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

Advanced Automotive Batteries Conference
June 19-22, 2016 | San Francisco, CA
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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
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**

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

Moss et al., 2013
LIBs Raw Materials Supply Chain
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)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Production</th>
<th>Reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>0.3%</td>
<td>99.7%</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1.8%</td>
<td>98.2%</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.9%</td>
<td>98.2%</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.4%</td>
<td>97.6%</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.5%</td>
<td>99.5%</td>
</tr>
</tbody>
</table>

- 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

Cobalt and Ammonia

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

Cobaltic hexamine complex (Co(NH₃)₆X₃)

Adding HX

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

Filtration

NaOH or KOH

Ball milling
particle size 2-5µm

Co Powder

Filtration and Washing

e.g., NH₄OH

e.g., HCL

Patent: US4218240
Ni Powder Preparation

1. **Ni ingot/alloy**

2. **Hydrazine (N\textsubscript{2}H\textsubscript{4})**

   - 2.0 to about 2.5 milliliters of hydrazine per gram of nickel

3. **NaOH**

4. **Heating**

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

5. **NaOH**

6. **Heating**

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

7. **Filtration and Washing**

8. **Ball milling**

   - Particle size < 10 µm

9. **Ni Powder**

Patent: US4089676
**MnO₂ Powder Preparation**

1. **Mn-Based alloy/ingot**
   - 1 hour at 40-90°C

2. **NaOH or KOH**

3. **MnOH**

4. **Oxidation**

5. **MnOOH**

6. **Ball milling**

7. **MnO₂ Powder**
   - Particle size < 10 µm

8. **Oxidation/Aeration**

Patent: US4006217
Lithium Carbonate from Li Brine

Well → Pumps → Evaporation Ponds in Series → Pumps/Transit

- Li Brine (1,500 ppm)
- KCl

Precipitator Reactor → Second Stage Extraction → First Stage Extraction → Boron Extraction

- Soda Ash
- Lime
- Soda Ash
- HCl, Alcohol, H₂SO₄

- Mg(OH)₂
- CaCO₃
- MgCO₃

Filtration → Drying → Compacting/Packaging

- Li₂CO₃

Dunn et al. 2014
• 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, Ni, Mn Precursors:**
- Sulphates ($x\text{SO}_4$)
- Acetates ($xC_2\text{H}_4\text{O}_2$)
- Hydroxides (OH)
- Nitrate ($x\text{NO}_3$)

**NMC-333 Formula**

$$\text{Li}_{1.05}(\text{Ni}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3})_{0.95}\text{O}_2$$

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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Positive electrode coating thickness (μm)</th>
<th>Negative electrode coating thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMC // Gr</td>
<td>49.0</td>
<td>50.0</td>
</tr>
<tr>
<td>NCA // Gr</td>
<td>45.0</td>
<td>50.0</td>
</tr>
<tr>
<td>LMO // Gr</td>
<td>50.0</td>
<td>30.4</td>
</tr>
<tr>
<td>LFP // Gr</td>
<td>50.0</td>
<td>34.2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Price ($ kg(^{-1}))</th>
<th>Price relatively to NCA (%)</th>
<th>Corresponding volume (kT y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMC</td>
<td>27</td>
<td>82</td>
<td>1.8</td>
</tr>
<tr>
<td>NCA</td>
<td>33</td>
<td>100</td>
<td>1.8</td>
</tr>
<tr>
<td>LMO</td>
<td>14</td>
<td>42</td>
<td>2.6</td>
</tr>
<tr>
<td>LFP</td>
<td>21</td>
<td>64</td>
<td>2.1</td>
</tr>
<tr>
<td>Graphite</td>
<td>18.5</td>
<td>56</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 3. Prices of cell materials and components.

<table>
<thead>
<tr>
<th>Material</th>
<th>Price ($ kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon black conductor</td>
<td>7.15</td>
</tr>
<tr>
<td>NMP binder</td>
<td>27.6</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>19.5</td>
</tr>
<tr>
<td>Aqueous binder</td>
<td>10.0</td>
</tr>
<tr>
<td>Binder solvent</td>
<td>3.2</td>
</tr>
<tr>
<td>Current collector, Al</td>
<td>0.8</td>
</tr>
<tr>
<td>Current collector, Cu</td>
<td>1.7</td>
</tr>
</tbody>
</table>

- 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 sensors; connector 10/16 pin
- Module cooling vents (sgnidom, 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 Management System**
  - Enclosure; BMS circuit board; connectors, fasteners
- High Voltage Wires
  - 4 Wires; 4 connectors

**Structural**
- Enclosure
  - Cable cover; end caps; 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
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)

LIB Pack _Part Cost=$1,408 (12 kWh Pack)

LIB Pack _Part Cost=$1,775 (30 kWh Pack)

Pack Assembly (12kWh)

$130/kW

Pack Assembly (30kWh)

$67/kW

$117/kW

$59/kW
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)

<table>
<thead>
<tr>
<th>Raw Materials</th>
<th>Processed Materials</th>
<th>Electrodes</th>
<th>Cells</th>
<th>Battery Pack</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALUE ($/kWh)</td>
<td>$50</td>
<td>$118*</td>
<td>$28*</td>
<td>$146* (cum. $342*)</td>
</tr>
<tr>
<td>SHARE</td>
<td>10%</td>
<td>24%</td>
<td>6%</td>
<td>30%</td>
</tr>
</tbody>
</table>

**CURRENTLY SHIPPED**
- Globally
  - Indigenous resources
  - Low export restrictions or limitations
- Globally
  - Critical to quality
  - Demand assurance
  - Cost of capital
  - Production cost inputs: e.g. regulatory, energy.
- Regionally
  - Critical to quality
  - Processing know-how: e.g. coating thickness uniformity, solvent & moisture content.
- Globally
  - Critical to quality
  - Processing know-how: e.g. stack uniformity, drying, formation, electrolyte additive
- Locally
  - End-product knowledge and integration know-how
  - Proximity to customers: shipping costs, exchange of technical specifications

**TOTAL**
- $150
- 30%
- 30%

- $492
- 100%

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* 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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www.manufacturingcleanenergy.org
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
References

http://www.google.ca/patents/US4218240
http://www.google.com/patents/US4089676
http://www.google.ca/patents/US4006217


Peixin Zhang, Li Zhang, Xiangzhong Ren*, Quihua Yuan, Jianhong Liu, Qianling Zhang. Preparation and electrochemical properties of LiNi1/3Co1/3Mn1/3O2–Ppy composites cathode materials for lithium-ion battery. Synthetic Metals 161 (2011) 1092–1097

Gerry M Clark. Lithium-ion batteries, Raw Material Consideration. 2013 American Institute of Chemical Engineers (AIChE)


Appendix
NMC Powder Cost

<table>
<thead>
<tr>
<th>Ore Grade</th>
<th>Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>28.8</td>
</tr>
<tr>
<td>Ni</td>
<td>12.6</td>
</tr>
<tr>
<td>MnO₂</td>
<td>1.63</td>
</tr>
</tbody>
</table>

† Prices from London Metal Exchange, 2016
NMC Powder Cost

* Chemicals Cost includes all chemicals used in purifying Co, Mn, Ni, Mn, Li and NMC-333 powders. Annual production= 1 million kg/yr
MnO$_2$ Powder Preparation

1. Mn-Based ore (~250 µm)

2. H$_2$SO$_4$ + H$_2$O$_2$
   - Separate insolubles

3. MnSO$_4$ solution with Fe- and Al-sulfate

4. NaOH
   - pH=5.4
   - Separate Fe- and Al-hydroxide precipitates

5. NaOH + NaCl
   - pH=7
   - Separate MnO$_2$ precipitates

6. MnO$_2$ Size Reduction
   - Ball milling
     - particle size < 10 µm

Patent: US2822243
Co Powder Preparation

1. Cobalt and Zinc in a non-reacting atmosphere at ~900°C.
2. Raising Temp to 960°C.
   - All cobalt will alloy with zinc.
3. Reaction Product (Co-Zn Alloy) below atmospheric pressure at ~950°C to evaporate all the zinc.
4. Cooling
5. Pulverization (CO purity >99.5%)

Patents: US4816069
## NMC Powder Cost

NMC cost estimates from 3M; 2016

<table>
<thead>
<tr>
<th>Co Price $/kg</th>
<th>NMC 442</th>
<th>LCO</th>
<th>NMC 111</th>
<th>LCO - NMC 442</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>9.38</td>
<td>18.06</td>
<td>11.19</td>
<td>8.68</td>
</tr>
<tr>
<td>40</td>
<td>10.36</td>
<td>24.08</td>
<td>13.22</td>
<td>13.72</td>
</tr>
<tr>
<td>60</td>
<td>12.32</td>
<td>36.12</td>
<td>17.29</td>
<td>23.8</td>
</tr>
<tr>
<td>80</td>
<td>14.28</td>
<td>48.17</td>
<td>21.37</td>
<td>33.89</td>
</tr>
<tr>
<td>100</td>
<td>16.25</td>
<td>60.21</td>
<td>25.44</td>
<td>43.96</td>
</tr>
<tr>
<td>120</td>
<td>18.21</td>
<td>72.25</td>
<td>29.51</td>
<td>54.04</td>
</tr>
<tr>
<td>140</td>
<td>20.17</td>
<td>84.3</td>
<td>33.59</td>
<td>64.13</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Gravimetric Energy Density, Wh/kg*</th>
<th>Power</th>
<th>Cycle Life</th>
<th>Safety</th>
<th>Price, S/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFP (LiFePO₄)</td>
<td>500 (3.8 V)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>15–22</td>
</tr>
<tr>
<td>LMFP (LiMnₓFe₁₋ₓPO₄)</td>
<td>570 (4.3 V)</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>15–22</td>
</tr>
<tr>
<td>LMO (LiMn₂O₄)</td>
<td>480 (4.3 V)</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>12–15</td>
</tr>
<tr>
<td>LCO (LiCoO₂)</td>
<td>570 (4.3 V)</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>30–70</td>
</tr>
<tr>
<td>LNMC (LiNiₓMnₓCo₁₋ₓ₋₂O₂)</td>
<td>570–690 (4.3 V)</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>20–50</td>
</tr>
<tr>
<td>LLNMC (xLi₂MnO₃·(1–x)LiMO₂)</td>
<td>960 (4.6 V)</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>20–40</td>
</tr>
<tr>
<td>LNMO (LiNi₁/₂Mn₃/₂O₄)</td>
<td>630 (5.0 V)</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>15–25</td>
</tr>
<tr>
<td>LCP (LiCoPO₄)</td>
<td>720 (5.0 V)</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>20–50</td>
</tr>
</tbody>
</table>

* Values in parentheses are charge voltage vs. Li₀.  
Key: (+) Clear strength, (-) Clear improvement opportunity, (0) Neither a strength nor weakness
NMC Powder Production

Co, MnO₂, Ni Powders

- Preparation of Ni, Mn, Co raw materials and NH₄OH/NaOH solutions
- Precipitation under stirring and heating at 40-80°C (spherical agglomerates)
- Washing
- Spray drying
- Dry mixing with Li source
- Heat treatment in air 550-700°C, then 800-1000°C
- Classification
- Post drying
- Packaging

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

NMC-333 Formula
\[ \text{Li}_{1.05}(\text{Ni}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3})_{0.95}\text{O}_2 \]
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.
Generic flowsheet for the production of nickel from sulphide concentrates
**LIB Cell Materials- Cobalt**

Generic flowsheet for cobalt production:

1. **Pre-treatment**
   - Ore concentrate
   - Secondary materials
   - a) matte
   - b) treated concentrate
   - c) alloy

2. **Leaching**
   - Purification
   - Bulk Ni or Cu separation

3. **Purification**
   - Co recovery

4. **Transformation**
   - Sale up to 99.85 % Co

5. **Leaching**
   - Purification
   - Sale up to 99.99 % Co
Figure 1. This continuous process makes lithium carbonate from spodumene. Source: www.galaxyresources.com.au/project_jiangsu.shtml.
LIB Cell Materials - Manganese

<table>
<thead>
<tr>
<th>Material/Energy</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese Ore</td>
<td>$140/t</td>
</tr>
<tr>
<td>Manganese Sinter</td>
<td>$224/t</td>
</tr>
<tr>
<td>Ferromanganese Alloy</td>
<td>$872</td>
</tr>
<tr>
<td>Electricity</td>
<td>$70/MWh</td>
</tr>
<tr>
<td>Diesel</td>
<td>$1.05/L</td>
</tr>
<tr>
<td>Coal</td>
<td>$65/t</td>
</tr>
<tr>
<td>Coke</td>
<td>$250/t</td>
</tr>
</tbody>
</table>
LIB Cell Materials- Manganese

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

<table>
<thead>
<tr>
<th>Process Stage</th>
<th>Primary Energy Demand (GJ)</th>
<th>Global Warming Potential (tCO₂e)</th>
<th>Grid Power (kWh)</th>
<th>Diesel (kg)</th>
<th>Coal (kg)</th>
<th>Coke (kg)</th>
<th>Explosives (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction</td>
<td>0.6</td>
<td>0.08</td>
<td></td>
<td>13.9</td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>Ore Processing &amp; Beneficiation</td>
<td>0.9</td>
<td>0.10</td>
<td>37</td>
<td>19.0</td>
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<tr>
<td>Sinter Production</td>
<td>3.0</td>
<td>0.30</td>
<td>32</td>
<td>7.3</td>
<td>35</td>
<td>49</td>
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<tr>
<td>Smelting</td>
<td>26.0</td>
<td>4.27</td>
<td>2811</td>
<td>149</td>
<td>372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casting, Crushing &amp; Screening</td>
<td>1.4</td>
<td>0.31</td>
<td>268</td>
<td>3.5</td>
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<tr>
<td><strong>Total Supply Chain</strong></td>
<td><strong>31.9</strong></td>
<td><strong>5.06</strong></td>
<td><strong>3148</strong></td>
<td><strong>43.6</strong></td>
<td><strong>184</strong></td>
<td><strong>421</strong></td>
<td><strong>3.2</strong></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Process Stage</th>
<th>Material Cost</th>
<th>Energy Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction</td>
<td>460.00</td>
<td>334.60</td>
<td>794.60</td>
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<tr>
<td>Ore Processing &amp; Refining</td>
<td>26.57</td>
<td>26.57</td>
<td>26.57</td>
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<tr>
<td>Sinter Production</td>
<td>25.98</td>
<td>25.98</td>
<td>25.98</td>
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<tr>
<td>Smelting</td>
<td>299.46</td>
<td>299.46</td>
<td>299.46</td>
</tr>
<tr>
<td>Casting, crushing &amp; Screening</td>
<td>23.18</td>
<td>23.18</td>
<td>23.18</td>
</tr>
<tr>
<td>Transportation</td>
<td>2.52</td>
<td>2.52</td>
<td>2.52</td>
</tr>
<tr>
<td><strong>Total ($/ton)</strong></td>
<td><strong>1172.30</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## LIB Materials - Nickel

### LCA results for nickel laterite processing routes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Embodied energy (GJ/t Ni)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>GHG emissions (t CO₂e/t Ni)</th>
<th>Overall nickel recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>With acid plant</td>
<td>Without acid plant</td>
</tr>
<tr>
<td><strong>Hydrometallurgical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High pressure acid leach</td>
<td>272</td>
<td>22.7</td>
<td>27.3</td>
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<tr>
<td>Atmospheric acid leach</td>
<td>167</td>
<td>14.6</td>
<td>25.1</td>
</tr>
<tr>
<td>Enhanced pressure acid leach&lt;sup&gt;b&lt;/sup&gt;</td>
<td>249</td>
<td>17.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Heap leach</td>
<td>211</td>
<td>17.6</td>
<td>28.0</td>
</tr>
<tr>
<td><strong>Pyrometallurgical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferronickel</td>
<td>236</td>
<td>NA</td>
<td>22.4</td>
</tr>
<tr>
<td><strong>Pyro/hydrometallurgical</strong></td>
<td></td>
<td>NA</td>
<td>44.8</td>
</tr>
<tr>
<td>Caron process</td>
<td>565</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Includes sulfur feedstock energy of 84–125 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.

<sup>b</sup> Based on 78% HPAL and 22% AL.

### Figure 2. Comparison of embodied energy results.

- This study
- Jessup and Mudd (2008)
- Mudd (2010)

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

<table>
<thead>
<tr>
<th>Machine</th>
<th>Cost ($)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robots (3 robots)</td>
<td>150,000</td>
<td>Staubli Robots</td>
</tr>
<tr>
<td>Hot Press</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic/Laser Welding Machine</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Charging/Station Testing (Bank of 6 stations from GE)</td>
<td>24,000</td>
<td>GE DURASTATION DOUBLE EVDN3 EV CHARGING STATION 30 AMP</td>
</tr>
<tr>
<td>Assembly line</td>
<td>574,000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6-axis robot</th>
<th>Hydraulic Press</th>
<th>Ultrasonic Tab welder</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
</tbody>
</table>

Charging Station

[Email: shirley@cysi.wang]
## LIB Pack- Purchased Parts

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

NREL/PR-6A20-68596