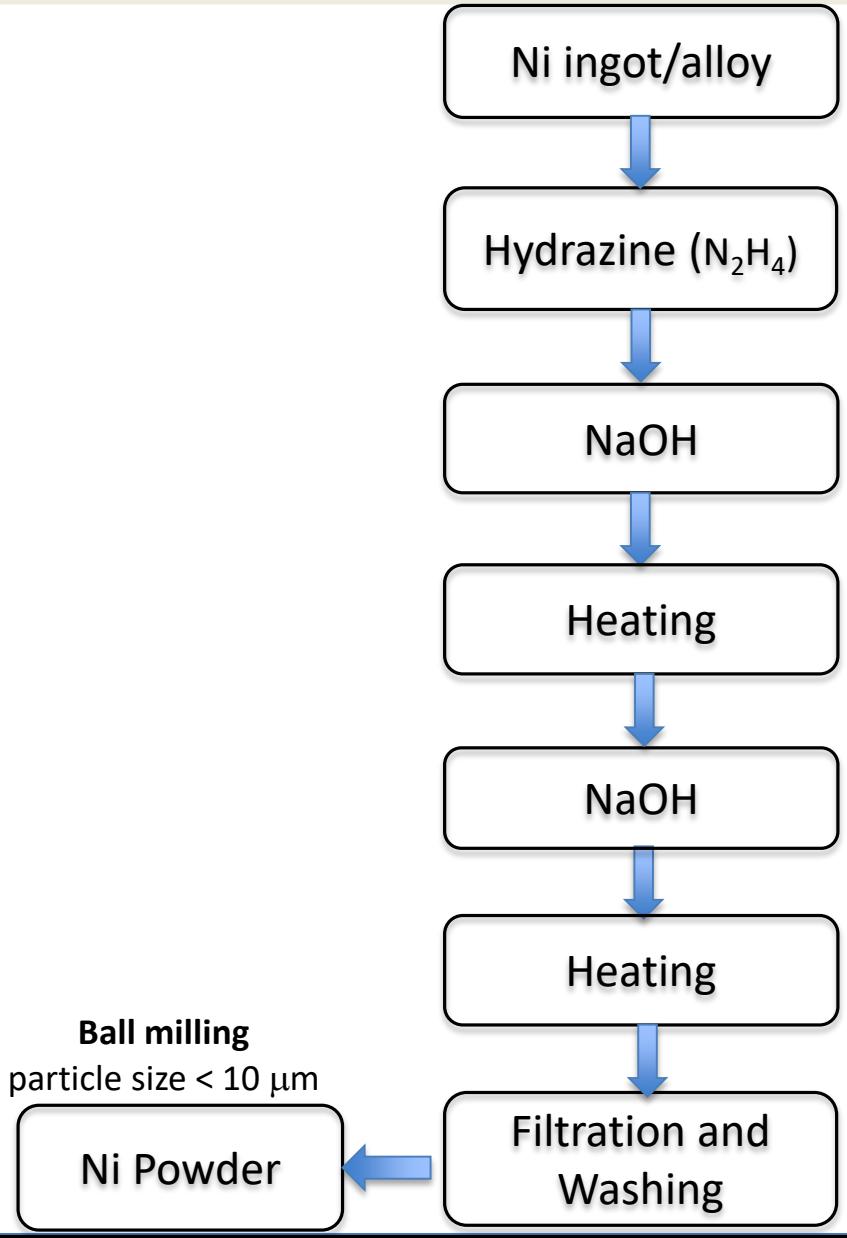


Catalyst
Ammonium hydroxide (or Ammonia)
10-80°C

The acid used is preferably a hydrogen halide of the formula HX wherein X is fluorine, chlorine, bromine, or iodine.

Patent: US4218240

Ni Powder Preparation



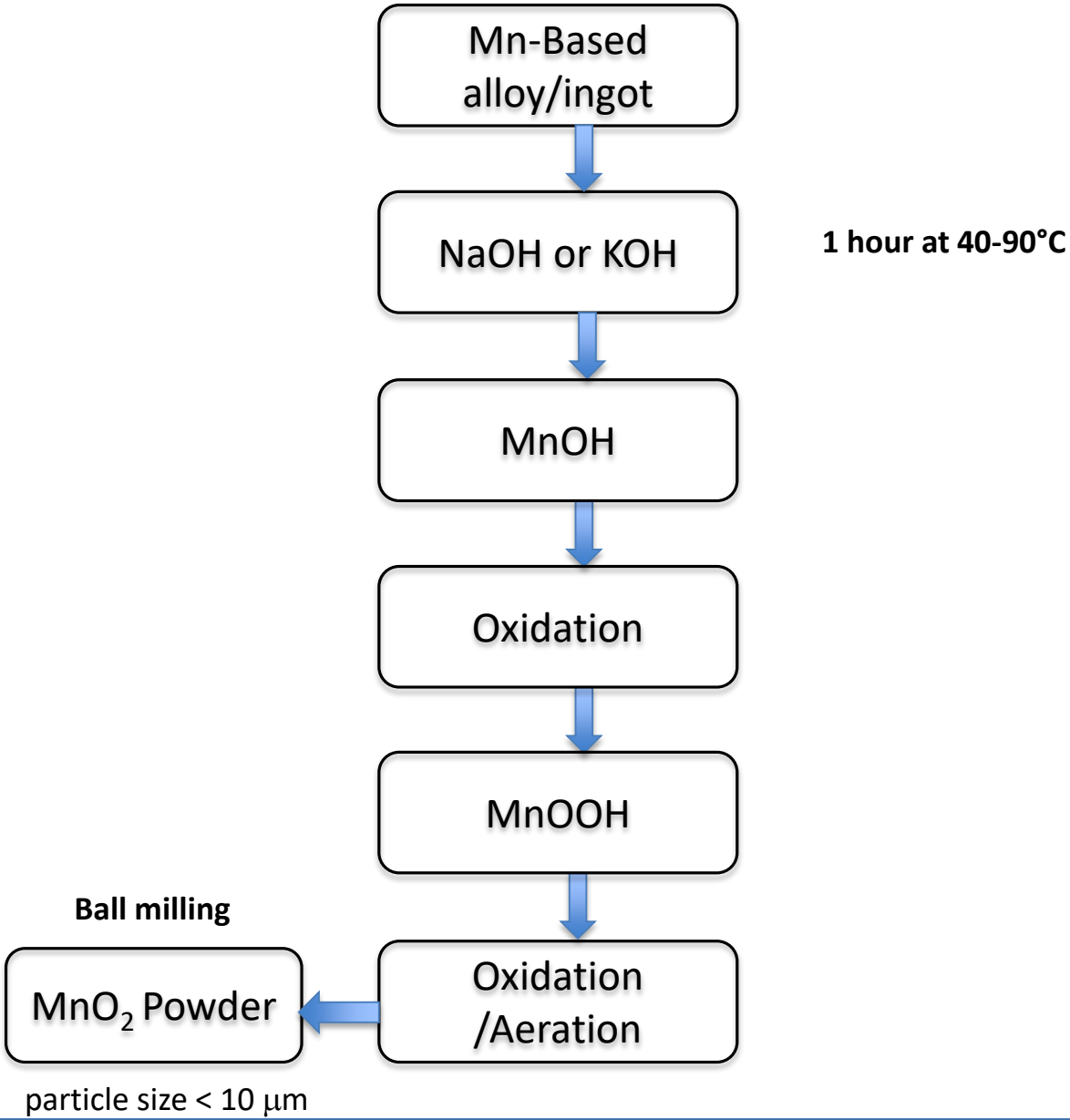
2.0 to about 2.5 milliliters of hydrazine per gram of nickel

88° C to about 92° C with stirring or agitation ambient pressure conditions

92° C to about 96° C with stirring or agitation ambient pressure conditions

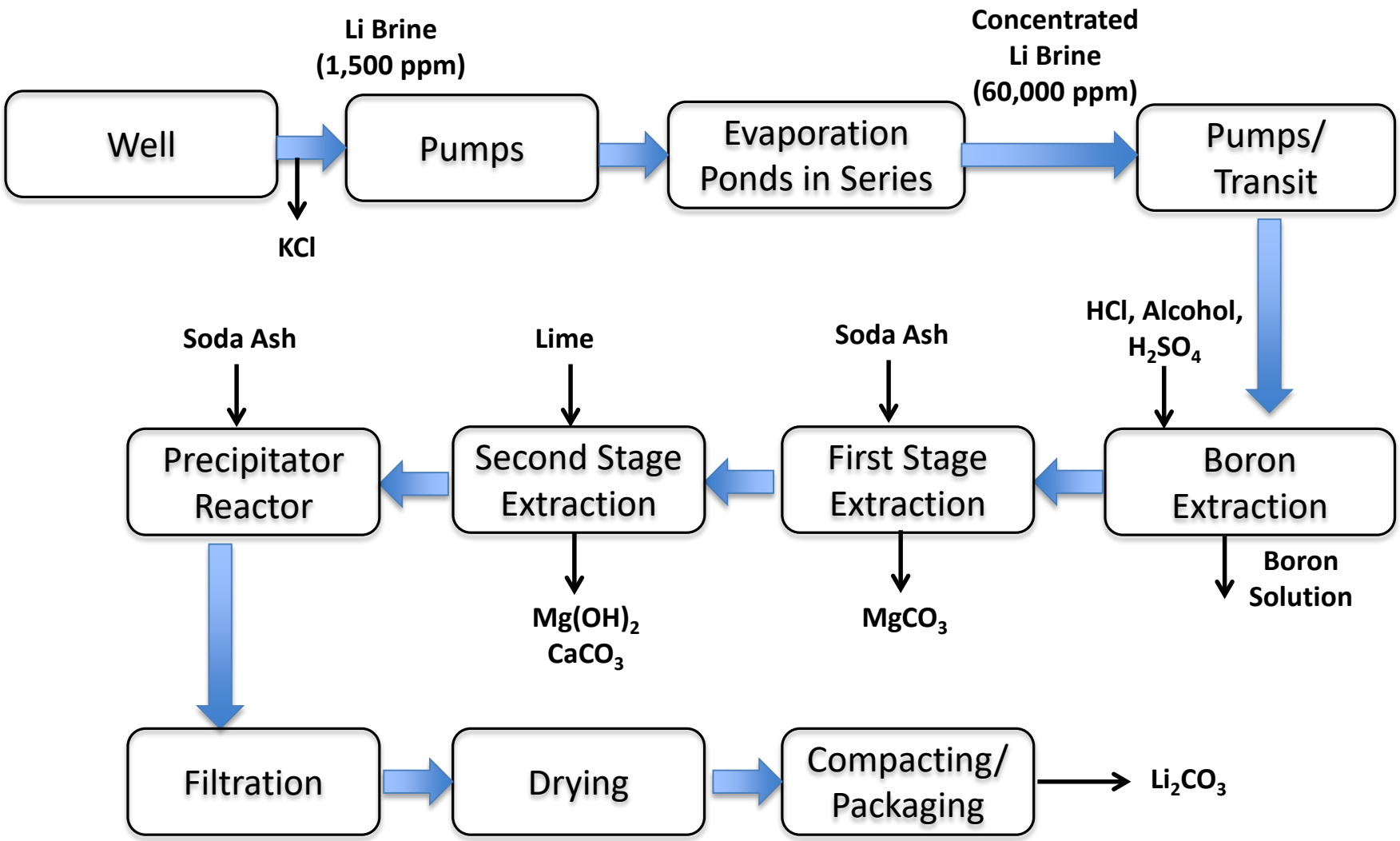
Patent: US4089676

MnO_2 Powder Preparation



Patent: US4006217

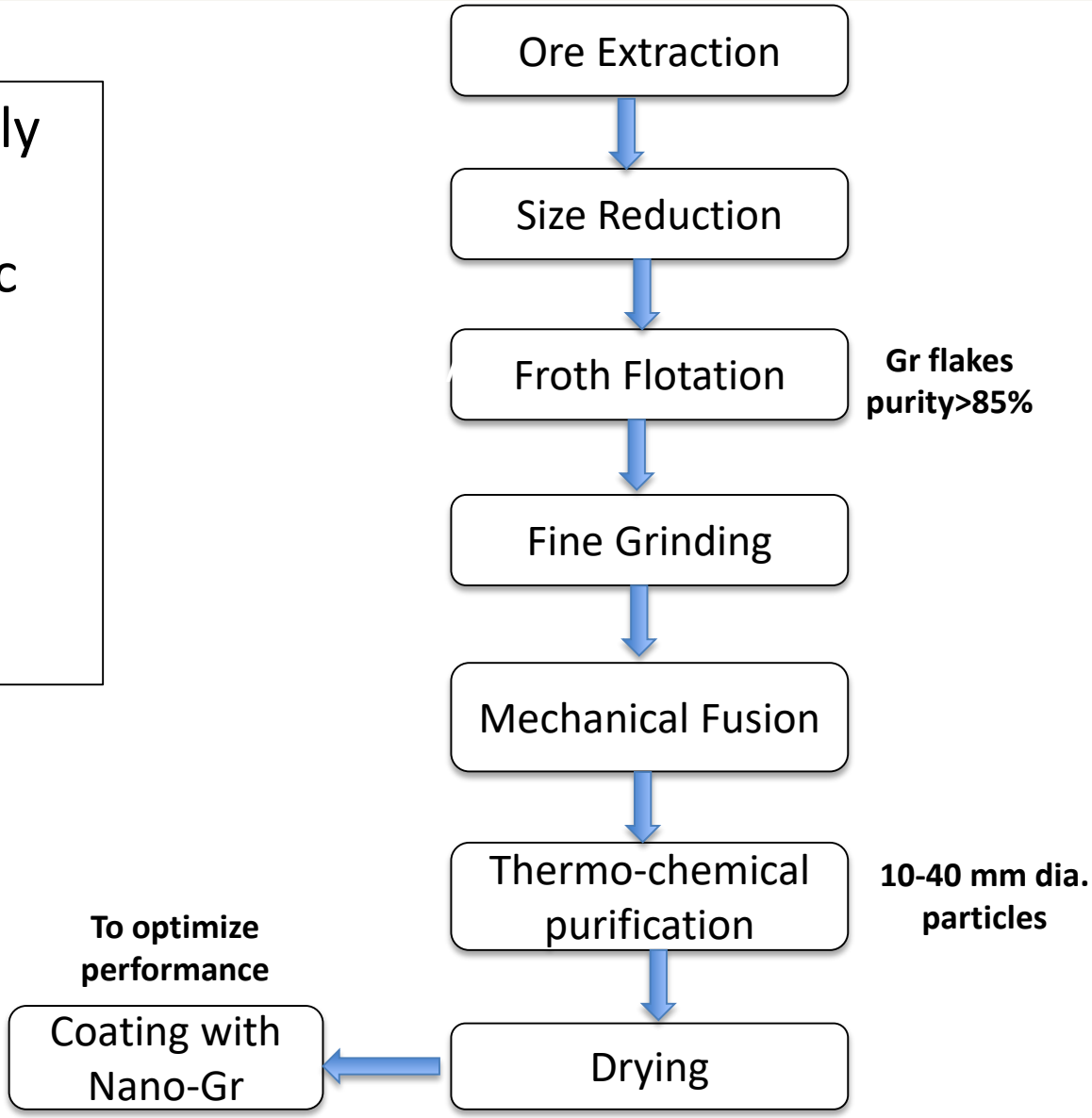
Lithium Carbonate from Li Brine



Dunn et al. 2014

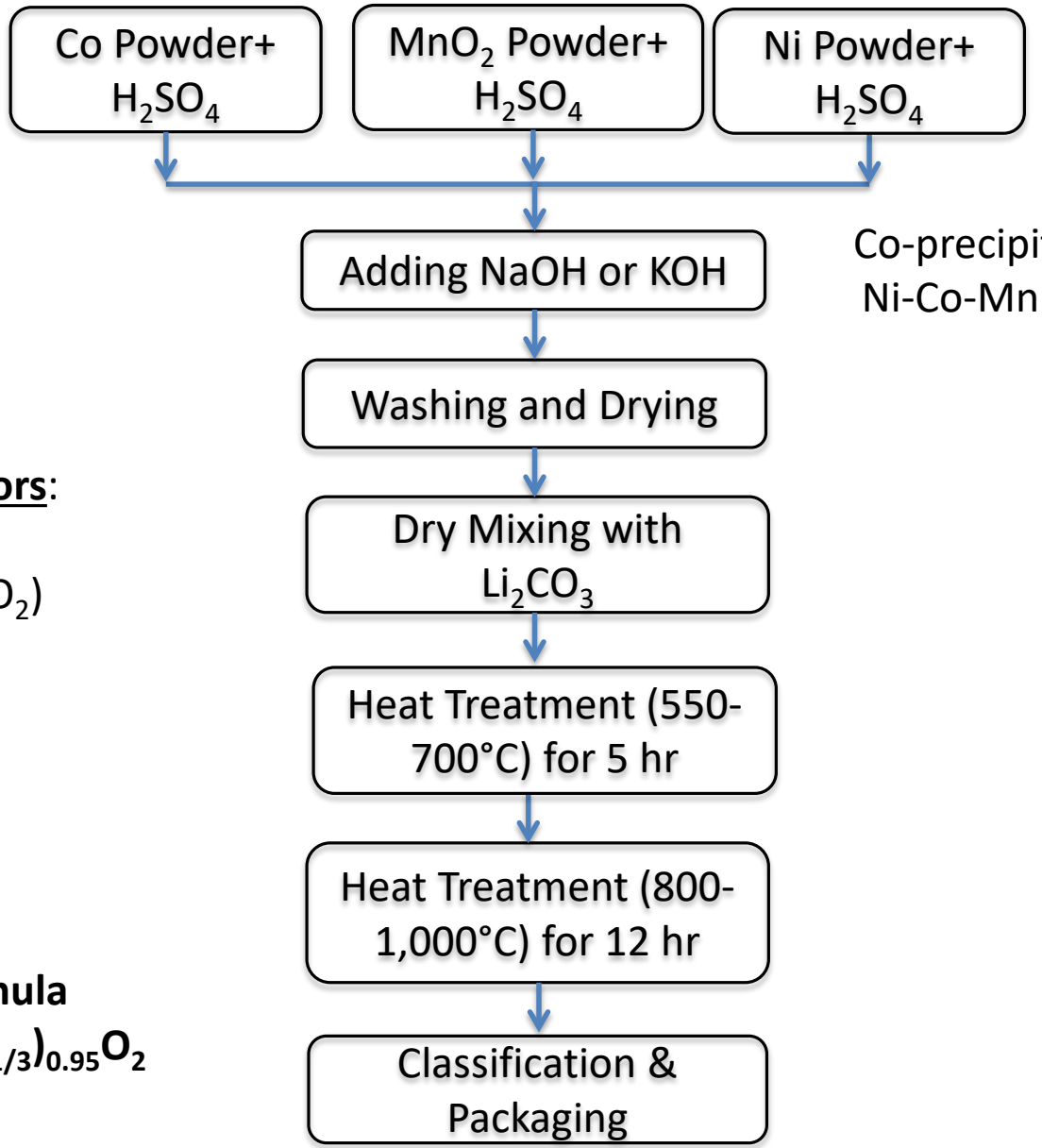
LIB Cell Materials- Graphite

- Flake graphite commonly minor constituent in crystalline metamorphic rocks
- For Li-ion battery applications, typical graphite purity is 98-99.95%



Clark, 2013

NMC Powder Preparation



Co-precipitation of Ni-Co-Mn Powder

<u>Co, Ni, Mn Precursors</u>:

- Sulphates (xSO_4)
- Acetates ($xC_2H_4O_2$)
- Hydroxides (OH)
- Nitrate (xNO_3)

NMC-333 Formula

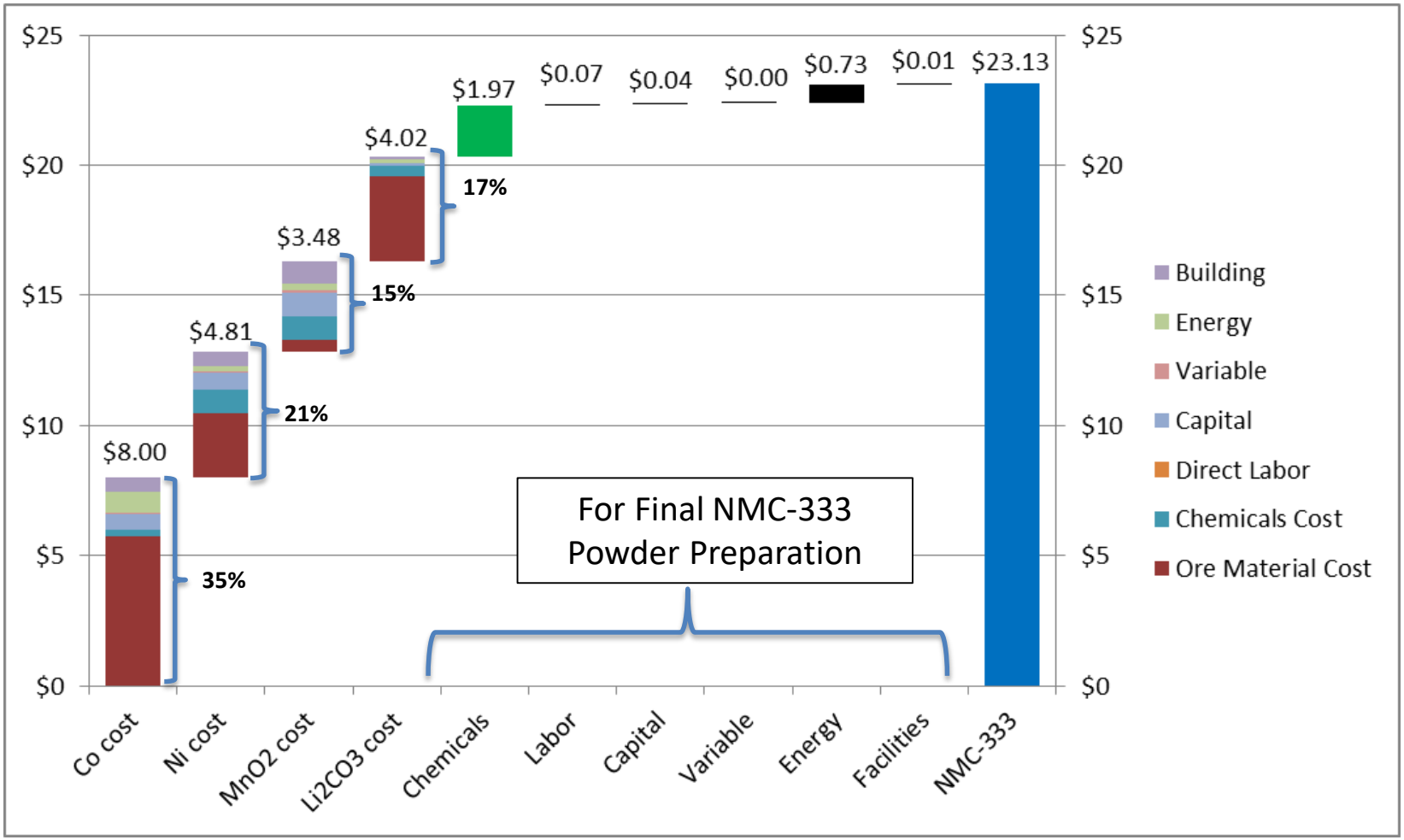
$$Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$$

Hashem et al., 2015
Zhang et al., 2011
Wang et al., 2004

IV Cost Analysis for LIB Materials Production

NMC Powder Cost

Ore-grade materials share about 52% of the final NMC-333 material followed by chemicals with 11% cost share



- Chemical for NMC-333 powder preparation prior to cell manufacturing. **Doesn't include** cost of chemicals used in purifying Co, Ni, Mn, or Li. (Annual production= 1 million kg/yr)

NMC Powder Preparation

While other cathode materials seem to have lower costs in relative to the NMC; NMC still provides lower $/kW cell cost among common cathode materials.

Table 1. Thickness of the positive and negative electrodes for each material for a maximum coating thickness of 50 μm.

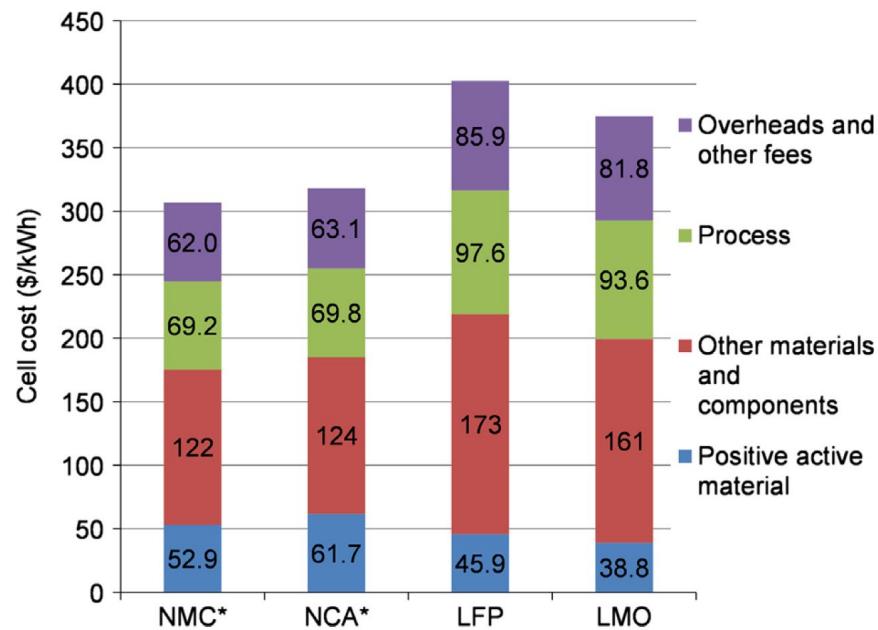
	Positive electrode coating thickness (μm)	Negative electrode coating thickness (μm)
NMC // Gr	49.0	50.0
NCA // Gr	45.0	50.0
LMO // Gr	50.0	30.4
LFP // Gr	50.0	34.2

Table 2. Prices of active materials obtained in the European project Helios [48].

	Price ($ kg^{-1})	Price relatively to NCA (%)	Corresponding volume (kT y^{-1})
NMC	27	82	1.8
NCA	33	100	1.8
LMO	14	42	2.6
LFP	21	64	2.1
Graphite	18.5	56	1.1

Table 3. Prices of cell materials and components.

Carbon black conductor	7.15 $ kg^{-1}
NMP binder	27.6 $ kg^{-1}
Electrolyte	19.5 $ kg^{-1}
Aqueous binder	10 $ kg^{-1}
Binder solvent	3.2 $ kg^{-1}
Current collector, Al	0.8 $ m^{-2}
Current collector, Cu	1.7 $ m^{-2}

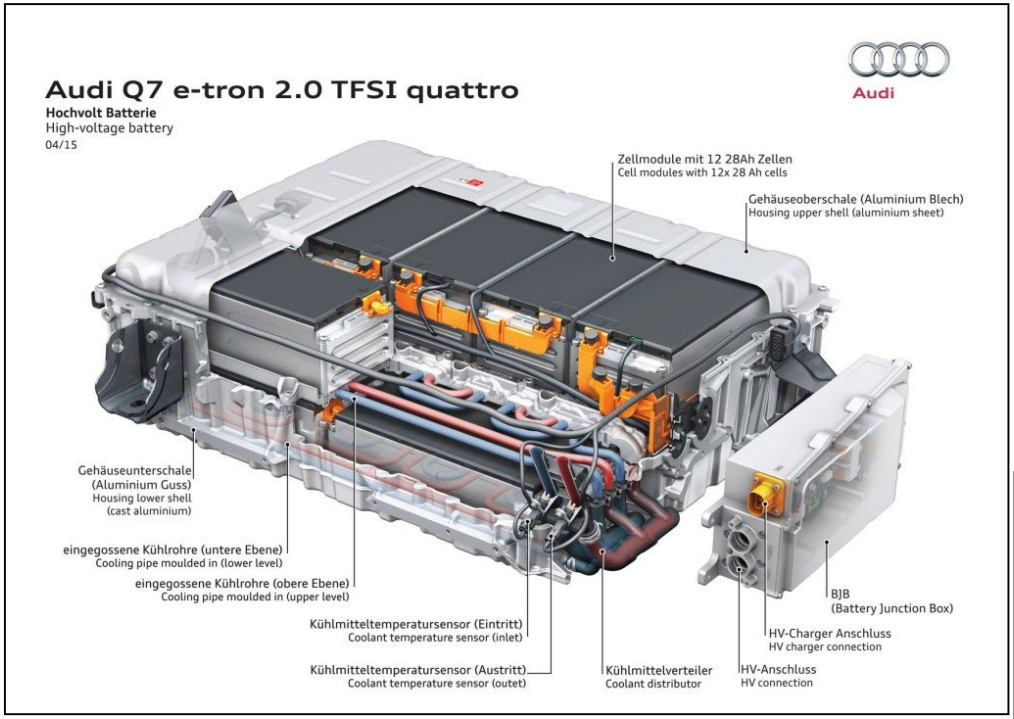


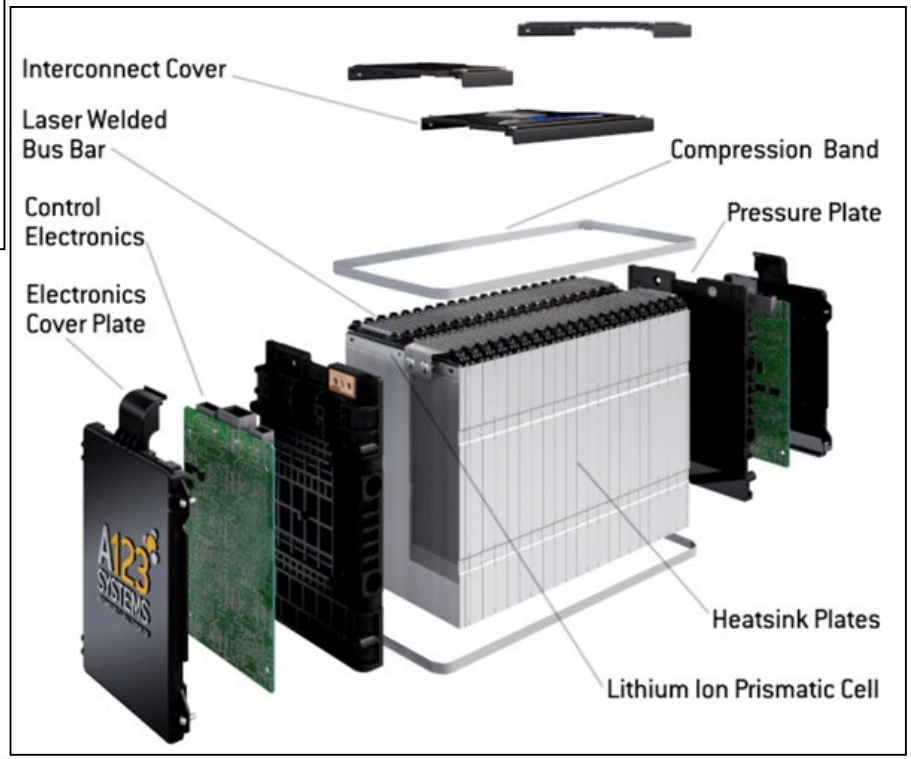
- The process cost includes direct labor, equipment depreciation, operating and maintenance costs, indirect factory costs, and infrastructure costs.
- The cells were designed using the cell design model from the ANL (BatPac)

Patry et al., 2015

V LIB Pack Assembly and Cost

LIB Battery Packs





LIB Battery Pack Components

Module

- **Battery cells**
- **Bus Assembly** Wires; point sensers; connector 10/16 pin
- **Module cooling vents**)sgnidlom ,stseksag)
- **End Plate**
- **Insulation sheet**
- **Cell separator/ insulation plate**
- **Tension straps**
- **Off-gas vent**
- **Brackets**
- **Fasteners**

Electrical

- **Junction Box** Enclosure; Bus bars; mounting plate; wire harness; resistor; fuses; current sensors; fasteners
- **Wire harness**
- **Fuse Module**
- **Service Disconnect** Cable; connectors
- **Battery Managment System** Enclosure;BMS circuit borad; connectors, fasteners
- **High Voltage Wires** 4Wires; 4 connectors

Structural

- **Enclosure** cable cover; end cpas; brackets

Air Cooling

- **Fan assembly** fan, flange nuts
- **Intake manifold**
- **Outlet manifold**
- **Plastic Rivets**

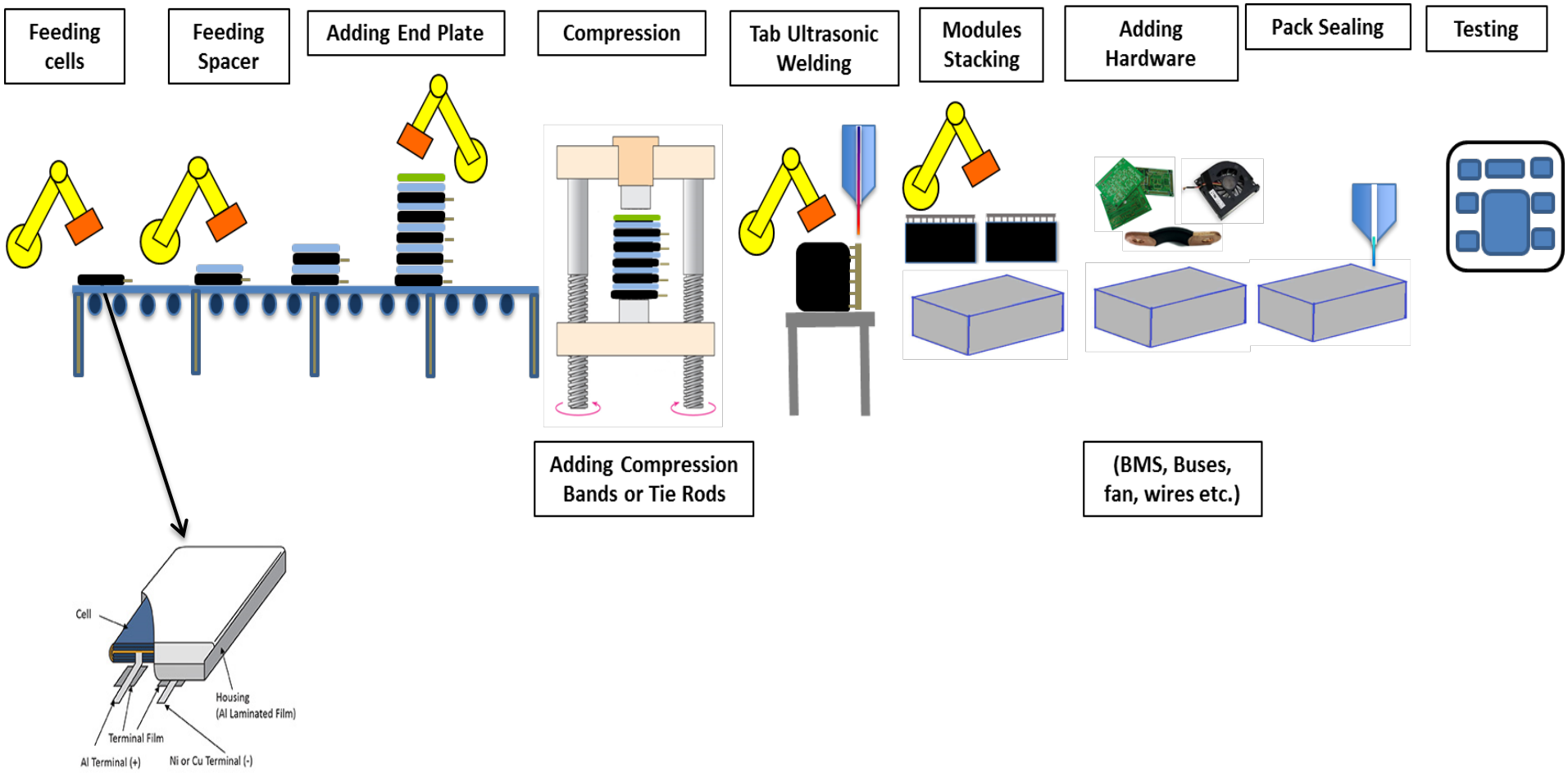
Off-gas Vent

- **Cell vent manifold** moldings, gaskets, clips
- **Vent outlet manifold** Tube, clips

Based on 2012MY PRIUS 1.8 PLUG-IN HYBRID BOM

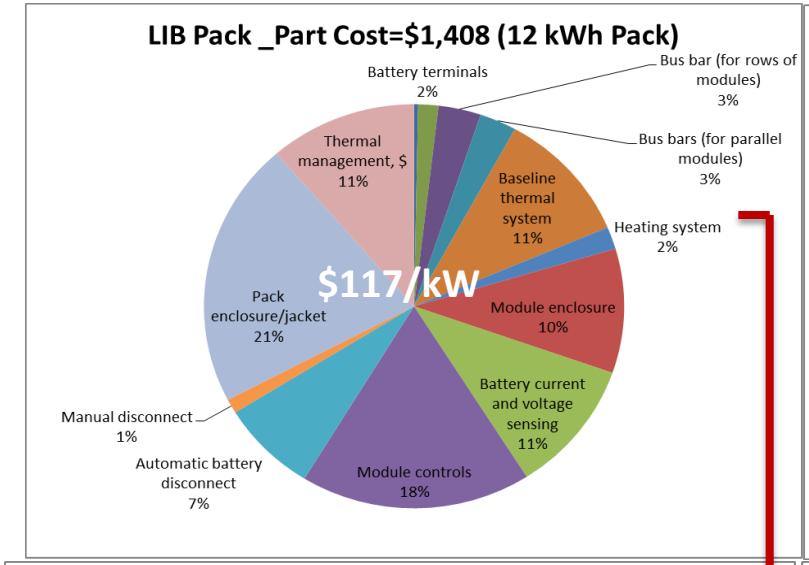
Assembly Line of LIB Pack

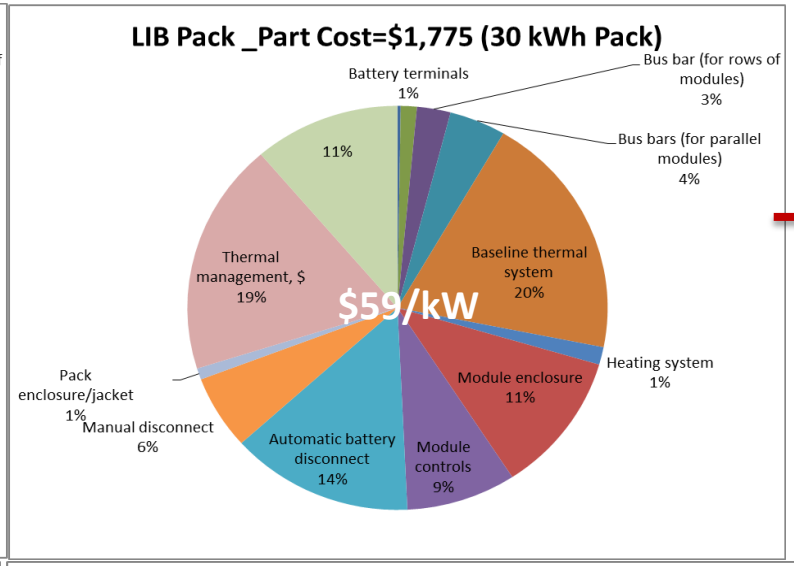
Today, LIB manufacturers use fully automatic pack assembly lines

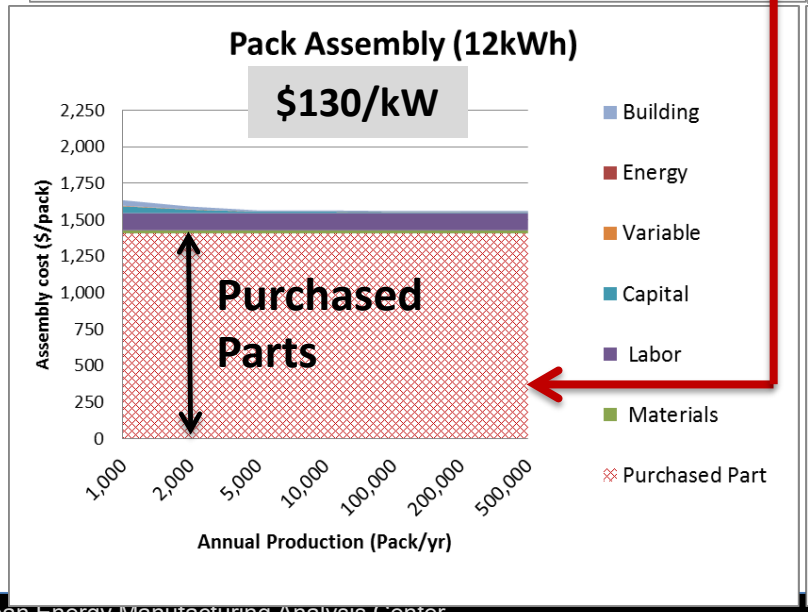


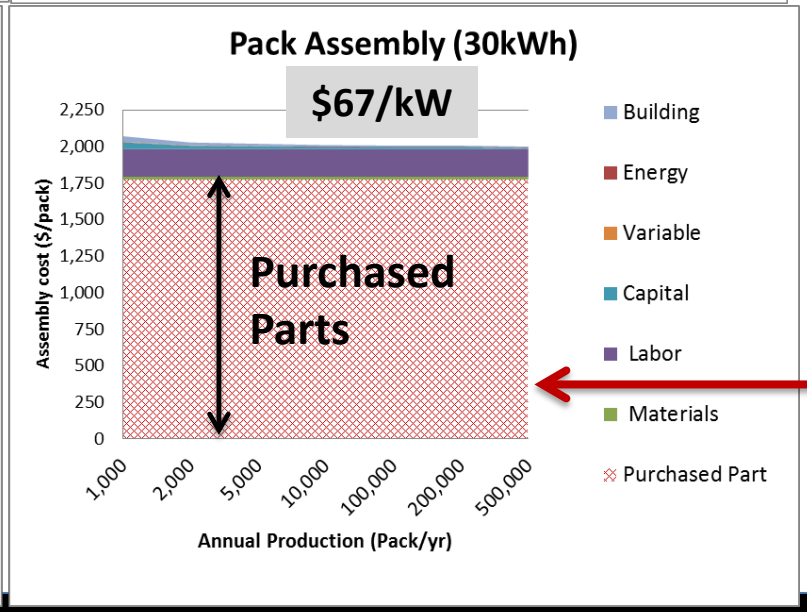
LIB Pack Assembly Cost

Purchased parts share more than 88% of pack assembly cost (excluding cells cost)



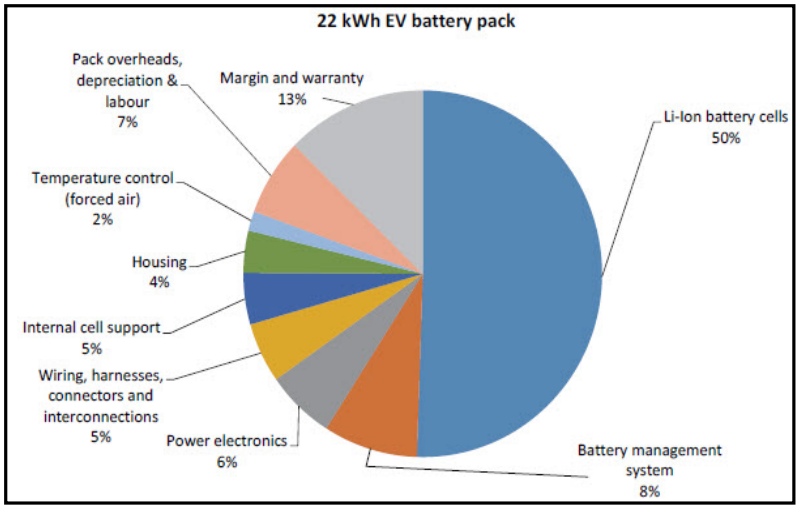






….. If Compared to Other Cost Studies

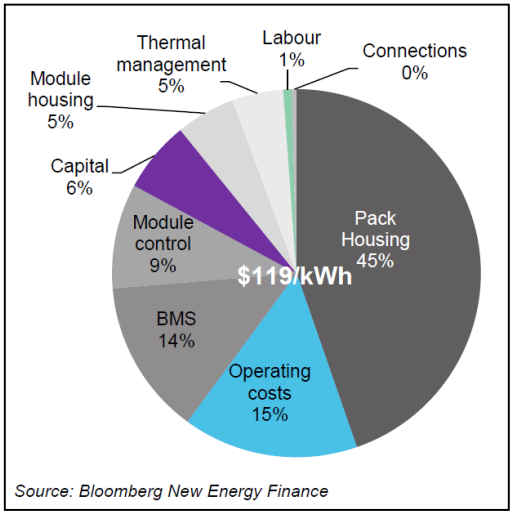
22 kWh battery pack cost, 2012



Parts	Percentage	Cost
BMS	8%	$1,408
Module Control	n/a	n/a
Module Housing	n/a	n/a
Thermal Management	2%	$352
Power Electronics	6%	$1,056
Wiring, harnesses and interconnects	5%	$880
Pack Housing	4%	$704
Internal cell support	5%	$880
Pack overheads, depreciation & labor	7%	$1,232
Total	**37% of systems cost**	**$6,512**

Source: Element Energy, 2012, BNEF 2016

24 kWh battery pack cost, 2015



Parts	Percentage	Cost
Pack Housing	45%	$1,285
BMS	14%	$400
Module Control	9%	$257
Module Housing	5%	$143
Thermal Management	5%	$143
Capital Cost	6%	$171
Operating cost	15%	$428
Labor	1%	$29
Total	100%	$2,856

A US plant producing 1 GWh/year has **cell costs of $265/kWh**, **battery packs at $384/kWh**.

Key xEV LIB Value Chain Characteristics

2016 Best-in-Class PHEV LIB Value Chain ($US/kWh)

	Raw Materials	Processed Materials	Electrodes	Cells	Battery Pack	TOTAL
VALUE ($/kWh)	$50	$118*	$28*	$146* (cum. $342*)	$150	$492
SHARE	10%	24%	6%	30%	30%	100%
CURRENTLY SHIPPED	Globally	Globally	Regionally	Globally	Locally	
SUCCESS FACTORS	• **Indigenous resources** • Low export restrictions or limitations	• **Critical to quality** • **Demand assurance** • **Cost of capital** • **Production cost inputs:** e.g. regulatory, energy.	• **Critical to quality** • **Processing know-how**: e.g. coating thickness uniformity, solvent & moisture content.	• **Critical to quality** • **Processing know-how**: e.g. stack uniformity, drying, formation, electrolyte additive	• **End-product knowledge and integration know-how** • **Proximity to customers**: shipping costs, exchange of technical specifications	

* Using 2015 analysis for electrodes and cells costs

- Example: factory gate – shipping from Asia to the west coast of the United States adds approximately $7/kWh

Sources: NREL estimates; BNEF (2014)

VI Conclusions

Conclusions

- Raw materials used in Li-ion batteries have medium-to-low criticality according to current mining and reserve estimates

- Consumption of Li, Co, Ni, Mn and Gr in xEV manufacturing still accounts for less than 9% of the total annual productions in 2016, however, these ratios are estimated to increase by 4-5x by 2020

- Module and pack parts make up about 30% of total LIB pack cost, the majority of cost savings are expected at the cell level

Thank you

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Notes

- Materials mined are reported in metric tons
  Total GWh of automotive lithium ion battery cells sold in 2016; 20.4 GWh based on vehicle sales data and average pack capacities of HEVs, PHEVs, and BEVs (http://insideevs.com/ev-battery-makers-2016-panasonic-and-byd-combine-to-hold-majority-of-market/)

- Assumptions for material requirements per cell: kWh per cell: 0.072 kWh; grams of element per gram of NMC: Co: 0.1987; Ni 0.1979; Li 0.0776; Mn 0.1852; grams of material per cell: NMC: 133 grams; Graphite: 78 grams/cell

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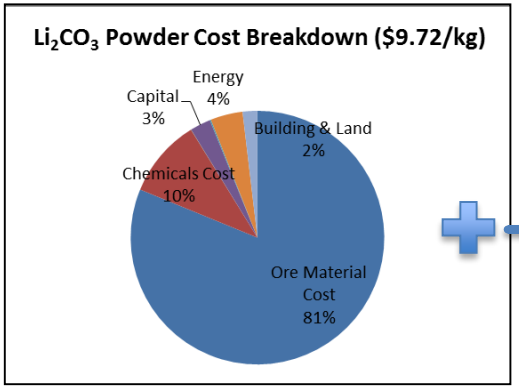
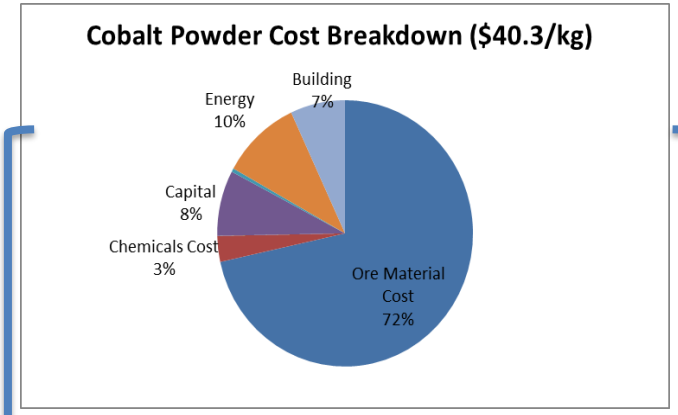
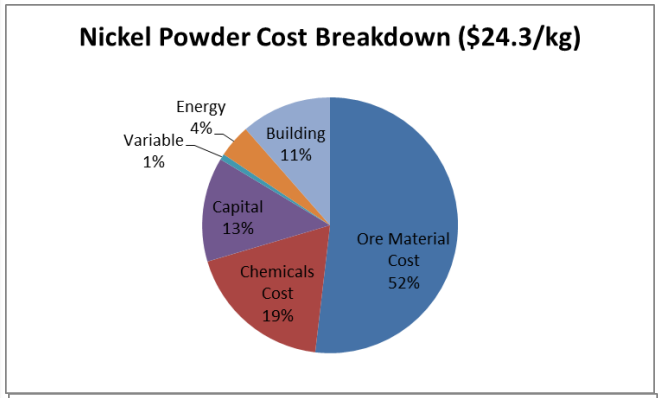
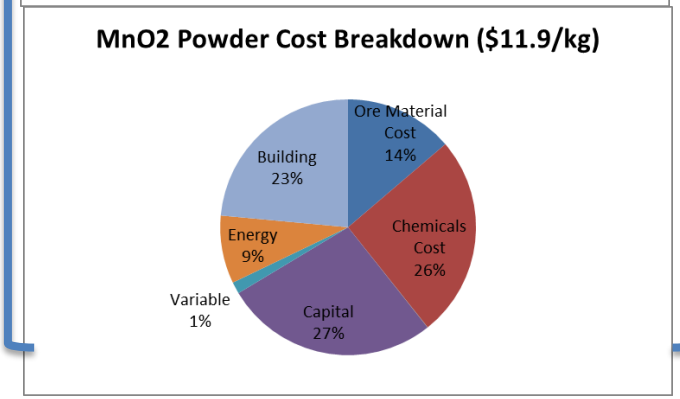
Appendix

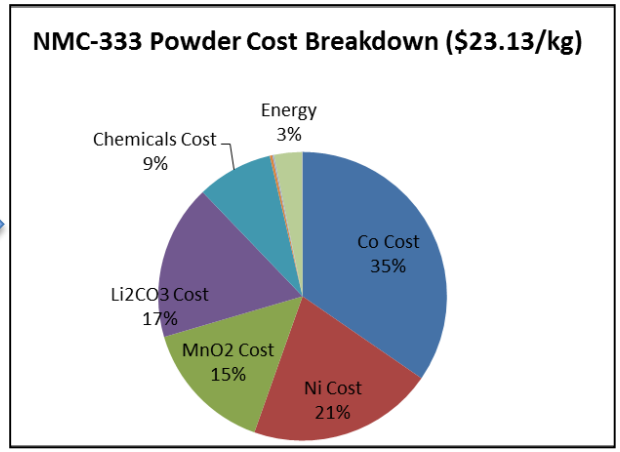
NMC Powder Cost







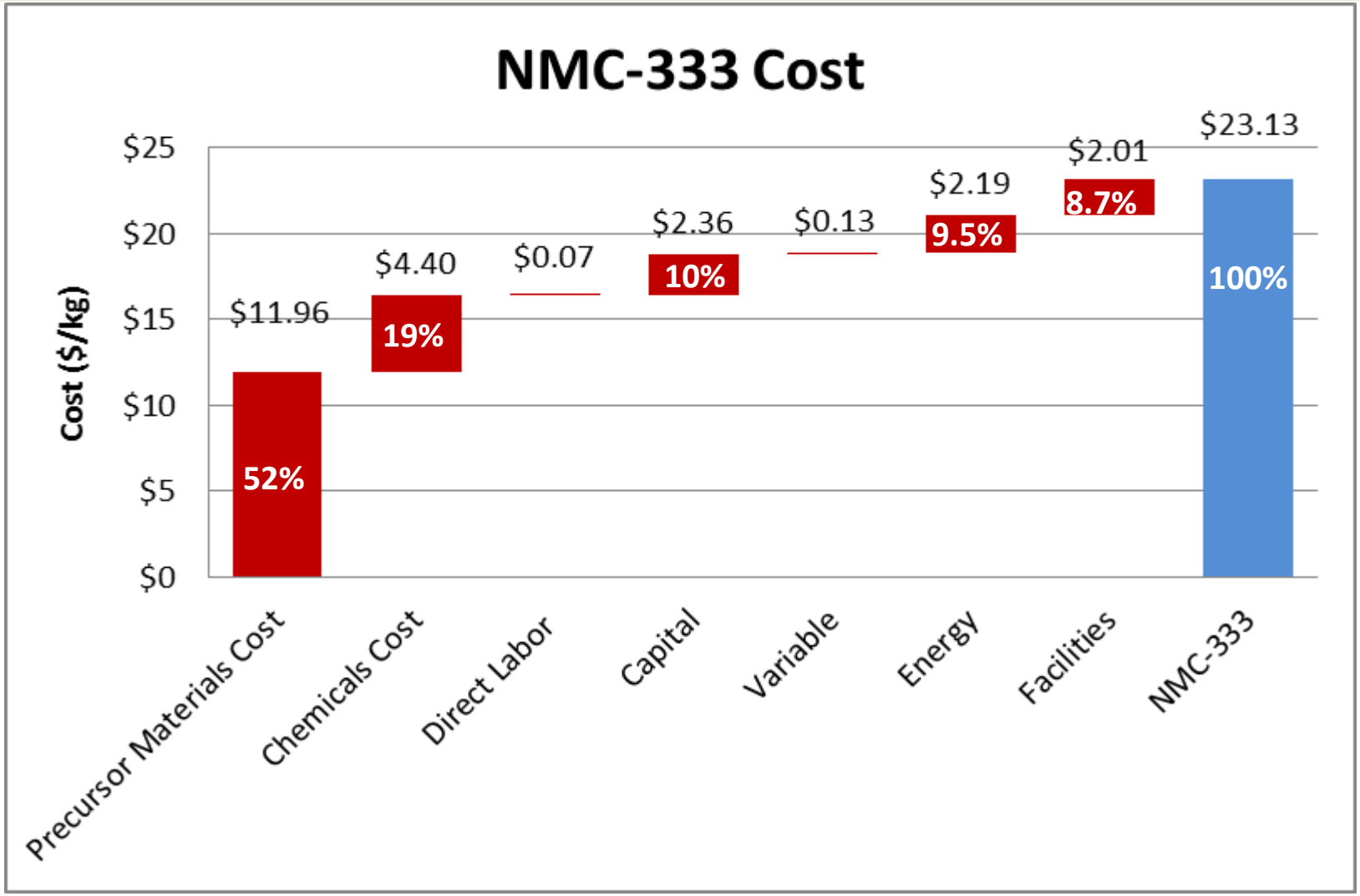




Ore Grade Price†	Price ($/kg)
Co	28.8
Ni	12.6
MnO_2	1.63

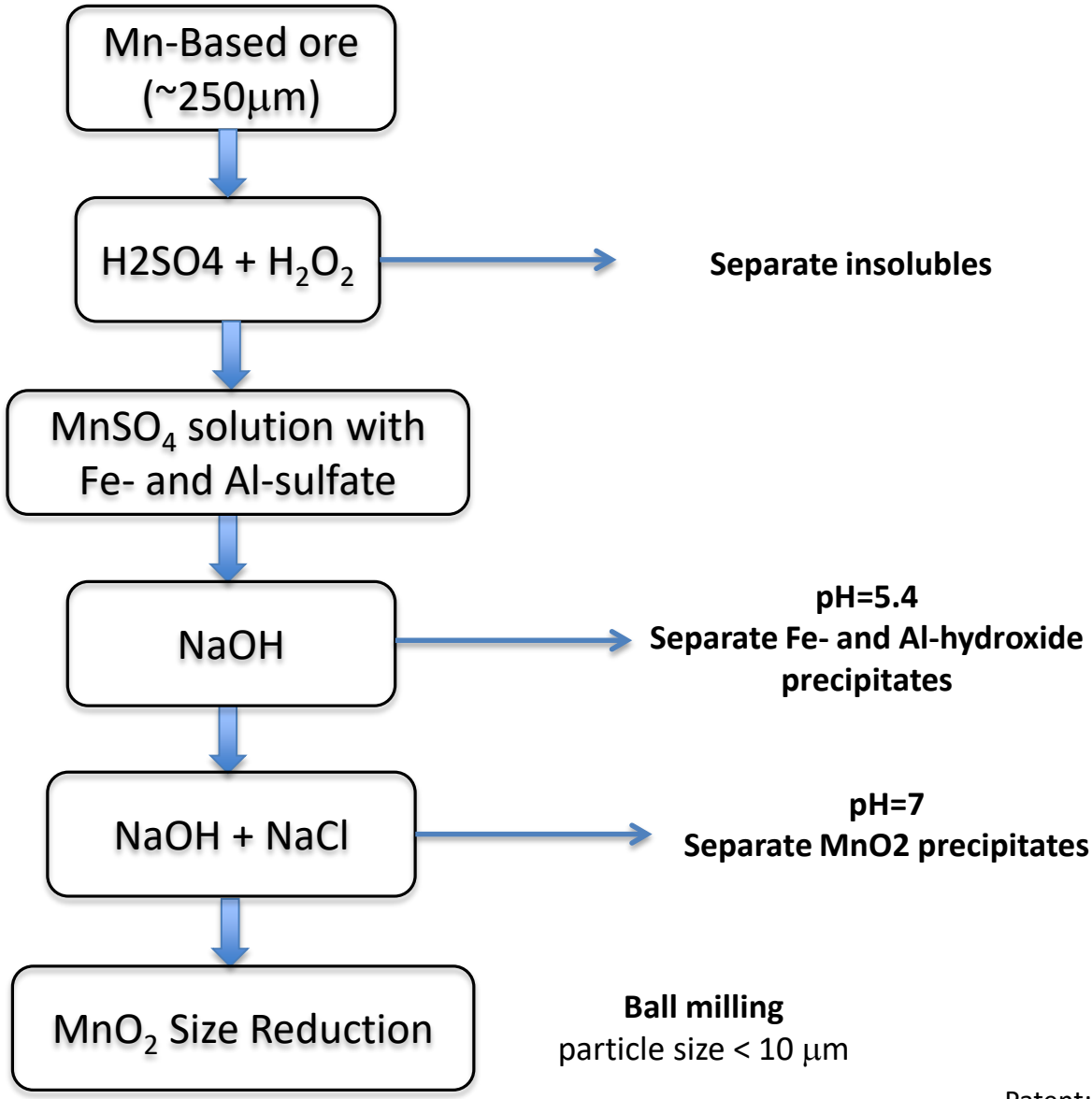
† Prices from London Metal Exchange, 2016

NMC Powder Cost



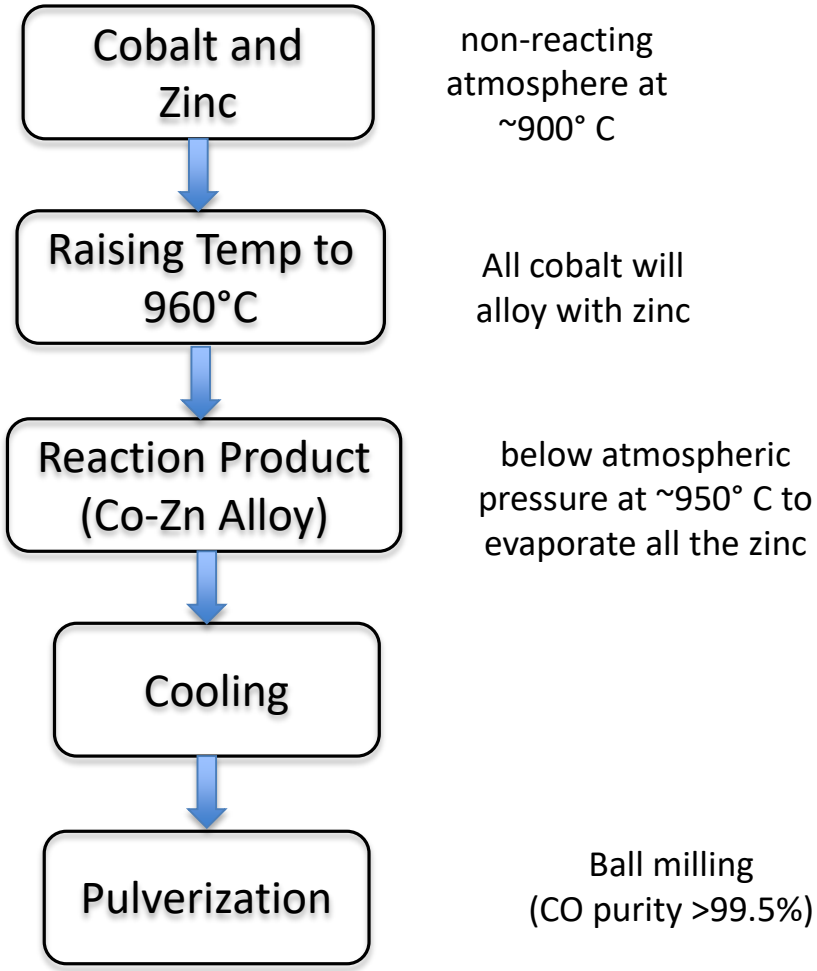
* Chemicals Cost **<u>includes</u>** all chemicals used in purifying Co, Mn, Ni, Mn, Li and NMC-333 powders.
Annual production= 1 million kg/yr

MnO_2 Powder Preparation



Patent: US2822243

Co Powder Preparation



Patents: US4816069

NMC Powder Cost

NMC cost estimates from 3M; 2016

	Metals Cost In 1 kg Cathode			
Co Price $/kg	NMC 442	LCO	NMC 111	LCO - NMC 442
30	9.38	18.06	11.19	8.68
40	10.36	24.08	13.22	13.72
60	12.32	36.12	17.29	23.8
80	14.28	48.17	21.37	33.89
100	16.25	60.21	25.44	43.96
120	18.21	72.25	29.51	54.04
140	20.17	84.3	33.59	64.13

NMC cost estimates from American Institute of Chemical Engineers (AIChE) 2013

Table 2. Cathode material performance characteristics relative to key design metrics.

Cathode	Gravimetric Energy Density, Wh/kg*	Power	Cycle Life	Safety	Price, $/kg
LFP ($LiFePO_4$)	500 (3.8 V)	+	+	+	15–22
LMFP ($LiMn_xFe_{1-x}PO_4$)	570 (4.3 V)	+	0	+	15–22
LMO ($LiMn_2O_4$)	480 (4.3 V)	+	0	+	12–15
LCO ($LiCoO_2$)	570 (4.3 V)	+	+	0	30–70
LNMC ($LiNi_xMn_yCo_{1-x-y}O_2$)	570–690 (4.3 V)	0	0	–	20–50
LLNMC ($xLi_2MnO_3 \bullet (1-x)LiMO_2$)	960 (4.6 V)	–	–	0	20–40
LNMO ($LiNi_{1/2}Mn_{3/2}O_4$)	630 (5.0 V)	+	0	0	15–25
LCP ($LiCoPO_4$)	720 (5.0 V)	+	0	0	20–50

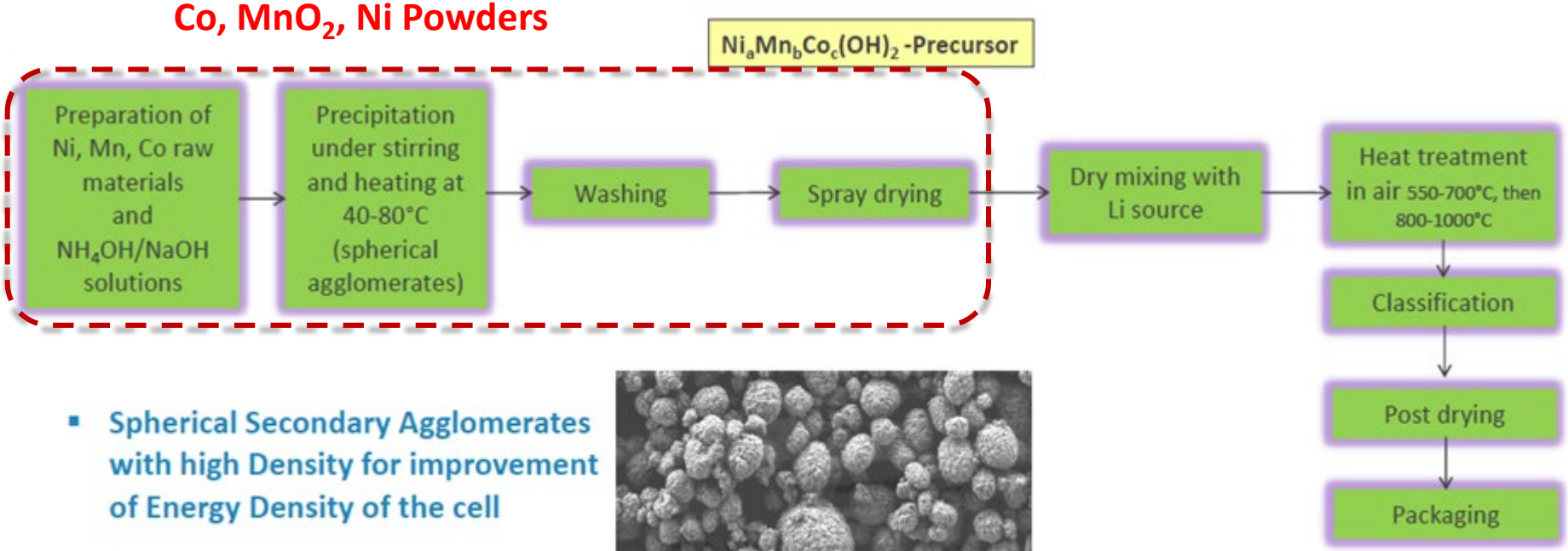
* Values in parentheses are charge voltage vs. Li^0.

Key: (+) Clear strength, (–) Clear improvement opportunity, (0) Neither a strength nor weakness

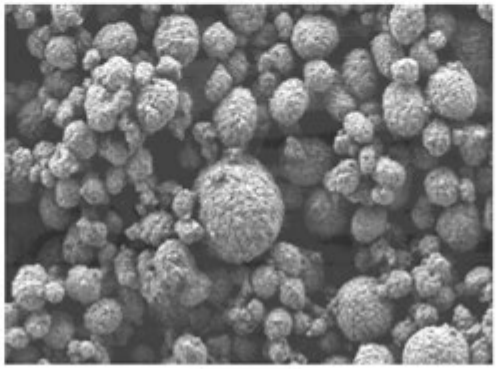
3M.com
(AIChE) 2013

NMC Powder Production

Co, MnO_2, Ni Powders



- Spherical Secondary Agglomerates with high Density for improvement of Energy Density of the cell



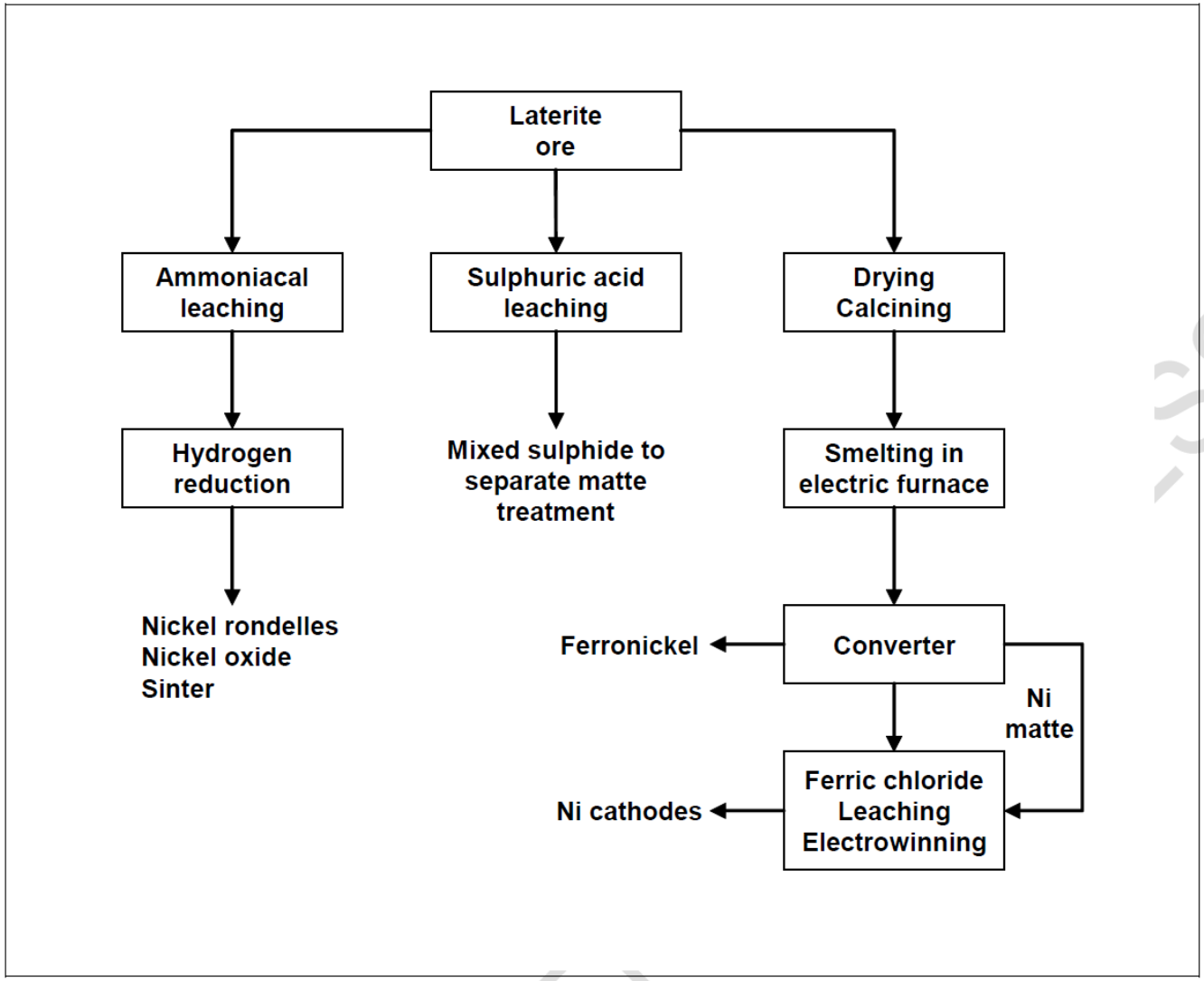
10 µm NCM

NMC-333 Formula

$Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$

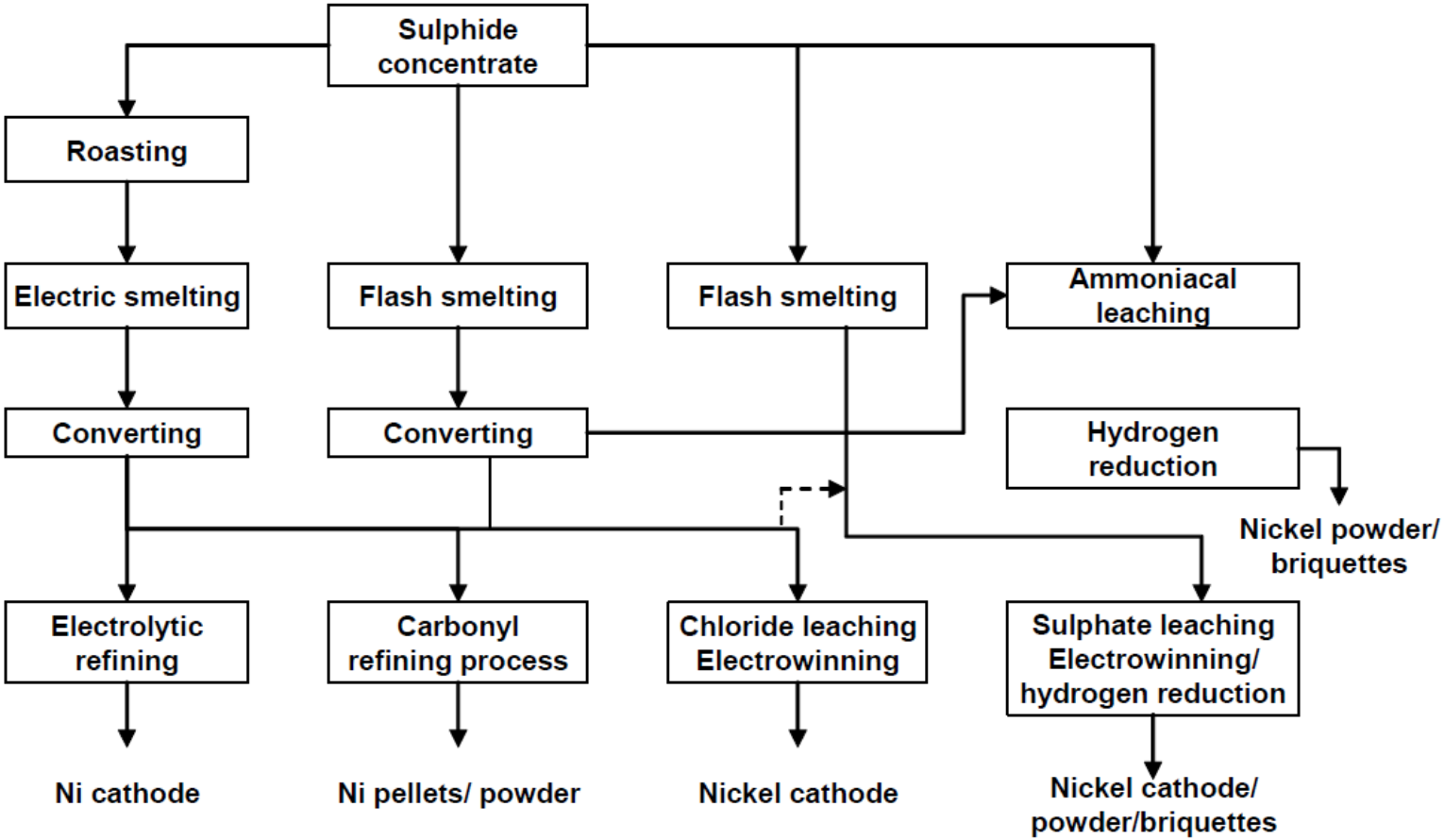
LIB Cell Materials- Nickle

Nickel is produced from oxidic (laterite and saprolite) or sulphidic ore, about 60 % of the nickel comes from sulphide deposits and 40 % from oxide deposits



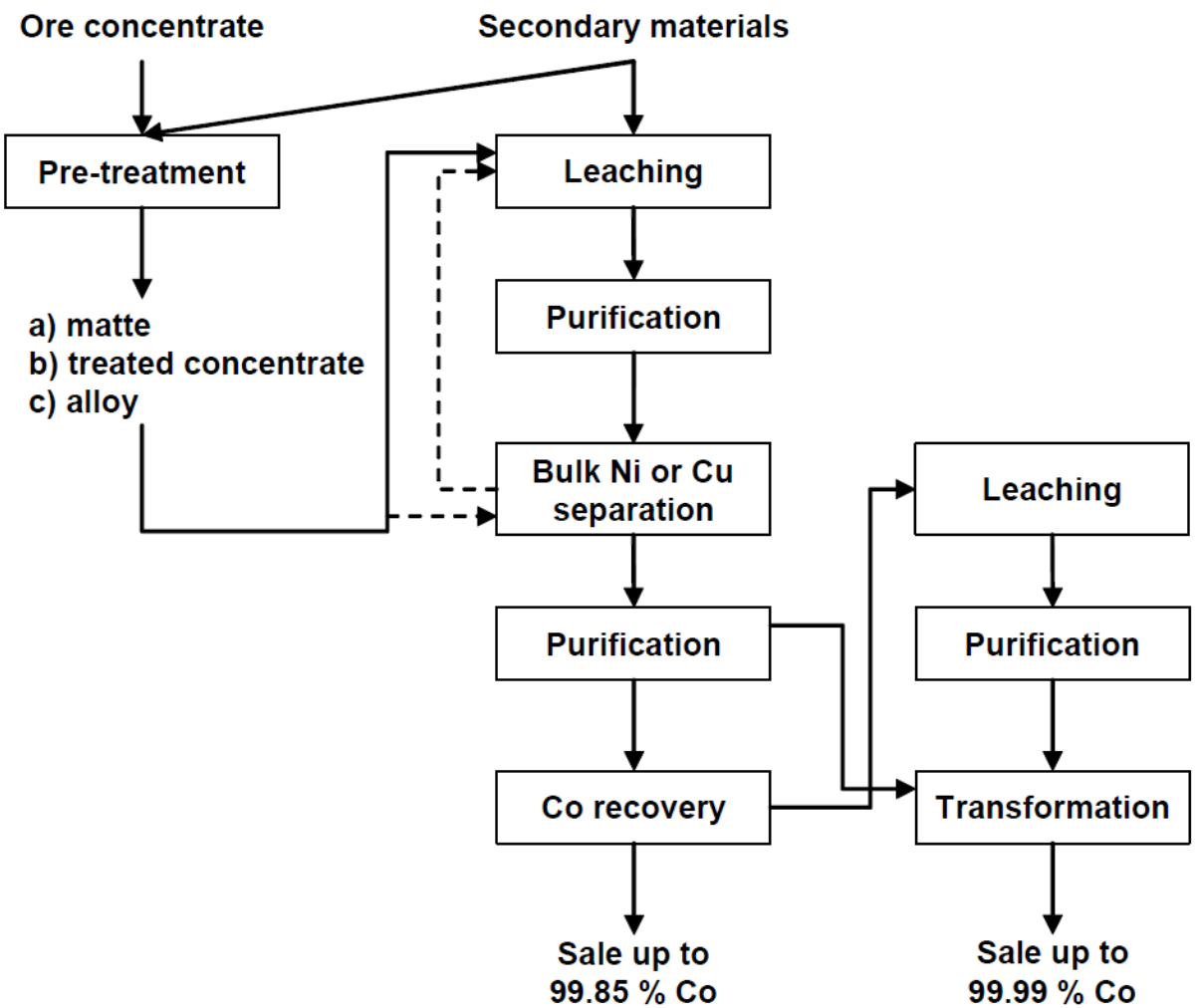
Generic flowsheet for nickel production from laterite ores

LIB Cell Materials- Nickle



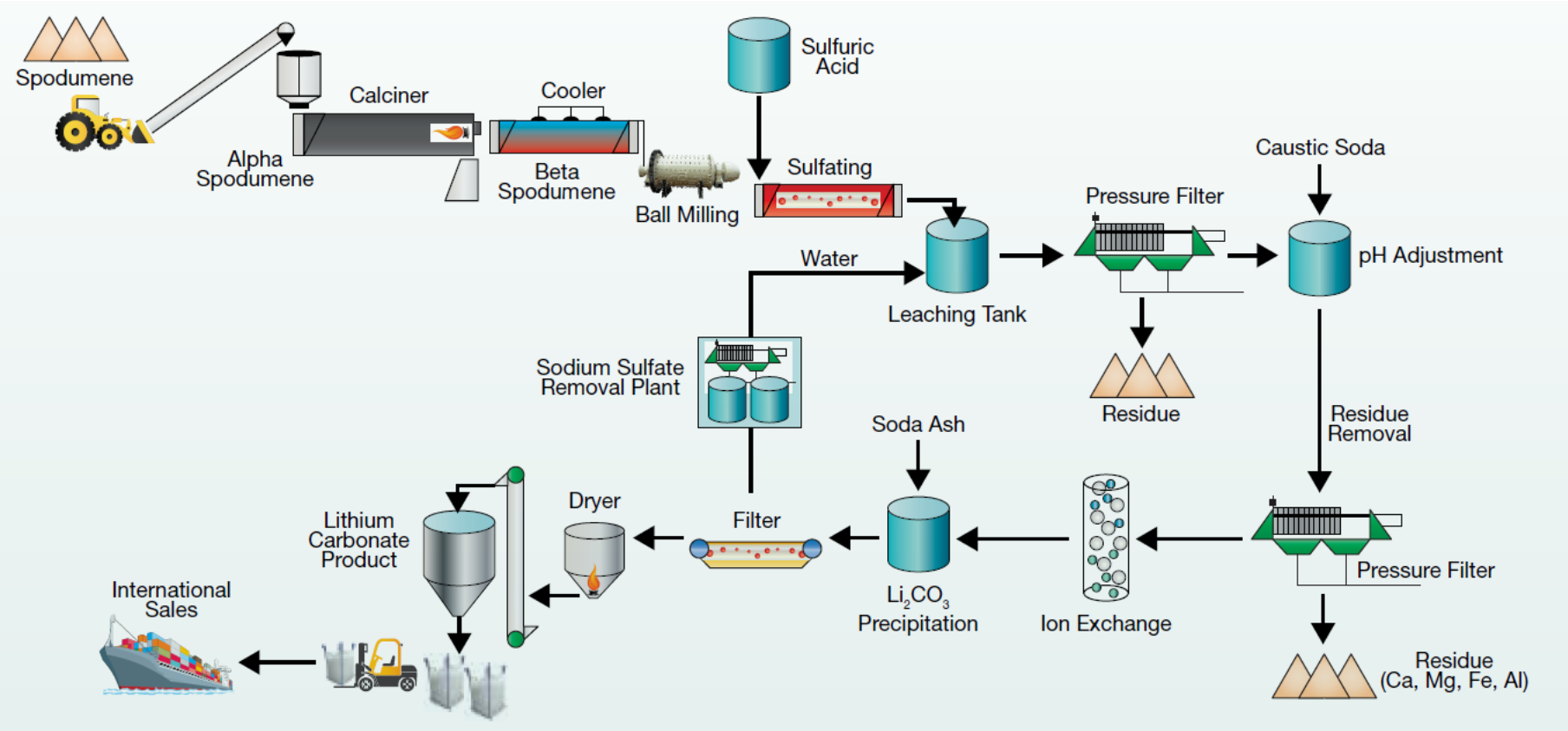
Generic flowsheet for the production of nickel from sulphide concentrates

LIB Cell Materials- Cobalt



Generic flowsheet for cobalt production

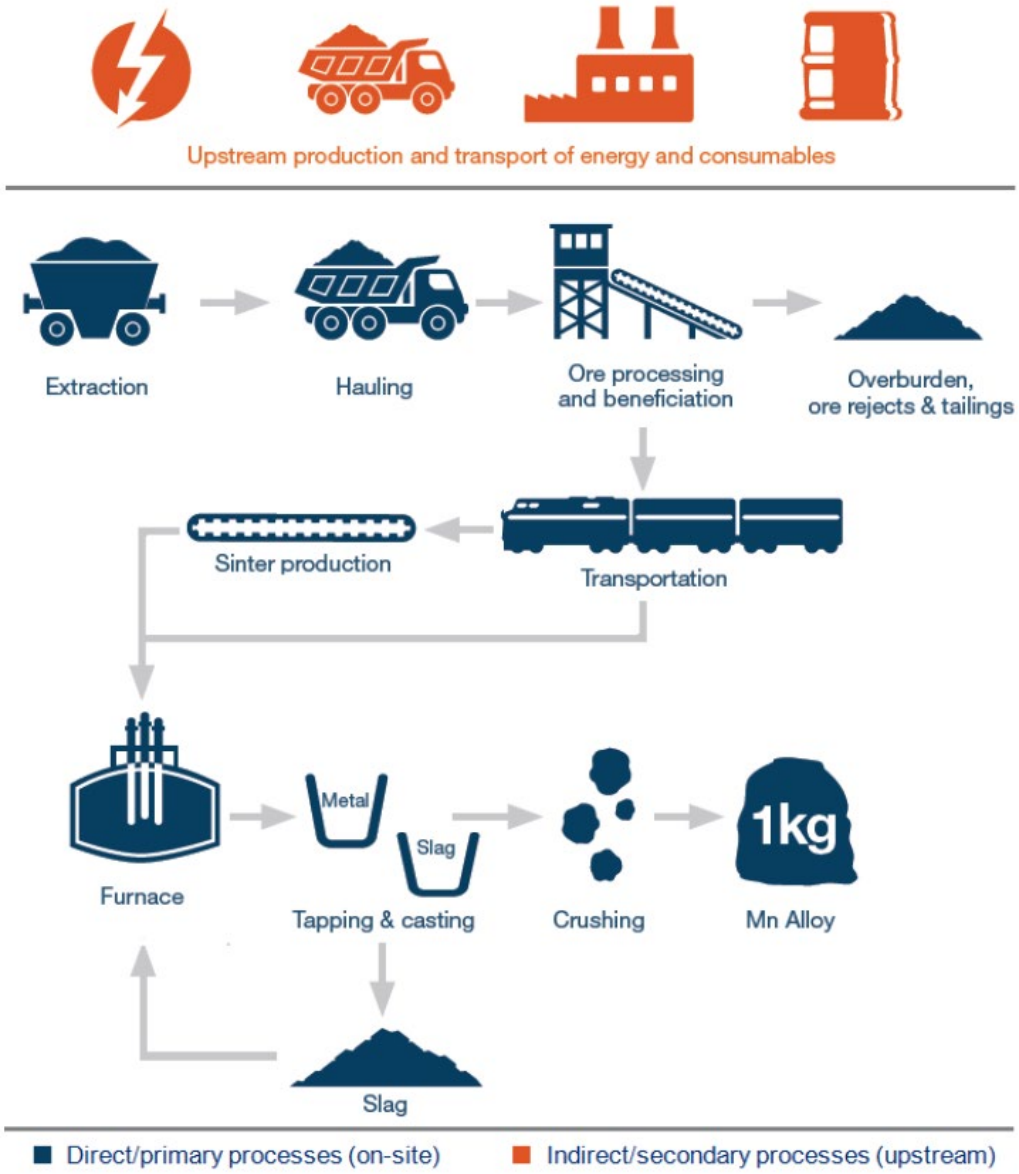
LIB Cell Materials- Lithium



▲ **Figure 1.** This continuous process makes lithium carbonate from spodumene. Source: www.galaxyresources.com.au/project_jiangsu.shtml.

LIB Cell Materials- Manganese

Material/Energy	Cost (USD)
Manganese Ore	$140/t
Manganese Sinter	$224/t
Ferromanganese Alloy	$872
Electricity	$70/MWh
Diesel	$1.05/L
Coal	$65/t
Coke	$250/t



LIB Cell Materials- Manganese

Table 7: Industry average energy consumption and greenhouse gas emissions by supply chain stage per tonne of ferro-manganese production.

Process Stage	Primary Energy Demand (GJ)	Global Warming Potential (tCO2e)	Grid Power (kWh)	Diesel (kg)	Coal (kg)	Coke (kg)	Explosives (kg)
Extraction	0.6	0.08		13.9			3.2
Ore Processing & Beneficia-tion	0.9	0.10	37	19.0			
Sinter Production	3.0	0.30	32	7.3	35	49	
Smelting	26.0	4.27	2811		149	372	
Casting, Crushing & Screen-ing	1.4	0.31	268	3.5			
Total Supply Chain	**31.9**	**5.06**	**3148**	**43.6**	**184**	**421**	**3.2**

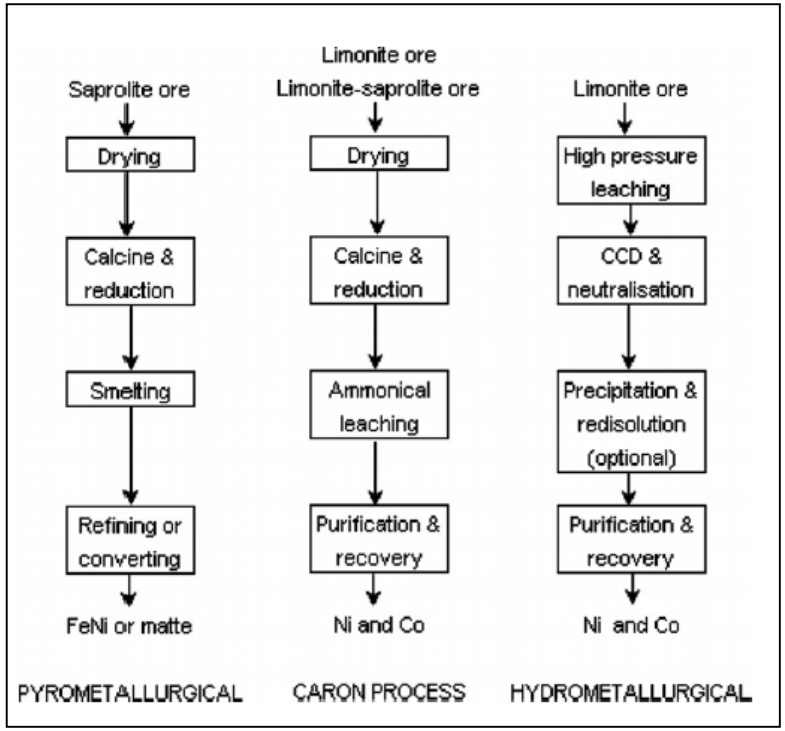
	Material Cost	Energy Cost	Total Cost
Extraction	460.00	334.60	794.60
Ore Processing & Refining		26.57	26.57
Sinter Production		25.98	25.98
Smelting		299.46	299.46
Casting, crushing & Screening		23.18	23.18
Transportation		2.52	2.52
Total ($/ton)			**1172.30**

LIB Materials- Nickel

LCA results for nickel laterite processing routes.

Process	Embodied energy (GJ/t Ni)[a]	GHG emissions (t CO_2e/t Ni)		Overall nickel recovery (%)
		With acid plant	Without acid plant	
Hydrometallurgical				
High pressure acid leach	272	22.7	27.3	92
Atmospheric acid leach	167	14.6	25.1	80
Enhanced pressure acid leach[b]	249	17.8	23.2	85
Heap leach	211	17.6	28.0	73
Pyrometallurgical				
Ferronickel	236	NA	22.4	95
Pyro/hydrometallurgical				
Caron process	565	NA	44.8	80

[a] Includes sulfur feedstock energy of 84–126 GJ/t Ni (depending on hydrometallurgical processing route) with on – site acid plant – corresponds to approximately 35 t steam (high and low pressure) per tonne of nickel.
[b] Based on 78% HPAL and 22% AL.



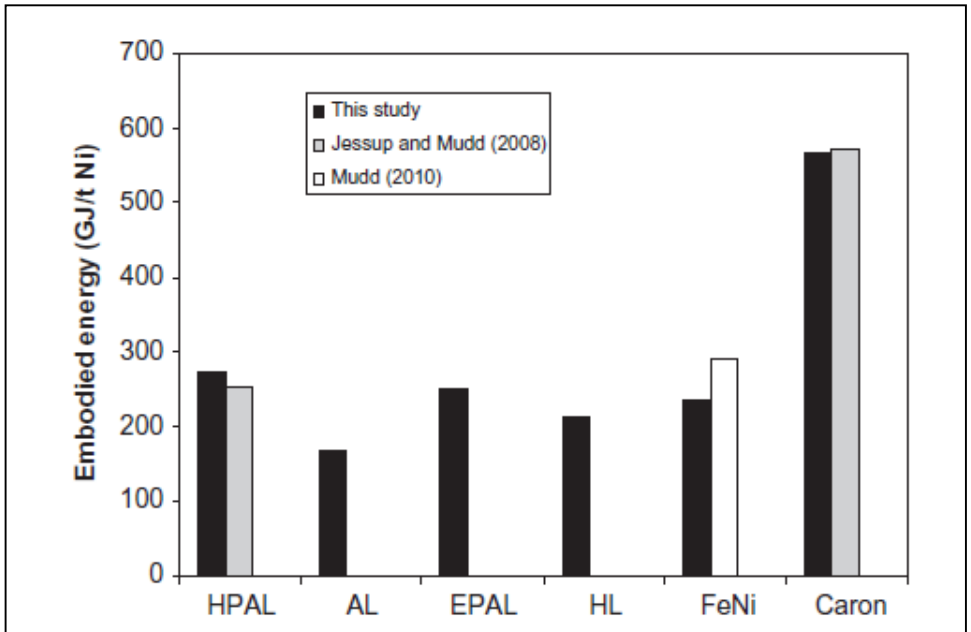


Fig. 2. Comparison of embodied energy results.

Norgate and Jahanshahi, 2011

Bat-Pac Architecture

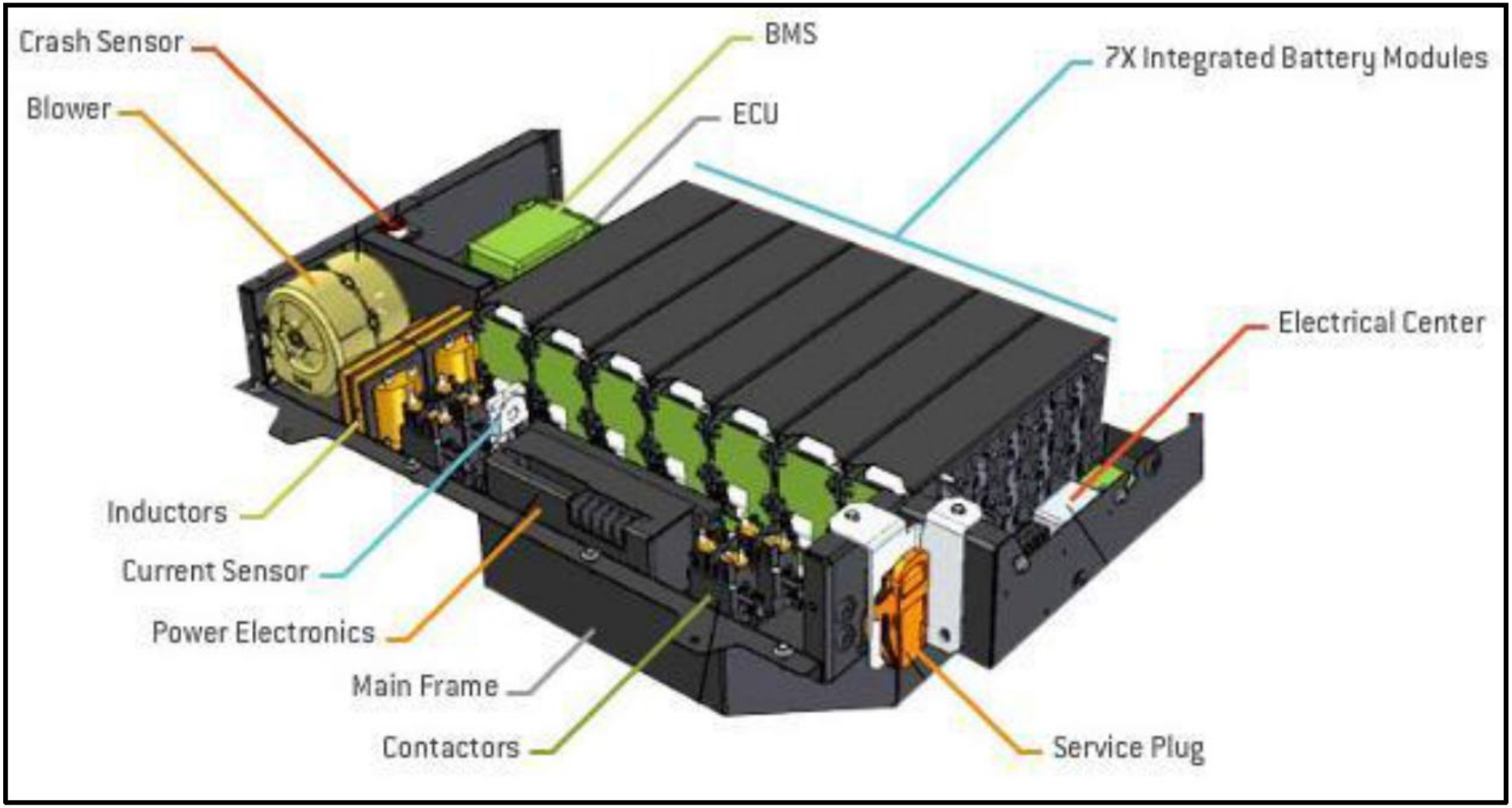
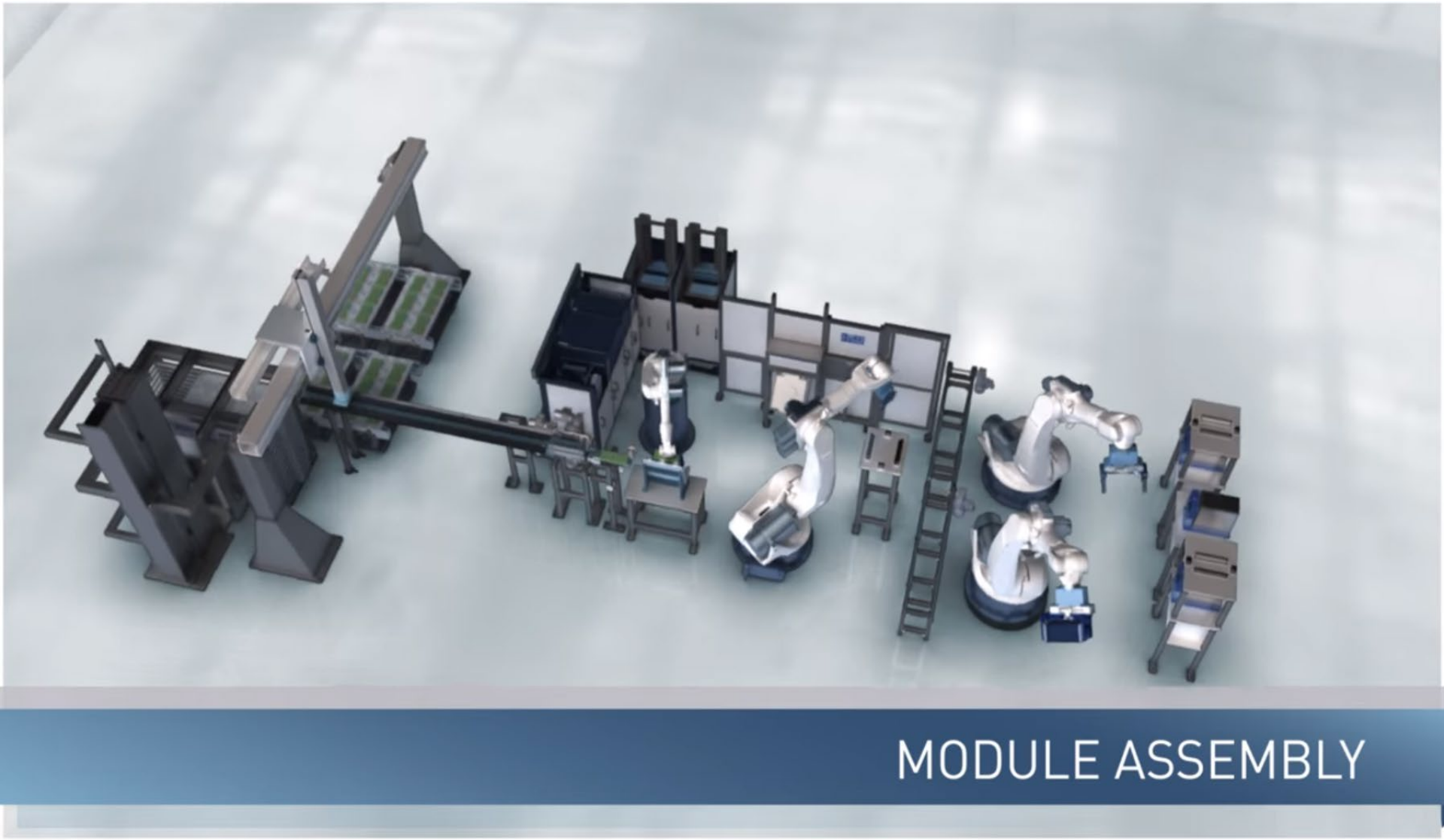


Figure 2: Li-Ion Battery Pack for a PHEV (A123 Systems, 2008b)

Battery Assembly Lines from Dürr

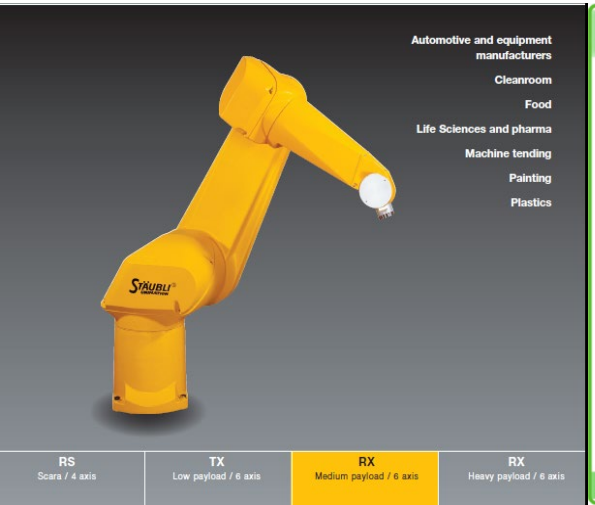


https://www.youtube.com/watch?v=_QEXZz14QL0

Equipment

Machine	Cost ($)	Notes
Robots (3 robots)	150,000	Staubli Robots
Hot Press	100,000	
Ultrasonic/Laser Welding Machine	200,000	
QC System (Optical System)	50,000	http://www.google.com/patents/US20130305835
Seal Dispenser (Robotic Arm)	50,000	http://www.google.com/patents/US20030096162
Charging/Station Testing (Bank of 6 stations from GE)	24,000	GE DURASTATION DOUBLE EVDN3 EV CHARGING STATION 30 AMP
Assembly line	**574,000**	

6-axis robot



Hydraulic Press

Ultrasonic Tab welder

Charging Station

LIB Pack- Purchased Parts

Battery size (kWh)	4	8	12	16	30	85	BatPac (4 kWh)
Purchased Parts; $							
Module Inter-connectors and signal wiring	$4.4	$4.4	$4.4	$4.4	$4.4	$4.4	$9.3
Module compression plates and steel straps							$1.0
Battery terminals	$21.9	$21.9	$21.9	$21.9	$21.9	$21.9	$21.0
Bus bar for battery packs with one row of modules	$46.0	$46.0	$46.0	$46.0	$46.0	$46.0	$20.0
Bus bars for battery packs with parallel modules	$23.0	$32.0	$40.0	$49.0	$77.0	$110.0	$0.0
Bus bars for interconnecting multiple battery packs							$0.0
Baseline thermal system	$90.0	$120.0	$150.0	$180.0	$350.0	$450.0	$120.0
Heating system	$25.0	$25.0	$25.0	$25.0	$25.0	$25.0	$20.0
Module Enclosure	$70.0	$70.0	$70.0	$70.0	$70.0	$70.0	$67.8
Pack integration (BMS & disconnects), $							
Battery current and voltage sensing	$150.0	$150.0	$150.0	$150.0	$150.0	$150.0	$100.0
Module controls	$250.0	$250.0	$250.0	$250.0	$250.0	$250.0	$80.0
Automatic battery disconnect	$104.0	$104.0	$104.0	$104.0	$104.0	$104.0	$200.0
Manual disconnect	$16.0	$16.0	$16.0	$16.0	$16.0	$16.0	$15.0
Pack Enclosure/Jacket	$260.0	$280.0	$300.0	$320.0	$330.0	$400.0	$260.0
Estimated cost to OEM for thermal management, $	$120.0	$160.0	$160.0	160	200	200	160
Total Module & Pack Part Cost	**1,180**	**1,279**	**1,337**	**1,396**	**1,644**	**1,847**	**1,074**

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NREL/PR-6A20-68596