MARITIME

Battery technology advancements: Solid state electrolyte

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Dr. Benjamin Gully

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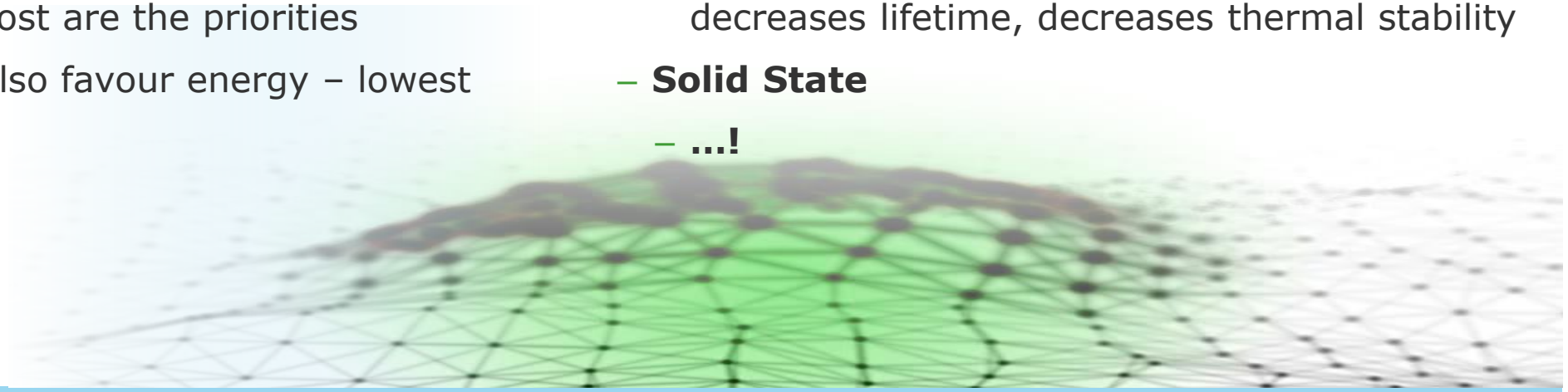
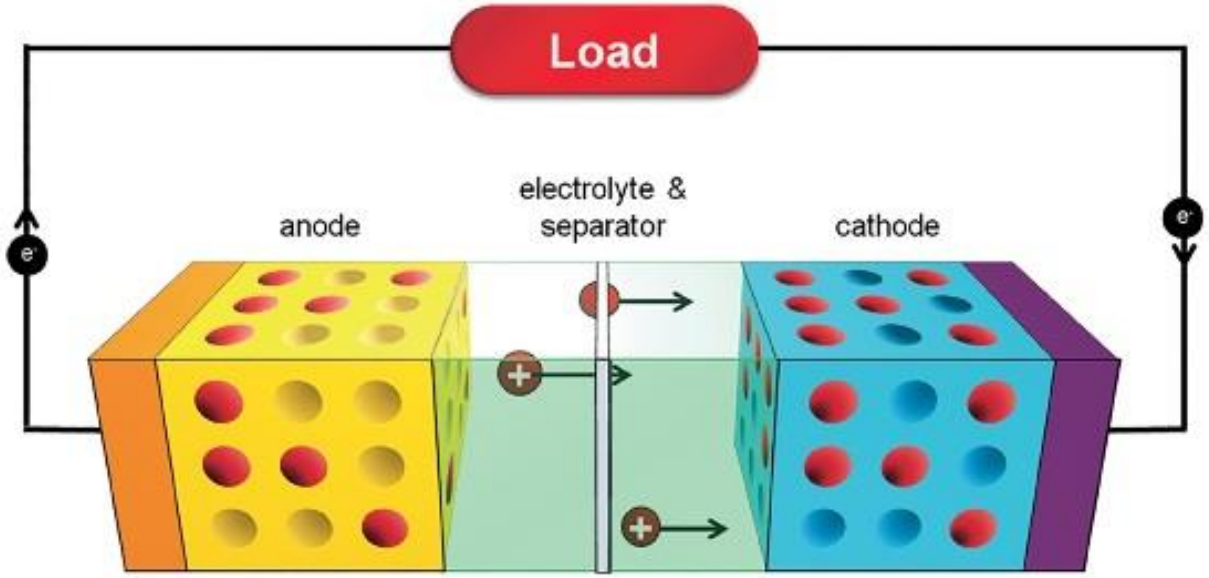
Lithium Ion battery technology development overview

- Current technology is a balance between energy and power
  - **Energy** (range) usually accompanies lower cost, lower thermal stability
  - **Power** (acceleration) usually accompanies higher lifetime, higher cost
- Technology development is driven by automotive and consumer electronics sectors
  - Energy density and cost are the priorities
  - Stationary systems also favour energy – lowest cost/kWh
- Technology advancement horizon
  - Silicon
    - Increases energy density, in products now
    - Decreases lifetime but many efforts underway
  - Lower cobalt
    - Reduce amount of cobalt as used in current batteries, now or within next couple of years
    - Reduces cost, increases energy density, decreases lifetime, decreases thermal stability
  - **Solid State**
    - **…!**

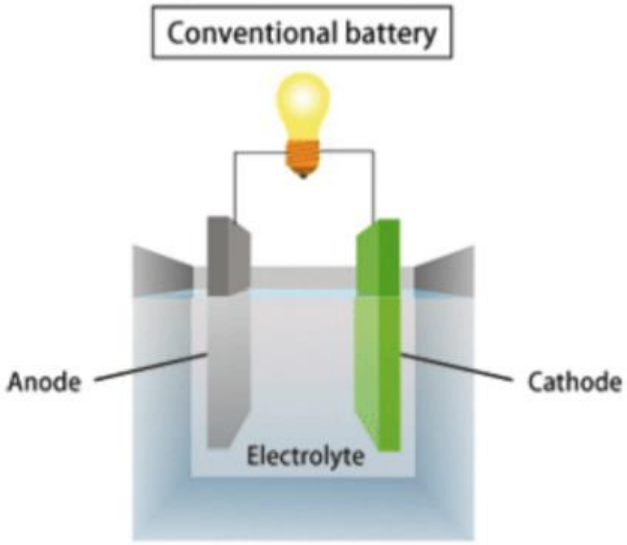


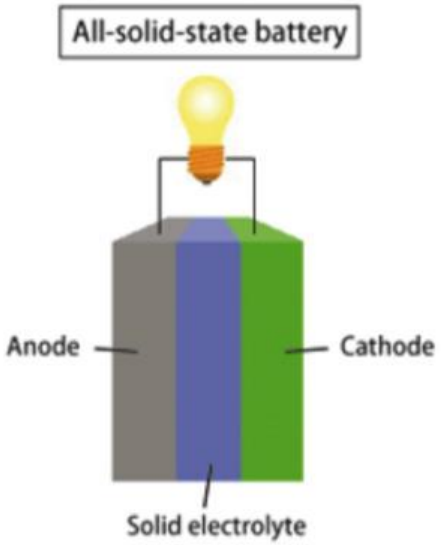
What is a lithium-ion battery?

- A single battery cell exchanges electricity between between a cathode and an anode
- The cathode and anode are separated by liquid electrolyte
  - This electrolyte is key as it keeps these two electrically insulated – we want the electricity flowing through our devices not inside the battery!
  - Yet this fluid must still allow lithium-ions to move back and forth (as quickly as possible) and be stable at high voltage
  - Only specific materials meet requirements



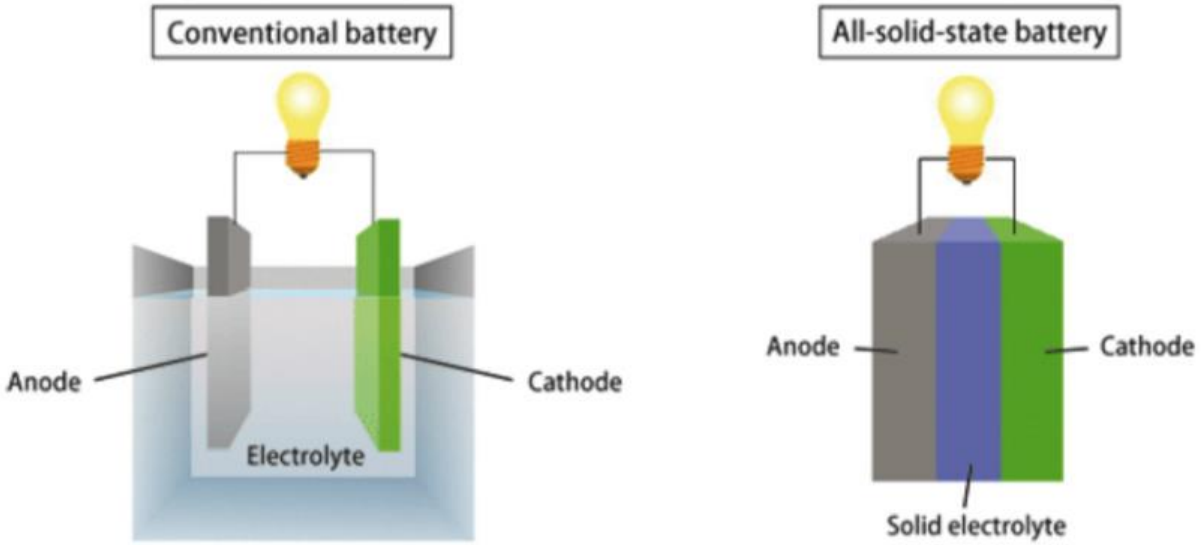
What ‘Solid State’ means for lithium-ion batteries





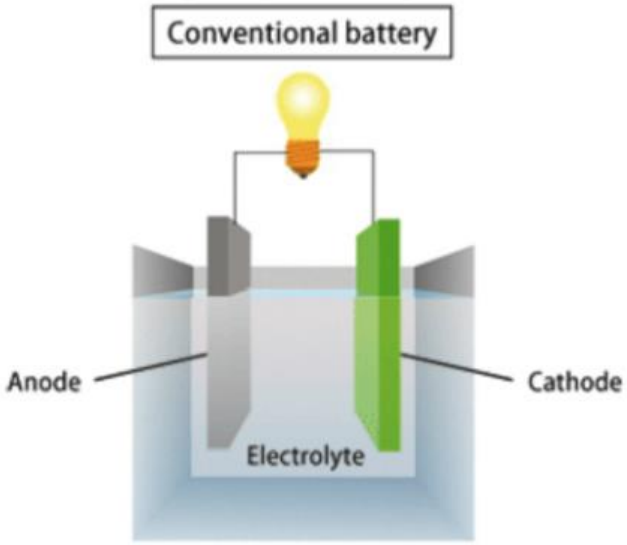
- When we are talking about ‘solid state’ batteries we are talking about batteries that use a solid electrolyte instead of the liquid one
- Wide range of different potential ‘solid state’ materials
  - Various kinds of dry polymer, silicates, metals, crystals, mineral composites, glass, etc

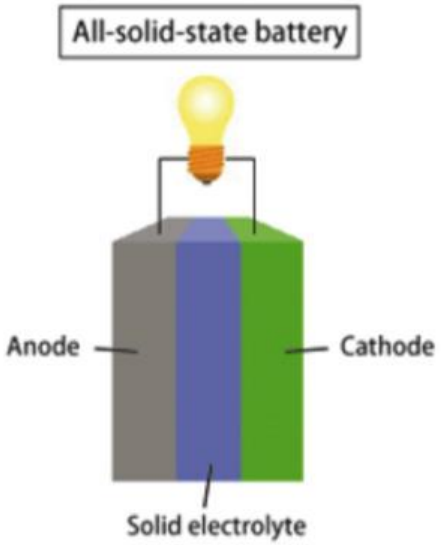
Benefits from Solid State Electrolyte



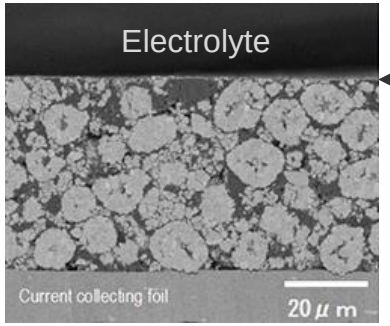
- Energy density
  - Increases because solid state material can be 80-90% thinner than separator + electrolyte
  - Energy density potentially doubles if we use lithium metal as anode
- Safety
  - Liquid electrolyte is flammable and becomes flammable gas – critical safety element in Li-Ion
  - Moving to solid state significantly changes these properties
- So some improvement in energy density and safety are quite certain – but difficult to quantify
- Many additional benefits are possible, but depends greatly on formulation of solid state solution
  - Lifetime, charge rates, stability at high voltage, lithium anodes, lithium-air feasibility

Challenges of implementing Solid State electrolytes



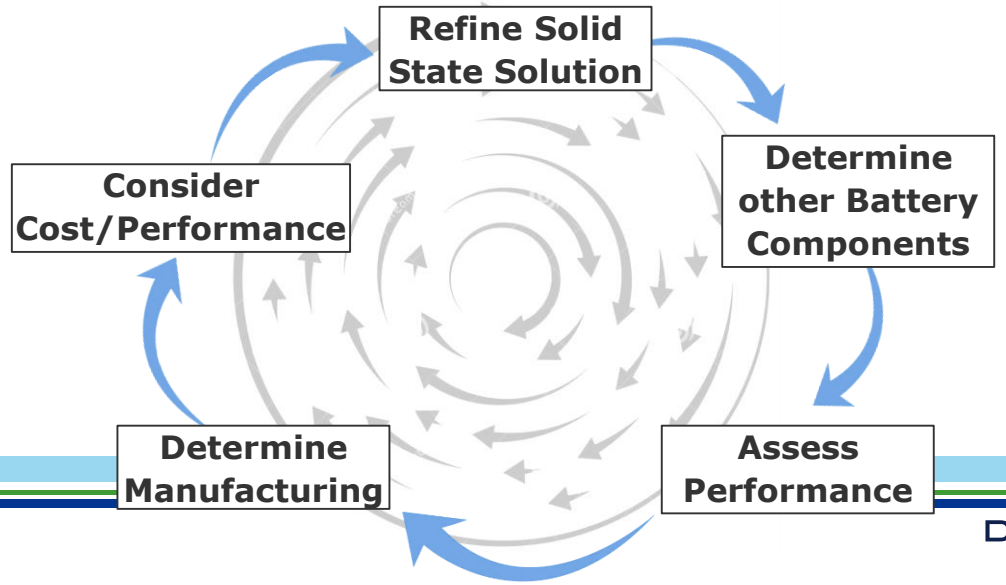


- **Power – conductivity and interface resistance**



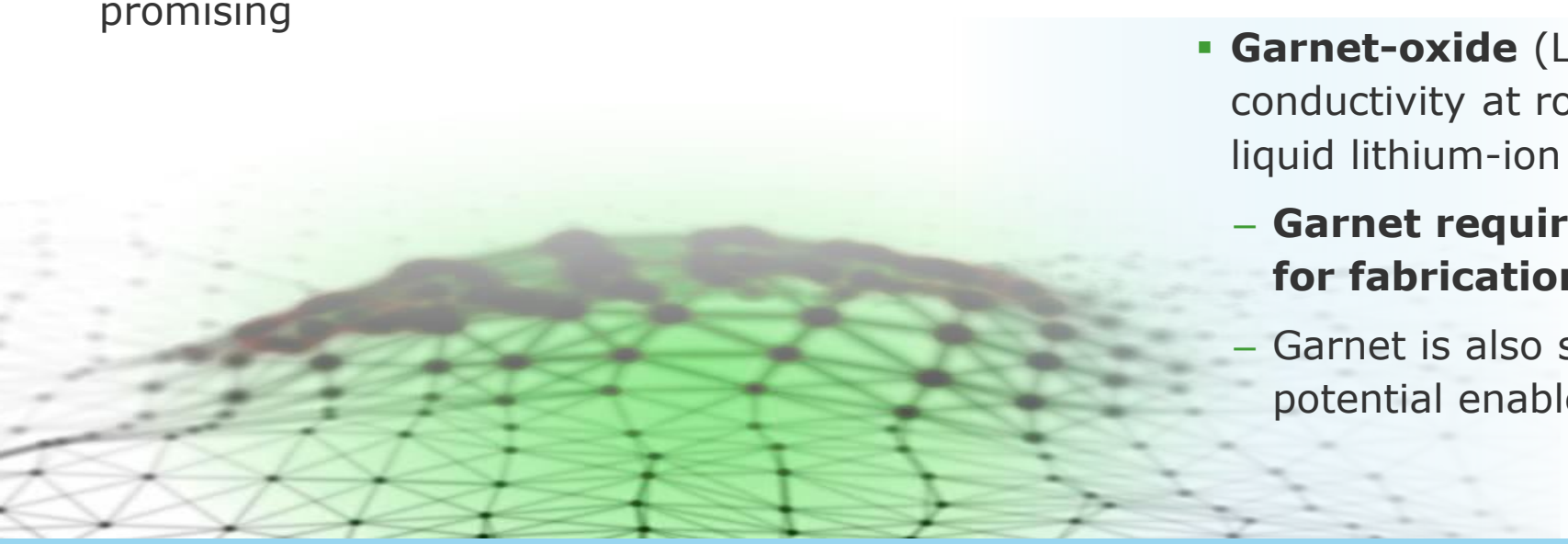
Not a smooth surface!

- Typically poor cold weather performance
- Production cost (also highly uncertain)



Different Solid State solutions under development

- Many different kinds materials under investigation:
  - Li-Halide, Perovskite, Li-Hydride, NASICON-like, Garnet, Argyrodite, LiPON, and LISICON-like
- Difficult to say whats going on behind closed doors but LiPON and Garnet cells are perhaps the most promising



- **LiPON** (sulfide-based thin film) is usually made with lithium anode
  - Great benefits for lifetime, also weight, thickness and flexibility
  - **Total energy capacity and conductivity are rather poor and thus cant be scaled up as easily**
- **Garnet-oxide** (LLZO) electrolytes have a high ionic conductivity at room temperature, only just less than liquid lithium-ion electrolytes
  - **Garnet requires expensive sintering process for fabrication**
  - Garnet is also stable in air and water, making it a potential enabler of Li-Air batteries

What does the research and development landscape look like?

- Significant investment from automotive companies. Summary of most public efforts:
  - Sakti3: Dyson DIVESTED, Fisker BOUGHT, claimed delivery 2020
  - Ionic: partnership with Hyundai, no timeline
  - Solid Power: partnerships with Mercedes & BMW, claimed delivery 2026
  - QuantumScape: partnerships with VW, claimed delivery 2025
  - LIBTEC: joint effort between Toyota, Honda, Nissan, Panasonic; highly worthy of attention
- Lots of academic research globally
  - Of particular note: Goodenough/Braga – glass, using lithium on both sides, one side plated
- Known industrial research efforts with few details:
  - Samsung
  - Bosch
  - General Motors

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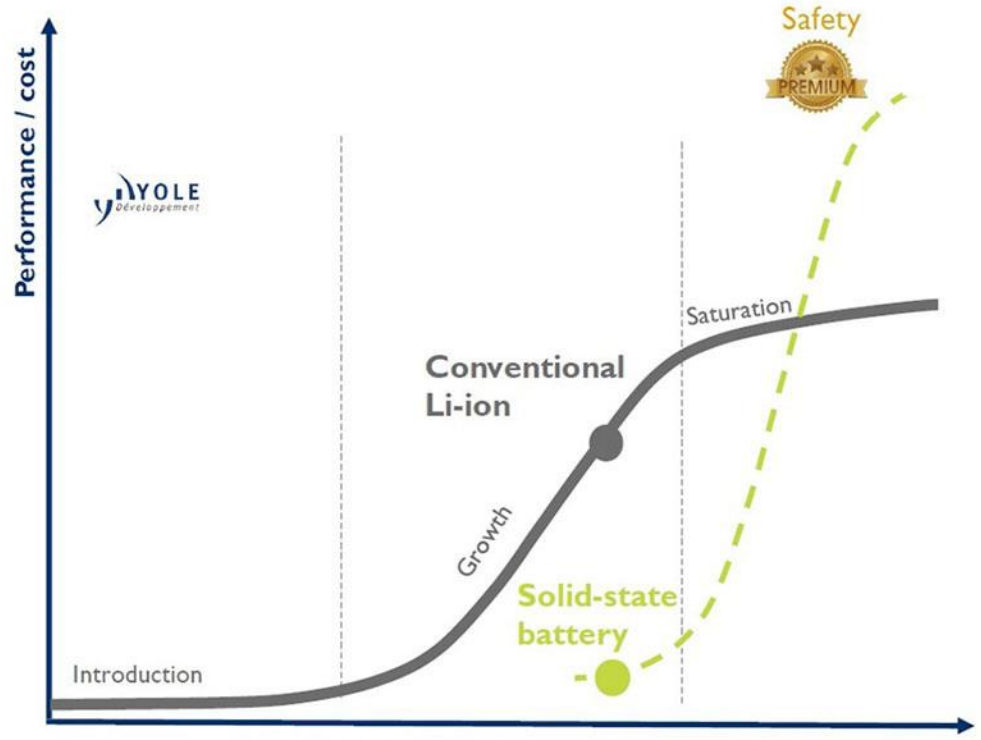
Summary

- Benefits really depend on end solution – results are uncertain
  - Benefit with regard to safety is most certain
  - Benefit with energy density is probable, but amount depends heavily on assumptions and actual solution
- Charge rates and power levels are biggest technical hurdle
  - Available solutions are prohibitively expensive
- Remember priorities of automotive industry and consumer electronics are energy density and cost
- When will it get here?
  - 2017 it seemed 10 years away, but competing investment from automotive sector likely changes the landscape
  - Answer ultimately depends on actual solution and how it fits with other components and manufacturing - COST
  - Remember lithium-ion is a continually developing moving target



Dr. Benjamin H. Gully
Benjamin.Gully@dnvgl.com
+47 906 77 213

www.dnvgl.com

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