High-Energy, Low-Weight Lithium Sulfur Batteries

Principal Investigator: Yuegang Zhang, Lawrence Berkeley National Laboratory
Battery chemistry breakthroughs over time

![Graph showing the specific energy (Wh/kg) of various battery chemistries over time](image)

- **Lead-Acid**
- **NiCd**
- **NiMH**
- **Li-ion**
- **Li-S**
What is a lithium-sulfur battery?

Today’s lithium-ion (Li-ion) battery

New lithium-sulfur (Li-S) battery
Battery performance comparison

Cycle life must be extended to facilitate commercialization of Li-S technology.
Cathode innovation enables Li-S battery

**Graphene Oxide-Sulfur (GO-S) Cathode Innovation**

**Benefits of GO-S Cathodes**

- High discharge rate
- Excellent energy capacity
- Promising cycle life

**GO-S Technology Readiness Level**

- TRL 1: Scientific Principle
- Current Status: 3
- TRL 9: Successful Product
Battery markets are large and continue to grow

Key criteria to evaluate potential markets of entry:

- Willingness to Pay (WTP)
- Tolerance for change

Priority markets: defense, consumer electronics, and automotive

Applications require different criteria performances

1. Applications
   - **Defense**
     - Storage
     - Manpack power
     - UAVs
     - ...
   - **Consumer Elec**
     - Tablet
     - Cellphone
     - Power tools
     - ...
   - **Vehicles**
     - Battery EVs
     - Range-extended EVs
     - Hybrid EVs
     - ...
   - **Medical**
     - Pace Maker
     - Defibrillator
     - Pulse Oximeters
     - ...

2. Application Needs vs. LiS Performance
   - **Weight**
   - **Volume**
   - **Cycles**
   - **Cost**

<table>
<thead>
<tr>
<th>Application</th>
<th>Weight</th>
<th>Volume</th>
<th>Cycles</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manpack power</td>
<td>20 lbs</td>
<td></td>
<td>300</td>
<td>$1-2/Wh</td>
</tr>
<tr>
<td>Tablet</td>
<td></td>
<td></td>
<td></td>
<td>½ of device</td>
</tr>
<tr>
<td>Power tool</td>
<td></td>
<td></td>
<td>400</td>
<td>$0.5/Wh</td>
</tr>
<tr>
<td>Battery EVs</td>
<td></td>
<td></td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Pace Maker</td>
<td></td>
<td></td>
<td>7 year life</td>
<td></td>
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<tr>
<td>Key markets and critical metrics</td>
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<tr>
<td>---------------------------------</td>
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<tr>
<td><strong>Defense</strong></td>
<td><strong>Consumer Elect.</strong></td>
<td><strong>Automotive</strong></td>
<td></td>
<td></td>
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<tr>
<td>Size</td>
<td>Size</td>
<td>Size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Smaller, $1B</td>
<td>▪ $4B (US market)</td>
<td>▪ $2.8B (US market) – high growth</td>
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<tr>
<td>Apps</td>
<td>Apps</td>
<td>Apps</td>
<td></td>
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<tr>
<td>▪ <strong>UAVs</strong> and other <strong>robotics</strong></td>
<td>▪ <strong>Power Tools</strong></td>
<td>▪ Starter battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ <strong>Portable</strong> electronics</td>
<td>▪ Cellphones and laptops</td>
<td>▪ <strong>Rechargeable batteries - EV</strong></td>
<td></td>
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<tr>
<td>Needs</td>
<td>Needs</td>
<td>Needs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Temperature range (-40°C)</td>
<td>▪ Form factor</td>
<td>▪ 400 Wh / kg, 1000 cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Shelf life (85% - 60 months)</td>
<td>▪ Safety</td>
<td>▪ Performance life of 10 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ 300 cycles</td>
<td>▪ 400 cycles</td>
<td>▪ Range of C/2 – 2C discharge</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Research grants</td>
<td>• <strong>Short cycle life</strong></td>
<td>• <strong>Cost, cost, cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Application fit</td>
<td>• Low battery-to-device cost ratio</td>
<td>• Slow dev cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large market</td>
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</tr>
</tbody>
</table>

Sources: IBISWorld – Battery Manufacturing Report 2012, CCC – Battery Cost report 2012, BCG batteries for electric cars
Li-S manufacturing can leverage existing capital

Li-S battery manufacturing can use existing, excess battery manufacturing facilities with minimal modifications

Li-ion prices are dropping

Sources: Bloomberg; McKinsey

Reduction in price from
- Performance
- Scale
- Margins

TODAY’S RANGE: $400-1500/KWH

Sources: Bloomberg; McKinsey
Li-S material inputs are competitive with Li-Ion

Sources: Industry interviews; Zhang group; McKinsey; Alibaba; Bloomberg New Energy Finance; Argonne National Lab
The Li-ion industry is highly concentrated

Top 3 countries = 88% market shares

Top 5 manufacturers = 80% market share

Production volume
By Country

- Japan 57%
- South Korea 17%
- China 14%
- RoW 10%
- U.S. 2%

Production volume
By Manufacturer

- Panasonic 24%
- Samsung 23%
- LG Chem 16%
- Other 21%
- Sony 8%
- BYD 8%

Sources: CCGC 2010; Credit Suisse 2012
Key trends in the advanced battery industry

1. Vertical integration
   - Manufacturers moving further upstream into components/materials

2. Margin compression
   - Component EBIT margins expected to be cut in half from today’s 20-40%

3. Production outsourcing
   - Relocating to countries with low labor costs (especially China)

4. Reduced VC appetite
   - History of failed battery start-ups (A123, Ener1, Imara, etc.)

5. Consolidation
   - Expect to see a continued shake-out with only the low-cost producers surviving

Challenging industry for small players
Partnerships with incumbents is critical
## Finding the optimal risk/reward balance

<table>
<thead>
<tr>
<th>Business Model</th>
<th>Examples</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP licensor</td>
<td>Argonne NL, LBNL</td>
<td>Very capital efficient, Minimal risk</td>
<td>Minimal upside, Investors unlikely to fund</td>
</tr>
<tr>
<td>Component supplier</td>
<td>Dow, Celgard</td>
<td>Ability to specialize, Capital efficient</td>
<td>Low margin, Long sales cycle</td>
</tr>
<tr>
<td>Cell manufacturer</td>
<td>Panasonic, A123</td>
<td>High margin, Largest market</td>
<td>High capex, Huge incumbents</td>
</tr>
</tbody>
</table>

### Recommendation

- Develop **complete cell** – exit *prior* to scaling manufacturing
- Finance with **grants**, **NRE**, and **corporate venture** investment
Recommended pathway to market

Laboratory
- Test cells
- DOE, DOD

Defense
- 400 Wh/kg
- 300+ cycles
- Safety
- 1000+ cycles
- Cost competitive

Consumer Electronics
- Prototypes
- Strategic

Automotive
- Full Scale
- Acquisition
- Timing
- Technology Development
- Production:
  - Test cells
  - Prototypes
  - Pilot Scale
  - Full Scale
- Funding:
  - DOE, DOD
  - Strategic
  - Acquisition
Recommendations for research next steps

- Extended cycle testing
- Ionic liquids required?
- Partnerships
  - Li-ion battery manufacturer
  - Defense battery integrator
- Focus on grant funding for applied R&D
  - DARPA, ARPA-e, SOCOM, etc.
Appendix
Theoretical Energy Capacity, Li-ion vs. Li-S

<table>
<thead>
<tr>
<th>Design</th>
<th>Sion</th>
<th>Oxis</th>
<th>PolyPlus</th>
<th>Vorbeck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Protected Li anode</td>
<td>Solid polymer electrolyte</td>
<td>Protected Li anode</td>
<td>Graphene oxide-based electrodes</td>
</tr>
<tr>
<td>Status</td>
<td>Demonstrated UAV</td>
<td>Electric scooters, bikes, boats in development</td>
<td>Proposed for military and consumer apps</td>
<td>Anode material sold as conductive ink</td>
</tr>
<tr>
<td>Funding</td>
<td>$50M – BASF</td>
<td>$24M – Sasol</td>
<td>$4.5M – ARPA-E</td>
<td>$1.5M – ARPA-E</td>
</tr>
</tbody>
</table>
Polysulfide Shuttle

Potential (V versus Li/Li⁺) vs. Capacity (mAh g⁻¹)

GO-S Cathode Full Cell Performance

The Problem

Soluble polysulfides lead to rapid performance degradation.

Our Solution

Graphene oxide-sulfur (GO-S) nanocomposite cathode retains capacity.

This invention overcomes one critical challenge for Li-S batteries. However, other breakthroughs are still required for commercialization.

Li-S Performance Improvement

![Graph showing Li/S Cell Specific Energy](image)

- **Previous**
- **This work (Initial)**

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**EV Battery Goal**

**Li-ion Cell**

Source: Prof. Elton Cairns, Min-Kyu Song
Practical vs. Theoretical Energy Capacity

Source: Rudiger Schmidt (BASF)
IP situation

• A PCT application was filed on 09/28/2012.
• National phase decisions (i.e. decision on which countries to file) will be made by 3/27/2014 based on the interest of potential licensees.
• If there isn't any interest of licensing the technology by then, it's likely LBNL will file in the US only.