Lithium-ion battery supply chain technology development and investment opportunities

Carnegie Mellon University – Battery Seminar
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Benchmark Mineral Intelligence
Due to policy statements and strong public opinion trends, major automakers have committed over USD$300B towards actively developing battery electric vehicles.

Global policy statements by governments supporting EV adoption

- **Canada**: Target of 30% penetration of electric vehicle sales by 2030. Quebec targeting 100% zero emissions by 2050.
- **Norway and Netherlands**: Proposal to end ICE sales by 2035. Germany by 2030. Considerations for EU wide ban by 2030.
- **UK and France**: Proposal to end ICE sales by 2040.
- **Mexico**: Target of 30% penetration of electric vehicle sales by 2030.
- **Brazil**: Target of 30% penetration of electric vehicle sales by 2030.
- **China**: Target of 5% penetration of electric vehicle sales by 2020, 20% by 2025.
- **Japan and South Korea**: Target of 30% penetration of electric vehicle sales by 2030.
- **Italy**: Target of 30% penetration of electric vehicle sales by 2030.
- **Israel**: Proposal to end ICE sales by 2030.

Examples of major passenger car and light duty vehicle OEM EV strategy announcements

- **Toyota**: Has set a sales target of ~1m EVs and FCVs by 2030, investing >$13 billion to develop and make batteries.
- **Volkswagen Group**: Plans to invest more than $24bn in zero-emission vehicles by 2030. Will develop 80 EV models by 2025.
- **VW Group**: Plans to invest more than $24bn in zero-emission vehicles by 2030. Will develop 80 EV models by 2025.
- **Ford**: Planning to invest $11bn in EVs by 2022, and will have 40 hybrid and full EV models.
- **Hyundai-Kia Motors**: Aiming to develop 8 EV models by 2025, with 30 panned by 2030.
- **HONDA**: Set target of two thirds of vehicle sales EV by 2030.

Note: ICE - Internal Combustion Engine
As a result, lithium-ion manufacturers are ramping up >2TWh capacity from 121 battery “megafactories”, the majority of which are expected in China.

Expected GWh battery cell manufacturing production through 2029 - major producers

Total lithium ion battery megafactory capacity by region, 2029 (GWh)

China will continue to dominate cell manufacturing with demand for European and US made cells out-stripping supply. This is especially the case for Tier 1 producers who may only have limited volumes available outside the large OEMs.

Note: Not all stated capacity is available in a given year as commissioning dates fall throughout the year and facilities take time to ramp up.
This significant global battery cell capacity ramp-up will compound the continuing decline of $/kWh battery cost of production

2014 is the year when meticulous cell price tracking across the industry was instituted

Cell-level cost reductions mostly concentrated on:
- Cost management along materials supply chain (largest opportunity)
- Manufacturing efficiency improvements and large-scale production
  - Yield loss improvements during manufacturing process
Pack-level cost reductions result from:
- Improved energy density of individual cells from chemistry evolution
- Improved cell density within packs from less volumetric intensity of interstitial materials

Best-in-class $/kWh for battery cell manufacturing (2014-2019)

Year | Price
--- | ---
2014 | 280
2015 | ~120
2016 | ~130
2017 | ~120
2018 | ~120
2019 | ~120

16% price decline per year on average
Cathode materials are the largest $/kWh cost, and is the focus of cost reduction through materials management and manufacturing efficiency improvements.
6 key trends shaping the lithium-ion battery cell industry

1. Western automotive push towards higher quality
2. Nickel-rich cathode chemistries
3. Cathode chemistry differentiation by application
4. Chinese control of global materials supply chain
5. Opportunities for supply chain co-location
6. Pending supply/demand imbalances
Market Trend #1 – While higher tier battery producers are preferred by Western automotive, lower tier battery suppliers will try to “level up”

- Higher likelihood of being used in Western automotive
- Longer supplier qualification timelines
- Higher material quality requirements
- More stringent spec tolerances
- Larger qualification sample requirements

But, does not necessarily mean:
- Trends in China are the same
- More innovative
- Better position to raise capital
- First choice for Western automotive in perpetuity

Product quality differentiation is the main reason that battery cells will not become “commoditized” like solar panels
Market Trend #2 - Nickel-rich cathode chemistries expected to capture larger market share as customers push for higher energy density, but LFP is a “dark horse”

NCA holds while NCM varieties take the majority of the market

Lithium is the only element common to all of these chemistries
Market Trend #3 - Long-term, as industry shifts towards autonomous driving and EVs penetrate new geographies, cathode chemistries will differentiate by application.

Present

- NCM
  - Standard battery chemistry across all vehicles

Future – custom chemistries by application

- NCA
- NCM811
- NCM523
- NCM622
- LFP

- Long-range vehicles with fast acceleration; premium product
- Medium-range vehicles; everyday product
- Fixed route, short-distance driving; geography-specific (China)
Market Trend #4 – China dominates capacity in the upstream cathode and materials supply chain, and expected to continue to do so at least for the next decade

- Current lithium chemicals supply:
  - China: 49%
  - Non China: 51%

- Current cobalt chemicals supply:
  - China: 38%
  - Non China: 62%

- Current cathode supply:
  - China: 35%
  - Non China: 65%

- Current nickel supply:
  - China: 48%
  - Non China: 52%
Market Trend #5 – Western markets’ EV demand and governments’ push towards new job creation in advanced industries creates capacity co-location opportunities

From – Globally Distributed Supply Chain

To – Vertically Integrated For Cost Optimization

General product flow towards Asia

General product flow towards end markets
Market Trend #6 – The dislocation in timeline to build each portion of the supply chain could lead to multiple battery material shortages

### Approximate timeline to progress supply step

<table>
<thead>
<tr>
<th>Step</th>
<th>Mining</th>
<th>Chemical Processing</th>
<th>Cathode Production</th>
<th>Cell Manufacturing</th>
<th>Application</th>
</tr>
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<tbody>
<tr>
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</tbody>
</table>

#### Example—Lithium chemicals demand/supply tonnes (’000)

- **Demand**
- **Secondary Supply**
- **Probable additional tonnes**
- **Highly Probable additional tonnes**
- **Possible additional tonnes**
- **Operational supply**

Unplanned new supply
6 key trends shaping the lithium-ion battery cell industry

1. Western automotive push towards higher quality

2. Nickel-rich cathode chemistries

3. Cathode chemistry differentiation by application

4. Chinese control of global materials supply chain

5. Opportunities for supply chain co-location

6. Pending supply/demand imbalances
Deep Dive on Lithium Chemicals Industry
Lithium is plentifully available today from a geology standpoint...

**Lithium resource availability – major countries**

- **Canada**
  - Yearly Mine production: 0
  - Reserves: 2,300,000 (1.5%)

- **United States**
  - Yearly Mine production: 3,400 (1.8%)
  - Reserves: 6,800,000 (4.6%)

- **Brazil**
  - Yearly Mine production: 966 (0.5%)
  - Reserves: 290,000 (0.19%)

- **Chile**
  - Yearly Mine production: 70,600 (36.7%)
  - Reserves: 45,300,000 (30.4%)

- **Bolivia**
  - Yearly Mine production: 0
  - Reserves: 54,300,000 (36.4%)

- **Argentina**
  - Yearly Mine production: 22,937 (11.9%)
  - Reserves: 12,100,000 (8.1%)

- **China**
  - Yearly Mine production: 13,300 (6.9%)
  - Reserves: 19,000,000 (12.7%)

- **Australia**
  - Yearly Mine production: 81,000 (42.1%)
  - Reserves: 9,100,000 (6.1%)
... but supply remains highly concentrated within a small number of regions...

**Lithium Raw Material Supply in 2019**
- Total: 359,000 tonnes LCE

**Lithium Chemical Supply in 2019**
- Total: 338,000 tonnes LCE
... with a small number of Tier 1 suppliers supplying the Western battery industry

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Primary production assets</th>
<th>Chemicals conversion assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALBEMARLE</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Ganfeng Lithium</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Tianqi</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Livent</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>SQM</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Supply breakdown - 2018 ('000s)

- Tier 1 - Albemarle: 46
- Tier 1 - Ganfeng Lithium: 43
- Tier 1 - Tianqi: 40
- Tier 1 - Livent: 18
- Tier 1 - SQM: 48
- Total Tier 1: 194
- Tier 2: 54
- Tier 3: 38
- Total: 285

1. Current production 2. Currently ramping up production asset in Western Australia
Brine and spodumene are the two most prolific sources of material today, although specific forms of clay have potential to enter the supply chain in the future.

<table>
<thead>
<tr>
<th>Brine ponds – SQM, Chile</th>
<th>Spodumene mine – Greenbushes, Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Brine ponds" /></td>
<td><img src="image2" alt="Spodumene mine" /></td>
</tr>
</tbody>
</table>
Carbonate and hydroxide, the two most common forms of lithium chemicals used for battery manufacturing today, mildly differ in price.

**Carbonate**
- >60% of the produced and consumed lithium chemicals today
- Expected to make-up a meaningful part of the market in the long-term

**Hydroxide**
- Fastest growing segment due to shift due to shift towards higher nickel chemistries

### Weighted Average Lithium Prices: Jan 2018- Dec 2019

<table>
<thead>
<tr>
<th>Month</th>
<th>Lithium Carbonate (Min 99.0%)</th>
<th>Lithium Hydroxide (Min 55.0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>20,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Apr</td>
<td>18,000</td>
<td>13,000</td>
</tr>
<tr>
<td>Jul</td>
<td>15,000</td>
<td>11,000</td>
</tr>
<tr>
<td>Oct</td>
<td>12,000</td>
<td>9,000</td>
</tr>
</tbody>
</table>

*2018* | *2019*

*Source: Benchmark Mineral Intelligence Lithium Price Assessment*
Given the growth in the industry, supply chain players have exercised creativity in structuring new business models to feed material into this evolving supply chain.

**EXAMPLE – Supply chain of spodumene material from Sigma Lithium in Brazil to a Western automaker**

- Sigma Lithium is ramping up 660k TPT spodumene production in Brazil.
- Secured $30m pre-payment from Mitsui, who are responsible to ship spodumene from Brazil for production in China to lithium chemicals ultimately bound for Western automotive batteries.
- Mitsui plays central role in piecing together the supply chain here.
However, projected severe shortages of lithium chemicals still plague the industry, which begs the question – why aren’t more people investing?

- The demand outlook for lithium is undoubted, the speed and rate of demand growth is the major question
- Entering a period of transition with new supplies beginning ahead of the roll out of megafactory capacity
- Major supply expansions still required to reach demand requirements of 2021 onwards
- The slow introduction of new projects into the market is a warning sign for a market which is only in the early stages of its growth cycle
**Reason #1** - Value chain is concerned about price volatility; after decades of stability, lithium prices have gone through a boom/bust cycle in just 6 years

Lithium prices: Mar 2014-Feb 2020

1. **Calm before the storm**
   - Lithium chemical prices had been relatively stable for >4 years in build up to 2015 spike

2. **Panic buying**
   - Availability concerns sparked by China NEV market acceleration

3. **Supply unresponsive**
   - Majors unable to respond to market deficit

4. **Next generation**
   - New market entrants increase supply, switching China sentiment

5. **Stabilization**
   - New supplies stabilize prices but at higher cost levels

6. **New normal**
   - Prices begin return to pre-boom levels, but establish new normal range
Reason #2 - Regardless of price swings the lowest cost producer is best position for value creation, and these projects are becoming harder to find and develop.

Lithium industry brine and hard rock total cost curve - 2019

USD/MT-LCE (real terms, 2019)

Notes on cost curves:
- Total cost includes capital repayment and royalty costs
- Hard rock includes pegmatite, petalite, lepidolite, jadarite and clay resources
- For operations producing spodumene, freight costs to processing point are included, as is a conversion margin to lithium carbonate
**Reason #3 – Even if a project is developed, it has to be “qualified” for battery-grade supply before a large supply contract can commence**

**Qualification** – the auditing process to ensure that material is **fit for purpose** before commercial supply commences

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**Example raw material qualification process and timeline – best case scenario**

<table>
<thead>
<tr>
<th>Does the material…</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 … comply with spec?</td>
<td>10 – 50 KG</td>
</tr>
<tr>
<td>2 … perform in cathode?</td>
<td>100 – 500 KG</td>
</tr>
<tr>
<td>3 … perform in battery cell?</td>
<td>1000 – 5000 KG</td>
</tr>
<tr>
<td>4 … come from a reliable manufacturing line?</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Month</th>
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</tbody>
</table>

**Concerns for OEMs**

- OEMs must qualify large quantities of new suppliers to create effectively large pool of available material to source
- Risk of qualification failure is high with new suppliers

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Reason #4 – Against a backdrop of rising ESG concerns in mining investing, the environmental footprint of this supply chain has faced tough scrutiny

**Comparative carbon footprint of VW’s EV vs. ICE**

- **Diesel**:
  - Vehicle production (cradle to gate): 29
  - Use phase (tank to wheel): 11
  - Fuel provision (well to tank): 100
  - Total: 141

- **BEV (EU mix)**:
  - Vehicle production (cradle to gate): 57
  - Use phase (tank to wheel): 62
  - Fuel provision (well to tank): 120
  - Total: 120

Source: VW ID.INSIGHTS Sustainable E-Mobility Presentation – February 15, 2019

**Technical grade lithium hydroxide carbon intensity (tCO₂/LiOH-H₂O)**

- **Chilean Brine**: 5.0 tCO₂/tLiOH-H₂O
- **Argentine Brine**: 7.4 tCO₂/tLiOH-H₂O
- **Australian Spodumene/Chinese Conversion**: 14.8 tCO₂/tLiOH-H₂O

Source: The CO2 Impact of the 2020s Battery Quality Lithium Hydroxide Supply Chain* by Alex Grant, David Deak, and Robert Pell (January 2020); Minviro
Reason #5 – Stalled innovation in the flow sheet for lithium chemicals production reinforces questions about environmental sustainability and value creation

- High electricity costs from high temperature baking of ore and electrodialysis of leach liquor
- High operations/labor cost from ore mining and material transport
- High lime slurry costs to neutralize acid addition and to promote impurity precipitation
- Low byproduct revenue

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing/Sorting</td>
<td></td>
<td>Hard rock ore (Spodumene)</td>
</tr>
<tr>
<td>Electric Heating</td>
<td></td>
<td>0.7wt% Li Non-Li containing rock</td>
</tr>
<tr>
<td>Acid H$_2$SO$_4$</td>
<td></td>
<td>Release of volatile phases increase in porosity, increase in acid solubility</td>
</tr>
<tr>
<td>Acid Roasting 250C</td>
<td></td>
<td>Lithium dissolved in to aqueous Li$^+$</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>Lithium dissolved in to aqueous Li$^+$</td>
</tr>
<tr>
<td>Lime Slurry Ca(OH)$_2$ pH:5-6</td>
<td></td>
<td>Precipitated impurities Al(OH)$_3$, Fe$_2$O$_3$</td>
</tr>
<tr>
<td>Lime Slurry Ca(OH)$_2$ pH:8-9</td>
<td></td>
<td>Precipitated impurities CaCO$_3$, Mg(OH)$_2$, Silicates</td>
</tr>
<tr>
<td>Ion Exchange</td>
<td></td>
<td>Multivalent cations Ca$^{2+}$, Mg$^{2+}$, Al$^{3+}$</td>
</tr>
<tr>
<td>3 Compartment</td>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>Electrodialysis</td>
<td></td>
<td>9 wt% Li</td>
</tr>
<tr>
<td>Mechanical Vapor</td>
<td></td>
<td>95 wt% Li</td>
</tr>
<tr>
<td>Recompression</td>
<td></td>
<td>99.9 wt%</td>
</tr>
<tr>
<td>Crystallization/Filteration</td>
<td></td>
<td>LiOH-H$<em>2$O$</em>{(s)}$</td>
</tr>
<tr>
<td>Final Drying</td>
<td></td>
<td>LiOH-H$<em>2$O$</em>{(s)}$</td>
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</tbody>
</table>

- High electricity costs from high temperature baking of ore and electrodialysis of leach liquor
- High operations/labor cost from ore mining and material transport
- High lime slurry costs to neutralize acid addition and to promote impurity precipitation
- Low byproduct revenue
5 reasons that lithium supply growth is projected to fall behind demand

1. Price volatility
2. Production operating cost
3. Project qualification
4. ESG concerns
5. Lack of technology innovation
Growing the battery recycling industry
Industry’s concerns about severe materials shortage, geopolitical risk, and governance has led them to seek alternatives to traditional mining/chemicals.

**Forecast lithium chemicals demand/supply tonnes (‘000)**

- **Demand**
- **Secondary supply**
- **Supply Probable**
- **Supply - Highly Probable**
- **Supply Possible**
- **Supply - Operational**

**Cobalt Raw Material Supply in 2018**

- Democratic Republic of Congo: 69%
- Canada: 3%
- Australia: 26%
- Other: 2%

Total: 128,000 tonnes

Source: Benchmark Mineral Intelligence data
Batteries sent to raw material recycling centers expected to grow nearly 4x by 2025, and in response multiple companies are pursuing capacity build-ups.

<table>
<thead>
<tr>
<th>Years</th>
<th>Tons of lithium ion batteries sent to recycling by geography ('000)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>China</td>
</tr>
<tr>
<td>2018</td>
<td>98</td>
</tr>
<tr>
<td>2019</td>
<td>119</td>
</tr>
<tr>
<td>2020</td>
<td>145</td>
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<td>2021</td>
<td>172</td>
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<td>2023</td>
<td>264</td>
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<td>2024</td>
<td>329</td>
</tr>
<tr>
<td>2025</td>
<td>398</td>
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</tbody>
</table>

Source: Hans Eric Melin - Circular Energy Storage
BMW/Northvolt/Umicore deal an example of European pan-industry collaboration on closed loop sustainable battery materials supply chain; more deals expected

- Project aims to create a “closed life cycle loop” for battery cells
- Cells will be manufactured using a recyclable design and used in electric vehicles, then possibly as stationary storage devices before finally being recycled and reused

Source: Reuters - BMW, Northvolt and Umicore team up on battery sustainability (Oct 2018)
Attractive project economics featuring a payback <1 year at demo plant scale, but sensitive to continuous process cost improvement and chemicals market prices

NCA demonstration plant project economics

<table>
<thead>
<tr>
<th>Metal</th>
<th>Market Price (USD/kg)</th>
</tr>
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<tbody>
<tr>
<td>Lithium Carbonate</td>
<td>$17.00</td>
</tr>
<tr>
<td>Cobalt</td>
<td>$79.00</td>
</tr>
<tr>
<td>Nickel</td>
<td>$14.70</td>
</tr>
<tr>
<td>Manganese</td>
<td>$2.03</td>
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<tr>
<td>Aluminium</td>
<td>$2.20</td>
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</table>

<table>
<thead>
<tr>
<th>Battery Chemistry</th>
<th>NCA</th>
<th>Lithium Carbonate (kg)</th>
<th>1.154</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cobalt (kg)</td>
<td>276</td>
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<tr>
<td></td>
<td></td>
<td>Nickel (kg)</td>
<td>1,466</td>
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<tr>
<td></td>
<td></td>
<td>Manganese (kg)</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td>Aluminium (kg)</td>
<td>42</td>
</tr>
</tbody>
</table>

| Total Annual Revenue | $23.02 M |

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<thead>
<tr>
<th>Annual Operating Expenses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reagents</td>
<td>$1.07 M</td>
</tr>
<tr>
<td>Labour and G&amp;A</td>
<td>$3.28 M</td>
</tr>
<tr>
<td>Utilities</td>
<td>$0.13 M</td>
</tr>
<tr>
<td>Feed Material Delivered</td>
<td>$2.3 M</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$0.53 M</td>
</tr>
<tr>
<td>Building Rent</td>
<td>$0.18 M</td>
</tr>
<tr>
<td>Shipping &amp; Packaging</td>
<td>$0.68 M</td>
</tr>
</tbody>
</table>

| Total Annual Operating Expense | $8.15 M |

<table>
<thead>
<tr>
<th>Interest Rate</th>
<th>10%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Cashflow</td>
<td>Balance</td>
</tr>
<tr>
<td>Year 0</td>
<td>$(10.0)M</td>
<td>$(10.0)M</td>
</tr>
<tr>
<td>Year 1</td>
<td>$14.9 M</td>
<td>$4.9 M</td>
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<tr>
<td>Year 2</td>
<td>$14.9 M</td>
<td>$19.7 M</td>
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<tr>
<td>Year 3</td>
<td>$14.9 M</td>
<td>$34.6 M</td>
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</table>

<table>
<thead>
<tr>
<th>NPV</th>
<th>Payback</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$26.97 M</td>
<td>0.68 Years</td>
<td>138%</td>
</tr>
</tbody>
</table>

Impact on NPV by Change in Assumption (NCA Battery Chemistry)

- Variability potentially introduced with changing perceptions of feed material value
- Potential premium due to low-carbon and closed-loop material could guarantee higher prices

Source: Argonne National Lab EverBatt recycling model for American Maganese 1,200 tpa plant
The recycling industry is in nascent stages, and faces multiple threats to reach full scale and profitability as global lithium-ion battery capacity ramps up.

1. Second use batteries
2. Low collection rates from consumers
3. Non-differentiated regulation between lead-acid and lithium-ion batteries
4. Input feedstock heterogeneity
5. Chemical process inefficiency
6. Competing priorities with battery life longevity push
OEMs and battery manufacturers are looking at opportunities to recycle used lithium-ion batteries and scrap to create a closed loop battery supply chain.

Main advantages of battery recycling:
- Lower CO2 footprint supply chain
- Decreased geopolitical and logistics risk
- Fulfills regulatory mandates
- More likely to be attractive to customers
- Reduces $/kWh battery costs
The battery industry is fundamental to the race for clean air worldwide, and requires innovative new solutions in this time of unprecedented change.
Reach out with any questions, and download presentation

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