Elektrotechnik und
Informationstechnologie

Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

Battery Technology
EPFL – Electrochemistry for materials technology

03-11-2025

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BFH-Zentrum Energiespeicherung

Organization

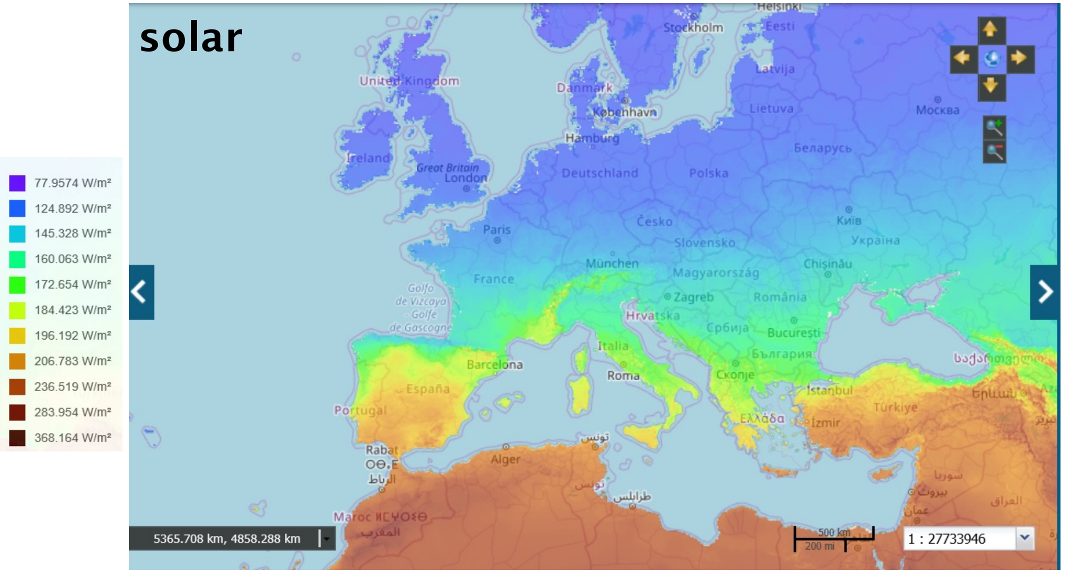
Program - Lecture

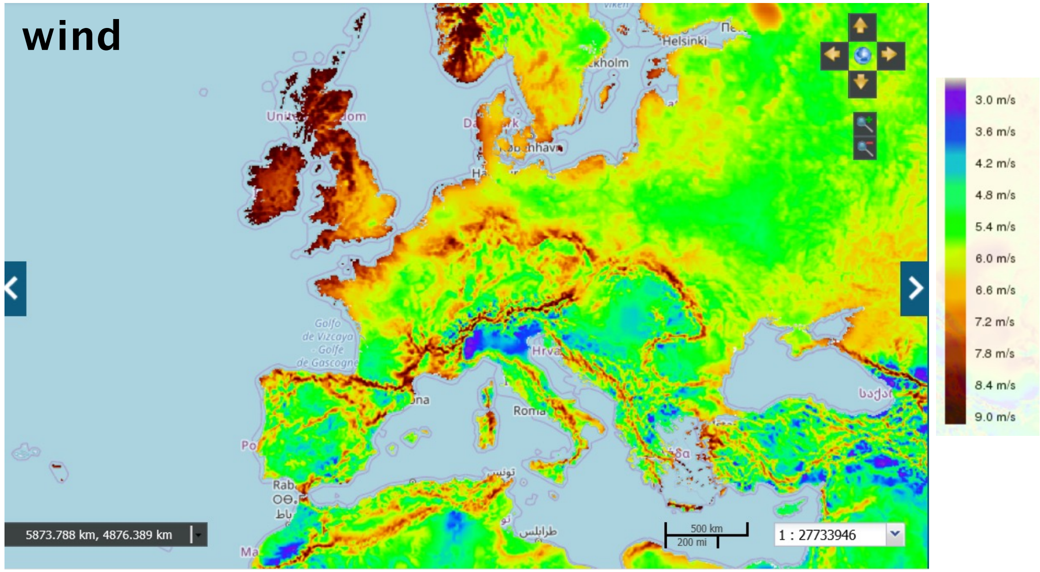
1. **Problem statement**
2. **Motivation**
3. **Battery materials**
4. **Battery definitions**
5. **Lifetime mechanisms and degradation**
6. **Testing and models**
7. **From theory to reality**

Problem Statement

Why do we need Energy storage?

Resources are unevenly spread over regions



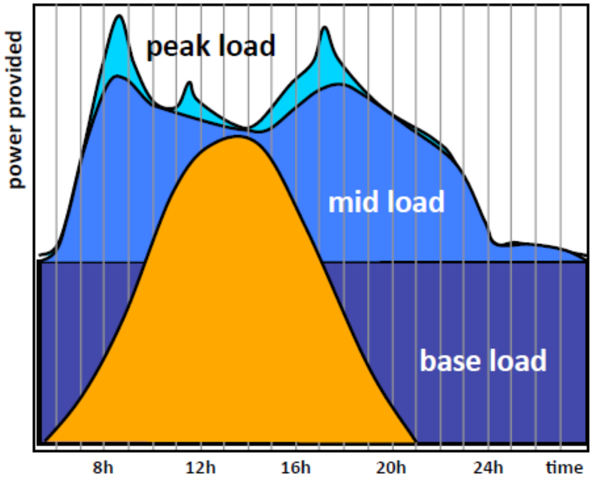


IRENA, VAISAL, global solar and wind maps https://irena.masdar.ac.ae/gallery/#map/543

and…

Why do we need Energy storage?

…they vary along the day

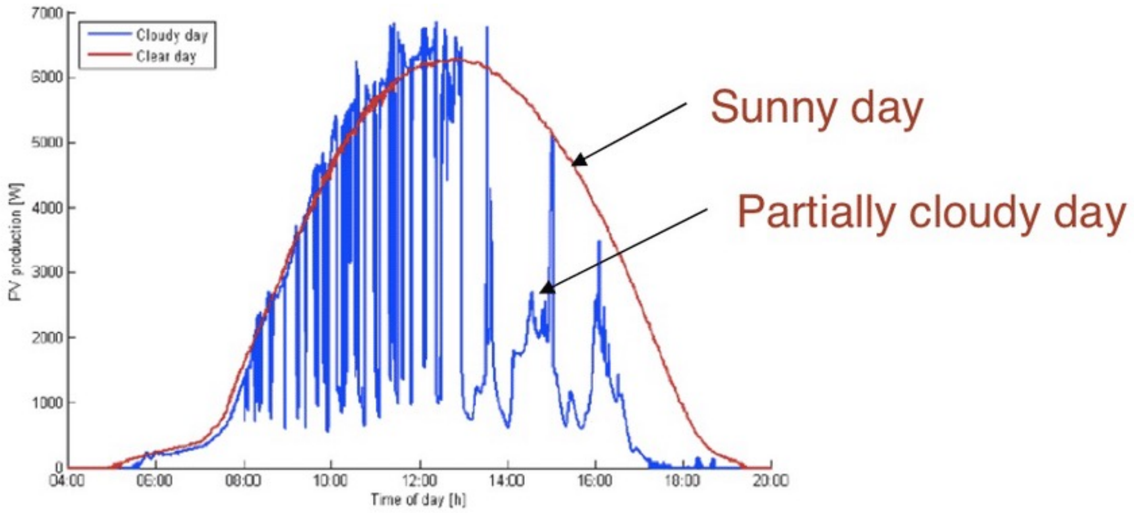


Problem 1:
Base load cannot be provided by renewables

Problem 2:
Peak load partially required when no renewables are generated

Why do we need Energy storage?

…they vary along the day



Problem 1:
Base load cannot be provided by renewables

Problem 2:
Peak load partially required when no renewables are generated

Need for energy storage to bring periods between when/where energy is **available** & when/where it is in **demand**

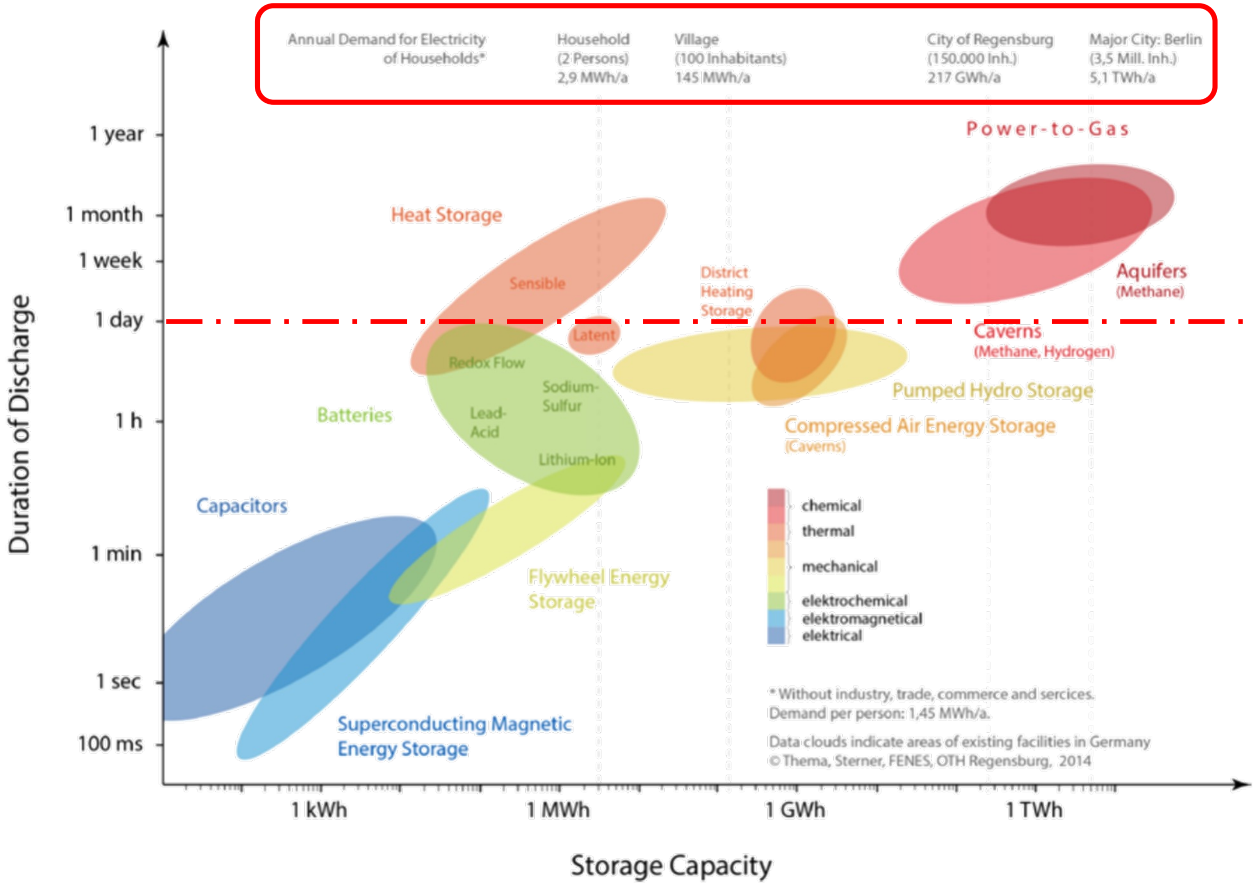
Why do we need Energy storage?

Energy storage can have different aims:

- Compensate **geographical distances** between supply and demand
- Compensate **time differences** between production and demand, fluctuations:
  - Bridging **seasonal differences** and imbalances
  - Leveling daily load cycles, ‘**peak shaving**’

- Improving stability, power quality, and reliability of supply

Comparison of Energy Storage technologies

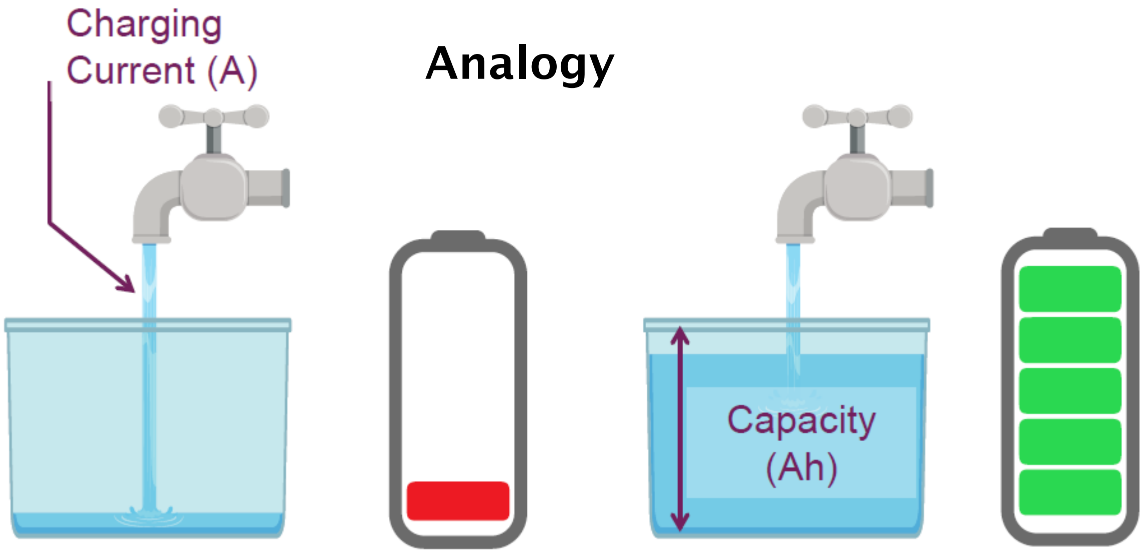


Observations:

- Reference energy needs as term of comparison
- Facilities comparison
- **Different technologies for different applications**
- Most technologies in the short-term storage range (t < 24h)
- Only chemical-energy storage systems using Power-to-Gas technologies reach the same scale and range as fossil fuel

Source: Energy storage as strategic reserve and synergies in existing infrastructures – a systematic view Prof. Dr.-Ing. Michael Sterner et al.

Energy Storage – Terminology



Current (Amps): Rate of electron flow (water flow)

Capacity (Amp -hours): Amount of electrons a battery can store (container size)

Voltage (Volts): How much work can be done by each electron (like water pressure)

Energy (Watt -hours): Total ability to do work –Capacity x Voltage

Electrochemical storage

Power density:
How quickly can that energy be delivered?

Supercapacitors:
specific energy 10^{-2}-10^{-1} Wh/kg
specific power 10^{1}-10^{4} W/kg
time scale 10^{-1}-10^{-5} h

- High power output
- Limited storage capacity

Batteries:
specific energy 10^{0}-10^{3} Wh/kg
specific power 10^{1}-10^{4} W/kg
time scale 10^{0}-10^{-1} h

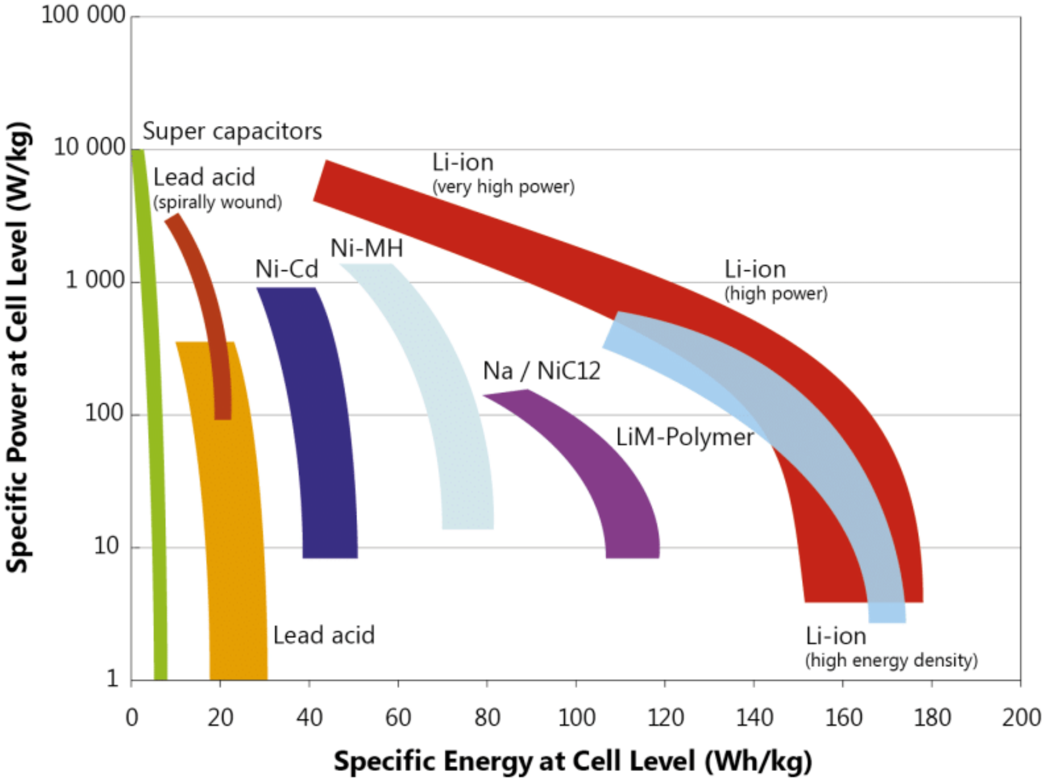
Fuel cells:
specific energy 10^{2}-10^{3} Wh/kg
specific power 10^{0}-10^{1} W/kg
time scale 10^{1}-10^{2} h

- low power output
- High storage capacity

Source: Rüdiger-A. Eichel, introduction to battery technology JESS 2014.

Energy density:
How much energy is available?

Batteries can be optimised for energy and power



Ragone diagram of the most common accumulators with distinction between high energy and high-power cells. Power values refer to the cell level

Electrochemical storage

Batteries are Electrochemical energy storage devices

Electrochemical devices can **convert electrical energy into chemical energy** and vice versa

Since the conversion from chemical energy into electric energy is direct, the **conversion efficiency is high** (for batteries above 90%)

- (Internal Combustion engine efficiency: ~30-40%)
- (Fuel Cells: ~40-60%)

Motivation

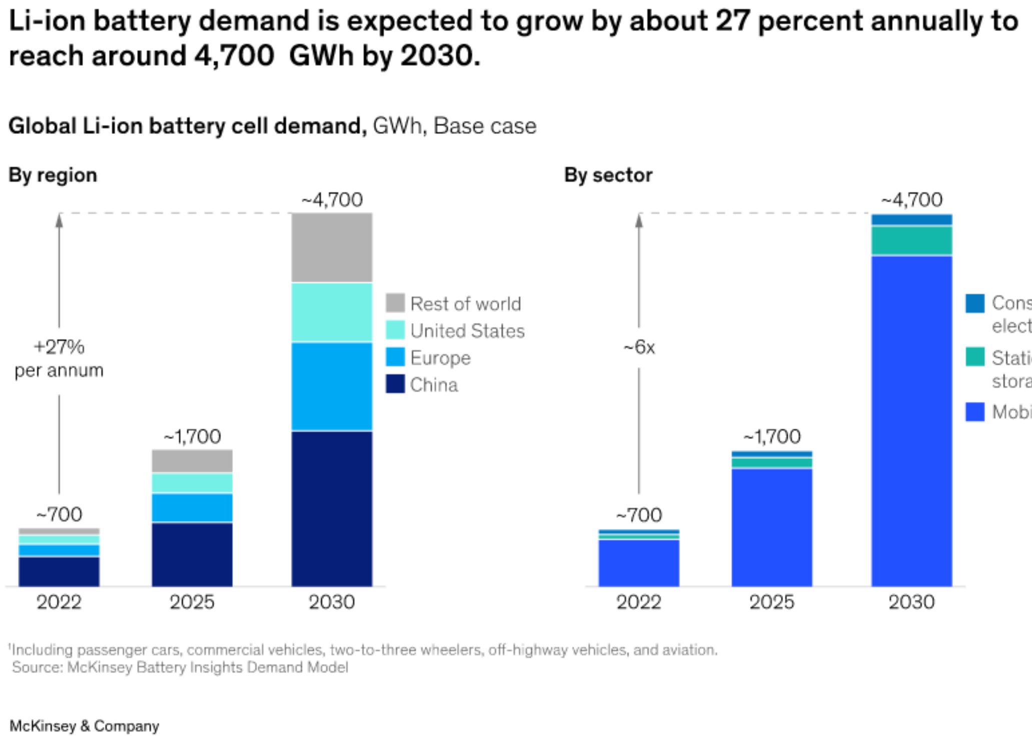
Battery capacity needed in 2030

4’700 GWh a year globally **by 2030**

In 2030, 40 % of demand for lithium-ion batteries is expected to come from China

Approximately **90 %** of the demand will come from **mobility** applications most importantly, electric vehicles (EVs)

Over 26 million electric cars were on the road in 2022. (IEA 2023)



Li-ion battery demand is expected to grow by about 27 percent annually to reach around 4,700 GWh by 2030.

Global Li-ion battery cell demand, GWh, Base case

[1] Including passenger cars, commercial vehicles, two-to-three wheelers, off-highway vehicles, and aviation.
Source: McKinsey Battery Insights Demand Model

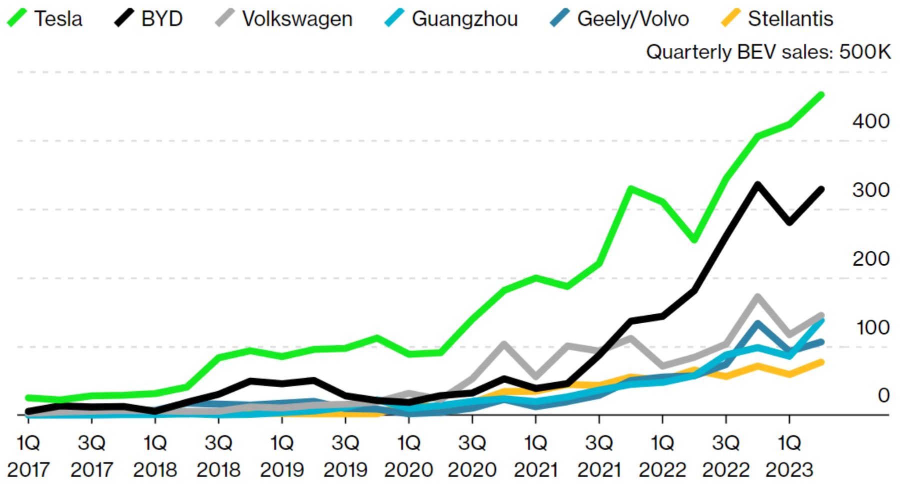
McKinsey & Company

Source: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular. McKinsey January 2023

Electrification of Light Duty Vehicles (LDV)

Old-school car manufacturers are losing the global **EV race.**

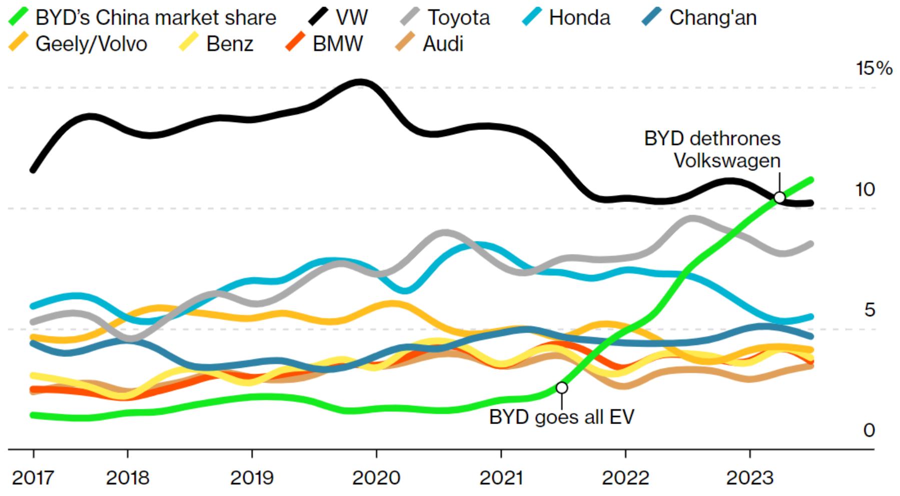
Volkswagen is a distant third behind the new giants of the industry



Source: BloombergNEF

Welcome to the future - China Edition

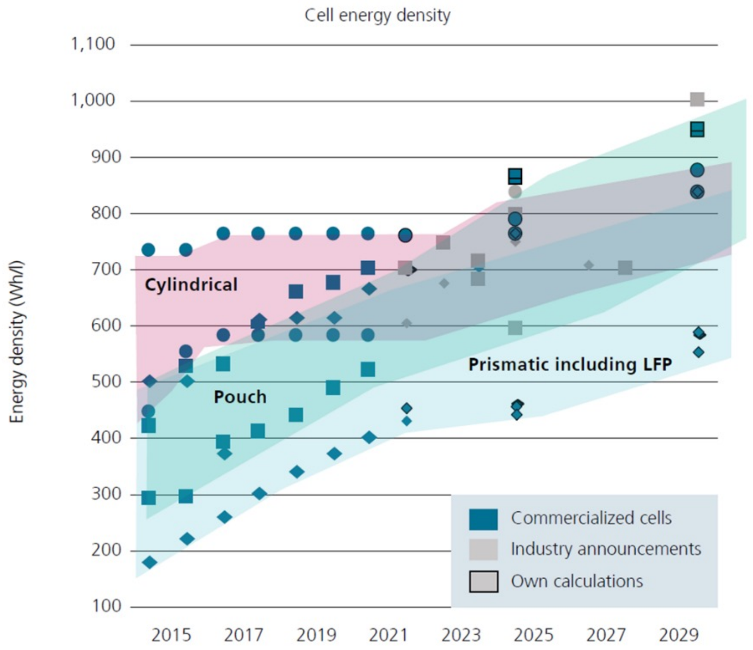
BYD became the **best-selling car brand in China** by winning the EV market



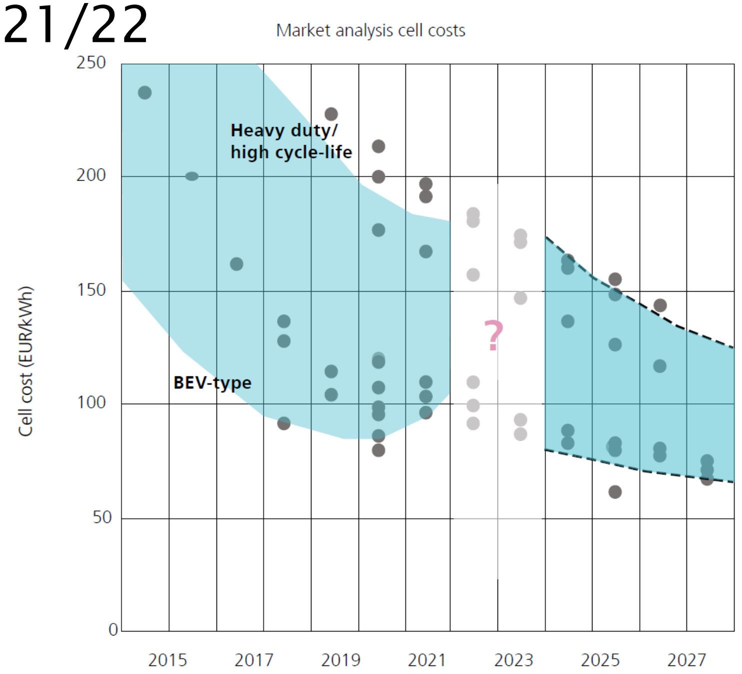
Source: China Automotive Technology and Research Center, Bloomberg Green

LIB Energy density increases, price falls

Density development for LIBs: Industry announcements and development activities



Analysis of the LIB cell cost forecasts of various analysts and the impact of the increase in raw material costs in 2021/22



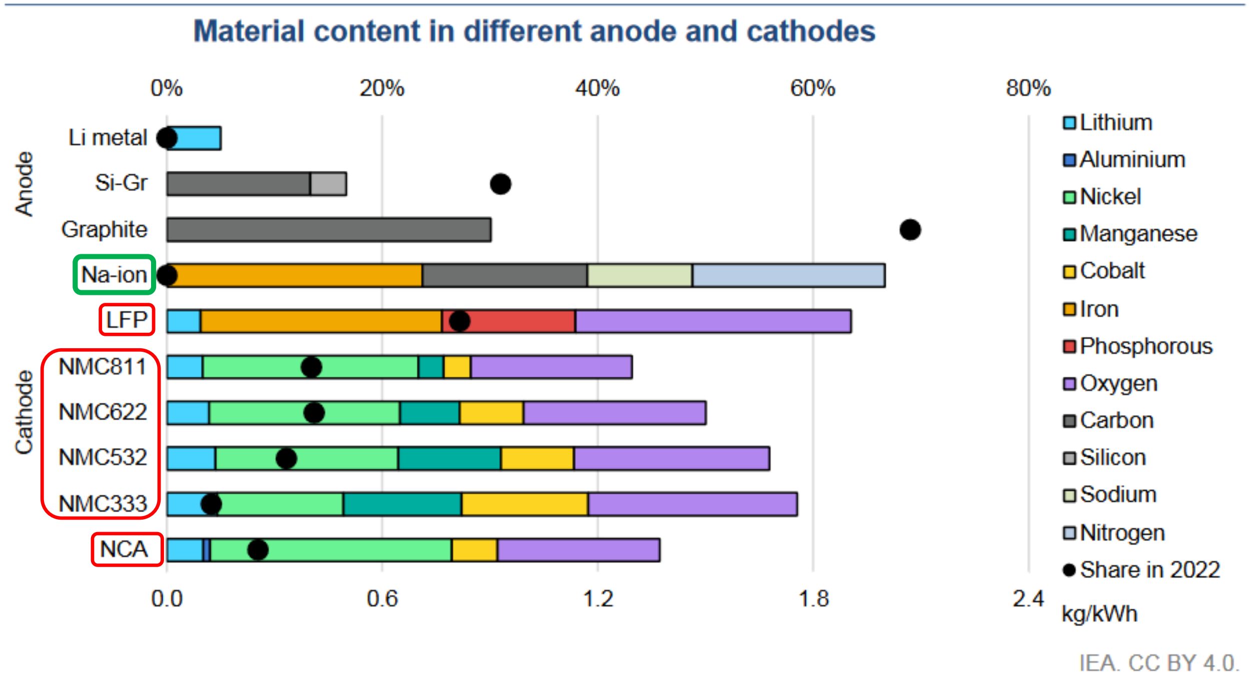
Quelle: Alternative Battery Technologies Roadmap 2030+; Fraunhofer ISI, Sept. 2023

Market shares of different Battery chemistries

In 2022, **NMC had market share of 60%, followed by LFP 25%,** and NCA with a share of about 8%.

With regards to anodes: Silicon-doped graphite, with the potential to increase Wh/kg account for 30% of market share.

Lithium metal anodes, which could yield even greater energy density when they become commercially available.

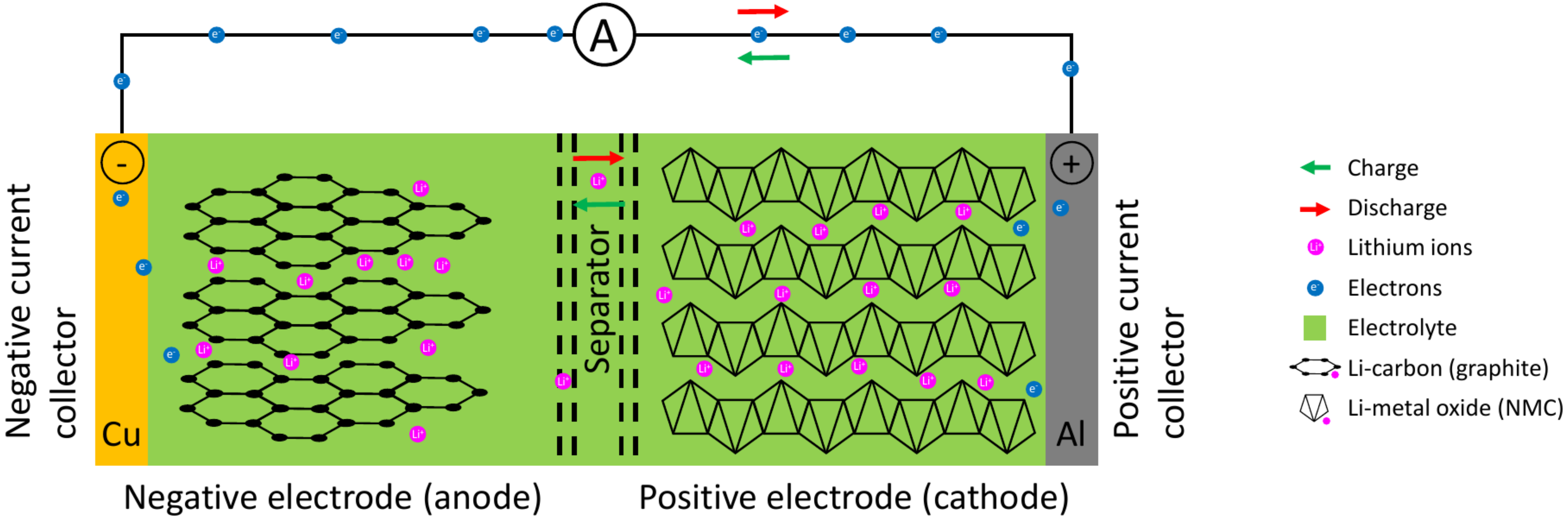


Source: Global EV Outlook 2023 Catching up with climate ambitions. IEA April 2023

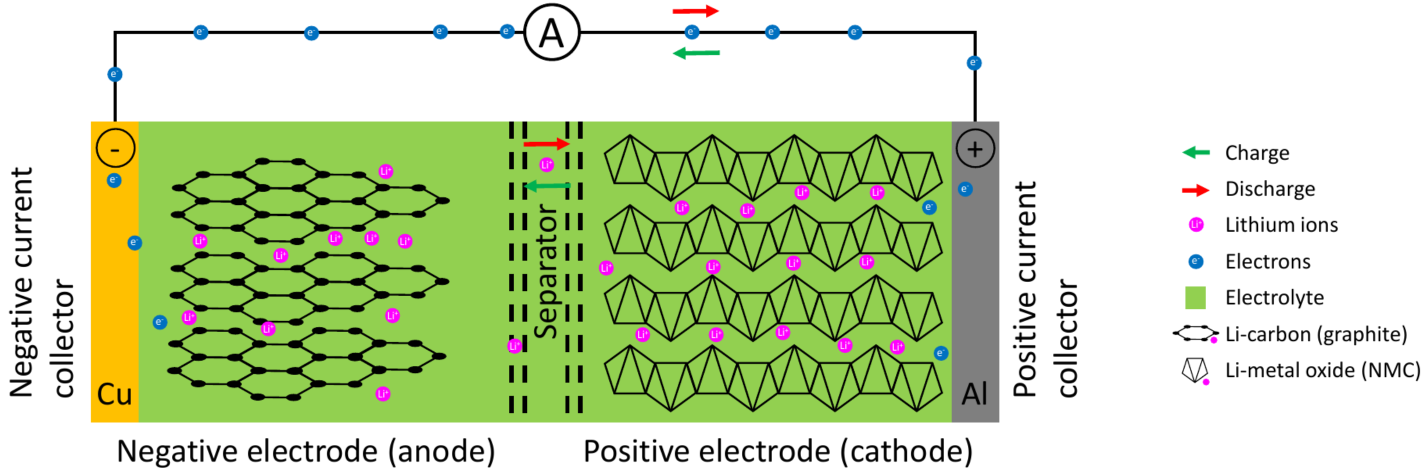
NMC = Lithium Nickel-Manganese-Cobalt oxides ($LiNi_xMn_yCo_{1-x-y}O_2$)
LFP = Lithium iron phosphate ($LiFePO_4$)
NCA = Lithium nickel cobalt aluminum oxide ($LiNi_xCo_yAl_zO_2$)

Battery Materials

Lithium-Ion Batteries



Lithium-Ion Batteries



A= ammeter (device to measure electric current)

The **collector** is a conductive material that **collects the current** generated by the electrochemical reactions occurring at the electrodes

Collectors are responsible for **conducting the electrical current** from the electrodes to the **external circuit**

Electrodes are conductive materials that facilitate the **electrochemical reactions** within the cell

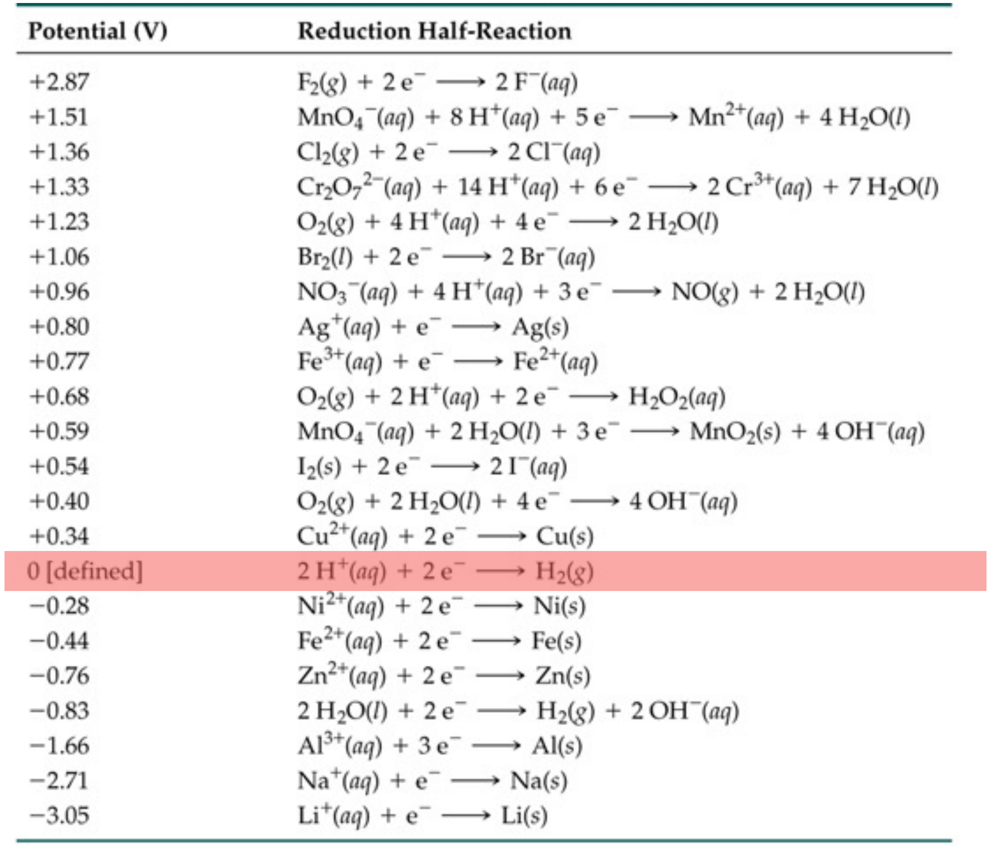
Electrodes are composed of active materials that undergo **oxidation and reduction** reactions during charge and discharge cycles

Separator made of a porous material that allows for the passage of ions while preventing direct contact between the electrodes

Why Lithium?

Lithium properties:
- Strong reducing agent
- High potential
- Light and stable
- Excellent reversibility
- High energy density

Strong oxidizing agent



Potential (V)	Reduction Half-Reaction
+2.87	$F_2(g) + 2e^- \longrightarrow 2F^-(aq)$
+1.51	$MnO_4^-(aq) + 8H^+(aq) + 5e^- \longrightarrow Mn^{2+}(aq) + 4H_2O(l)$
+1.36	$Cl_2(g) + 2e^- \longrightarrow 2Cl^-(aq)$
+1.33	$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \longrightarrow 2Cr^{3+}(aq) + 7H_2O(l)$
+1.23	$O_2(g) + 4H^+(aq) + 4e^- \longrightarrow 2H_2O(l)$
+1.06	$Br_2(l) + 2e^- \longrightarrow 2Br^-(aq)$
+0.96	$NO_3^-(aq) + 4H^+(aq) + 3e^- \longrightarrow NO(g) + 2H_2O(l)$
+0.80	$Ag^+(aq) + e^- \longrightarrow Ag(s)$
+0.77	$Fe^{3+}(aq) + e^- \longrightarrow Fe^{2+}(aq)$
+0.68	$O_2(g) + 2H^+(aq) + 2e^- \longrightarrow H_2O_2(aq)$
+0.59	$MnO_4^-(aq) + 2H_2O(l) + 3e^- \longrightarrow MnO_2(s) + 4OH^-(aq)$
+0.54	$I_2(s) + 2e^- \longrightarrow 2I^-(aq)$
+0.40	$O_2(g) + 2H_2O(l) + 4e^- \longrightarrow 4OH^-(aq)$
+0.34	$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s)$
0 [defined]	$2H^+(aq) + 2e^- \longrightarrow H_2(g)$
−0.28	$Ni^{2+}(aq) + 2e^- \longrightarrow Ni(s)$
−0.44	$Fe^{2+}(aq) + 2e^- \longrightarrow Fe(s)$
−0.76	$Zn^{2+}(aq) + 2e^- \longrightarrow Zn(s)$
−0.83	$2H_2O(l) + 2e^- \longrightarrow H_2(g) + 2OH^-(aq)$
−1.66	$Al^{3+}(aq) + 3e^- \longrightarrow Al(s)$
−2.71	$Na^+(aq) + e^- \longrightarrow Na(s)$
−3.05	$Li^+(aq) + e^- \longrightarrow Li(s)$

Strong reducing agent

Lithium-ion batteries

Lithium-Nickel-Manganese-Cobalt Graphite Oxide (NMC)

Lithium-Nickel-Cobalt-Aluminum and Graphite Oxide (NCA)

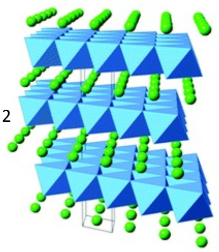
Lithium Iron Phosphate (LFP)

Lithium Titanate (LTO)

Electrodes materials of conventional Li ion battery

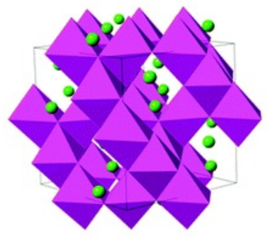
MeOx: Layered structure

$LiCoO_2$
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
$LiNiO_2$



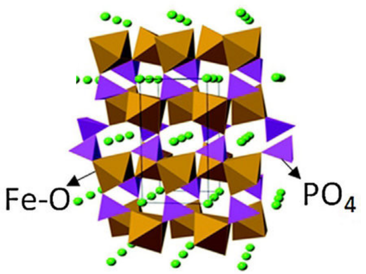
MeOx: Spinel structure

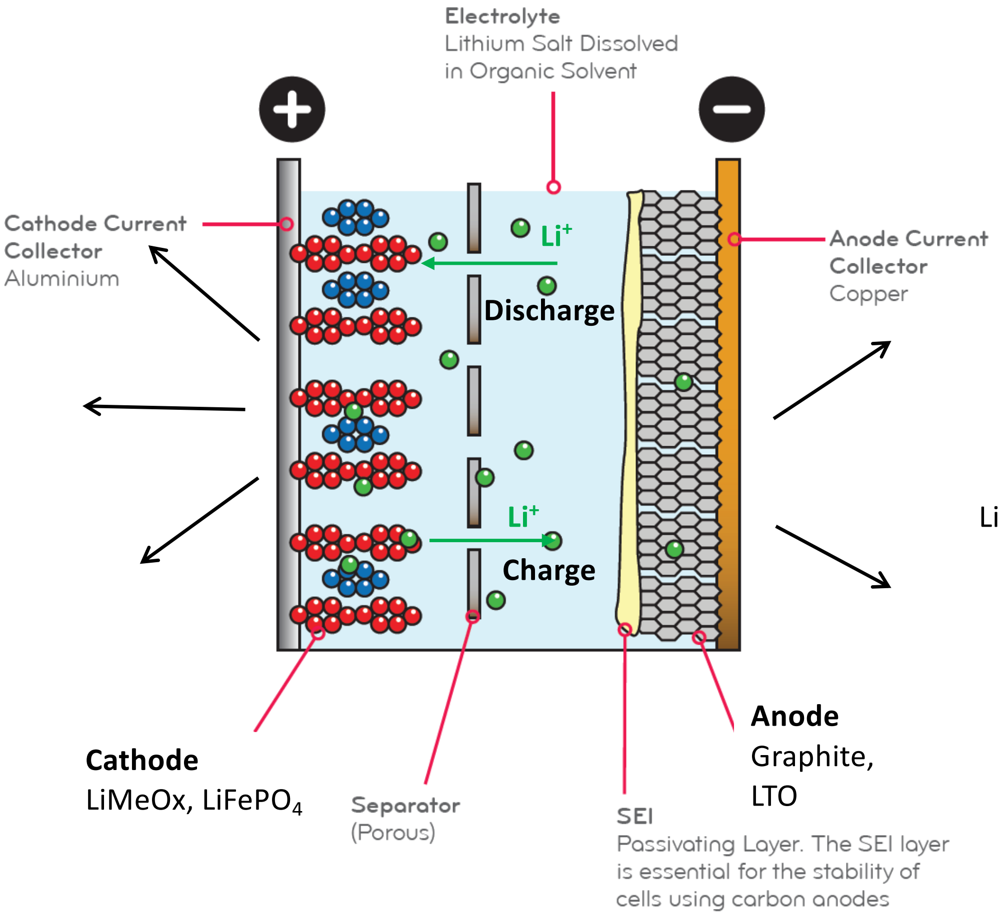
$LiMn_2O_4$



$FePO_4$: Olivine structure

$LiFePO_4$

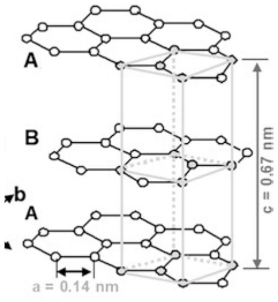




Cathode
$LiMeOx, LiFePO_4$

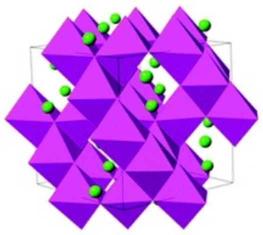
Anode
Graphite,
LTO

Graphite or C: Layered structure



C

Lithium titanate LTO: Spinel structure



$Li_4Ti_5O_{12}$

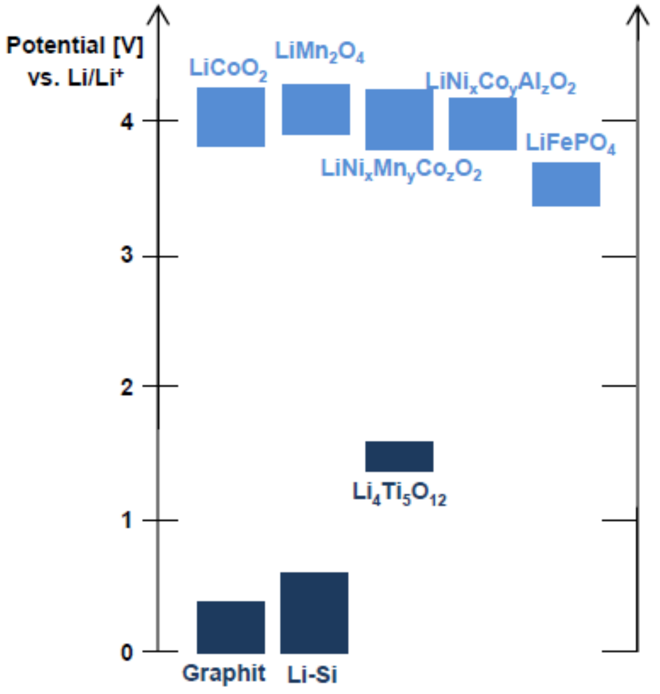
Source: Nitta et al., Materials Today, „Li-Ion battery materials: present and future", 2014

Overview of electrode materials

Positive Electrode materials

Metal -oxide	$LiCoO_2$	«LCO»
	$LiNi_xMn_yCo_{1-x-y}O_2$	«NMC»
	$LiNi_aCo_bAl_{1-a-b}O_2$	«NCA»
	$LiNiO_2$	«LNO»
	$LiMn_2O_4$	«LMO»
Phosphate	$LiFePO_4$	«LFP»

x mostly 0.33; y mostly 0.33 (Less Co in the Future, but more Ni)
a mostly 0.80; b mostly 0.15;



Quelle: Moderne Akkumulatoren richtig einsetzen, Inge Reichardt Verlag, 2006

Negative Electrodes materials

C	«Graphite»*
$Li_4Ti_5O_{12}$	«LTO»

Electrodes materials of conventional Li ion battery

	CATHODE MATERIAL
Good lifetime **high safety risk**	$LiCoO_2$
Highest safety risk, **good performance**	$LiNiO_2$
Cheaper, safety better than for Co & Ni	$LiMn_2O_4$
Popular, wide variability for optimizing prop.	$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$
Wide variability in materials	$LiCo_xNi_yMn_zO_2$
“3.3 V material”, **cheap & safe**	$LiFePO_4$

ANODE MATERIAL	
Hard Carbon LiC_6	“3.7 V material”, **small number of full cyles**
Graphite LiC_6	“3.7 V material”, expensive, **high number of full cycles**
Titanate $Li_4Ti_5O_{12}$	“2.2 V material”, safe, **low energy density**
Silicium $Li_{22}Si_6$	“3.7 V material”, high energy density

Adapted from Dirk Uwe Sauer - Summer School on Fuel Cells, Battery, and Hydrogen Technology Greece, 19.09.2013

Electrodes materials of conventional Li ion battery

Electrolyte and binding materials are central component regarding low-temperature and lifetime performance.

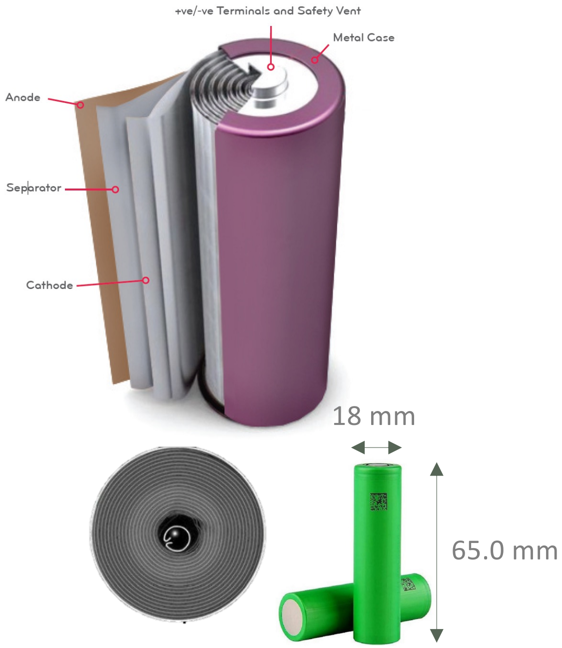
	SEPARATORS
Generally: expensive subcomponent in Li-Ion cells	Standard
Multilayered separator with melting layer (**high resistance when overheating**)	Shut-Down
Ceramic separator **avoids short-circuits when overheated**	Separion

ELECTROLYTES	
Standard	**Electrolytes**: EC, PC, DMC, DEC, EMC **Conducting Salt**: $LiPF_6$, $LiCF_3SO_3$, $LiN(CF_3SO_2)_2$ **Additive**
LIBOB	Higher safety
Polymere	Safe, low conductance at room temperature
Ionic Liquids	Possible electrolyte for 5-volt cells

Adapted from Dirk Uwe Sauer - Summer School on Fuel Cells, Battery, and Hydrogen Technology Greece, 19.09.2013

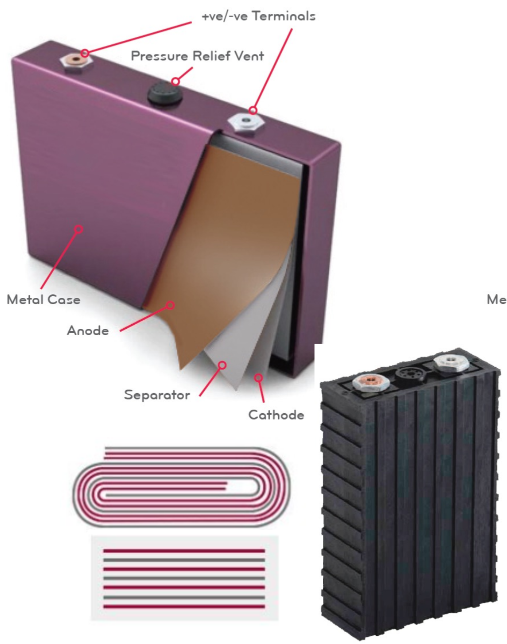
Different cell formats

Cylindrical



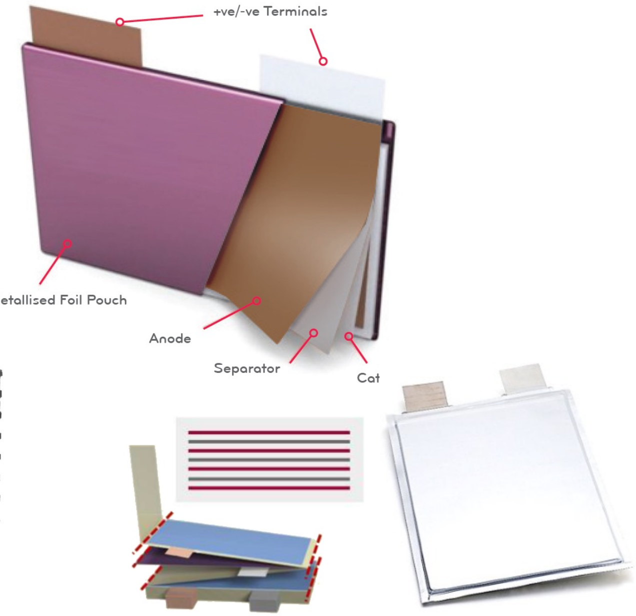
- A lot of experience in cell design
- High life-time
- Complex Cooling
- Supplier e.g. Saft, Sanyo, LG

Prismatic



- Easy stacking in battery packs
- Combines characteristics of the other cell designs
- Supplier e.g. Sanyo, Lishen

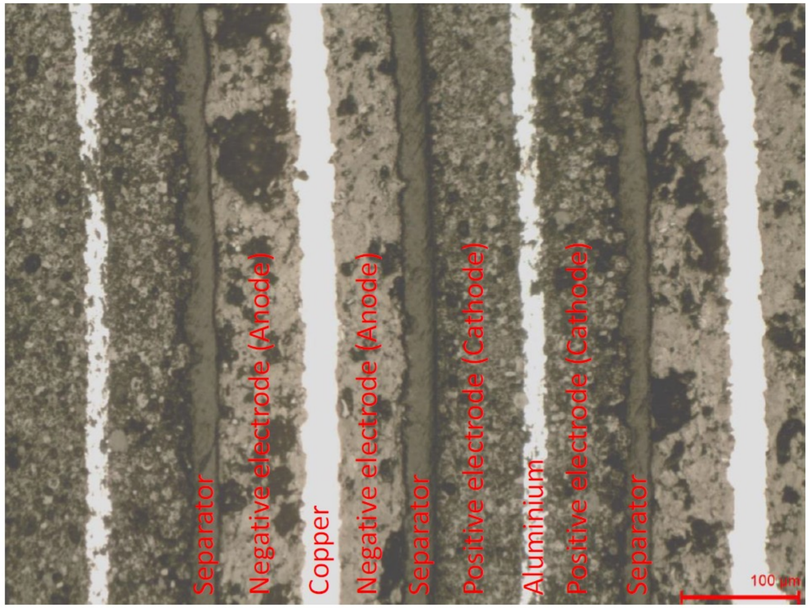
Pouch



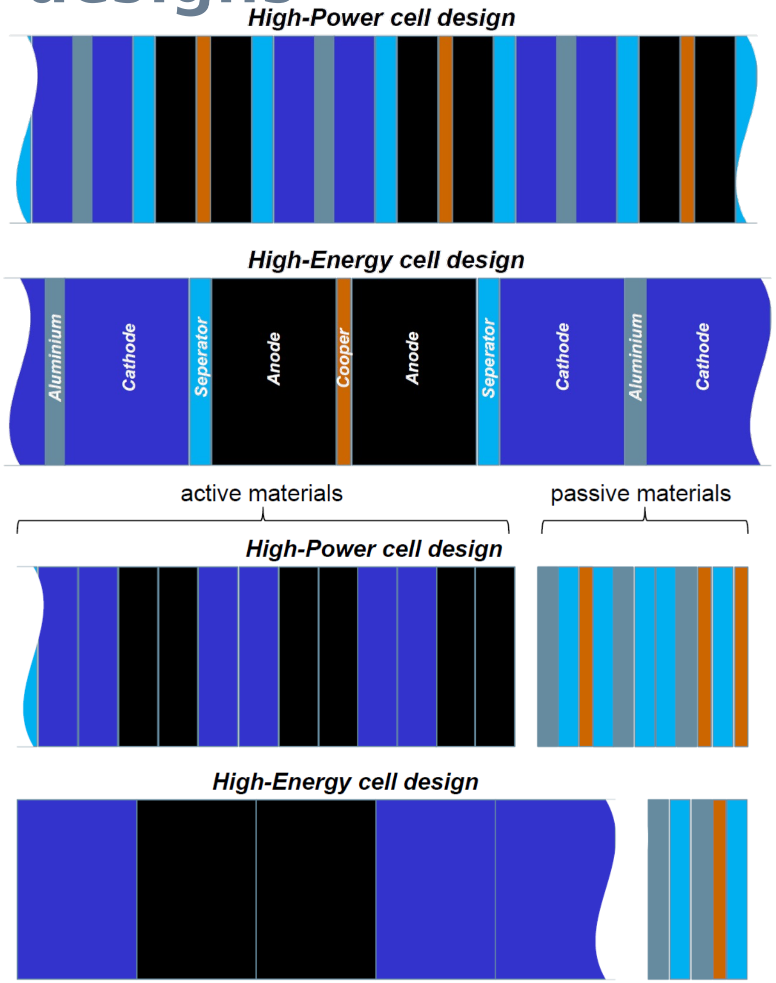
- Good cooling character
- High energy density
- Main question: Tightness of the film
- Supplier e.g. Kokam, Leclanche

Quelle: Johnson Matthey Battery Systems, 2012, „Our Guide to Batteries“

High-Power and High-Energy cell designs

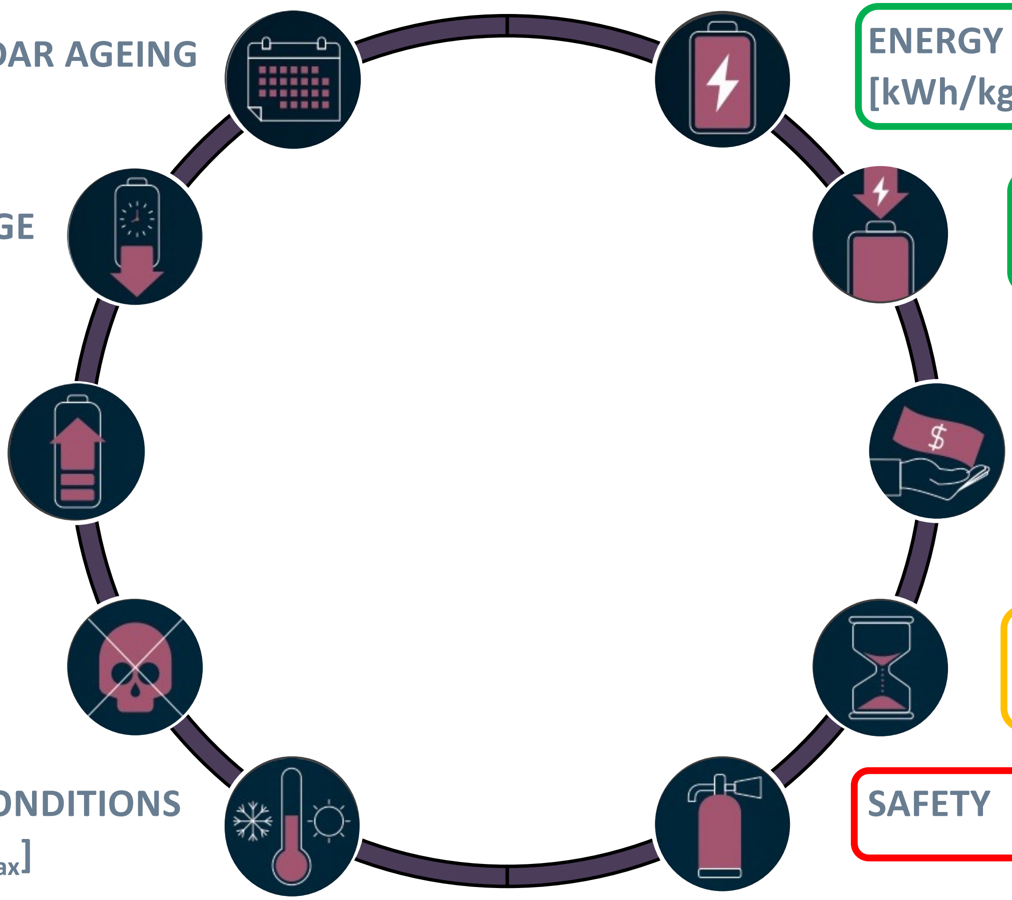


View of the jelly roll design



Adapted from Dirk Uwe Sauer - Summer School on Fuel Cells, Battery, and Hydrogen Technology Greece, 19.09.2013

Evaluation criteria and key challenges



CALENDAR AGEING

AUTO DISCHARGE

FAST CHARGE/DISCHARGE
[C-Rate]

TOXICITY; RECYCLABILITY

OPERATING CONDITIONS
[T_{min}, T_{max}]

ENERGY DENSITY
[kWh/kg, kWh/m^3]

POWER DENSITY
[kW/kg, kW/m^3]

COST
[CHF/kWh, CHF/kW]

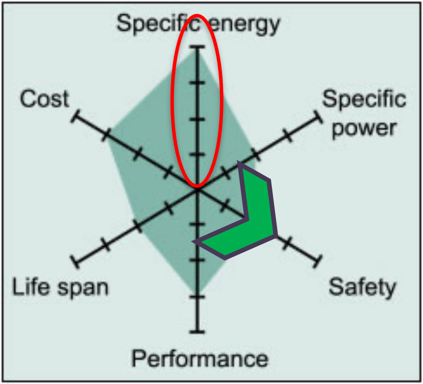
LIFESPAN
[Full Cycles]

SAFETY

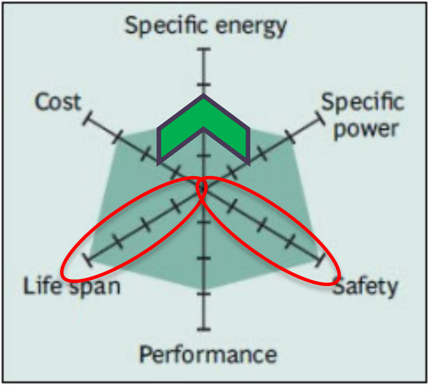
Source: https://www.visualcapitalist.com/evolution-of-battery-technology/

Versatility of lithium-ion technology

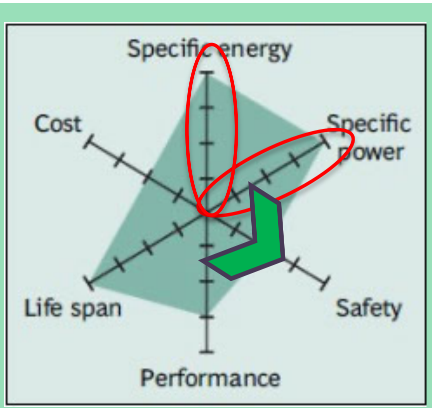
Positive Elektrode
(Kathode)



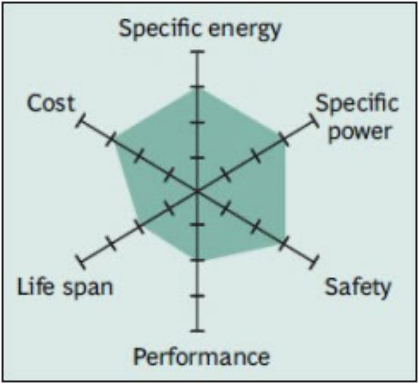
Lithium-Kobalt-Oxid
LCO ($LiCoO_2$)



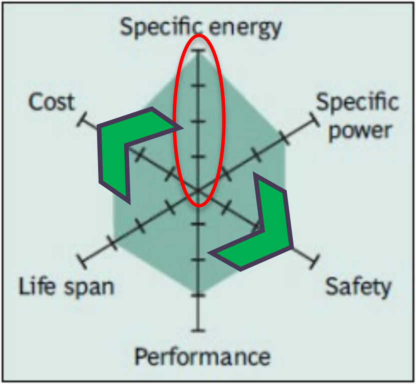
Lithium-Eisenphosphat
LFP ($LiFePO_4$)



Lithium-Nickel-Kobalt-Aluminium-Oxid
NCA ($LiNi_aCo_bAl_{1-a-b}O_2$)

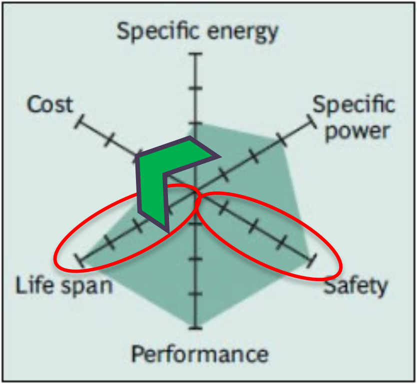


Lithium-Mangan-Oxid
LMO ($LiMn_2O_4$)



Lithium-Nickel-Mangan-Kobalt-Oxid
NMC ($LiNi_xMn_yCo_{1-x-y}O_2$)

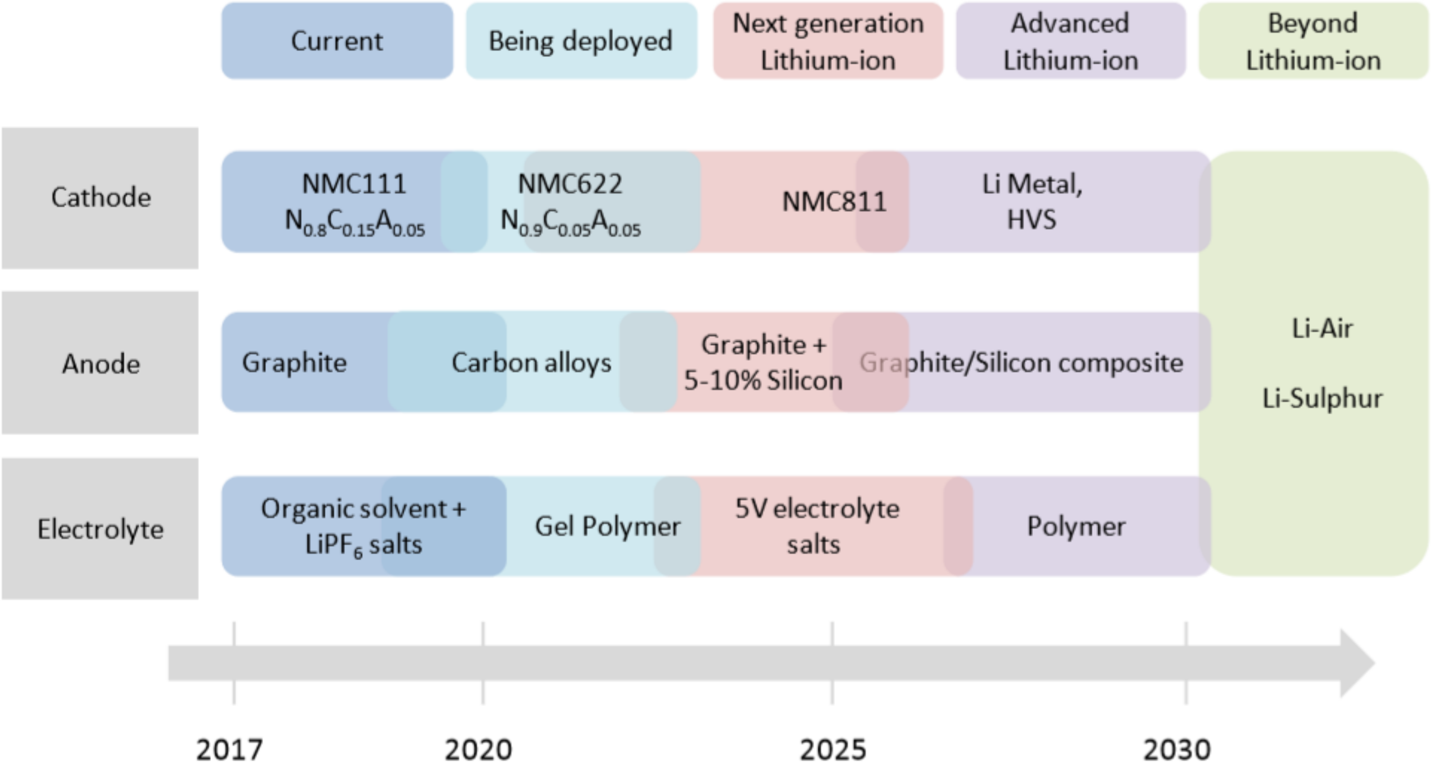
Negative Elektrode
(Anode)



Lithium-Titan-Oxid oder Lithium-Titanat
LTO ($Li_4Ti_5O_{12}$)

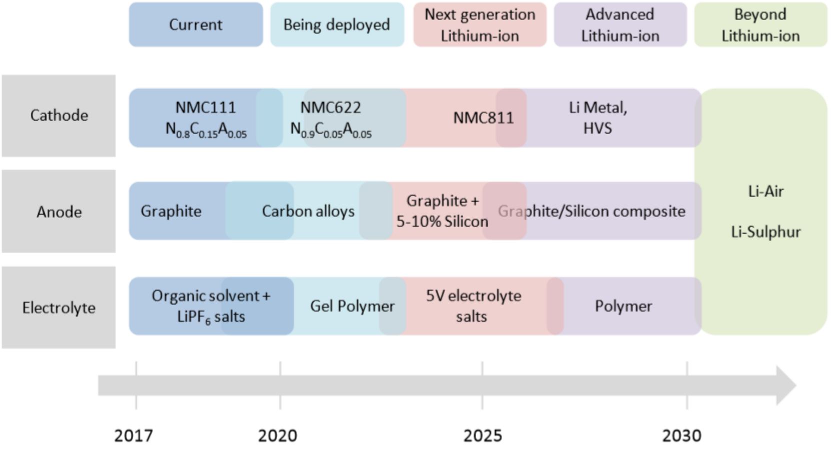
Source: Battery University & Yu Miao et al. 'Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements' Energies 2019, 12(6), 1074; https://doi.org/10.3390/en12061074

Next Li-ion batteries



Quelle: Global EV Outlook 2018, IEA, https://www.empa.ch/documents/56164/1537214/EmpaQuarterly_58d.pdf/c82dc4e8-b577-40fc-9faa-786b2556783d, https://batteryuniversity.com/learn/article/bu_218_summary_table_of_future_batteries

Next Li-ion batteries



Current | Being deployed | Next generation Lithium-ion | Advanced Lithium-ion | Beyond Lithium-ion

Cathode: NMC111 $N_{0.8}C_{0.15}A_{0.05}$ | NMC622 $N_{0.9}C_{0.05}A_{0.05}$ | NMC811 | Li Metal, HVS

Anode: Graphite | Carbon alloys | Graphite + 5-10% Silicon | Graphite/Silicon composite

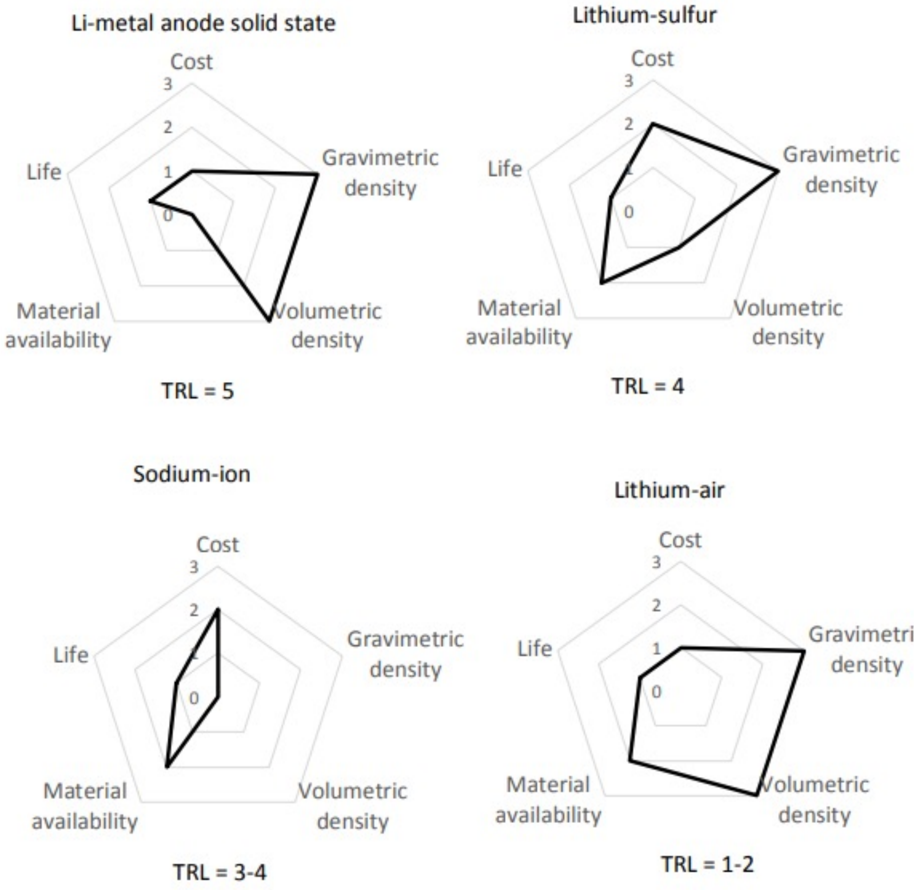
Electrolyte: Organic solvent + $LiPF_6$ salts | Gel Polymer | 5V electrolyte salts | Polymer

Li-Air

Li-Sulphur

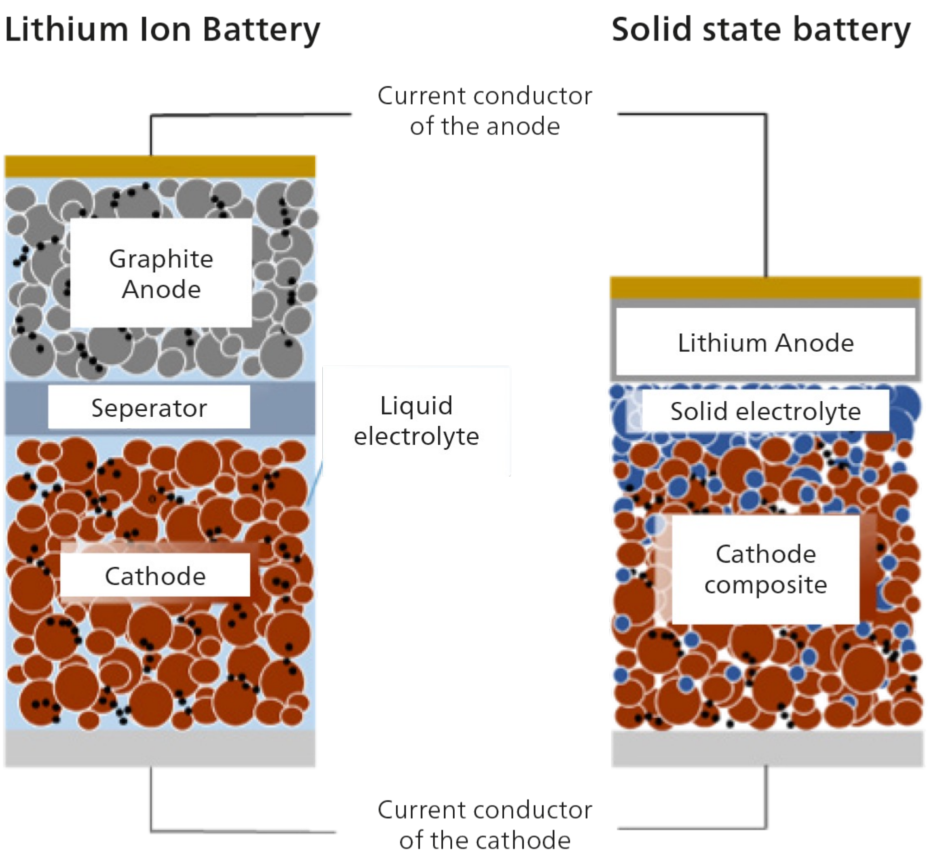
2017 2020 2025 2030

Quelle: Global EV Outlook 2018, IEA, https://www.empa.ch/documents/56164/1537214/EmpaQuarterly_58d.pdf/c82dc4e8-b577-40fc-9faa-786b2556783d, https://batteryuniversity.com/learn/article/bu_218_summary_table_of_future_batteries



Quelle: Global EV Outlook 2020, IEA & Innovation Gaps, 2019 IEA; Energy Technology Perspectives 2020, IEA

Solid State Batteries (SSB)



Advantages:

- **High energy density**
- **Increased safety**
- **Thermal runaway eliminated**
- **Longer service life**
- Compact design
- Potential for fast charging

Disadvantages:

- High cost (complex manufacturing)
- Sensitivity to temperature fluctuations
- Problems at the interface between electrodes and electrolyte
- Self-discharge

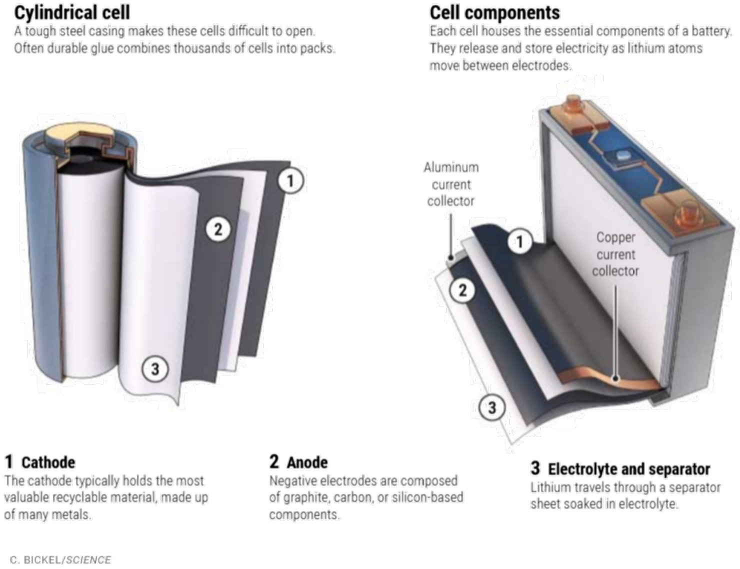
Immagine: Raylase, https://www.raylase.de/en/applications/Battery-Production-electric-mobility/solid-state-batteries-1.html

Battery Definitions

EV Battery Pack

Cells are the smallest individual electrochemical unit and deliver a voltage that depends on the cell chemistry.

Batteries modules and **packs** are made up from groups of cells connected in series and parallel



Cylindrical cell
A tough steel casing makes these cells difficult to open. Often durable glue combines thousands of cells into packs.

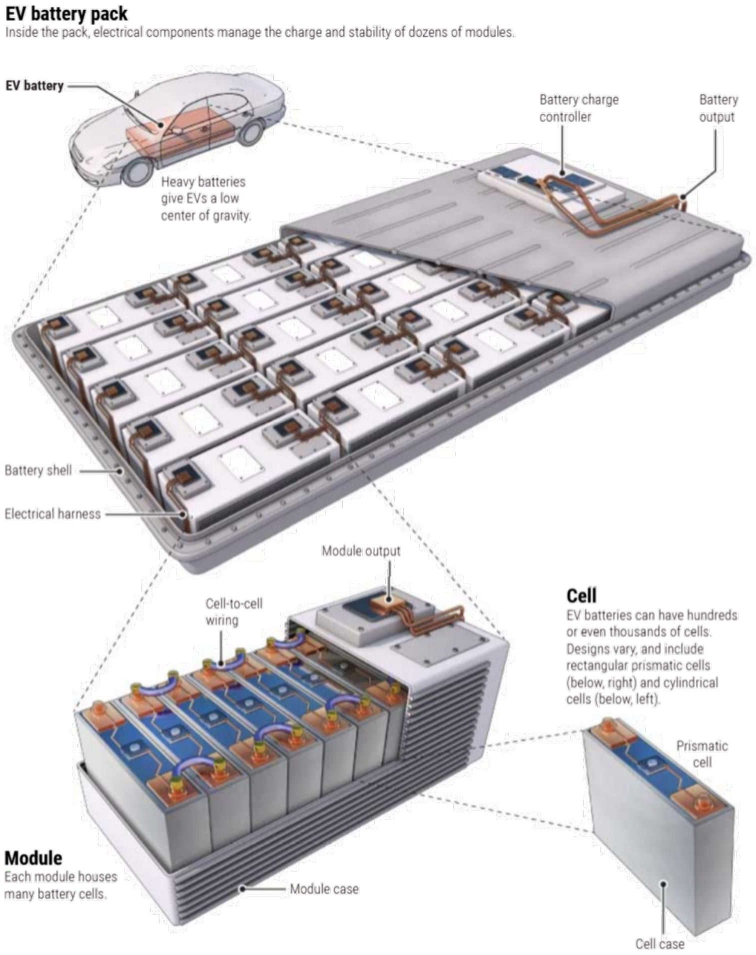
Cell components
Each cell houses the essential components of a battery. They release and store electricity as lithium atoms move between electrodes.

1 Cathode
The cathode typically holds the most valuable recyclable material, made up of many metals.

2 Anode
Negative electrodes are composed of graphite, carbon, or silicon-based components.

3 Electrolyte and separator
Lithium travels through a separator sheet soaked in electrolyte.

C. BICKEL/*SCIENCE*

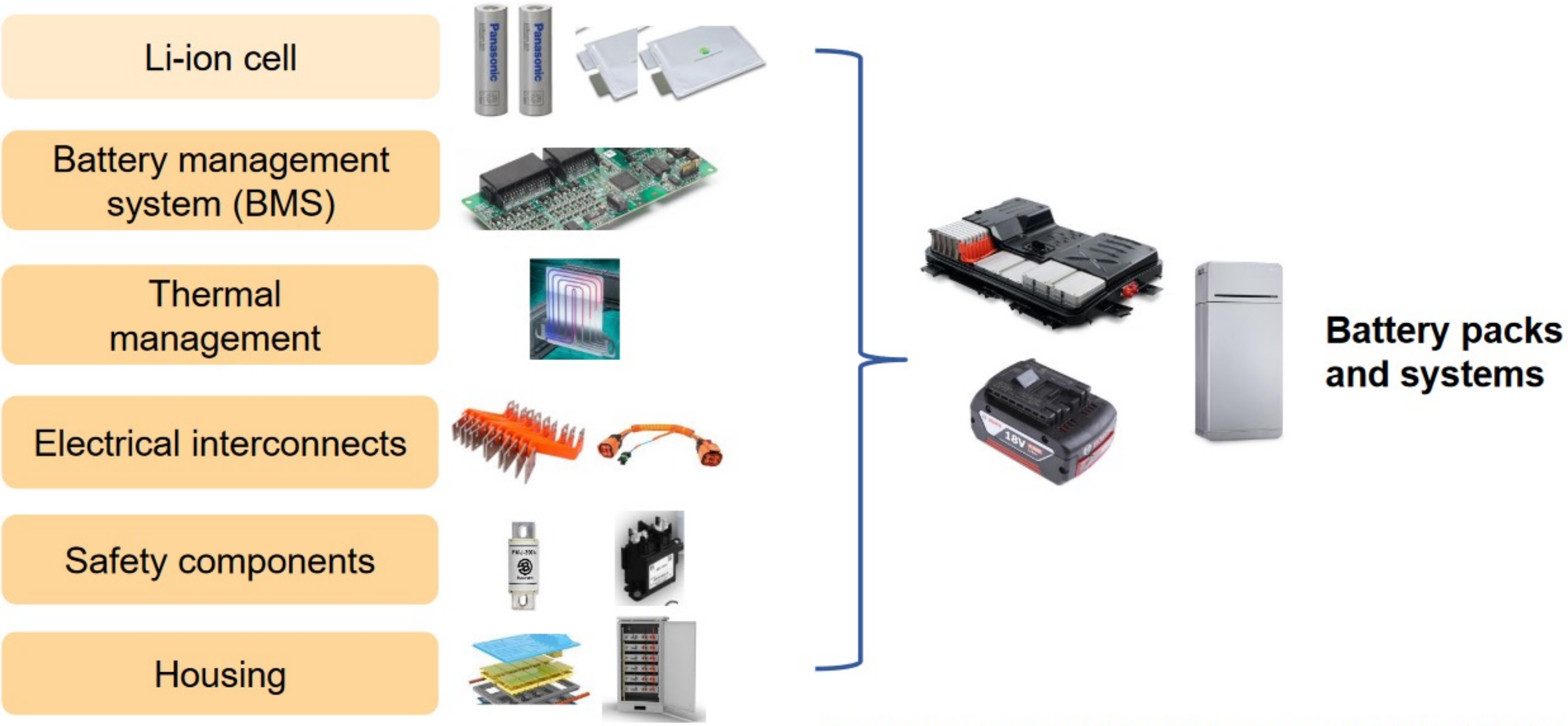


EV battery pack
Inside the pack, electrical components manage the charge and stability of dozens of modules.

Module
Each module houses many battery cells.

Cell
EV batteries can have hundreds or even thousands of cells. Designs vary, and include rectangular prismatic cells (below, right) and cylindrical cells (below, left).

But what exactly is a lithium-ion battery pack?



- Li-ion cell
- Battery management system (BMS)
- Thermal management
- Electrical interconnects
- Safety components
- Housing

Battery packs and systems

Image sources: Panasonic, AESC Envision, Samsung SDI, Nissan (The Elec), Chevrolet, General Motors, Lithium Balance, Eaton, EG Electronics, Bizlinktech, Voltacon, Sabic, Bosch, LG ES.

Source: The State of the Li-ion Industry, November 2022. IDTechEx Research

Definitions I

U [V]: Voltage or electrochemical **potential difference between the electrodes** (+Pole und –Pole) of a cell, a pack, or a system

I [A]: Current, in form of electrons, which flows between the poles

P [W]: Power

P = U x I
[W] = [V] x [A]

t [h]: Time, during which the current flows

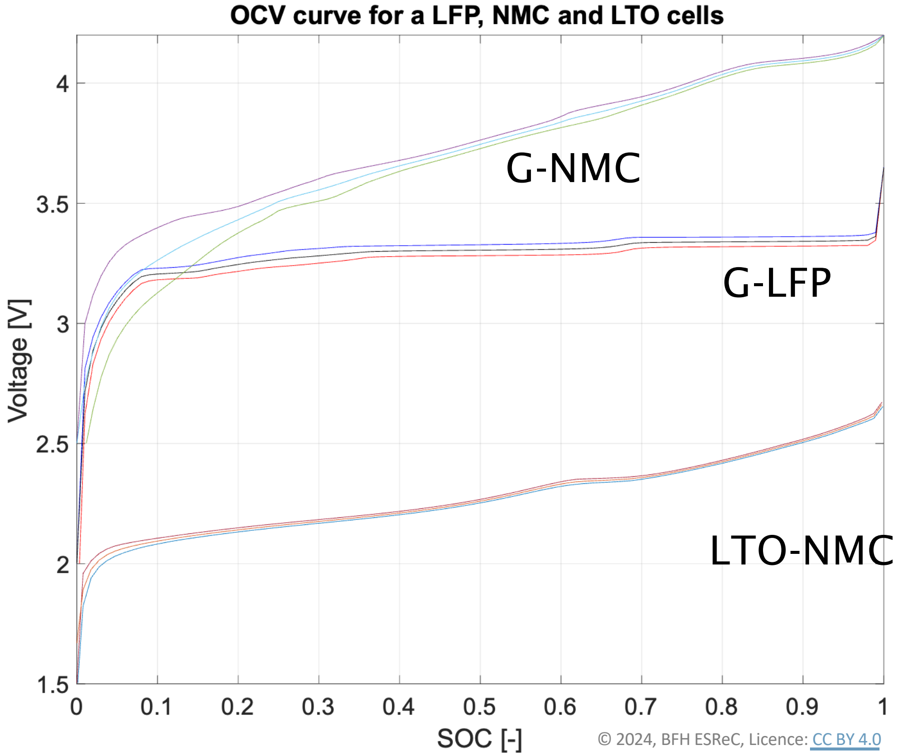
Q [Ah]: Battery capacity or charge
Amount of **electrical charge in a cell**, pack or system

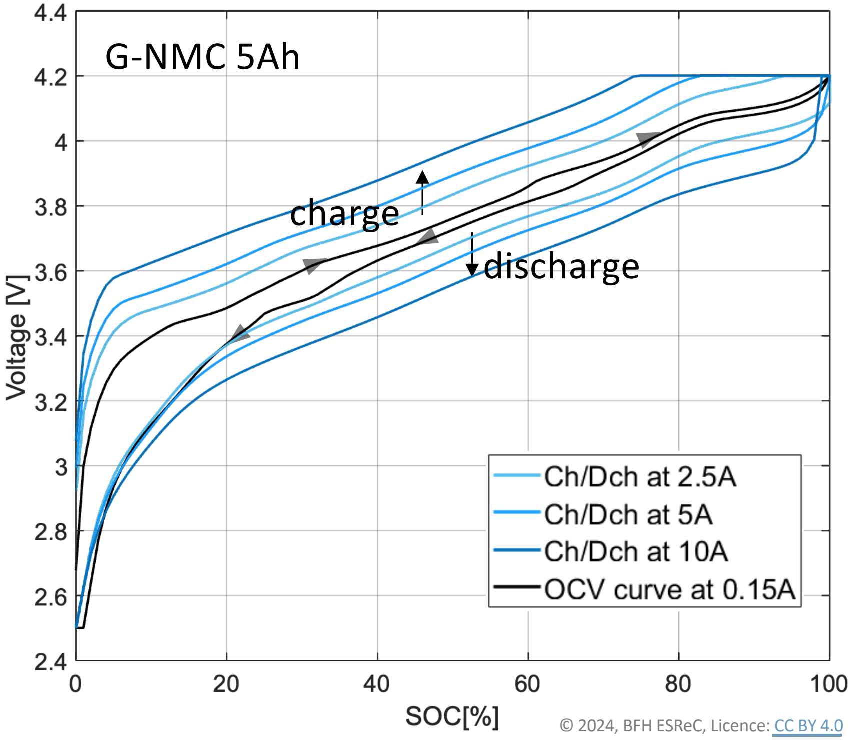
$Q = \int_{\Delta t} I\,dt$ or Q = I x t
[Ah] = [A] x [h]

E [Wh]: Energy
Energy stored in a battery

$E = \int_{\Delta t} U_{battery} * I\,dt$ or E = U x I x t
[Wh] = [V] x [A] x [h]

Li-ion Battery Voltage





The voltage of a cell is the **difference in potential between the two electrodes**

It depends on Li particle average concentration in the two electrodes, the materials used as electrodes and temperature

If the cell is under current the **voltage deviates from the OCV because of losses**

Stored energy and open circuit voltage

The multiplication of open circuit voltage by capacity defines the **maximal removable energy** from the battery.

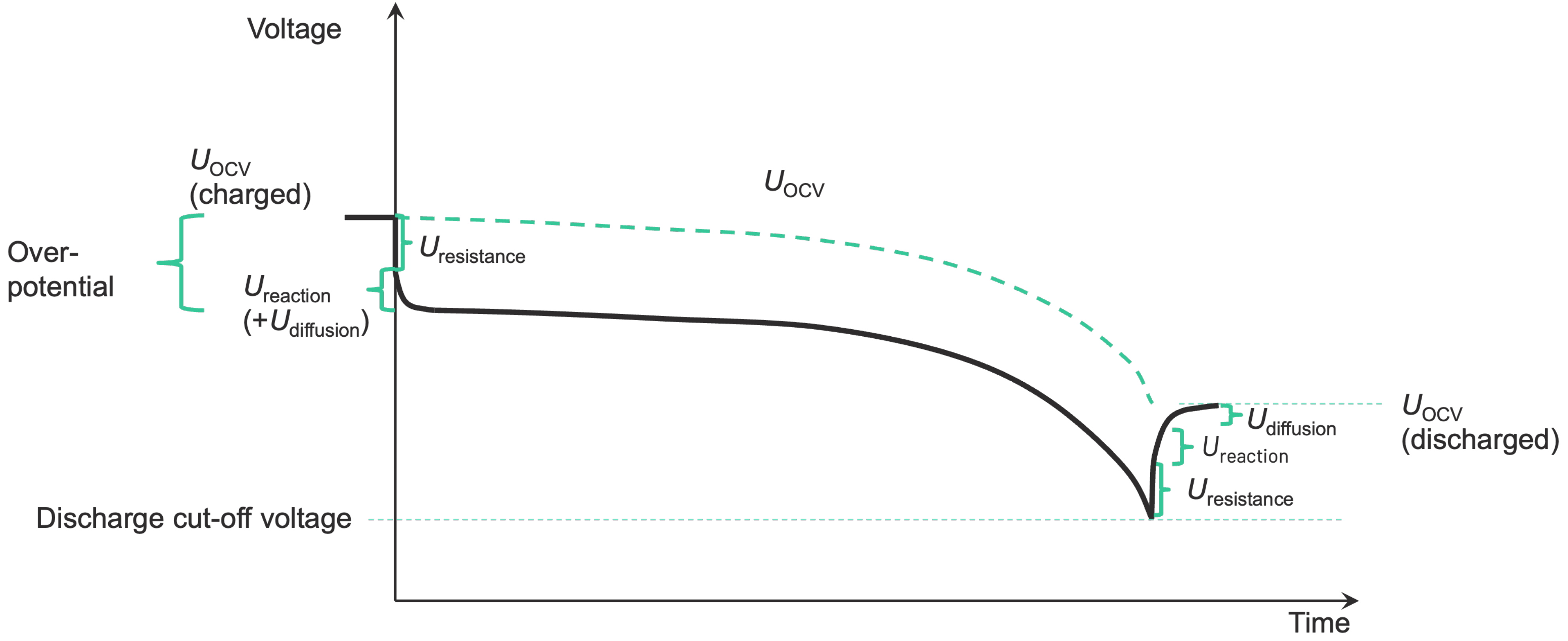
The capacity has a linear relationship with the available amount of electrode materials.

The voltage of the battery during discharge is always lower than the open circuit voltage at every state of discharge.

The voltage of the battery during charging is always higher than the open circuit voltage at every state of discharge.

Deviations from the open circuit voltage are losses.

Voltage of a battery during discharge



Voltage of a battery during charging and discharge

Ucharge/discharge = Uequilibrium + Uresistance + Ureaction + Udiffusion

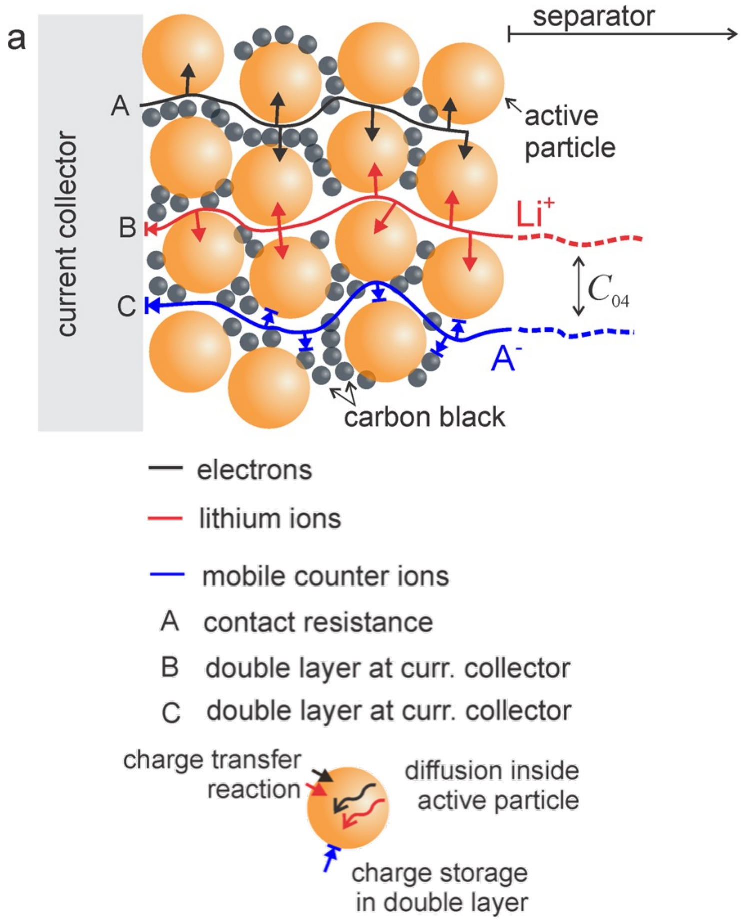
$U_{equilibrium}$ (OCV) depends on electrode materials, electrolyte concentration and temperature

$U_{resistance}$ ohmic drops in poles, current collectors, grid and electrolyte.

$U_{reaction}$ voltage drops caused by electrochemical and chemical reaction at inner surfaces (Butler-Volmer equation).

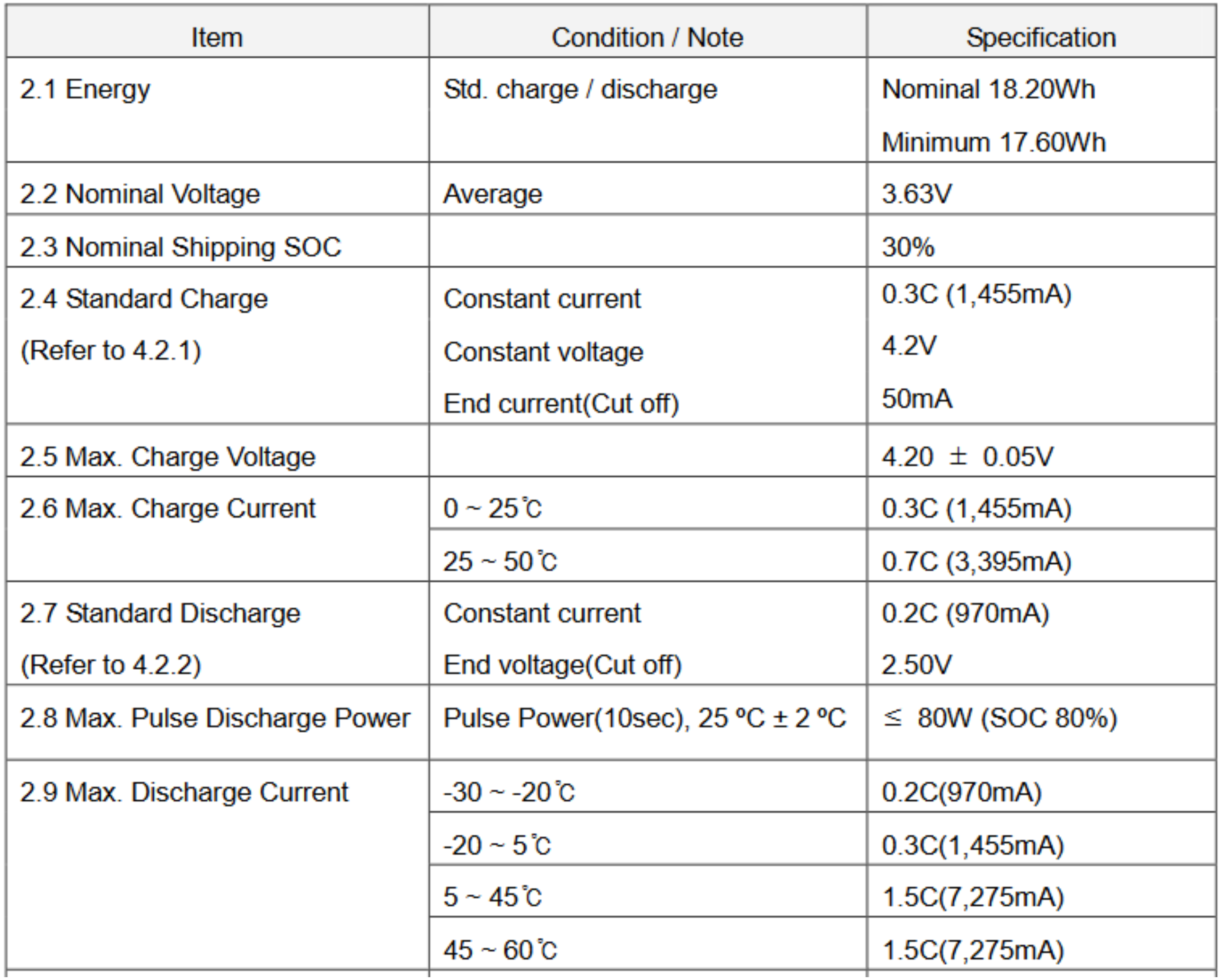
$U_{diffusion}$ voltage drops through a deficit or surplus of reactants at the reaction locations.

$U_{resistance}$, $U_{reaction}$, $U_{diffusion}$ will be normally considered as positive during charging and negative during discharge.



https://www.nature.com/articles/s41467-021-26894-5

Cell Datasheet

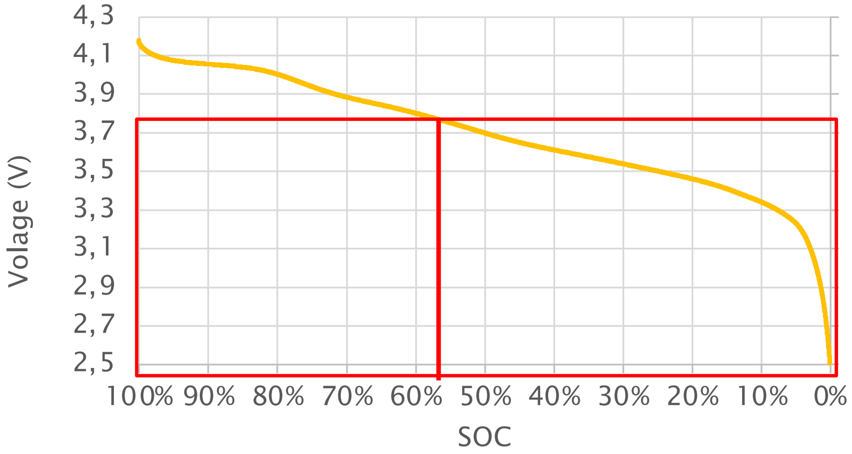


Item	Condition / Note	Specification
2.1 Energy	Std. charge / discharge	Nominal 18.20Wh Minimum 17.60Wh
2.2 Nominal Voltage	Average	3.63V
2.3 Nominal Shipping SOC		30%
2.4 Standard Charge (Refer to 4.2.1)	Constant current Constant voltage End current(Cut off)	0.3C (1,455mA) 4.2V 50mA
2.5 Max. Charge Voltage		4.20 ± 0.05V
2.6 Max. Charge Current	0 ~ 25℃	0.3C (1,455mA)
	25 ~ 50℃	0.7C (3,395mA)
2.7 Standard Discharge (Refer to 4.2.2)	Constant current End voltage(Cut off)	0.2C (970mA) 2.50V
2.8 Max. Pulse Discharge Power	Pulse Power(10sec), 25 °C ± 2 °C	≤ 80W (SOC 80%)
2.9 Max. Discharge Current	-30 ~ -20℃	0.2C(970mA)
	-20 ~ 5℃	0.3C(1,455mA)
	5 ~ 45℃	1.5C(7,275mA)
	45 ~ 60℃	1.5C(7,275mA)

https://www.dnkpower.com/wp-content/uploads/2019/02/LG-INR21700-M50-Datasheet.pdf

Cell Datasheet

Cell (nominal) voltage depends on the combination of active chemicals used in the cell.

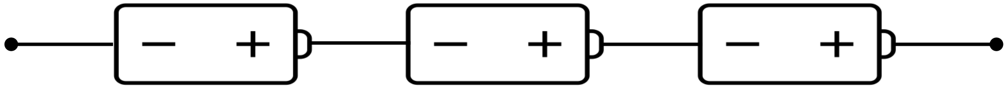


Cell (nominal) capacity specifies the quantity of charge, in ampere hours (Ah), that the battery is rated to hold.

$Q = \int_{\Delta t} I \, dt$ or $Q = I \times t$

[Ah] = [A] x [h]

Basic concepts of Li-ion Battery

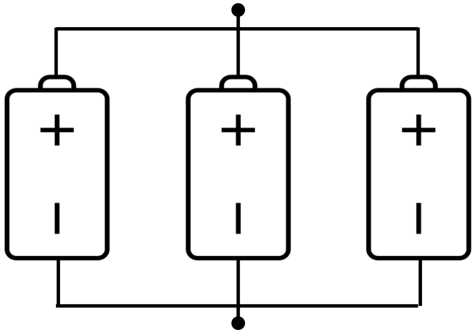


<u>Cells connected in series:</u>

increases voltage proportional to the number of cells

capacity remains unchanged

Energy and power increase proportional to the number of cells.



<u>Cells connected in parallel:</u>

voltage remains unchanged

increase capacity proportional to the number of cells

And energy and power increase proportional to the number of cells.

Recap

Battery cell: The smallest component of a battery pack or system. A cell may have ca. 2.5 – 4.2 V.

Voltage: 3.5V
Capacity: 3.0 Ah
} Energy: 10.5 Wh

Voltage: 2.3V
Capacity: 20 Ah
} Energy: 46 Wh

Battery pack: cells connected in series and/or parallel

Parallel connection

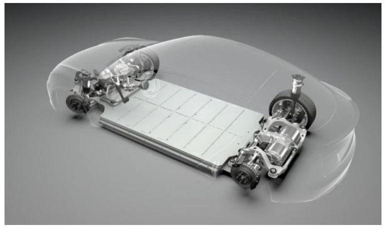
Voltage:
Capacity:
} Energy:

Series connection

Voltage:
Capacity:
} Energy:

Battery (Battery system): battery packs connected incl. batterie management system.

Voltage: 360 V
Capacity: 60 Ah
} Energy: 21.6 kWh



Voltage: 350 V
Capacity: 230 Ah

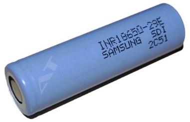
→ Energy: 80.5 kWh

Recap

E = U x Q
[Wh] = [V] x [Ah]

Battery cell: The smallest component of a battery pack or system. A cell may have ca. 2.5 – 4.2 V.

Voltage: 3.5V
Capacity: 3.0 Ah
Energy: 10.5 Wh



Voltage: 2.3V
Capacity: 20 Ah
Energy: 46 Wh

Battery pack: cells connected in series and/or parallel

Parallel connection

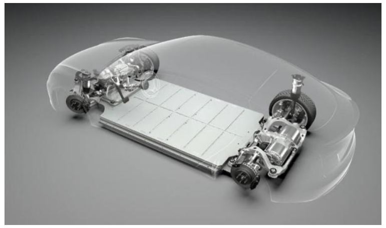
Voltage: 3.5V
Capacity: 4 x 3.0Ah = 12 Ah
Energy: 42 Wh

Series connection

Voltage: 3.5V x 8 = 28 V
Capacity: 3.0 Ah
Energy: 94 Wh

Battery (Battery system): battery packs connected incl. batterie management system.

Voltage: 360 V
Capacity: 60 Ah
Energy: 21.6 kWh



Voltage: 350 V
Capacity: 230 Ah
→ Energy: 80.5 kWh

Definitions II

Capacity efficiency or Charge factor

$$L = Q_{discharge} / Q_{charge}$$

Energy efficiency

$$\eta = E_{discharge} / E_{charge}$$

SoC: State of charge

$$SoC = Q_{actual} / Q_{full}$$

Influence factors: current density, charge characteristics, temperature

Typical data for the energy effectiveness are:

☐ Lead-acid batteries: 80 - 90 %
☐ Lithium-ion batteries: 90 - 95 % (ηAh ~ 100%)
☐ NiMH: 75 - 85 %

SoH: State of health, an indicator of the battery aging

$$SoH = Q_{c,full} / Q_{c,full,new}$$

$$SoH = E_{c,full} / E_{c,full,new}$$

$$SoH = Q_{d,full} / Q_{d,full,new}$$

$$SoH = E_{d,full} / E_{d,full,new}$$

SOC & SOH definition

The SOC is a percentage value that expresses the remaining charge Q of a battery

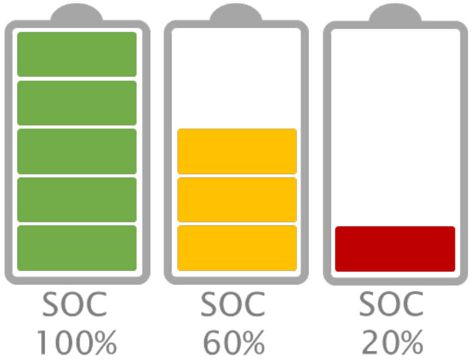
SOC is something like a dashboard fuel gauge that reports a value from “Empty” (0%) to “Full” (100%) → no sensor is available to directly measure SOC.

$$\text{SoC} = Q_{\text{actual}} / Q_{\text{full}}$$

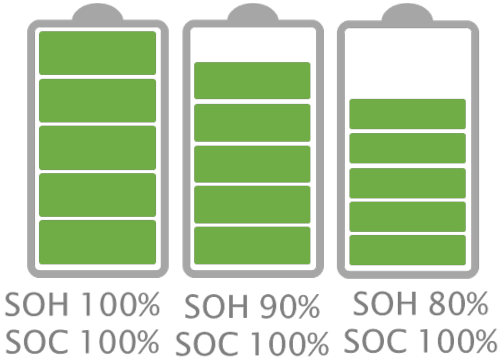
SOH is defined as the fade of the capacity of the cell or the increase of the internal resistance of the battery

$$\text{SoH} = Q_{\text{d,full}} / Q_{\text{d,full,new}}$$

Full → Empty



New → Old



Charging Lithium-Ion Batteries

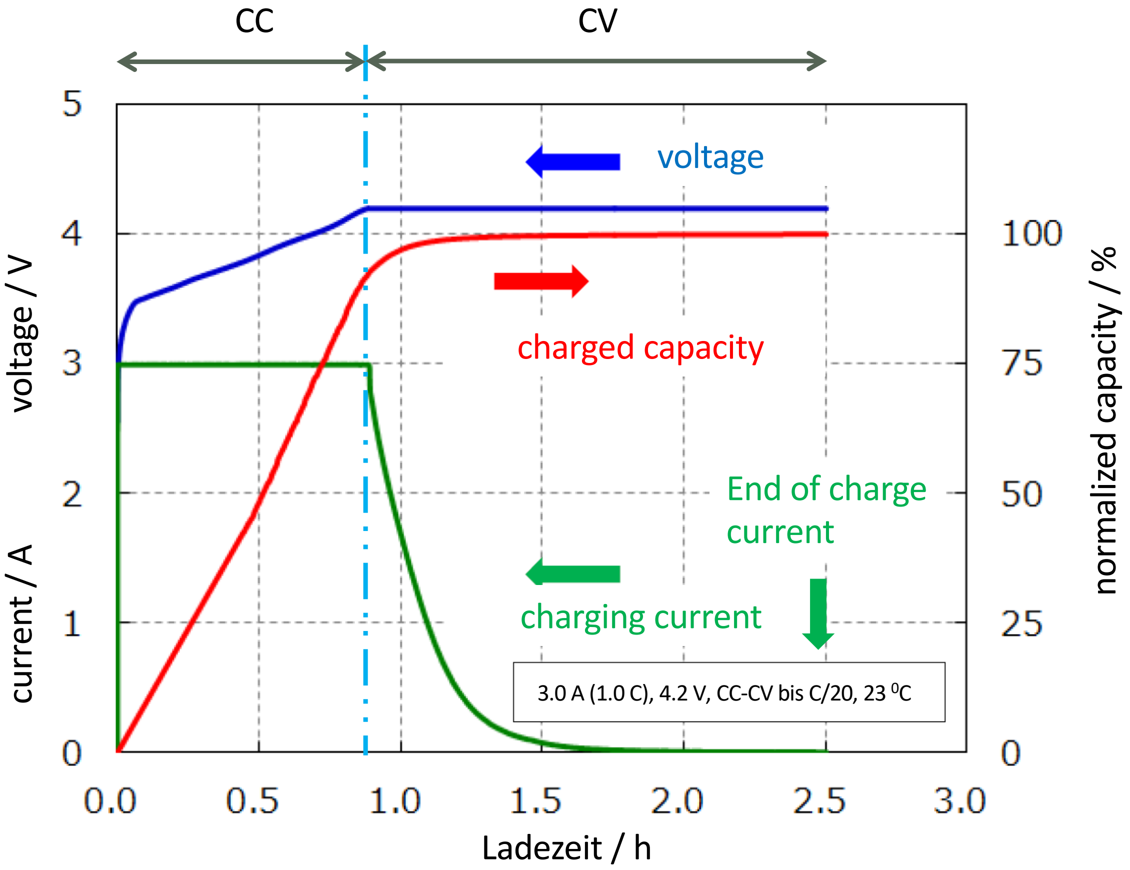
C-Rate [h-1]: Rate, at which the battery is charged or discharged using a constant current

C-Rate = I / Q_{nom}
$[h^{-1}]$ = [A]/[Ah]

Lithium-ion batteries are charged with a **constant current** (CC or constant current) up to the final charging voltage.

Once the end-of-charge voltage has been reached, charging continues at a **constant voltage** (CV).

Charging stops when the **end-of-charge current is reached** → generally C/10 to C/20 or 0.10 C to 0.05 C.



Discharging Lithium-Ion Batteries

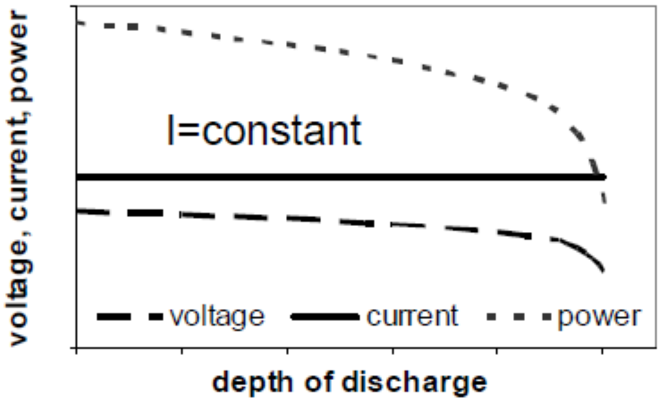
Depth of Discharge: DOD = 100% - SOC

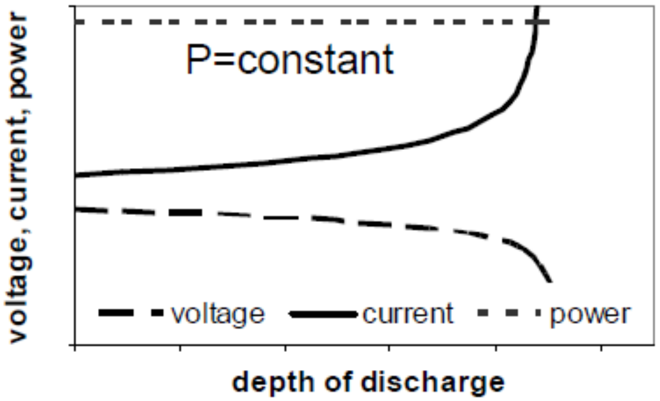
SOC = 100 % ➔ DOD = 0 %

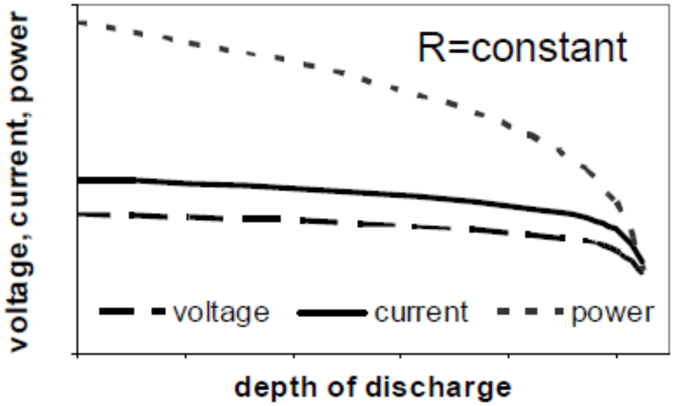
SOC = 0 % ➔ DOD = 100

Lithium-ion batteries can be discharge in three different ways:

- Constant current
- Constant power
- Constant resistance

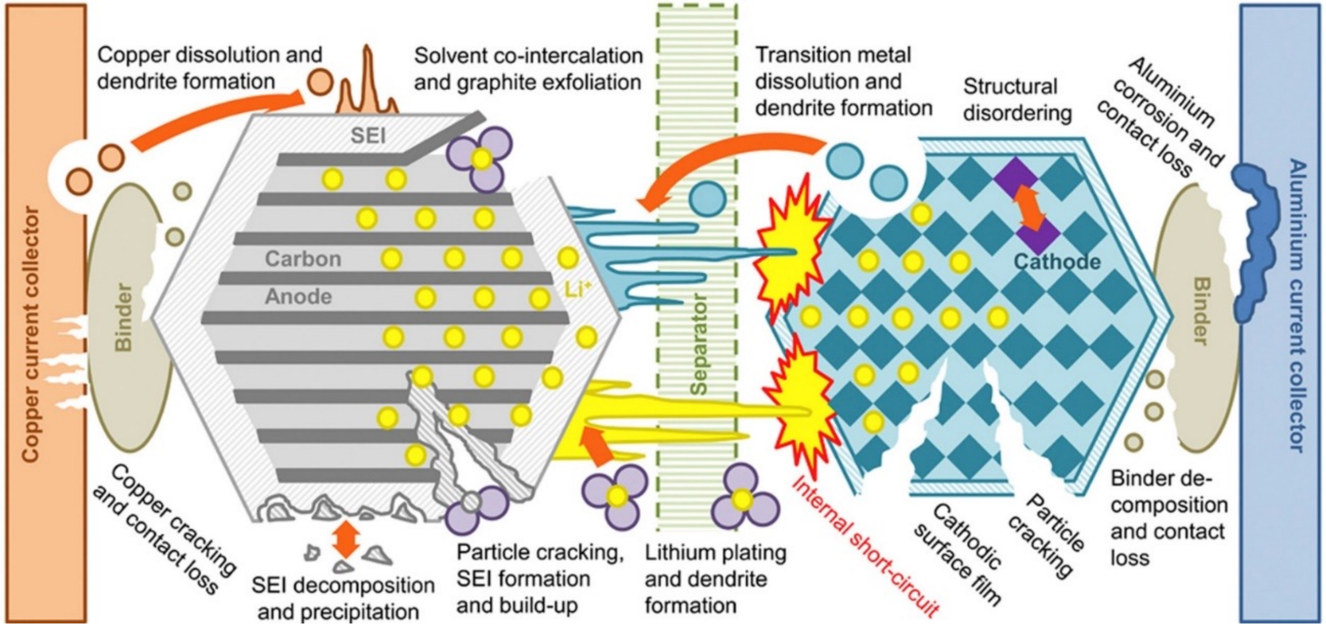






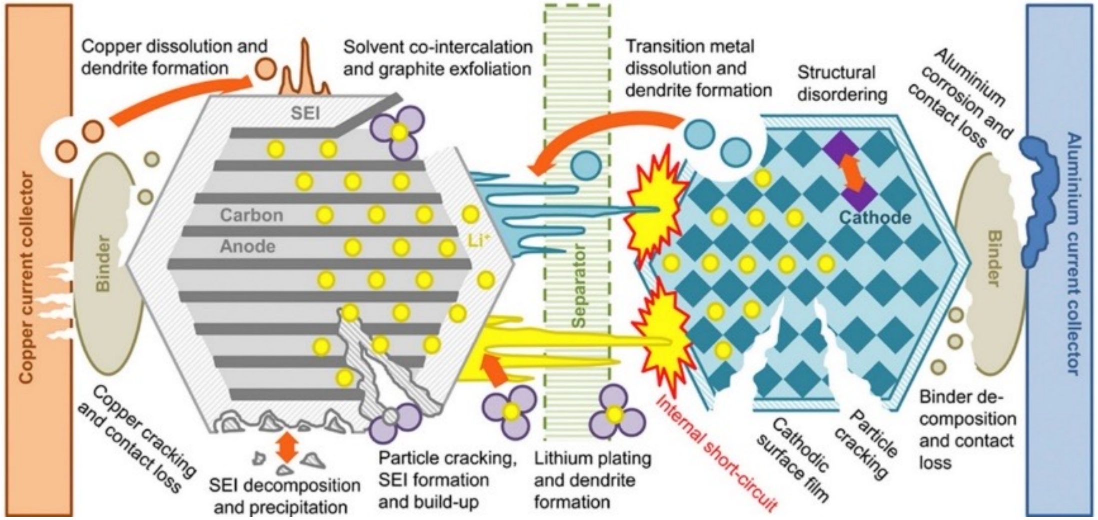
Lifetime mechanisms and degradation

Degradation mechanisms

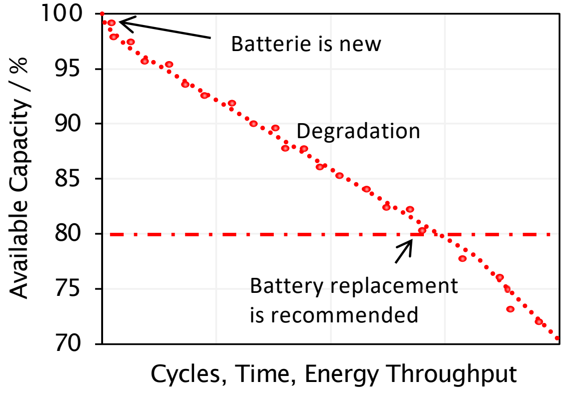


Christoph R. Birkl, Matthew R. Roberts, Euan McTurk, Peter G. Bruce, David A. Howey, Degradation diagnostics for lithium ion cells, Journal of Power Sources, Volume 341, 2017, Pages 373-386, https://doi.org/10.1016/j.jpowsour.2016.12.011.

Degradation mechanisms



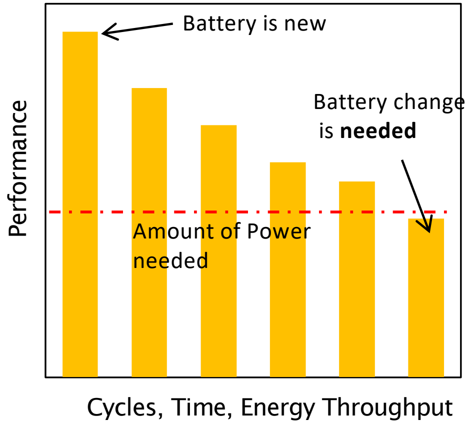
Christoph R. Birkl, Matthew R. Roberts, Euan McTurk, Peter G. Bruce, David A. Howey, Degradation diagnostics for lithium ion cells, Journal of Power Sources, Volume 341, 2017, Pages 373-386, https://doi.org/10.1016/j.jpowsour.2016.12.011.



Effects

CAPACITY FADE

POWER FADE



Definition of Lifetime of lithium-ion batteries

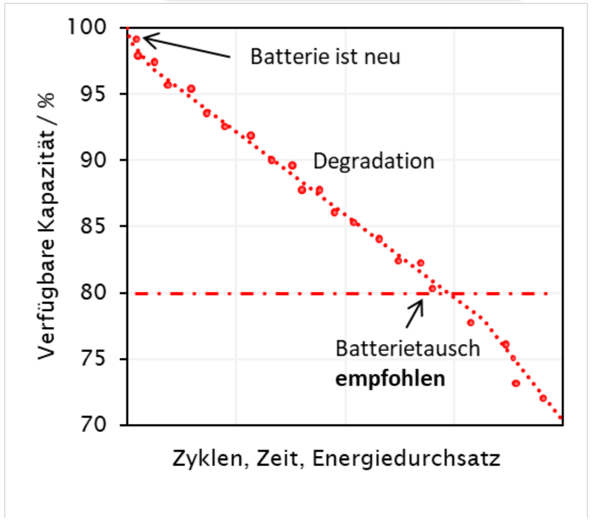
EoL: End of Life (end of battery life for specific application)

$\text{SoH} \leq 0.8$

$\text{EoL} = Q_{\text{voll}} / Q_{\text{voll,neu}} \leq 0.8$

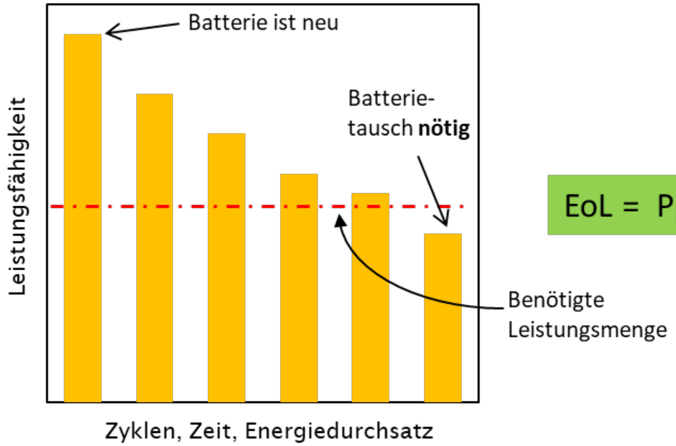
$\text{EoL} = E_{\text{voll}} / E_{\text{voll,neu}} \leq 0.8$

Energy relatd EoL



- Range of vehicle
- Running time (e.g. Smartphone)

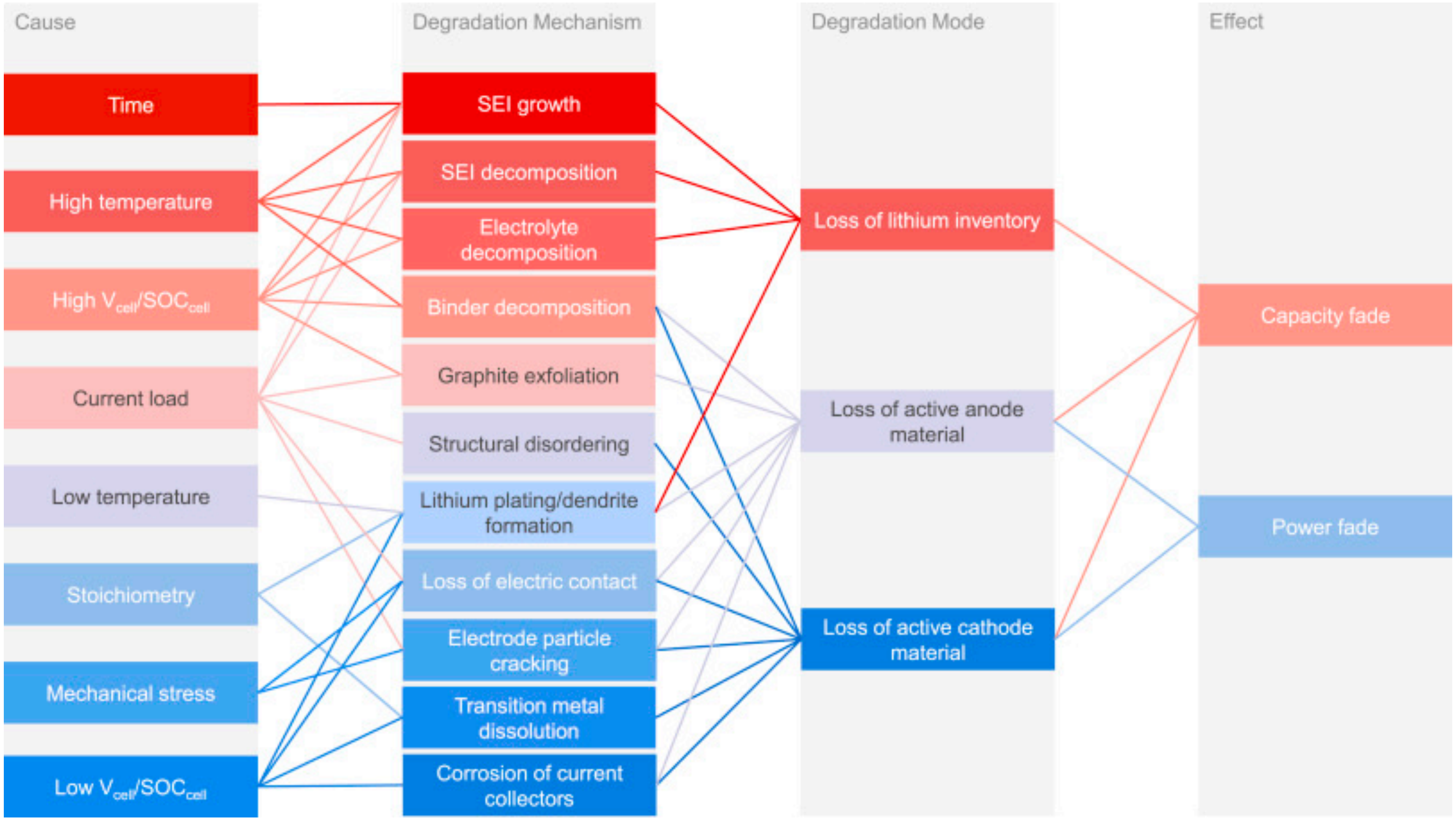
Power related EoL



$\text{EoL} = P_{\text{Last}} > P_{\text{Batterie}}$

- Power applications (e.g.. Starter-Batteries)
- Higher peak speed (e.g. Formula E, swissloop)

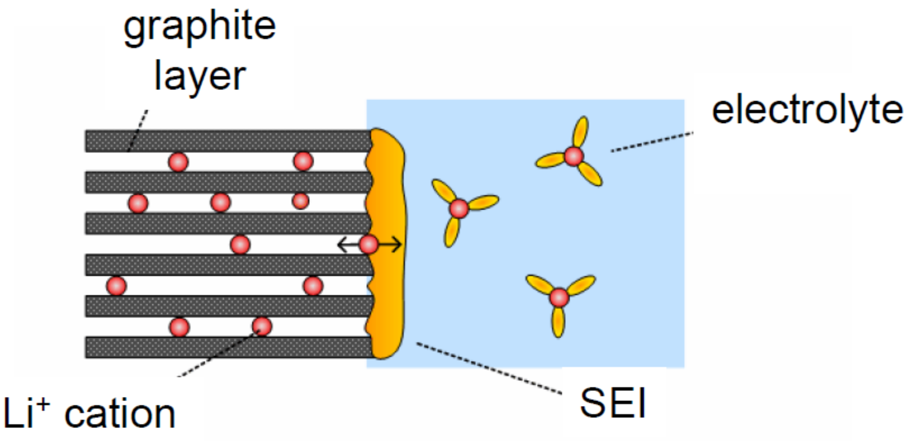
Degradation mechanisms



Lithium plating

Charge transfer process:

- De-solvation of solvated Ions
- Li-ion pass through SEI layer
- Solid-state Li diffuse into graphite particles



https://onlinelibrary.wiley.com/doi/full/10.1002/er.3762

SEI : Solid Electrolyte Interphase

Lithium plating

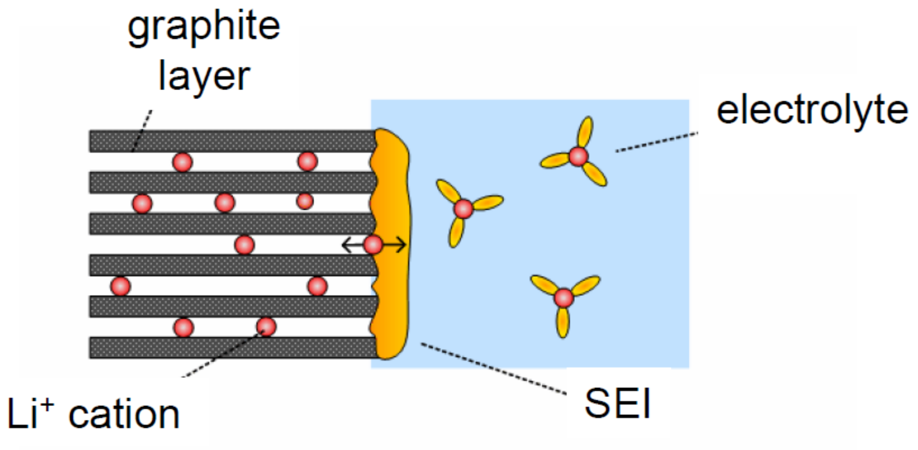
Charging at high SOC

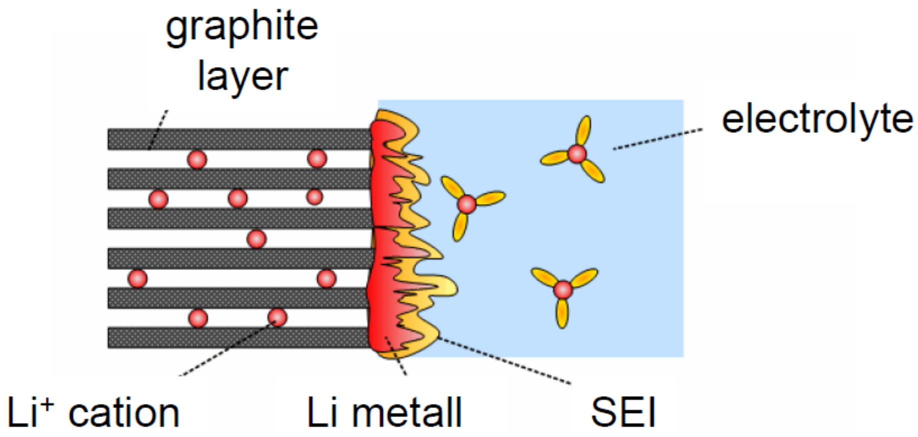
High rate charging

Long term Cycling

Non Uniform Charging

Low temperature





https://onlinelibrary.wiley.com/doi/full/10.1002/er.3762

SEI : Solid Electrolyte Interphase

Two types of aging

Cyclic aging

Function of:

- cell chemistry
- state of charge (SoC)
- temperature
- level of discharge or DoD (depth of discharge)
- charge and discharge rate

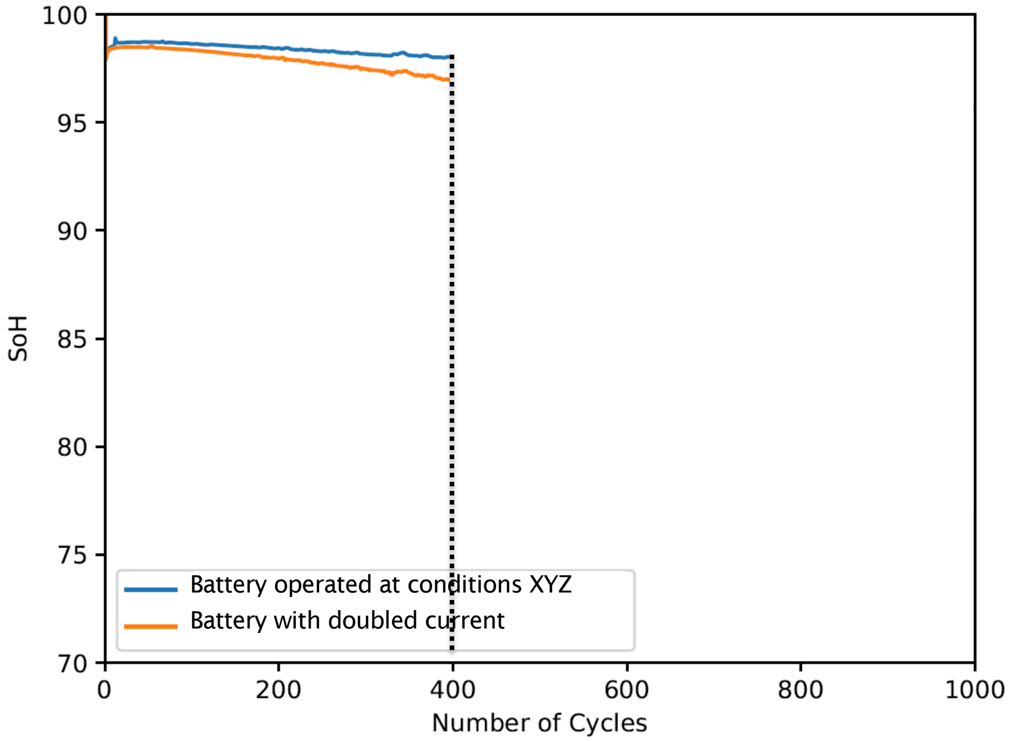
Calendar aging

Function of

- cell chemistry
- state of charge (SoC)
- temperature

Operating conditions determine Battery Aging

Knowing how the battery is operated is the only way to define its remaining useful life



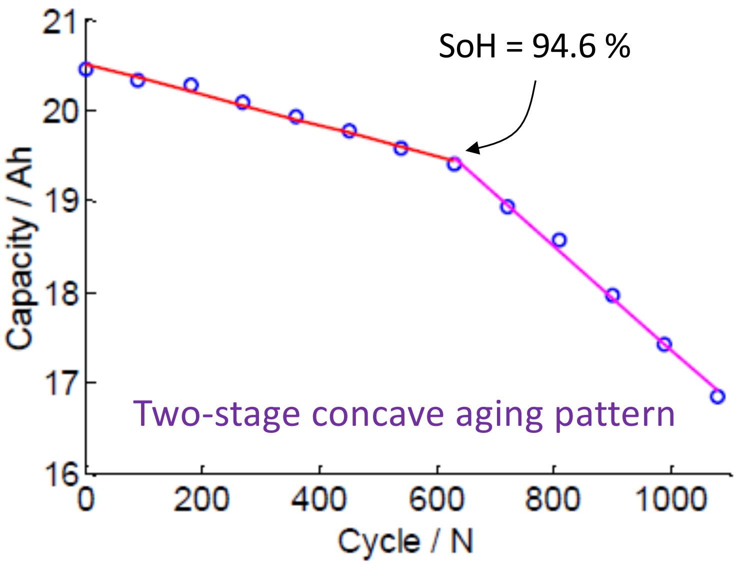
Some results from literature with Toshiba NMC/LTO cell

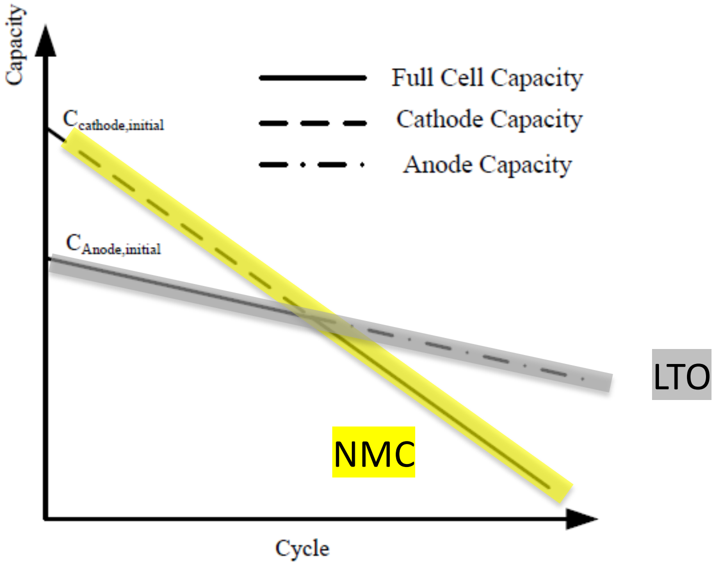
Charge: 3C (CC)

Discharge: 2C (CC)

20 min Pause

T = 55 ^{0}C

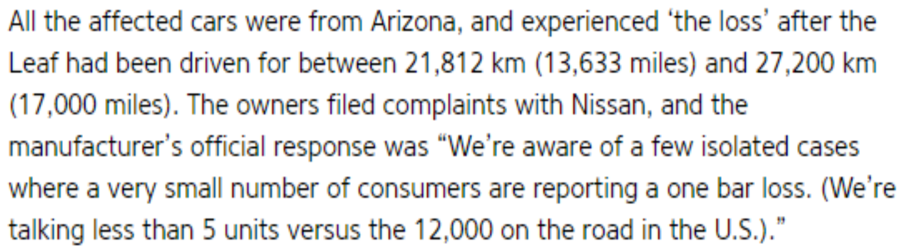




Source: Han Xuebing et al., Energies (2014), 7, 4895-4909

Source: www.autoevolution.com

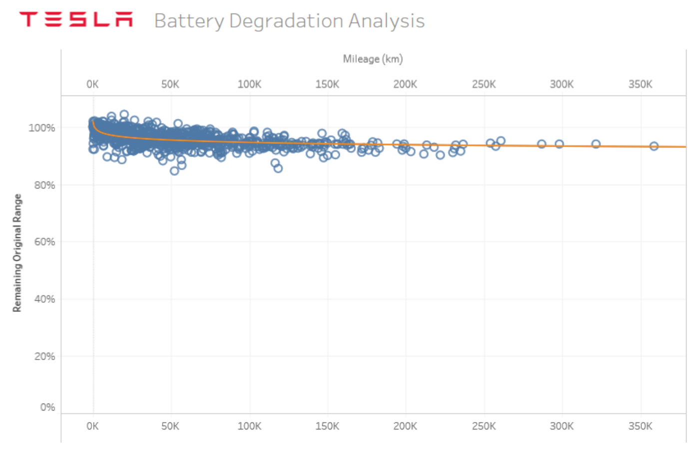
Ca. 25 % battery capacity loss within 1 -2 years of operation;



All the affected cars were from Arizona, and experienced 'the loss' after the Leaf had been driven for between 21,812 km (13,633 miles) and 27,200 km (17,000 miles). The owners filed complaints with Nissan, and the manufacturer's official response was "We're aware of a few isolated cases where a very small number of consumers are reporting a one bar loss. (We're talking less than 5 units versus the 12,000 on the road in the U.S.)."

18,588 owners were covered by the settlement. Some brought their Leaf vehicles to Nissan to repair the battery to at least 70% capacity or, if not possible, get the battery replaced.

2012



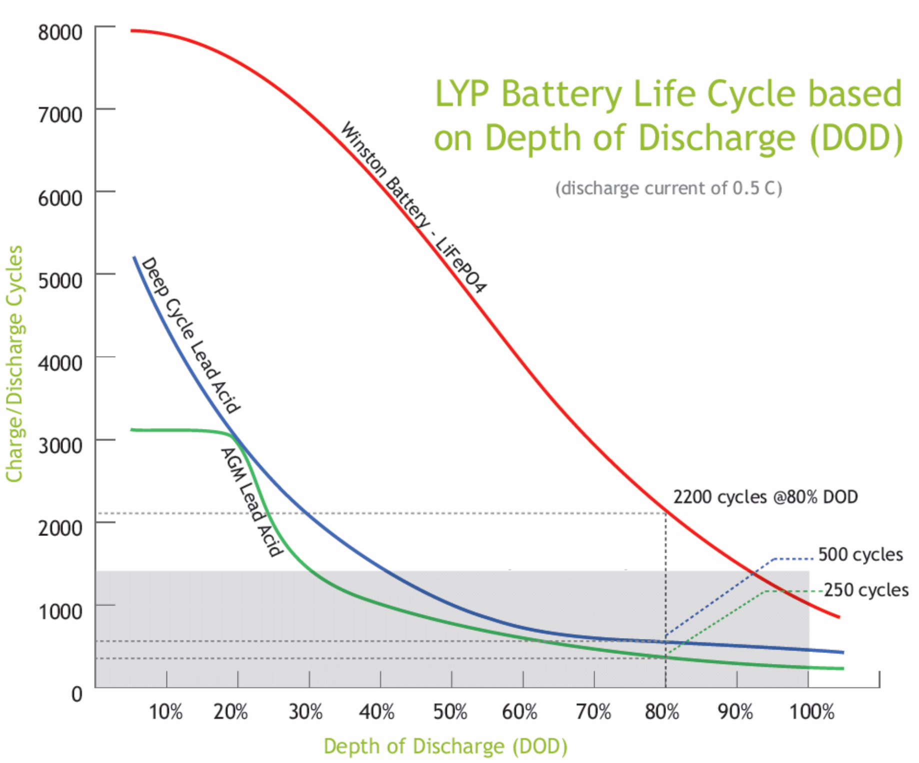
Source: www.teslarati.com

Discharge depth (DoD) and voltage (V) vs. SoH

For some chemistries (e.g. NMC) there is a strong correlation between the **end-of-charge voltage and the number of cycles to the end of life**.

Operating strategies should therefore consider voltage levels to maximize battery life.

This increases the **complexity** of the overall system or a **battery management and energy management system**.



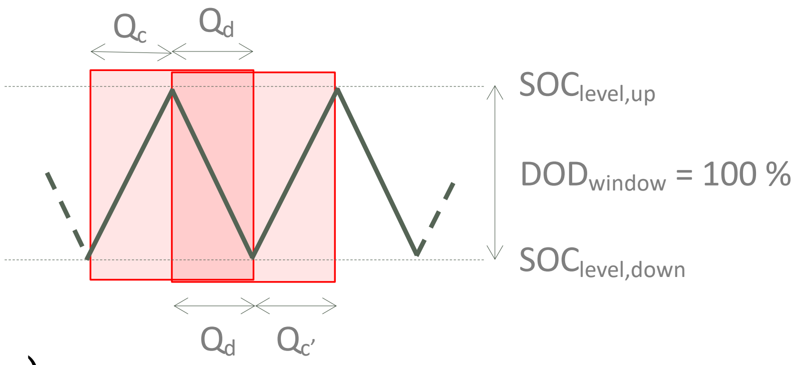
Quelle Bild: https://www.ev-power.eu/blog/The-Cycle-life-of-Winston-Batttery-cells-versus-lead-acid.html

Testing and models

Lifespan Estimation (Q-and CE measurements)

Goal

Quantify and compare the decrease in Capacity (Q) and **Coulometric Efficiency (CE = Qd/Qc)**



Theory

$CE = Q_d/Q_c$ (= 1.0000 → Perfect discharging)

$CE' = Q_{c'}/Q_d$ (= 1.0000 → Perfect charging)

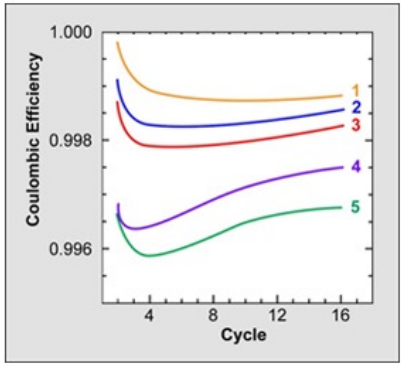
Test conditions

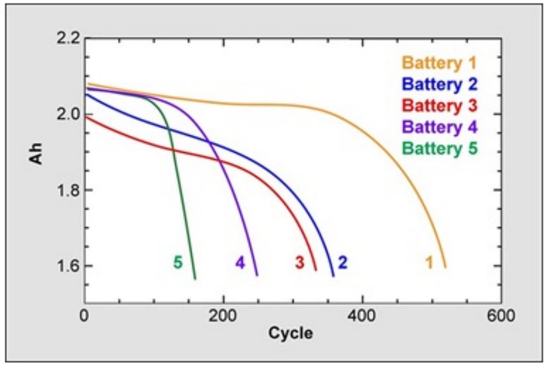
Charge- and discharge rate = 0.20 C (ca. 10 h per cycle)

Always only CC mode, without pause between charge and discharge

Results

After few cycles, CE can indicate the cell that will have lower degradation





Source: https://batteryuniversity.com/learn/article/bu_808b_what_causes_li_ion_to_die
Results Dalhousie University – J. Dahn group

Time-efficient Life Studies using CE

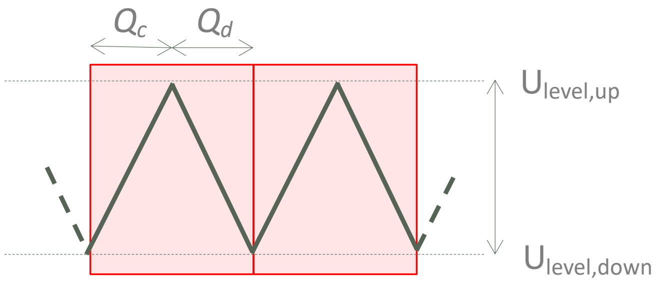
Test performed in BFH laboratory

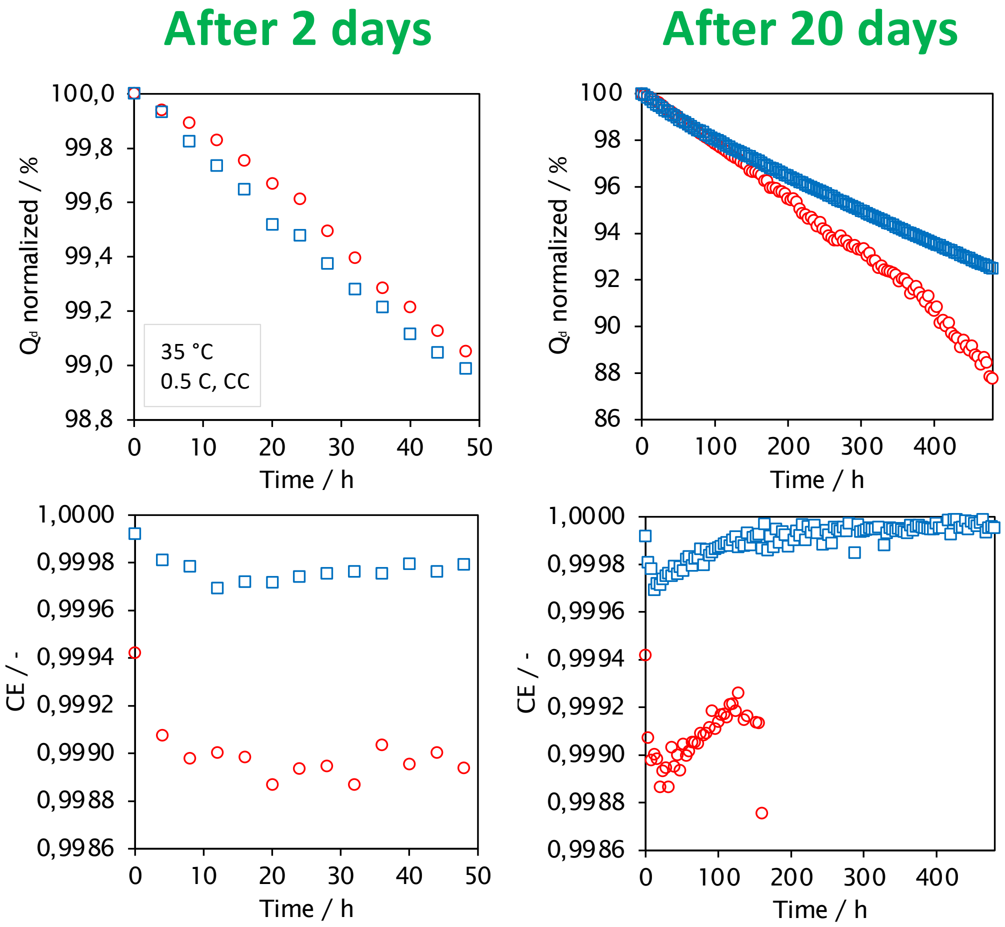
Comparison of two NMC cells

Temperature 35° C

Current 0.5C

CE = Q_d/Q_c (= 1.0000 → Ideal)

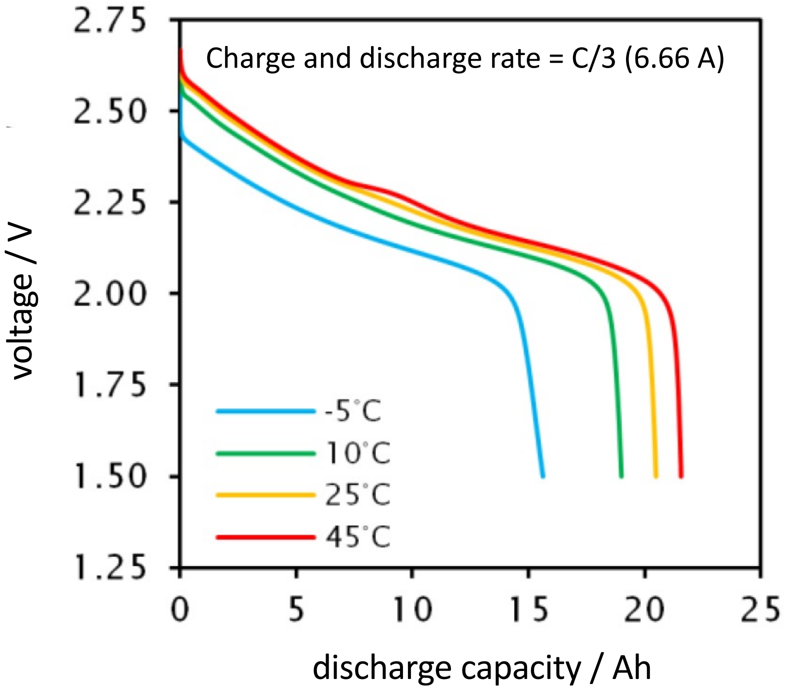




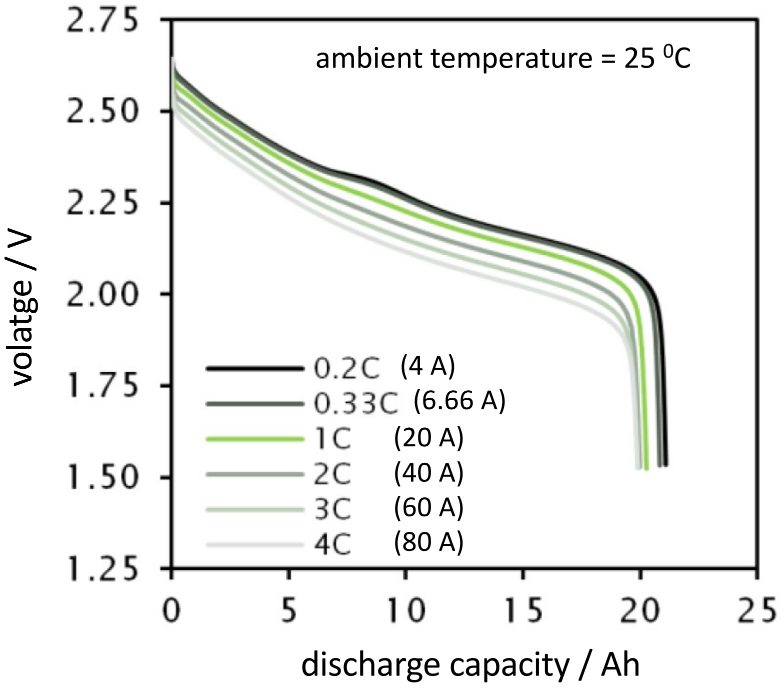
Already after few hours it was clear that the red sample was degrading more than the blue one

Capacity depends on load and temperature

Influence of ambient temperature



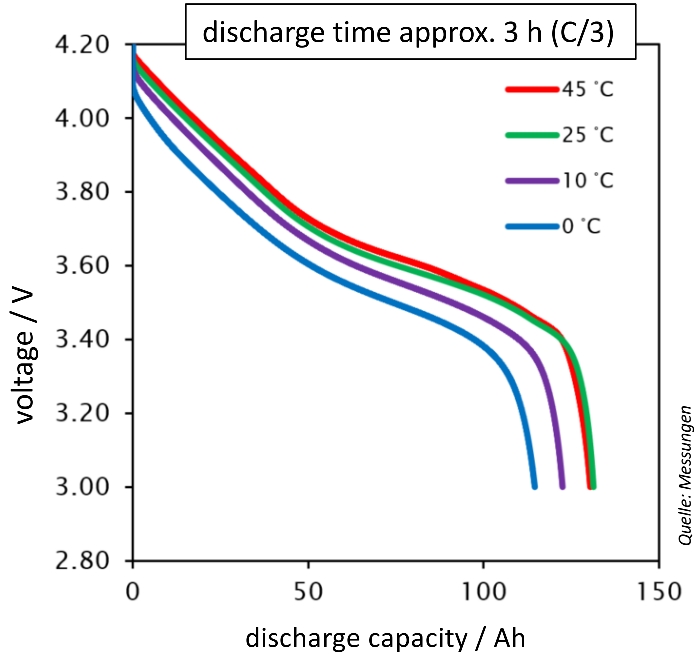
Influence of the discharge rate



Quelle: Messungen BFH-Zentrum Energiespeicherung

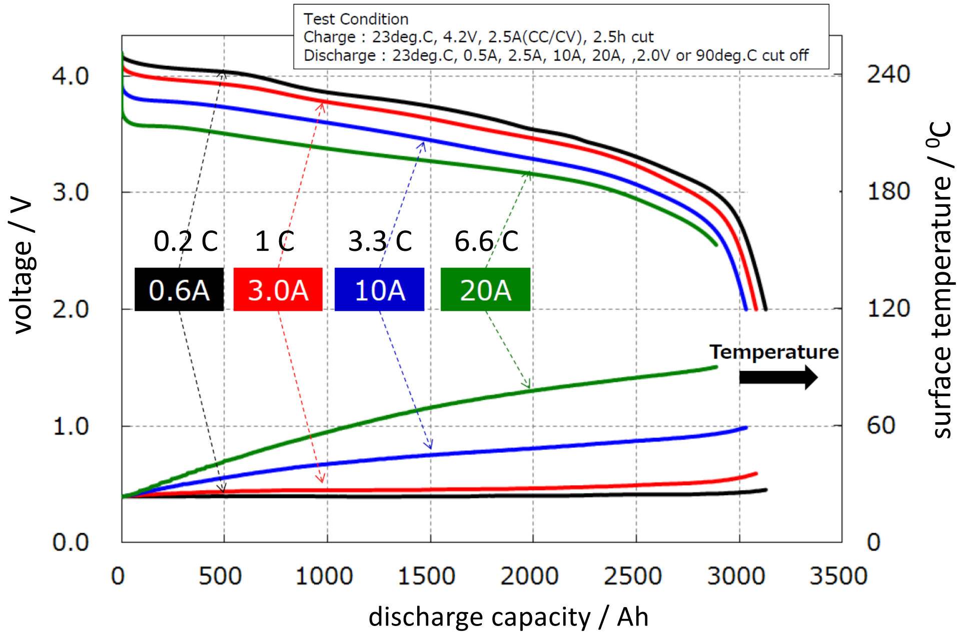
Capacity depends on load and temperature

Influence of ambient temperature



Quelle: Messungen BFH-Zentrum Energiespeicherung

Influence of the discharge rate

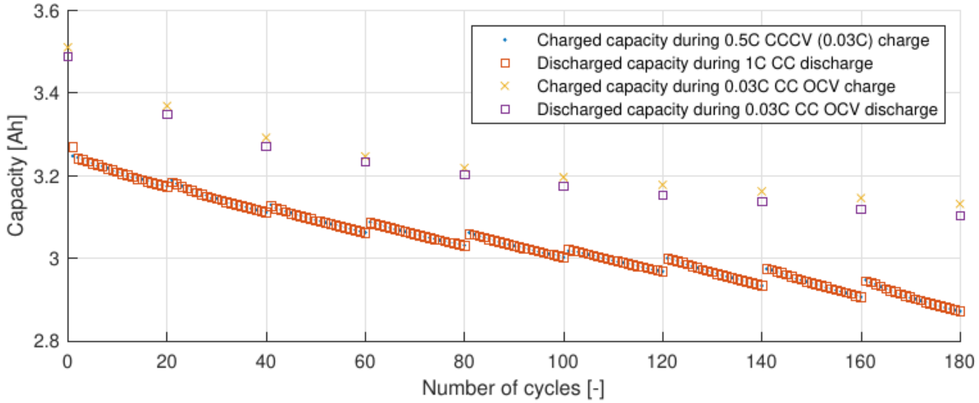

Test Condition
Charge : 23deg.C, 4.2V, 2.5A(CC/CV), 2.5h cut
Discharge : 23deg.C, 0.5A, 2.5A, 10A, 20A, ,2.0V or 90deg.C cut off

Quelle: Datenblätter Sony 18650-Zelle

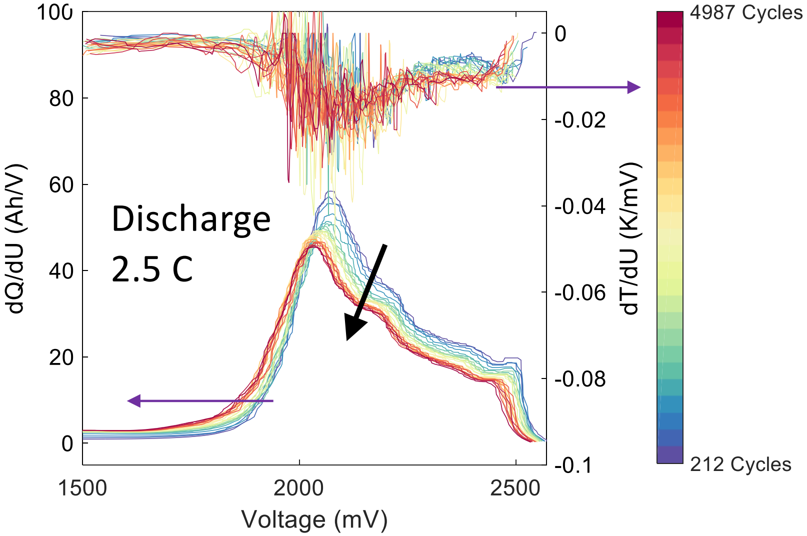
Aging Tests with intermediate Diagnostic Cycles

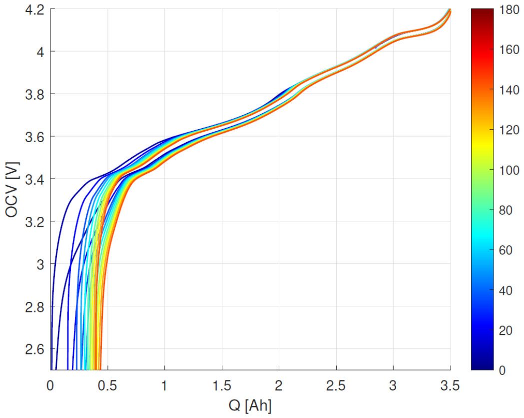
Change of dQ/dU vs. U towards the left: <u>increase of internal resistance</u>

Change of dQ/dU vs. U <u>downwards</u>: material change during operation

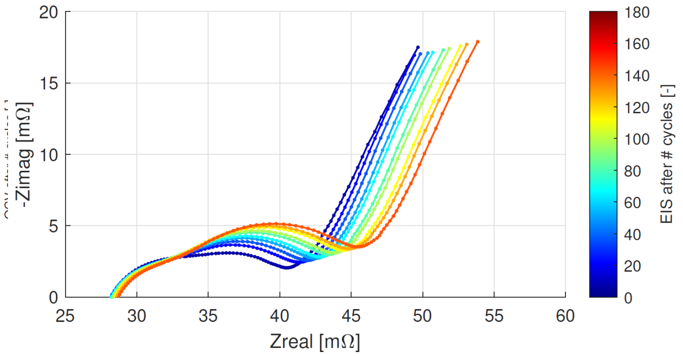


Incremental Capacity Analysis





Intermediate OCV

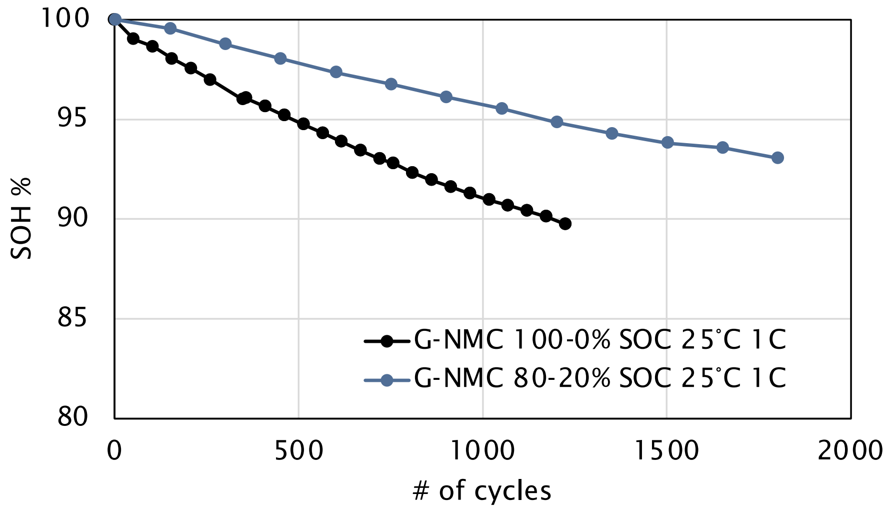


Intermediate EIS @ 10% SOC

Two types of aging

Cyclic aging

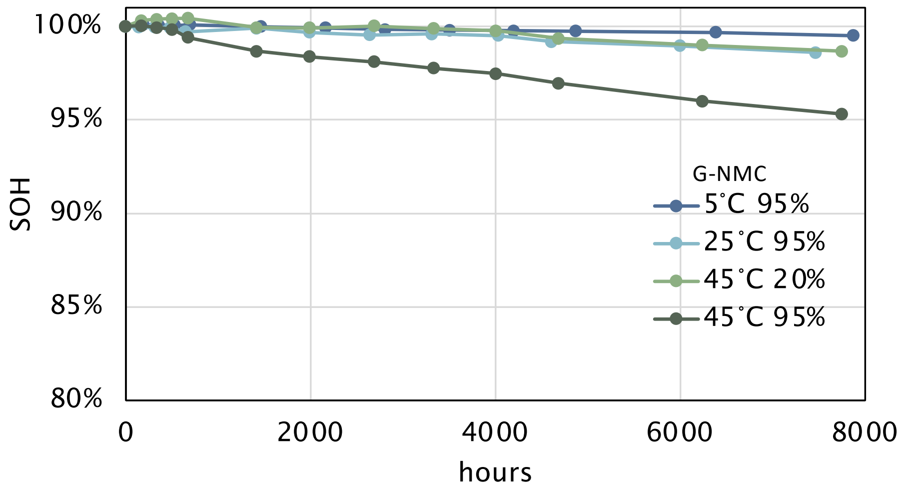
Decrease in available capacity due to use (charge/discharge)



Calendric aging

Regardless of use

Relevant for storage/non-use



Quelle: Lebensdauertests im Auftrag der Industrie am BFH-Zentrum Energiespeicherung

Electrochemical Characterization

Performance @ different operating conditions

Charge-Discharge Cycling

Rate Capabilities Testing

Diffusion coefficients and thermodynamic properties

Galvanostatic Intermittent Titration Technique (GITT)

Efficiency of charge transfer processes and the extent of side reactions

Coulombic Efficiency Measurements (CE)

Incremental Capacity Analysis (dQ/dV)

Phase transitions and electrochemical processes

Electrochemical Impedance Spectroscopy (EIS)

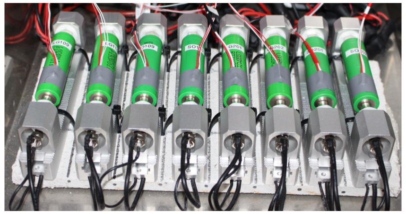
Identification of elementary losses processes

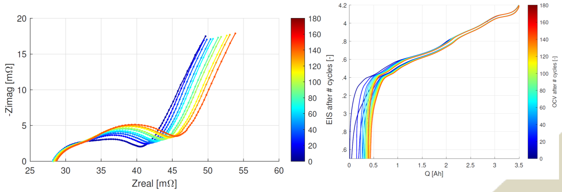
Long-term Cycling

Degradation and remaining useful life

From Theory to Reality

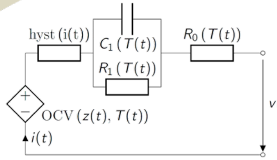
Research focus and core competences

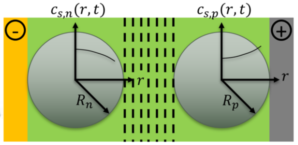




1 Battery & BMS Testing

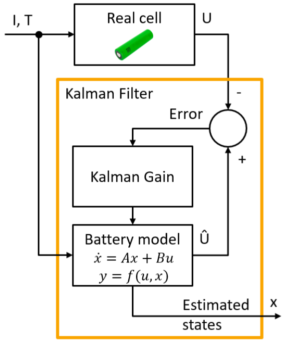
2 Battery Modelling



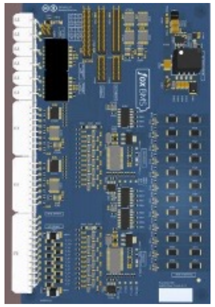


Single Particle Model (SPM)
with electrolyte dynamics

3 Algorithm creation and Hardware implementation



Extended Kalman Filter



4 Battery management and cloud

From Research to Products

Industry/ Startups

HESS since 1882
CH-4512 Bellach

EVOLARIS AVIATION
CH-2560 Nidau

SBB CFF FFS
CH-3000 Bern

EMINING SWITZERLAND
CH-3627 Heimberg

AEBI
CH-3401 Burgdorf

elringklinger
ABB
ALSTOM
BOMBARDIER
EFORCE
RUAG
+STROMER-
libattion Smart Cycles
Leclanché Energy Storage Solutions
INDRIVETEC Innovative Drive Technologies AG
wetrok
Thömus
designwerk

Demonstration R&D program

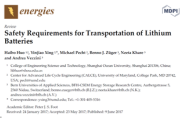





Communication KTT


BFH-CSEM Energy Storage Research Centre

ESReC Brochure


energies
MDPI
Review
Safety Requirements for Transportation of Lithium Batteries
Haibo Huo 1,2, Yinjiao Xing 2,*, Michael Pecht 2, Benno J. Züger 3, Neeta Khare 3 and Andrea Vezzini 3
Academic Editor: Peter J. S. Foot
Received: 24 January 2017; Accepted: 23 May 2017; Published: 9 June 2017

Transport regulation Report


KLiB Kompetenznetzwerk Lithium Ionen Batterien

Kompetenznetzwerk Li-Batterien


Studie: Technologiefolgenabschätzung und Prüfrichtlinien von lithiumhaltigen Batterien

Armasuisse Report


mont-soleil PHD SUMMER SCHOOL BERNE / SWITZERLAND
07.08.2019
École Polytechnique Fédérale de Lausanne and Bern University of Applied Sciences organize in collaboration with Société Mont-Soleil
PhD Summer School Mont-Soleil
12th – 16th/17th August 2019
Field-Based Insights into the Implementation of Renewable Energies
Conference program 12th – 16th August 2019
- Climate change and the 1.5°C goal of the Paris agreement
- Climate and environmental physics labs at University of Bern
- Mont-Soleil PV plant – layout, long-term measurements, LCA
- PlanetSolar, the first around the world tour with a solar boat
- Design of high efficiency solar cells
- Strategies for hydropower deployment
- Excursion to hydropower plant La Goule at the Doubs river
- JUVENT wind power plant, landscape challenges, plant visit
- Wind turbine design and repowering

PhD summer school


News /
Presentation Master Theses BFH Energy storage research centre 2020

Master Thesis Presentation

iBAT


sccer mobility
Pathways to a net zero CO2 Swiss mobility system
White Paper – March 2021

SCCER Mobility White Paper

CircuBAT

Big Leap

Funding/ Investment

Berner Fachhochschule

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Federal Office of Civil Aviation FOCA

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Federal Office of Energy

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Innosuisse - Swiss Innovation Agency

Clean Sky 2

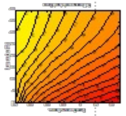
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Federal Office of Transport FOT

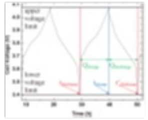
Berner Fachhochschule

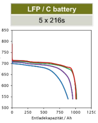
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Innosuisse - Swiss Innovation Agency

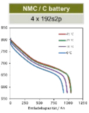
Co-funded by the European Union
Funded by the European Union under grant agreement N° 101137815. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.
Project funded by
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

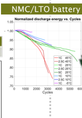
Applied Research


Performance Tests


Life Cycle testing








Functional Safe BMS

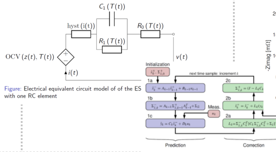
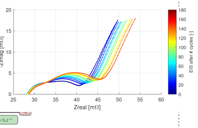
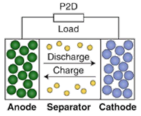
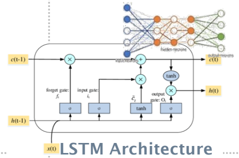


Figure: Electrical equivalent circuit model of of the ES with one RC element







LSTM Architecture

Infrastructure









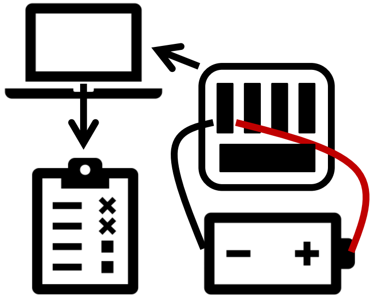
2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023/24

Li-ion battery models

Battery Testing

Battery Modelling

Battery State Functions



Research Projects

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

Flagship
unterstützt von

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Innosuisse – Schweizerische Agentur
für Innovationsförderung

Clean Sky 2

STORE

CIRCUBAT
2021-2025

Swiss eBus plus
2021-2025

BIENE
2022-2026

MWCharger
CIS4BET
2021-2025

GENESIS
2020-2023

Research interests:

- Experimental testing and modelling for BMS algorithms
- Operational strategies for improving performance and service life

ADAPTES
2024-2027

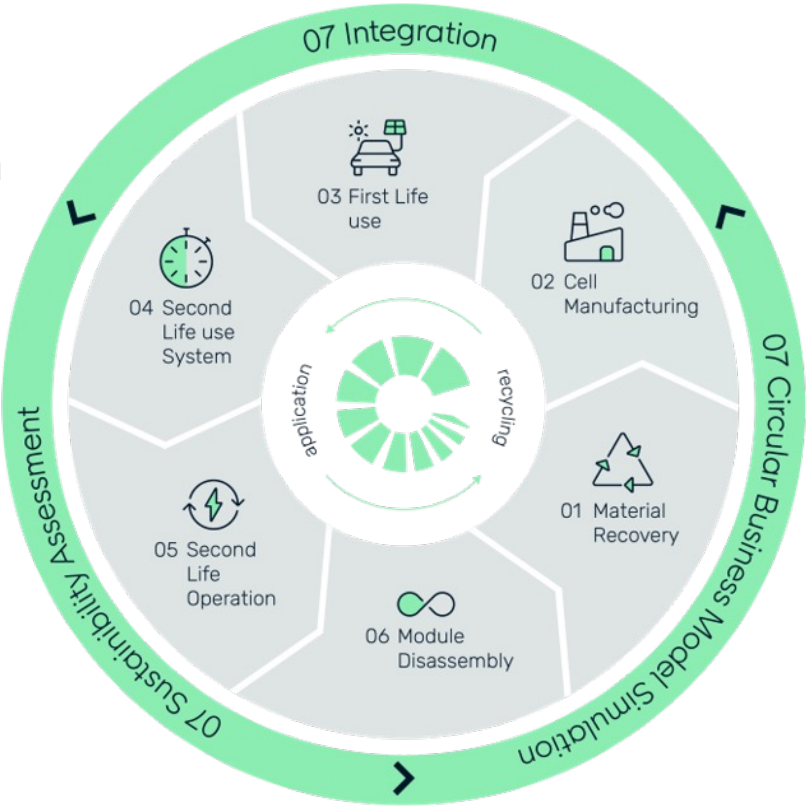
OPEN SESAME – BAT-ReUse
2020-2023 2024-2027

Circubat

CircuBAT aims to close the lithium-ion battery value chain by transitioning from a linear to a circular model.

OBJECTIVES :

- Develop a circular economy model for lithium-ion batteries in the mobility sector in Switzerland.
- Develop solutions to improve the life cycle assessment of batteries.
- Create a second use for energy storage devices to facilitate the energy transition.
- Preserve valuable resources.
- 24 industry partners
- 11 research groups from 7 research institutes



Research Partners

1 BFH Bern University of Applied Sciences
2 csem
3 Empa Materials Science and Technology
4 EPFL
5 OST Ostschweizer Fachhochschule
7 University of St.Gallen Institute for Economy and the Environment
6 Swiss Battery Technology Center

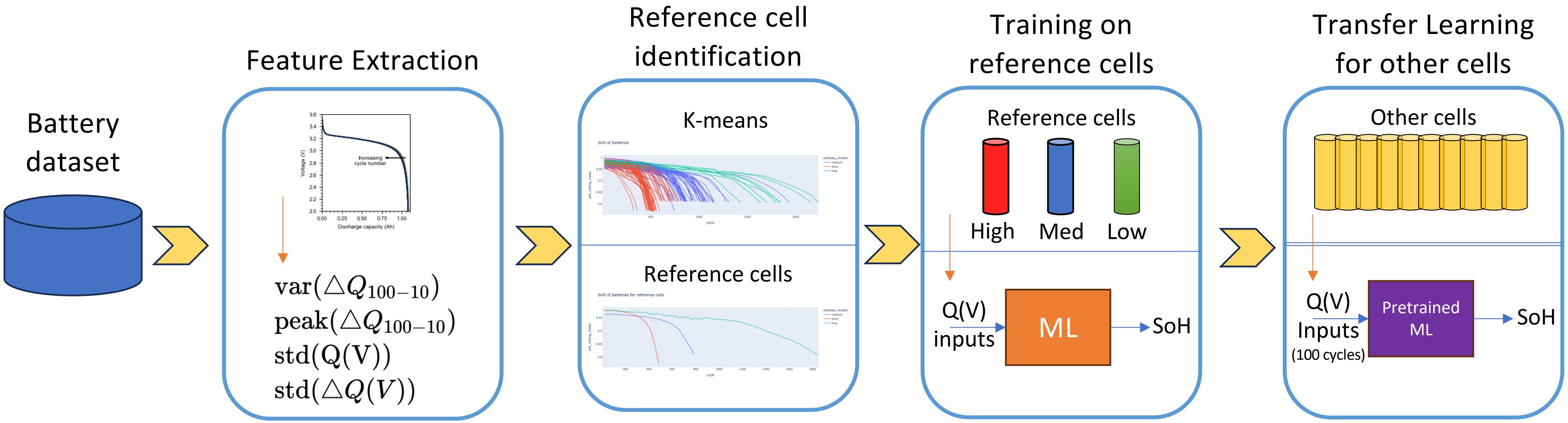
AI solutions – prediction of remaining useful life

General Approach:

- Key parameters extraction
- Data sets for complete life cycles

Model training on reference cases

Implementation of the method for other cells



$$\mathrm{var}(\triangle Q_{100-10})$$
$$\mathrm{peak}(\triangle Q_{100-10})$$
$$\mathrm{std}(\mathrm{Q(V)})$$
$$\mathrm{std}(\triangle Q(V))$$

*Slide content: Circubat Project, Deniz Ira and Prof. Dr. Priscilla Caliandro

Biene – Battery Manager for asset optimization

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

BIENE

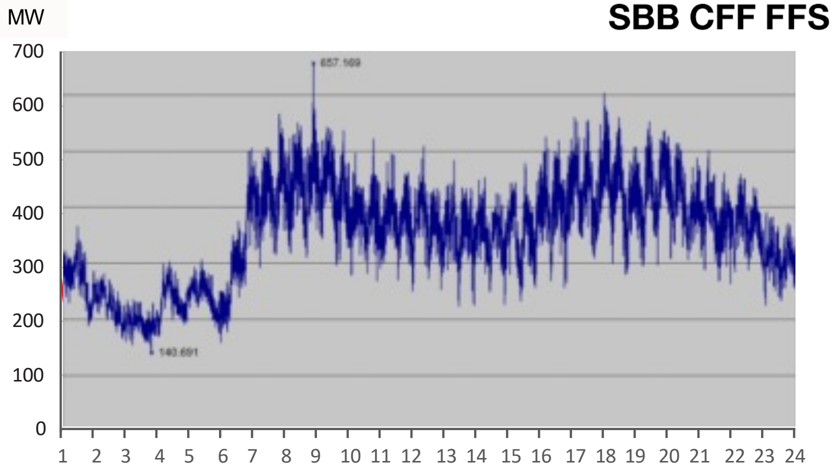
Replacement of diesel cargo vehicles: 11 million litres/year

Total capacity: >100 MWh

Development of a battery manager to fully exploit the potential of the batteries

1 day at SBB (16.7 Hz)

SBB CFF FFS



Biene – Added value

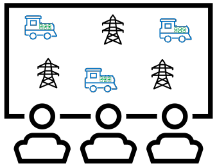
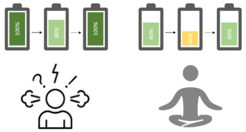
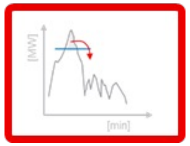
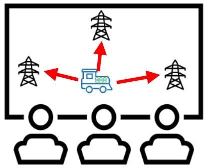
To compare:

60 MW,
>1 h
(neue 16.7Hz Turbine & Generator)

42 MW,
>1.4 h

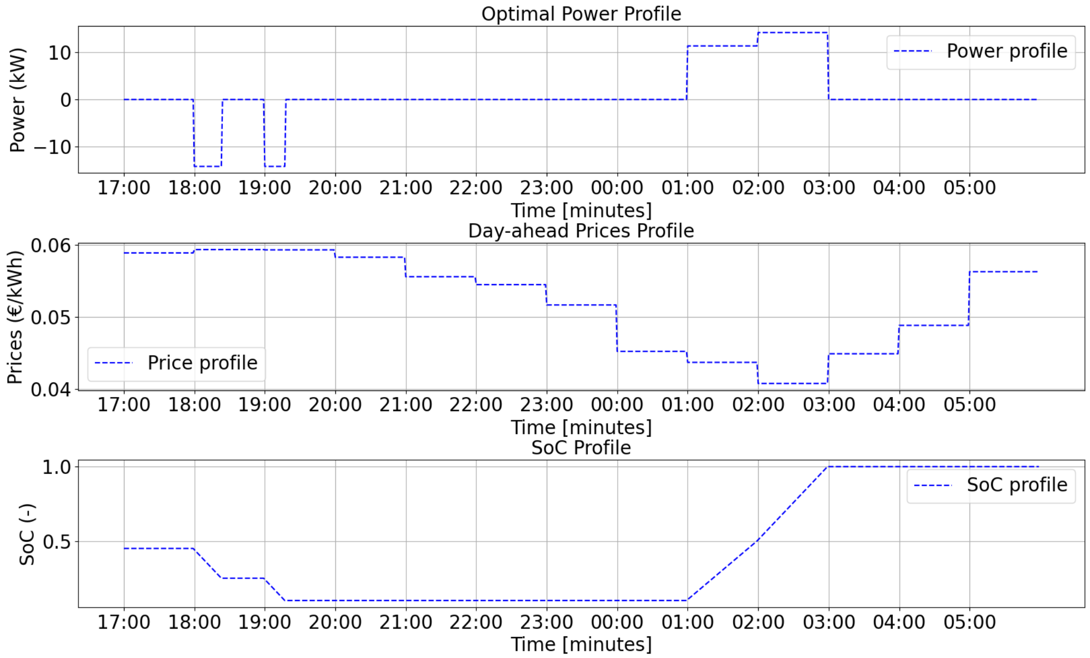
- Battery capacity available in the grid: > 60 MWh

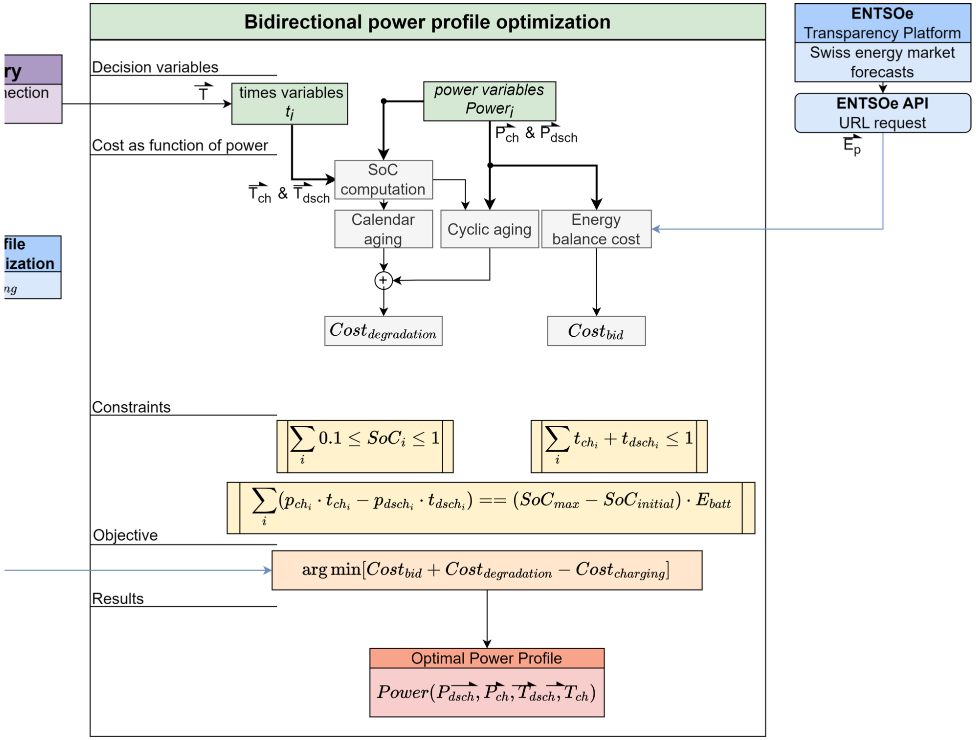
Biene - Overview

	Asset Management	Smart Charging	Operational Flexibility	Service readiness	Grid Services	Vehicle Procurement Requirements
						
Requirements	• Operational data • Battery models	• Energy needs • Mission profiles schedules	• Accessibility	• Vehicle charge visibility • Mission profiles schedules	• Services forecast • Services effects	• Define interfaces
Goals	• Performance monitoring • 2nd Life possibilities	• Optimum charging profile	• Unlock full capacity • Increase usage modes	• Customizable service profiles	• Power peak shaving • Energy provision in overload situations	• Battery vehicle requirements

STORE - Control Strategy Algorithm

Optimization of bidirectional power profile based on flexible energy tariff and battery degradation





Bidirectional power profile optimization

Decision variables

$\vec{T}$

times variables t_i

power variables $Power_i$

$\vec{P}_{ch}$ & $\vec{P}_{dsch}$

Cost as function of power

$\vec{T}_{ch}$ & $\vec{T}_{dsch}$

SoC computation

Calendar aging

Cyclic aging

Energy balance cost

$Cost_{degradation}$

$Cost_{bid}$

Constraints

$$\sum_i 0.1 \leq SoC_i \leq 1$$

$$\sum_i t_{ch_i} + t_{dsch_i} \leq 1$$

$$\sum_i (p_{ch_i} \cdot t_{ch_i} - p_{dsch_i} \cdot t_{dsch_i}) == (SoC_{max} - SoC_{initial}) \cdot E_{batt}$$

Objective

$$\arg\min[Cost_{bid} + Cost_{degradation} - Cost_{charging}]$$

Results

Optimal Power Profile

$$Power(\overrightarrow{P_{dsch}}, \vec{P}_{ch}, \vec{T}_{dsch}, \vec{T}_{ch})$$

ENTSOe
Transparency Platform

Swiss energy market forecasts

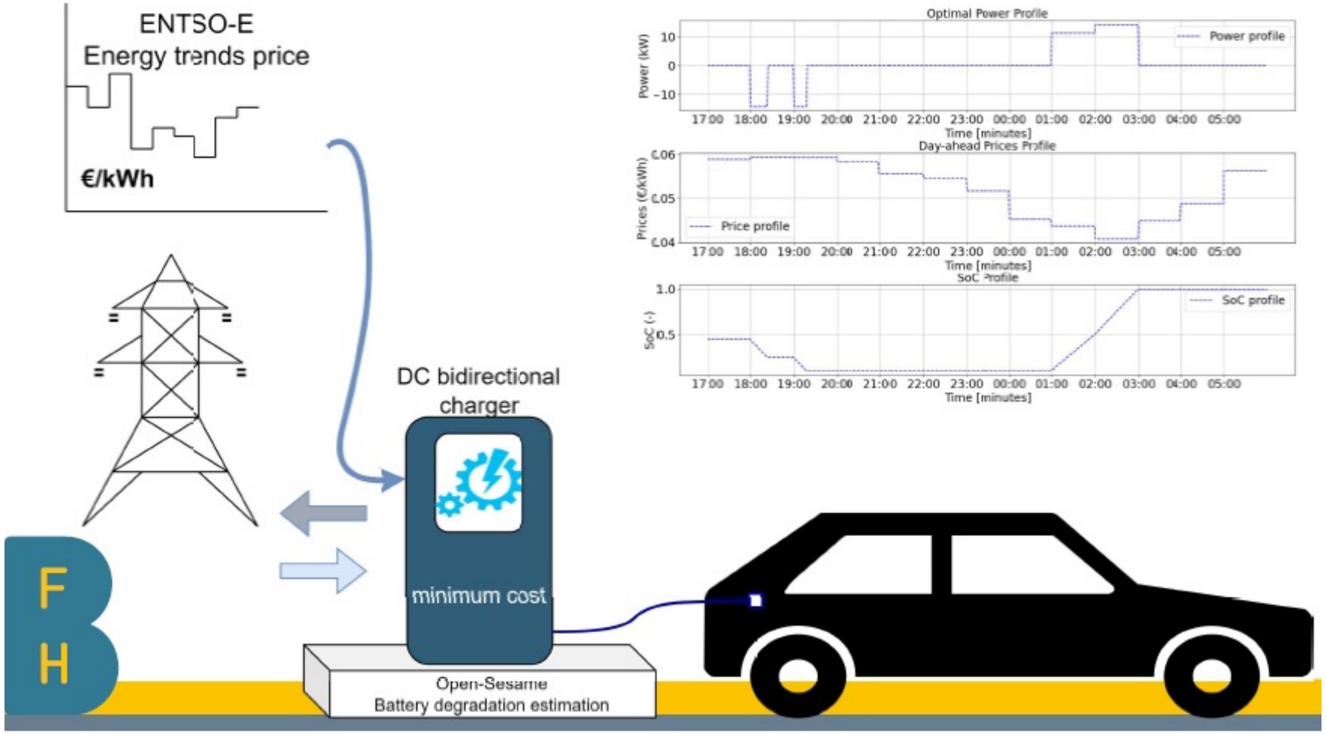
ENTSOe API
URL request

$\vec{E}_p$

Energy storage system optimization

Bi-directional Charger Control Strategy

- Usage pattern
- Day ahead price fluctuation
- Open-Sesame battery degradation
- Maximize to Return Of Investment (ROI)
- Charging Strategy development



*Master Thesis project of Bastien Binz

SwissTrolley plus

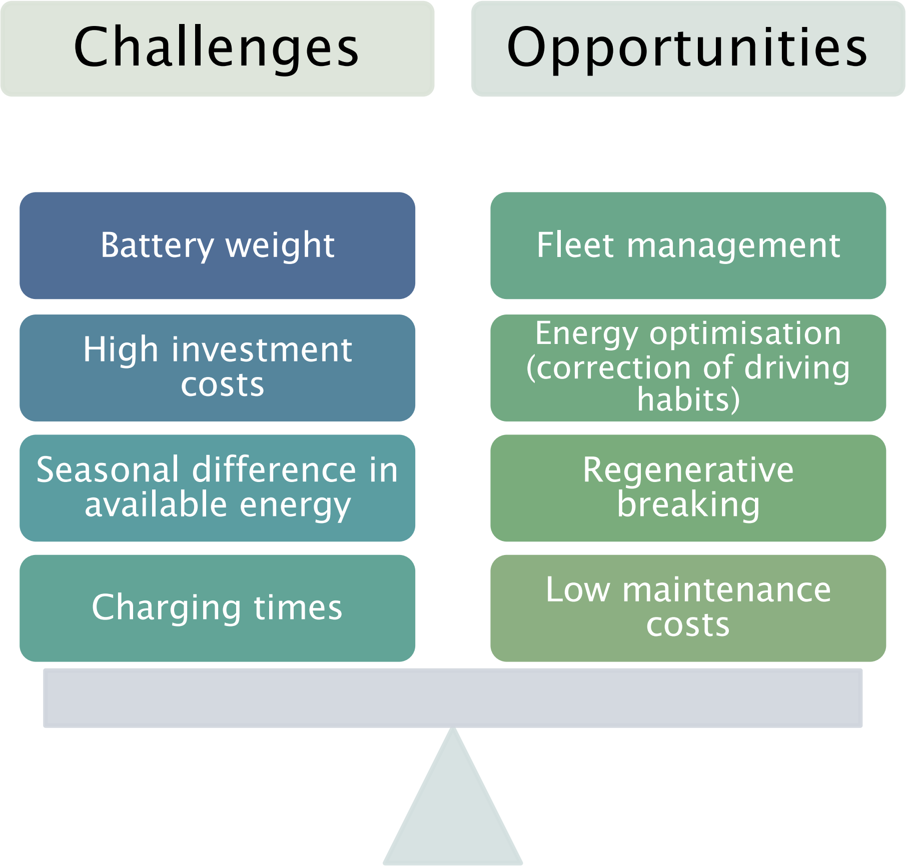
Swiss eBus plus

Conclusion:

- Battery capacity: 15% increase
- Energy consumption for comfort: ~30% less

With 2 major advantages:

- The **optimised battery size and charging infrastructure** will help **ensure significantly longer service life.**
- Additional innovations make **everyday operation even more flexible.**



Challenges	Opportunities
Battery weight	Fleet management
High investment costs	Energy optimisation (correction of driving habits)
Seasonal difference in available energy	Regenerative breaking
Charging times	Low maintenance costs

Thank you for your attention!

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