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BATTERIEN

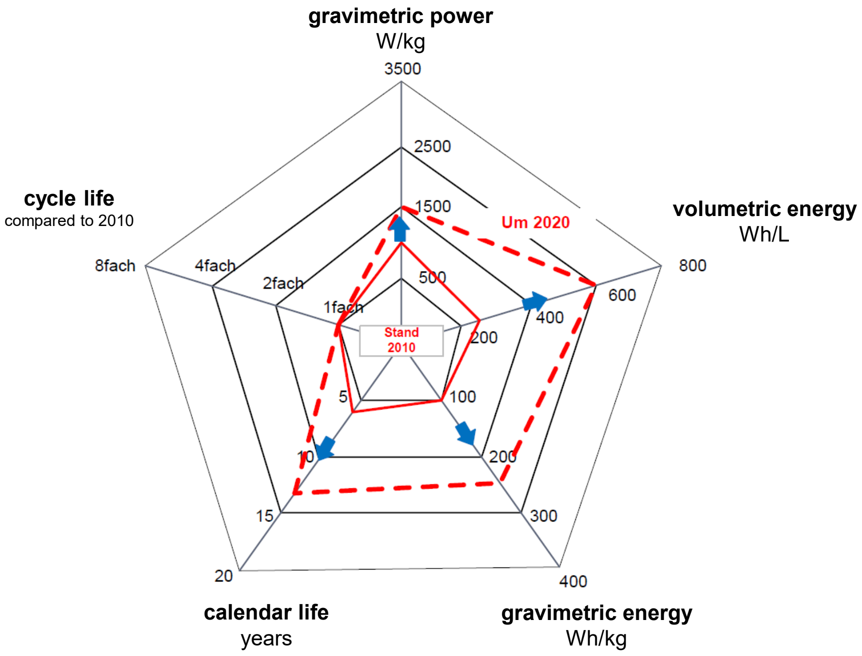
Fraunhofer Battery Alliance

The Path to higher Performance and Safety of Batteries - Technological Milestones

Kai-Christian Möller

The path to higher energy density of batteries

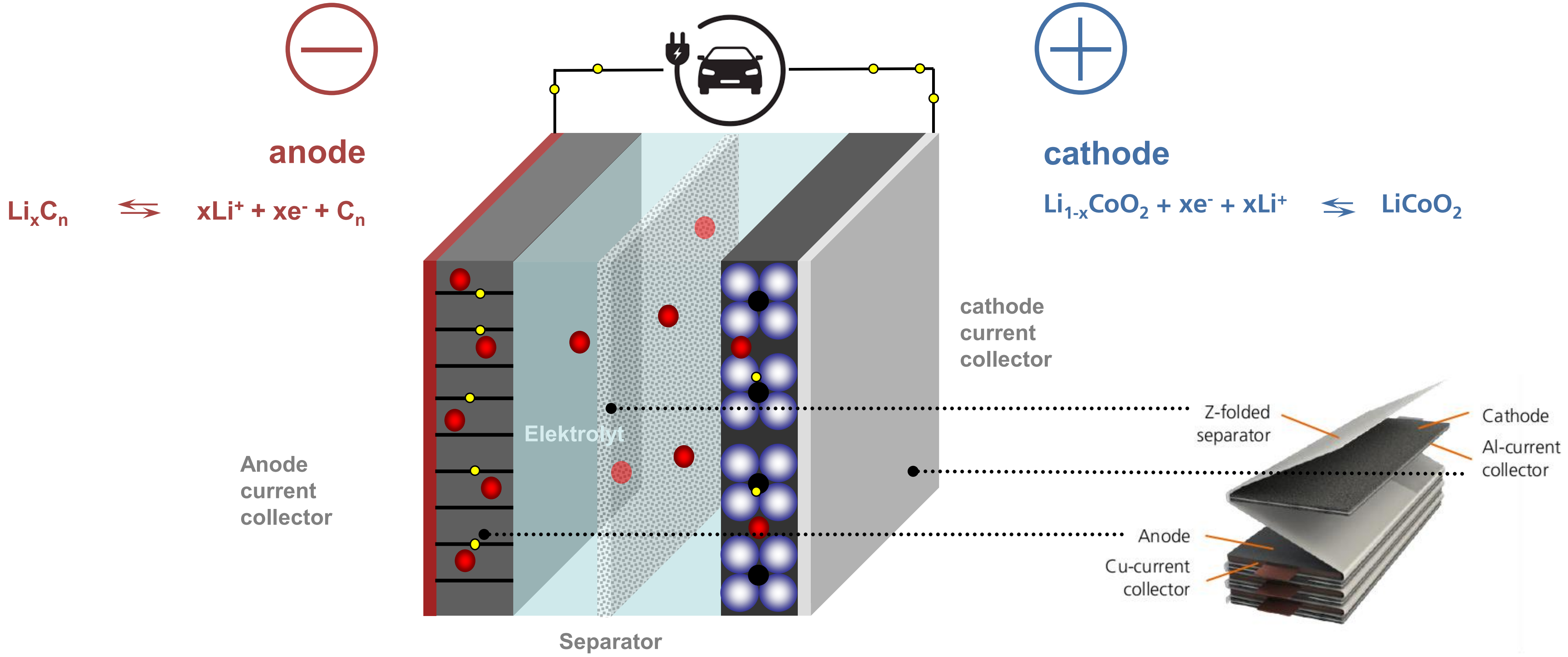
Requirements for rechargeable batteries



Roadmap of the NEDO (New Energy and Industrial Technology Development Organization), Japan

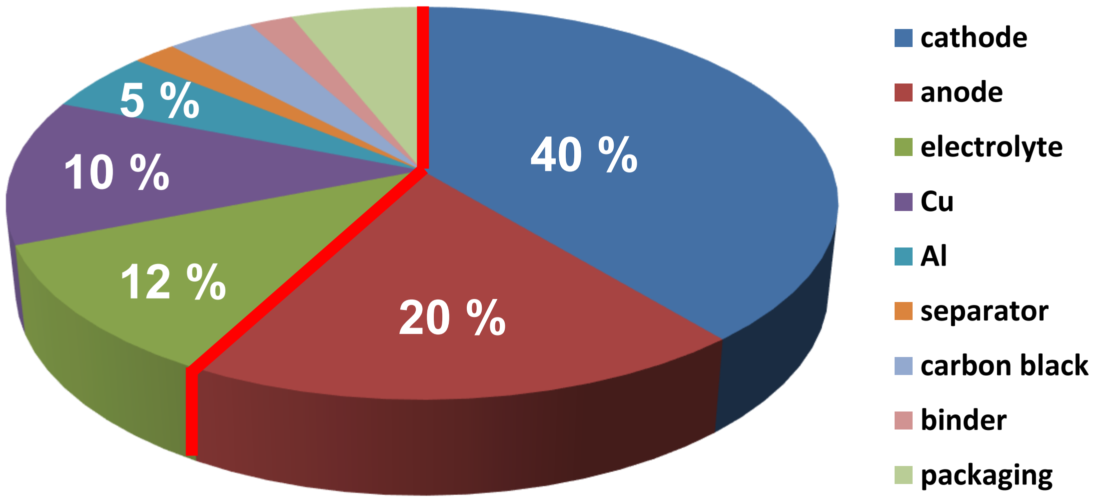
The path to higher energy density of batteries

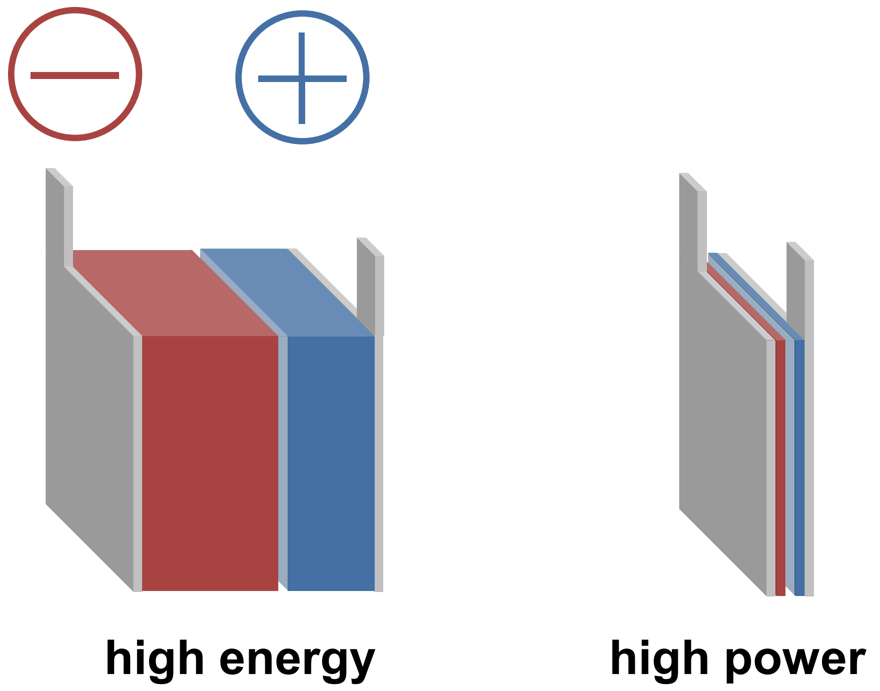
Structure and Components of a Lithium-Ion Cell



The path to higher energy density of batteries

Composition of a typical pouch cell (mass fractions)





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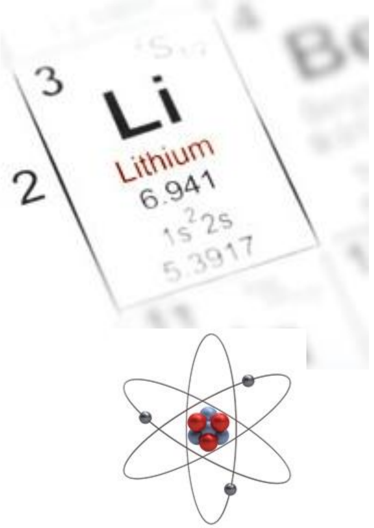
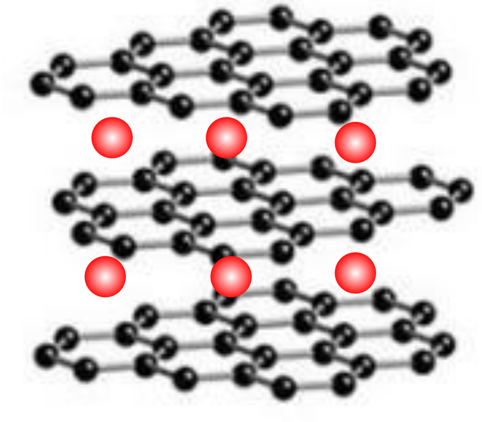
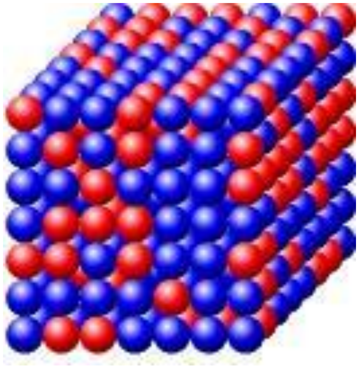
The path to higher energy density of batteries

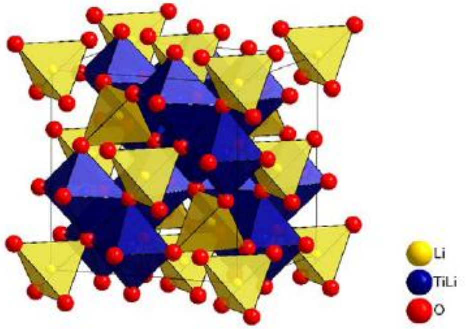
Anode materials and development trends towards higher energy density

lithium	graphite	silicon	lithium titanate
Li	C	Si	$Li_4Ti_5O_{12}$ (LTO)









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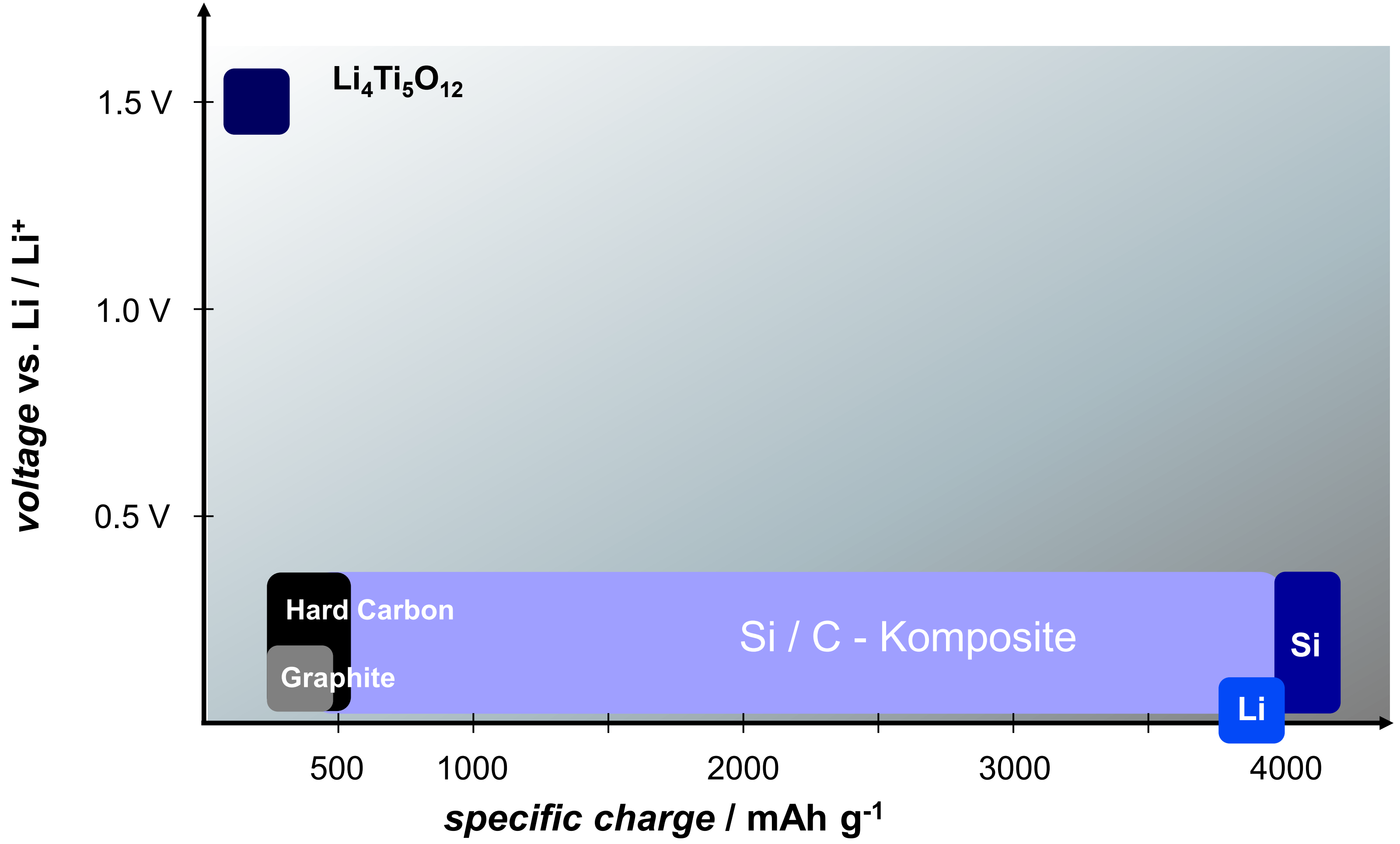
The path to higher energy density of batteries

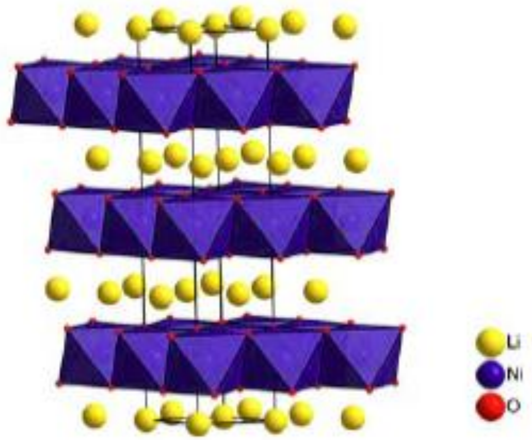
Anode materials and development trends towards higher energy density

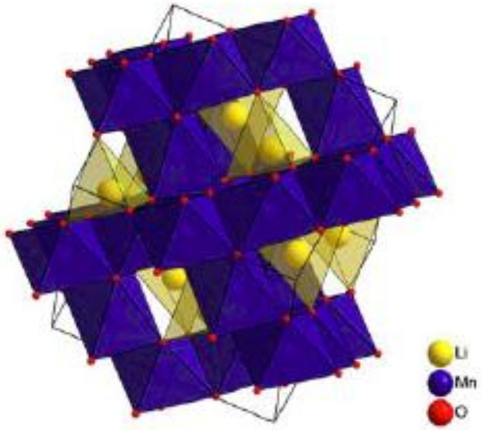


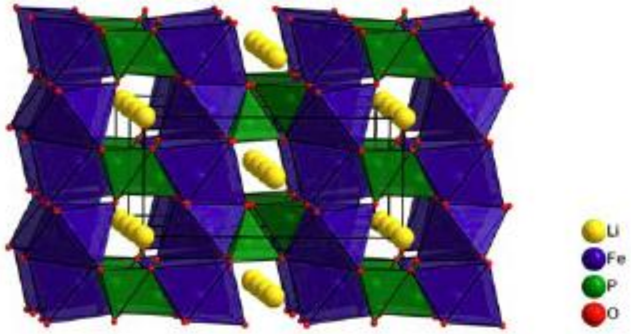
The path to higher energy density of batteries

Cathode materials

layered structures	spinels	olivines
$LiCoO_2$ (LCO)	$LiMn_2O_4$ (LMO),	$LiFePO_4$ (LFP)







$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ (NCM-111)

$Li(Ni_{0.8}Co_{0.1}Mn_{0,1})O_2$ (NCM-811)

$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ (NCA)

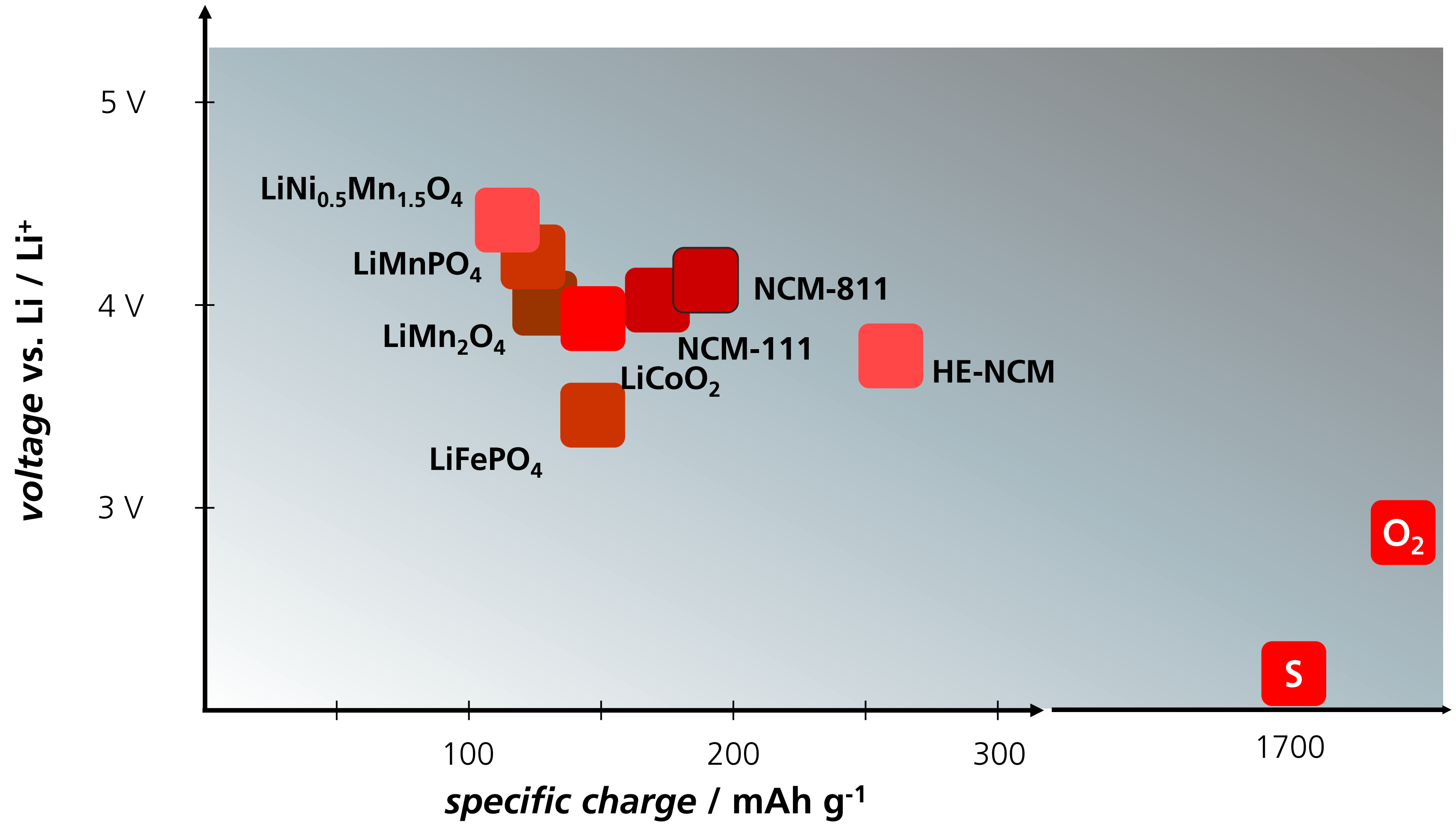
$Li_{1.2}Ni_{0.133}Mn_{0.533}Co_{0.133}O_2$ (HE-NCM, LMR-NCM)

$Li(Ni_{0,5}Mn_{1,5})O_2$ (HV spinel)

$LiFeMnPO_4$ (LFMP)

The path to higher energy density of batteries

Cathode materials and development trends towards higher energy density



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The path to higher energy density of batteries

Safety on Material Level

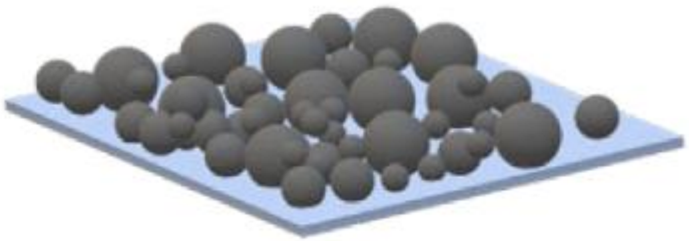
**Lithium cobalt oxide,
can release oxygen on overcharge**

**highly flammable,
combustible electrolyte**

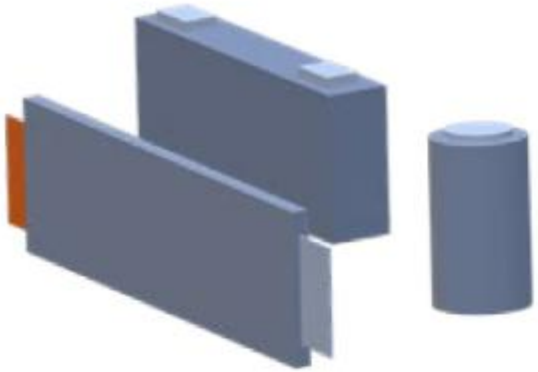
SUMITOMO CHEMICAL

**20 µm thin, but puncture resistant
battery separator**

The path to higher energy density of batteries



Material

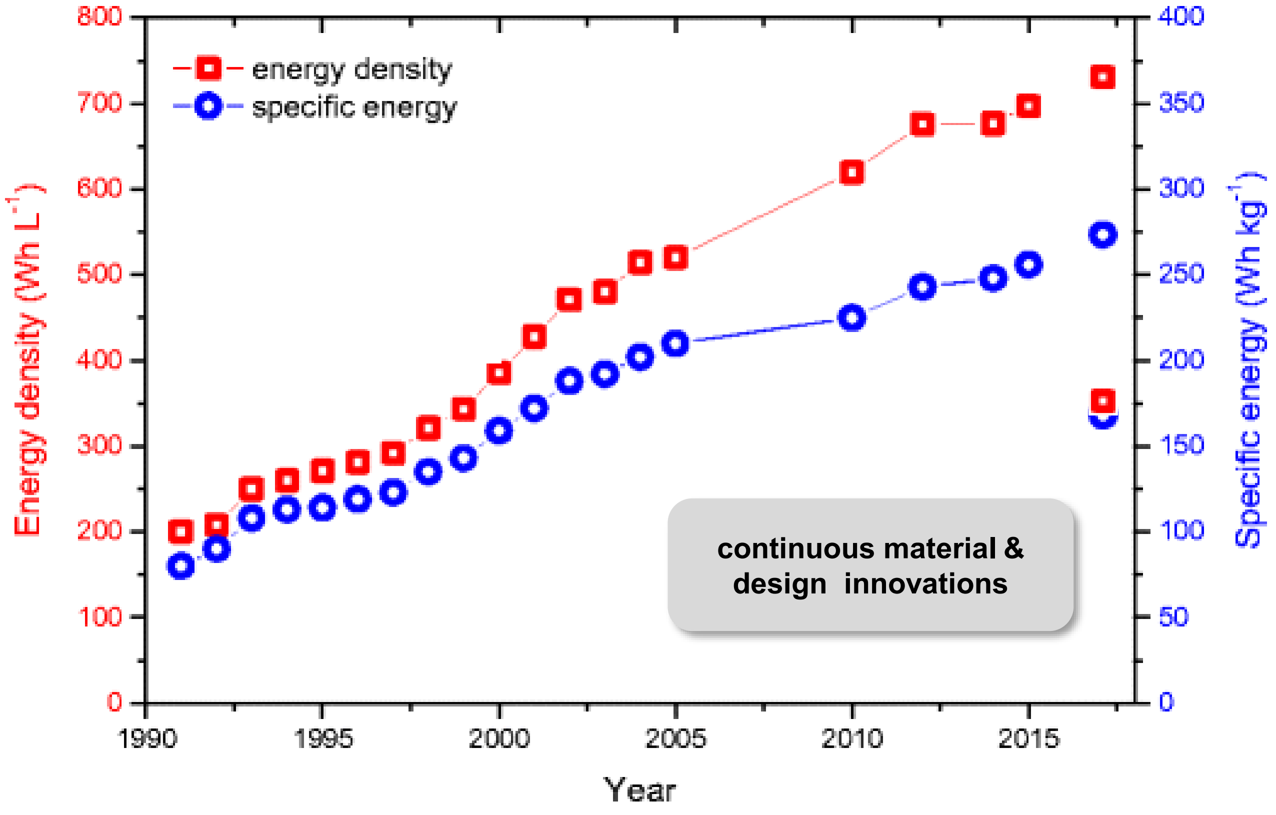


Cell

Trends in Automotive Battery Cell Design: A Statistical Analysis of Empirical Data, *Batteries* **2023**, *9(5)*, 261-282.

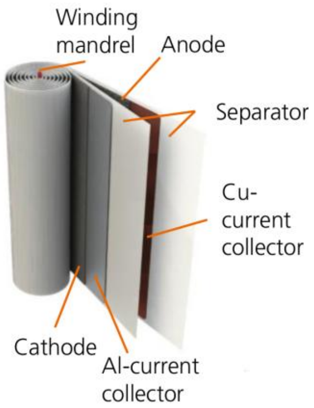
The path to higher energy density of batteries

Material to cell: development of the energy density of a „standard“ cylindrical cell (18650)



J. Solid State Electrochem. **2017**, *21*, 1939-1964.

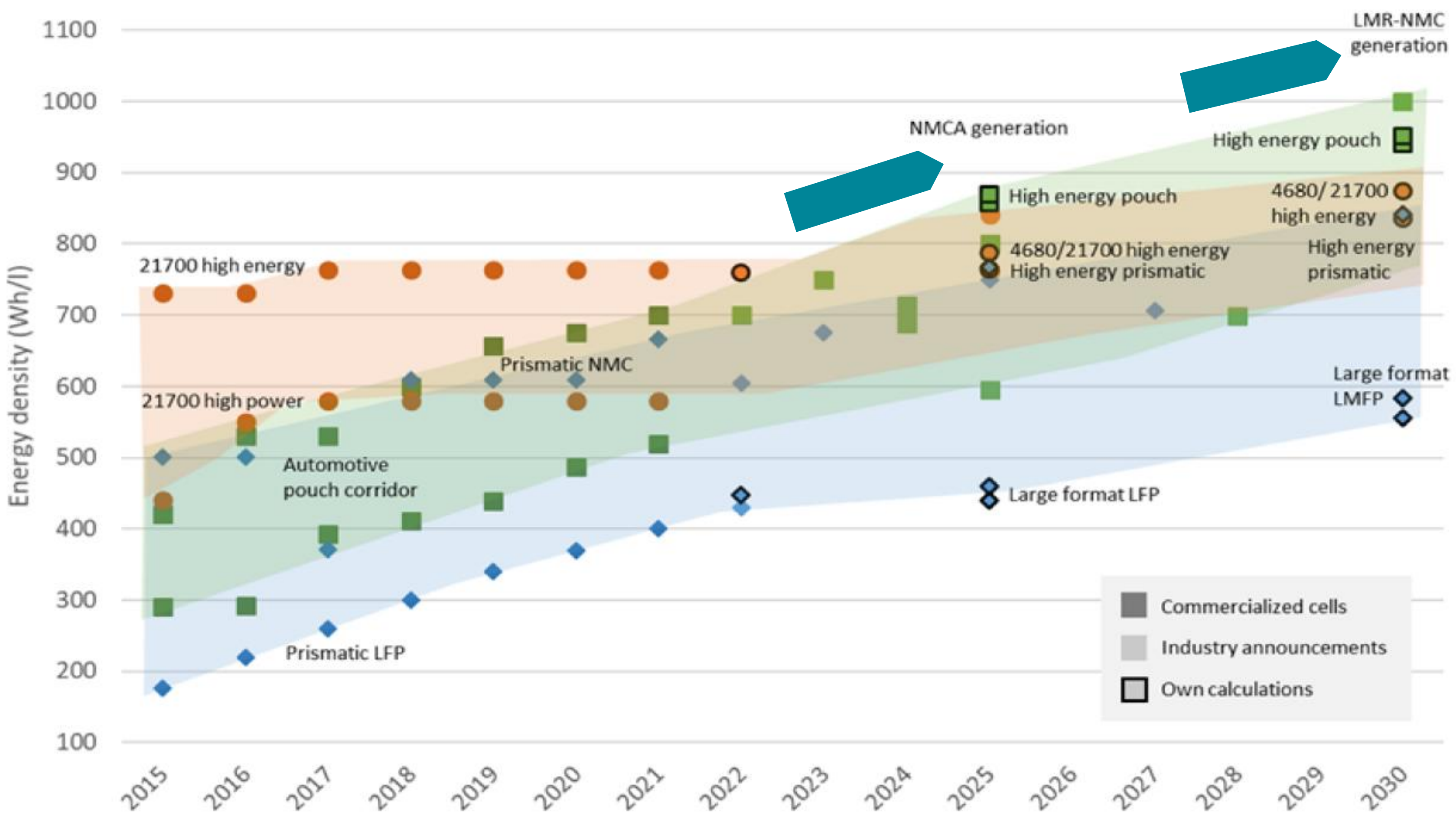
18650 cyclindrical cells



60 Ah prismatic Cell

The path to higher energy density of batteries

Fraunhofer – Development perspectives for lithium-ion battery cell formats



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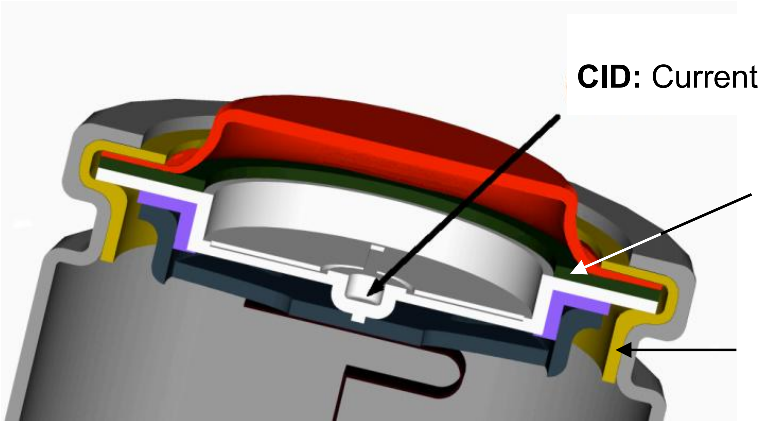
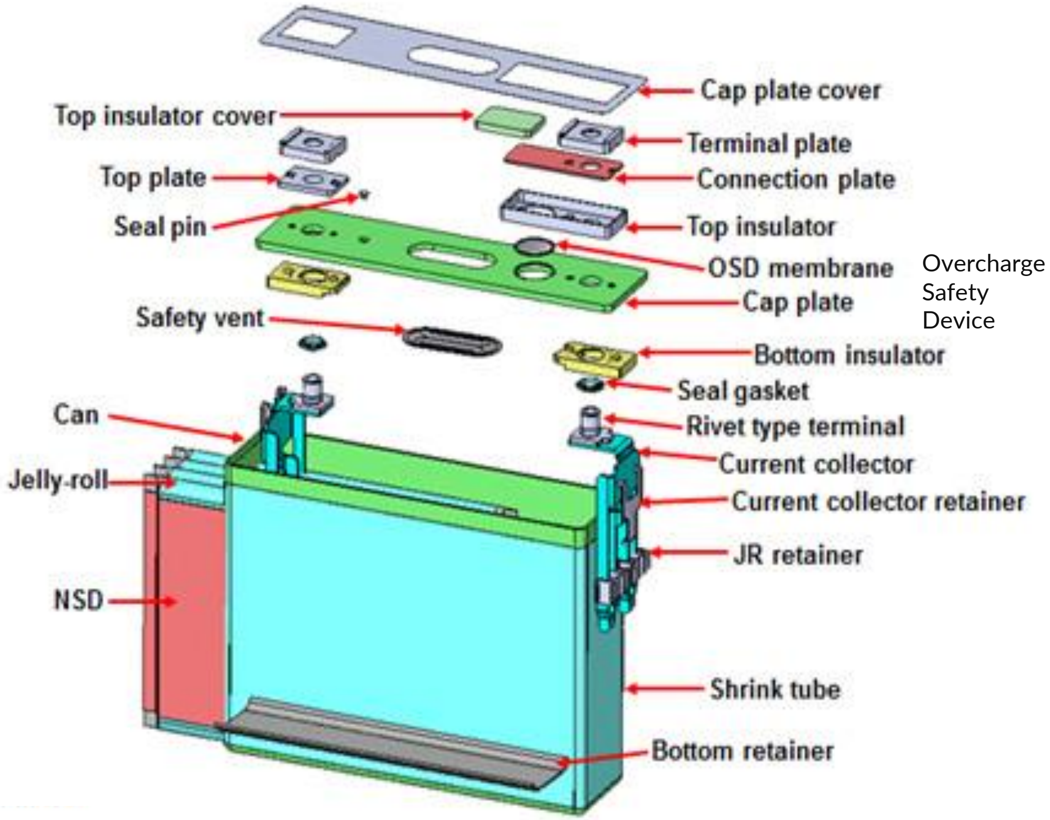
Safety on Cell Level

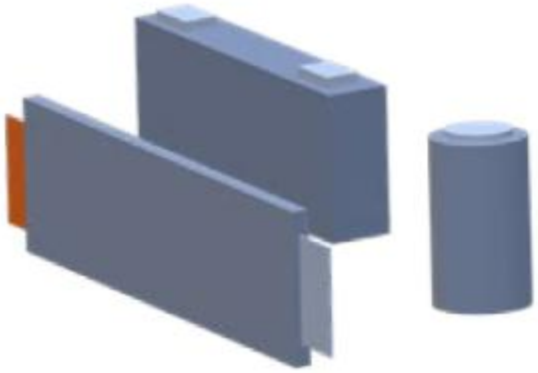


Safety features of a cylindrical cell

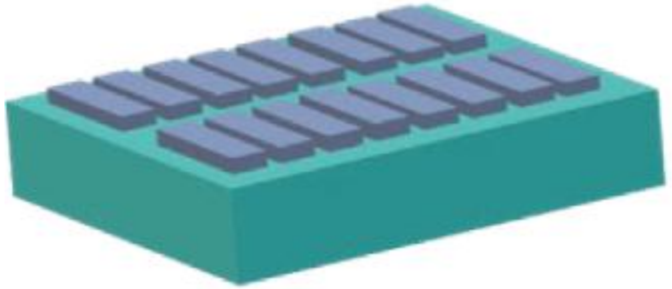


Construction of a prismatic cell SAMSUNG SDI SAMSUNG

The path to higher energy density of batteries



Cell

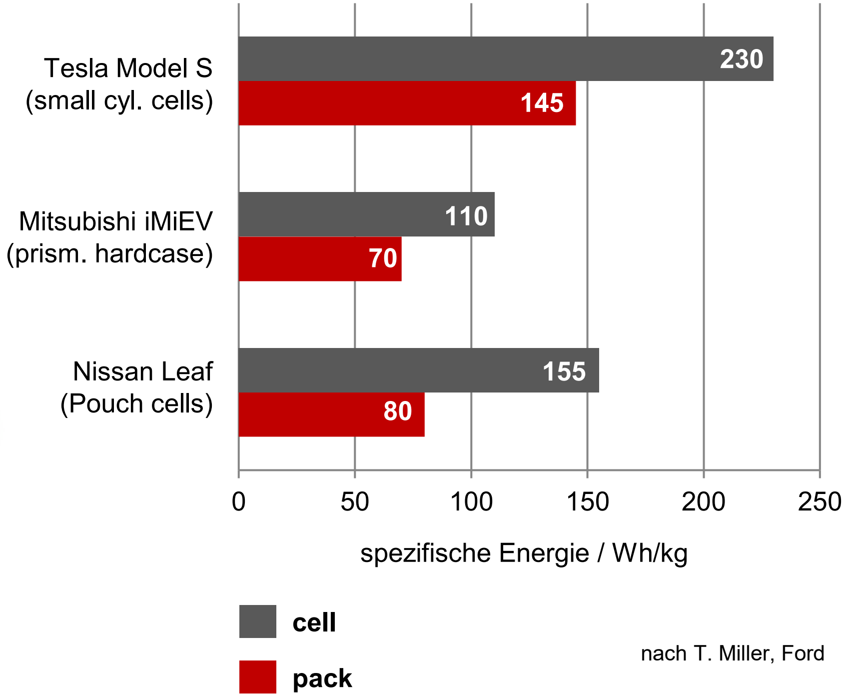


Module / Pack

Trends in Automotive Battery Cell Design: A Statistical Analysis of Empirical Data, *Batteries* **2023**, *9(5)*, 261-282.

The path to higher energy density of batteries

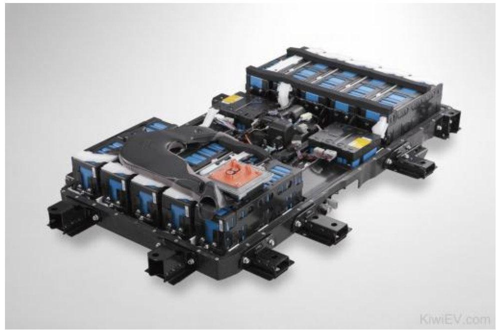
Cell to pack – loss of energy density



nach T. Miller, Ford

Tesla Model S Battery Pack, Ricardo Strategic Consulting

Nisan Leaf Battery Pack



Mitsubishi iMiEV Battery Pack

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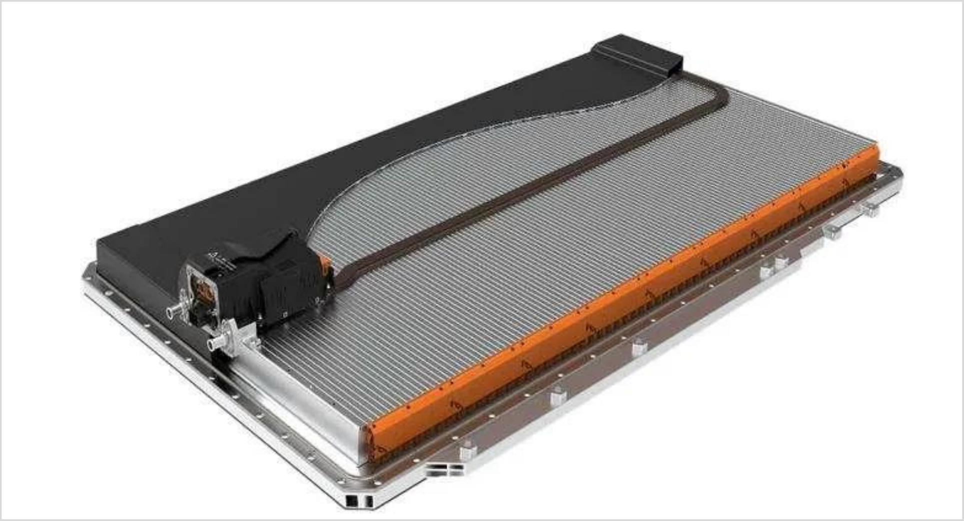
From "cell-to-pack" to "cell-to-chassis" technology



BYDs “Blade technology” , 50 % improved space utilisation

Teslas “Structural Battery” Pack

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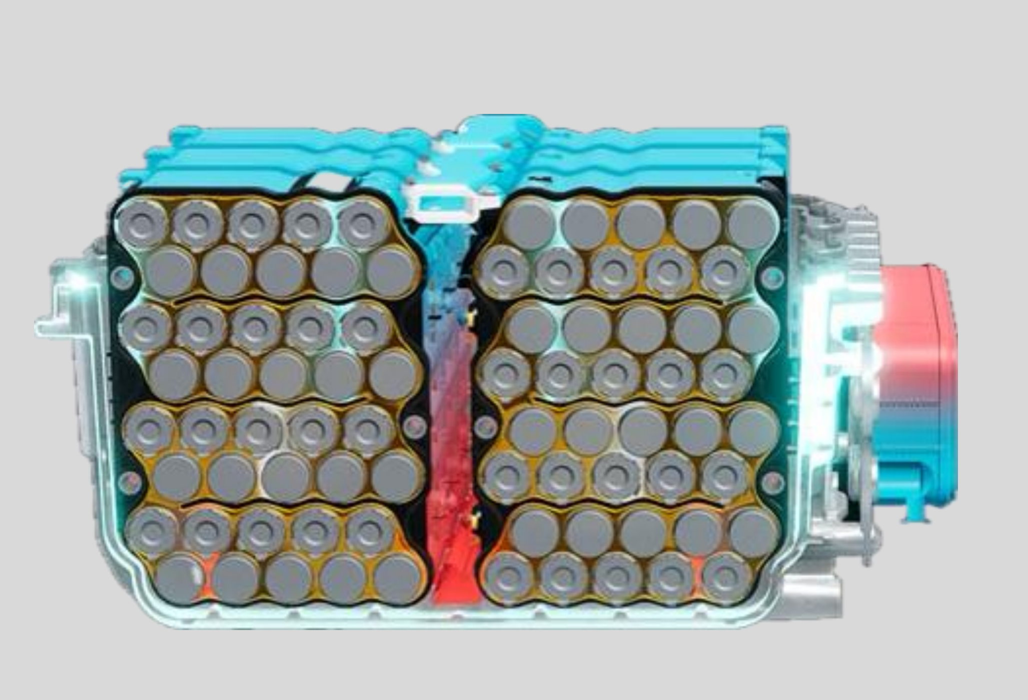
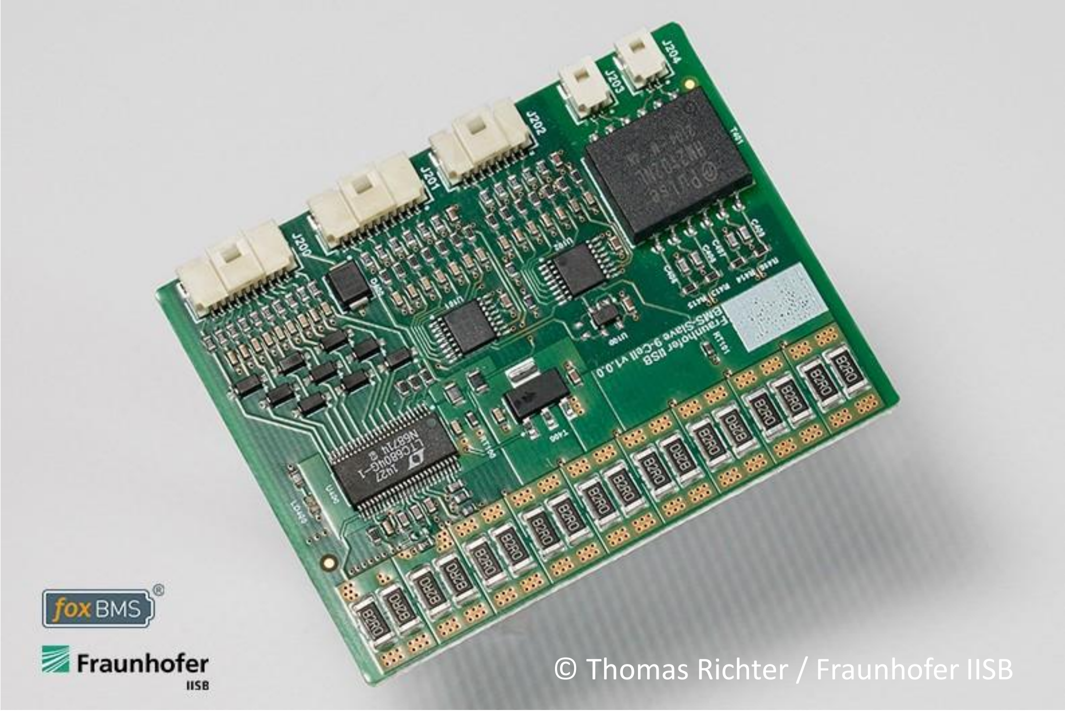
Safety on Pack Level – Thermal Management and Battery Management Systems

AMG E PERFORMANCE



Mercedes AMG High Performance Battery – Immersion Cooling

Fraunhofer IISB



Battery cell voltages and temperatures are monitored by the customized and compact BMS-Slave

The path to higher energy density of batteries

Safety on Pack Level

EUCAR Hazard Levels

Hazard level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50 %	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50 % of electrolyte weight (electrolyte = solvent + salt).
4	Leakage Δ mass > 50 %	No fire or flame*; no rupture; no explosion. Weight loss ≥ 50 % of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (i.e., disintegration of the cell).

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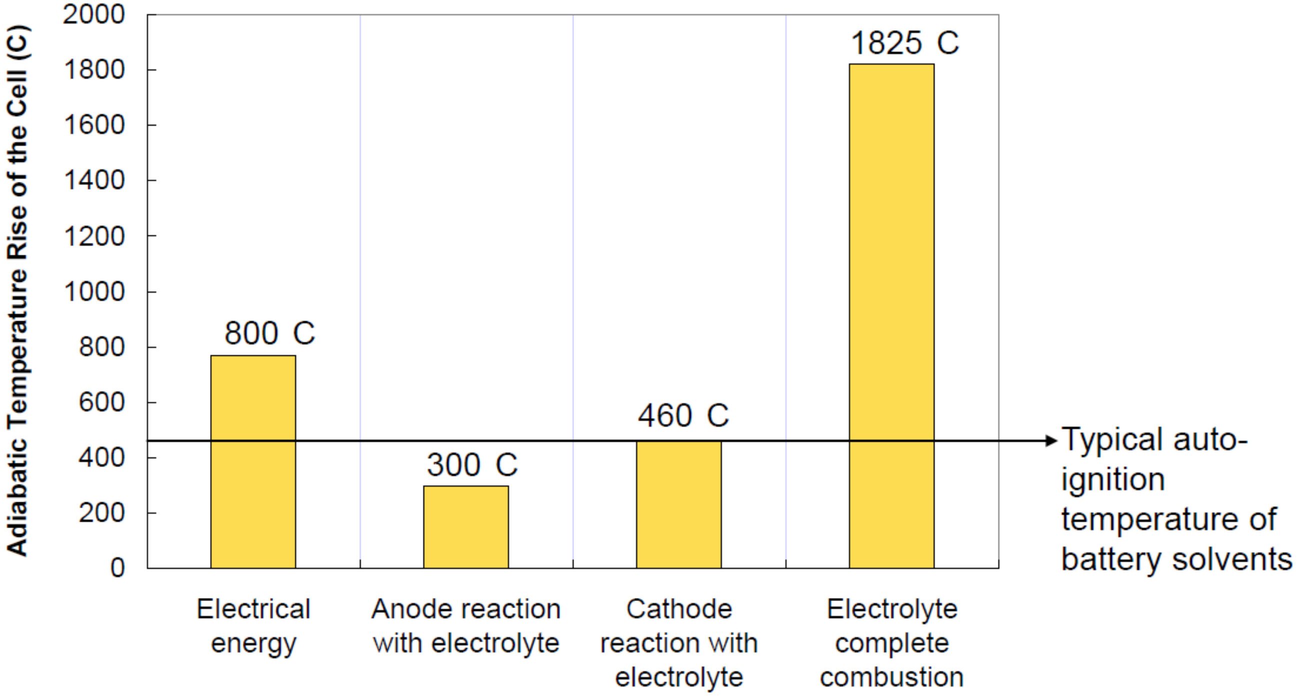
The impact of various factors on the rise in temperature in a thermal runaway



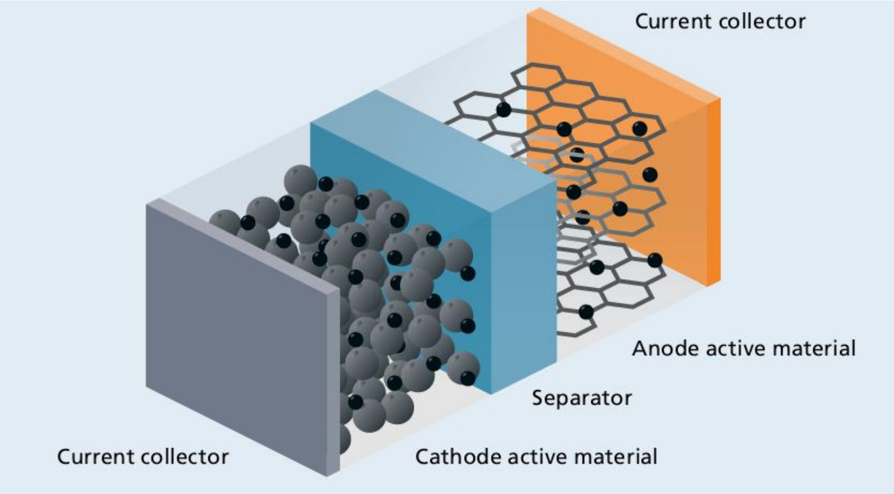
(2.6 Ah, LCO 18650 Cell)

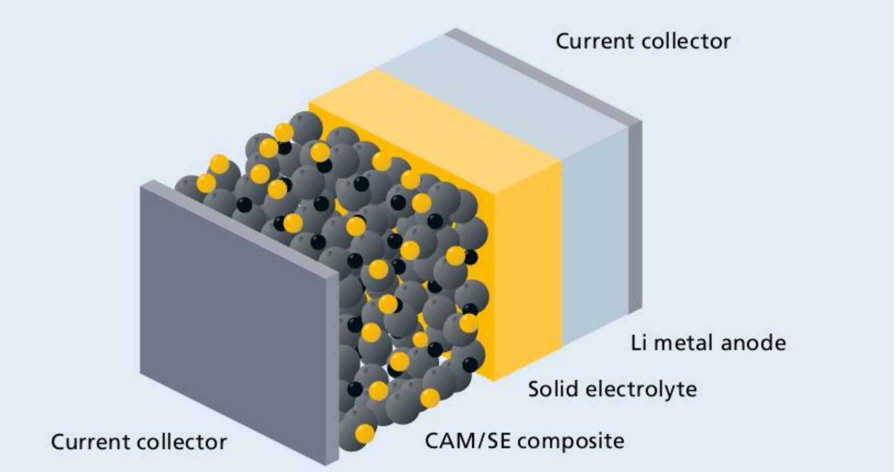
- The electrical energy of a cell is sufficient to raise the cell temperature above 700 °C under adiabatic conditions
- The combustion of the highly combustible electrolyte is responsible for the largest proportion of the temperature rise

The path to higher energy density of batteries

Solid-State Batteries - advantages

- No highly flammable electrolyte
- Li dendrite-stable membrane
- Higher energy density through the use of metallic lithium
- Improved packaging efficiency, as the cell design can allow in-series stacking and bi-polar structures.





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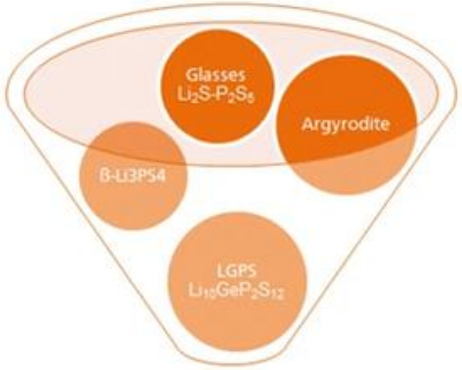
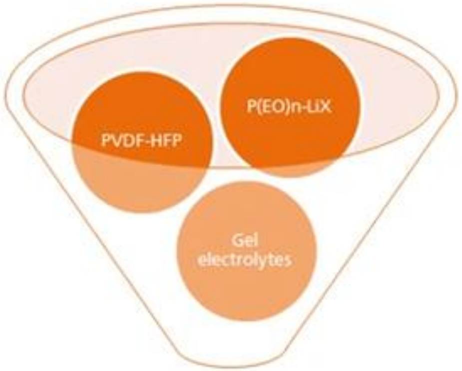
Solid-State Batteries – classification of solid-state electrolytes



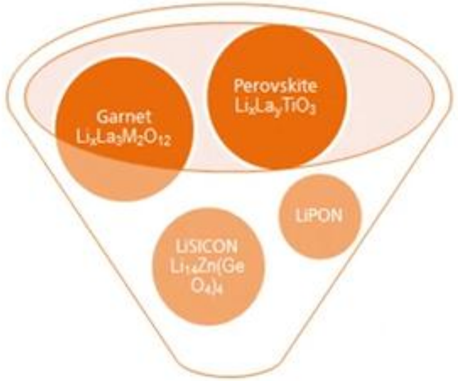
Sulfides

good ionic conductivity
enables thicker, stable layers
not stable in air
elaborate to process



Polymers

mechanically flexible
easy to process
requires thermal management
only stable up to approx. 4 V



Oxides

good ionic conductivity
stable in air
brittle and difficult to process
Sintering at high temperatures

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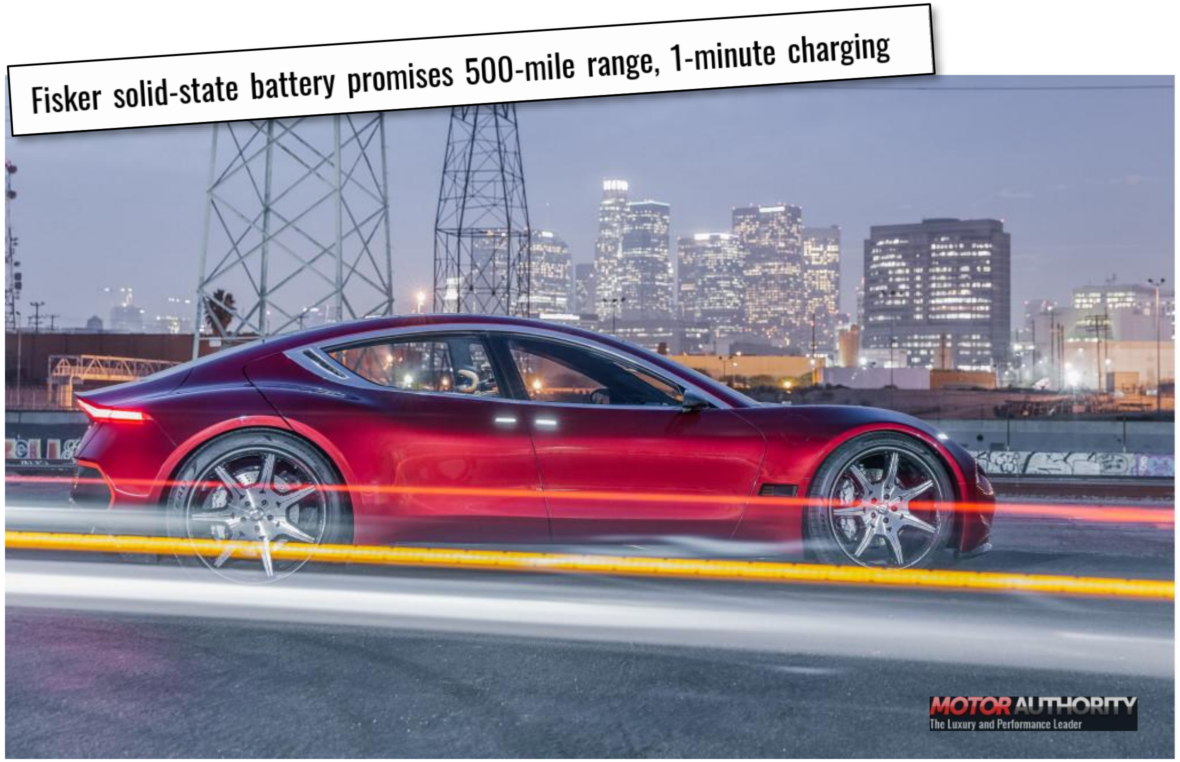
Lithium Solid-State Batteries



„"It's the kind of technology where, when you feel like you're 90 percent there, you're almost there, until you realize the last 10 percent is much more difficult than the first 90." (Henry Fisker, 26. Februar 2021)

The path to higher energy density of batteries

Lithium Polymer Batteries – BlueCar EV

Bolloré

autolib'

- Bolloré/BatsCap: LMP batteries with 30 kWh combined with supercap
- Range: 250 km
- mostly in the Autolib' car sharing programme, > 4000 cars (as of 2017) in Paris, Lyon (305), Indianapolis (282), Bordeaux (201), Turin (80), ...
- Over 200 million kilometres since 2011

Bolloré's BlueCars recharging at Rue des Pyramides, 11, Paris for the Autolib electris-car sharing service, Sep 2016

The path to higher energy density of batteries

Lithium solid-state battery – Toyota

NIKKEI

2011: Toyota Motor Corp. has developed a prototype solid-state Li-ion storage battery and aims to improve and then commercialize it in the **2015-2020** timeframe.

FT FINANCIAL TIMES

2023: Toyota announced a “technical breakthrough” for solid-state electric vehicle batteries for their next-generation EVs, which are expected to launch by **2027**

Scailing-up from 1 cm^2 (1 layer) to 7×7 cm^2 (20 layers) „big challenge“

prototype electric kick-board with Solid-state Cells by Toyota

C. Yada, C. Brasse (2014) “Better batteries with Solid-state instead of liquid-based electrolytes,” *ATZelektronik worldwide* **2014**, *9 (3)*, 10-15.

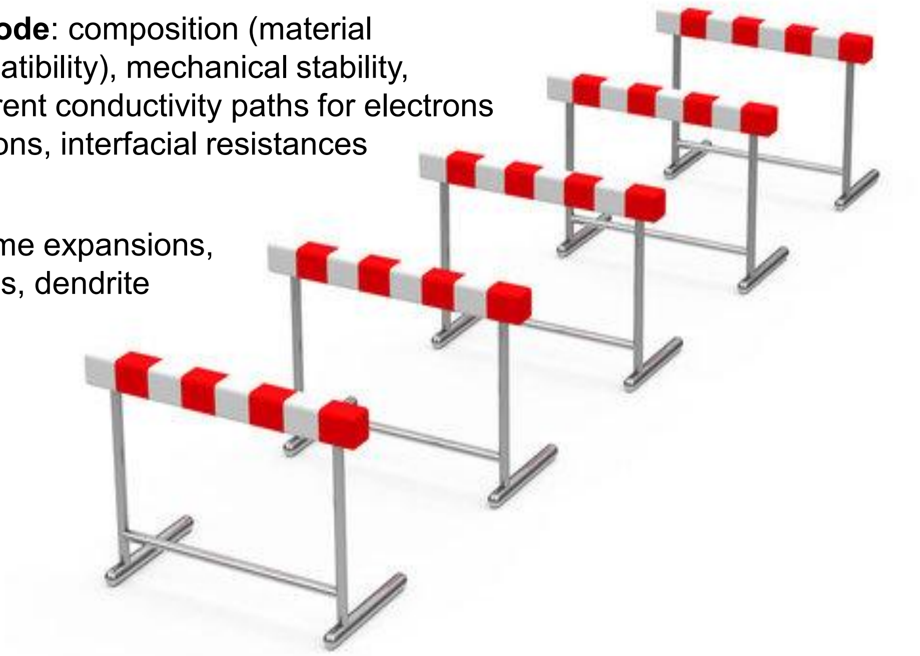
The path to higher energy density of batteries

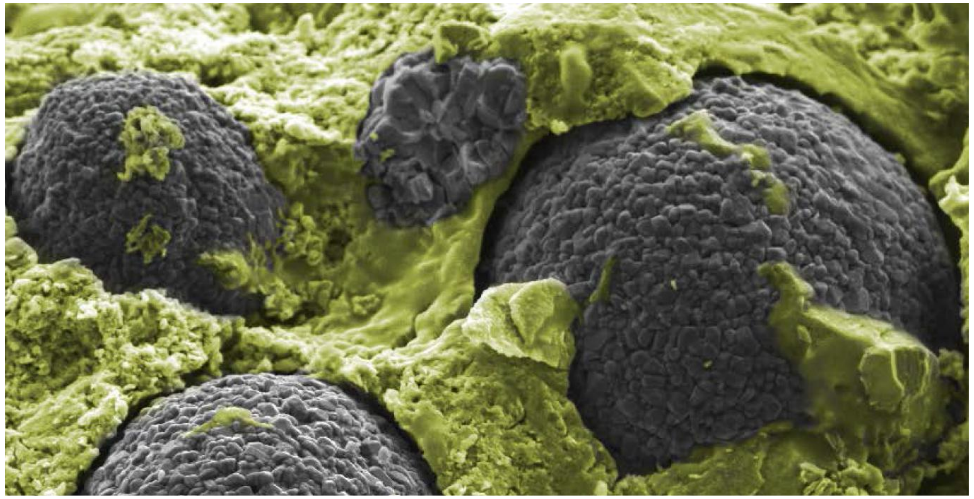
Lithium solid-state battery (ceramic) – Hurdles and Challenges

Separator: conductivity, thickness, mech. & dendrite stability, boundary layers to anode & cathode (mech. bonding, resistances, chem. stability)

Cathode: composition (material compatibility), mechanical stability, coherent conductivity paths for electrons and ions, interfacial resistances

Anode: volume expansions, contact losses, dendrite formation





NCM-811 in a bulk-type solid-state battery with β-Li_3PS_4 as a sulfide-based solid electrolyte after 50 cycles.
***Chem. Mater.* 2017, *29 (13)*, 5574 - 5582.**

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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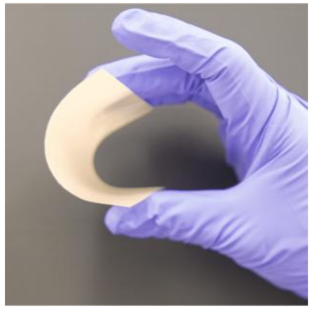
Lithium solid-state battery (ceramic) – QuantumScape's history

QuantumScape



Founded

2010

World-first demonstration of solid-state separator meeting automotive requirement

2016

Commercial-size single-layer Prototype cell

2020

A0 prototype battery cell, 24-layer

2022

Cobra separator process, shipping QSE-5 B1 samples

2025

Eagle production line inauguration

2026

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Lithium solid-state battery (ceramic) – Specifications of a ~5 Ah QSE-5 B Cell

QuantumScape

QSE-5 B Sample

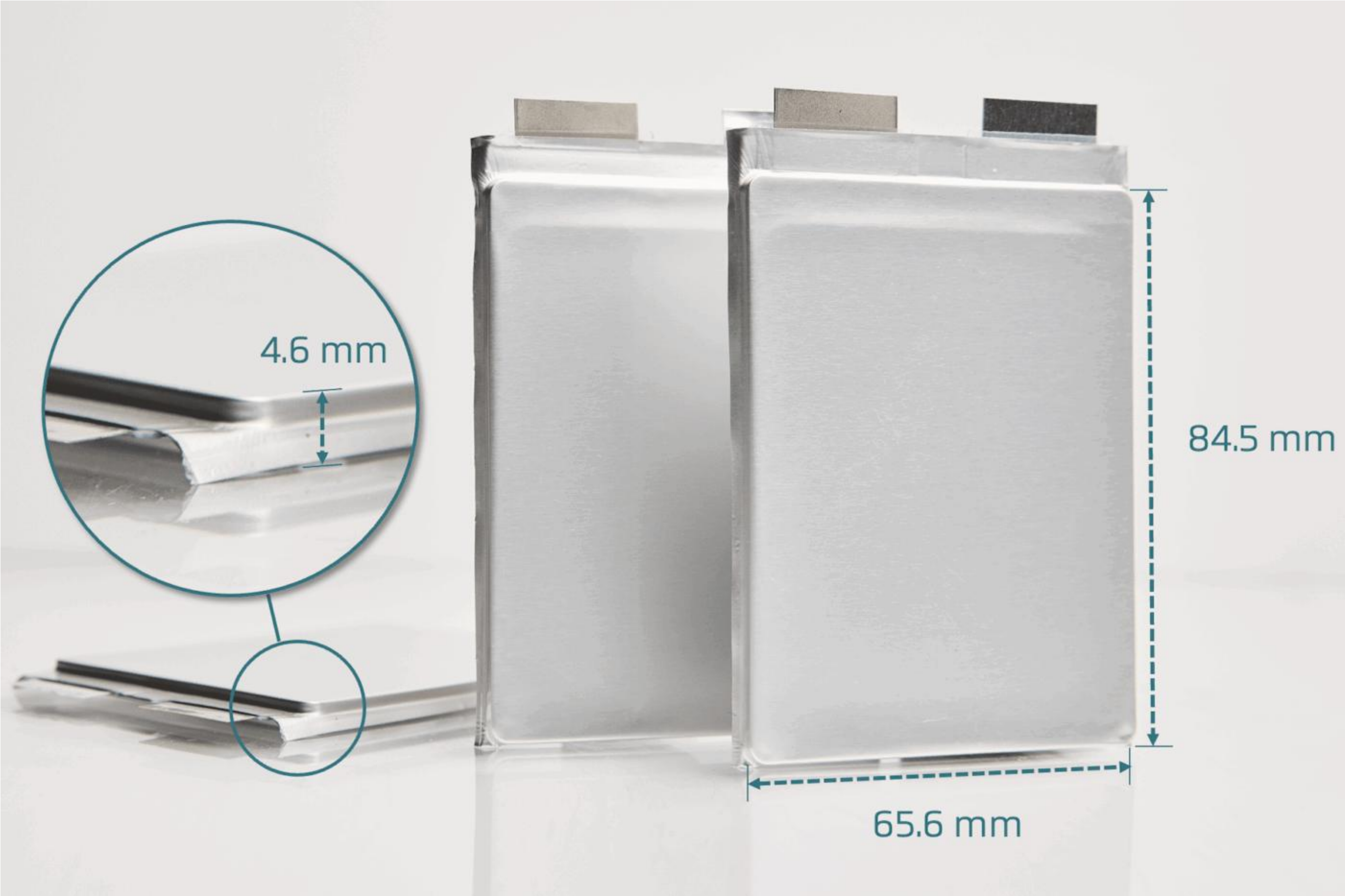
844 Wh/L

301 Wh/kg

< 15-min fast charge

QSE-5 B Sample Product Specs	
Measured cell energy [C/5, 25 °C]	21.6 Wh
Cell dimensions	84.5mm x 65.6mm x 4.6mm
Mass	71.8 g
Nominal voltage	3.84 V
Cathode loading	6.2 mAh/cm²
Operating pressure	< 3.4 atm

Values rounded. Volume at 100% SoC under operating pressure, excluding tabbing area



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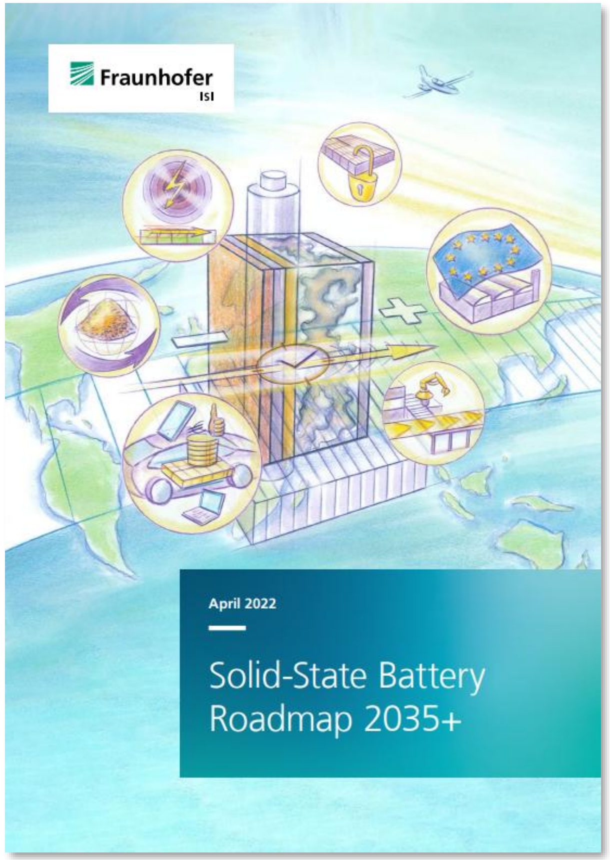
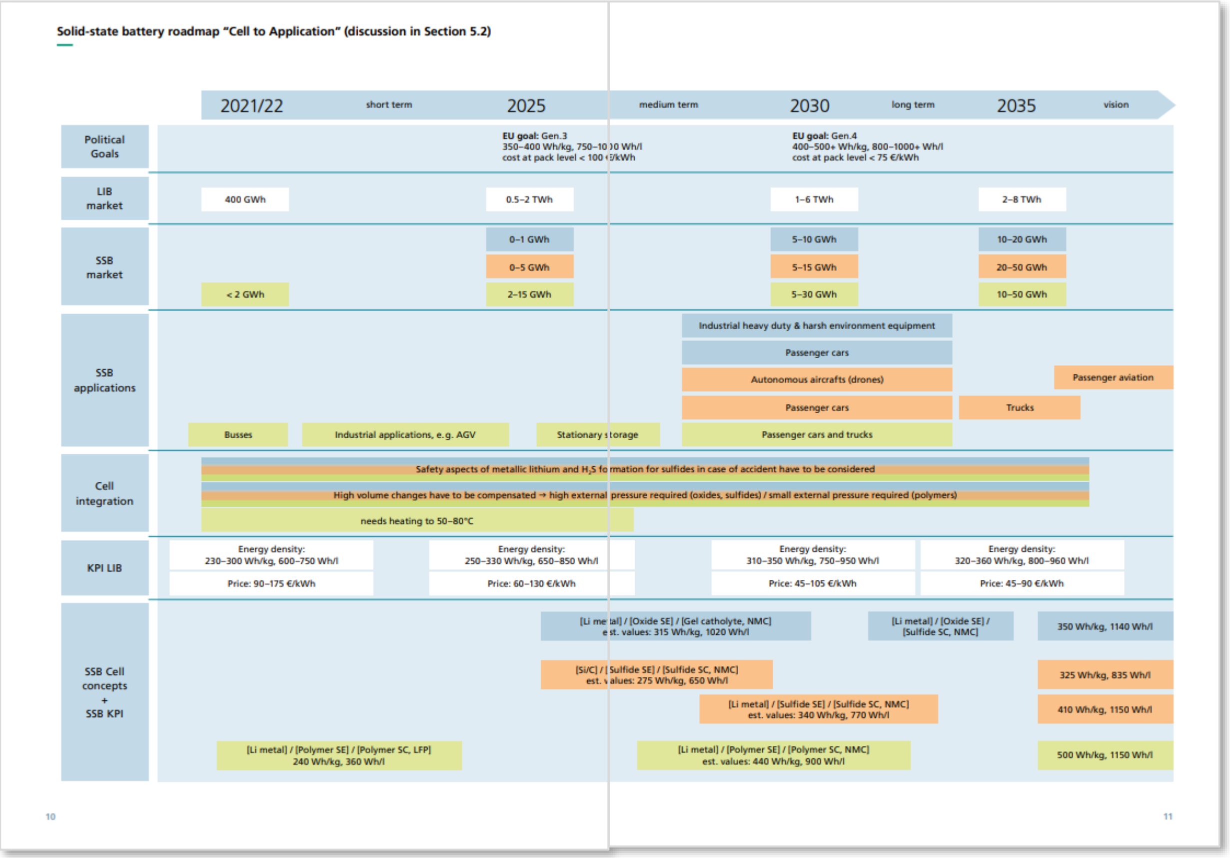
Fraunhofer – Solid State Battery Roadmap 2035+





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Contact

Dr. Kai-Christian Möller

Fraunhofer Headquarters

Acquisition, Project Management and Transfer Coordination – Energy Storage Systems

Hansastraße 27c, 80686 München

kai-christian.moeller@zv.fraunhofer.de

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