Solid-State Batteries for Electromobility

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Electric vehicle sales have rapidly increased, driven by the significant decrease in the price of lithium-ion batteries.
An iPhone battery has 10 W-h of energy.

The Tesla Powerwall has 13.5 kW-h of energy.

A Tesla Model 3LR has 75 kW-h of energy (320 mile range)

A single gallon of gasoline has 33 kW-h of energy.

The average American home uses 30 kW-h/day of energy. This corresponds to 1250 W of power.

Electric vehicle range is fundamentally limited by how much energy we can store per volume and per mass.

Specific energy: Wh/kg
Energy density: Wh/L
Other Mobility Applications

Other mobility applications require even more extreme energy metrics.

Freightliner eCascadia – 438 kWh pack, 230 mile range

Beta Alia eVTOL – ~400-500 kWh, 250 mile range

Current Li-ion capabilities:
- Cell level – 270 Wh/kg
- Pack level – 160 Wh/kg

Mid-range-50 passenger aircraft:
- Cell level – 600 Wh/kg
- Pack level – 400-500 Wh/kg

2017 NASA Workshop on Advanced Batteries
V. Viswanathan et al., *Nature* (2022), 601, 519-525
Specific Energy of Li-Ion Batteries has Plateaued

*Source: [Battery 2030+ Roadmap](https://www.battery2030plus.org); Redrawn from Li, et al, cited from Figure 1 in Energy Storage Materials, 23(2019) 144-153*
Lithium-Ion Battery Anatomy

18650 cell

Copper foil current collector
Graphite anode
Polymer separator
Cathode
Aluminum foil current collector

Liquid “electrolyte” fills all pores.

Exponent, Inc.

How Can We Fit More Energy in a Battery?

Need to use **new active materials** that can hold more lithium atoms per volume and mass.

Challenge: Large structural changes lead to unstable interfaces and capacity decay in liquid electrolytes.
Solid-State Batteries to the Rescue?

Why don’t we already have solid-state batteries?

Only recently has the field developed solid-state electrolytes with high ionic conductivity.

So now that we have solid-state electrolytes, shouldn’t solid-state batteries be commercialized?

Well…no – there are fundamental challenges associated with 1) interfaces, 2) transport, and 3) manufacturing that must be overcome.

The all-solid nature of interfaces are thought to enable improved stability and cycle life of high-capacity materials.

State-of-The-Art Performance

High-capacity lithium metal anode

Excellent reported performance has inspired the field, but critical
scientific and technical challenges face the community:

1. Understanding and controlling solid-state electrochemical interfaces
2. Enabling fast charge/discharge for vehicle applications
3. Manufacturing and integration

Level of effort vs. what is needed:

P. Albertus et al., *ACS Energy Lett.* 2021, 6, 4, 1399-1404.
1. Interfacial Challenges

Conventional electrochemical interface between solid and liquid:

- Mechanical properties and contact evolution at interfaces play key roles in determining electrochemical performance
- Community is figuring out how to control these aspects

Consequences of Interfacial Challenges: Fracture

Lithium filaments can grow to fracture solid electrolyte, resulting in short circuit.

Imaging of lithium growth to cause fracture in solid electrolyte.


Consequences of Interfacial Challenges: Void Growth

\[ J_{\text{self diffusion}} + J_{\text{deformation}} < J_{\text{Li^+ migration}} \]


Scientific Tools to Understand Interfaces

Operando and in situ tools have become critical for understanding dynamic phenomena within batteries.
State of the Art: Operando Experimentation

X-ray tomography of interphase growth

Li_{10}SnP_2S_{12} Solid Electrolyte

Lithium

Current Collector

2. Enabling Fast Charge/Discharge

Composite electrodes containing ion storage material and solid electrolyte needed to attain sufficient ionic conductivity.

Attainable charge/discharge rates are not sufficient for 15-20 min charge of electric vehicles.

Still need solid electrolytes with even higher ionic conductivity!

3. Manufacturing and Integration

Conventional Li-ion battery manufacturing:

- Material processing
- Component production
- Cell production
- Module production
- Pack assembly
- Vehicle integration
- Recycling or second life

Challenges for manufacturing:
- New materials
- New form factors
- Ceramic synthesis and processing
- Control of defects at interfaces


Electrode slurry

Film on Al current collector

QuantumScape Inc.
Companies and Relationship with Academia/National Labs

R&D within startups has been heavily supported by OEMs and venture firms

Some interaction with academia/labs, but distinct knowledge gap

### Technology Map: Higher Energy Density - Solid State

<table>
<thead>
<tr>
<th>Company</th>
<th>Anode</th>
<th>Electrolyte</th>
<th>Fund Raised</th>
<th>JV/JD/Investment</th>
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<td>QuantumScape</td>
<td>Anode-free Lithium</td>
<td>Oxidic &amp; Sulfidic Ceramic</td>
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<td>ProLogium</td>
<td>Lithium/Graphite/Si</td>
<td>Oxidic Ceramic</td>
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<td>Semi-Solid Solvent-in-Salt</td>
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<td>Doped Pi-Conjugated Polymer</td>
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<td>Lithium</td>
<td>Hybrid Ceramic-Polymer</td>
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<td>BASF, AIRBUS</td>
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<td>Sulfidic Glass-Ceramic</td>
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<td>Lithium</td>
<td>PEO-based Polymer</td>
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<td>Related reading: <a href="#">BatteryBits-Solid State</a></td>
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</tbody>
</table>

*Source: Roland Zenn, updated by BatteryBits*
Sustainability and Recycling

Lithium-ion batteries harness the properties of various minerals to power electric vehicles. The cells in the average lithium-ion battery with a 60 kWh/sheet (kWh/kg) capacity contain around 185 kg of minerals.

**The Key Minerals in an EV Battery**

- **Anode**
- **Cathode**
- **Current Collectors**
- **Cell Casings**

In 2020, nickel-based cathodes powered 80% of the battery capacity deployed in new plug-in EVs.

Source: Visual Capitalist
Conclusions

Solid-state batteries offer improved energy density and safety.

Fundamental scientific and manufacturing challenges must be overcome for development.

Commercialization will happen, but don’t expect replacement of Li-ion batteries in this decade.

Source: Battery Bits