Outline

1. Market forecasts for electric vehicles and Li-ion batteries
2. Market forecasts for lithium and cobalt supply and demand
3. Can Li and Co supply sustain fast EV adaption?
4. Sustainability of Li and Co supply chains
5. How much can battery recycling contribute?
6. Effect of technology choices
7. Recycling processes
8. Vanadium redox flow batteries
9. Other redox battery chemistries
10. Summary
1a. EV market forecasts

Li battery need based on EV market share and 50 kWh units size

- 35 million EVs/a
- 10 million EVs/a
1b. Li-ion battery market forecasts

Li-battery demand and production estimates

- 40 gigafactories

**Chart:**
- 645 GWh in 2025
- Electric Vehicles: 78%
- Stationary: 15%
- Consumer electronics: 7%

**Graph:**
- Deutsche Bank 2017
- Navigant Research 2016
- Bloomberg 2016
- Lux Research 2017
- BNEF 2017
- Economist 2017
- VW 2017
- CloseLoop Demand
2a. Lithium supply and demand

Global Lithium LLC 2017 (top right) and 2015 (bottom right).
2b. Cobalt supply and demand

Petersen 2017 (top right) and MIT 2017 (bottom right).
3. Can Li and Co supply sustain EV growth?

10 kg Co and 42 kg LCE (8 kg Li) assumed per average EV
4a. Sustainability of Li value chain

Washington Post 2016:
- Brine pumping is risking local water resources in arid regions.
- Local communities are not sufficiently compensated by the mining companies.
Amnesty 2015:

- 20% of the DRC cobalt comes from artisanal miners including child labor.
- OEMs are unable to identify their cobalt source.
5. How much can battery recycling contribute?

- By 2025 mainly batteries from consumers electronics will be available for recycling.
- This could be an important source for Co if effective global collection and recycling infrastructure could be established.
- Recycling rates: Co 68 %, Li <1 % (UNEP 2011)
6. Effect of technology choices

- Cobalt can and should be replaced by LFP in stationary applications.
- Should alloy cathodes be used in consumer electronics?
- Are LMO and LNO real alternatives to NMC and NCA, and how soon?
- Increasing demand for Nickel.

![Image of a diagram showing the chemistry of cathodes with various battery models and their compositions including NCA, LCO, LMO, and NMC, with a focus on the transition from high to low cobalt options over time.](Electrek 2016)

![Image of a diagram showing the development of battery materials, including advanced chemistry enhancements and future materials.](Johnson Matthey 2017)
7a. Pyrothermal recycling (Umicore)

- Ultra High Temperature (UHT) process for mixed battery waste.
- 7000 tons per annum capacity.
- Batteries are directly fed into furnace as-is.
- Pre-heating is performed in the same furnace, an innovation.
- Nickel, cobalt and copper matte is produced and then hydrometallurgically treated.
- Slag fraction with lithium which is not recovered.
- Lithium could be recovered, however it is economically unattractive.

7b. Hydrothermal recycling (Aalto)

- Industrially processed battery waste has been investigated.
- Investigations done in mineral and organic acids with different reductants.
- Simple precipitation route investigated via neutralization and carbonate precipitation.
- Lithium is an evasive element and difficult to recover from solution once dissolved.
- Complex waste stream adds to difficulty: robust and flexible processes are needed.
- The hydrothermal process should be preferably integrated into existing metal (Co,Li,Ni) refining processes.

CloseLoop 2017; Aaltonen et al. 2017
8. Vanadium redox flow battery (VRFB)

- Rongke Power (China) is planning to build a 3 GW/12 GWh/a VRFB gigafactory (UET 2016).
- About 54.000 Tn/a Vanadium would be needed to supply the electrolyte, the amount produced in China today (AGM 2015).
- The recycling rate of Vanadium is < 1 % (UNEP 2011).
- VRBF electrolytes should be straightforward to recondition and recycle.
- Vanadium was added to the EU new CRM list in 2017 (EU 2017).
9. Other RFB chemistries

<table>
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<th>Chemistry</th>
<th>R&amp;D</th>
<th>Pilot</th>
<th>Commercial</th>
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<tbody>
<tr>
<td>Zn-Br2</td>
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<tr>
<td>Zn-Fe, Fe-Fe</td>
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<tr>
<td>Zn-air, H2-Br2, Cu-Cu, organic</td>
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<table>
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<th>Element</th>
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<th>Cu</th>
<th>Fe</th>
<th>Br</th>
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<tbody>
<tr>
<td>Production</td>
<td>Million Ton/a</td>
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<td>19.4</td>
<td>3.000</td>
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<tr>
<td>Reserves</td>
<td>Million Ton</td>
<td>63</td>
<td>200</td>
<td>720</td>
<td>80.000</td>
<td>Plenty</td>
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<tr>
<td>Recycling</td>
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<td>35-60</td>
<td>43-53</td>
<td>52-90</td>
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<td>Main producers</td>
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USGS 2013-2017
10. Summary

- Cobalt appears to be the most critical Li-ion battery raw material and resource scarcity can limit EV market growth.
- Co free chemistries should be used in non-critical, e.g. stationary, applications.
- Consumer electronics will remain as the most Co intensive application until 2025.
- Lithium production appears to be capable of responding to the market demands.
- More efficient battery recycling is needed: first for consumer electronics, later for EV batteries.
- Resource scarcity could affect the scale-up of vanadium batteries, too.
- RFB chemistries based on abundant raw materials like Fe, Zn or Cu would be preferred for stationary energy storage.
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