

# ***BATTERIES AS ENABLER FOR ELECTRIFICATION OF MOBILITY – DEVELOPMENT TRENDS OF MATERIALS AND SYSTEMS***

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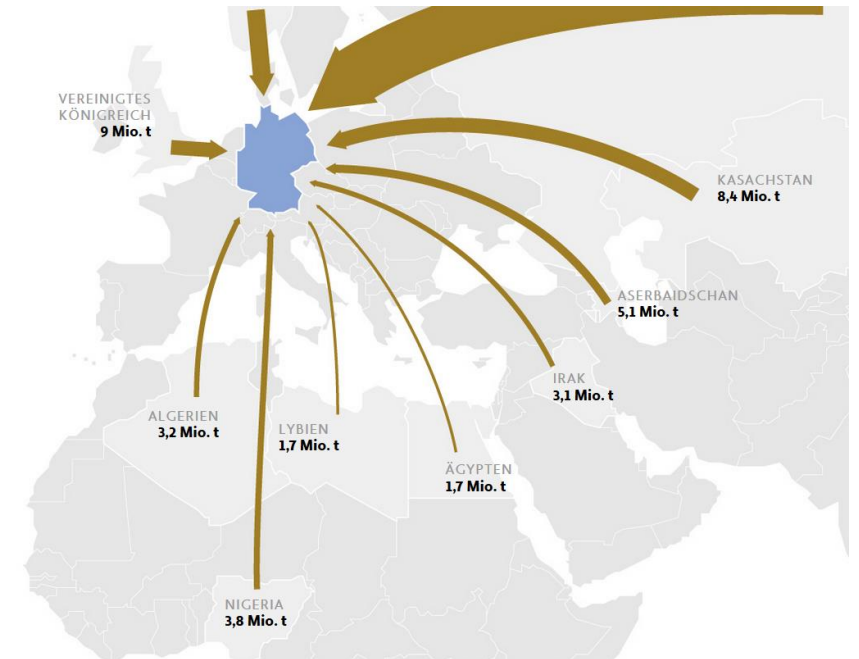


# WHY THE HYPE ABOUT BATTERIES?

Batteries connect industries



Convergency of Energy Supply and Mobility



Crude Oil Supply Germany 2018

Quelle Frankfurter Allgemeine Zeitung 2018. :<https://www.faz.net/aktuell/wirtschaft/schneller-schlau/schneller-schlau-woher-kommt-deutsches-oel-her-infografik-15914568.html>

# BATTERY TECHNOLOGIES

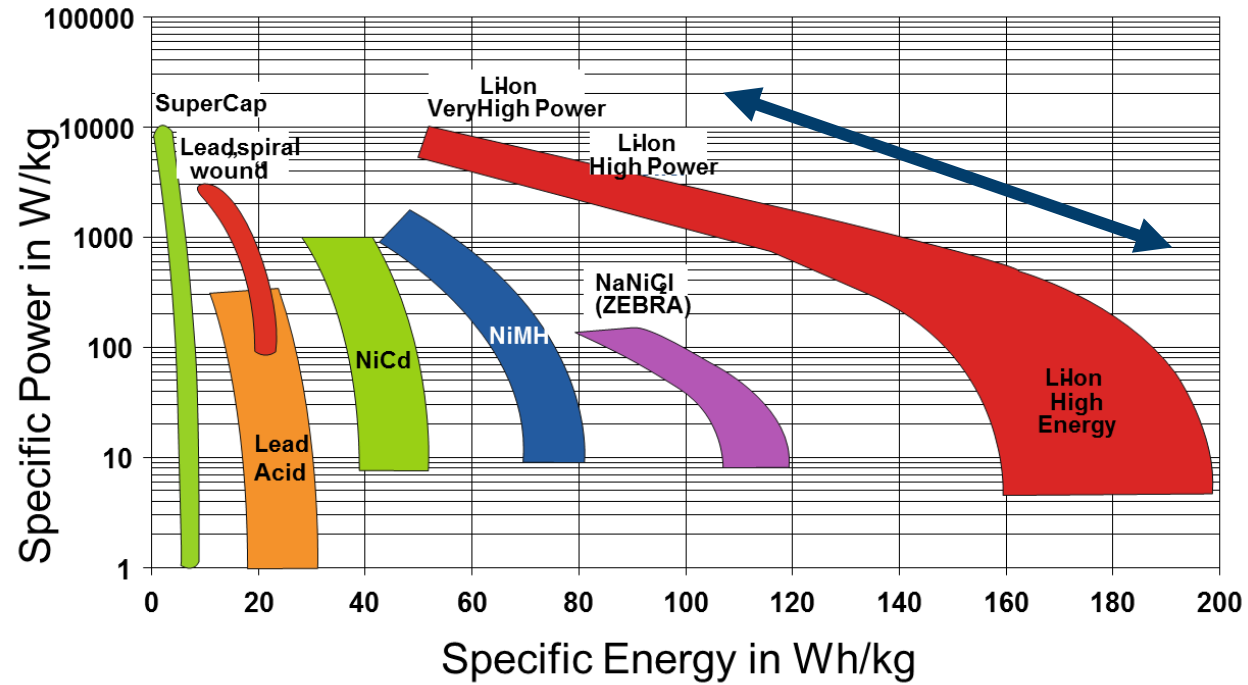
It's a long story.....

- 1780: Luigi Galvani – Frog legs react when in touch with Cu and Fe
- 1799-1800: Volta pile by Alessandro Volta
- **1859: Invention of the rechargeable lead acid battery**
- 1866: Leclanche Zelle (Zn/MnO<sub>2</sub>)
- 1899: Invention of the nickel-cadmium battery
- 1901: Invention of the nickel-iron battery
- 1990: First commercialization of nickel-metal hydride battery
- 1991: **First commercialization of Lithium-ion battery by Sony**

....and the Nobel-price 2019...

Look at the time frames of battery developments!!!

# BATTERY TECHNOLOGIES



# LITHIUM-IONEN-BATTERIEN TRENDS

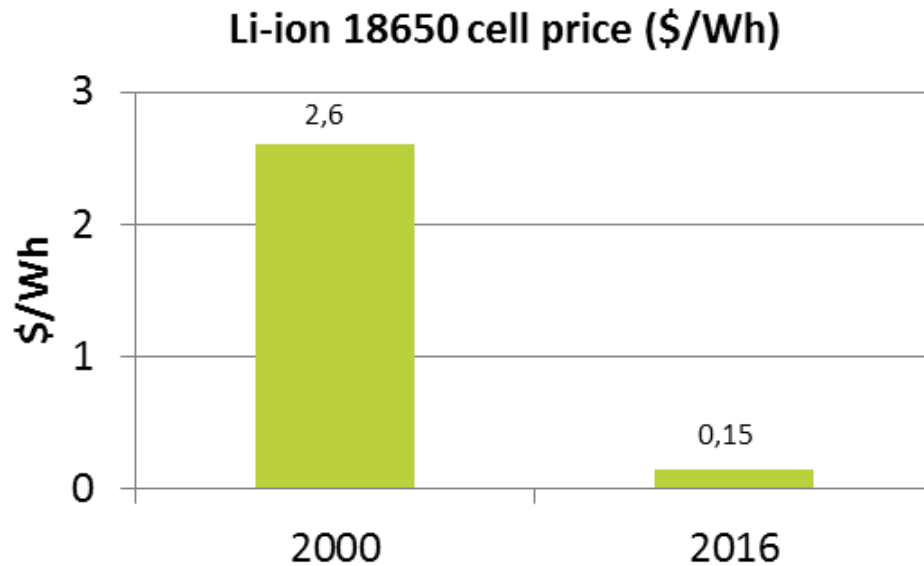
# THE BATTERY INDUSTRY - TRENDS

Technology Switch in Automotive Industry at ....not behind...the Horizon

Speciality

- Larger numbers, faster assembly
- **Cost is key for automotive applications!**
- Cell price for OEMs at 100 €/kWh
- Trend to larger cells (bis 150 Ah).....?

Commodity



Source: Avicenne Energy, 2017

# THE BATTERY INDUSTRY - TRENDS

Fast growth – even accelerating



avicenne  
ENERGY  
INFORMATION FOR GROWTH  
www.avicenne.com

Current Status and Future Trends of the Global Li-ion Battery Market



Nb  
Niobium  
CHARLES HATCHETT AWARD

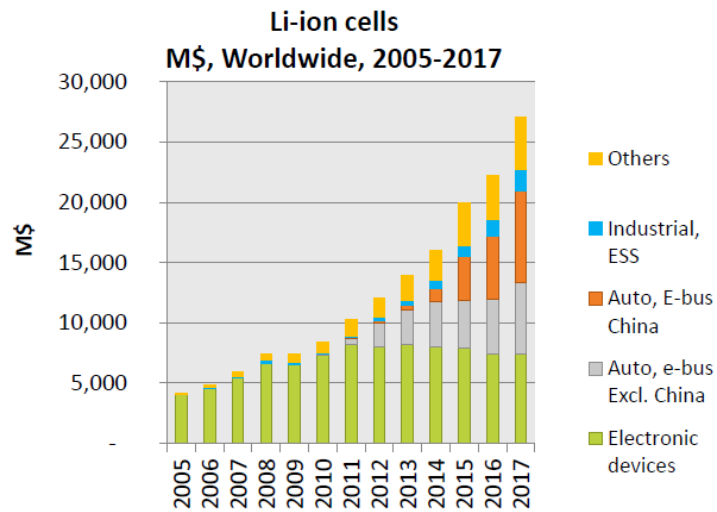
July 4<sup>th</sup>, 2018  
London

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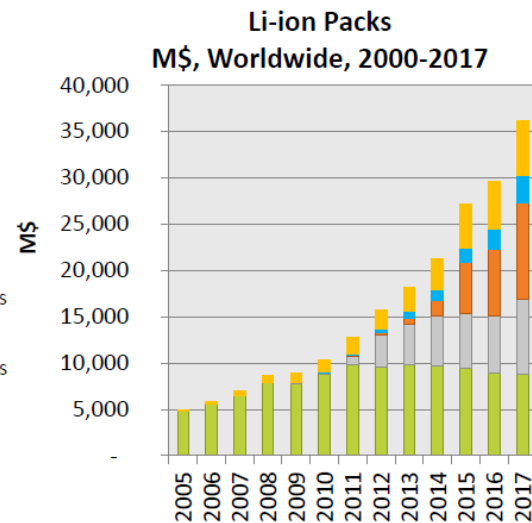
## LI-ION IN 2017 - MAIN APPLICATIONS

+120000 MWh - 27 B\$ (1)  
7 300 M small cells

CAGR 2007/2017  
+25% per year in Volume  
Cell: +16% per year in value  
Pack: +18% per year in value



Others: medical devices, power tools, gardening tools, e-bikes...  
Source: AVICENNE Energy 2018



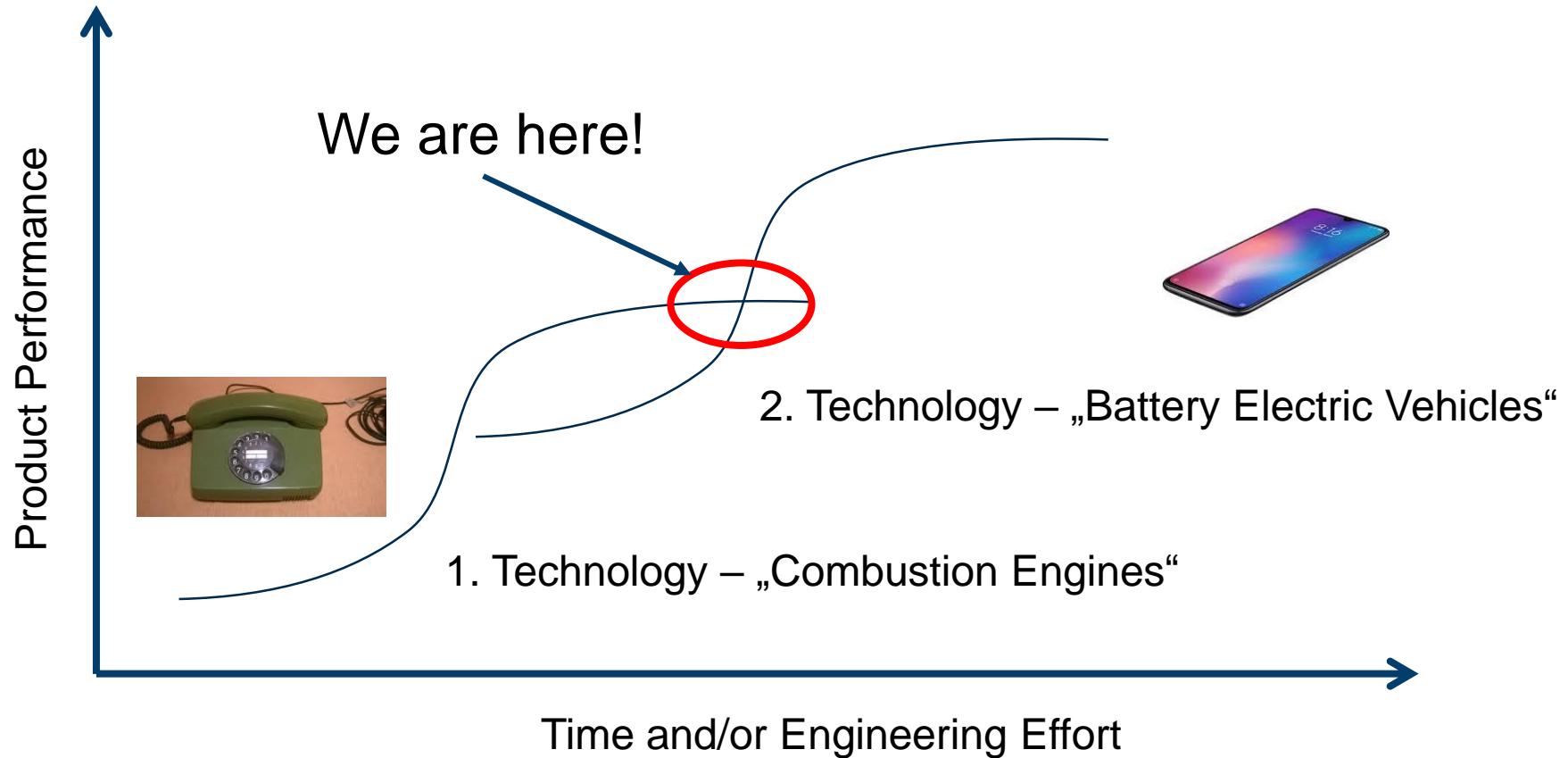
- And expected CAGR til 2025: 17 %.
- 520 GWh market in 2025
- > 500 Billion€ market in 2025

7

Source: Avicenne Energy 2018

# THE BATTERY INDUSTRY – TRENDS

Exciting times.....

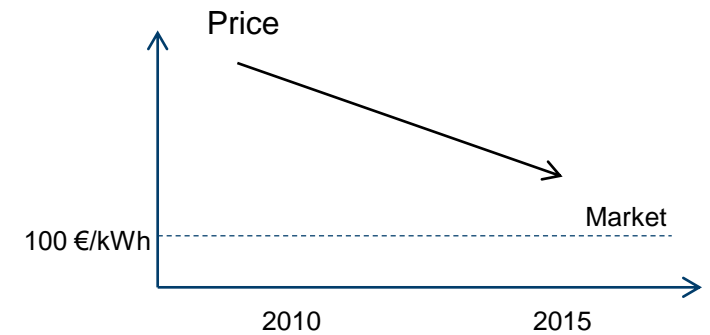
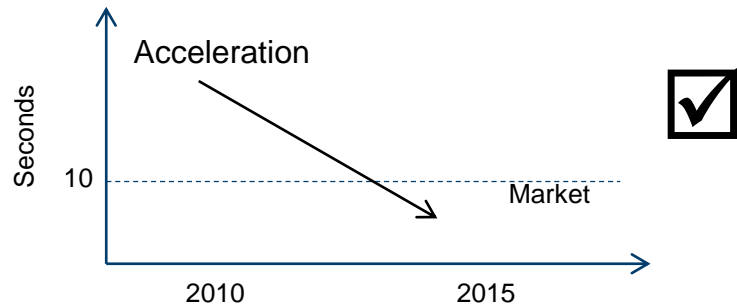
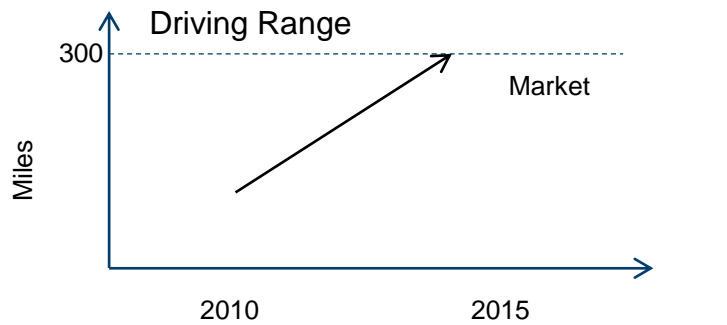
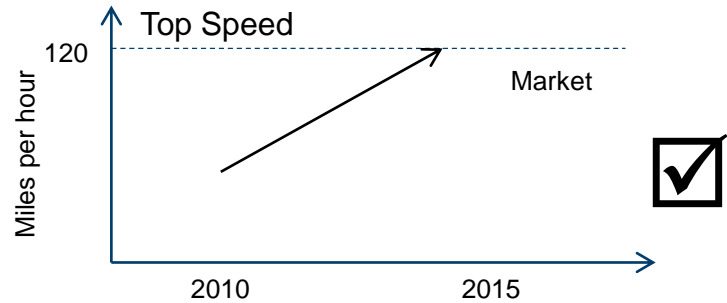


Quelle: Clayton M. Christensen, „The Innovator’s Dilemma“, Harper Business, 2000.



# LITHIUM ION BATTERIES

## Customer Expectations....????



Customer segment decides!

# SWITCH OF TECHNOLOGY

Reaching Maturity for Mass Market

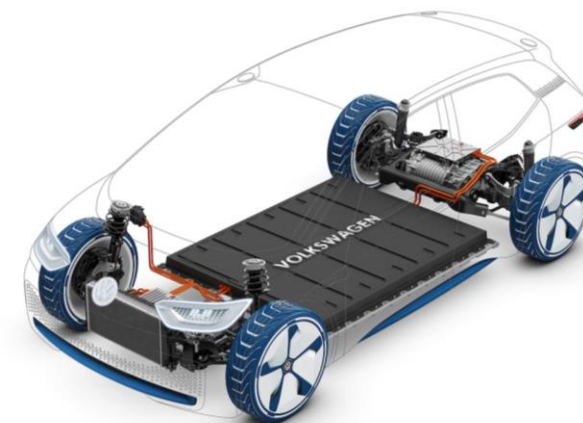


VW Golf – Internal Combustion Engine



**e-Golf's High-Voltage Battery System**

A total of 264 25 Ah cells in 27 different modules for 24.2 kWh of capacity



**Modular Electric Building Block (MEB)**  
e.g. for VW I.D.



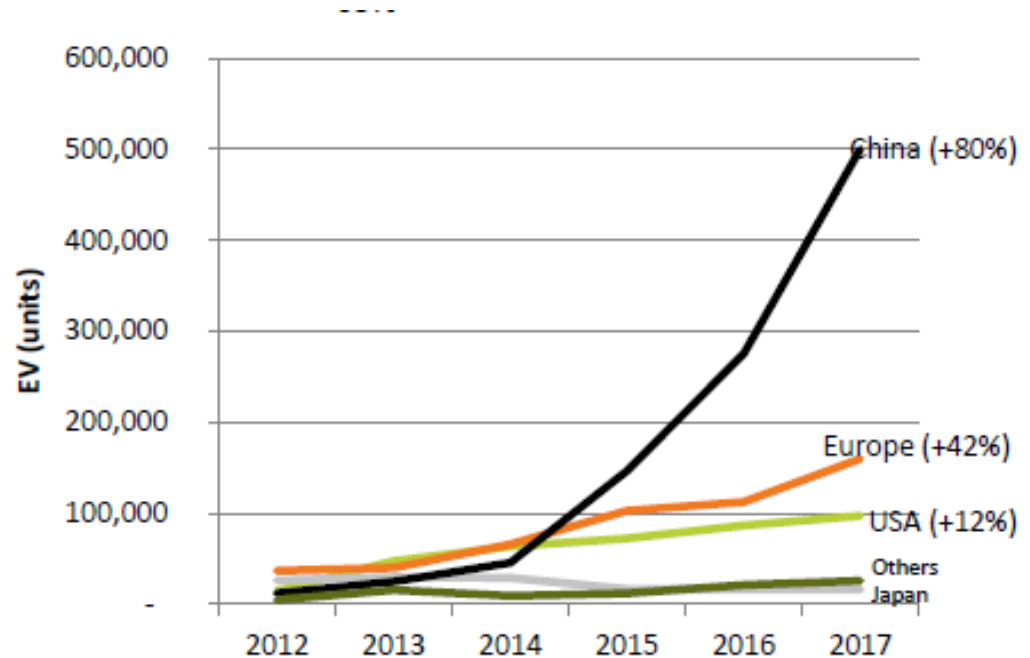
At same costs and price!

Source: Volkswagen AG

# THE BATTERY INDUSTRY - TRENDS

Automotive is the driver....and it's a global trend picking up speed

- Hybrids and battery electric vehicle sales pick up speed
- China leading the pack: Strategic decision of China to go for full electric
- EU requirements on CO2-emissions together with cost decrease render battery electric vehicles competitive
- US Tesla technology lead out of the niche.....
- BEV with > 40 kWh battery pack compared to ca 0.015 kWh for a smartphone!

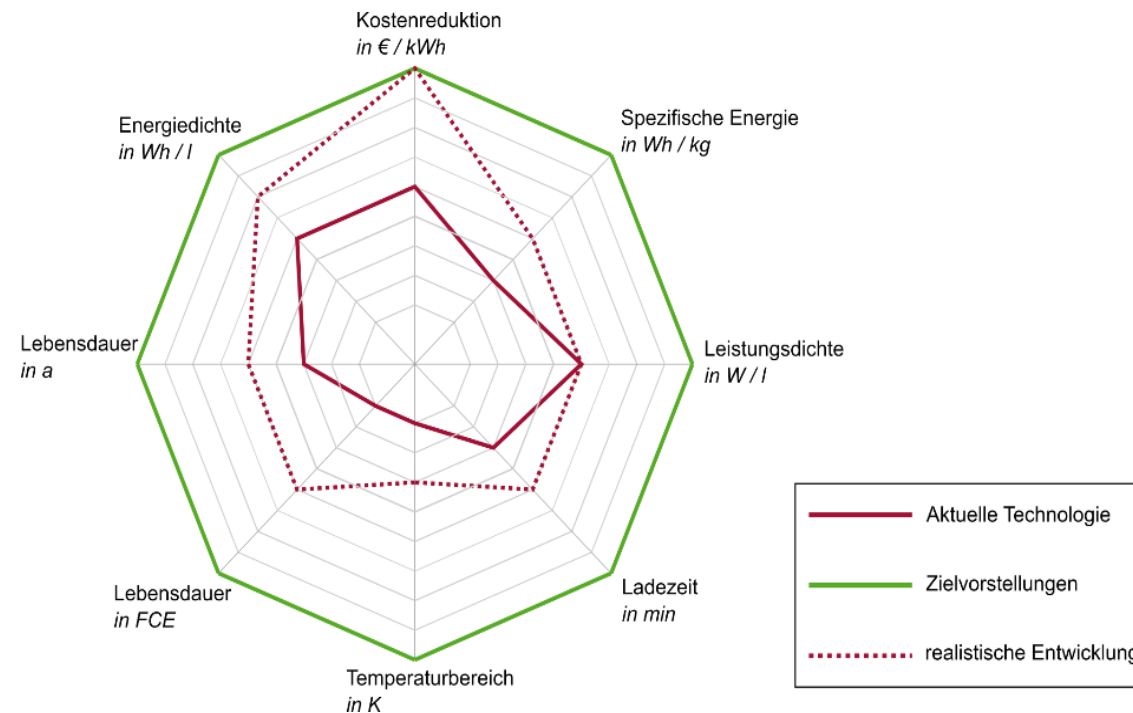


Source: Avicenne Energy 2018

# THE BATTERY INDUSTRY

## Application Engineering

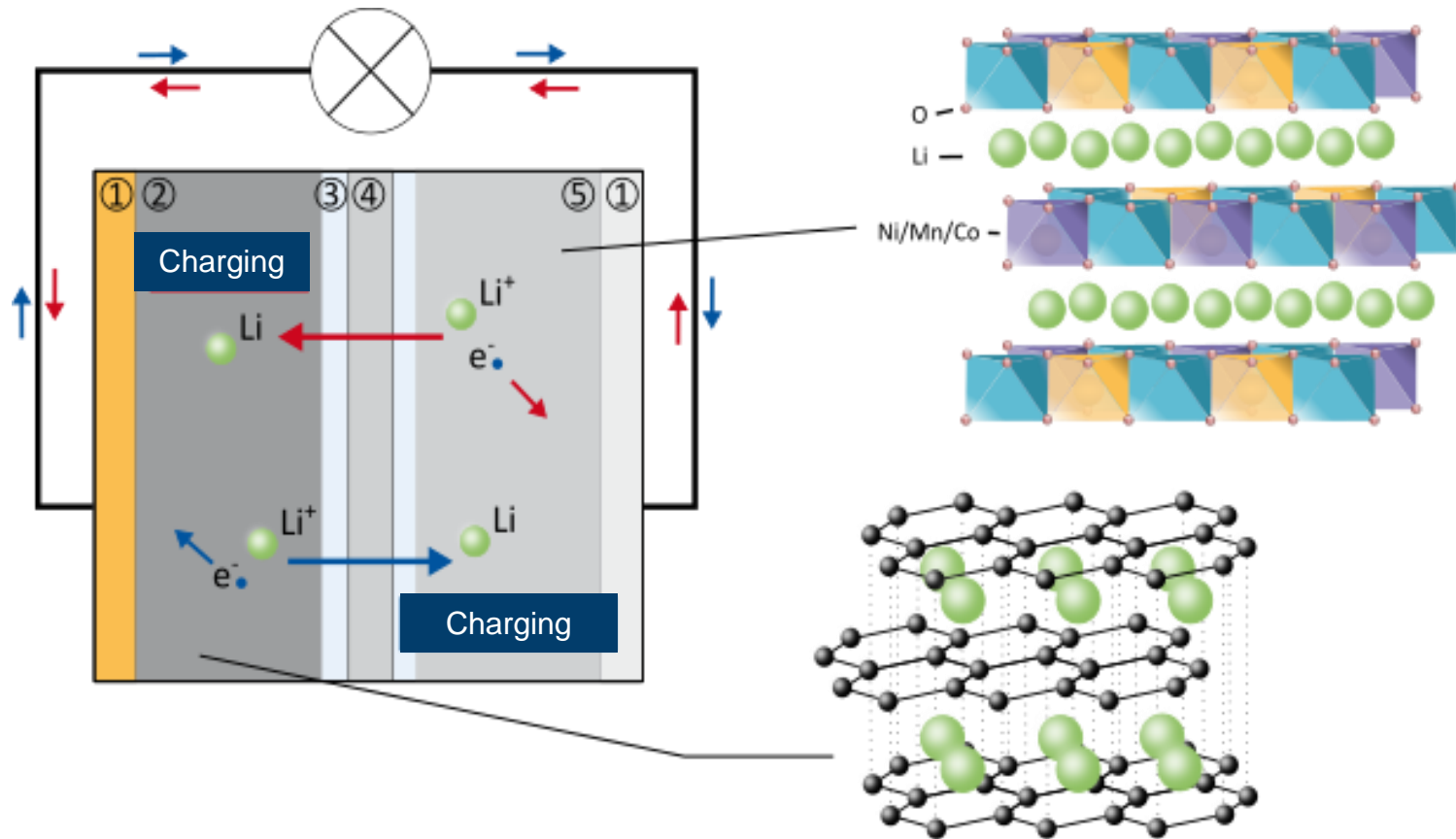
- It is a multi-parameter optimization for each and every application!



# LIHTIUM ION BATTERIES THE BASICS

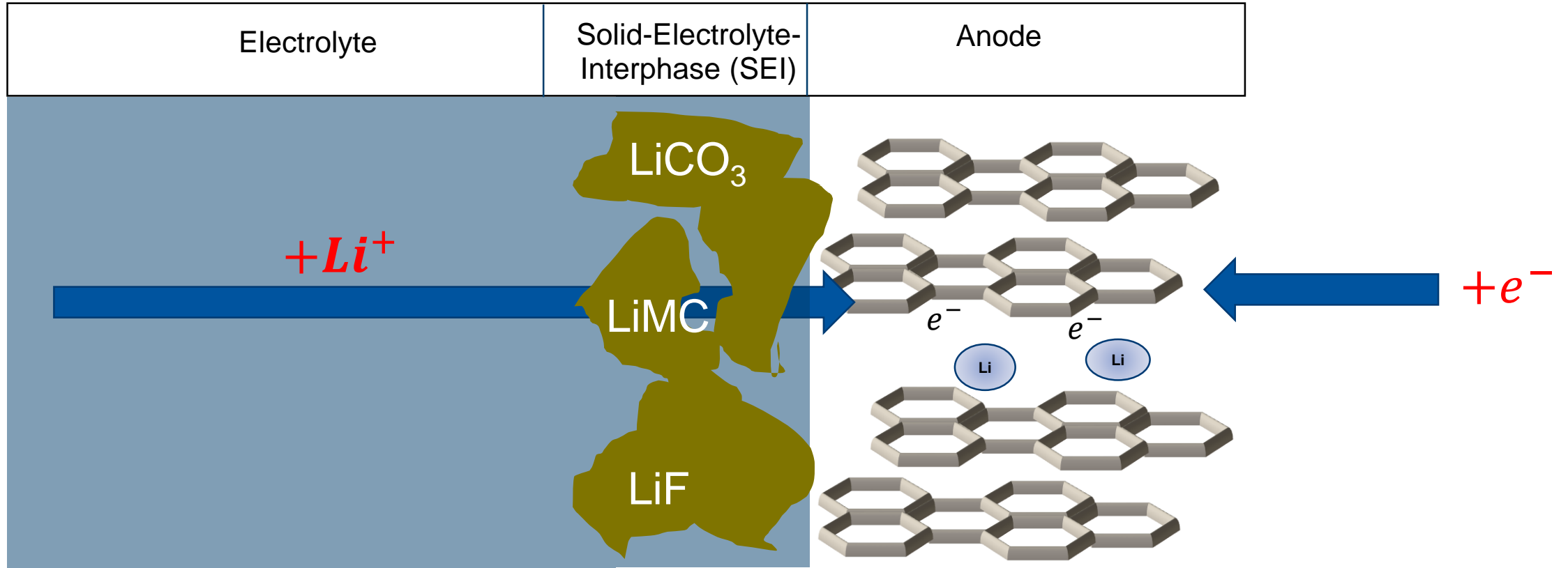
# LITHIUM ION BATTERIES

## Working Principles



# LITHIUM ION BATTERIES

## Working Principles

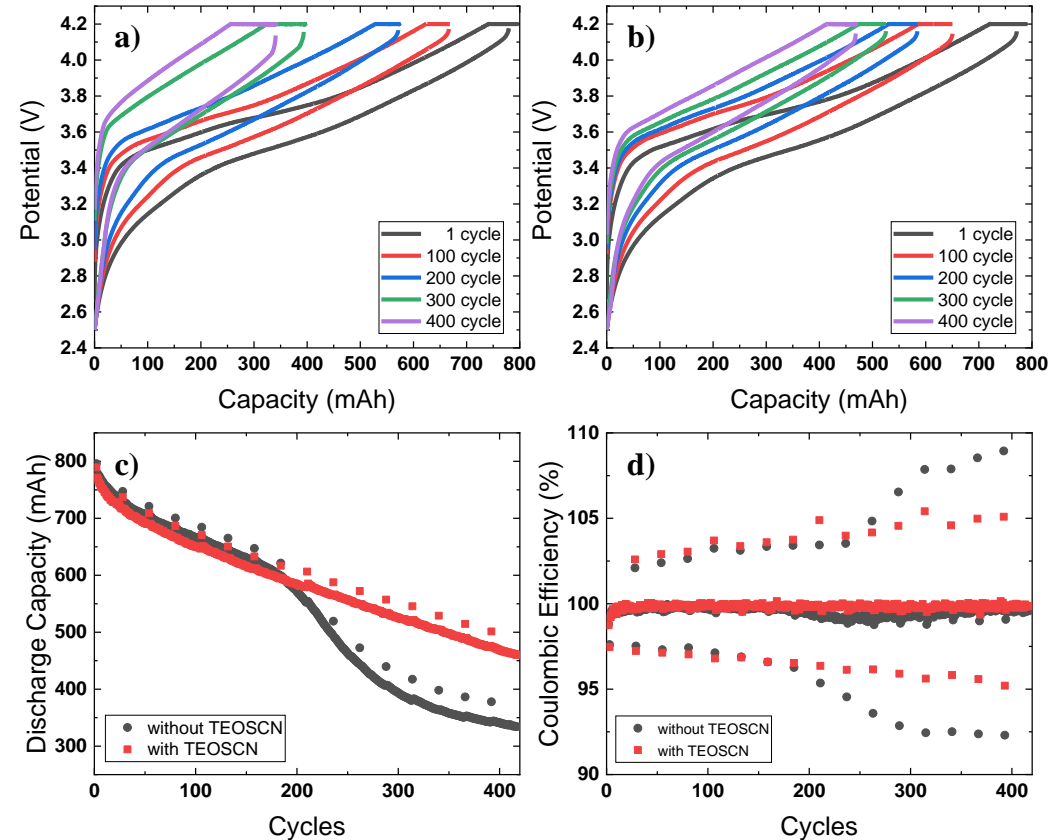
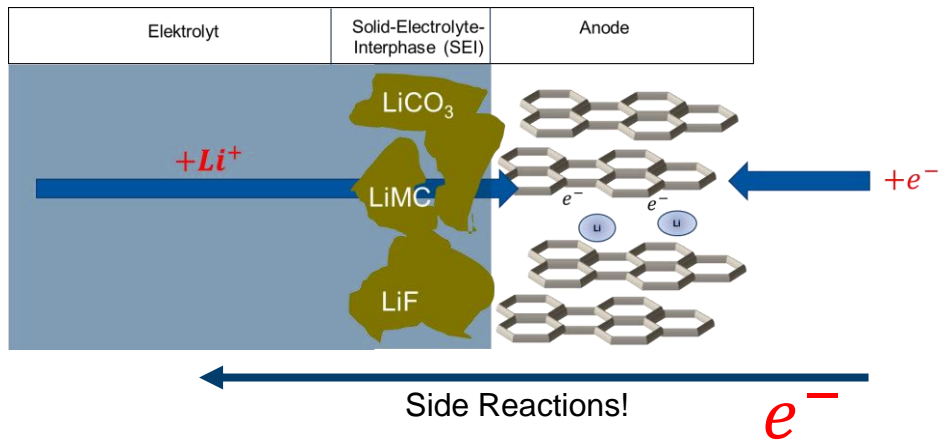


> 4 V: Decomposition of electrolyte → Passivation!

# LITHIUM ION BATTERIES

## Charge-Discharge-Efficiencies

- Charge-Discharge-Efficiency > **99,999 %**
- → >> 1000 Full Cycles!
- 0,0001 %: Side reactions, electrolyte decomposition, lithium inventory loss

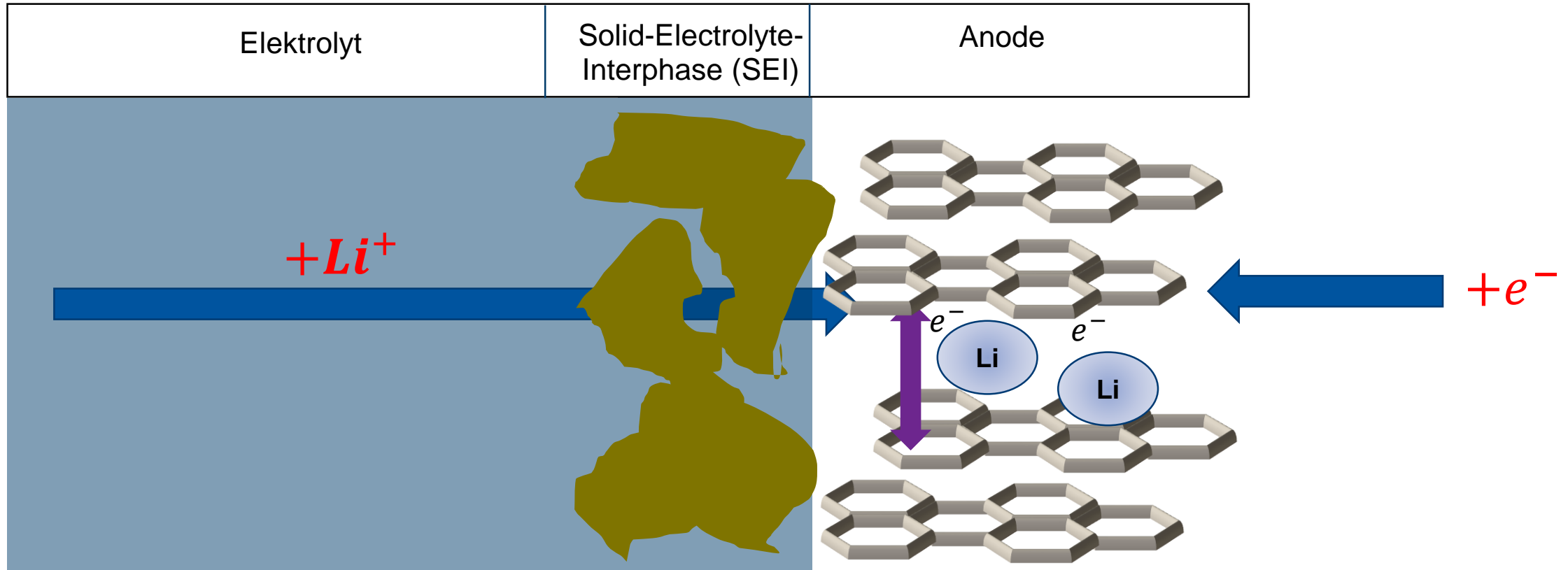


Source: F. Aupperle, G. G. Eshetu, E. Figgemeier et al. Accepted in *Applied Energy Materials*, 2019.



# LITHIUM-IONEN-BATTERIEN

## Mechanische Arbeit



Einlagerung von Lithium in Graphit → Volumenänderung!

# AGEING / FATIGUE IN LITHIUM ION BATTERIES

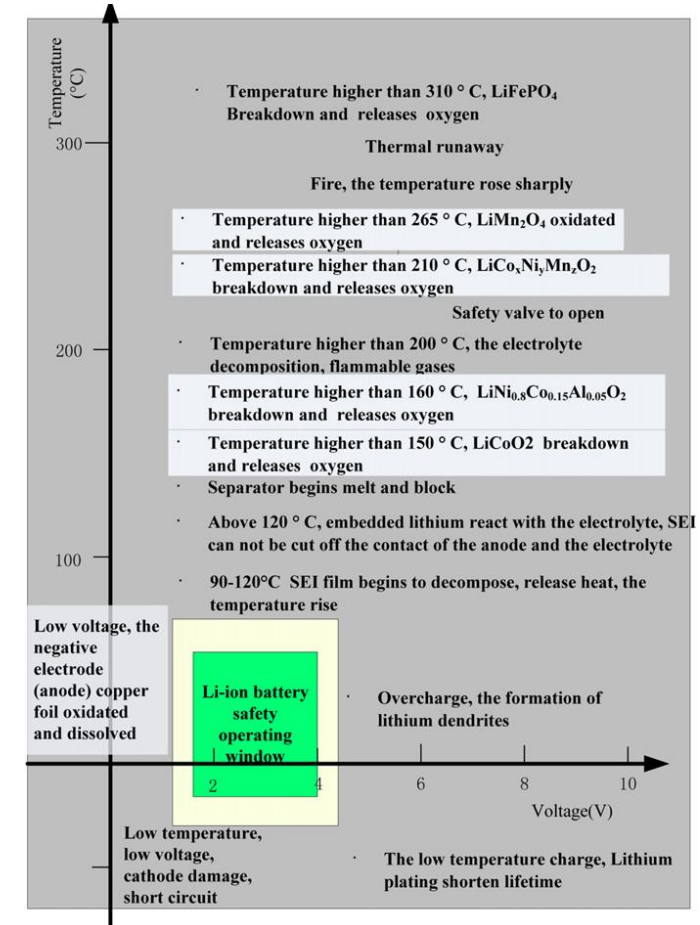
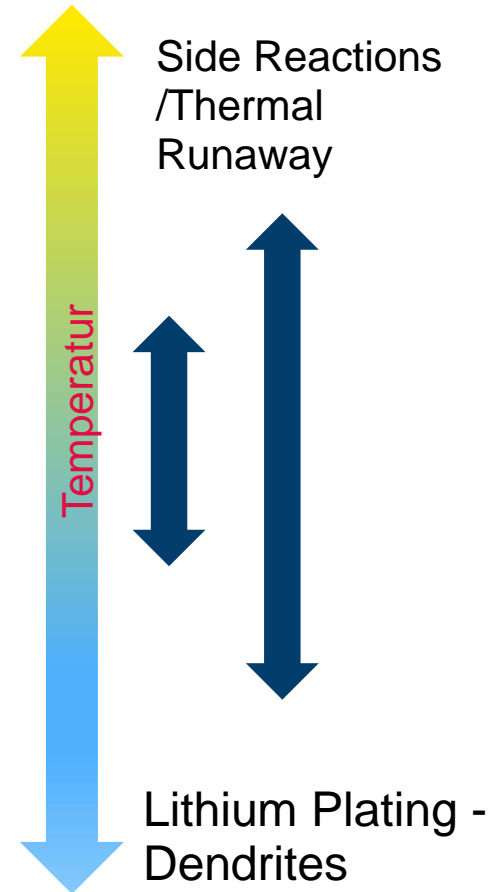
# LITHIUM-ION-BATTERIES

## Ageing and Safety

Window of Stability Smaller than Window of Safety

Stability Determines Business Case

Safety Defines Application

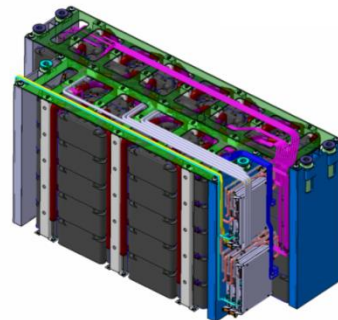
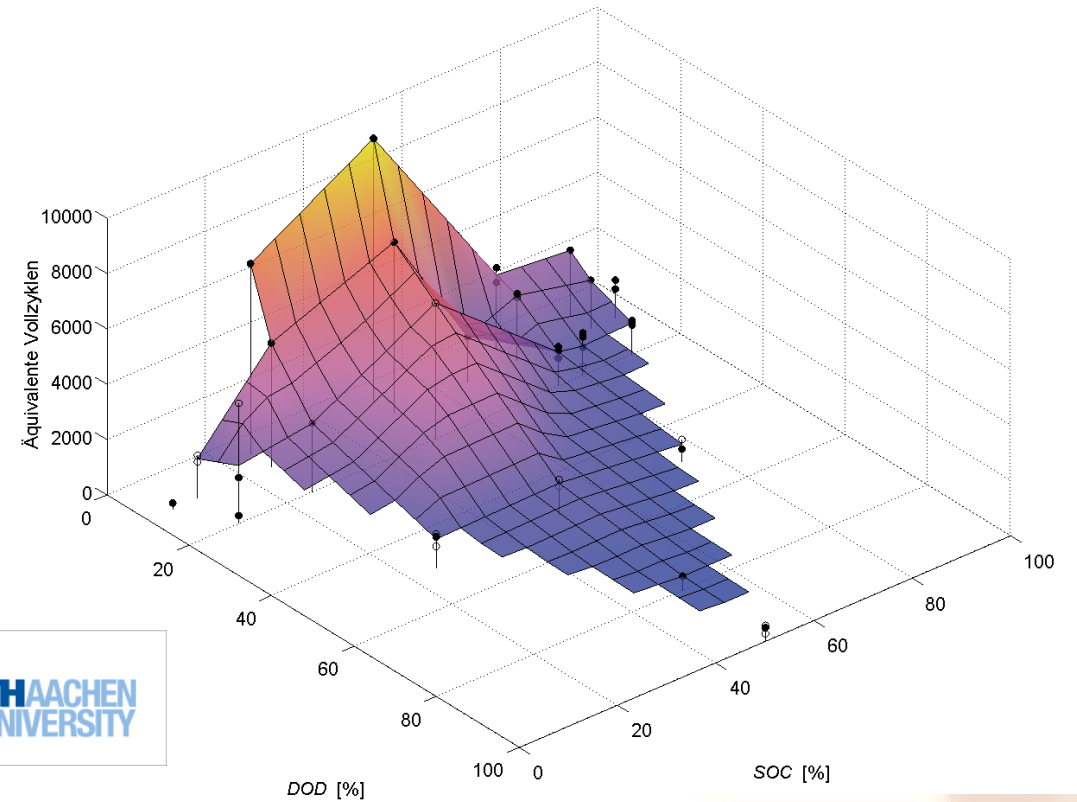


Source: L. Lu et al. / Journal of Power Sources 226 (2013) 272e288

# LITHIUM-ION-BATTERIES

## Ageing: Sanyo UR18650E

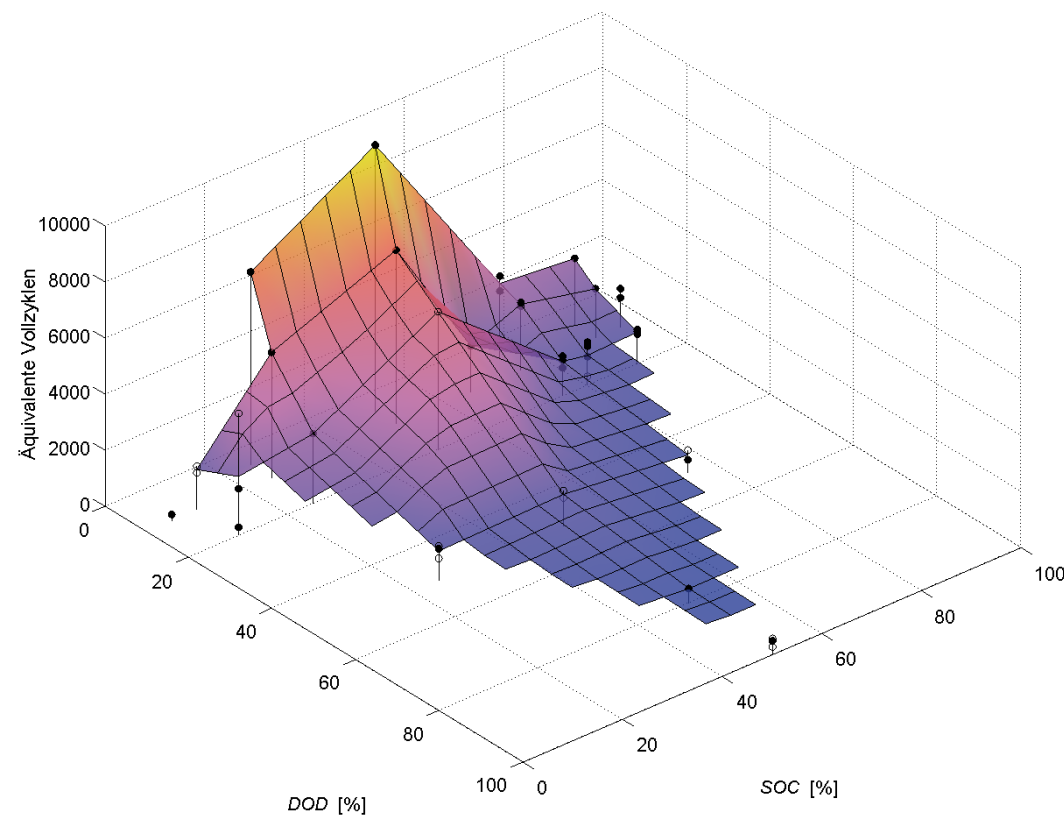
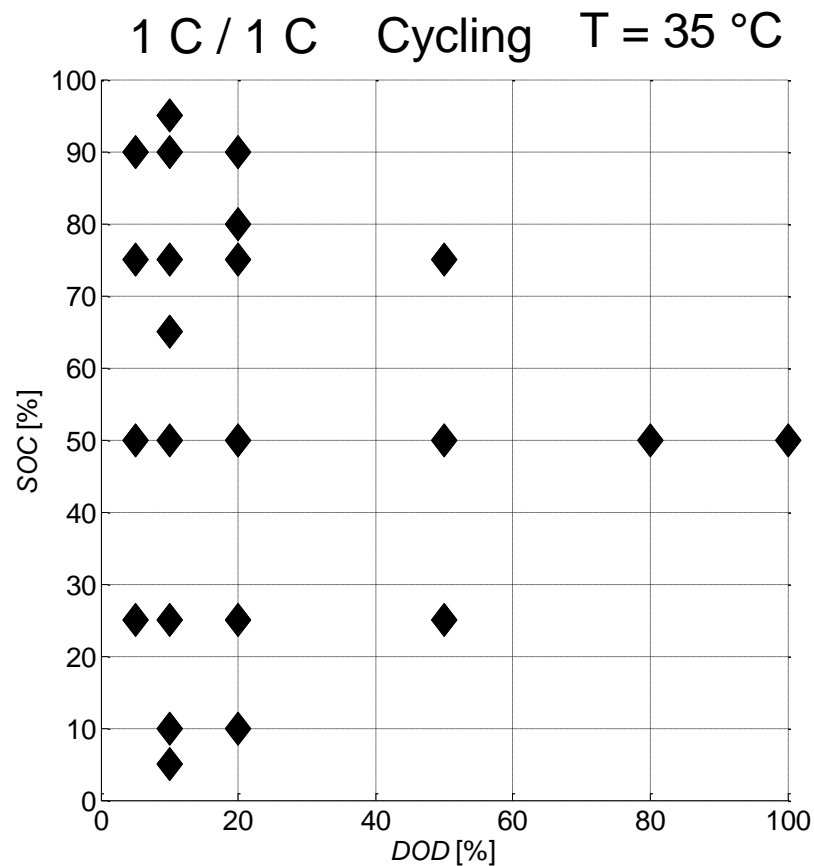
- NMC/Graphite
- 2.05 Ah nominal capacity
- 2012-2014: Intensive ageing matrix
- Complete parametrization of electrochemical models (porosity, electrode design, impedance etc.)
- Project: E-Performance: Audi/RWTH



Source: Stefan Käbitz, Dissertation, RWTH Aachen Universität, 2016. ISEA.

# LITHIUM-ION-BATTERIES

## Ageing: Test Matrix – Sanyo UR18650E

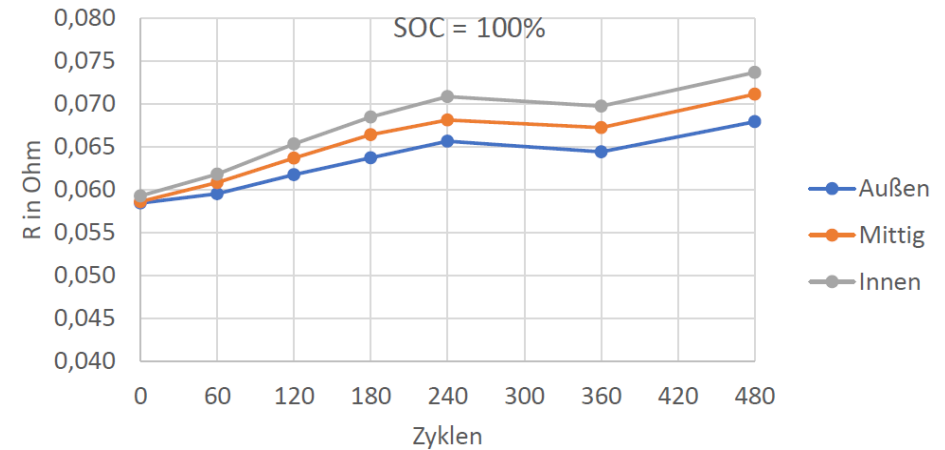
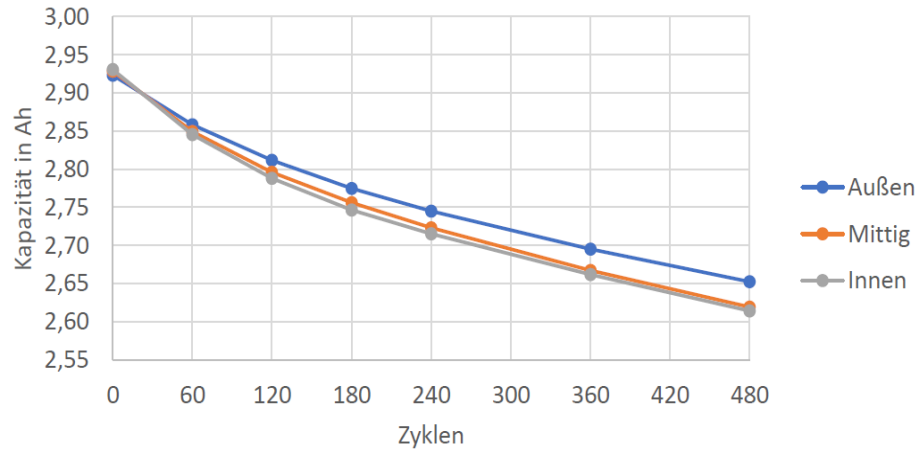
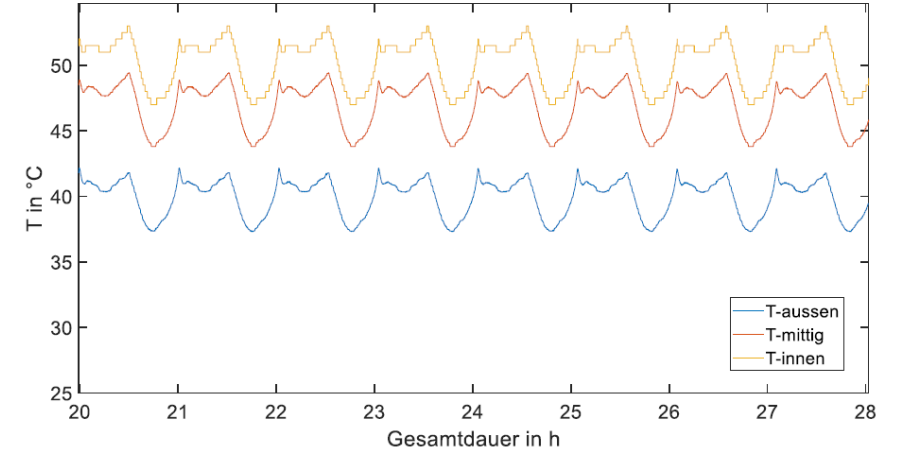
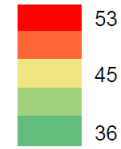
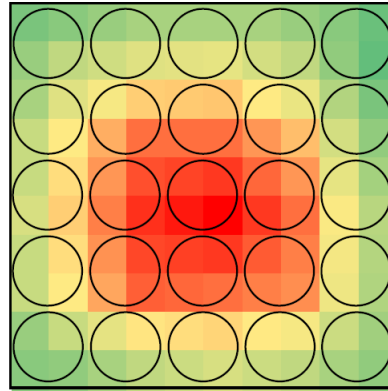


Source: Stefan Käbitz, Dissertation, RWTH Aachen Universität, 2016

# LITHIUM-ION-BATTERIES

## Thermal Management and Ageing

- Air cooling is not able to ensure homogeneous temperature within stack of cells
- Capacity loss of cells at higher temperature insight module higher!

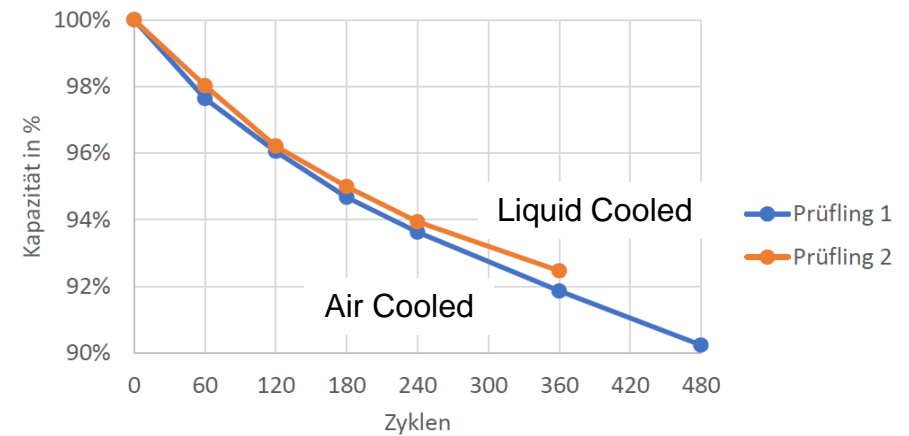
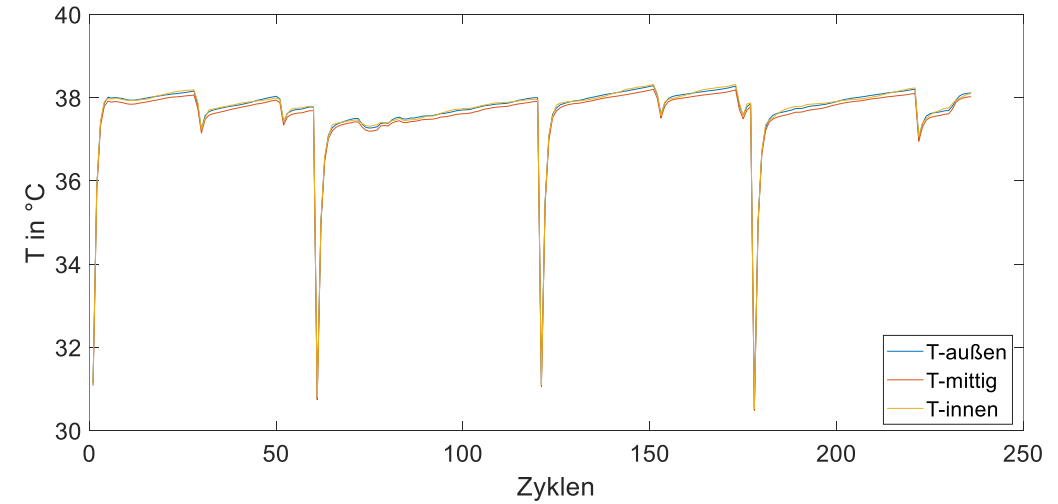
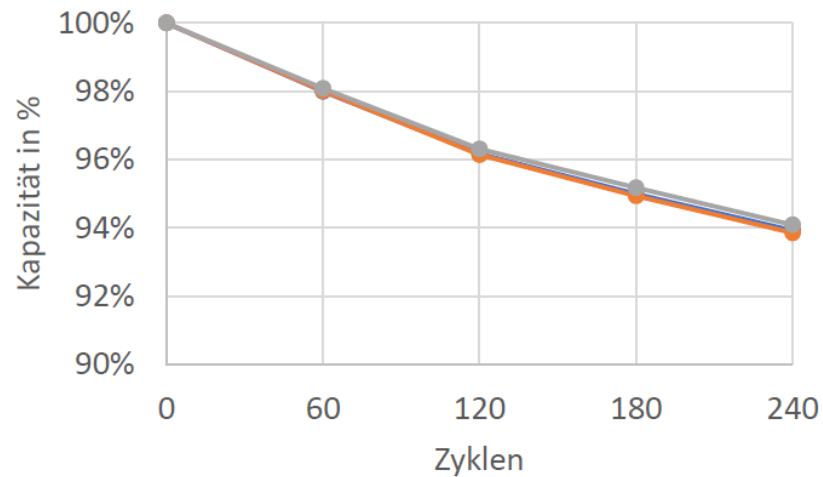


Source: Master Thesis Carl Felix Braun, BatterieIngenieure GmbH, RWTH Aachen 2018.

# LITHIUM-ION-BATTERIES

## Thermal Management

- Stack liquid cooled
- Significantly better thermal homogeneity
- Low capacity loss



## Capacity fade comparison between two battery modules

Quelle: Master Thesis Carl Felix Braun, BatterieIngenieure GmbH, RWTH Aachen 2018.



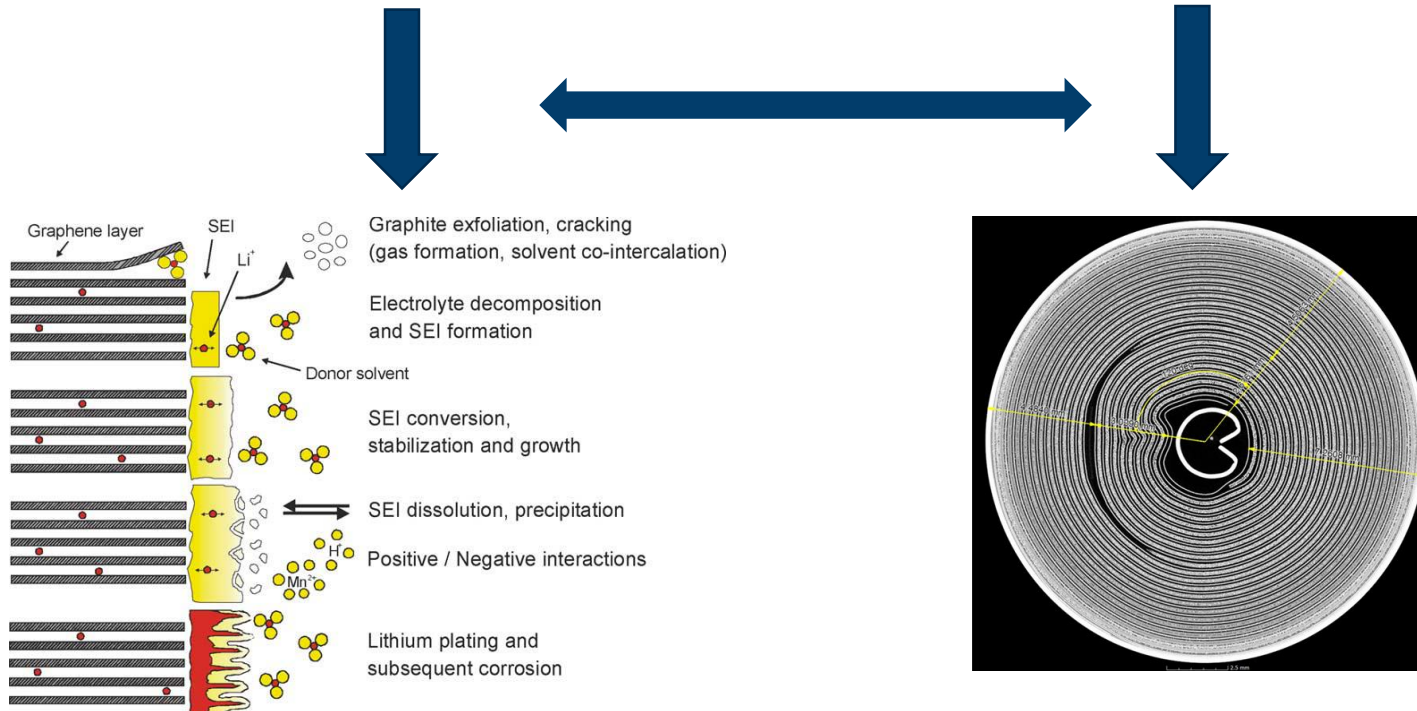
# LITHIUM-ION-BATTERIES

## Ageing

### Ageing Mechanisms

Electrochemical/Chemical

Geometric/Mechanical

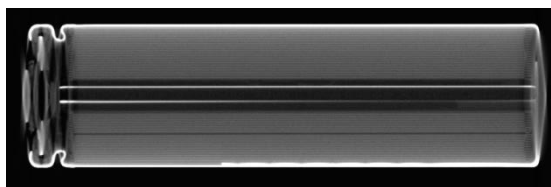
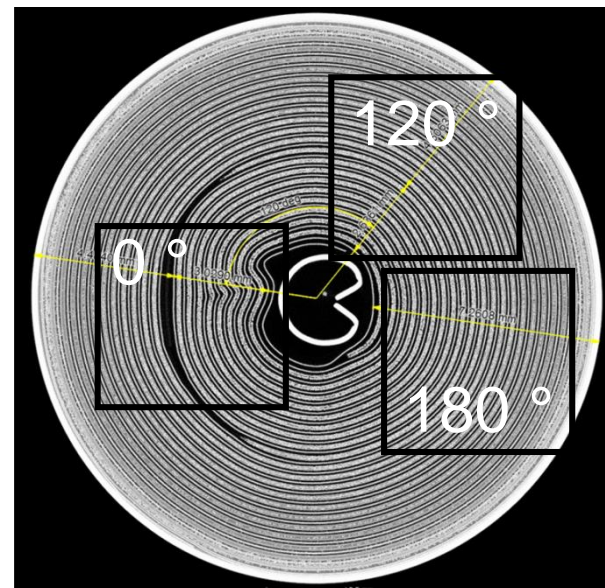
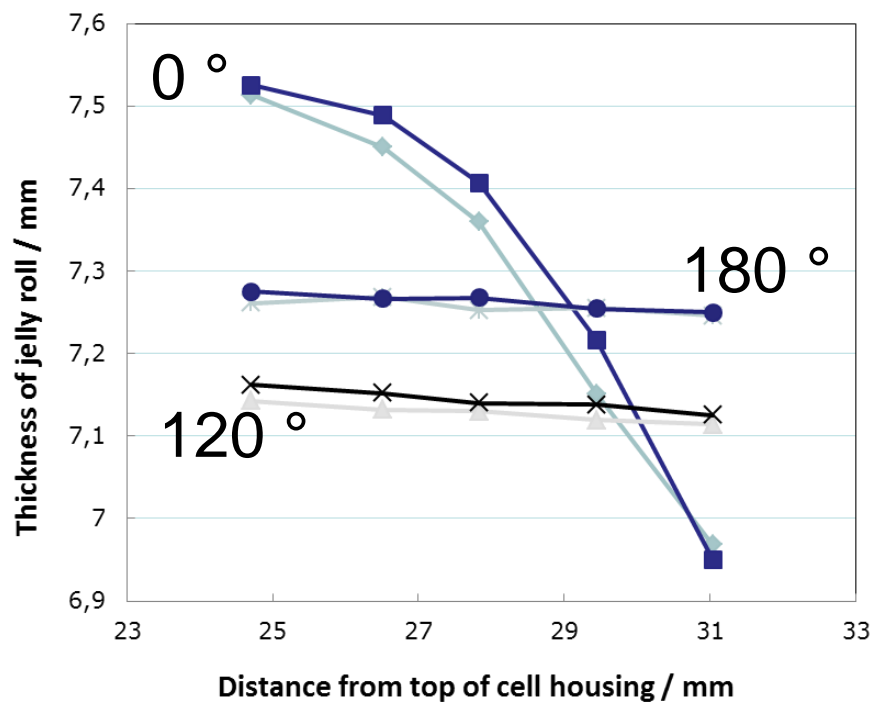


Vetter, J., Novák, P., Wagner, M. R., Veit, C., Möller, K. C., Besenhard, J. O., Winter, M... & Hammouche, A. (2005). Ageing mechanisms in lithium-ion batteries. *Journal of power sources*, 147(1), 269-281. Pfrang, Figgemeier et al, *Journal of Power Sources* 392 (2018) 168-175.



# MECHANICAL AGEING IN LIB

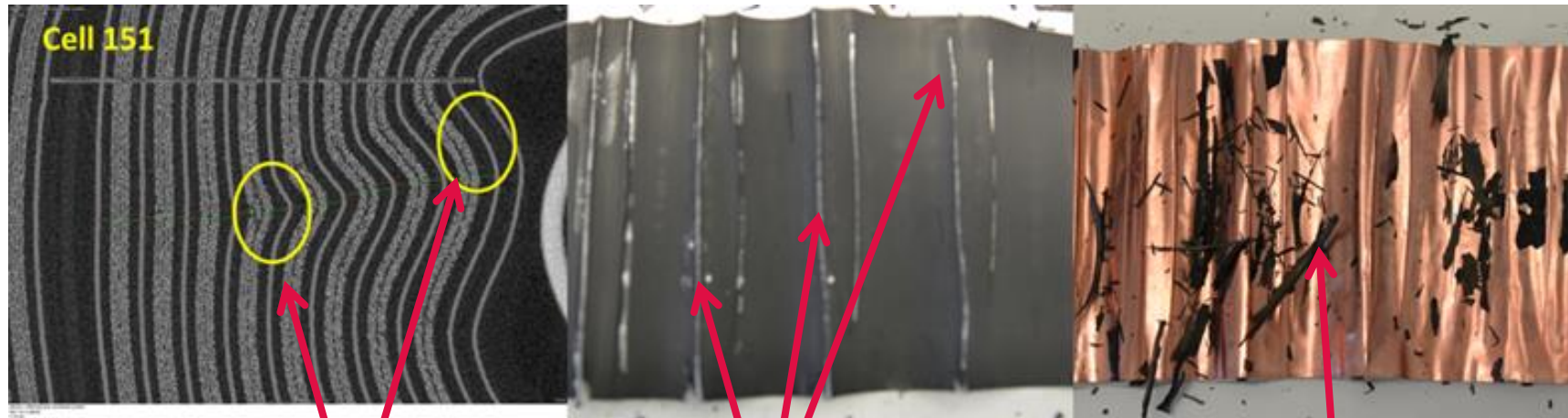
## Jelly Roll Expansion/Contraction



Source

# MECHANICAL AGEING IN LIB

## Jelly Roll Deformation and Electrode Delamination



Deformations

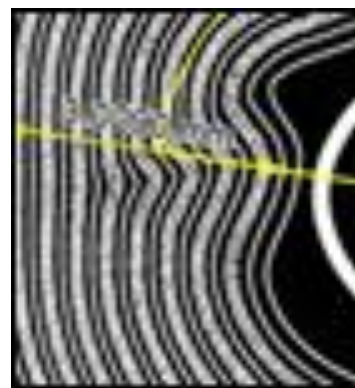
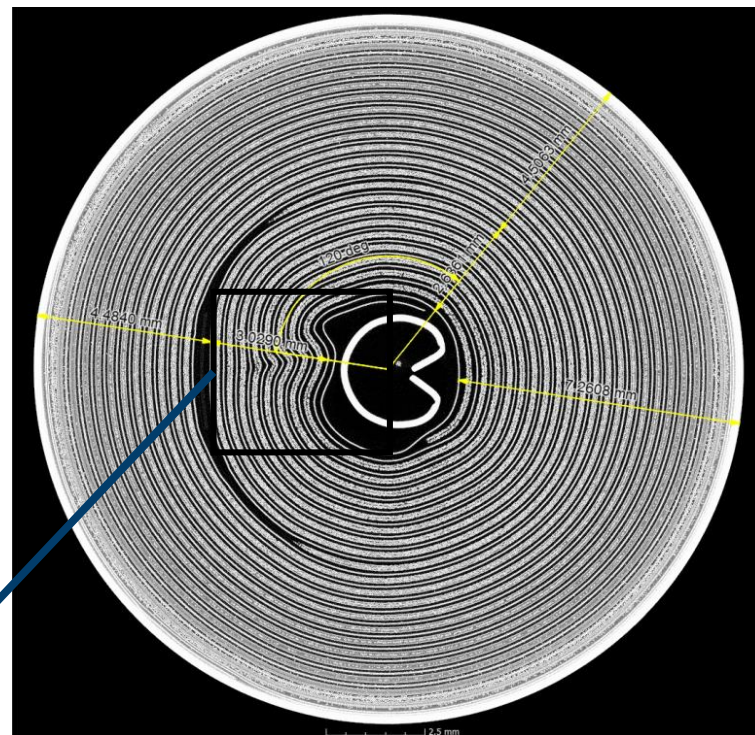
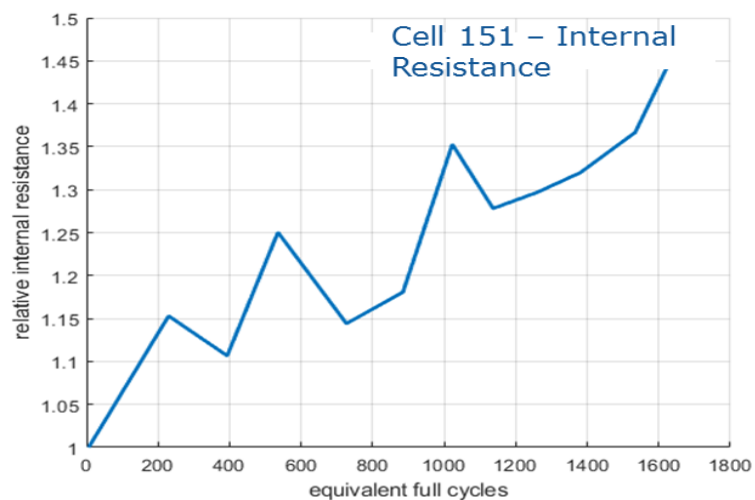
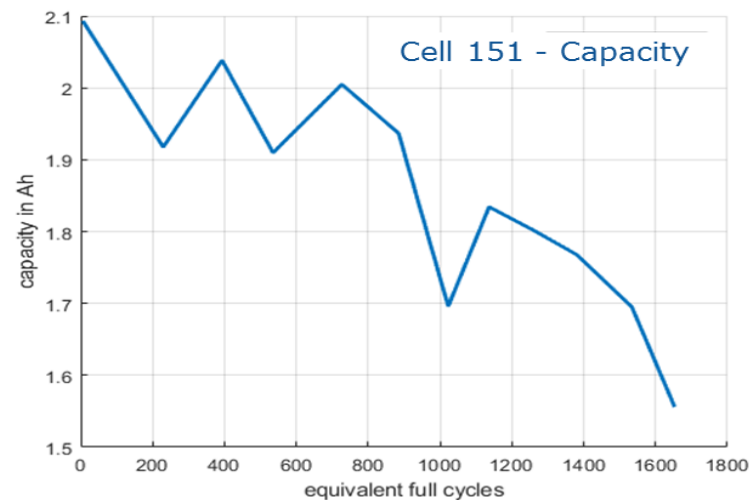
Desorption - Cathode

....Anode almost always comes off....

- Mechanical stress on current collectors!

# MECHANICAL AGEING IN LIB

## Capacity Loss & Jelly Roll Deformation



Micro-Shorts?

# MATERIALS IN LITHIUM ION BATTERIES

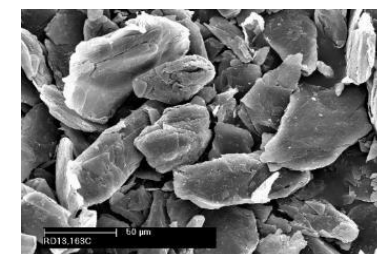
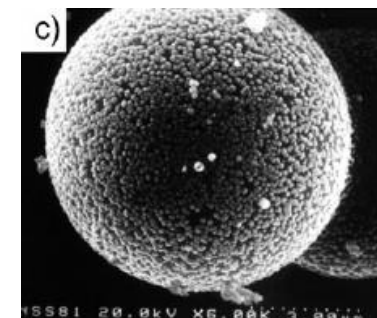
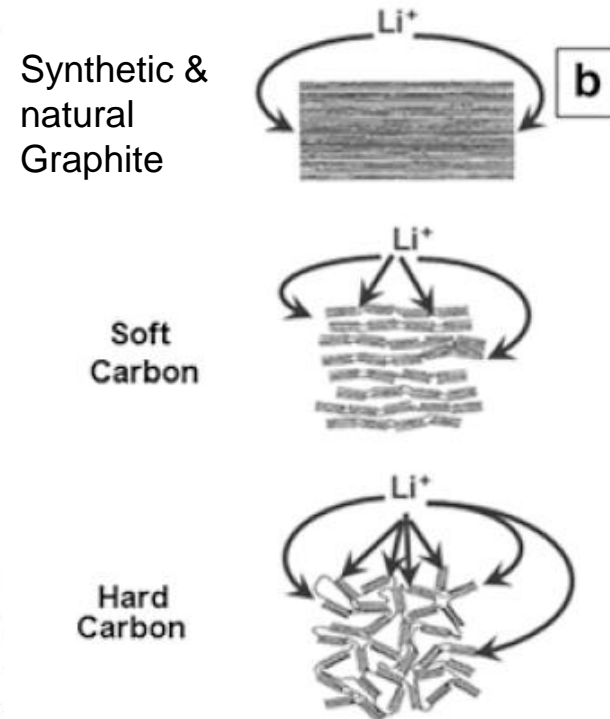
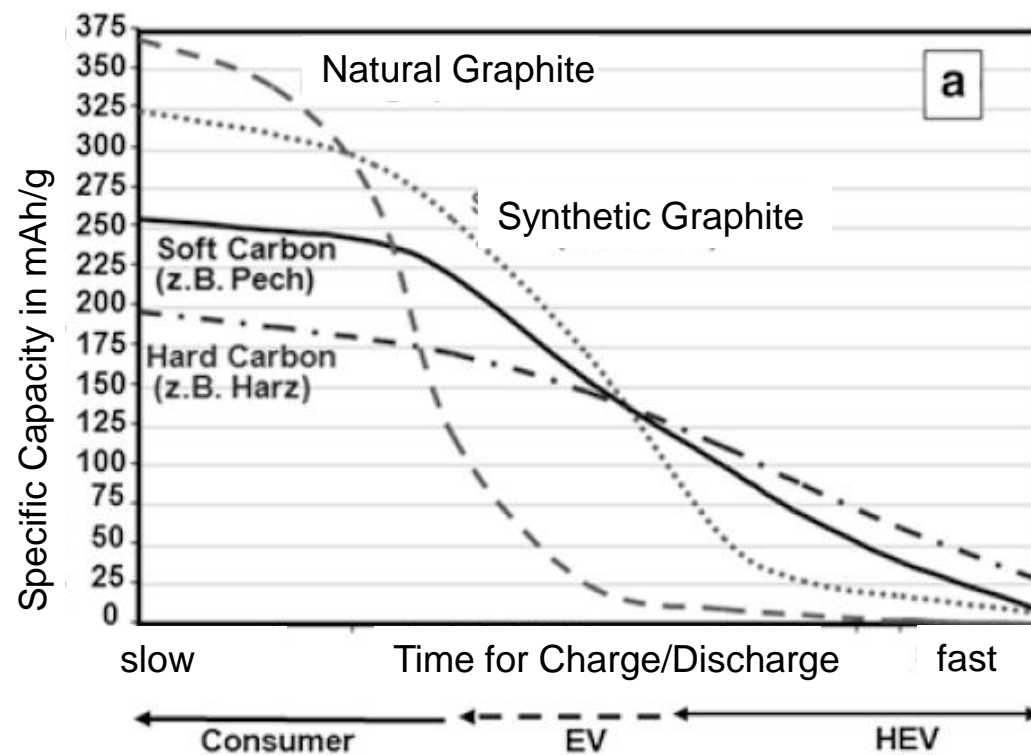
# MATERIALS IN LIB

A hot topic.....

- Copper
- Aluminum
- **Lithium**
- Organic solvents
- Polymeric separators
- Transition metals: **Cobalt**,  
Nickel, Manganese etc.
- Fluor (LiPF<sub>6</sub>)
- Etc.



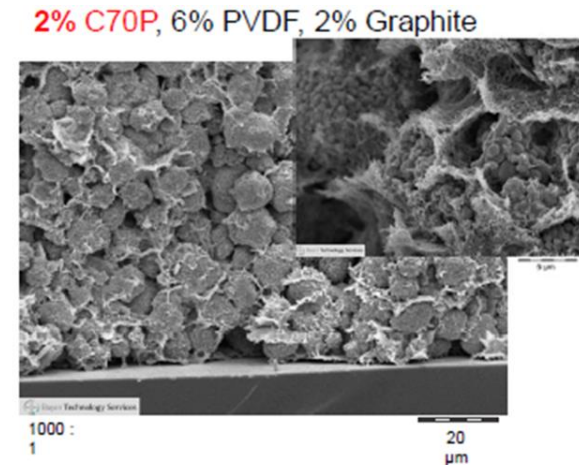
# ANODE MATERIALS



- Various graphites lead to optimized performances for applications

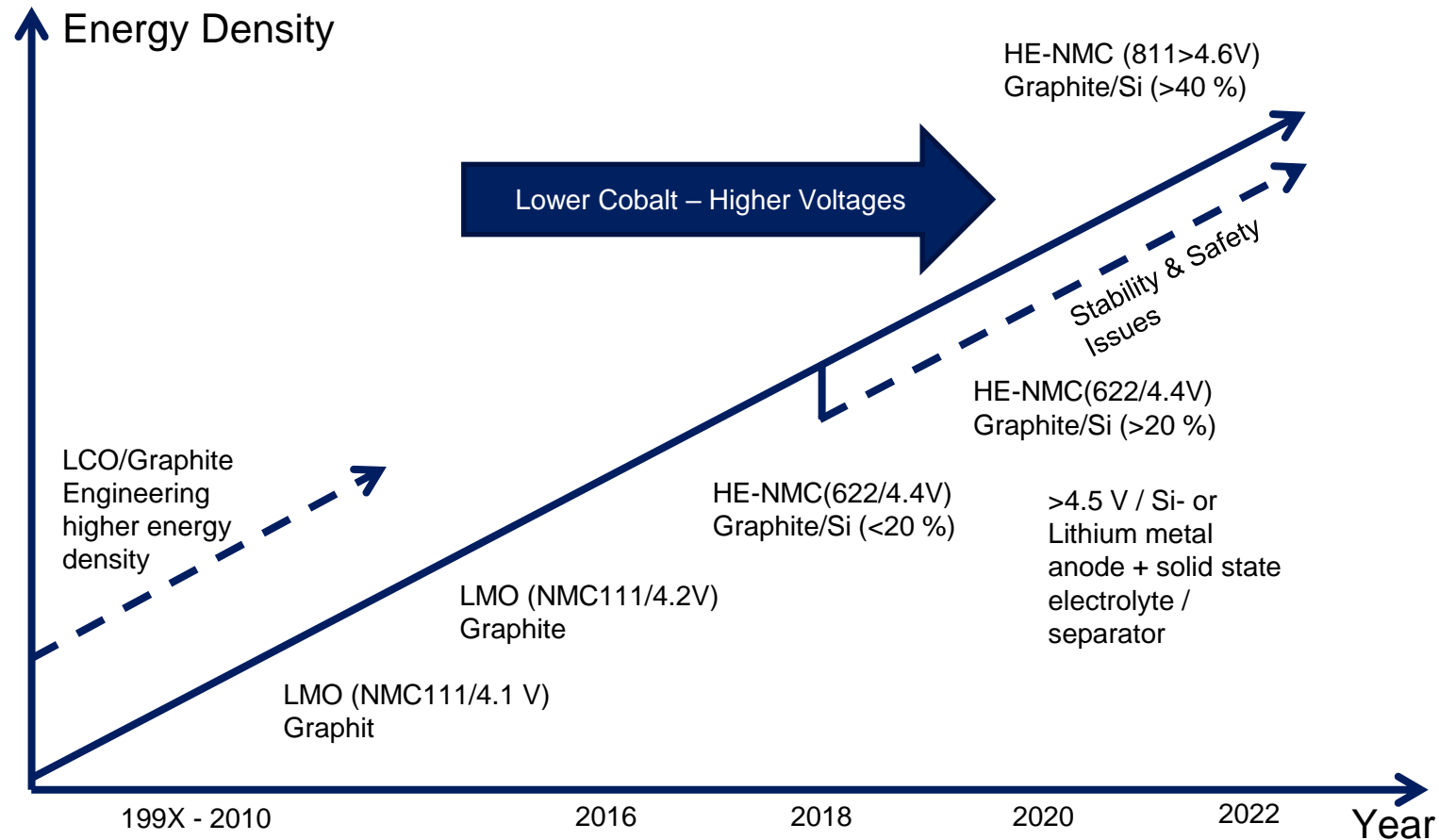
# CATHODE MATERIALS

Material	Energy Density	Power Density	Safety	Stability	Costs per Ah	Example
LCO – Lithium Cobalt Oxide	0	+	--	0	--	Consumer electronics
NCA – Nickel Cobalt Aluminum	+	+	--	-	0	Tesla
NMC – Nickel Manganese Cobalt	0	0	-	-	0	BMWi3
LMO – Manganese Cobalt	--	+	0	--	0	?
LFP – Iron Phosphate	--	+	+	+	+	Busses in China



Scale: Very bad -- / - / 0 / + / ++ very good

# LITHIUM ION BATTERY MATERIALS ROADMAP



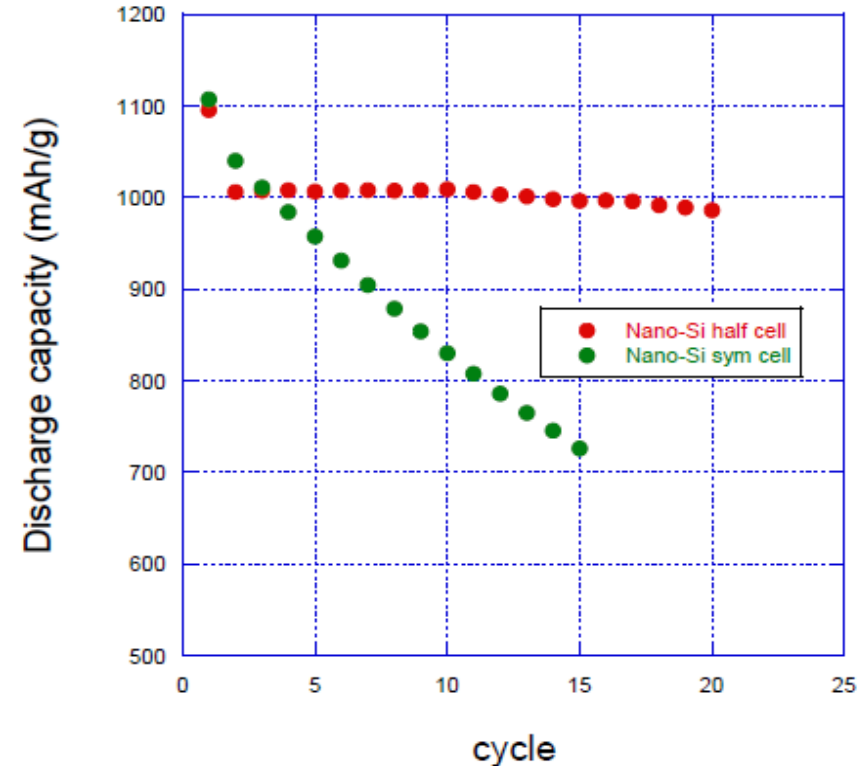


# LIB – TRENDS

Nano Materialien is a great hype.....

- Nano-Materials enable high power due to high surface area
- Nano-Materials suffer from high rate of side reactions → Degradation!
- Published data is almost never enough to judge the promise of the material for real applications

**Nano does not solve the problem!**



# ALUMINUM IN LIB

Plenty.....

- Cathode: NCA active material (e.g. Tesla/Panasonic Cells)
- Anode: Aluminum as active material
- Casing:
  - Hard case prismatic cells
  - Pouch bag cells
- Current collector



# ALUMINUM IN LIB

## Current Collector

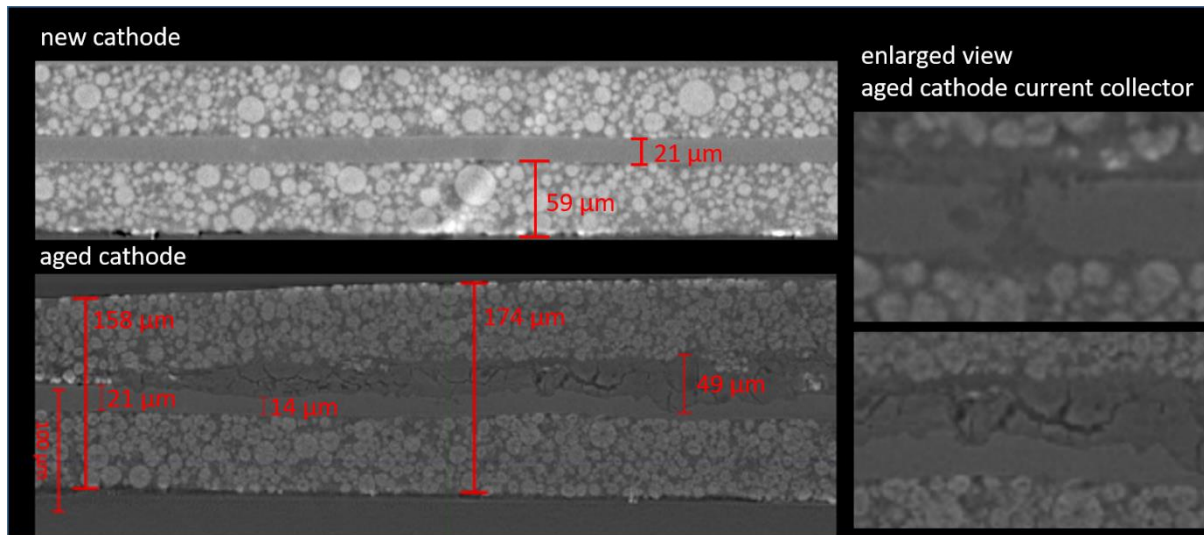
- Requirements:
  - Cathode material with high adhesion
  - High tear strength → Fast continuous coating process
  - Corrosion resistant....whatever that means at such voltages



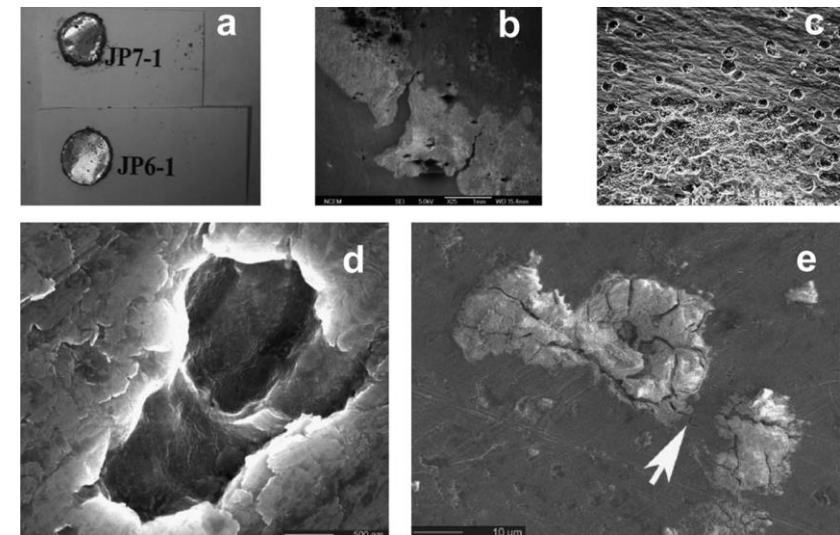
# ALUMINUM IN LIB

## Current Collector Corrosion

- HF created in-situ leads to corrosion of Al-current-collector in LiB
- Water-free electrodes and carbon coatings as preventive measures



Source: C. Rahe, DU Sauer, E. Figgemeier et al., Journal of Power Sources Volume 433, 1 September 2019, 126631.

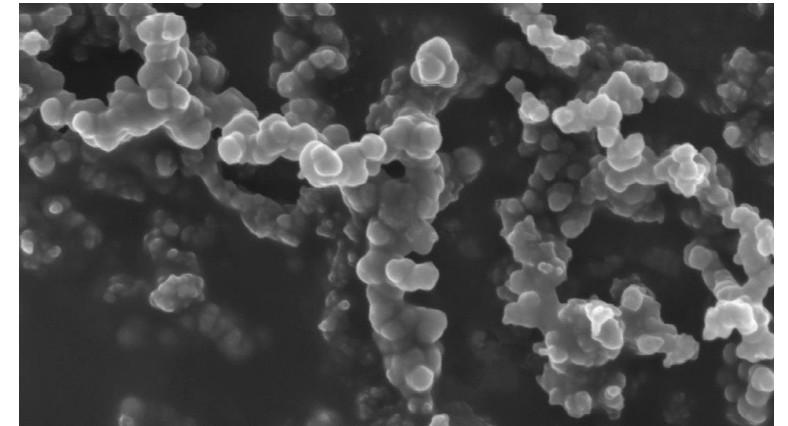
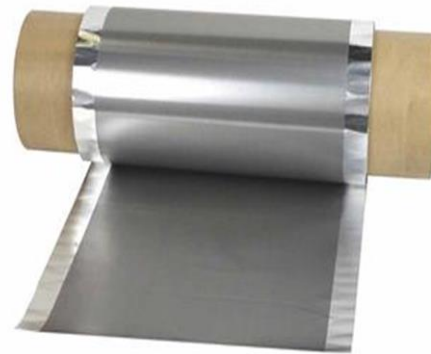


Source: J. Mater. Chem., 2011, 21, 9891–9911 | 9893

# ALUMINUM IN LIB

## Current Collector – Carbon Coating

- Up to  $\mu\text{m}$ -thick carbon coatings for preventing corrosion of Al-current-collector in LiB
- Most commonly wet-deposition of carbon slurry
- Improves adhesion and corrosion properties
- Commercial products: e.g. – „Cambridge Energy Solutions:
  - Conductive carbon coating
  - Double side coating with 1 micron thickness each side
  - Density:  $0.5 \text{ g/m}^2$
  - Surface resistivity:  $< 30 \text{ ohms per } 25 \mu\text{m}^2$
  - Substrate of Aluminum foil
  - Purity  $> 99.9\%$
  - Aluminium Thickness: 16 micron



# ALUMINUM IN LIB

## Casings and Pouch Cell Bags

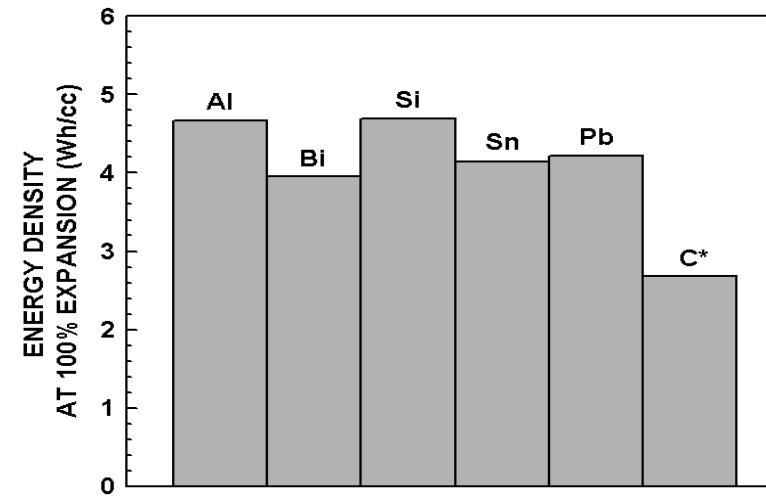
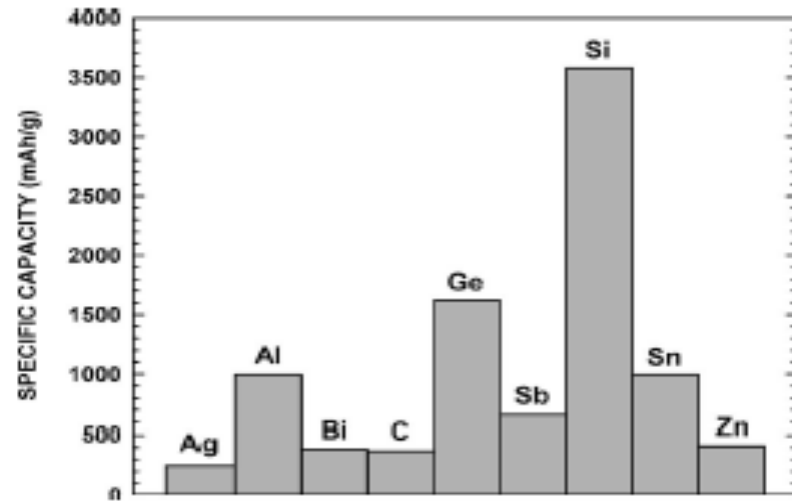
- Pouch bag foils:
  - Multilayer architecture: PE-Al-PP, sometimes mechanically enhanced by....
  - Tab sealing remains a challenge
  - Cooling along the rim is difficult
  - Notorious for electrolyte leakage
- Prismatic cell casings:
  - Laser welded sealing
  - Sometimes coatings insight for corrosion inhibition





# ALUMINUM IN LIN

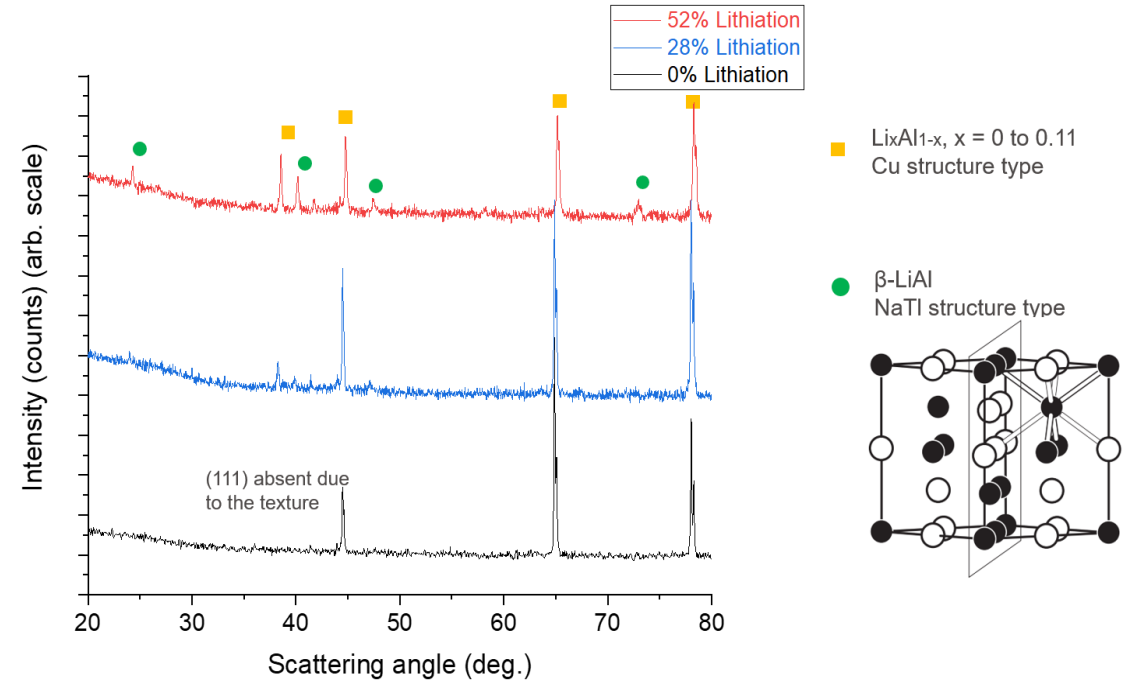
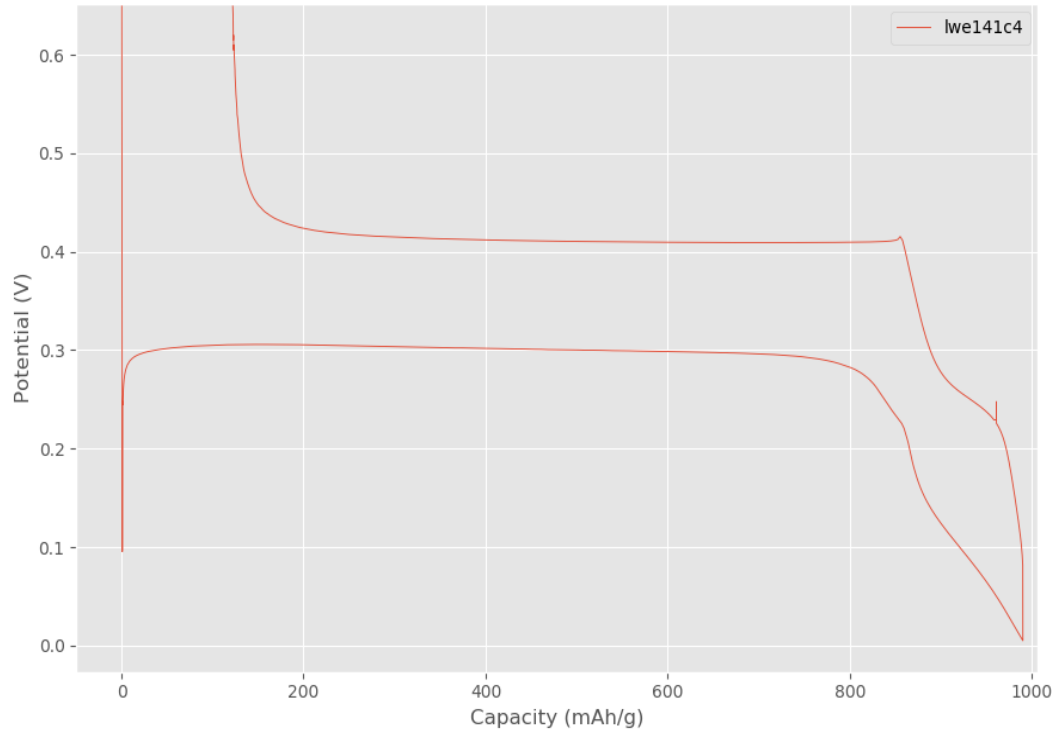
## Aluminum as anode active material



High energy density! Potentially low cost and abundant material

# ALUMINUM IN LIB

## Anode active material



Very slow insertion of Li into Al / Large irreversibility / Pulverization of foil



# SUMMARY

- Batteries market is growing double-digit and will grow for at least the next 10 years to come: Automotive is the driver, but many applications come with it.....
- Current developments are cost not performance driven!
- Development times for new battery technologies are counted in decades → Don't wait for a revolution! ...it won't come....
- Development times for new materials in established battery technologies: > 5 years!....minimum
- Multiple ageing mechanisms: Chemical, electrochemical, mechanical....

**Aluminum plays a major role!**  
**....maybe even more in the future...**



# Thanks!