Electric Vehicle Battery Technologies

Lecture 4

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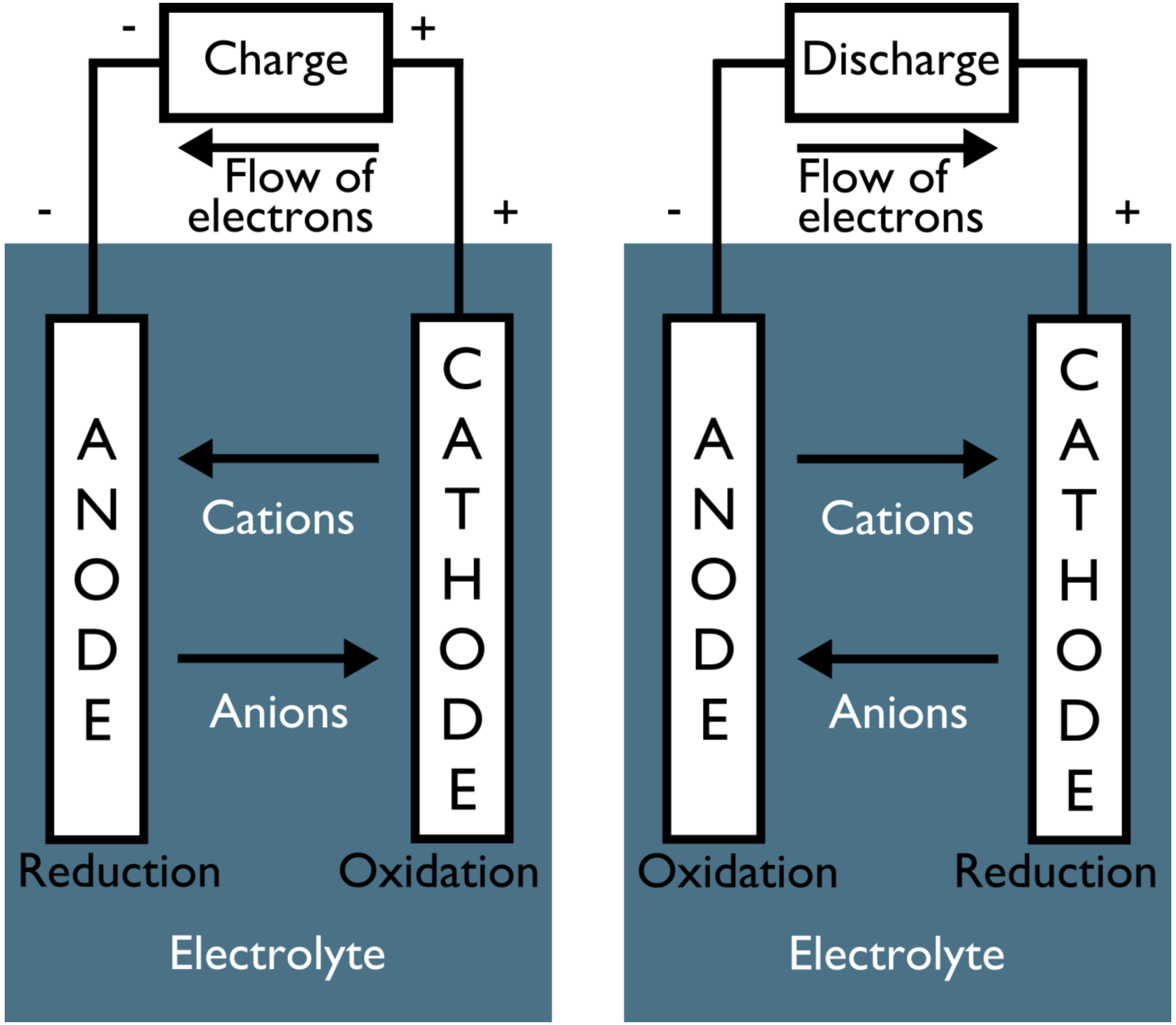
Structure of a battery and how it works

- Batteries are comprised of three major components: cathode (positive terminal), anode (negative terminal), and electrolyte (electrical conducting medium)
- Electrical potential difference is where energy is "stored". When the circuit is connected, electrons are allowed to flow and thus generate electricity



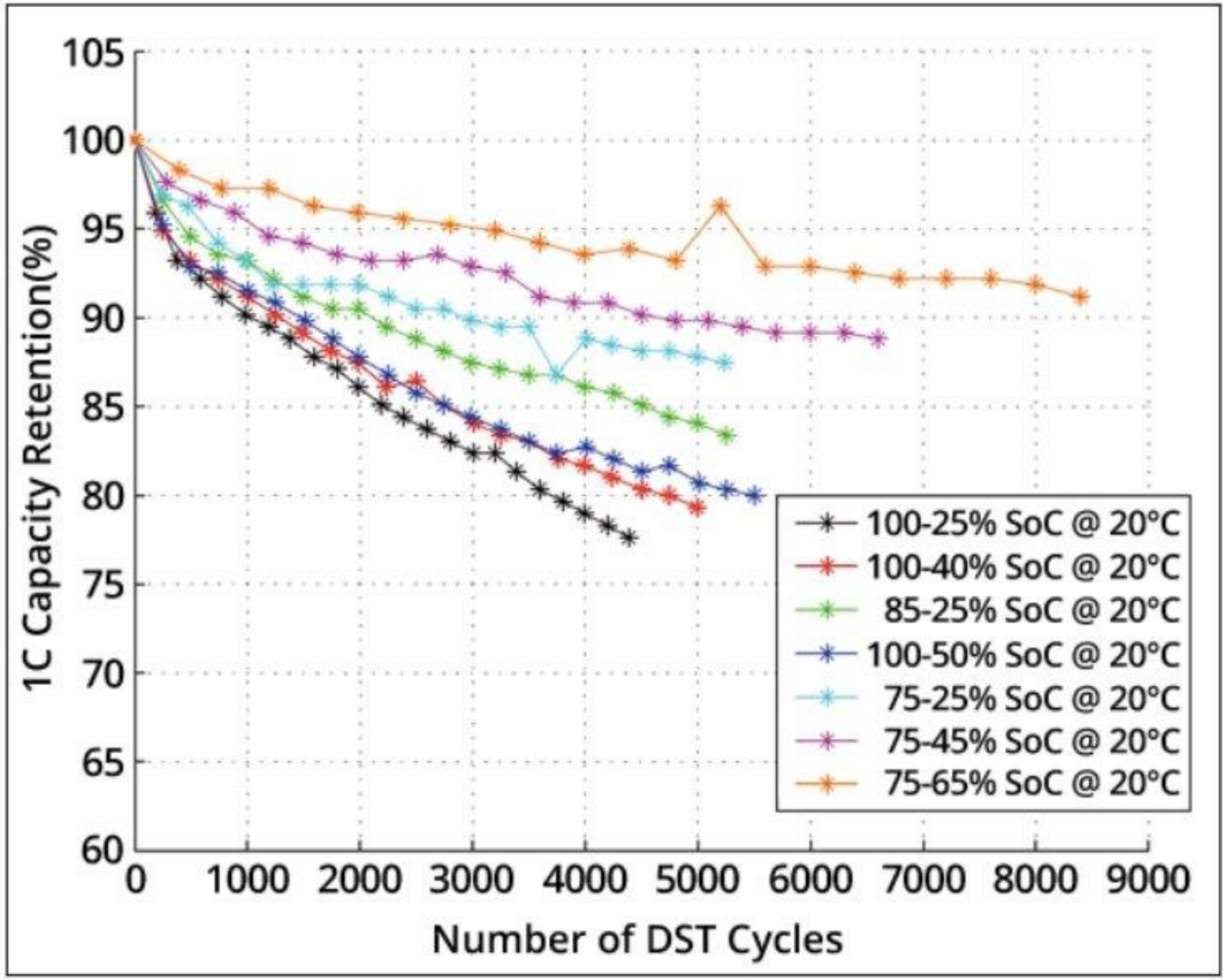
Battery Operation in EVs

Battery nomenclature

- SOC (state-of-charge): How much energy is left in the battery, typically expressed as a percentage
- Capacity: Dictates how much energy can be stored in the battery when it is full
- Effective/net capacity: The usable range of the battery
- Battery cycle (charge cycle): The process of discharging then charging a battery
- Depth-of-discharge: Amount of a battery discharged in a cycle

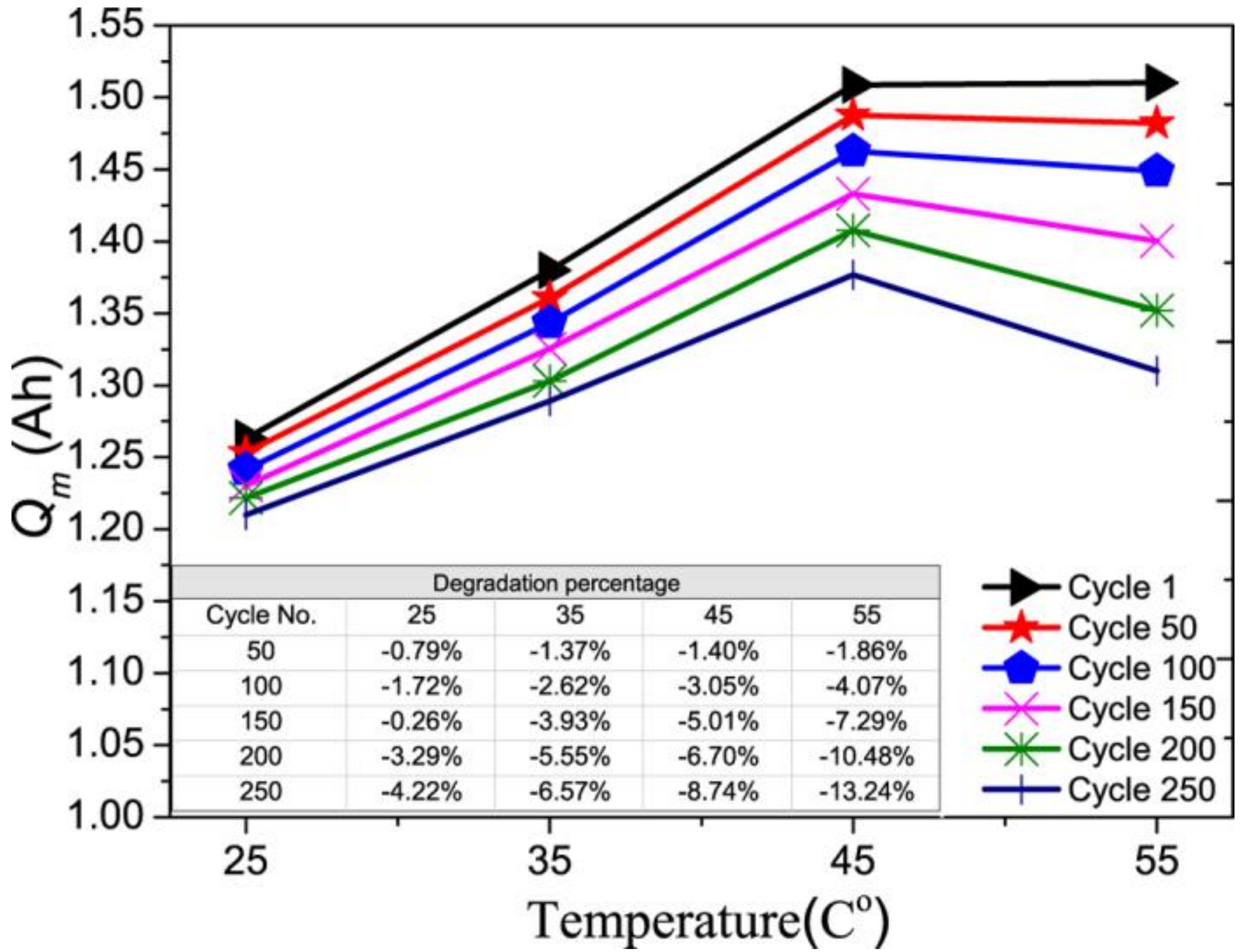
Battery degradation (SOC)

- The rate at which a battery degrades (loses overall capacity) depends on many factors
- Larger depth of discharge = faster degradation
- More battery cycles = more degradation
- Speed of charging/discharging = faster degradation

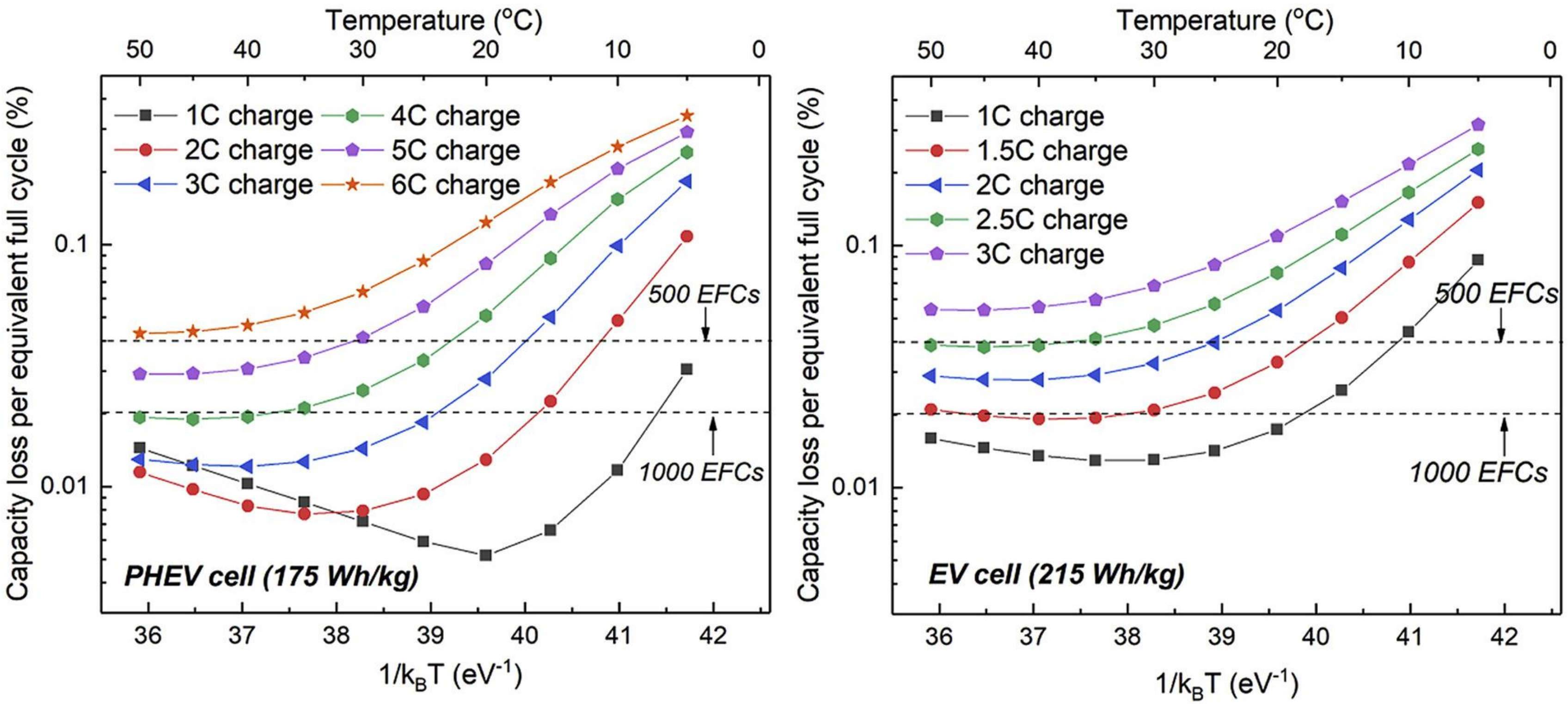


Battery degradation (Temperature)

- Battery degradation can also be accelerated at different temperatures
- Extreme temperatures on either end (hot or cold) can lead to accelerated degradation



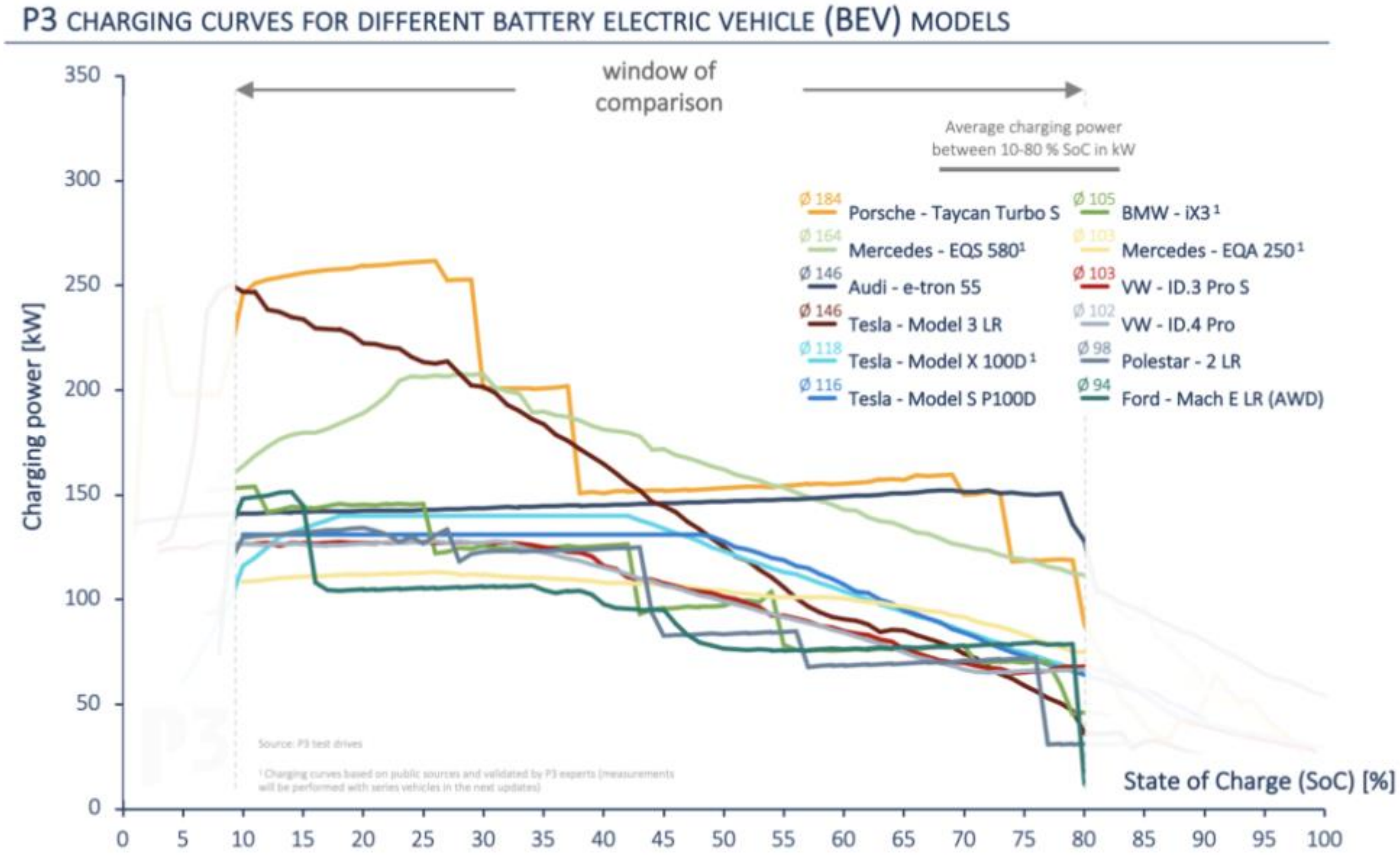
Battery degradation (Charging speed)



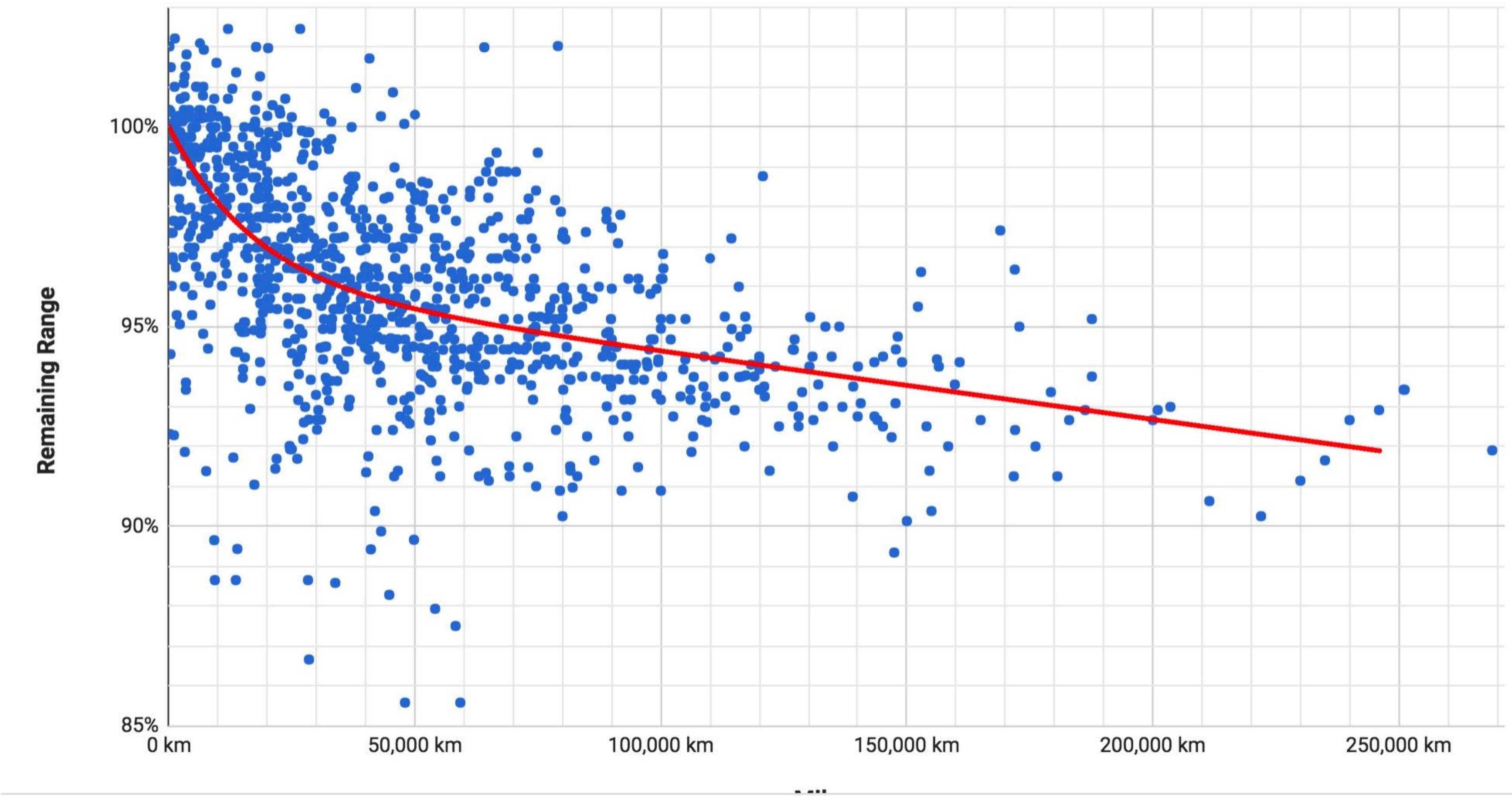
- Charging at higher rates of power can accelerate battery degradation!

Charging speed vs SOC

- Unlike filling a tank of gas, when you charge your vehicle the speed of charging will change depending on the SOC
- This is because the voltage of the battery will change! As SOC increases, charging speed decreases
- Charging 80% to 100% can take as long as 0% to 80%



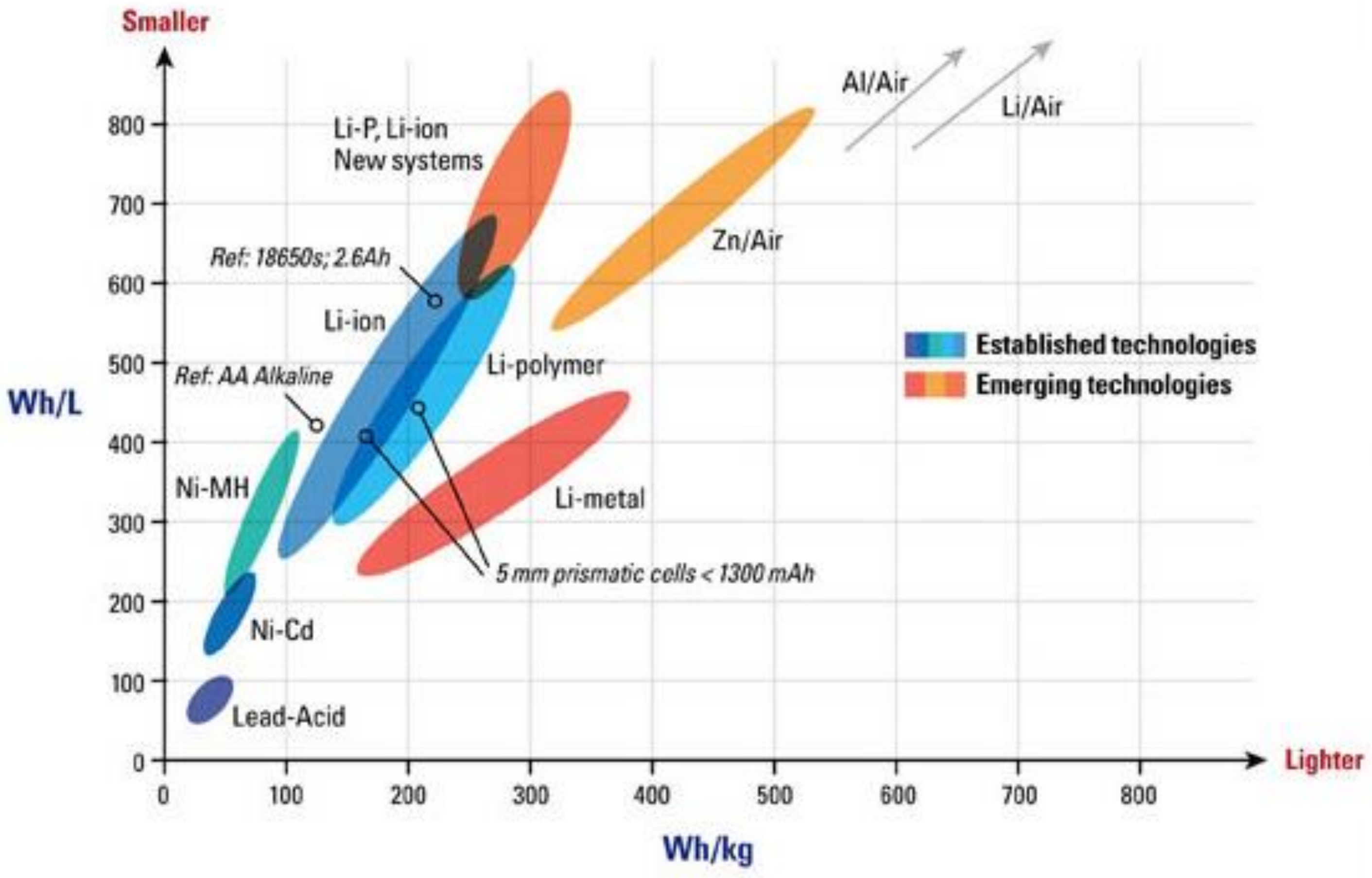
Empirical Tesla degradation



EV Battery Chemistries

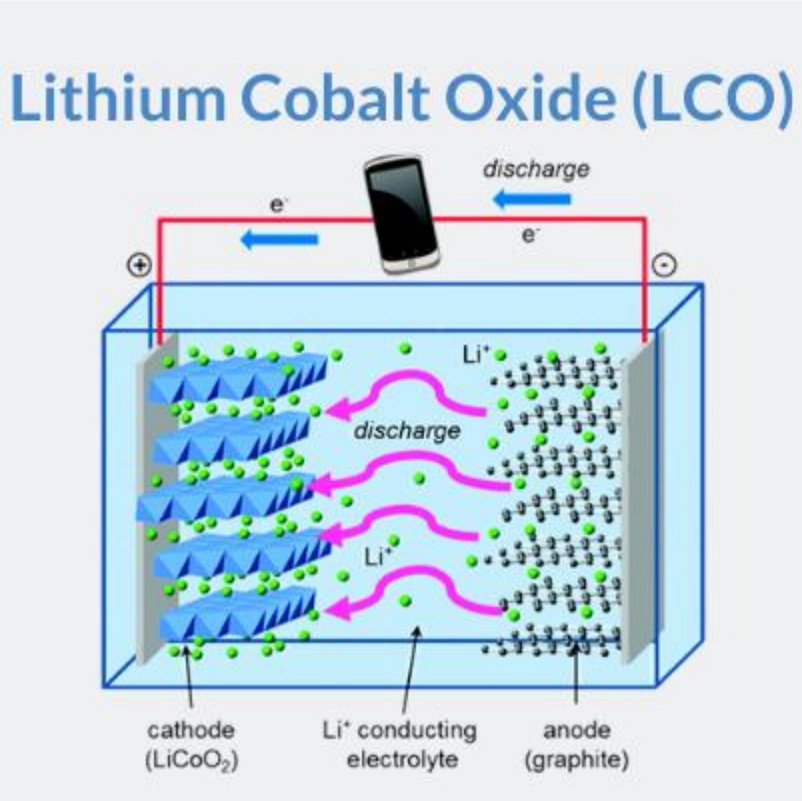
Energy versus power density

- Battery chemistries have different properties for both energy density (weight and capacity issues) and power density
- Oftentimes there is a direct tradeoff between energy and power density—but "better" chemistries may alleviate these issues in the future



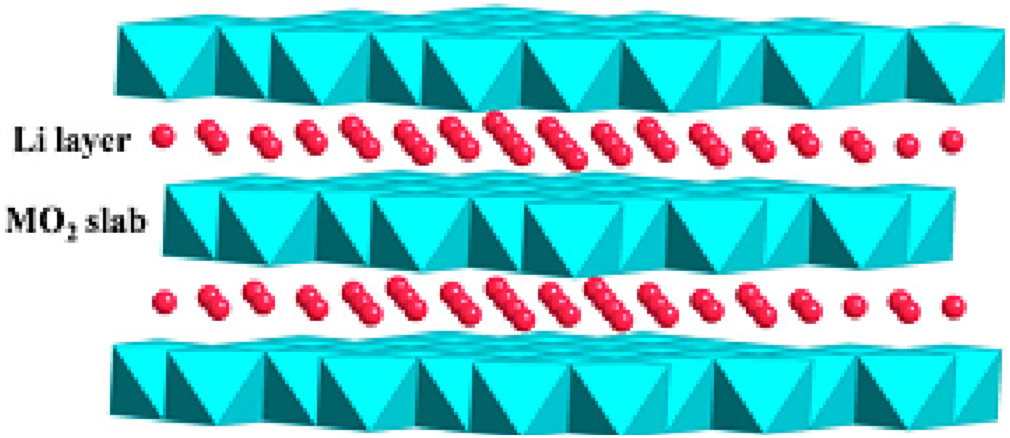
Lithium Cobalt Oxide (LCO) battery

- Primary application in smartphones, tablets, and laptops (not automotive applications)
- High specific energy but low specific power
- Relatively more expensive materials (cobalt)
- Low thermal stability and short life-cycles



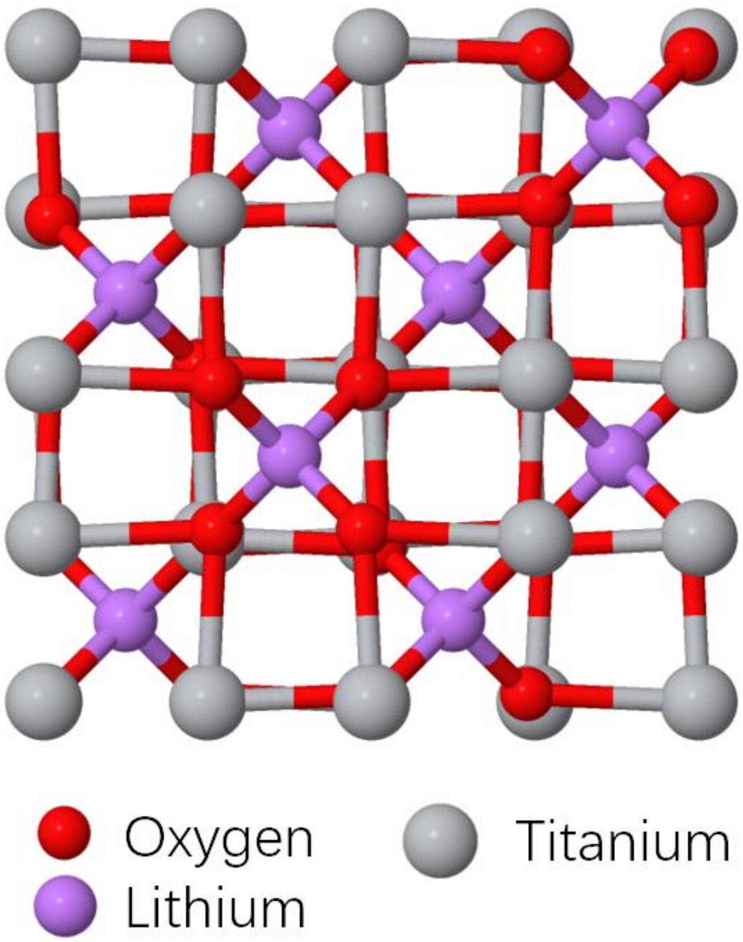
Lithium Manganese Oxide (LMO) battery

- By excluding cobalt, LMO batteries can avoid thermal runaway events (fires!)
- Charge quickly and have high specific power
- Energy density is much lower and have relatively low cycle-life
- Original Nissan Leaf used LMO
- A variant known as LMNO (containing nickel) is a promising candidate for commercialization



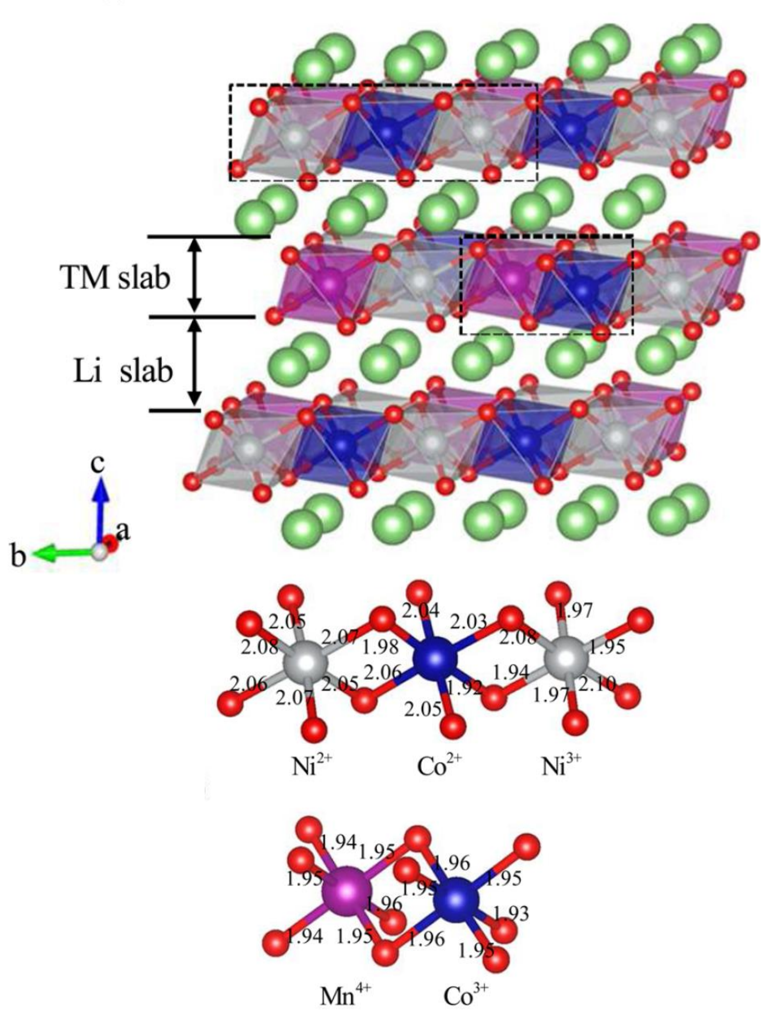
Lithium titanium oxide (LTO)

- Uses lithium-titanate nanocrystals instead of carbon on the anode.
- Faster recharging time and high power with long life cycles
- Relatively low specific energy compared to other Li batteries
- Employed by the Mitsubishi i-MiEV



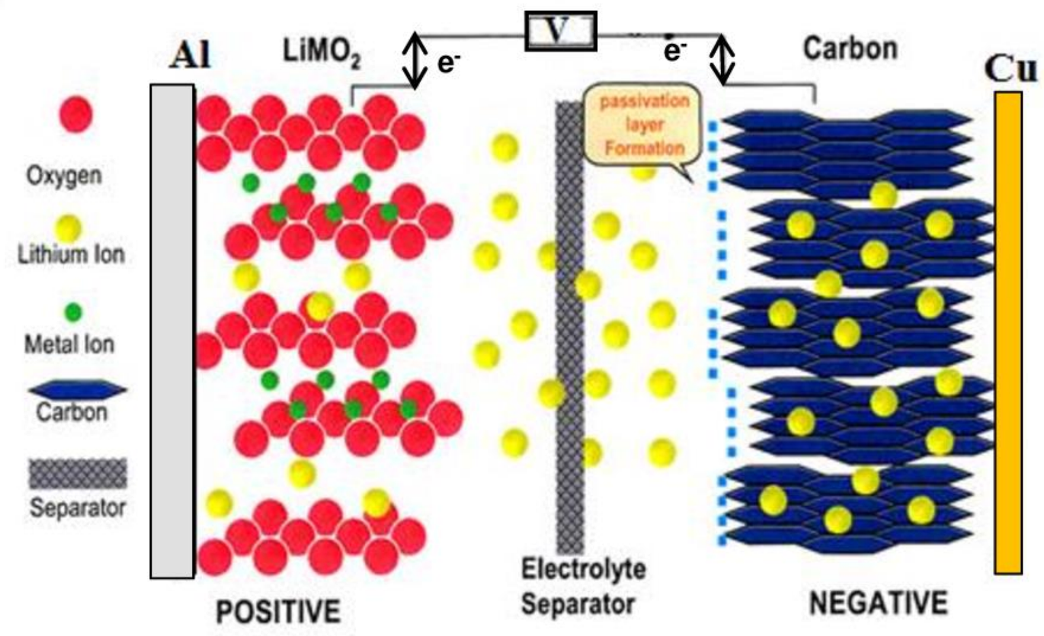
Lithium Nickel-Cobalt-Aluminum Oxide (NCA) battery

- Nickel enhances energy density
- Decent specific power and has a long life-cycle
- Not as safe as other lithium technologies
- Materials are fairly expensive (combination of nickel and cobalt)
- Employed by Tesla: Model S, Model Y, Model X, Model 3



Lithium Nickel-Manganese-Cobalt Oxide (NMC) battery

- High energy density and longer life-cycle
  - Nickel – high energy, unstable; manganese – stable, low energy; combined: stable chemistry and high energy
- Slightly lower power than other cobalt batteries
- Higher thermal stability than LCO
- One of the most popular batteries for existing models:
  - Renault ZOE, BMW i3, Peugeot e208, Nissan Leaf, Hyundai Kona, Hyundai Ionic, Chevrolet Bolt, Jaguar i-Pace
- GM's Ultium batteries are NMC



$$LiMO_2 \xrightarrow{charge} Li_{1-x}MO_2 + xLi^+ + xe^-$$

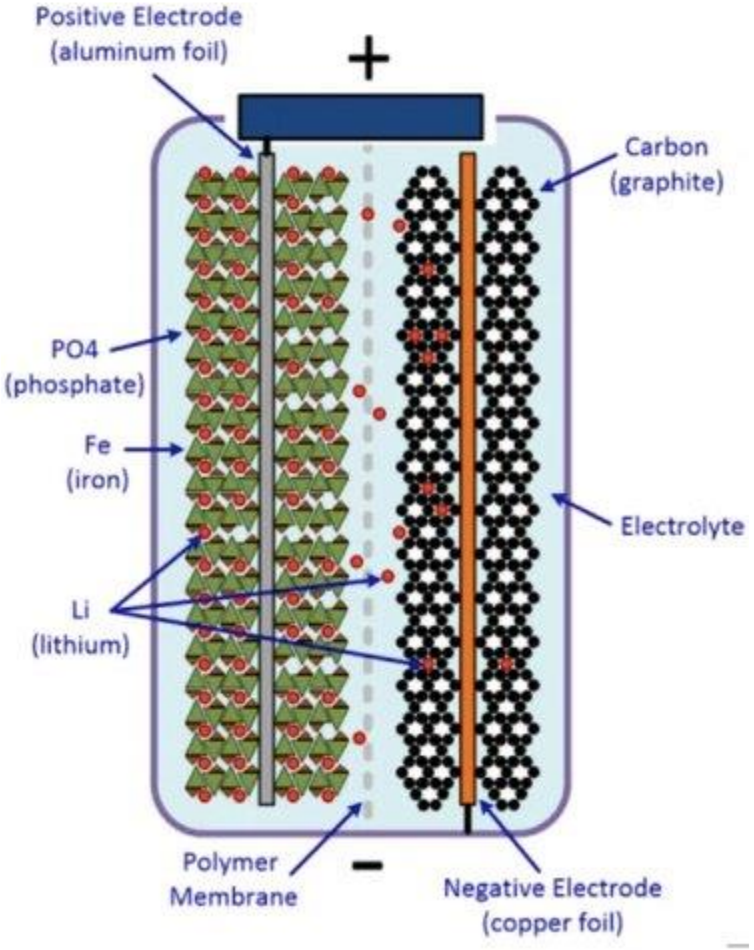
$$LiMO_2 \xleftarrow[discharge]{} Li_{1-x}MO_2 + xLi^+ + xe^-$$

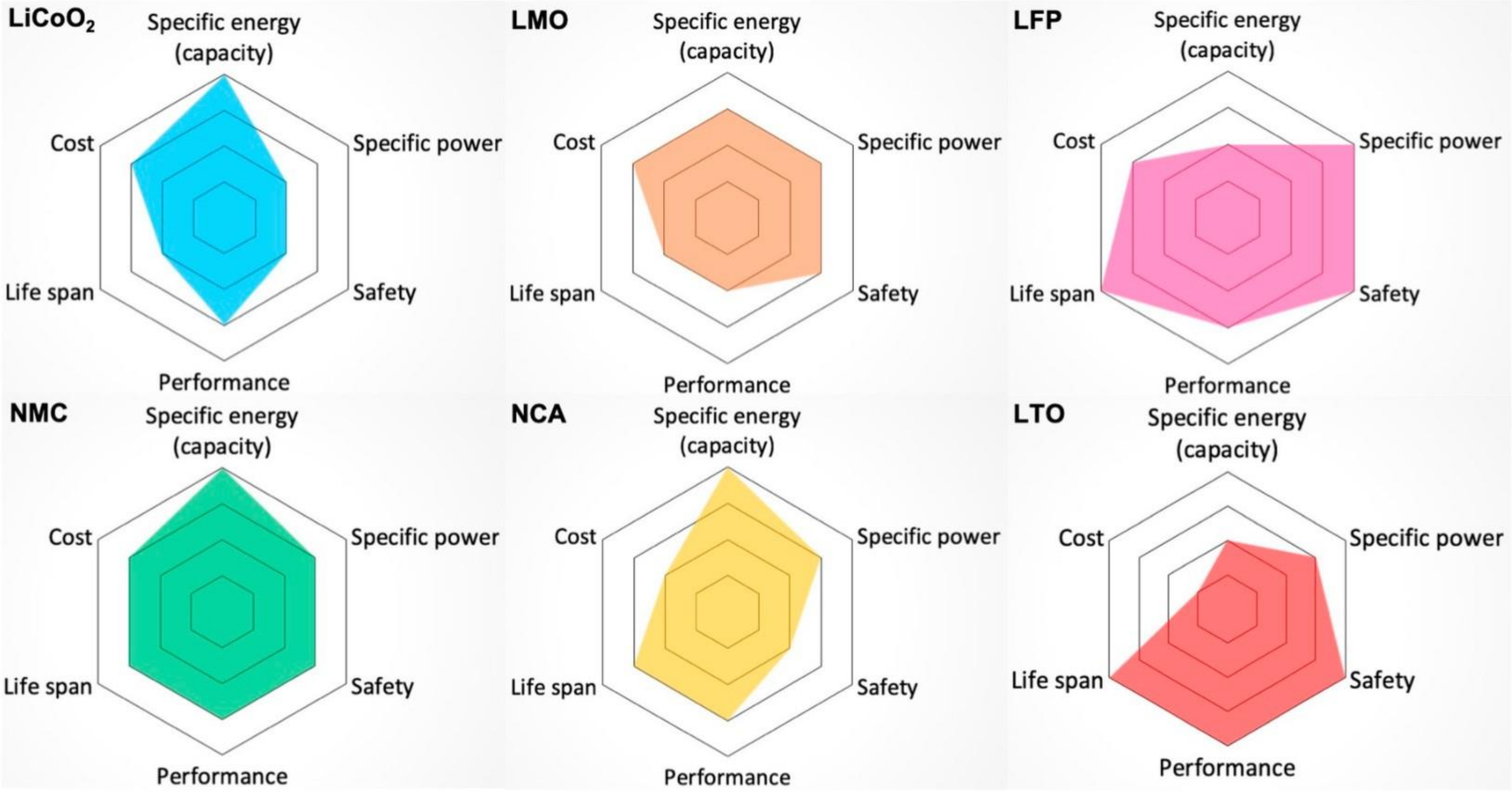
$$C + xLi^+ + xe^- \xrightarrow{charge} Li_xC$$

$$C + xLi^+ + xe^- \xleftarrow[discharge]{} Li_xC$$

Lithium Iron Phosphate (LFP) battery

- Materials are relatively cheap
- High cycle life and power density, considered to be very safe!
- Relatively lower energy density
- Tesla has recently shifted Model 3 and Model Y to LFP. Mercedes-Benz, Ford, and Volkswagen have also announced a switch to this chemistry

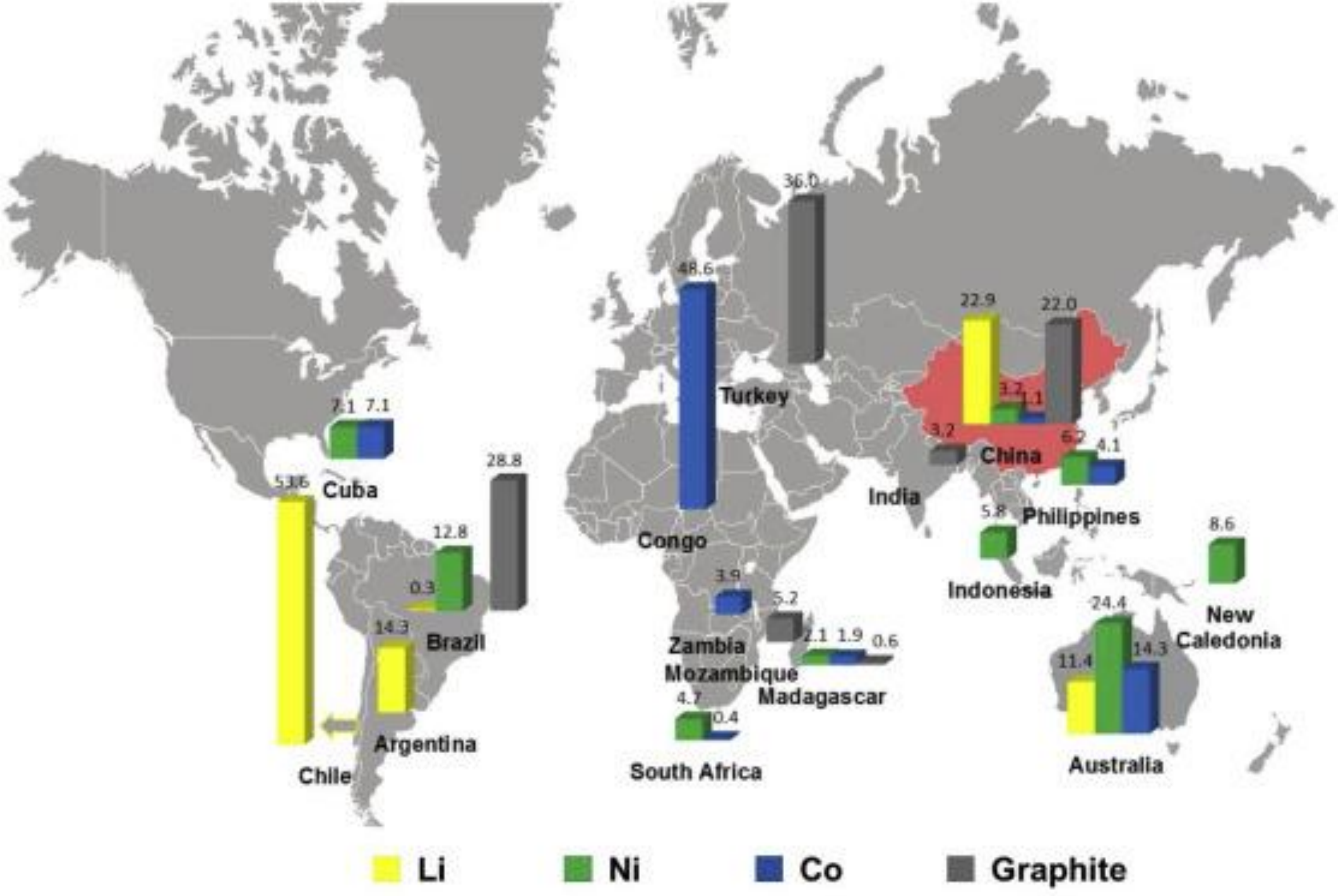




LiCoO$_2$
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost
LMO
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost
LFP
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost
NMC
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost
NCA
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost
LTO
Specific energy (capacity)
Specific power
Safety
Performance
Life span
Cost

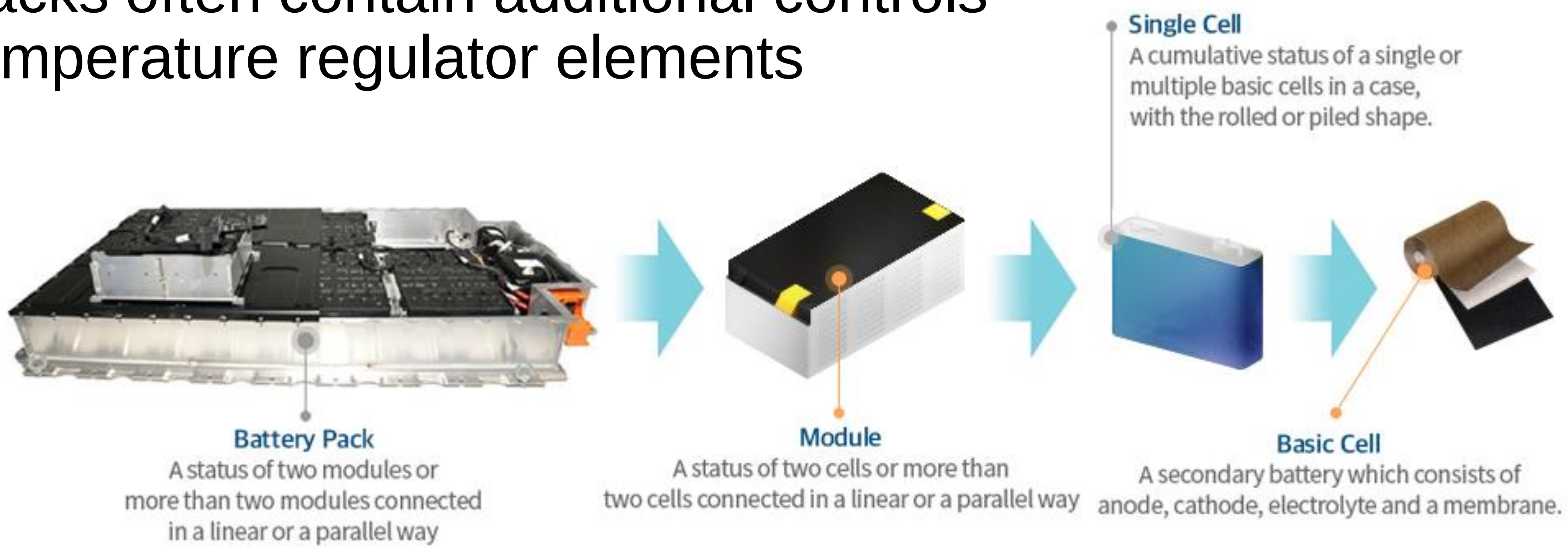
Battery Production

Sourcing battery materials

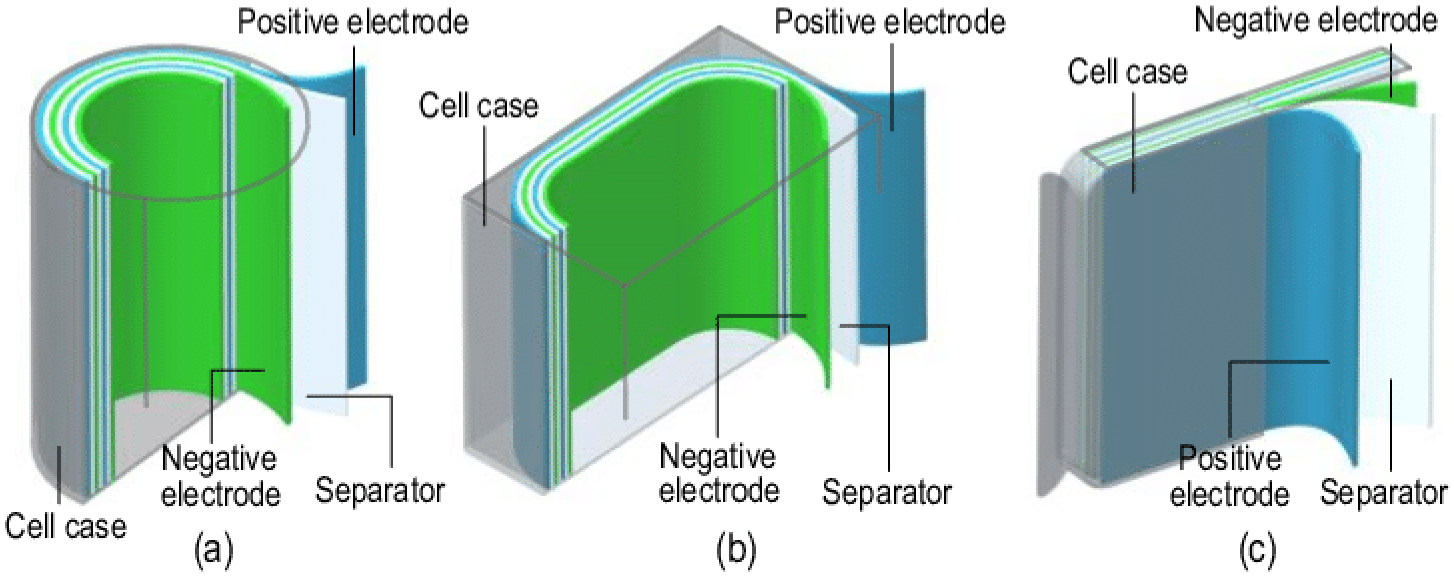


Cell versus module versus pack

- Batteries are comprised of different subdivisions from cells to modules to packs
- Costs do not scale linearly since modules and packs often contain additional controls and temperature regulator elements



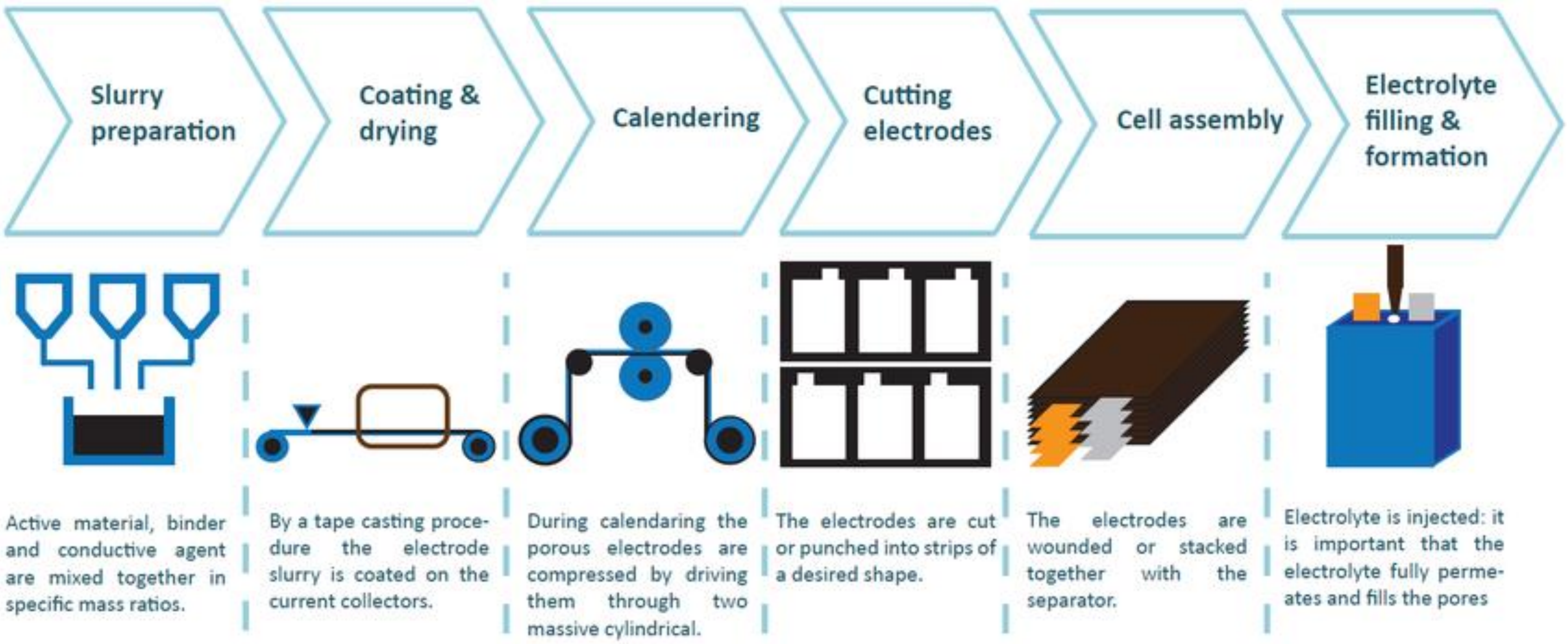
Battery form factors



Cylindrical
Prismatic
Pouch

- Battery cells can differ in their design and the ideal factor varies with chemistry, use case, and pack design
- Cylindrical cells have lower packing density, but have higher mechanical stability and better thermal management
- Prismatic cells are “rolled up” or stacked by layers. Corners can experience more stress but have higher packing density.
- Pouch cells do not have rigid enclosure and can swell in use.

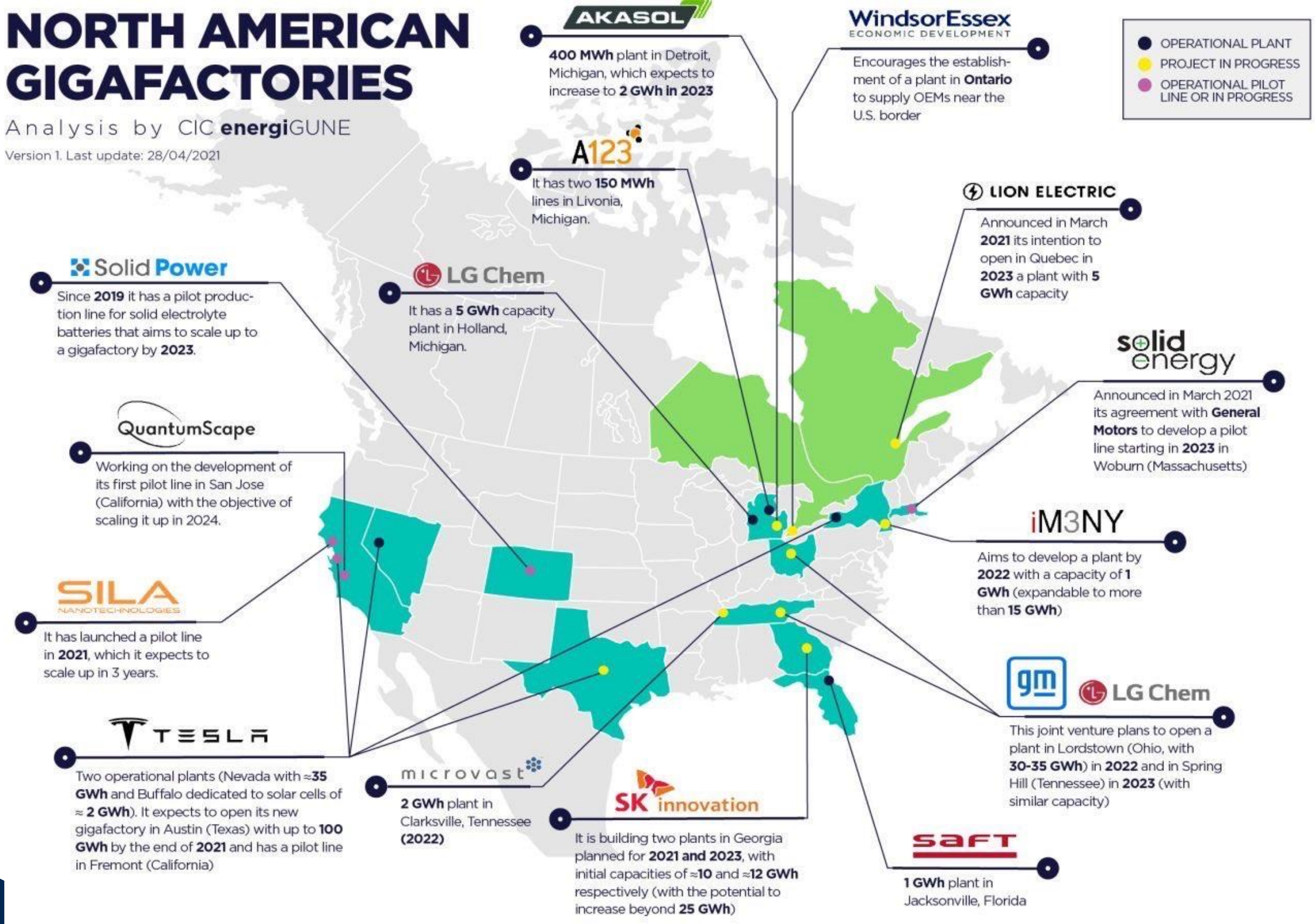
Battery manufacturing process



- The manufacturing process has many steps and therefore many opportunities for cost reductions
- As more batteries are produced: better equipment, superior production techniques, innovation in the process line, etc.

Battery production – “Gigafactories”

- As electric vehicles become more popular, battery production must ramp up dramatically
- Large-scale “gigafactories” have been built all around the world to keep up with demands


NORTH AMERICAN GIGAFACTORIES
Analysis by CIC energiGUNE
Version 1. Last update: 28/04/2021
OPERATIONAL PLANT
PROJECT IN PROGRESS
OPERATIONAL PILOT LINE OR IN PROGRESS
AKASOL
400 MWh plant in Detroit, Michigan, which expects to increase to 2 GWh in 2023
WindsorEssex
ECONOMIC DEVELOPMENT
Encourages the establishment of a plant in Ontario to supply OEMs near the U.S. border
A123
It has two 150 MWh lines in Livonia, Michigan.
LION ELECTRIC
Announced in March 2021 its intention to open in Quebec in 2023 a plant with 5 GWh capacity
Solid Power
Since 2019 it has a pilot production line for solid electrolyte batteries that aims to scale up to a gigafactory by 2023.
LG Chem
It has a 5 GWh capacity plant in Holland, Michigan.
solid energy
Announced in March 2021 its agreement with General Motors to develop a pilot line starting in 2023 in Woburn (Massachusetts)
QuantumScape
Working on the development of its first pilot line in San Jose (California) with the objective of scaling it up in 2024.
iM3NY
Aims to develop a plant by 2022 with a capacity of 1 GWh (expandable to more than 15 GWh)
SILA
NANOTECHNOLOGIES
It has launched a pilot line in 2021, which it expects to scale up in 3 years.
gm
LG Chem
This joint venture plans to open a plant in Lordstown (Ohio, with 30-35 GWh) in 2022 and in Spring Hill (Tennessee) in 2023 (with similar capacity)
TESLA
Two operational plants (Nevada with ≈35 GWh and Buffalo dedicated to solar cells of ≈ 2 GWh). It expects to open its new gigafactory in Austin (Texas) with up to 100 GWh by the end of 2021 and has a pilot line in Fremont (California)
microvast
2 GWh plant in Clarksville, Tennessee (2022)
SK innovation
It is building two plants in Georgia planned for 2021 and 2023, with initial capacities of ≈10 and ≈12 GWh respectively (with the potential to increase beyond 25 GWh)
saft
1 GWh plant in Jacksonville, Florida

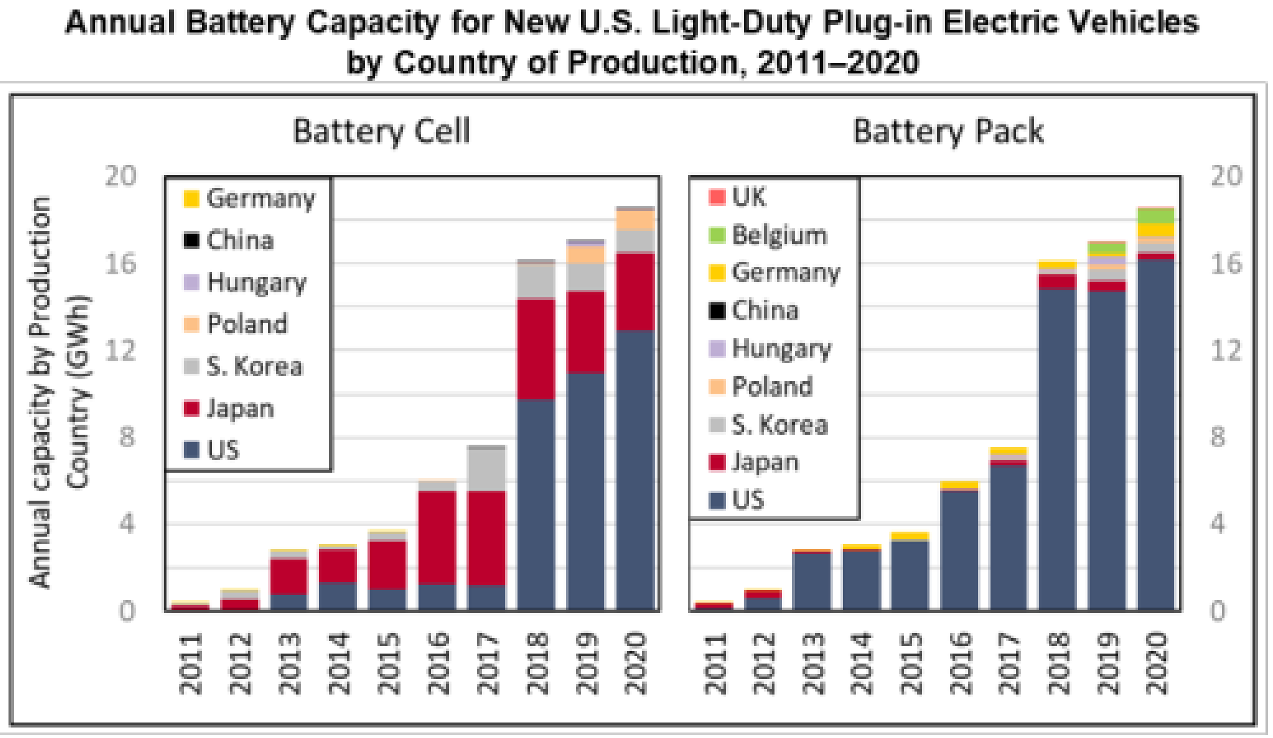
...and lots of planned expansion

New Battery Plants Announced by Vehicle Manufacturers as of October 25, 2021

Manufacturer	Location	Expected Opening
Ford	Northeast of Memphis, TN	2025
Ford & SK Innovation	Central KY	2025
Ford & SK Innovation	Central KY	2026
General Motors & LG Chem	Lordstown, OH	2022
General Motors & LG Energy Solution	Spring Hill, TN	2023
General Motors & LG Energy Solution	TBD	TBD
General Motors & LG Energy Solution	TBD	TBD
SK Innovation	Northeast of Atlanta, GA	2022
SK Innovation	Northeast of Atlanta, GA	2023
Stellantis & LG Energy Solution	TBD	2024
Stellantis & Samsung SDI	TBD	2025
Toyota	Southeast of Greensboro, NC	2025
Volkswagen	Chattanooga, TN	TBD

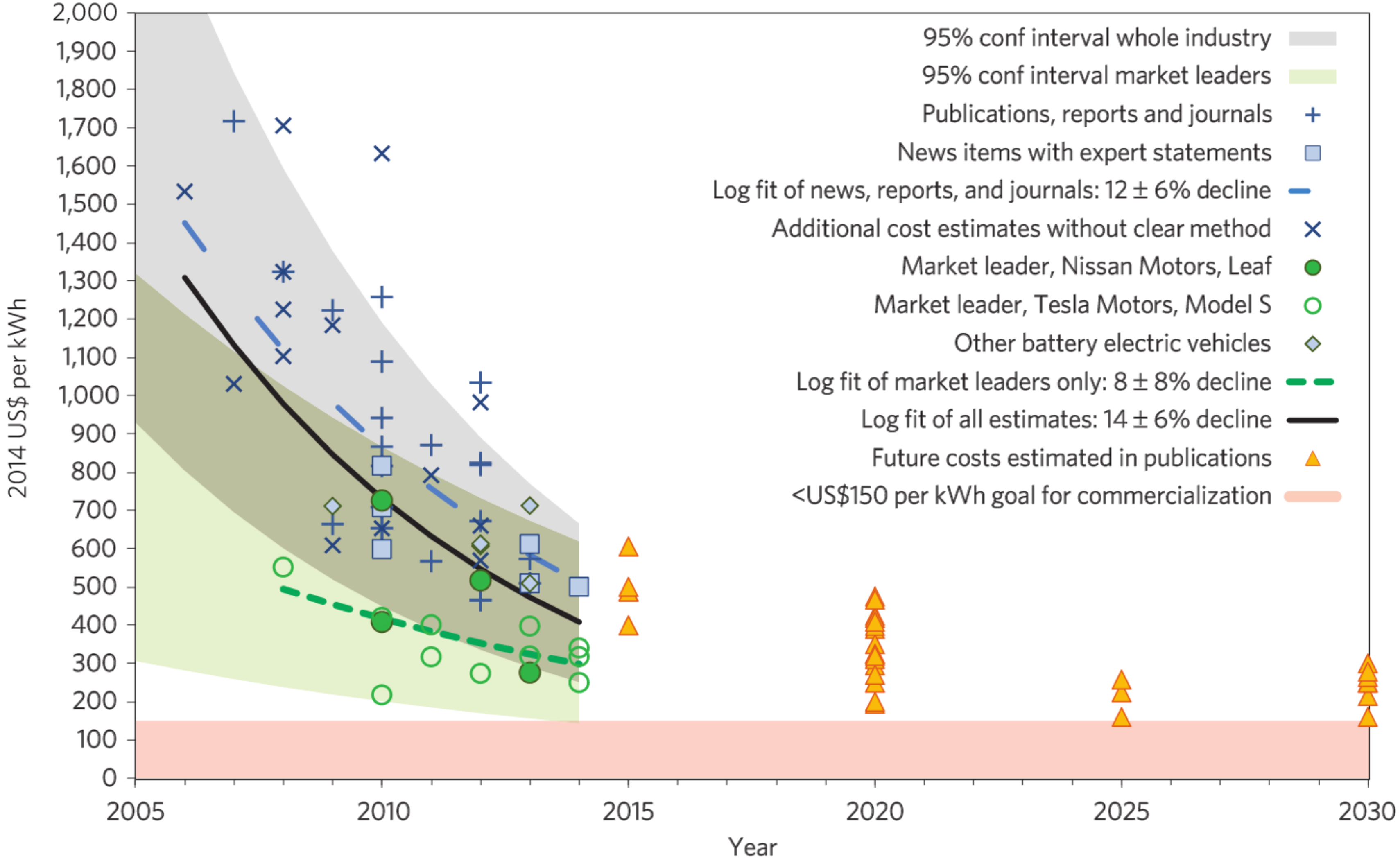
International Battery Production

- Continuous rapid growth of battery production across the world to supply the US
- The US imports a substantial amount of battery cells, but the vast majority of pack production happens domestically

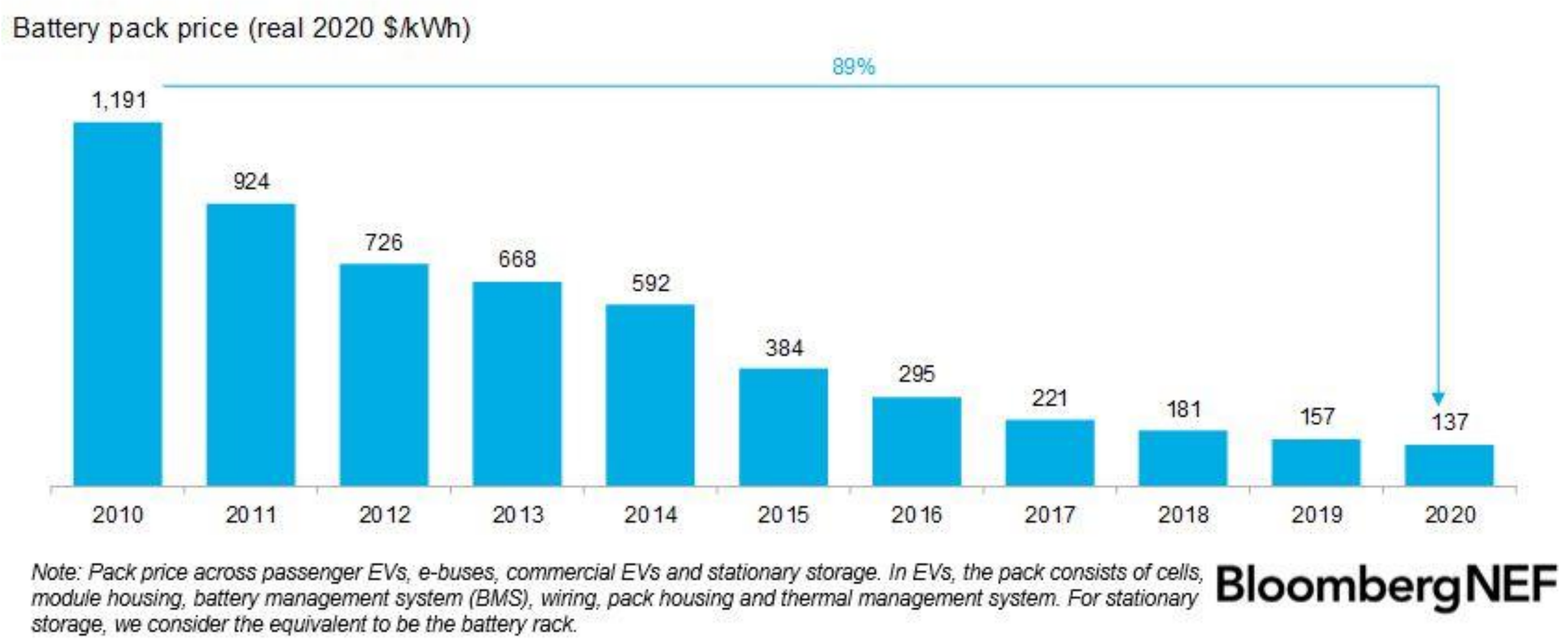


Battery costs

- Battery pack projections from *Nature Climate Change*
- Experts predicted prices wouldn't fall to $150/kWh until past 2030
- That cost point has already been reached! Next up: $85/kWh



Battery pack price trends

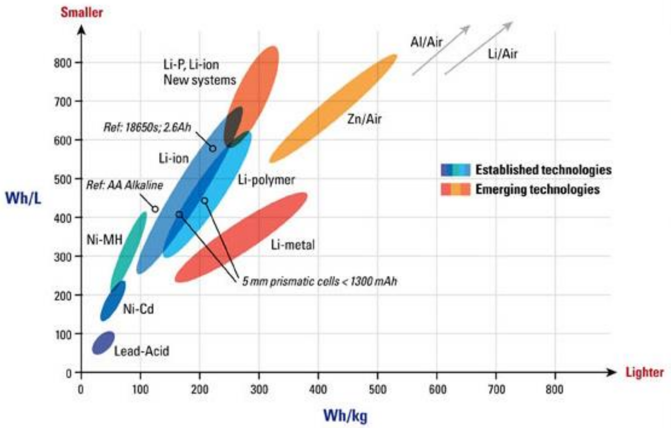


New Battery Chemistry Technologies

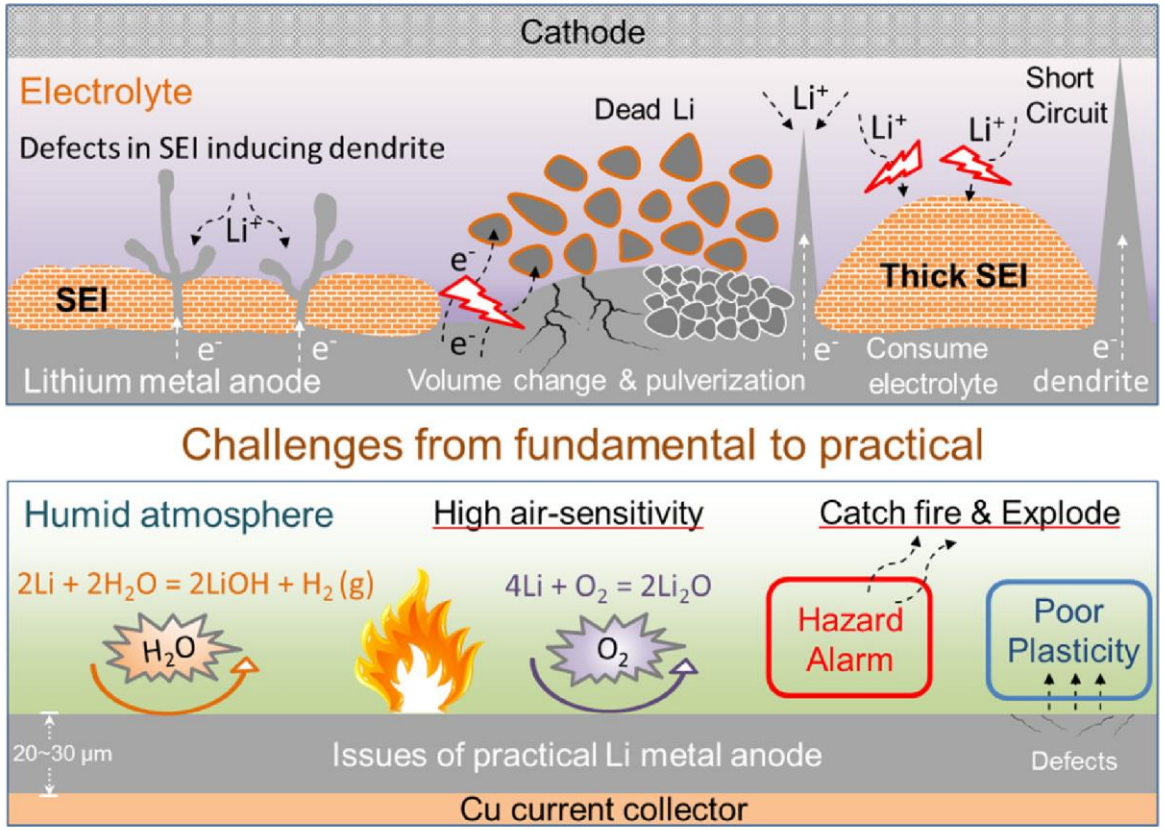
Future battery chemistries

- While improvements in current lithium-ion battery chemistries are still plentiful, other chemistries may offer revolutionary benefits to batteries
- Most “future” battery chemistries are still in the laboratory phase and face many barriers to commercialization such as costs and safety

Lithium metal anodes

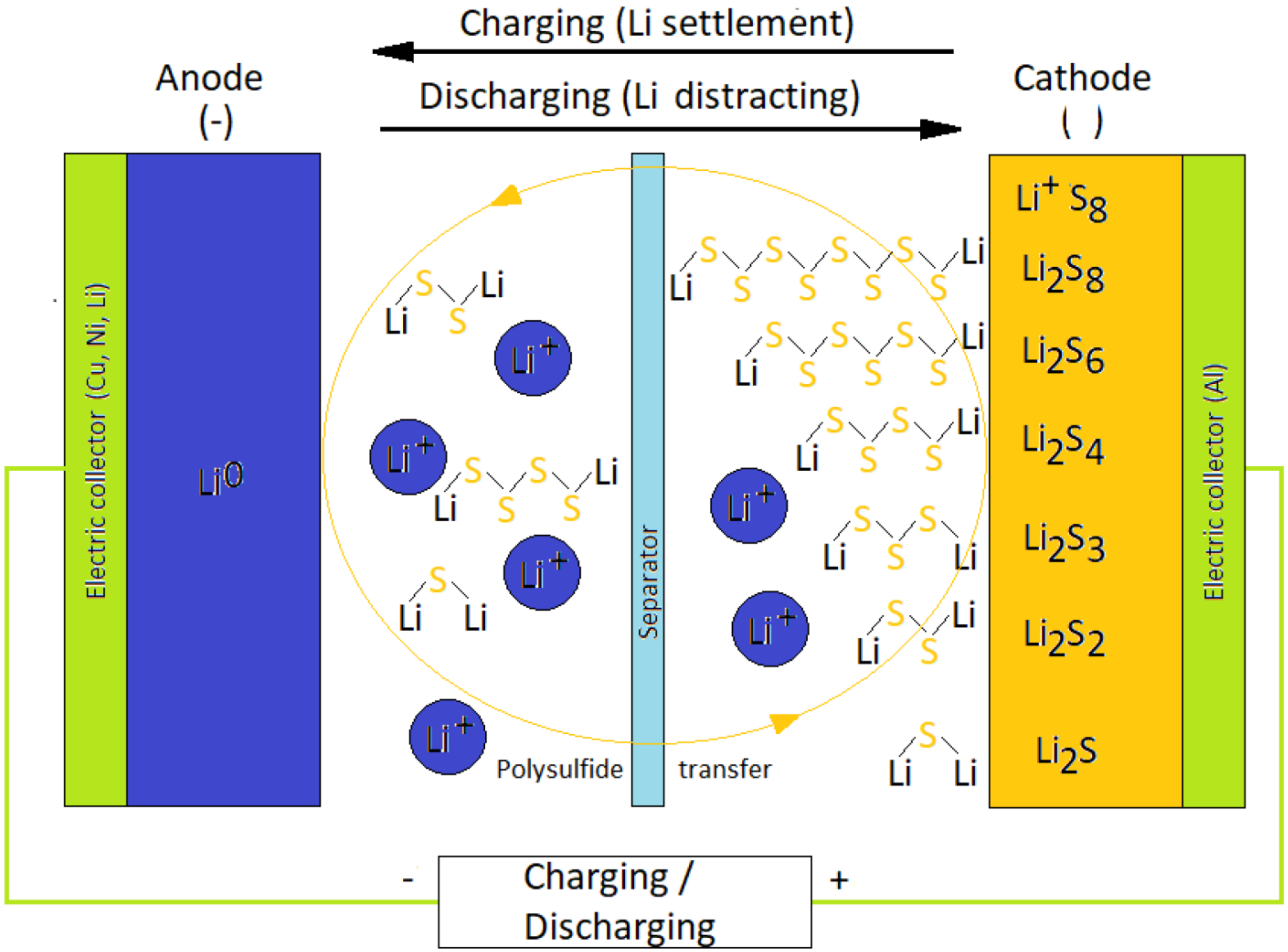


- Lithium metal refers to replacement of the *anode*, not the cathode material
- Li metal have revolutionary potential in high energy density
- Commonly form “dendrites”, a tree-like crystal structure that can penetrate through the electrolyte. If a dendrite touches the cathode—watch out!



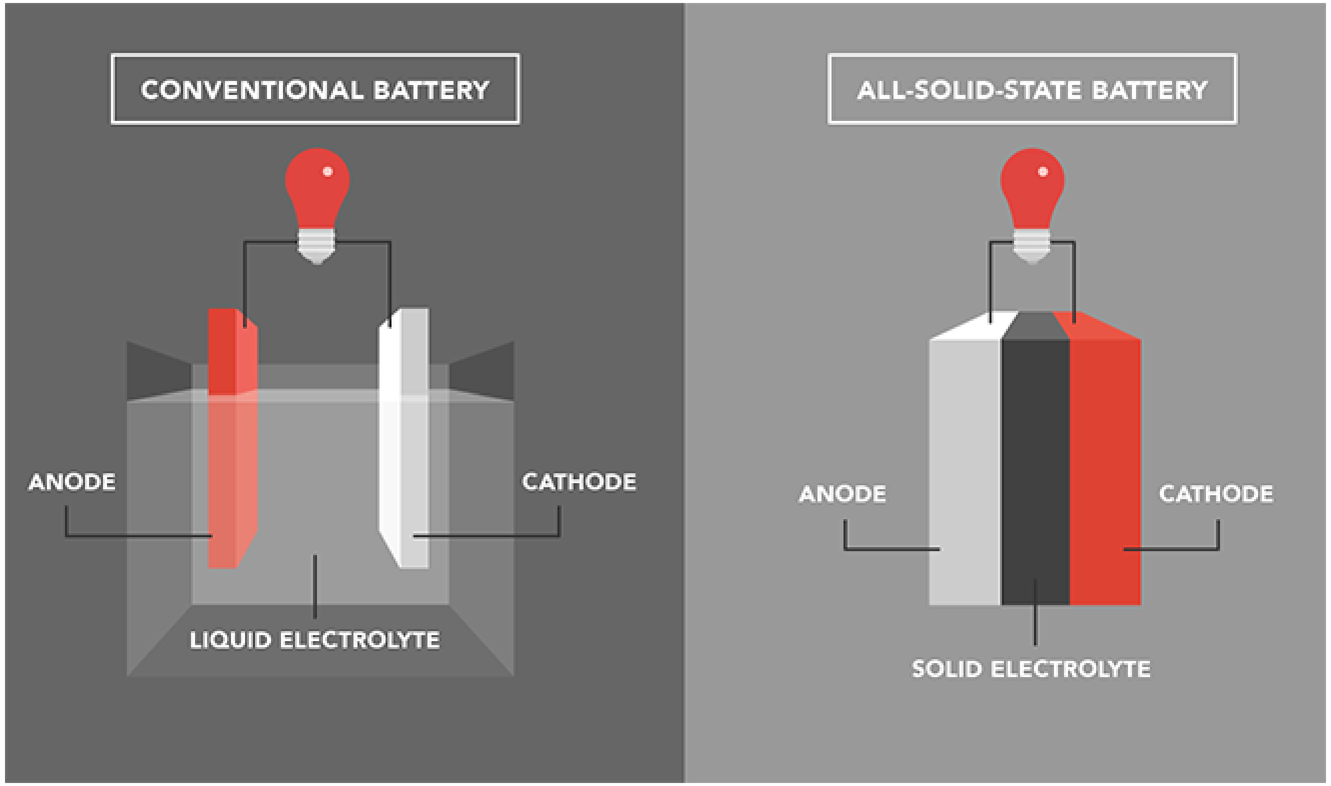
Lithium sulfur (Li-S)

- Very high specific energy
- Big benefit of Li-S is the reduced cost of sulfur compared to cobalt
- Key issues:
  - Polysulfide leakage of active material from the cathode
  - Volume expansion from S to Li_2S
  - Large amount of electrolyte needed



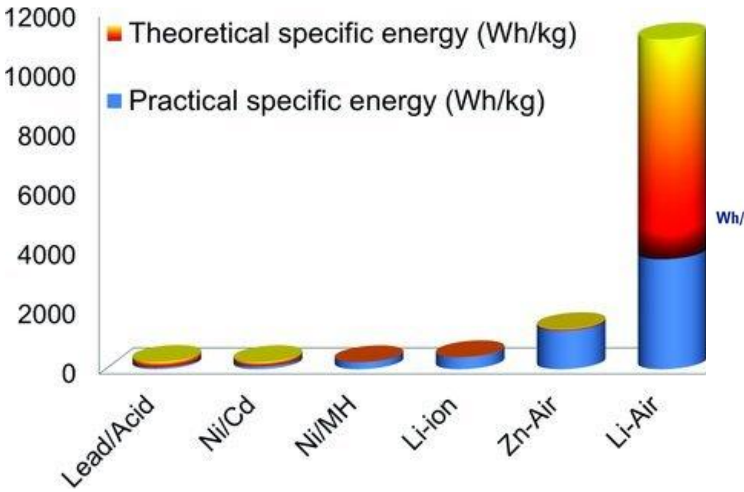
Solid state batteries

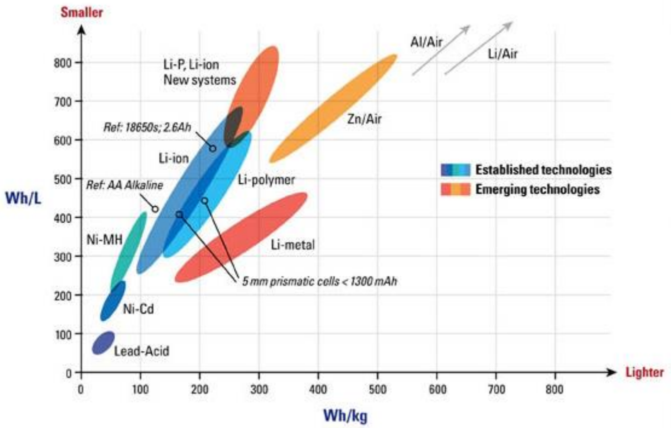
- Higher energy densities (2.5x higher than existing chemistries)
- Avoids toxic materials in organic electrolytes, lower risk of catching fire
- Current challenges:
  - Expensive
  - Temperature sensitivity (leads to poor performance)
  - Dendrites in Li-metal anodes

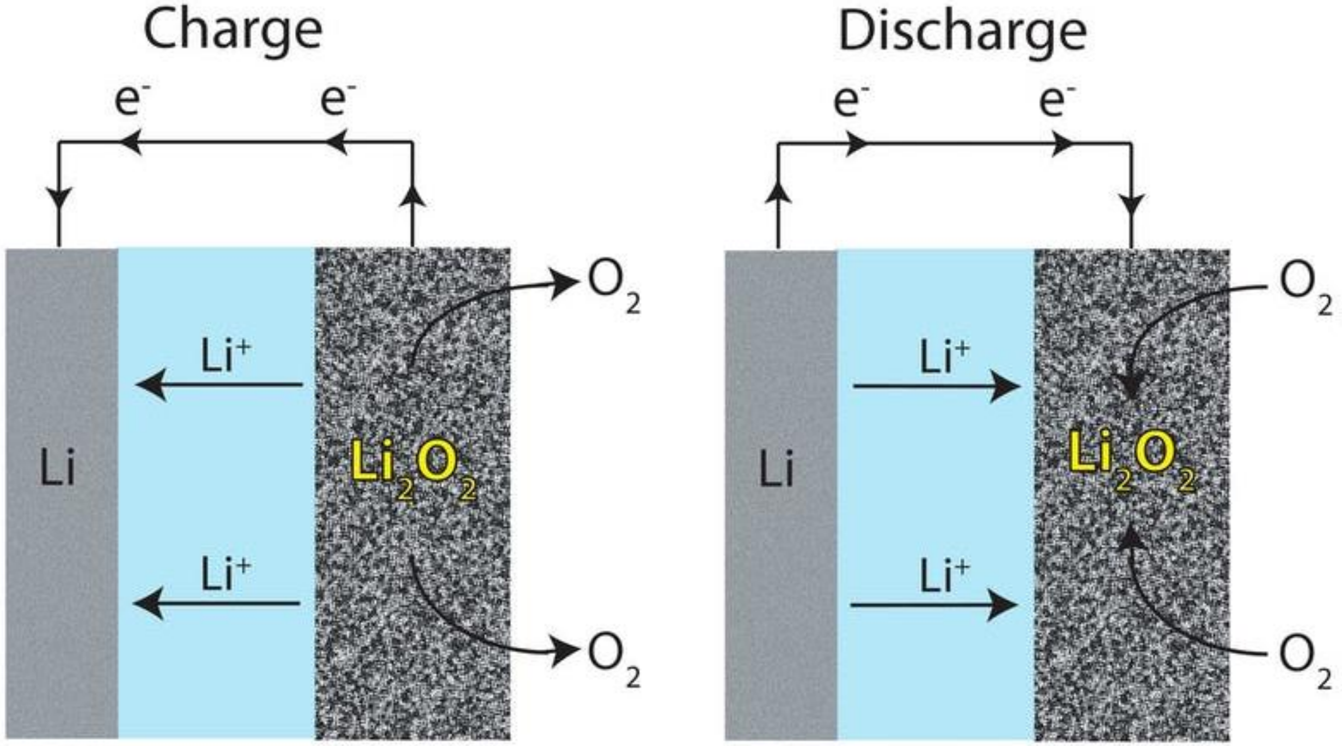


Lithium-air

- Li-Air uses oxygen from the air to reduce at the cathode
- Theoretically can reach energy density comparable to gasoline (~40 MJ/kg), have been demonstrated to reach 5x higher than existing batteries

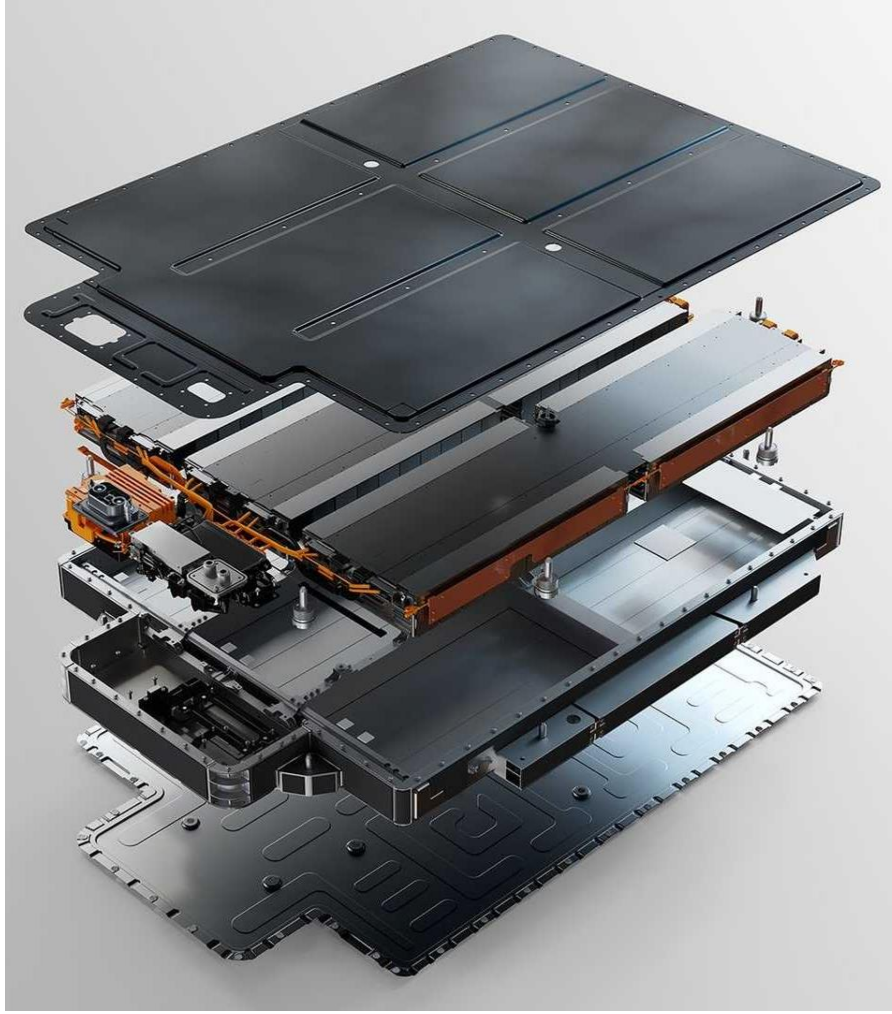






“Hybrid-cell” batteries

- Automakers and battery manufacturers are now exploring “hybrid-cell” batteries that combine cells with different chemistries into a single pack—cutting down on “cons” of certain chemistries by exploiting the “pros” of each
- NIO is producing a 75-kWh hybrid-cell battery combining NCM and LFP chemistries
  - High energy density of NCM with low cost of LFP



What does the future hold for batteries?

- More growth of electric vehicles = stronger pressure to improve batteries
- For existing batteries, expect “evolutionary” improvements:
  - Power density, energy density, costs
- For new battery chemistries, “revolutionary” improvements may introduce batteries with properties beyond anything achievable with existing chemistries today