MECH 328
Batteries

Guest lecture by Ania Mitros, PhD

September 2022

Who am I?

Ph.D. in
Computation and
Neural Systems

Analog chip design
for BMS chips

BMS chips in Model 3
(Tesla's 1st custom ASICs)

BMS for traditional
OEMs (car makers)

BMS for truck
batteries

BMS for home
energy storage

B.A. in
Computer
Science

 https://www.linkedin.com/in/aniamitros/

Goal and optimization parameters

- **Mech 328 Goal:** Electrify diesel power in Metro Vancouver (e.g., Sea Bus, delivery vehicles, heavy machinery, etc.). Identify a potential application and demonstrate feasibility through appropriate sizing, costing, and other analysis.
- **Optimization parameters:**
  - Energy density (with a nod to power density)
  - Safety
  - Lifetime: Chemistry, temperature, voltage
  - Charge rate
  - Temperature range

Inspired by: https://www.smartpropel.com/nickel-cobolt-manganese-lithium-battery-vs-lithium-iron-phosphate-battery-this-is-the-most-comprehensive-interpretation

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Energy density vs power density

Energy density: How much energy is available per a given volume or mass of cells (kWh per liter, or kWh per kg)

Power density: How much power is available per a given volume or mass of cells (kW per liter, or kW per kg)

Example: Tesla Model 3 Long Range battery

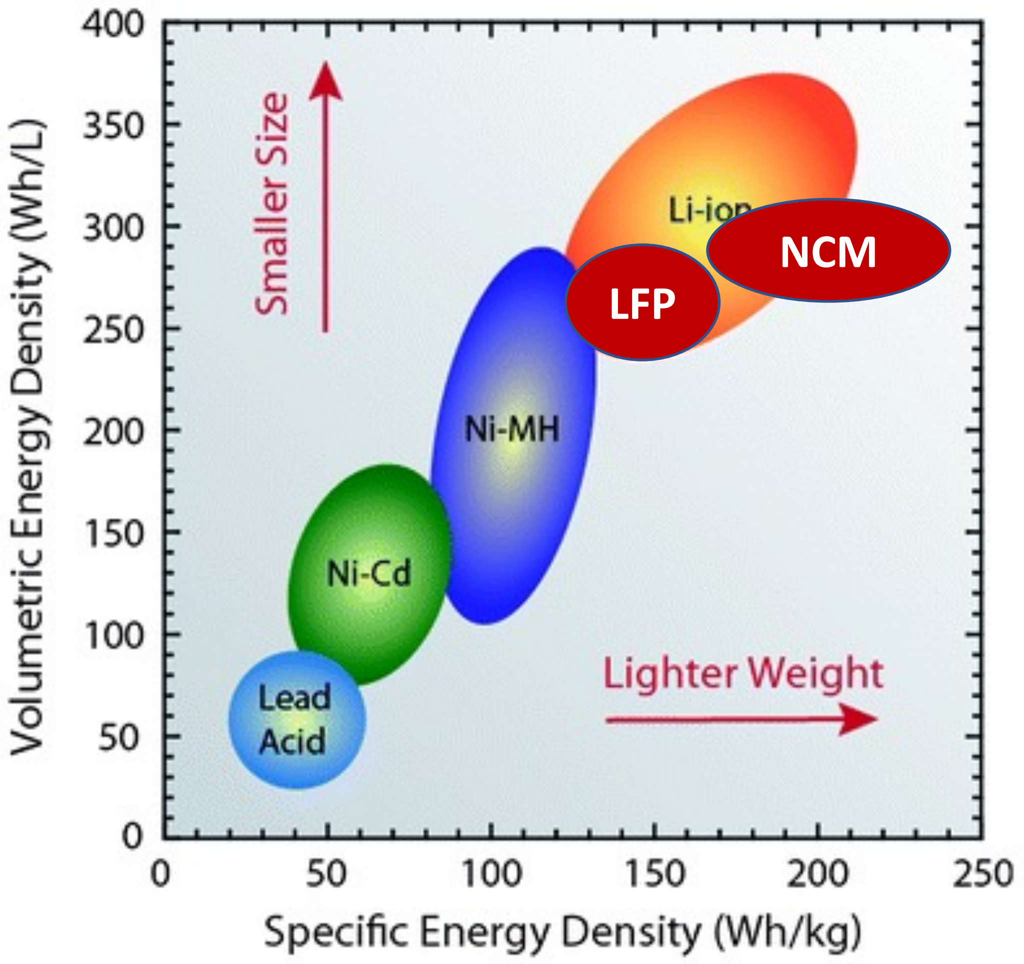
- 75kWh capacity, 480 kg → 156 **Wh/kg energy density**
- Peak power of 258 kW, 480 kg → 538 **W/kg power density**

Vehicle specs from: https://en.wikipedia.org/wiki/Tesla_Model_3

When to optimize power vs energy density?

Energy density	Power density
In applications where current draw is fairly constant and we want the energy to last for a long time	In applications where the current draw is expected to have large peaks
Long-range truck	Race car
Family car	RC helicopter

Energy density differs by chemistry



Lithium-ion batteries include: lithium titanate, lithium cobalt, lithium manganese oxide, **nickel cobalt manganese (NCM)** and **lithium iron phosphate (LFP)**.

For energy density, the NCM battery can reach 240Wh / kg, nearly 1.7 times of LFP battery density 140Wh / kg

What do YOU want to use for your vehicle?

(To optimize energy density)

From: https://www.epectec.com/batteries/cell-comparison.html and https://www.smartpropel.com/nickel-cobolt-manganese-lithium-battery-vs-lithium-iron-phosphate-battery-this-is-the-most-comprehensive-interpretation

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Safety through cell chemistry

Specifications	Lead Acid	Nickel Cadium (NiCd)	Nickel Metal Hydride (NiMH)	Li-ion: Cobalt Oxide (LCO)	Li-ion: Manganese Oxide (LMO)	Li-ion: Nickel Manganese Cobalt Oxide (NMC)	Li-ion: Nickel Cobalt Aluminum (NCA)	Li-ion: Iron Phosphate (LFP)
Safety Requirements	Thermally stable	Thermally stable, fuse protection common		Can go into thermal runaway				Vary
Toxicity	Very High	Very High	Low	Low				

Modified from table at: https://www.epectec.com/batteries/cell-comparison.html

Some are thermally stable

Causes of thermal runaway:

- Over-heating
- Over-current → Over-heating
  - internal short (cell anode to cathode)
  - external short (battery pack terminals)
- Over-charge → Damage → Local short → Over-heating

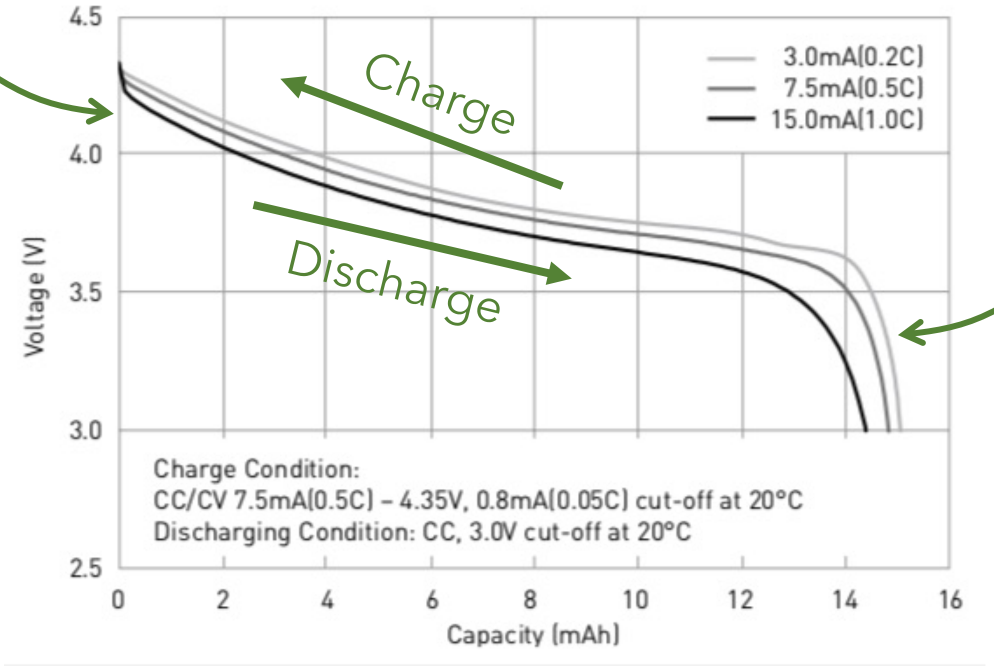
What do YOU want to use for your vehicle?

(To avoid thermal runaway...
...and optimize energy density)

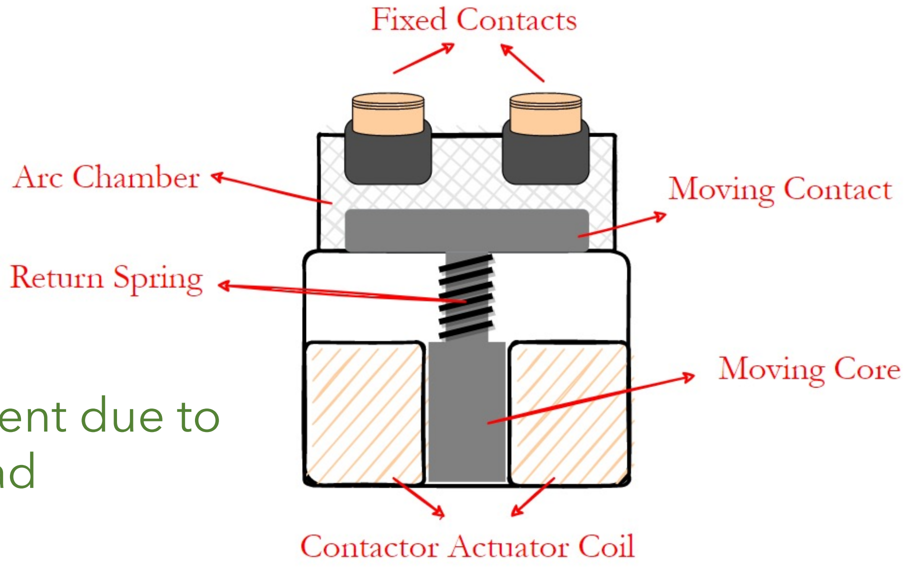
Battery Management Systems

BMS is my job!

Prevent over-charge



Prevent over-discharge (and consequent damage)



Monitor temperature, and reduce operating power or activate heating/cooling system as needed

Prevent over-current due to external short/load (open contactor)

https://www.batterydesign.net/hv/contactors/

But…

What about internal shorts?

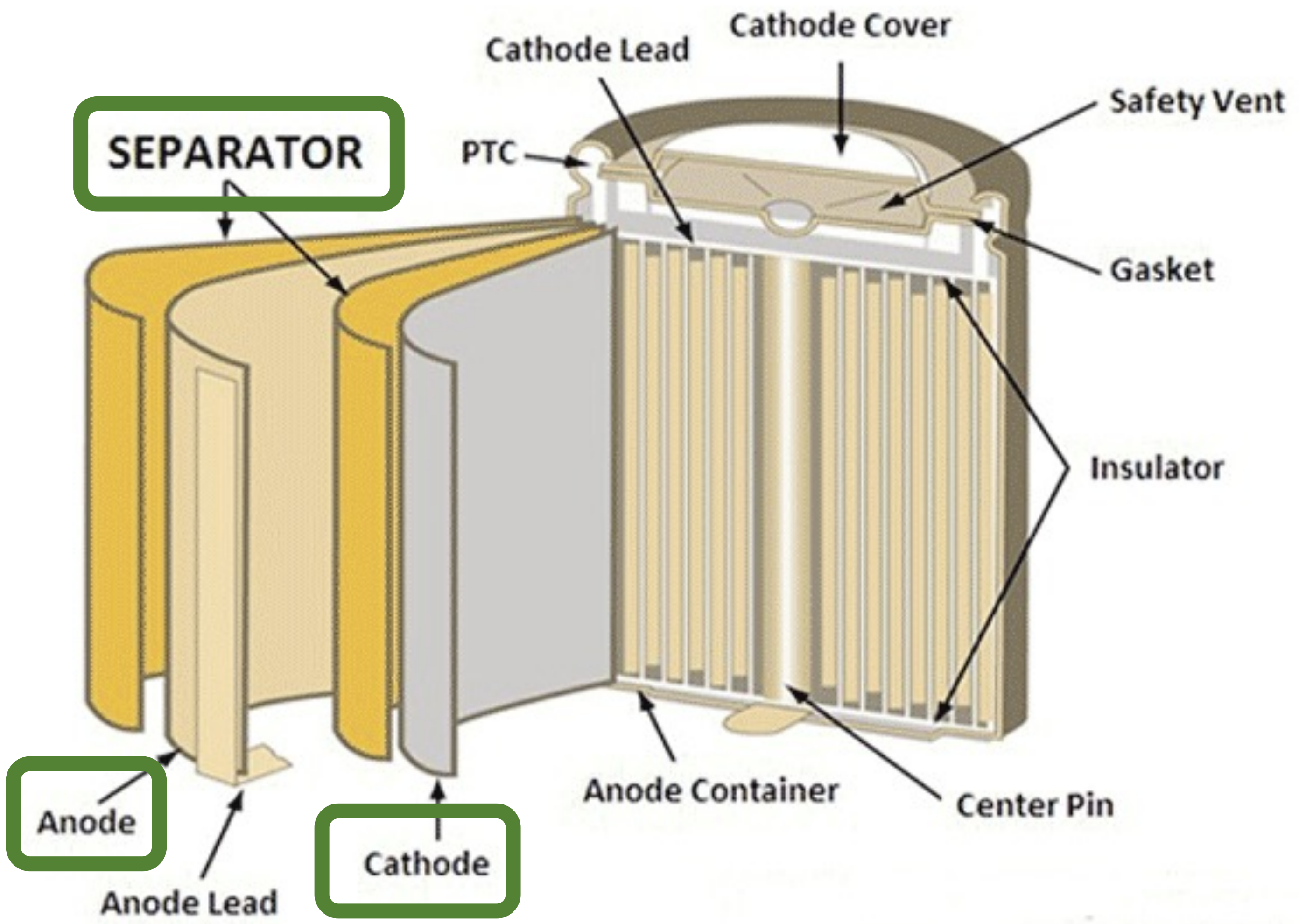
(Thank goodness for mechanical engineers)

Battery construction with pouch or prismatic cells

Chevy Bolt

Hyundai Kona

Cell construction



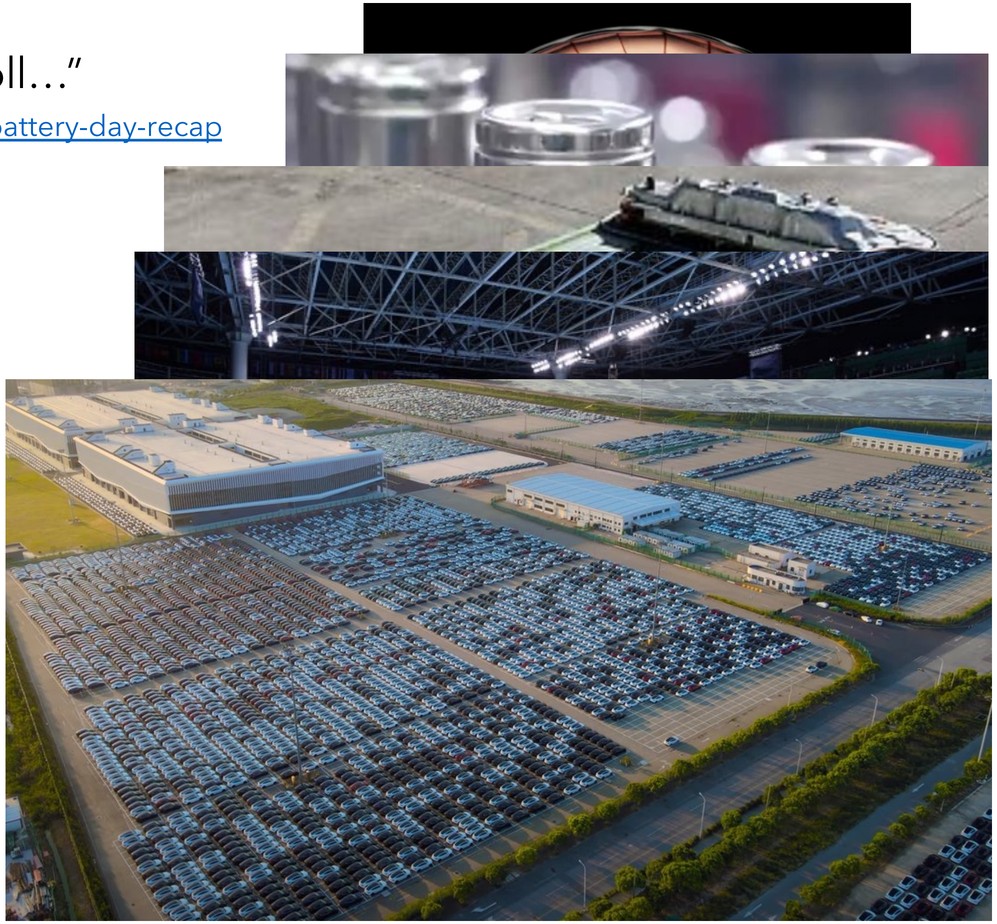
https://components101.com/articles/battery-seperators-types-and-importance

Order of magnitude: Area of separator in one car

- "In a 2170 Tesla cell, there's about one meter's length of jellyroll…"
  - https://www.popularmechanics.com/science/energy/a34114885/elon-musk-tesla-battery-day-recap
- A 2170 cell is 21 mm by 70 mm

→ Separator area in one cell is 2 × 1m × 70mm = **$0.14 m^2$**

- Long Range Model 3 has 4416 cells
  - https://www.evspeedy.com/how-many-batteries-teslas/
- → Separator area in one car is $0.14 m^2$ × 4416 = **$618\ m^2$**
- Olympic-size swimming pool are 50m × 25m = 1250 m^2
  - google.com
- → **Separator area in one Long Range Model 3 is similar to half an Olympic-size swimming pool**
- Tesla sold 936,222 cars in 2021
  - https://en.wikipedia.org/wiki/Tesla,_Inc.



Should we expect the area of 500,000 swimming pools to be perfect?

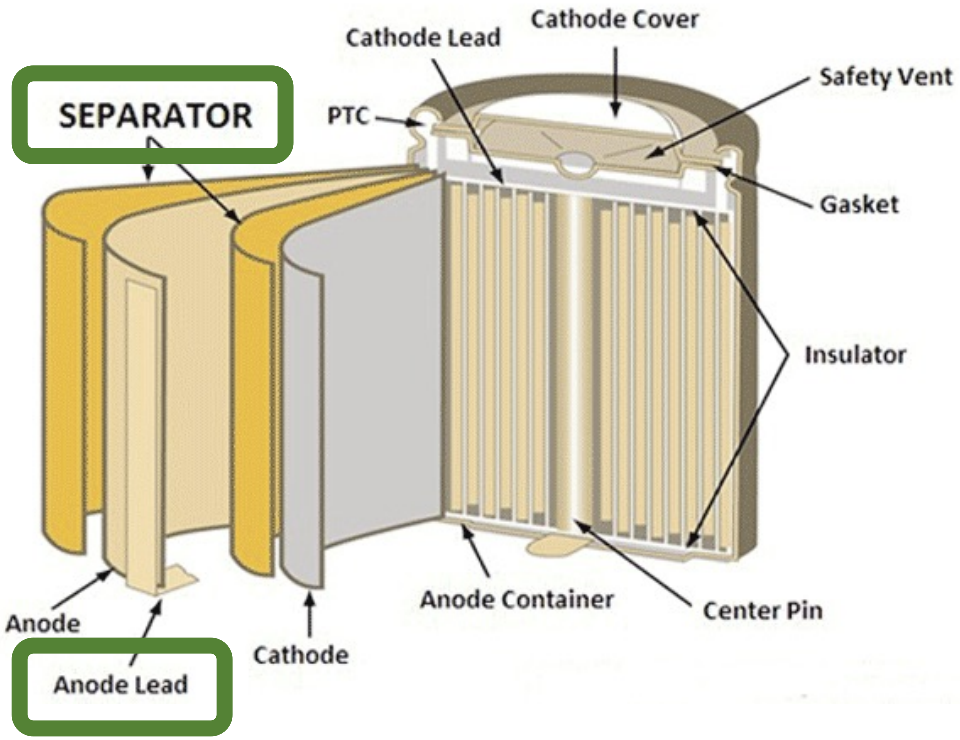
→ Chevy: Yes

→ Tesla: No

Chevy Bolt recall

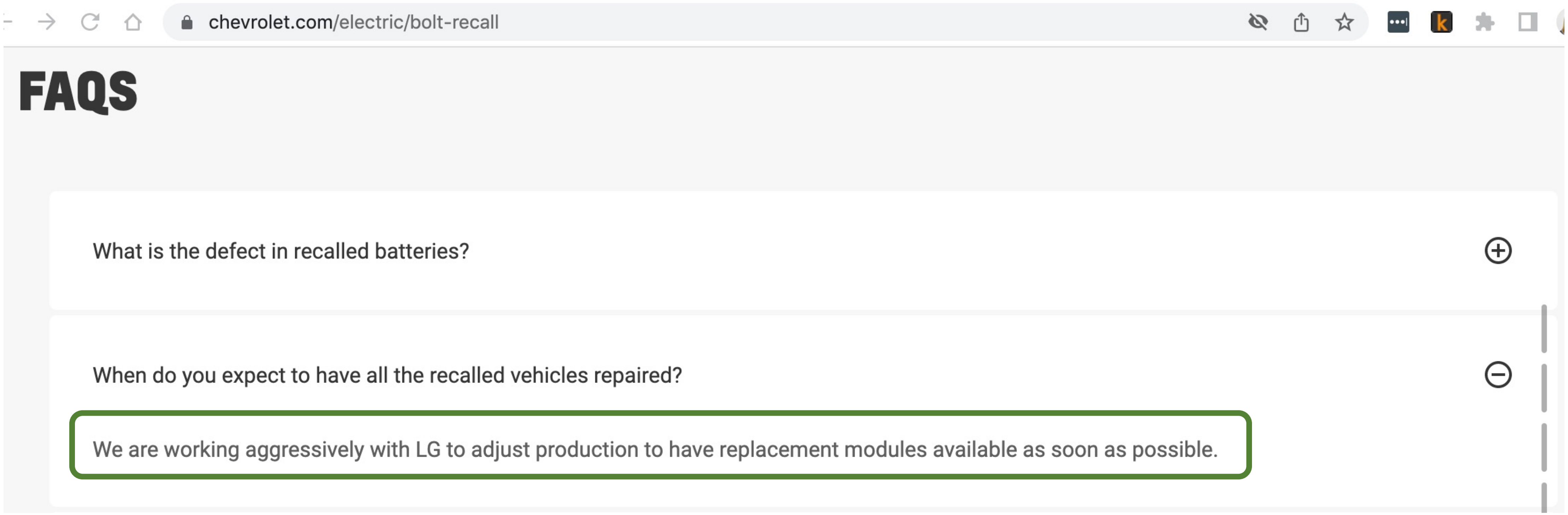
https://www.chevrolet.com/electric/bolt-recall

The simultaneous presence of two rare manufacturing defects (a torn anode tab and folded separator) in the same battery cell are the root cause of battery fires in certain Chevrolet Bolt EVs.
https://www.chevrolet.com/electric/bolt-recall



Chevy’s solution to the Chevy Bolt recall

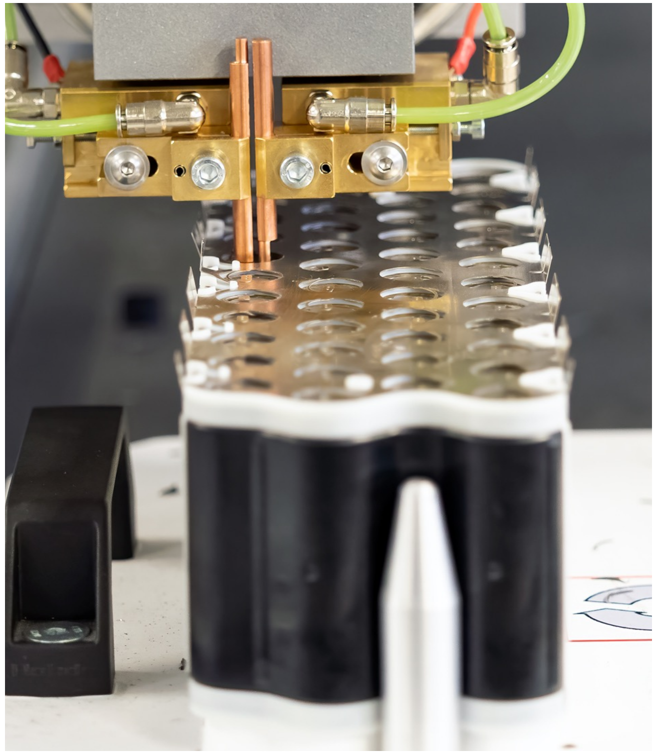
Chevy: Ask LG to manufacture more perfect cells



Tesla: Safety through mechanical construction

Patent: US20100075221A1
Assignee: Tesla Inc
A means for inhibiting the propagation of thermal runaway within a plurality of batteries is provided, wherein the means is comprised of at least one layer of intumescent material interposed between the interior surface of the casing of a battery and the corresponding electrode assembly.

https://www.greencarreports.com/news/1128060_tesla-s-battery-approach-vs-others-teardown-video-breaks-it-down



Individually fused cells embedded in a fire-retardant medium

https://lionsmart.com/en/lion-light-battery-en/

Summary of Design for Safety

Li-ion		
Nickel Manganese Cobalt Oxide (NMC)	**Nickel Cobalt (NCA)**	**Iron Phosphate (LFP)**
Can go into thermal runaway		Can be thermally stable

What do YOU want to use for your vehicle?

(To avoid thermal runaway…
…and optimize energy density)

Safety through excellence in cell manufacturing

- **Chevy Bolt**
- Volkswagen E-Golf
- BMW i3
- Hyundai Kona, IONIQ
- Nissan Leaf
- Jaguar iPace
- Audi e-tron Quattro
- Porsche Taycan
- …and many large OEMs

https://pushevs.com/2020/04/04/comparison-of-different-ev-batteries-in-2020/

Safety through mechanical construction

Limit propagation of exothermic events

- **Tesla**
- **LionSmart**

Safety through thermally-stable chemistry

- **Tesla**: Switched to LFP for standard range vehicles (Oct 2021)
- **Ford**: Switching to LFP for 2023 Mach-E and 2024 F-150 Lightning (July 2022)
- **Hyundai**: Started developing for LFP in 2021 (July 2021)
- **MG ZS EV**: Switched to LFP (Sept 2022)
- …

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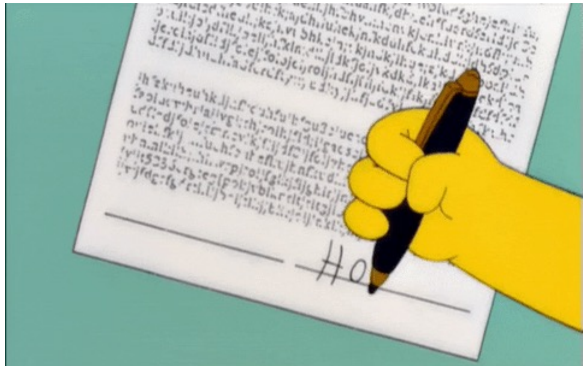
From: https://www.smartpropel.com/nickel-cobolt-manganese-lithium-battery-vs-lithium-iron-phosphate-battery-this-is-the-most-comprehensive-interpretation

Lifetime: A disclaimer

Best data is proprietary! ☹



Lifetime: Rules of thumb

Differs between chemistries

- LFP vs NCM: LFP has higher cycle life than NCM/NCA.

Affected by usage profile:

- Hot temperatures cause faster degradation
- Voltage: Storage near 100% causes faster degradation. (More for NCM than LFP)
- High currents cause faster degradation

Lifetime: Cycle life differs across chemistries

Cycle life: How many times a battery can be recharged.

Specifications	Lead Acid	Nickel Cadium (NiCd)	Nickel Metal Hydride (NiMH)	Li-ion		
				Cobalt Oxide (LMO)	Manganese Oxide (LMO)	Iron Phosphate (LFP)
Life Cycle (80% discharge)	200-300	1000	300-500	500-1,000	500-1,000	1,000-2,000

Modified from table at: https://www.epectec.com/batteries/cell-comparison.html

Specifications		Li-ion		
		Nickel Manganese Cobalt (NCM)	Nickel Cobalt (NCA)	Iron Phosphate (LFP)
Life Cycle (to 80% capacity)		1,000	1,000	2,500

From: https://zecar.com/post/what-are-lfp-nmc-nca-batteries-in-electric-cars

Lifetime: Cycle life differs across chemistries

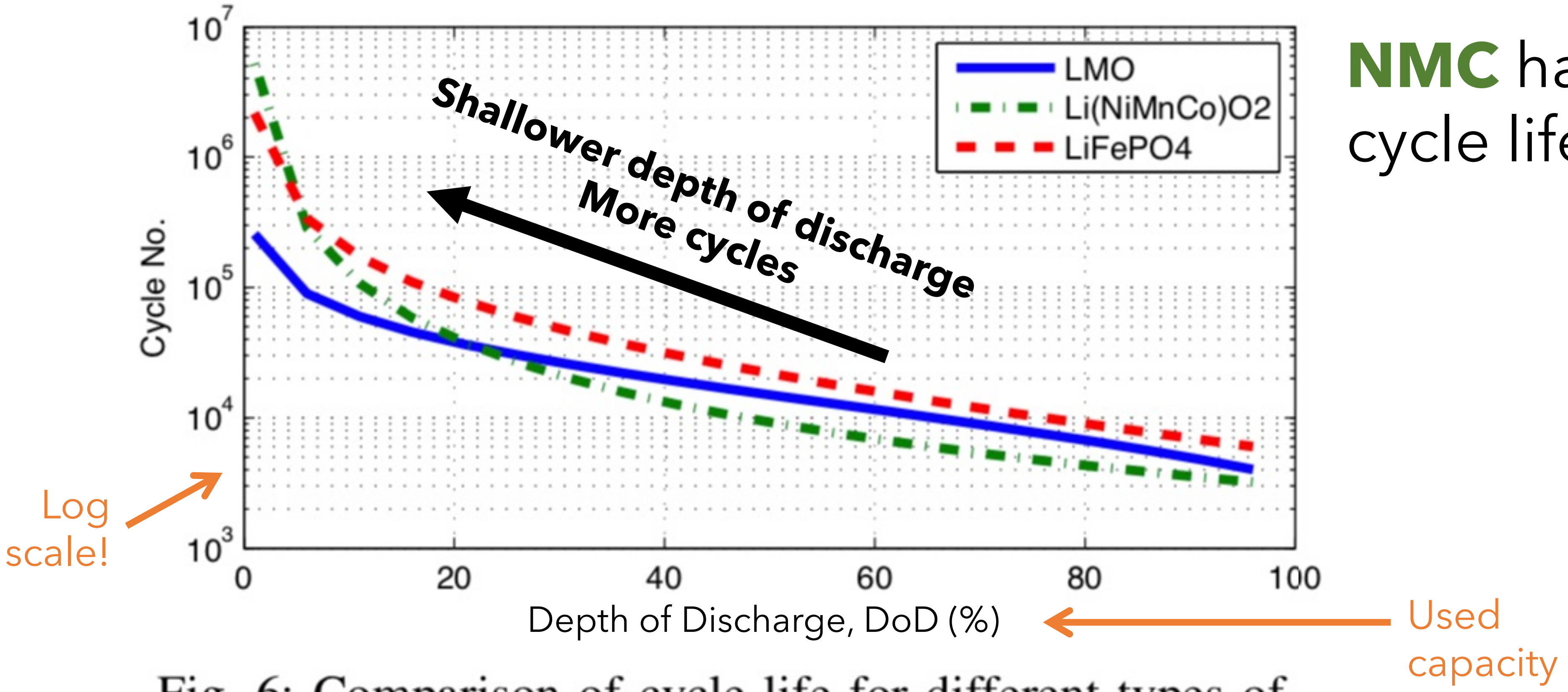


Fig. 6: Comparison of cycle life for different types of lithium-ion batteries adjusted to reference conditions.

NMC has shorter cycle life than **LFP**

Fig. 6 in https://ieeexplore.ieee.org/document/7488267 [Xu 2018]

Capacity loss: Time, SoC, Temperature, Chemistry

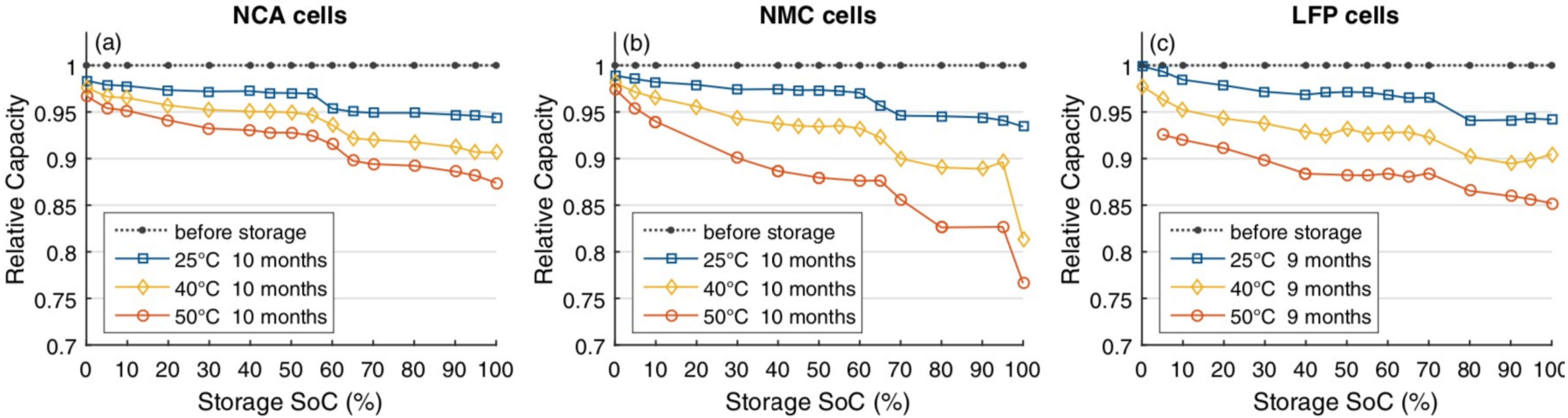
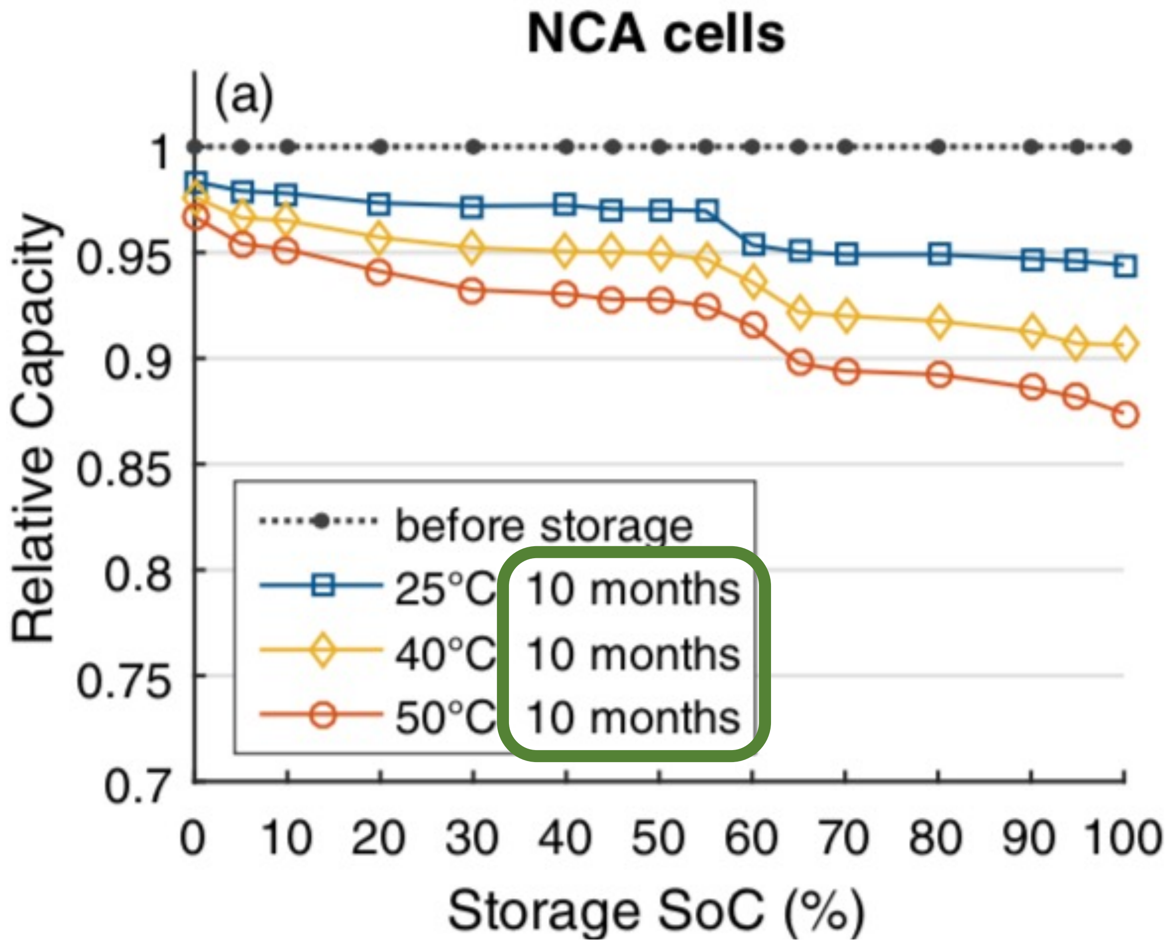


Fig. 2 in DOI: 10.1149/2.0411609jes [Keil 2016]

Capacity loss: **Time**, SoC, Temperature, Chemistry



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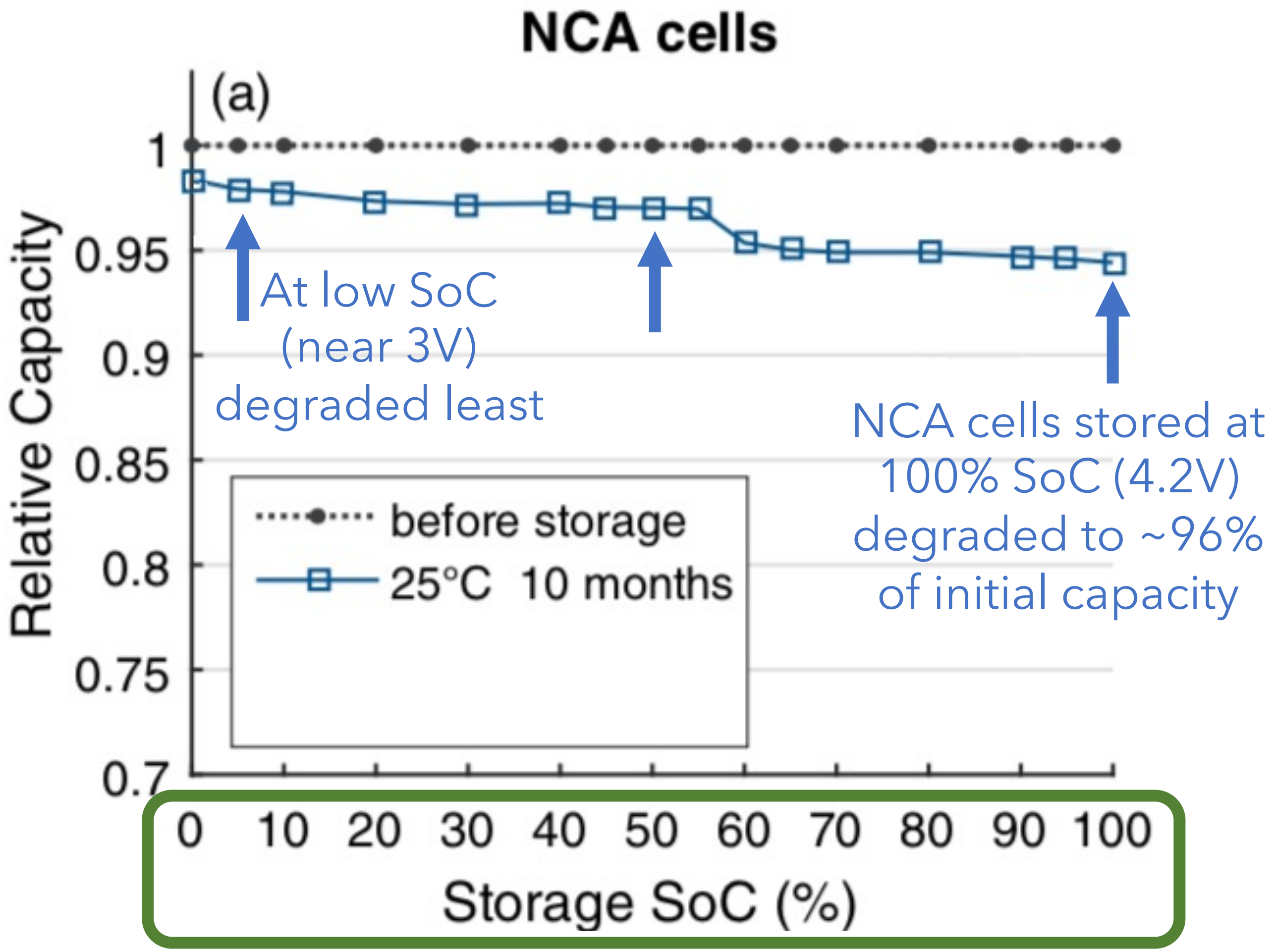

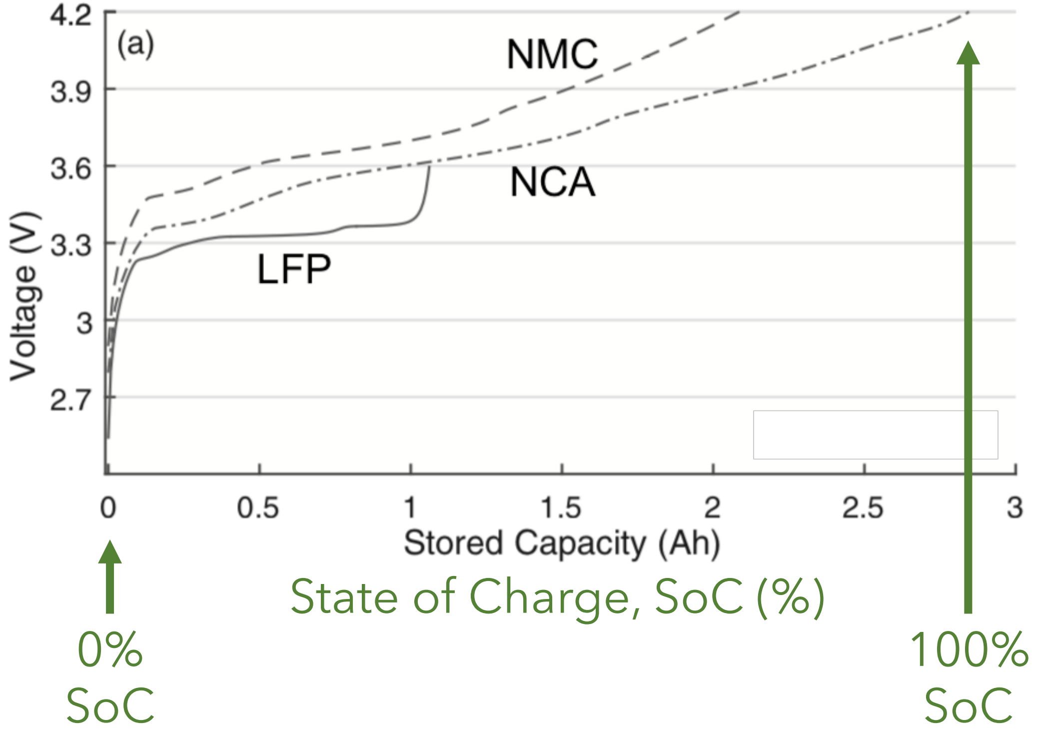

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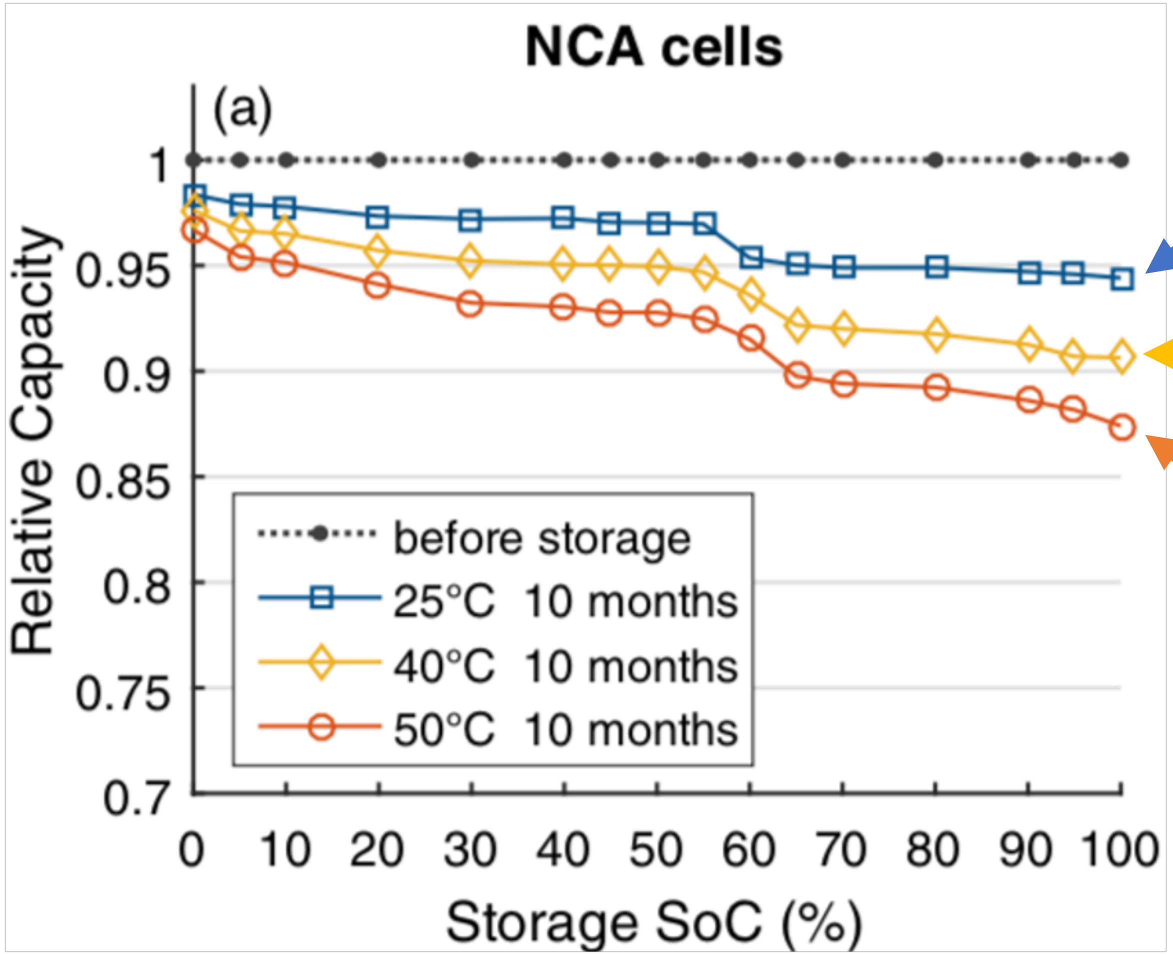
Capacity loss: Time, SoC, **Temperature**, Chemistry



At 25°C, cells degraded to ~96% of initial capacity

At 40°C, cells degraded to ~91% of initial capacity

At 50°C, cells degraded to ~87% of initial capacity

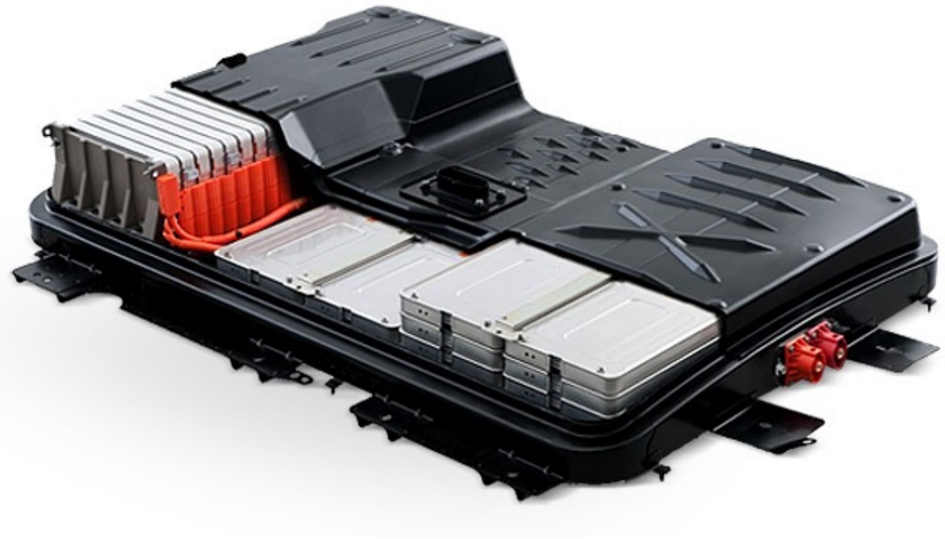
Aging accelerates with temperature.

Fig. 2 in DOI: 10.1149/2.0411609jes [Keil 2016]

Capacity loss: Case study (Nissan Leaf in Arizona)

2011-2012 Nissan Leaf

- Reports of 1 of 12 bars (8.3%) capacity loss in 1st year
- Nissan initially claimed a dashboard instrumentation problem
- Leaf owners performed a controlled range test in Phoenix, confirming range loss.



What did Nissan's mechanical engineers do differently than other car makers?

Leaf: Air-cooled battery

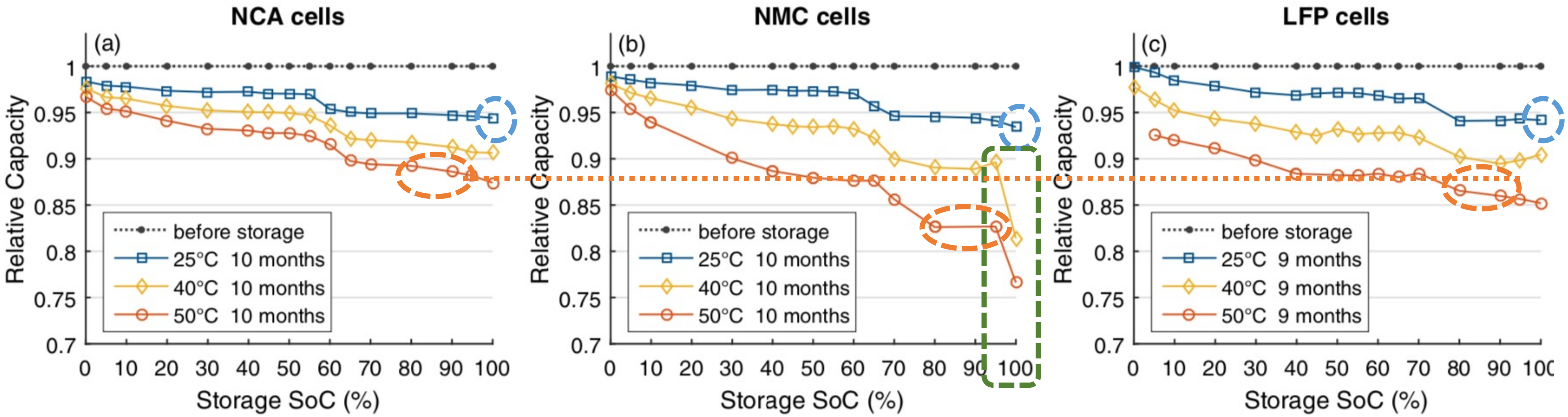
https://www.technologyreview.com/2012/09/19/85161/are-air-cooled-batteries-hurting-nissan-leaf-range/

Capacity loss: Time, SoC, Temperature, **Chemistry**

At 25C, all age similarly

NMC is most sensitive to high temperature

NMC is most sensitive to high SoC



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Lifetime: Summary

Engineering options include:

- Cell selection
- Avoid charging to 100%
- Implement a good cooling system

Side note: Omission of impedance (or resistance).

- Cell impedance also increases with aging
- High cell impedance reduces available peak power

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“C” or “C rate”

C : a measure of a cell’s current relative to its total capacity.

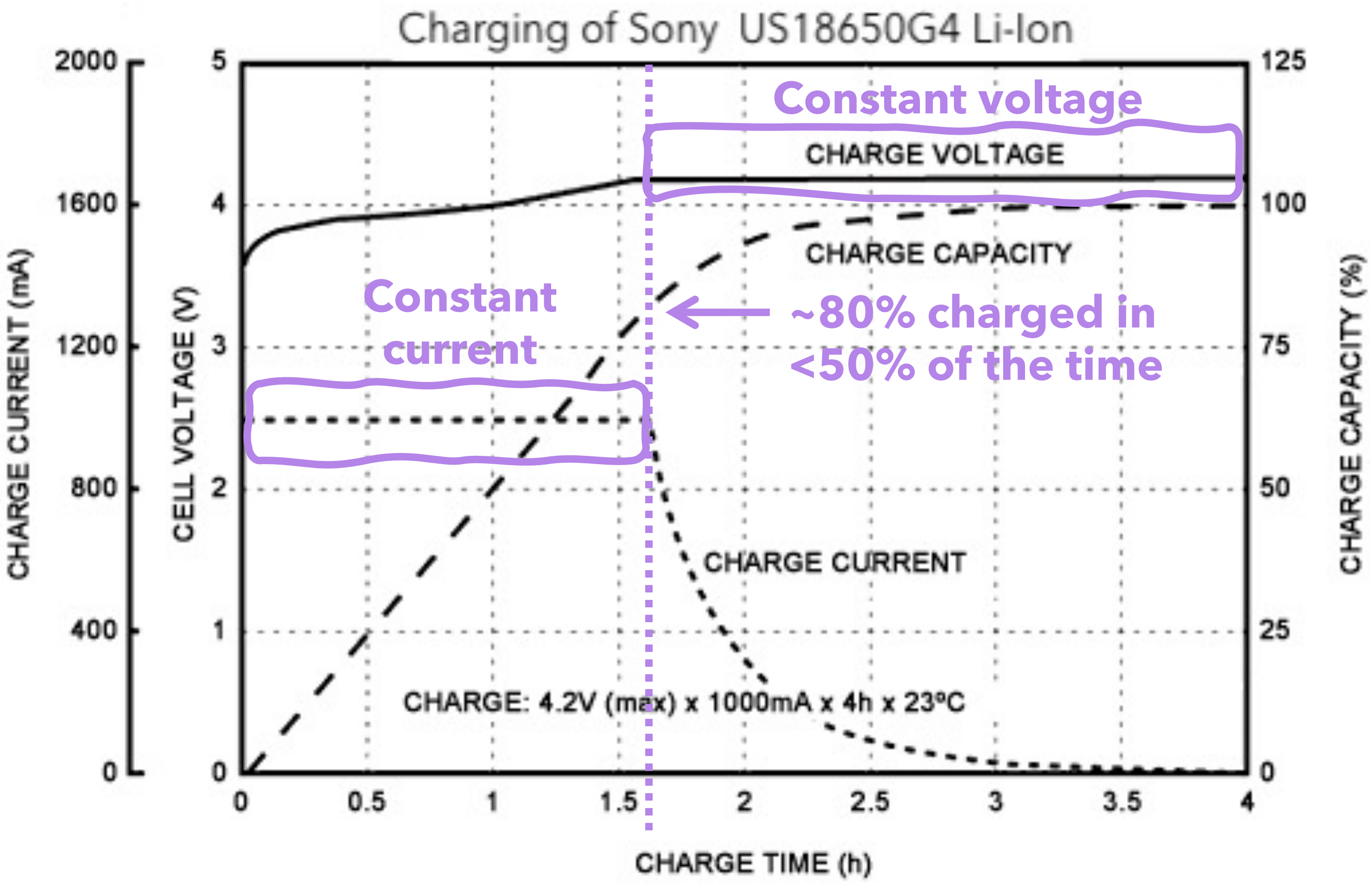
- A 1C current will discharge the battery in 1 hour.
- For a battery with a capacity of 100 Ah (Amp hours), 1C means a discharge current of 100 A.

Charge rate: Key concepts

- Charge profile: CC/CV
- Temperature dependence
- Fast charging

CC-CV charge profile

Constant-current constant-voltage charging prevents overcharge



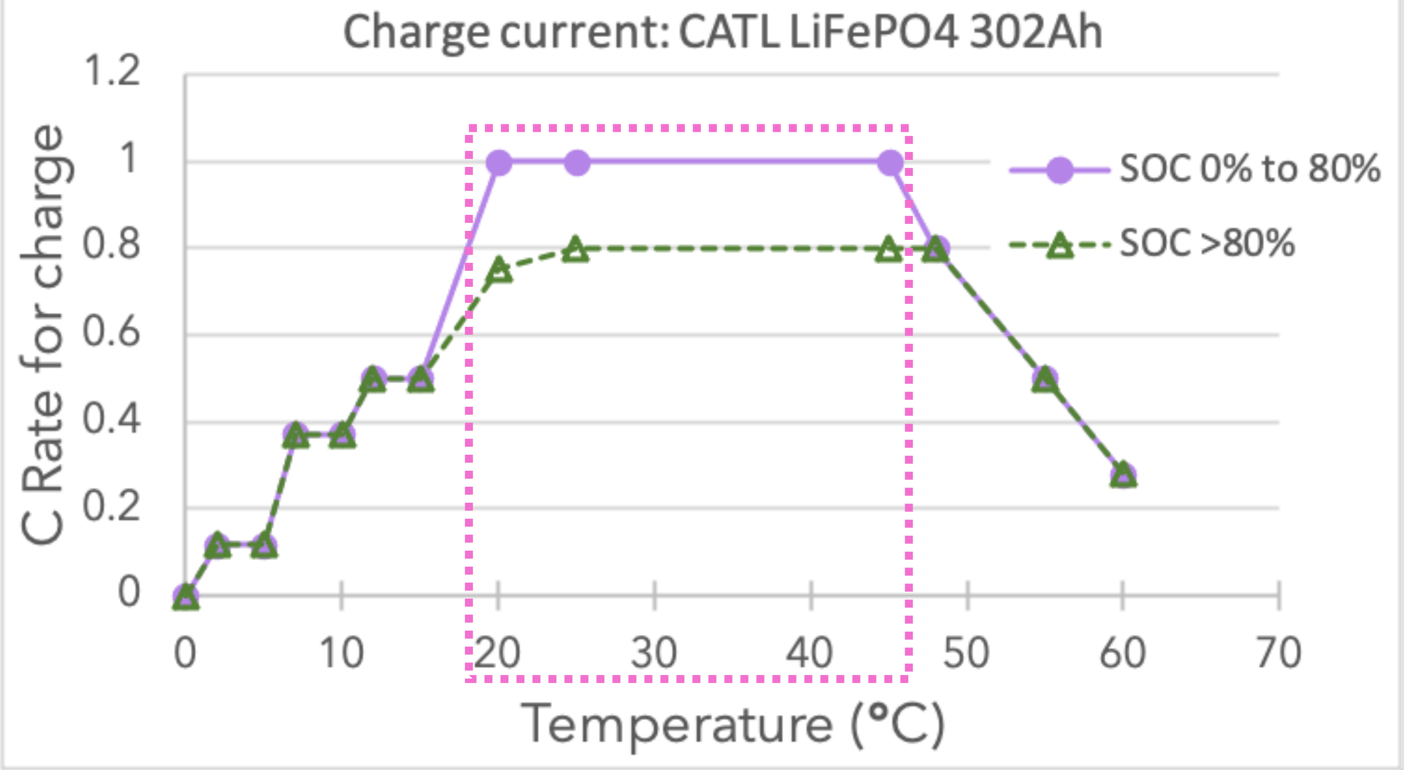
Slower near top of charge

https://www.maximintegrated.com/en/design/technical-documents/app-notes/4/4169.html

Temperature dependence of charge rate

2.2.7 其他充电条件(模式)　C-Rate Other charge Condition (C-Rate)

电芯温度/℃ Cell temperature		**0**	**2**	**5**	**7**	**10**	**12**	**15**	**20**	**25**	**45**	**48**	**55**	**60**
SOC	0%~<80%	0	0.116	0.116	0.372	0.372	0.5	0.5	1.0	1.0	1.0	0.8	0.5	0.2 79
SOC	＞80%	0	0.116	0.116	0.372	0.372	0.5	0.5	0.75	0.8	0.8	0.8	0.5	0.2 79



https://batteryfinds.com/wp-content/uploads/2022/06/CATL-302Ah-LiFePO4LFP-Battery-Cell-Product-Specification.pdf

Temperature dependence of discharge rate

参数 Parameter	产品规格 Specification
工作温度(充电) Operating temperature (charging)	0~65℃
工作温度(放电) Operating temperature (discharge)	-35~65℃

CATL LFP

https://batteryfinds.com/wp-content/uploads/2022/06/CATL-302Ah-LiFePO4LFP-Battery-Cell-Product-Specification.pdf

Item	Specification
Operating Temperature	Charge:0°C~55°C Discharge: -30°C~55°C
Storage Temperature	－30°C~60°C

Lithium Storage LFP

https://www.lithiumstoragebattery.com/product-lfp71173204e-280ah-lithium-ion-battery.html

Items		Parameter
Operating Temperature	Charging Temperature	-5~55°C
	Discharging Temperature	-30~55°C

CALB NMC

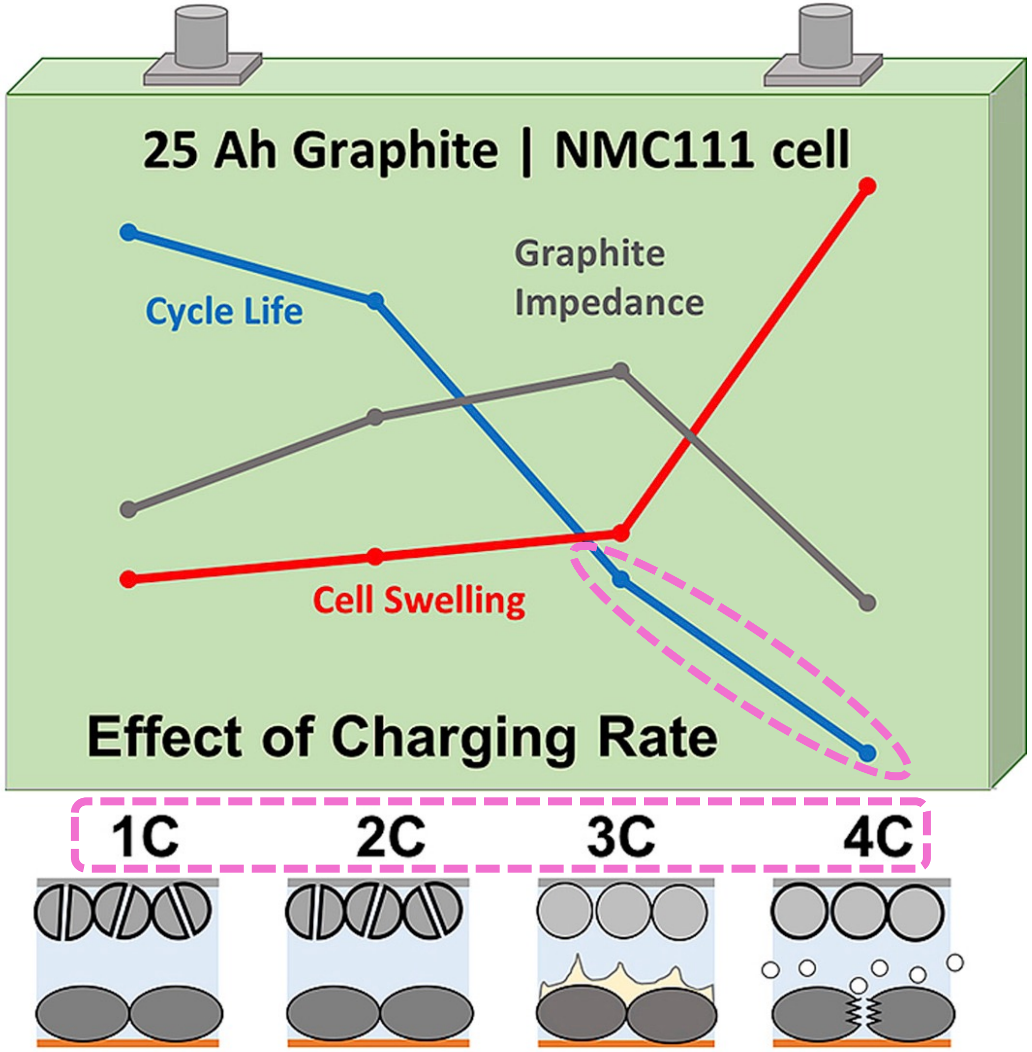
https://www.evlithium.com/nmc-battery/calb-50ah-lithium-nmc-battery.html

Item		Parameter Specification
Battery Module		Lithium ion NCM Battery
Operation Thermal Ambient	Charging	0°C ~ 65°C
	Discharging	-20°C ~ 55°C

Samsung NMC

https://www.evlithium.com/nmc-battery/samsung-sdi94-94ah-nmc-battery.html

Fast charging and capacity loss



https://www.sciencedirect.com/science/article/pii/S0378775319302265 [Mussa 2019]

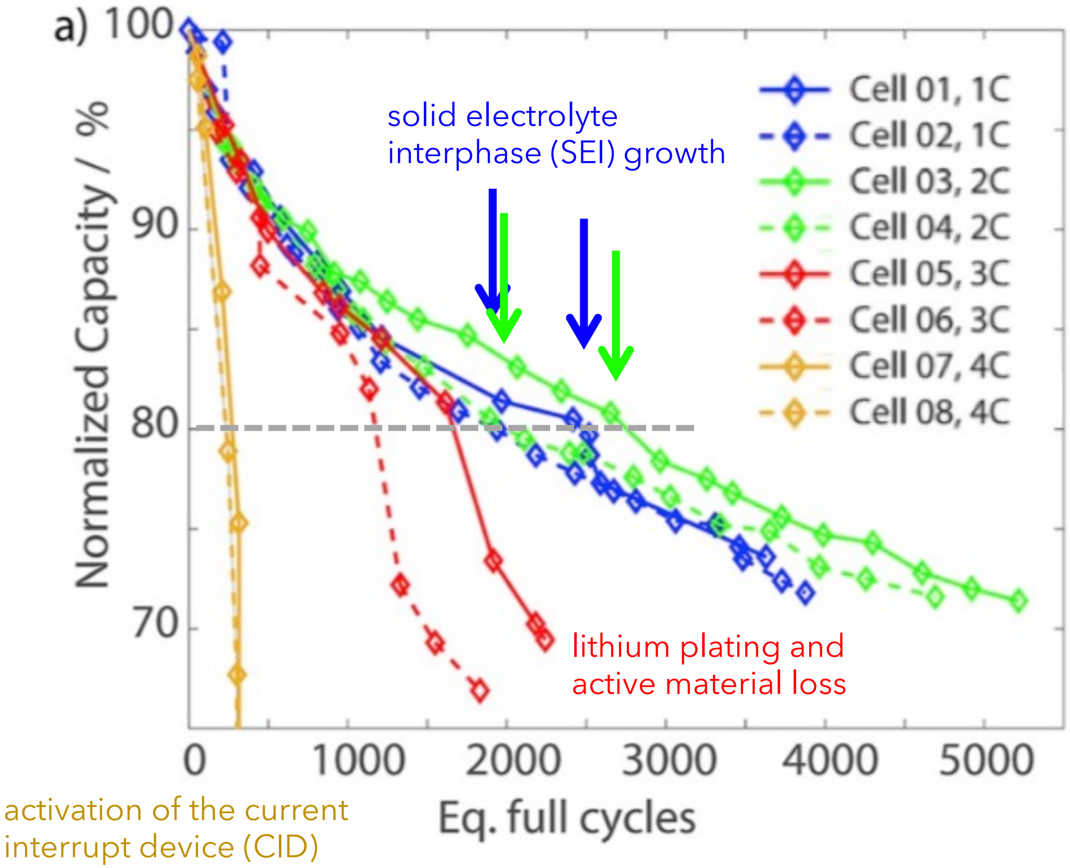
Cycle life decreases with increasing current.

- Engineering trade-off!

Details:

- NMC cells targeted at PHEVs (Plug-In Hybrid Electric Vehicles)
- Cycling between 20% and 80% SoC.
- 1C discharge.
- No rest between charge/discharge.

Fast charging and capacity loss



Capacity decreases with increasing current.

- Engineering trade-off!

Details:

- Cycling between 20% and 80% SoC.
- 1C discharge.
- No rest between charge/discharge.

Introduction to this paper has a really nice, readable discussion of electric cars vs buses.

Side note: Similar concern for discharge current.

https://www.sciencedirect.com/science/article/pii/S0378775319302265 [Mussa 2019]

Higher C-rate cells

Category			Power Cell	Energy Cell		
Model			P41	E65D	E61V	E78
Image						
Performance	Capacity (Min, 25℃, 0.3C)	Ah	40.8	64.5	60.0	78.0
	Energy Density (Min)	Wh/L	486	444	532	602
		Wh/kg	226	234	253	265
	Max Charge Current (A)	Pulse Charge * (10sec, SoC 50%, 25℃, BOL)	380	300	200	184
	Max Discharge Current (A)	Continuous Discharge (25℃, BOL)	204	130	180	234
		Pulse Discharge * (10sec, SoC 50%, 25℃, BOL)	380	400	400	496

(204 A)/(40.8 Ah) = **5C**

(130 A)/(64.5 Ah) = **2C**

(180 A)/(60 Ah) = **3C**

(234 A)/(78 Ah) = **3C**

From p.4 in https://www.lgensol.com/assets/file/LGES_Automotive_CommercialEV_Leaflet_2022.pdf

Fast charging

- Easier with cells optimized for power
- May reduce lifetime
- Thermally limited
- Requires infrastructure.
  - Typical home outlet provides 120V × 15 A = 1.8kW
    - For 70kWh battery: 70kWh/1.8kW = 39 hours
  - Dryer outlet: 240V × 30 A = 7.2kW
    - For 70kWh battery: 70kWh/1.8kW = 9.7 hours
  - Fast charge: You do the math.
- Rule of thumb to avoid charging >1C: Not enough to fast-charge, and many Li-Ion chemistries can withstand more.

Cooling mitigated aging impact of high currents. https://doi.org/10.1016/j.est.2020.101310 [Barcellona 2020]

Charge rate: Summary

- **CC-CV charge profile** prevents over-charge
- **Temperature** affects charge rate. May need:
  - Heating system, cooling system, power reduction at temperature extremes
- **Fast charging** requires care
- **Optimizing:** Different applications benefit from different cells and different management.

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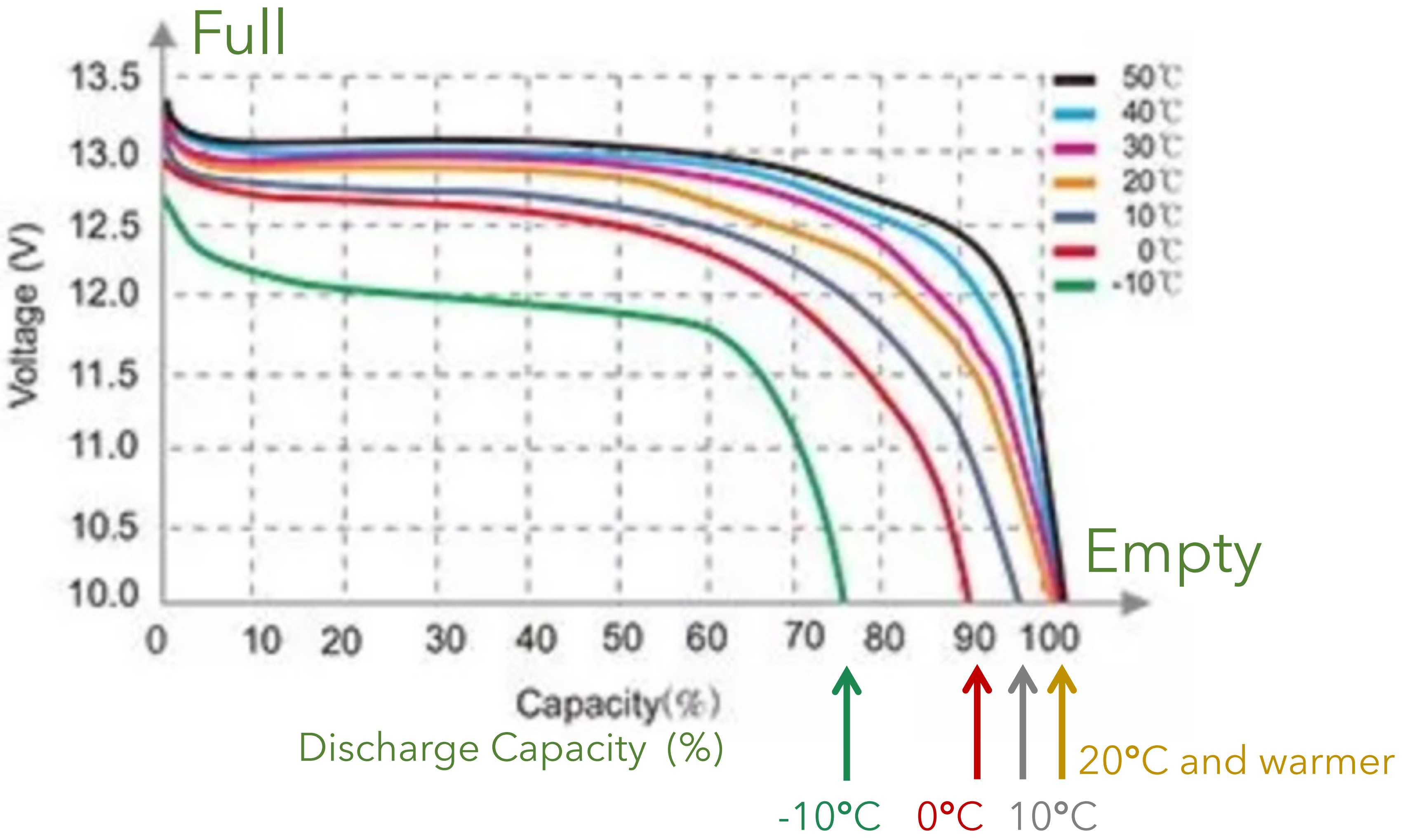
Temperature range

- Capacity vs temperature
- Review previous learnings:
  - Lifetime vs temperature
  - Charge current vs temperature

Specifications	Lead Acid	Nickel Cadium (NiCd)	Nickel Metal Hydride (NiMH)	Li-ion		
				Cobalt Oxide (LMO)	Manganese Oxide (LMO)	Iron Phosphate (LFP)
Charge Temperature	-20 to 50°C -4 to 122°F	0 to 45°C 32 to 113°F		0 to 45°C 32 to 113°F		
Discharge Temperature	-20 to 50°C -4 to 122°F	-20 to 65°C -4 to 149°F		-20 to 60°C -4 to 140°F		

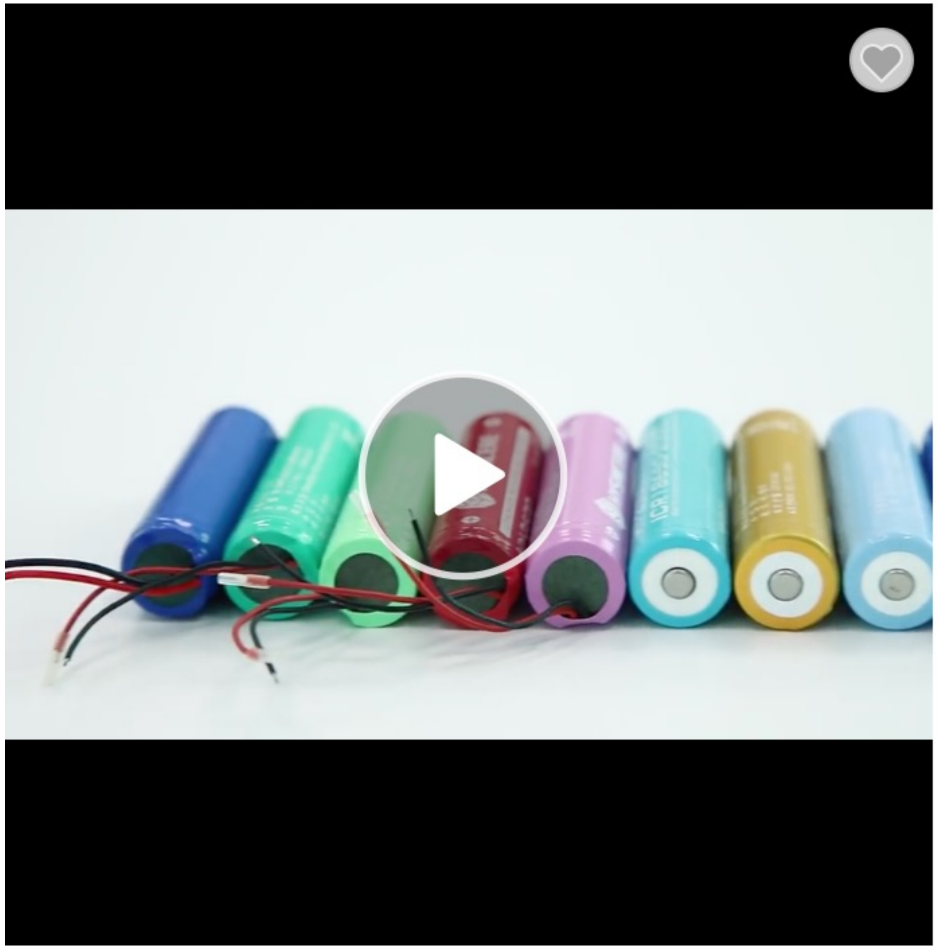
Excerpted form a more detailed table at: https://www.epectec.com/batteries/cell-comparison.html

Temperature dependence of capacity



https://www.alibaba.com/product-detail/Customized-KC-Nmc-Accu-LED-Lights_1600125028451.html

Side note: What’s sketchy about these curves?



Click here to expended view

Super Customized KC Nmc Accu LED Lights Flashlight Li ion Battery 18650 Cell Pack 3.6V 3.7V Rechargeable 18650 Lithium Battery Popular

6 buyers

FOB **Reference** Price: Get Latest Price

$0.20 - $0.99/ piece | 1 piece/pieces(MOQ)

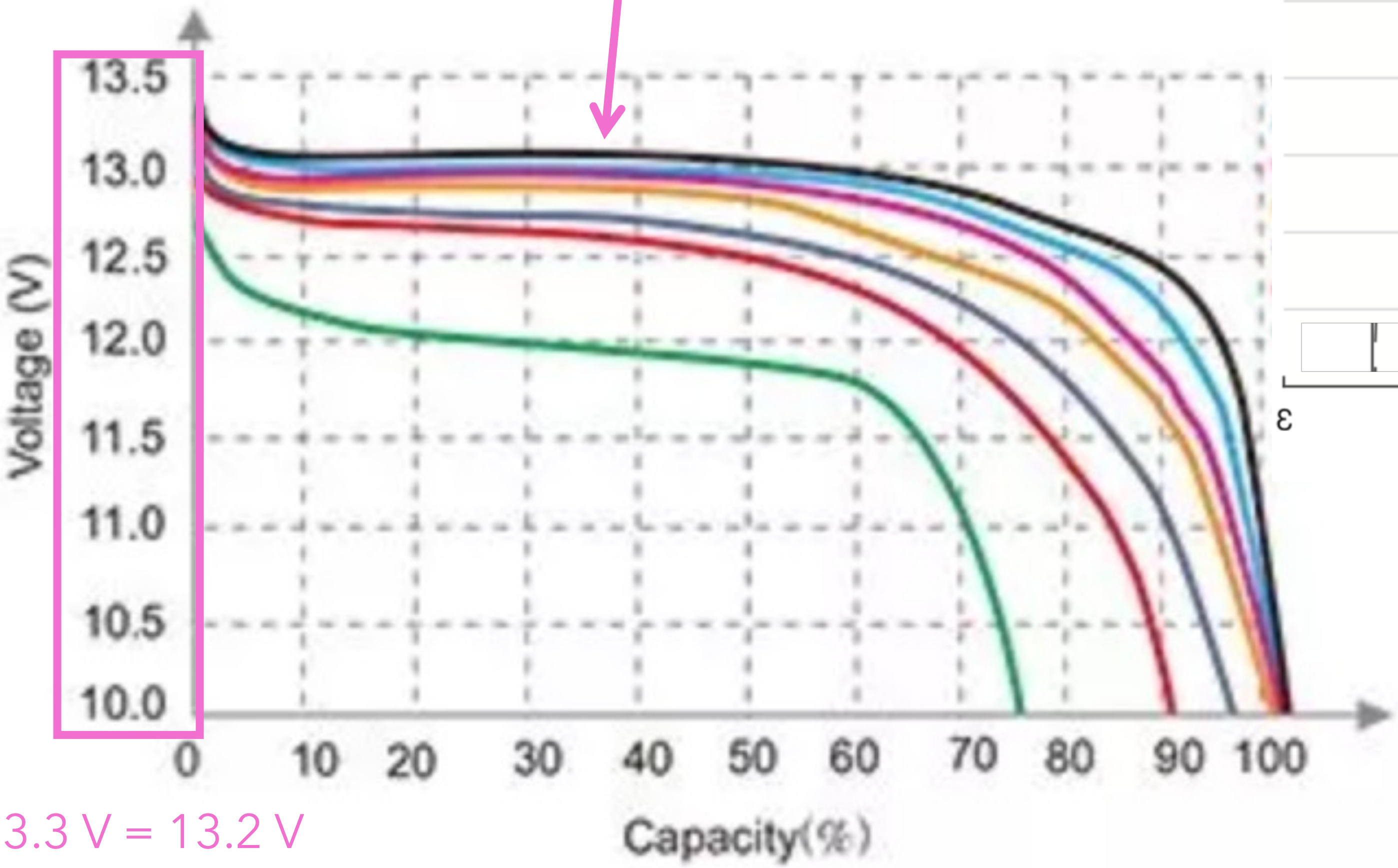
Benefits:	3-day coupon giveaway: up to US $80 off Claim now >
Battery Type	cylindrical
Nominal Capacity	1200~3500mAh
Nominal Voltage	3.7V

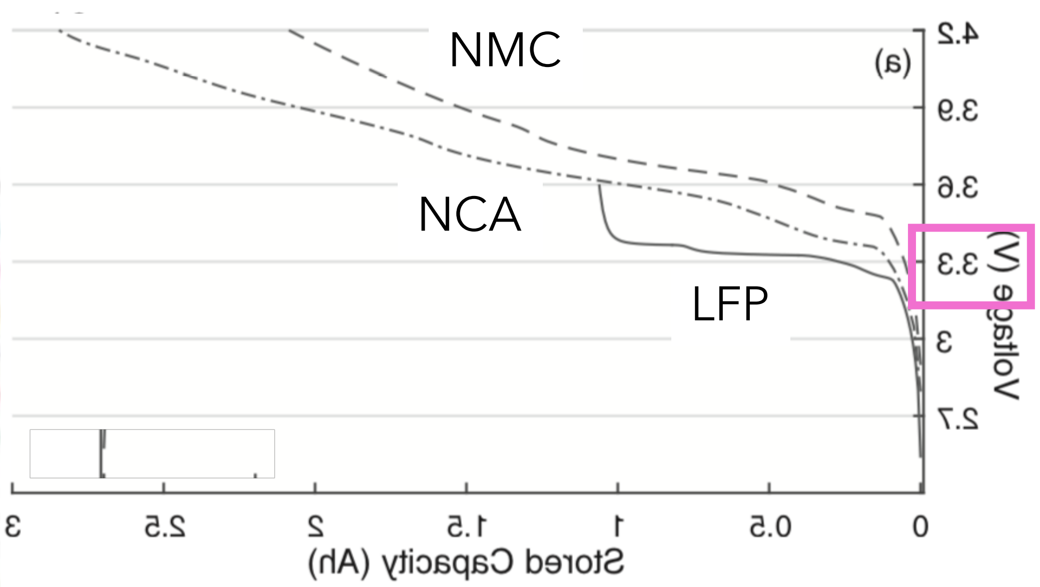
3.7V is typical for NMC cells

https://www.alibaba.com/product-detail/Customized-KC-Nmc-Accu-LED-Lights_1600125028451.html

Side note: What's sketchy about these curves?

Flat flat flat… like LFP.





4 × 3.3 V = 13.2 V

4s → 4 cells in series

https://www.alibaba.com/product-detail/Customized-KC-Nmc-Accu-LED-Lights_1600125028451.html

Temperature dependence of capacity

Samsung NMC cell

7.6 Temperature dependence of discharge capacity
Capacity comparison at each temperature, measured with discharge constant current 10A and 2.5V cut-off after the standard charge is as follows.

Discharge temperature				
-20℃	-10℃	0℃	25℃	60℃
60%	75%	80%	100%	100%

Samsung INR18650-20R

https://docs.rs-online.com/84c8/0900766b812fdd47.pdf

SK Innovation NMC cell

3.3.1. Charge Capacity

- Test Conditions
  - -. Discharge (CC): 1/3C, 2.7 V cut-off @ 25 ℃
  - -. Charge (CC): 1/3C, 4.2 V cut-off @ each temperature

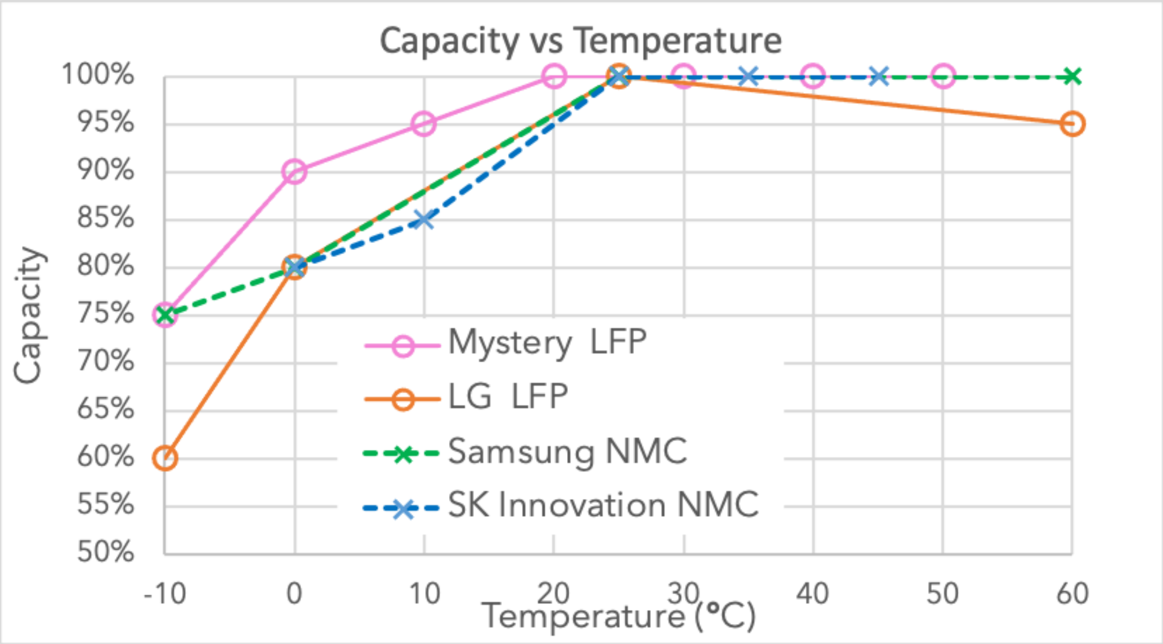
Temperature	45 ℃	35 ℃	25 ℃	10 ℃	0 ℃
Charge Capacity, (%)	≥ 100%	≥ 100%	100%	≥ 85%	≥ 80%

SK Innovation S004A

LG LFP cell

4.3.4 Temperature Dependency of Capacity	Cells shall be charged per 4.1.1 at 23℃ ± 2℃ and discharged per 4.1.2 at the following temperatures.		
	Charge	Discharge	Capacity
	25℃	-10℃	60% (of C_{nom} in 2.1)
		0℃	80% (of C_{nom} in 2.1)
		25℃	100% (of C_{nom} in 2.1)
		60℃	95% (of C_{nom} in 2.1)

LG 18650 HG2 3000mAh



Temperature review: capacity loss

Calendar aging

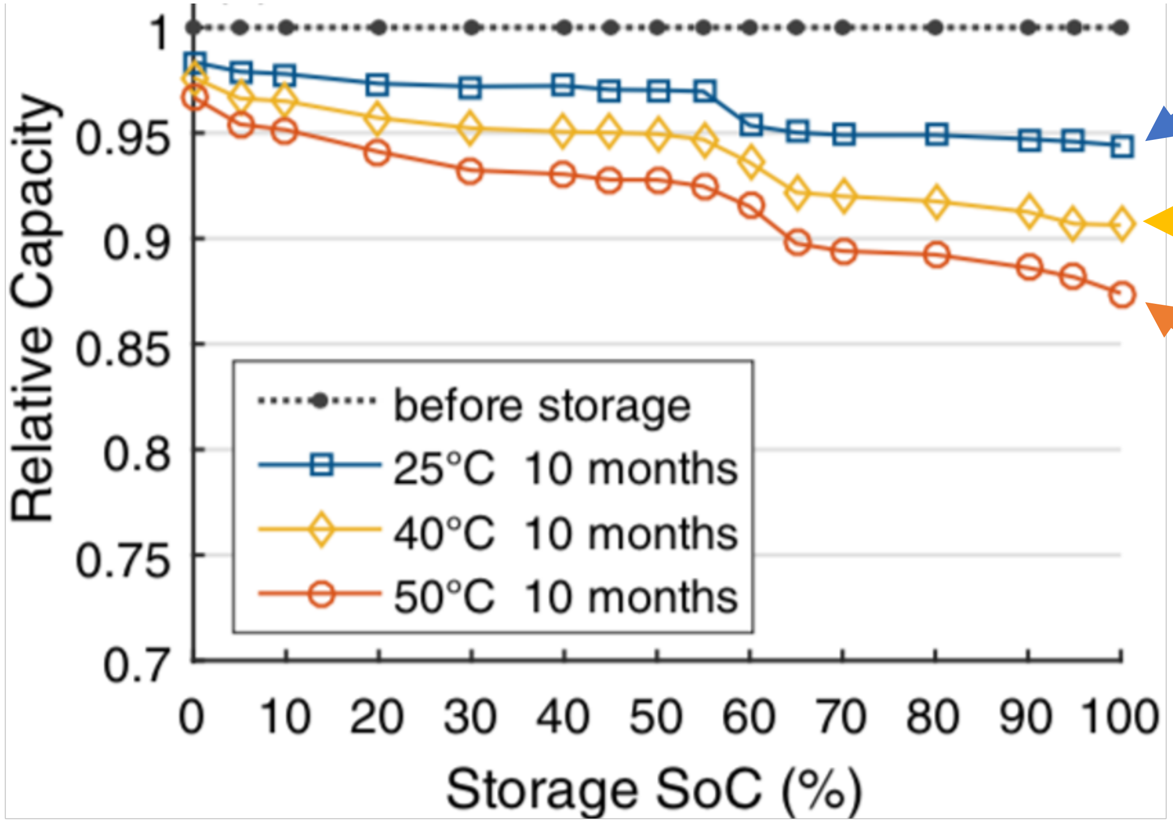


Fig. 2 in [DOI: 10.1149/2.0411609jes](https://doi.org/10.1149/2.0411609jes) [Keil 2016]

At 25°C, cells degraded to ~96% of initial capacity

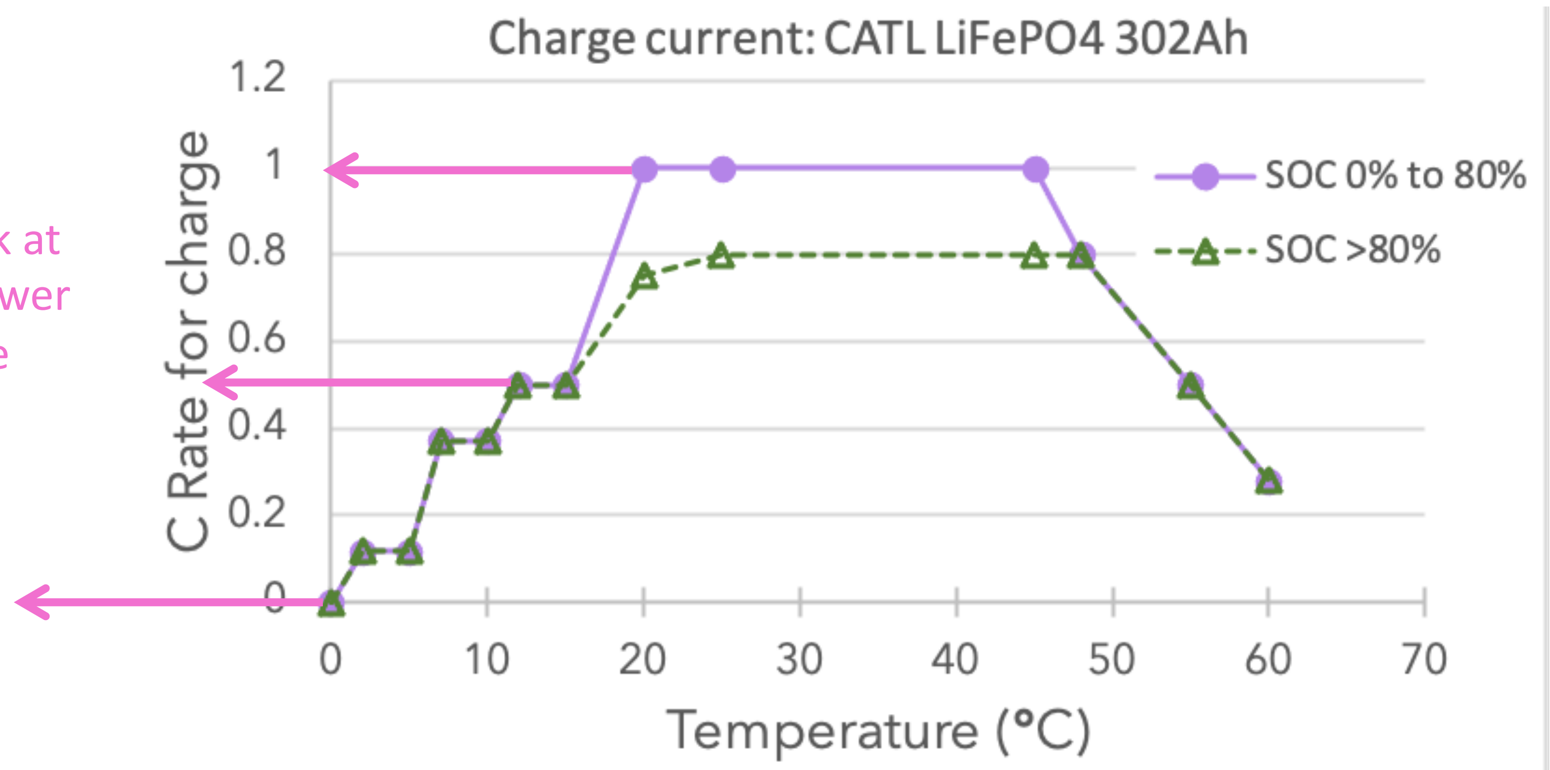
At 40°C, cells degraded to ~91% of initial capacity

At 50°C, cells degraded to ~87% of initial capacity

Aging accelerates with temperature.

Temperature review: Charge rate

Discharge ok at 20 to 30C lower temperature



Temperature summary

20°C to 45°C is the operating sweet spot for Li-Ion

- Aging
- Capacity
- Current (and thus power)

Temperature management is important

- temperature sensing
- heating system
- cooling system
- reduced power operation

Goal and optimization parameters

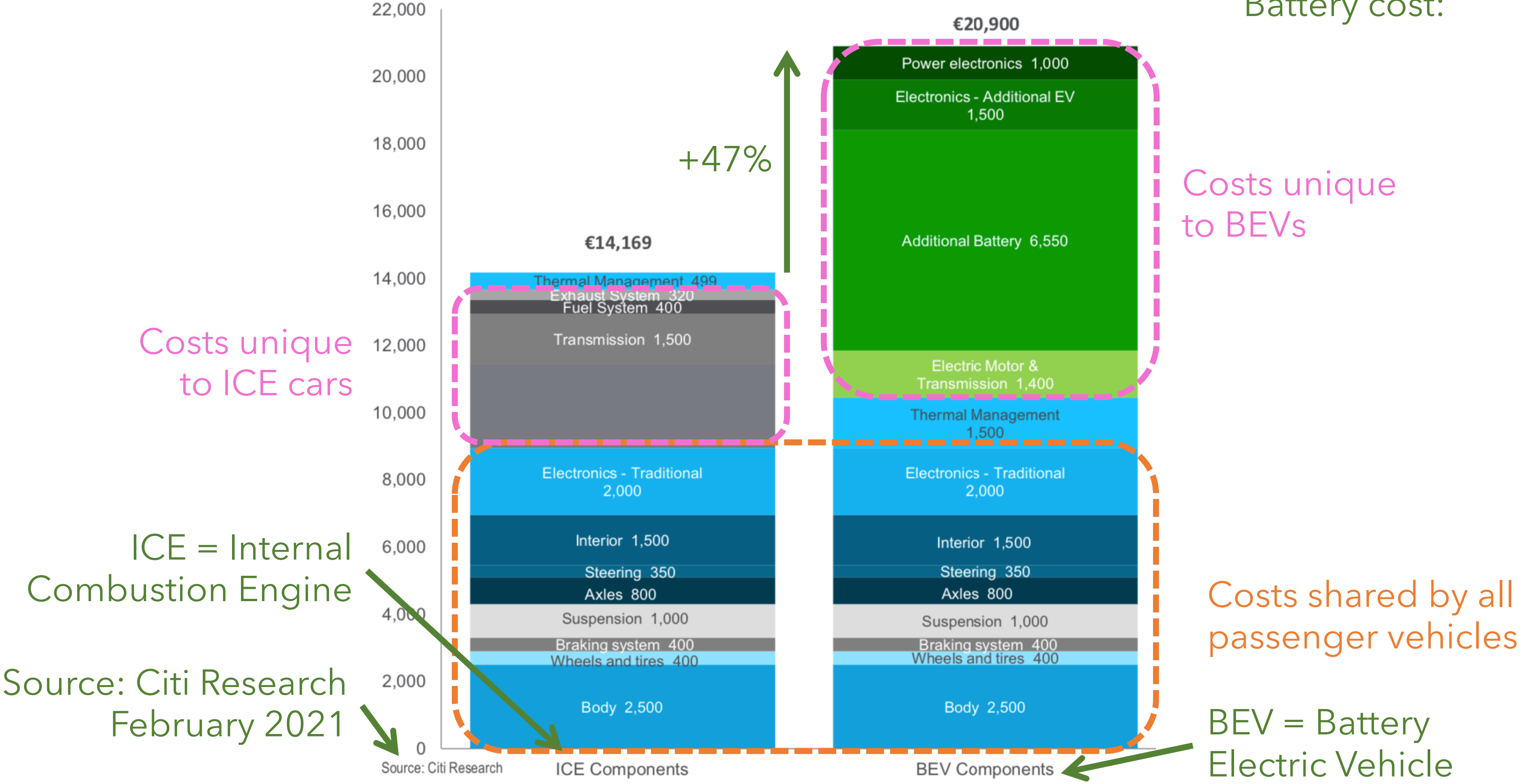
- **Goal:** Electrifying diesel power in Metro Vancouver (e.g., Sea Bus, delivery vehicles, heavy machinery, etc.). Identify a potential application and demonstrate feasibility through appropriate sizing, costing, and other analysis
- **Optimization parameters:**
  - Energy density (with a nod to power density)
  - Safety
  - Lifetime: Chemistry, temperature, voltage
  - Charge rate
  - Temperature range

Inspired by: https://www.smartpropel.com/nickel-cobolt-manganese-lithium-battery-vs-lithium-iron-phosphate-battery-this-is-the-most-comprehensive-interpretation

Cost: Overview

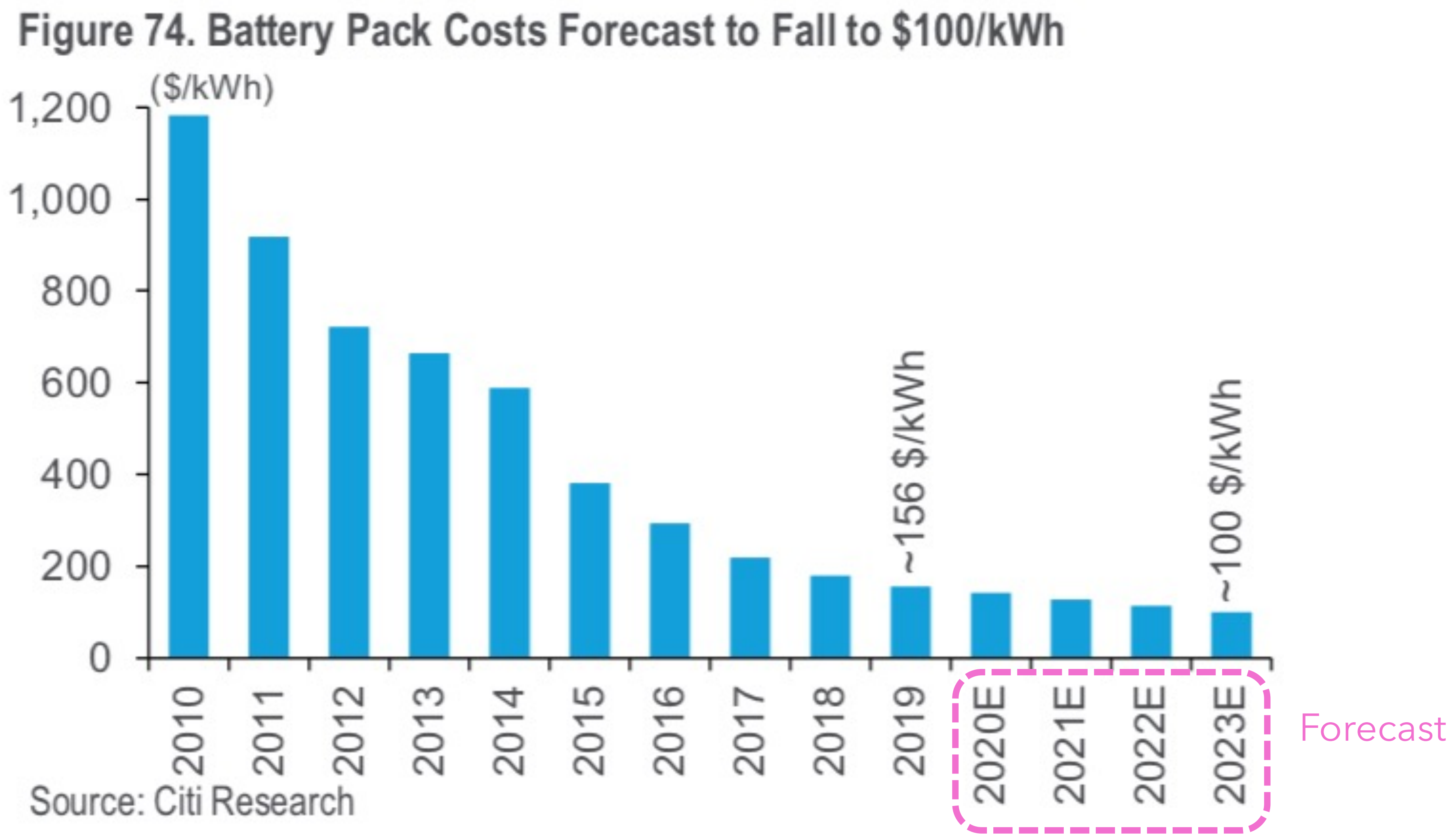
Cost difference: € 6,741
Battery cost: € 6,550

Figure 60. ICE vs. BEV Vehicle Manufacturer Suggested Retail Price (MSRP) by Component (€)



From: https://www.citifirst.com.hk/home/upload/citi_research/AZ7ON.pdf (Feb 2021)

Battery Cost is Falling

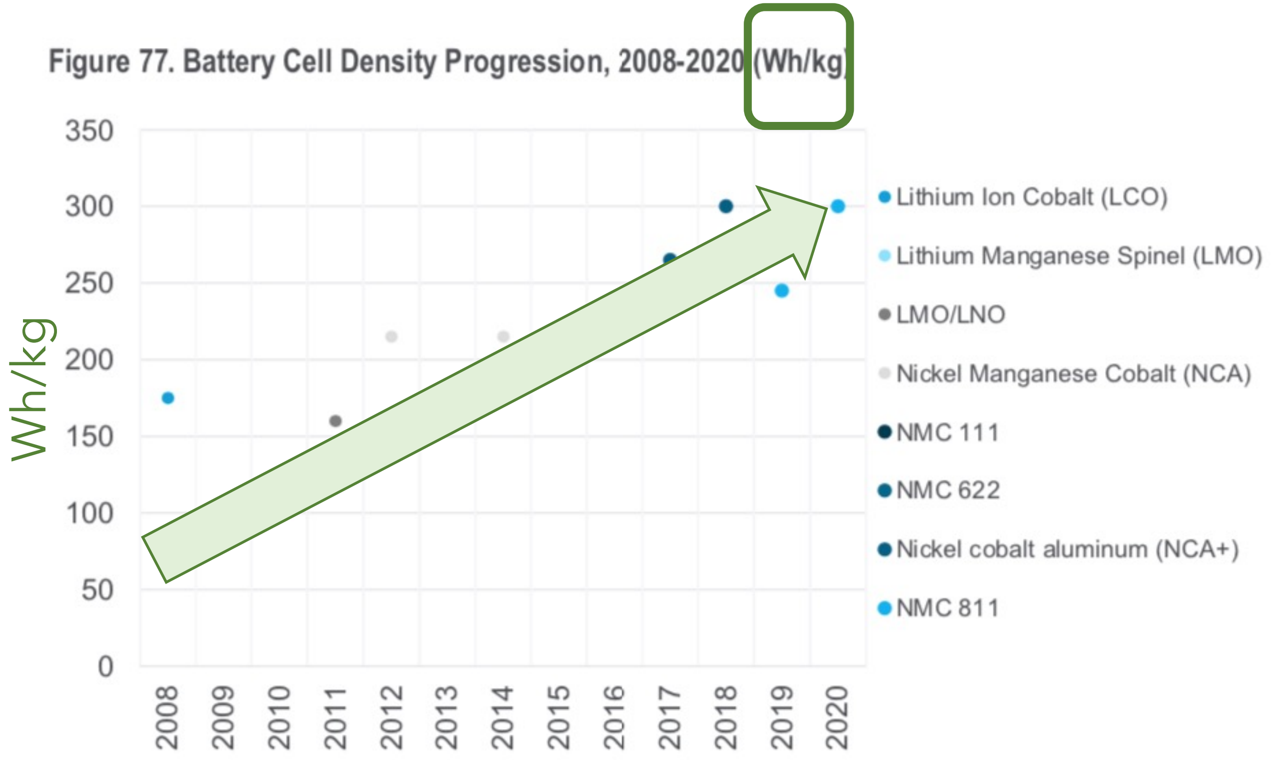


From: https://www.citifirst.com.hk/home/upload/citi_research/AZ7ON.pdf (Feb 2021)

Drivers behind cost decreases

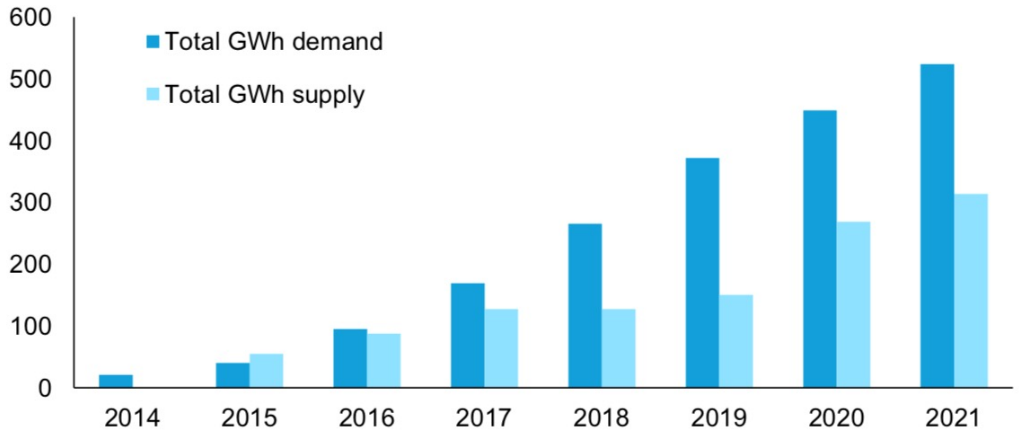
- Energy density improvements
- Economies of scale

Figure 77. Battery Cell Density Progression, 2008-2020 (Wh/kg)



Source: Citi Research, BNEF

Figure 63. Global Cell Supply/Demand Balance (GWh)



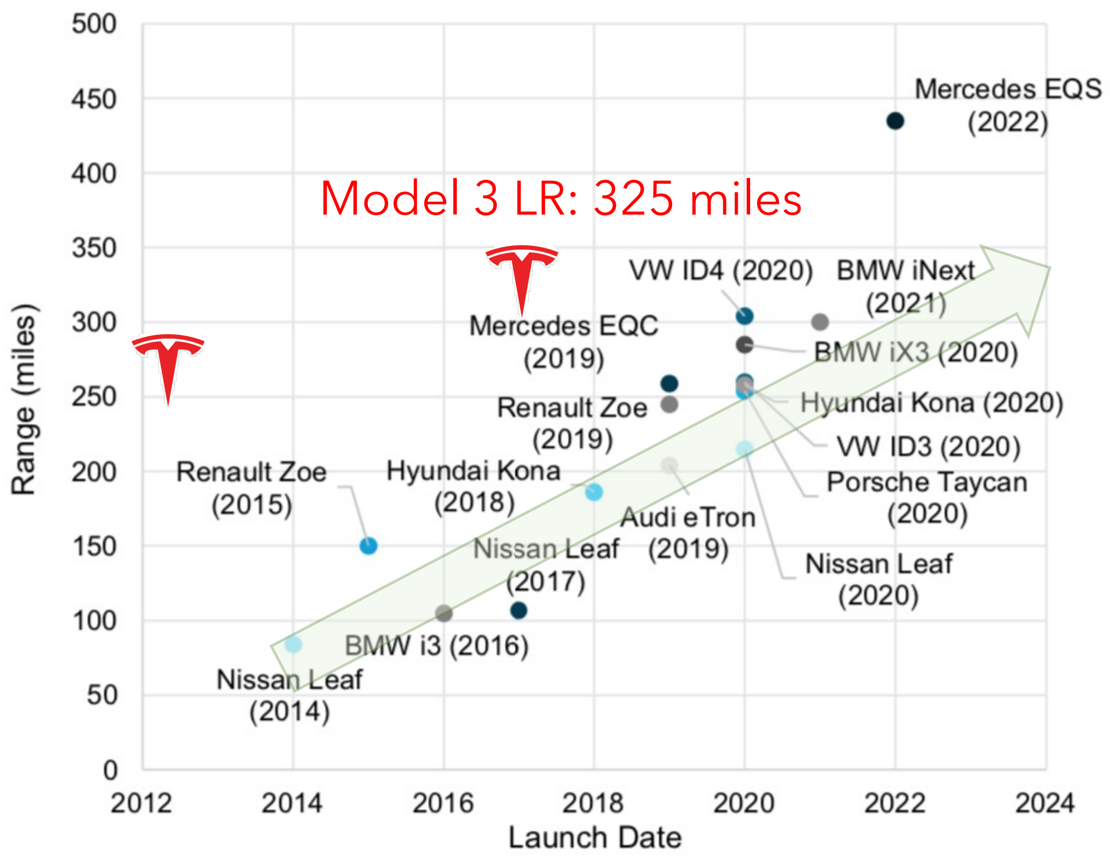
Source: Citi Research

From: https://www.citifirst.com.hk/home/upload/citi_research/AZ7ON.pdf (Feb 2021)

Blinds spots and biases

Figure 15. Newer Model Launches Improve Significantly on Range

Model S LR: 265 miles



Source: Citi Research, Clean Technical, Autocar, Greencar reports, Inside EVs, electrek

Plot: https://www.citifirst.com.hk/home/upload/citi_research/AZ7ON.pdf

Tesla info: https://en.wikipedia.org/wiki/Tesla_Model_S and https://en.wikipedia.org/wiki/Tesla_Model_3

Cost: LFP vs NMC

	LFP	NMC	NCA
Material composition	Lithium	Lithium	Lithium
	Iron	Nickel	Nickel
	Phosphate	Manganese	Cobalt
		Cobalt	
Average cost *US$ per kWh*	$90/kWh	$130/kWh	$130/kWh
Energy density *pack level*	160 Wh/kg	200 Wh/kg	200 Wh/kg
Discharge recommendation	100%	80-90%	80-90%
Discharge cycles *until 80% capacity*	2,500	1,000	1,000

These are estimates only, actual figures will vary depending on make and model of electric vehicle.

From: https://zecar.com/post/what-are-lfp-nmc-nca-batteries-in-electric-cars

Citi, for 2023: $100/kWh

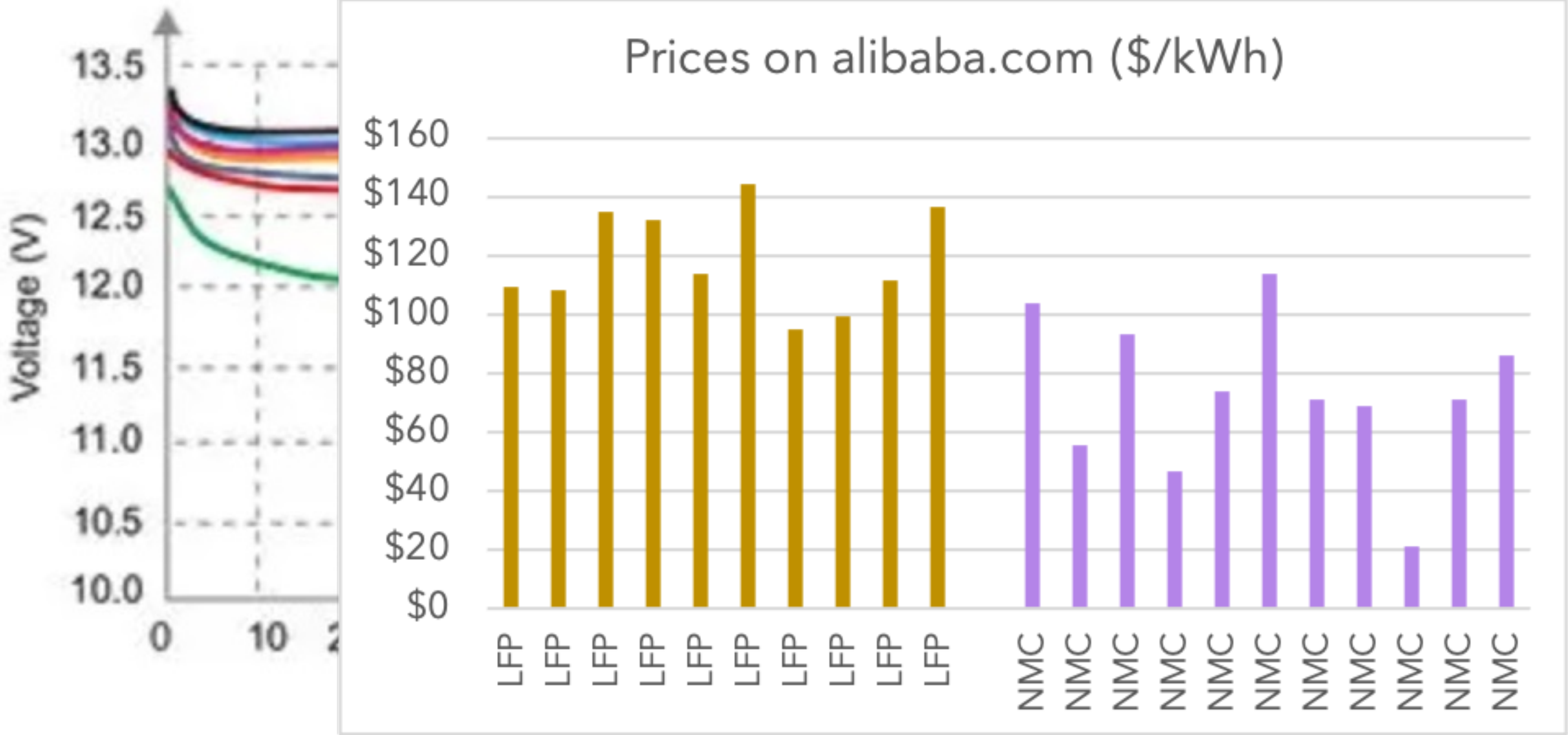
	LFP	NMC
2021	$178.80	$211.44
2030	$117.00	$138.36

← Higher than other sources

← Narrow price gap

From: https://www.pnnl.gov/lithium-ion-battery-lfp-and-nmc ← Slick system cost estimator

Cost: **YOUR** cost.



"LFP lithium battery"
(prismatic)

"NMC lithium battery"
(prismatic)

Wrap up

	NCM	LFP
Energy density	Better	
Safety		Better
Lifetime		Better
Charge rate (related to power density)		Often better
Temperature range	Both need active management	
Cost	Less expensive on Alibaba.com	Less expensive per industry estimates

Cell chemistry options

<table>
<tr><th rowspan="2">Specifications</th><th rowspan="2">Lead Acid</th><th rowspan="2">Nickel Cadium (NiCd)</th><th rowspan="2">Nickel Metal Hydride (NiMH)</th><th colspan="3">Li-ion</th></tr>
<tr><th>Cobalt Oxide (LMO)</th><th>Manganese Oxide (LMO)</th><th>Iron Phosphate (LFP)</th></tr>
<tr><td>Specific Energy Density (Wh/kg)</td><td>30-50</td><td>45-80</td><td>60-120</td><td>150-190</td><td>100-135</td><td>90-120</td></tr>
<tr><td>Life Cycle (80% discharge)</td><td>200-300</td><td>1000</td><td>300-500</td><td>500-1,000</td><td>500-1,000</td><td>1,000-2,000</td></tr>
<tr><td>Fast-Charge Time</td><td>8-16h</td><td>1h typical</td><td>2-4h</td><td>2-4h</td><td>1h or less</td><td>1h or less</td></tr>
<tr><td>Overcharge Tolerance</td><td>High</td><td>Moderate</td><td>Low</td><td colspan="3">Low. Cannot tolerate trickle charge</td></tr>
<tr><td>Self-Discharge/month (room temp)</td><td>5%</td><td>20%</td><td>30%</td><td colspan="3"><10%</td></tr>
<tr><td>Peak Load Current
Best Result</td><td>5C
0.2C</td><td>20C
1C</td><td>5C
0.5C</td><td>>3C
<1C</td><td>>30C
<10C</td><td>>30C
<10C</td></tr>
<tr><td>Charge Temperature</td><td>-20 to 50°C
-4 to 122°F</td><td colspan="2">0 to 45°C
32 to 113°F</td><td colspan="3">0 to 45°C
32 to 113°F</td></tr>
<tr><td>Discharge Temperature</td><td>-20 to 50°C
-4 to 122°F</td><td colspan="2">-20 to 65°C
-4 to 149°F</td><td colspan="3">-20 to 60°C
-4 to 140°F</td></tr>
<tr><td>Safety Requirements</td><td>Thermally stable</td><td colspan="2">Thermally stable, fuse protection common</td><td colspan="3">Protection circuit mandatory</td></tr>
<tr><td>Toxicity</td><td>Very High</td><td>Very High</td><td>Low</td><td colspan="3">Low</td></tr>
</table>

Excerpted form a more detailed table at: https://www.epectec.com/batteries/cell-comparison.html