Why are solid state batteries the technology of the future?
Who and what are the leaders?

Presentation Outline
- Solid-State Batteries
- Segmentation and Market Forecasts
- Investments Announcements and Production
- Conclusions
AVICENNE PROFILE

Information for Growth - Powering your company’s market strategy with in-depth research and strategic consulting

- Creation: 1992, by Ali MADANI
- Headquarter: Paris
- Liaison Office: Japan, USA, China
- AVICENNE Energy Director: Christophe Pillot
- 4 consultants
  - A Madani
  - C Pillot
  - JP Salvat
  - A Yassari
- 2 Senior advisors
  - X Zhang
  - M. Sanders
- Database: >20 000 contacts in the battery value chain
WHY ARE SOLID STATE BATTERIES THE TECHNOLOGY OF THE FUTURE?

- Solid State Battery Description
- Solid State Battery Challenges
- Developers and Technologies
- Market Segmentation and Forecast
- Investments Announcements and Production
- Automotive Solid State
SOLID STATE BATTERY

Today’s design: Graphite/liquid electrolyte/metal oxide
Pack level: 150 Wh/kg – 250 Wh/l

Solid State design: Li/solid electrolyte/metal oxide
Pack level: 250 Wh/kg – 750 Wh/l

Technology Status
- Over 4 decades of SS TFB R&D
- Accelerated since Oak Ridge National Labs’ LiPON electrolyte patent (1994)
- Over $1.5B industrial development effort since 1996

Main advancement:
- Energy density – thick cathode, thin substrate, compact sealing, compact stacking; from <30Wh/L to >800 Wh/L
- Capacity – thick cathode, large area, and stacking; from <1mAh to >100mAh
- Manufacturing – 100 cm² deposition tool to >1m² deposition tools
- Market awareness and acceptance

Feature of Solid state battery
- Ultra thin, flexible & small
- Environmental Benign (biocompatibility)
- Safe
- Flexible design (size, shape)
- Continuous power output
- High power density
- Long life
- High temperature stability
- Low self discharge

Source: DOE – ARPA.e November 2017
RAGONE PLOT FOR LIB, SOLID STATE, LI-AIR

Figure 1. Ragone plots for various battery systems

Source: TOYOTA 2017
SOLID STATE BATTERY CHALLENGES

- Limited ionic conductivity of electrode & electrolyte materials
- Limited electrical conductivity of electrode materials
- Interface reactions
- Interface resistance
- Development of manufacturing methods for large scale batteries
- Electrochemical stability
- Cost compare to Li-ion, rechargeable coin cells or single use coin cell

Finally, Challenges for wide-spread adoption include:

- Reducing the cost of SS for higher mAh capacities
- Availability, cost and capital of High-Volume Manufacturing solutions
- Industry awareness of capabilities of SS batteries
THE GOOD NEWS

Impressive recent room temperature solid state Li+ conductivity gains

THE BAD NEWS

Full suite of requirements for commercial cells lagging

- **Mechanics:** Material often brittle
- **Cell size:** usually 1cm², how to scale if brittle
- **Thickness to compensate for brittle nature**
  - Lower energy density
  - High resistance – low power
  - Where is all the resistance coming from? Interface?
- **Handling:** Many materials not air stable
- **Cost**
  - Raw material quality needs definition, supply chain not established
  - Manufacturing must be low cost – therefore likely continuous
  - How to integrate solid electrolyte to Li metal of “right thickness” effectively
- **Electrochemistry**
  - Low current density, lower critical current densities for dendrites
  - Low areal capacities (low cell energy density)
  - Low Li metal utilization
SOLID STATE BATTERY DEVELOPERS

Competition and investment can help drive speed, but returns are not certain

 Ranked based on outside investment and market publicity, technology readiness, commercial capability and IP would produce a different ranking

- Solid State Start-ups with plans to produce batteries
  - Investment mostly started with private equity and has moved to mostly OEMs establishing partners/technology choices
  - SPAC funding could drive acceleration, but is technology competitive with LIB?
  - High activity in US based start-ups

- Governmental Consortium, National Labs and Universities
  - Major efforts at most leading battery developing countries and unions:
    - CN, EU, UK, US, JP, KR, TW and others

- Lithium-Ion Cell Producers
  - Major cell producers have quietly been developing, have significant R&D teams and have filed high number of patents

- Materials Producers
  - Leading LIB materials and systems producers are also participating in developments, but mainly focused at the material or system component levels

 Partnership risk is still high as the technology is still in development and capital investment for production may be higher than LIB, it will also be difficult for SS to compete with LIB costs

- Major write-offs by Dyson-Sakti3 $90M investment, Bosch-Seeo $70M investment shutdown
SOLID-STATE TECHNOLOGY APPROACHES

Solid-state technology remains challenging

- Multiple technology pivots and some programs have been stopped with the leading developments mainly due to interface resistance, production challenges and competitiveness
  - Lithium Air – major industry consortium led by IBM spent over $500M and was stopped due to electrode fouling, lithium metal cost/safety/production issues and inferior cell performance
  - Inorganic Solid State – Inorganic electrolytes efforts have also been reduced for similar challenges to as lithium air, remains mostly at university level
  - Polymeric Solid State – Most promising of the approaches and most going to pilot level production mainly for smaller cells
    - Solid Electrolyte – challenges with conductivity has reduced short-term focus and technology pivots to partial liquid systems
    - Partial Liquid Electrolyte – conductivity improvements being driven by moving to a liquid or gel component in electrolyte, likely to be a source of significant learnings for the market to advance with solid systems – does this reduce the value proposition for solid state?

- Significant advances have been made in electrode manufacturing utilizing LIB technology for Cathode and in Li metal anodes including protective layers for safety/corrosion management
Key Takeaway: Major battery manufacturing participants have proprietary technologies for developing solid-state batteries using in-house polymer/ceramic/inorganic solid-state electrolytes.

EMPA institute discovered that Boron-hydrogen type of compounds can be used as solid-state electrolytes in batteries. However, the origin of conductivity is yet to be studied.

KalpTree Energy is currently working on introducing solid-state battery in the form of wires.

NEI corporation and American elements offer solid-state electrolytes to battery manufacturers as specialty materials.

Seeo Inc. is focusing on developing proprietary nano-structure based solid-state polymer electrolyte called DryLyte™.

Flashcharge Batteries is working on proprietary solid-state batteries with solid-state super capacitors.

Ilika plc has a patented battery technology called Stereax™ which uses ceramic ion based solid-state electrolytes.

Johnson Battery Technologies, Inc. has a proprietary and patented process for solid-state battery production using ceramic electrolytes.

Planar Energy follows proprietary manufacturing process called SPEED which uses inorganic solid-state electrolytes

PolyPlus Battery Company uses patented conductive monolithic glass separators for making Glass protected Li metal battery

Prietio Battery Inc. has a patented technology for 3D Li-ion battery with ultra thin solid polymer electrolyte.

Sakti3 is working on proprietary solid-state battery cells.

Solid Power is developing solid-state battery with Li metal anode and high ionic conductivity separator.

Excellatron uses LiPON electrolyte for making thin film solid-state batteries in a proprietary technology.

Blue Solutions Bollore group has a patented thin film solid-state battery called LMP® (Lithium Metal Polymer) with current annual production capacity of 300 MWh. The company is working onto increase this to 1GWh by 2019-20 in order to cater the demands in EVs and energy storage applications.

R & D Level

Prototype

Pilot Production

Commercialization

2017 Data
Towards Safer Electrolytes

Thin layer technology
Polymer technology

Xolid-based technology
Sulfide based technology

Hydro-Quebec
Apple
Seeo
QuantumScape
Sakti3
EMBATT
Schott
STMicroelectronics
CATL
SolidEnergy

Samsung SDI
LG Chem
Toyota
muRata – Sony
Panasonic
Hitachi
Ohara
Prologium

Source: Daimler
## MAJOR PLAYERS – NOT ALL INCLUSIVE

<table>
<thead>
<tr>
<th>Company</th>
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<tbody>
<tr>
<td>24m Technologies</td>
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<tr>
<td>Biophan</td>
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<td>Blue Solutions (Bollore)</td>
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<td>Blue Spark (source: Nanomarkets)</td>
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<td>BrightVolt, Inc. (U.S.)</td>
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<td>CATL</td>
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<td>Cymbet Corporation (U.S.)</td>
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<td>Enable IPC</td>
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<td>Enfucell</td>
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<td>Excellatron (Plasma Enhanced Chemical Vapor deposition)</td>
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<tr>
<td>Fisker</td>
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<tr>
<td>Flashcharge Batteries</td>
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<tr>
<td>Front Edge</td>
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<td>Geomatec</td>
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<tr>
<td>Hitachi Zosen</td>
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<tr>
<td>Ilika</td>
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<tr>
<td>Infinite Power Solutions, Inc. (U.S.)</td>
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<td>ITN Energy Systems</td>
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<tr>
<td><strong>Ionic Materials</strong></td>
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<td>Johnson Battery Technologies</td>
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<td>Kalptree</td>
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<td>LG</td>
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<td>NEC</td>
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<td>Nuricell (Korea)</td>
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<td>Oak Ridge Micro-Energy Inc</td>
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<td>Planar Energy</td>
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<tr>
<td>PolyPlus Battery Company</td>
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<td>Power paper (Israel) (Alcaline)</td>
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<td>Prelonic technologies</td>
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<td>Prieto Battery Inc</td>
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<td><strong>QuantumScape</strong></td>
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<td>Robert Bosch GmbH (Germany)</td>
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<td>Rocket Electric</td>
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<td>Samsung</td>
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<tr>
<td>Sakti3 (Dyson)</td>
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<tr>
<td>Seeo</td>
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<tr>
<td>Solicore (Li Polymer)</td>
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<tr>
<td><strong>Solid Power</strong></td>
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<tr>
<td><strong>SolidEnergy</strong></td>
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<td>STMicroelectronics N.V. (Switzerland)</td>
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<td>Toshiba</td>
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<td><strong>Toyota</strong></td>
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<td>Ultralife</td>
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<td>ULVAC</td>
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<tr>
<td>Varta and the GREENBAT Project</td>
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<td>Voltaflex (Li Polymer)</td>
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MARKET SEGMENTATION

<table>
<thead>
<tr>
<th>Market Segment</th>
<th>Capacity Range</th>
<th>Feature</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>IoT</td>
<td>1 mAh</td>
<td>Rechargeable, Small footprint, Life time, Rapid discharge, Energy harvesting</td>
<td>Small volume production</td>
</tr>
<tr>
<td>Medical</td>
<td>1 mAh</td>
<td>Disposable or rechargeable, Laminar &amp; thin, Low power, Cost sensitive</td>
<td>Available, mostly customized</td>
</tr>
<tr>
<td>Smart Cards</td>
<td>5-10 mAh</td>
<td>High energy density, Long working hrs, Flexible</td>
<td>Prototype</td>
</tr>
<tr>
<td>RFID</td>
<td>5-10 mAh</td>
<td>High energy density, Long working hrs, Flexible</td>
<td>Research, Prototype</td>
</tr>
<tr>
<td>Sensors</td>
<td>5-10 mAh</td>
<td>High energy density, Low power, Cost sensitive</td>
<td>Research (after 2025)</td>
</tr>
<tr>
<td>Wearable, E-textile</td>
<td>100 mAh</td>
<td>Safe, Reliable, High power, High capacity</td>
<td>Early stage (after 2030)</td>
</tr>
<tr>
<td>Portable Electronics</td>
<td>1 Ah</td>
<td>Cost, Life time, Reliable, High capacity</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>100 Ah</td>
<td>Higher cost for special app (military), High T°C</td>
<td></td>
</tr>
<tr>
<td>Large scale energy storage</td>
<td>&gt; 1 kAh</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Feature**
  - Rechargeable
  - Small footprint
  - Life time
  - Rapid discharge
  - Energy harvesting
  - Disposable or rechargeable
  - Laminar & thin
  - Low power
  - Cost sensitive
  - High energy density
  - Long working hrs
  - Flexible
  - High energy density
  - Long working hrs
  - High power
  - Safe
  - Reliable
  - High power
  - High capacity
  - Cost
  - Life time
  - Reliable
  - High capacity
  - Higher cost for special app (military)
  - High T°C

- **Status**
  - Small volume production
  - Available, mostly customized
  - Prototype
  - Research, Prototype
  - Research (after 2025)
  - Early stage (after 2030)
Forecasts from different sources are not convergent

- **Market scope:** rechargeable solid state or thin film batteries
- **Be careful:** some market research are talking about TFB market, including non rechargeable
- **Main application (middle term):**
  - IoT
  - Wearables
  - Sensors
  - Medical
  - Smart cards
  - RFID
  - Smart packaging
- **Long term application (>2025-2030):**
  - Automotive
  - Large scale energy storage

*Source: AVICENNE Energy 2018, Desk research*
THE SOLID STATE BATTERY MARKET

Forecasts from different sources are not convergent

IoT and wearable could became the most important market – Optimistic scenario
SOLID STATE BATTERY MARKET

Solid state batteries market – Million USD

<table>
<thead>
<tr>
<th></th>
<th>Likely</th>
<th>Optimistic</th>
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<tbody>
<tr>
<td>Medical</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Military, industrial sensors (High T°C)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Special Semiconductor (High T°C)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Wearables</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>IoT</td>
<td>30</td>
<td>250</td>
</tr>
<tr>
<td>Smart cards</td>
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<td>15</td>
</tr>
<tr>
<td>RFID</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Others</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>400</td>
<td>610</td>
</tr>
</tbody>
</table>

1-10 mAh: MEMs, sensors, CMOS, smart card, drug delivery system, medical implantable devices

100 mAh: wearables (watch, glass...), medical (pacemaker, hearing aid, capsule endoscope)

Source: AVICENNE ENERGY 2018
SOLID STATE BATTERIES ANNOUNCEMENTS

Recent Investment Announcements with Press Comments

**Nedo (Japan) - $90M Solid State Battery** – Goal by 2022 - The ¥10-billion (US$90-million) project, which involves 23 automobile, battery, and material manufacturers as well as 15 universities / public research institutes, will tackle technologies that are currently bottlenecks for mass production of solid-state Li-ion batteries (SSLIB) such as the solid electrolyte; electrolyte coating with active material, and the sheet formation of the electrolyte-electrode layer.

**VW – Quantumscape - $200M** - Volkswagen is investing $200 million in QuantumScape, a leading Silicon Valley solid-state battery developer. Most of the major players in the electric vehicle game are in a race to develop solid-state battery technology, since it will give the victor a massive advantage in weight and power density.

**Samsung and Dyson – Ionic Materials - $65M** - According to Axios, technology giants like Samsung and Dyson have collectively invested $65 million in Massachusetts-based Ionic Materials. This enormous vote of confidence is a bit shocking, as most people probably haven’t even heard of the small company before. But if Ionic Materials delivers on its recent claims, the investment will certainly pay off. It claims to be close to creating a safe, working solid-state battery.

**A123 Systems - announced its investment in Ionic Materials – Undisclosed Investment** - This step is the latest in a series of strategic investments that A123 has completed in order to augment its own developments in the field of next generation batteries. A123 will work jointly with Ionic Materials to apply their respective innovations in materials, cell design and manufacturing to achieve new levels of safety in high performing batteries for plug-in electric vehicles.
SOLID STATE BATTERIES ANNOUNCEMENTS
Recent Investment Announcements with Press Comments

Total Ventures – Ionic Materials – Undisclosed Investment - Total said Ionic Materials’ breakthrough technology could significantly improve battery safety, performance and cost. “Solid-state batteries are considered as the next generation of batteries with various range of applications including the electric vehicles,”

Ford – Solid Power – Undisclosed Investment - The announced partnership will focus on further developing ASSBs toward automotive requirements. Solid Power’s solid-state technology combines a cathode, metallic lithium anode, and a safe, inorganic solid electrolyte layer. Solid-state batteries offer improved energy and safety as compared to current industry-standard lithium-ion batteries.

Caterpillar Venture Capital, the business investment arm of Caterpillar, has invested in Fisker Inc. to further its EV technology developments into the off-highway industry. “It’s not just the automotive industry that’s going electric,” Henrik Fisker, Chairman and CEO of Fisker, told Truck and Off-Highway Engineering. “Caterpillar and Fisker are in two very different industries serving very different customers, but we’re both interested in being part of developing the next-generation, game-changing battery technologies that may power vehicles of all varieties.”

Samsung and Hyundai – Solid Power – part of Series A investment - Solid Power wins $20 million from automotive and electronics players. Automotive and electronics giants are flooding the battery ecosystem with strategic investments. Solid-state battery startup Solid Power, based in Louisville, Colorado, just won $20 million in a Series A investment round from Hyundai, Samsung Venture Investment and others.

ITOCHU -24M – Undisclosed Investment - ITOCHU and 24M will jointly promote a business involving the global production and development of next-generation lithium-ion batteries. 24M engages in the research and development of semisolid lithium-ion batteries, which surpass existing lithium-ion batteries in terms of safety, energy density, manufacturing cost, and other aspects.
SOLID STATE BATTERIES - AUTOMOTIVE

Significant Issues Remain Unsolved

Many announcements are being made by throughout the value chain, significant investments at various levels of the value chain, delayed launches and limited vetting of information, technology pivots, competitive landscape and lower costs from LIB, new partnerships and business models being announced, consortiums, DOE, etc. – significant progress needed to be viable in automotive.

Not expected to be resolved until late 2020s or 2030s

Current Major Issues:

- **High Temperature Operation** – the only demonstrated technology for solid state by Bolloré in the Blue Car
- **Durability** – most of the developers have focused on non-automotive applications to demonstrate technology and have commercial production at very small scale
- **Processing costs** – Many of the battery developers lack significant scale to understand coating and laminating process and leaders are just moving to pilot production.
- **Lithium Requirements and Costs**– Lithium anode production methods, safety validation and costs
- **Conductivity** – Conductivity of polymeric and inorganic solid state remain significant hurdles.

Solid state technology has the promise of providing better safety for larger formats, but we are not convinced that solid state will provide longer life, smaller battery, lighter battery, cheaper battery.
SOLID STATE PRODUCTION

Investment is Increasing

- Production facilities – Small Batteries
  - Cynbet
  - Front Edge
  - Illika

- As technology is showing progress and investment by OEMs has increased multiple pilot plants have been announced and most are still in construction phases
  - AMG Lithium - Germany
  - 24M
  - Solid Power
  - QuantumScape

- SPAC investment could change landscape
  - QuantumScape – Kensington Capital – raised $500M through private equity – expected evaluation with SPAC - $3.3B
CONCLUSIONS

Who and what are the leaders?

- Market still in the very early stages of commercial deployment
- Solid State Batteries have been in development on the thin film level for 40 years, broader technology for 25 years – Battery technologies normally take in excess of 20 years to reach significant starting points
- It appears that the efforts to improve conductivity and cell performance are making progress with a mix liquid and solid system
- Commercial applications have been limited to mostly TFB and small cells for IoT and wearables.
- Pilot scale production being built for medium and larger format, results will be critical for validating technology and commercial progress
- Forecast for 2030 will be established later in 2021 with early results understanding from pilot plants and automotive/ESS market fit is better defined
- No companies have a significant leadership position in this early market – Who and What are the Leaders? Stay Tuned.......
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