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Progress in EV-Battery Cell Cost and Performance: How Far and How Fast?

An Extract from **The xEV Industry Insider Report**

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Dr. Menahem Anderman,
President, Total Battery Consulting, Inc.

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Presentation Outline

- **Roadmap for Li-Ion Cell**
  - **Design & Performance**
  - **Cost**
- **Li-Metal Chemistries: Different Flavors, Current Opportunities, and Challenges**

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Cell Design: Pouch, Cylindrical, or Prismatic

- No consolidation since 2010
- Cylindrical and pouch designs have the advantage at the cell level but cost and performance are quite similar at the module and pack levels
- Cylindrical designs are judged less reliable at the module level
  - It is easier to pack cylindrical cells into tight uneven spots
  - Cylindrical cells will be used by major automakers if fit better into limited space or if increased energy density of larger cells hits a safety snag
  - Long-term reliability/durability and safety, which will not be confirmed for several years, could shift the advantage to prismatic or pouch


Anode: Graphite-Based

Graphite is almost an ideal anode!

- Operates 3V negative of H_2 potential, well negative of thermodynamic stability
- Protected by a relatively stable SEI
- Specific capacity around 350 mAh/gram and over 700 Ah/liter, larger than that of the cathode
- Excellent cycle life
- Good power
- Inexpensive raw material
- Cost impact \$6-8/kWh about 1/5th that of the cathode

Areas of desired improvement

- Faster charge at low temperatures
- Higher capacity density
- More stable SEI at intermediate temperatures
- Lower processing cost is always nice

Si-Blend Anode

- Si possesses high gravimetric and volumetric capacity >2,000 Ah/gram
- Si stores lithium islands internally, not truly intercalation into a dimensionally stable structure
  - High irreversible capacity is a drawback
  - Significant swelling
- Small, 3% to 6% Si with > 1,200 mAh/gram cyclable can be added to graphite anode and still support acceptable cycle life
- 6% Silica at 1200 mAh/gram brings the blend's capacity to 400mAh/gram
- For higher than 10-15% silica, pre-lithiation is needed as well as cell engineering that can accommodate the large expansion/contraction of the material upon cycling

Cathode: NMC is the Focus for EV Batteries

Status, Prospects, and Challenges of NMC 8,1,1

- The industry has just moved from NMC 1,1,1 to NMC 6,2,2
  - Specific cathode capacity is up from about 145 to 175 mAh/gram
- The next step will be introduced this year: NMC 7,1.5,1.5 and NMC 8,1,1
- Higher nickel content provides higher energy density + lower cost of raw materials
- However, higher nickel content brings some challenges:
  - **Safety**
  - **Life**
  - **Manufacturing**
- With even higher nickel, which is desired for lower cobalt content, life and safety will be more difficult.

Electrolyte and Separator

- LIPF$_6$ salt in blend carbonates has been the standard electrolyte solution from day one
- Microporous Polyolefin-based separators have been the baseline from day one

Why not replace both components with a solid electrolyte (inorganic or polymer?) and thus enjoy many benefits?

✓ Solid Electrolytes don't burn as easily

? 'Solid Electrolytes are chemically more stable'

? 'Solid Electrolytes will take less volume'

! 'Solid Electrolytes will enable a cheaper battery'—??

So we will get:

✓ Better safety—Probably

? Longer life—Not convincing

? Smaller battery—Not convincing

! Lighter Battery—Surely not

! Cheaper Battery—Surely not

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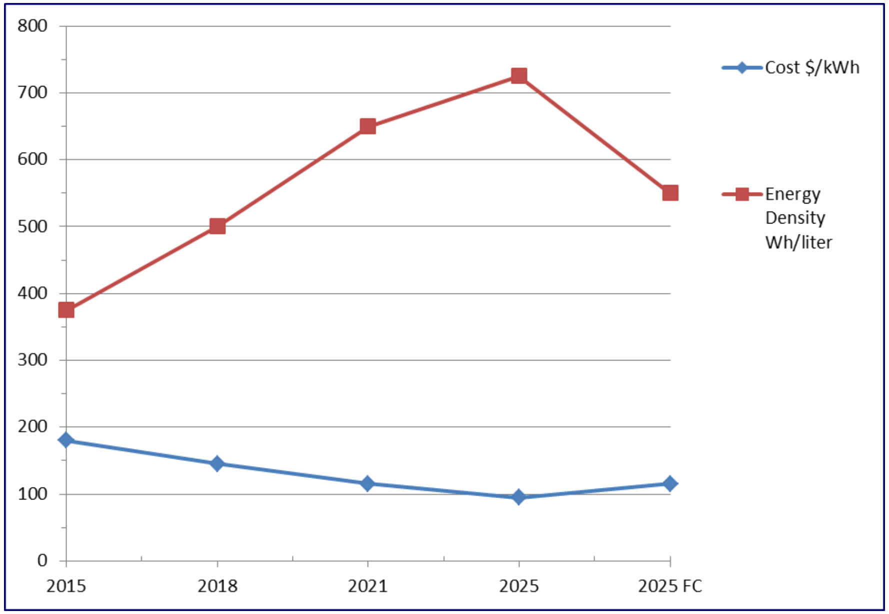
Li Ion Performance Progress

	BEV Li Ion projected pouch cell level parameters	2015	2018	2021	2025	2025 Fast Charge
1	Cost $/kWh	180	145	115	90	115
2	Energy Density Wh/liter	375	500	650	725	550
3	Abuse Tolerance, VDA level	4	4	4	4	4
4	Charge time 10-90% SOC, minute	30	20	20	30	12
5	Cycle life, better than	1200	1200	1200	1200	1500
6	Specific Energy, Wh/kg	170	220	260	280	220



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Li-Ion Automotive Battery Development Direction

1. Reduce Cost
2. Increase Volumetric Energy Density
3. Increase Charge Acceptance Rate
4. Expand operating temperature range
5. Improve specific energy
6. Ensure material availability and price stability (reduction)

❖ While maintaining or enhancing:

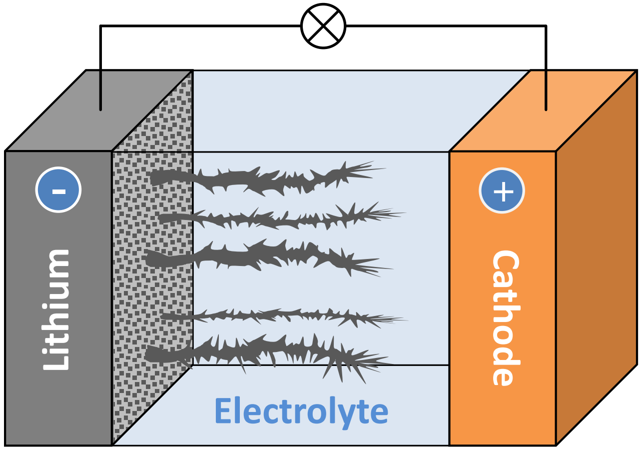
- ✓ Safety
- ✓ Durability
- ✓ Manufacturability

Metallic Lithium Anode

- ✓ With low weight and volume per unit charge, and an enabler of cells with high cell voltage, metallic lithium is an obvious attraction for the anode
- ➢ Due to dendritic plating on charge, Cycle life and safety have been a handicap for 40 years
- ➢ Many electrolyte choices
- ➢ Many cathode choices

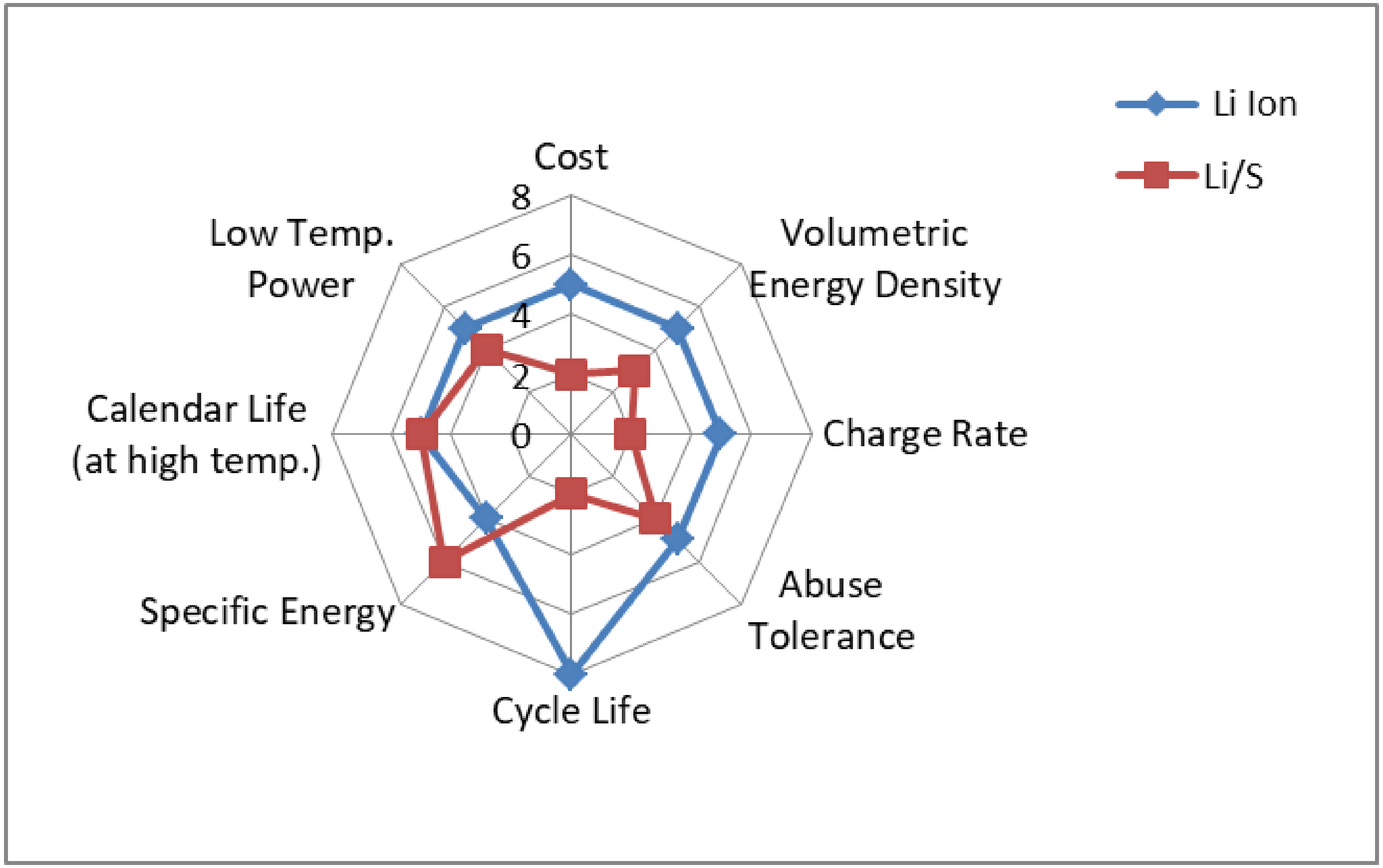
Facing the Main Challenge

- All metal-lithium-based rechargeable batteries must solve the dendrite problem to become commercially viable for BEV applications
- A secondary but still critical issue is that of the high cost of thin metallic lithium
- Thirdly, the fast charge of lithium metal typically worsens the dendrite problem
- The above is true regardless of cathode choice



Li/S Cannot Compete with Li Ion

2018 Situation



CONCLUSIONS

- Li Ion with Silica at the anode and 90% or higher Nickel oxide at the cathode is likely to exceed 750Wh/liter while providing nearly all other automotive battery requirements.
- Cell cost lower than $100/kwh is achievable but to obtain a cost lower than $80/kWh will require a significant reversal in metal pricing or new cathode chemistry.
- Any 'post-Li-ion' mass-market battery EV technology will have to provide at least 20-25% improvement in energy density and/or cost against the numbers above, while maintaining parity with all other key cell parameters.
- Li-Metal Oxide (NMC or related) chemistry can meet the first criterion (energy desity) but adequate cycle life and cost parity are a longer shot.
- The 2025 mass-market EV technology will be advanced Li Ion; probably also in 2030.

TOTAL BATTERY CONSULTING INDUSTRY REPORTS

The xEV Industry Insider Report

● Author: Menahem Anderman ● November 2017 edition available, April 2018 edition coming soon!

The Tesla Battery Report

● Author: Menahem Anderman ● July 2017 edition

The Li Ion Batteries and Beyond Report

● Author: Martin Winter ● February 2017 edition

The Li Ion Battery Safety and Abuse Tolerance Report

● Author: Daniel Doughty ● November 2017 edition

The Battery Packs of Modern xEVs Report

● Authors: Kevin Konecky and Menahem Anderman ● June 2017 edition

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