Batteries: Fundamentals and Applications – Part I
Batteries for the future transportation sector

47202: Introduction to Future Energy; 2023-11-14

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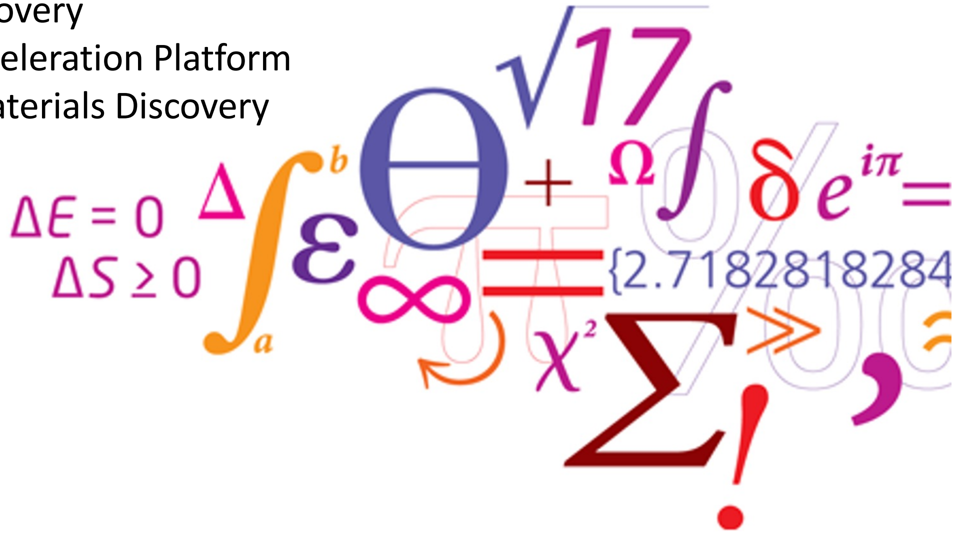
Director of CAPeX, Pioneer Center for Accelerating P2X Materials Discovery
DTU Energy



Plan for today

Batteries: Fundamentals, Applications and Integration

13-15:15 (Building 303A auditorium 42):

Part I: Batteries for future transportation sector
Part II: Battery fundamentals
Part III: From Li-ion to grid-scale storage and autonomous materials discovery

15:15-17:

Exercises: Building 303A area OEST and area VEST

Learning objectives

- Discuss the volumetric and gravimetric storage capacities of different battery chemistries (lead-acid, Ni-Cd, Ni-MH and Li-ion)
- Explain the working principle of a Li-ion battery, incl. redox reactions
- Calculate the open circuit voltage (V_{OC}) of a battery cell from the chemical potentials of the negative and the positive electrode
- Explain why the charge/discharge potentials differ from V_{OC}
- Describe different ways to improve the energy density of a lithium-based battery
- Explain the concept of C-rates in batteries
- Discuss advantages and disadvantages of redox flow batteries relative to Li-ion batteries
- Assess and discuss the scalability of different battery chemistries

Energy Storage Technologies

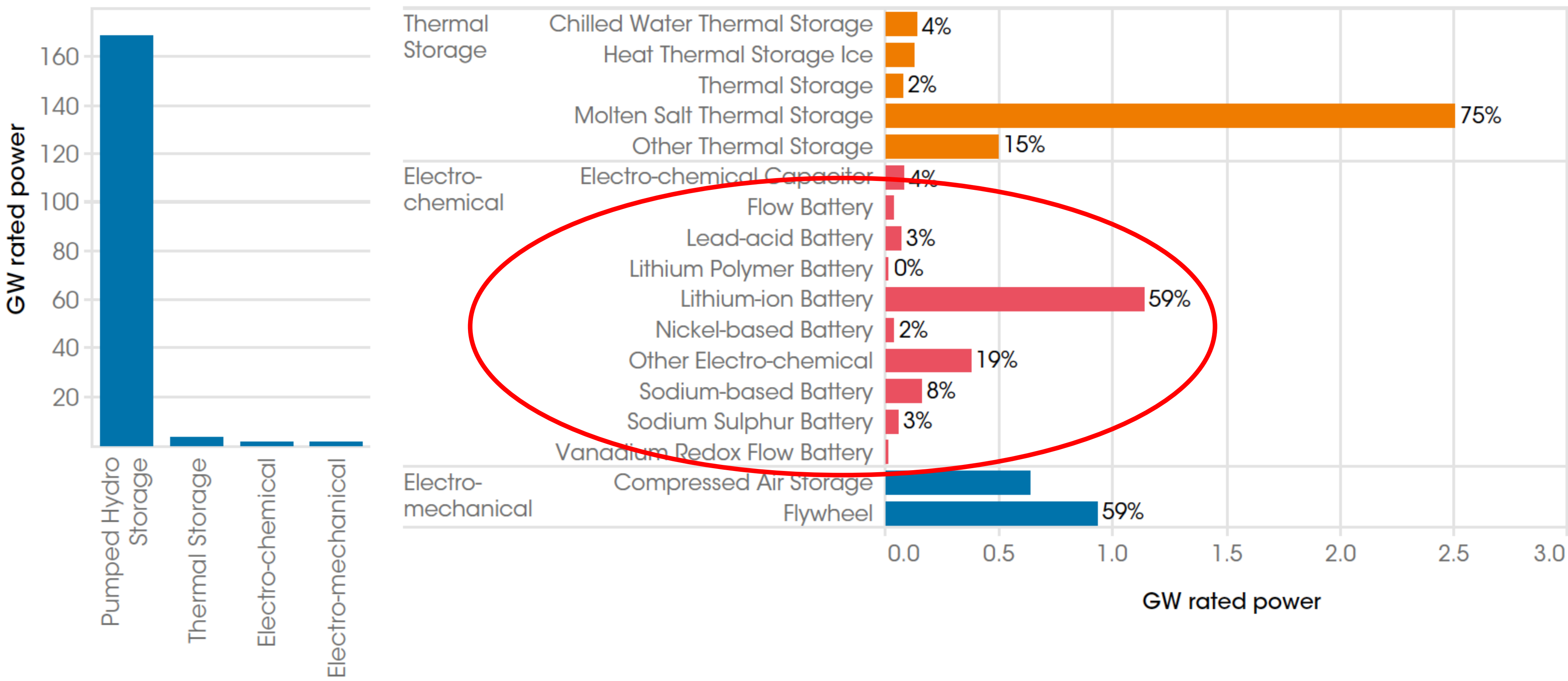
- **Mechanical**
  - Pumped hydro (PHS)
  - Compressed Air (CAES)
  - Flywheel (FES)
- **Electrochemical**
  - Secondary (rechargeable) batteries: Lead-acid, Li-ion, Sodium-Sulfur, Zn-Air,...
  - Flow Batteries
    Redox flow, Hybrid flow
- **Electrical**
  - Capacitor, Supercapacitor
  - Superconducting Magnetic (SMES)
- **Thermochemical**
  - Solar Fuels
    Solar hydrogen
- **Chemical**
  - Hydrogen, (Methane...)
    Fuel Cell / Electrolyzer combinations
- **Thermal**
  - Heat storage

Adapted from: Luo et al, "Overview of Current Development in Electrical Energy Storage Technologies and the Application Potential in Power System Operation. Applied Energy 2015, 137, 511–536 DOI: 10.1016/j.apenergy.2014.09.081.

Globally accessible E-storage power capacity

Massive projected increase in storage capacity (12 GW in 2024)
Can any of these technologies can be scaled to the TW/TWh scale?

Figure ES8: Global operational electricity storage power capacity by technology, mid-2017

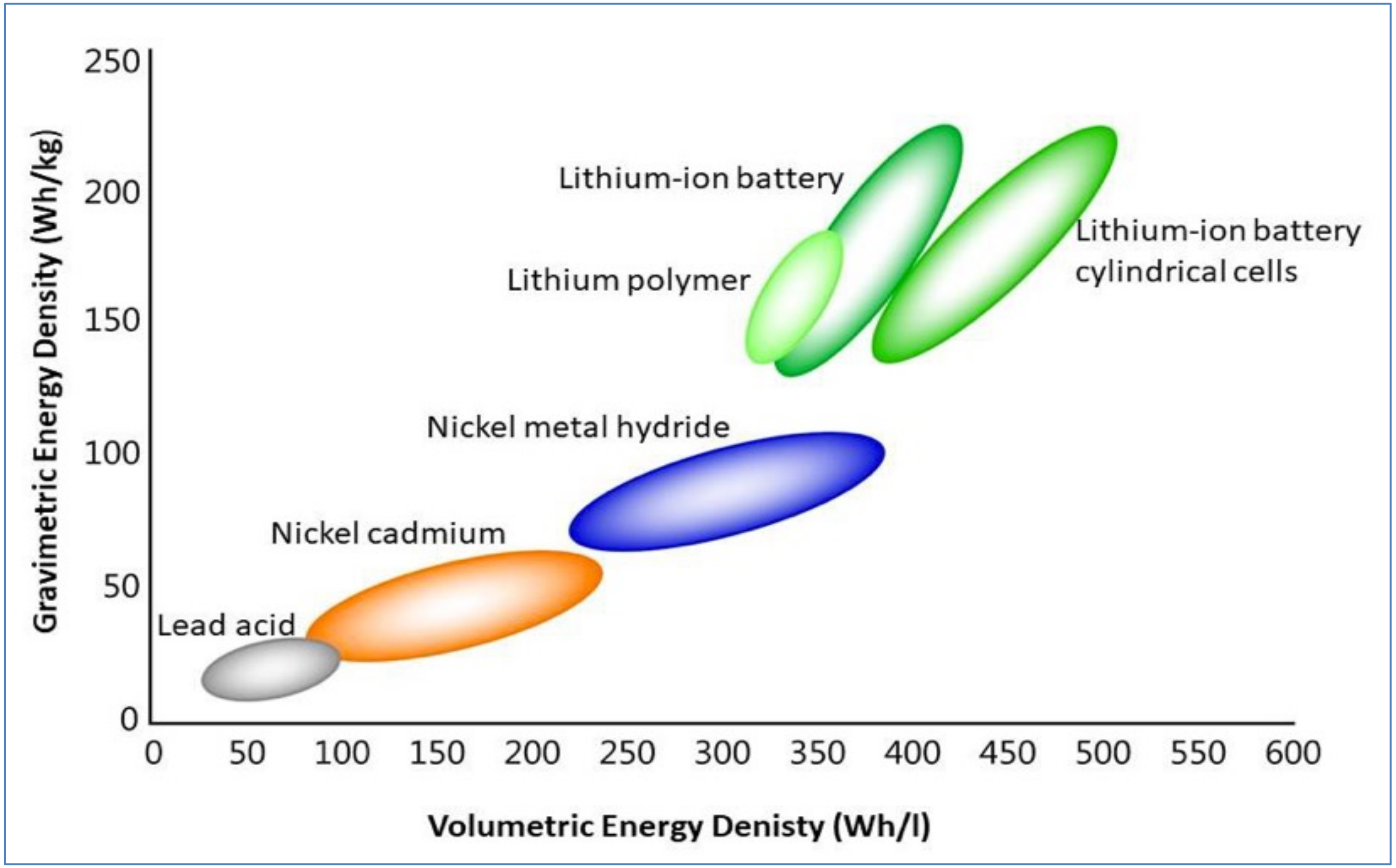


IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

Energy Storage World Forum, Navigant Research (2017)

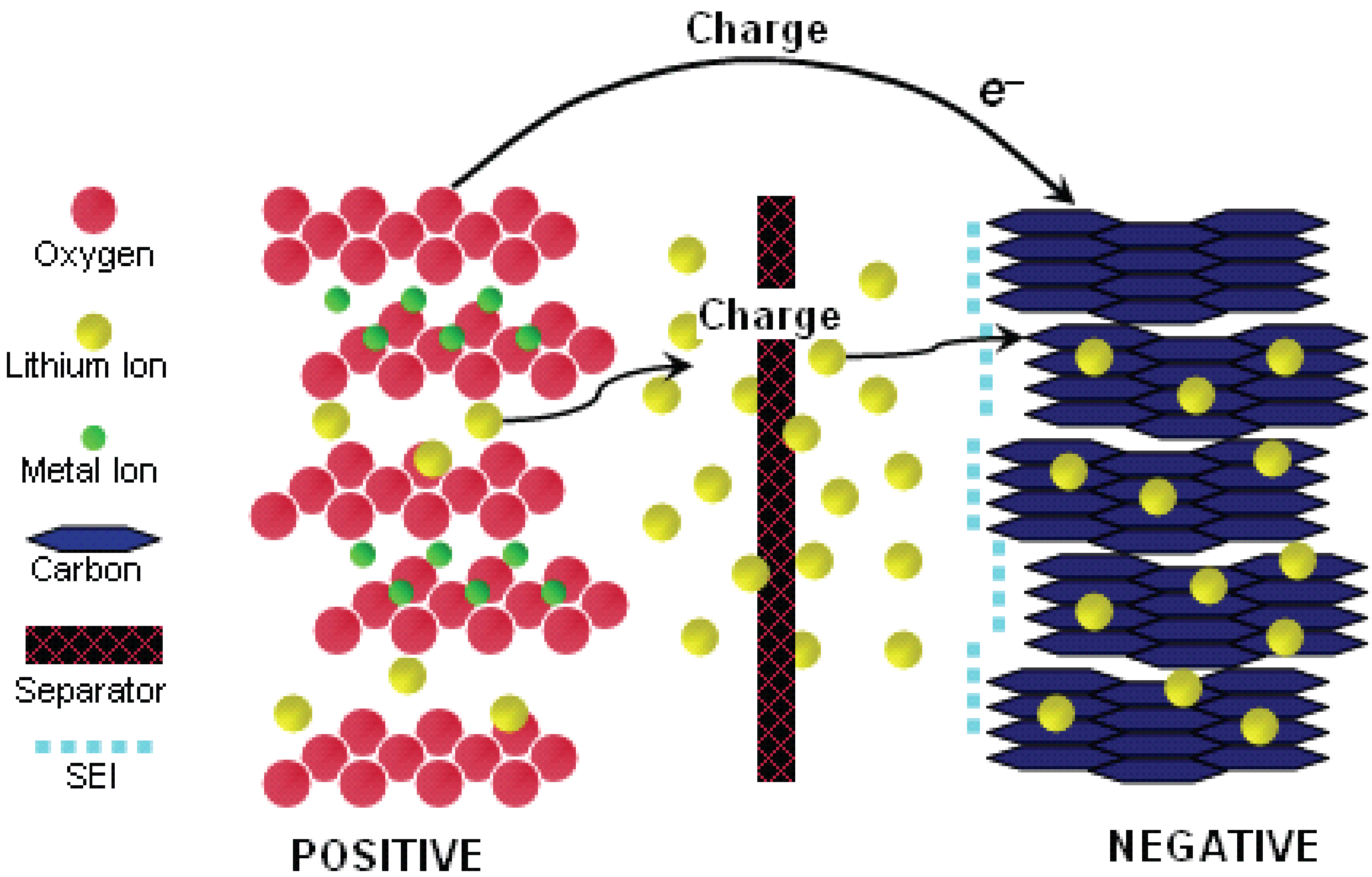
Specific energy and energy density of batteries

- Energy densities for Li-ion are up to 5-10 times higher than lead-acid



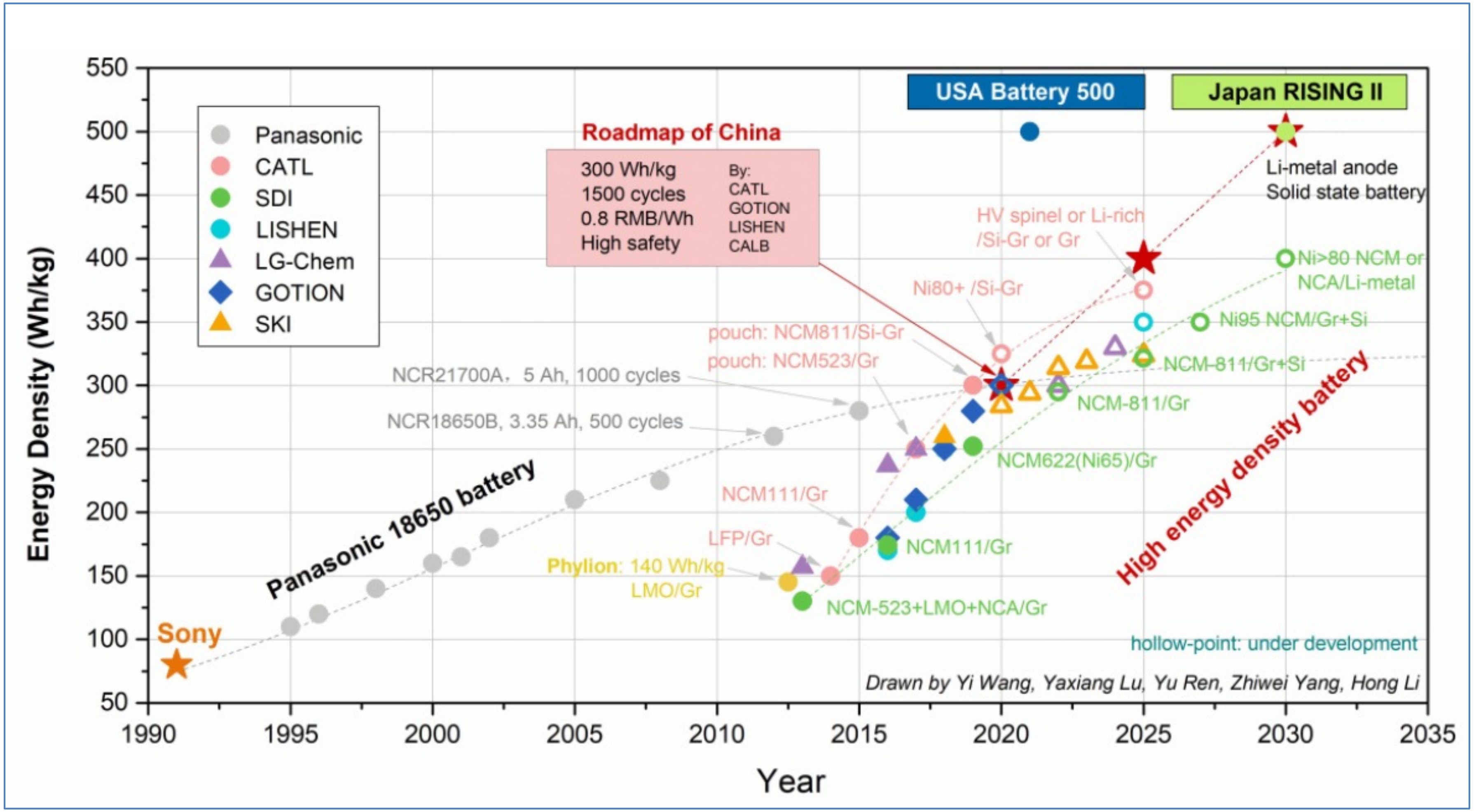
Edström, Dominko, Fichtner, Otuzewski, Perraud, Punckt, Tarascon, Vegge, Winter, BATTERY 2030+ Roadmap (2020)

A Li-ion battery



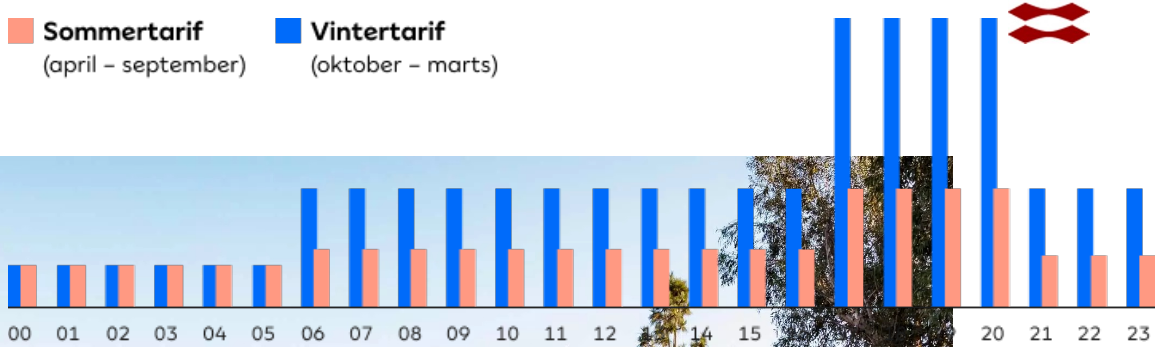
Historic developments for Li-ion

- Energy density increases on the order of ~4-5%/year



Edström, Wenzel, Vegge, et al., Advanced Energy Materials, doi: 10.1002/aenm.202102785 (2022)

Centralized/decentralized renewable storage solutions



Grid o

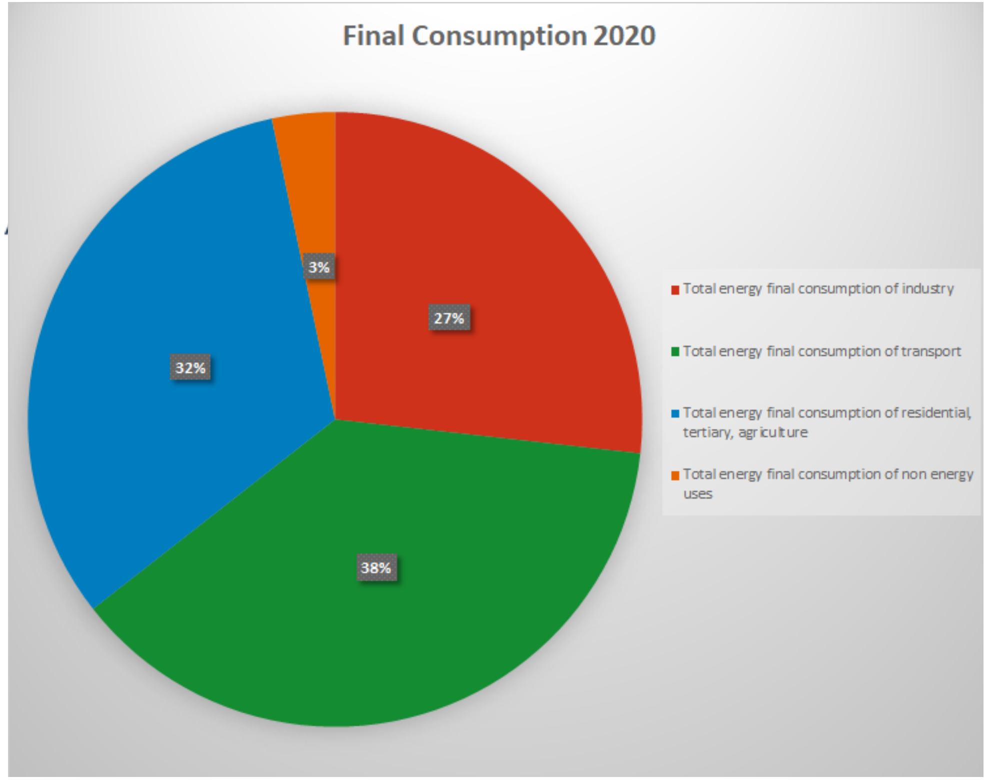
6 am
12 pm
6 pm
direct consumption reduces evening peak load

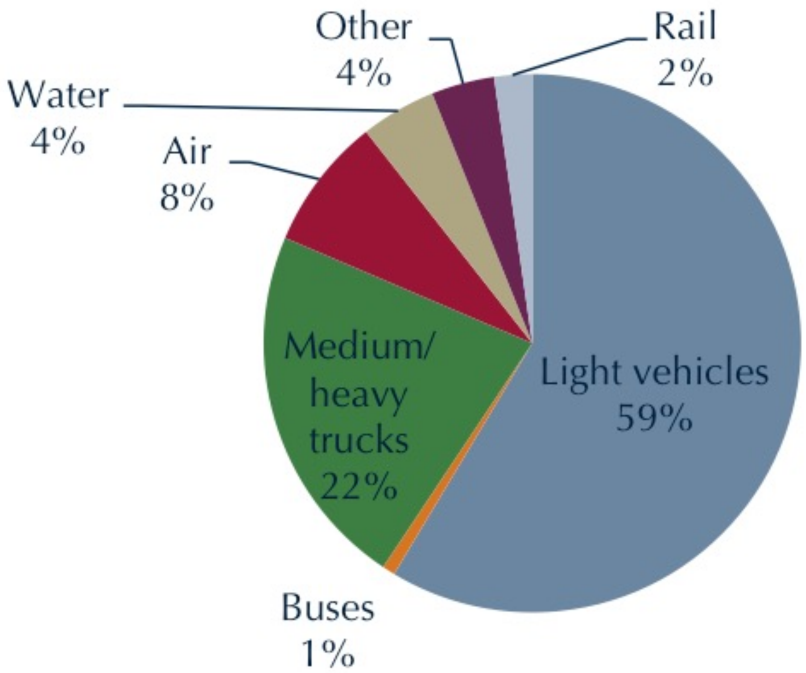
International Renewable Energy Agency (IRENA), Battery Storage for Renewables: Market Status and Technology Outlook (2015)

Tesla – Solar Roof (2023)

Energy Demand: Sector by Sector

- Electricity only accounts for part of the total energy consumption
- Sectors like the transportation sector hold special needs in terms of energy storage - and it's growing





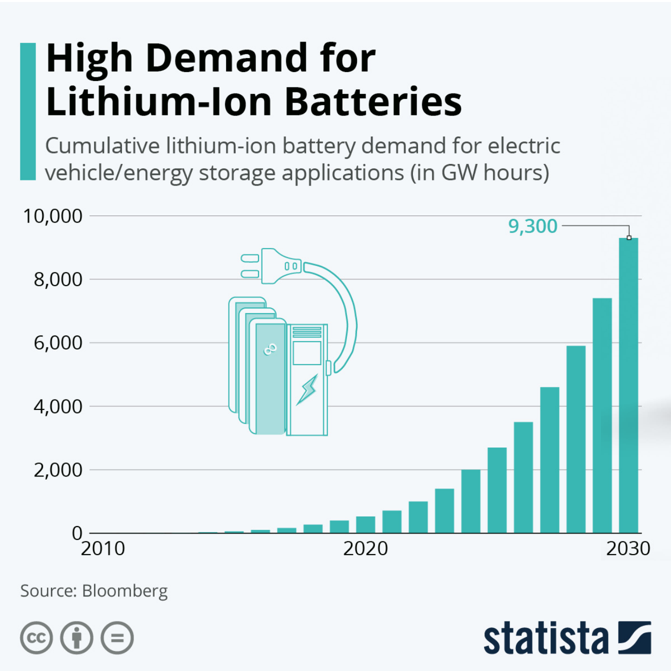
U.S. Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012, Table ES-7, 2014; U.S. Department of Energy. Transportation Energy Data Book, Table 2.5, 2014

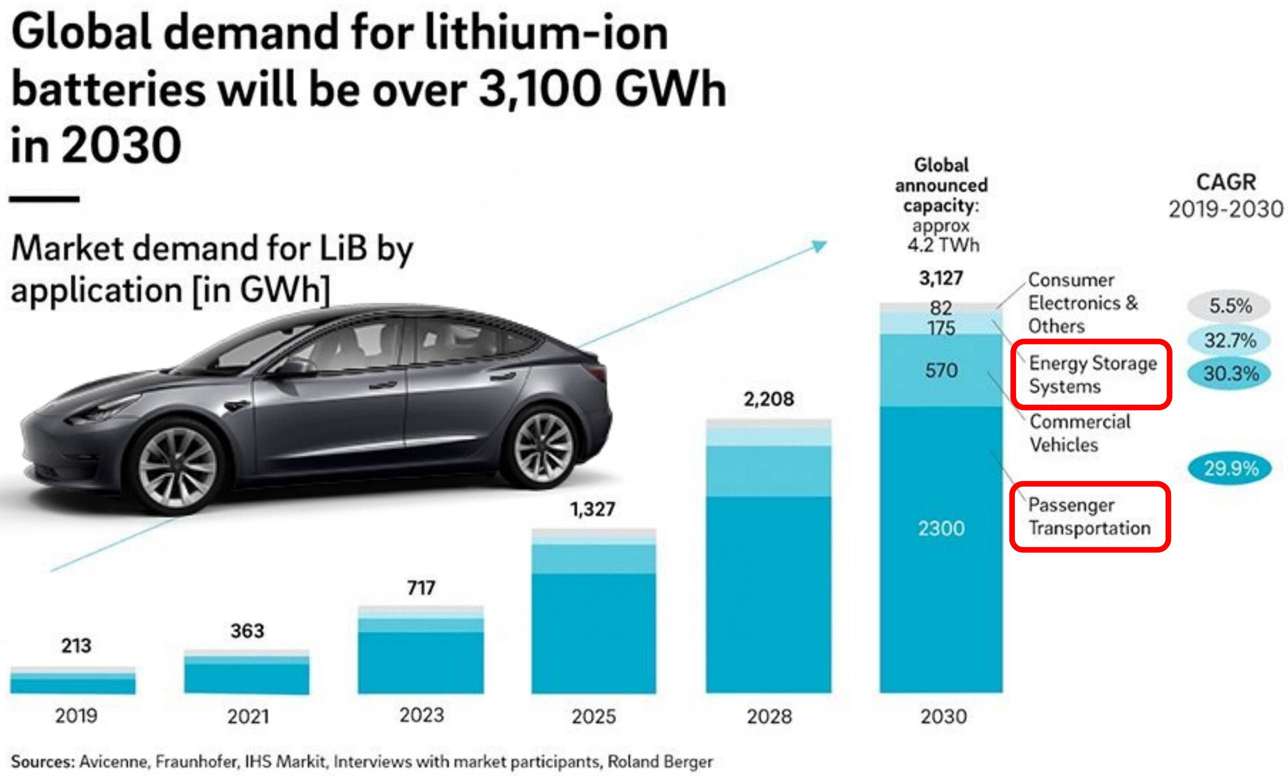
From Renewable Energy to Transportation

- Transportation requires very high energy and power densities
- Are battery technologies up to these challenges?

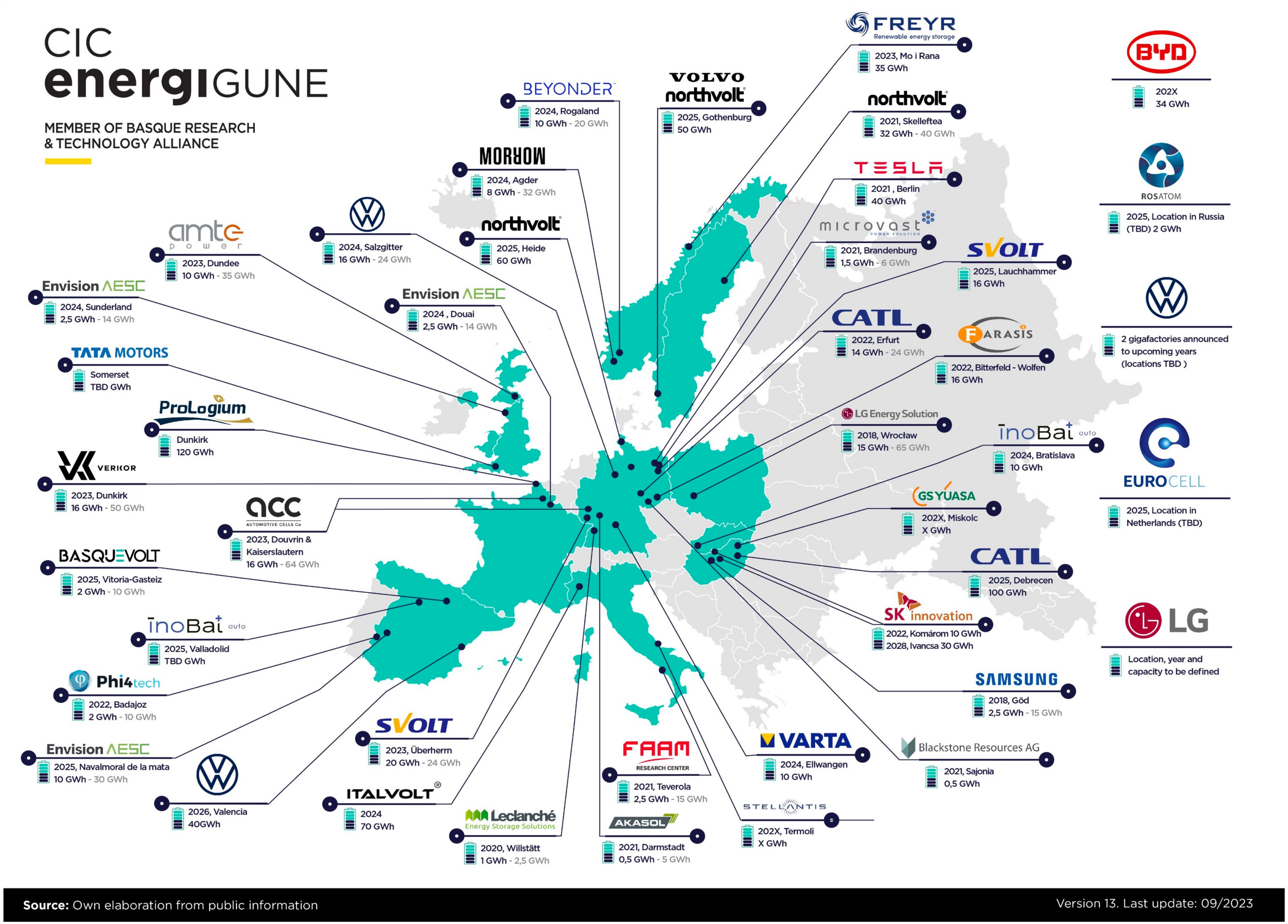
Li-ion battery demand explodes

- The demand for Li-ion batteries is growing fast
- Projected to exceed 2(3) TWh/year in 2030



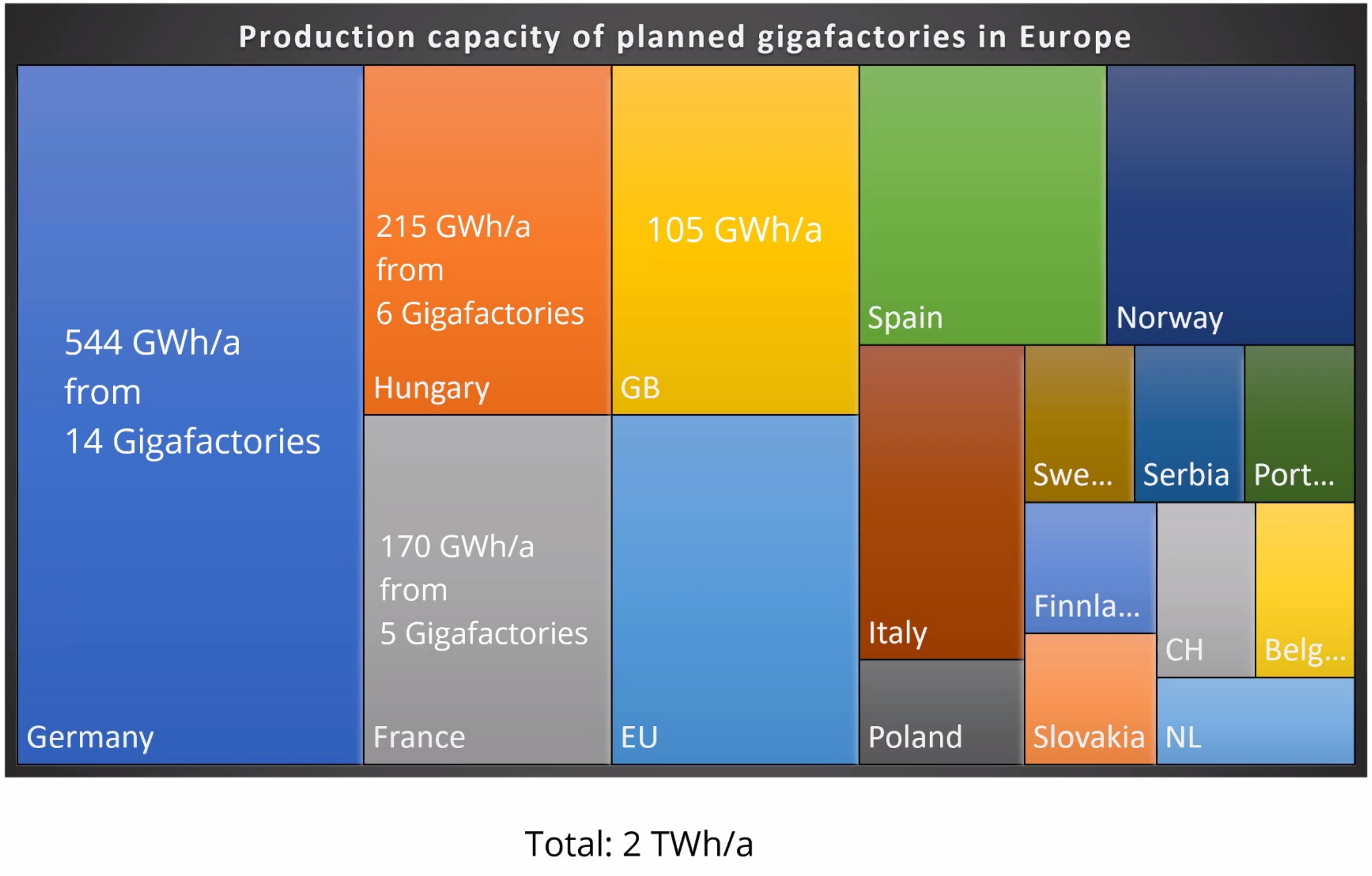


European battery production is expanding



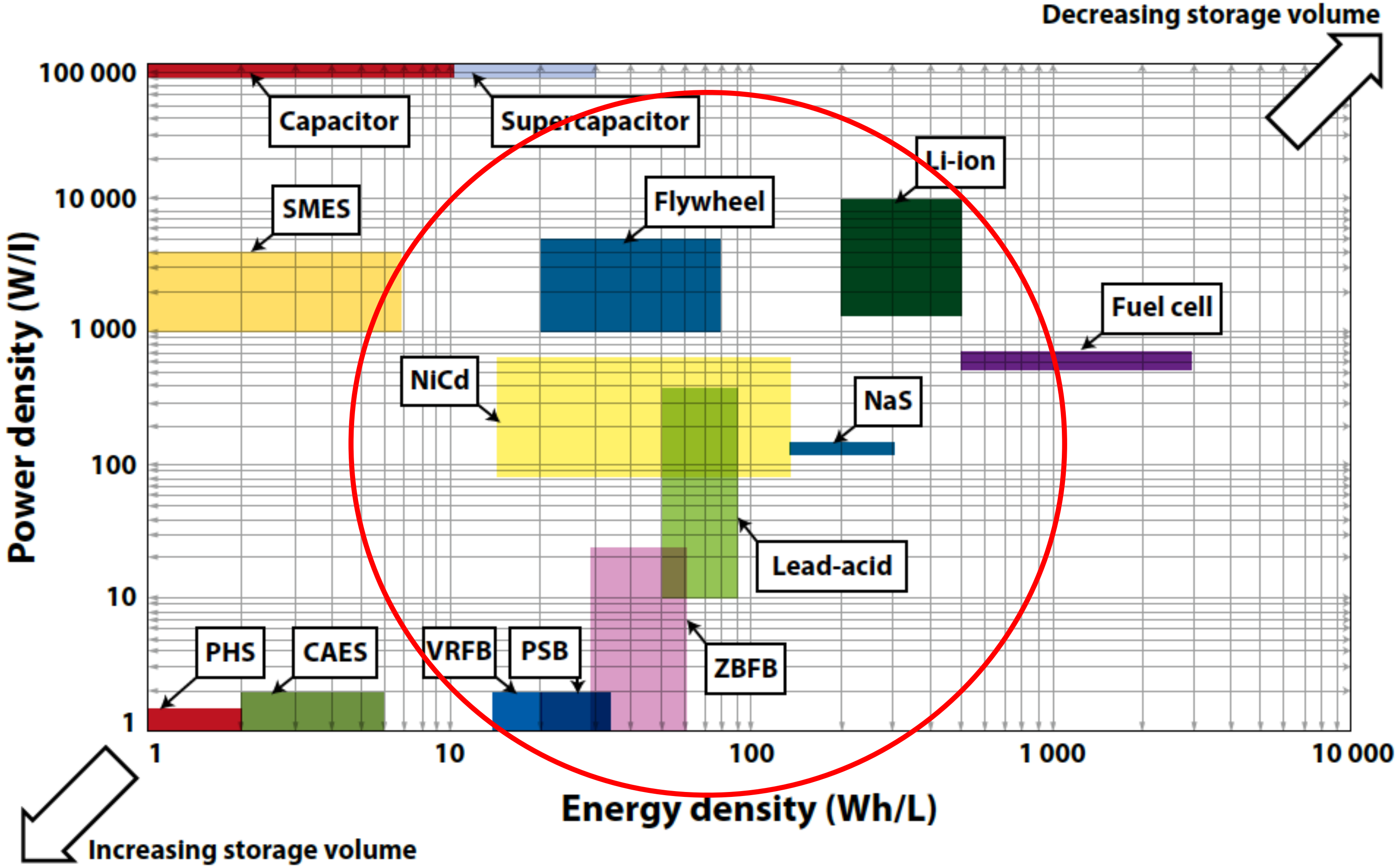
Battery production in Europe (June 2023)

- Germany is leading, but Hungary just announced plans for 1 TWh!
- Where is Denmark?



Energy storage and power capacity

Figure 12: Comparison of power density and energy density for selected energy storage technologies



Source: Luo *et al.*, 2015.
Note: SMES = superconducting magnetic energy storage; NiCd = nickel cadmium; NaS = sodium sulphur; PHS = pumped hydro storage; CAES = compressed air energy storage; VRFB = vanadium redox flow battery; PSB= polysulfide bromine flow battery; ZBFB = zinc bromine flow battery.

IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

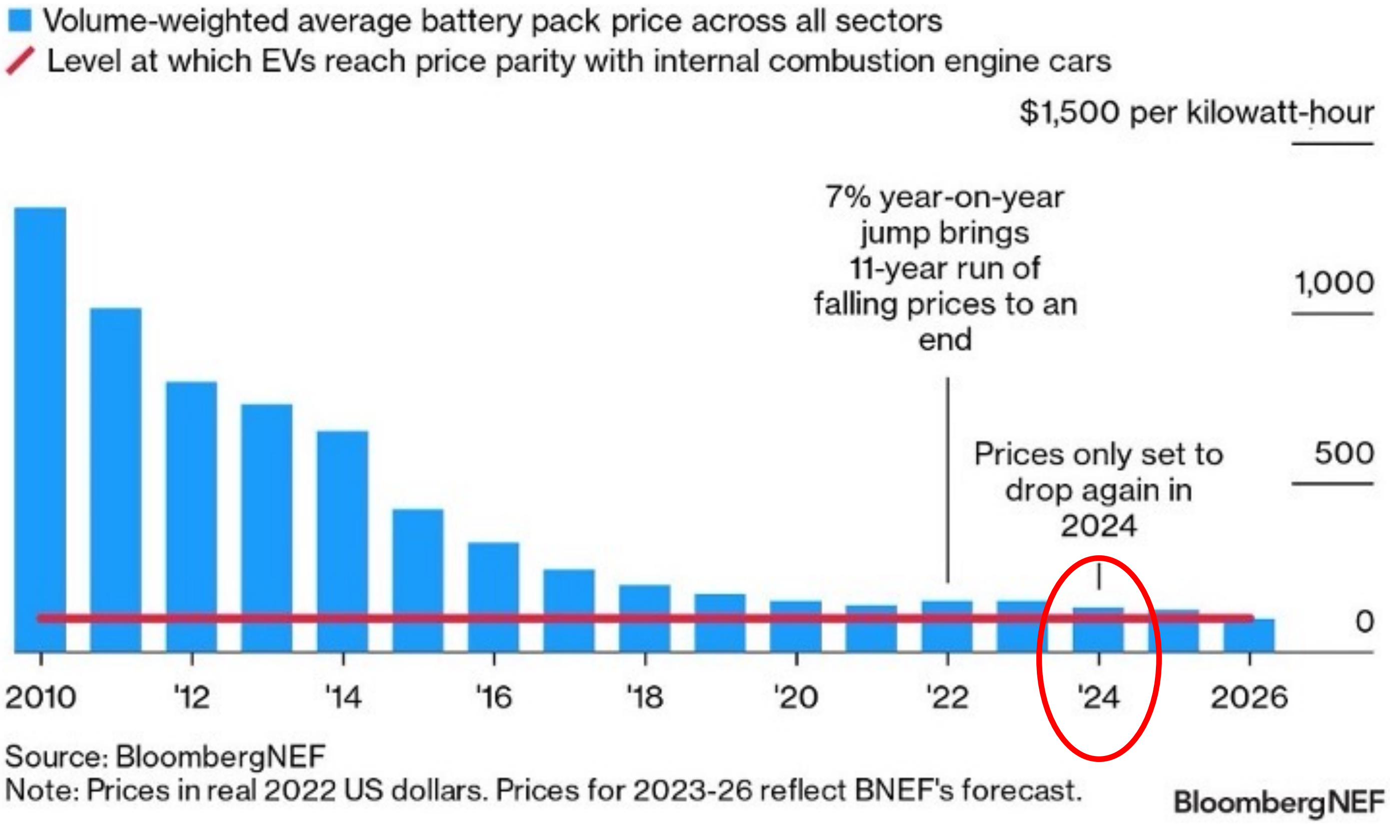
Are Batteries for all Transportation purposes already here?

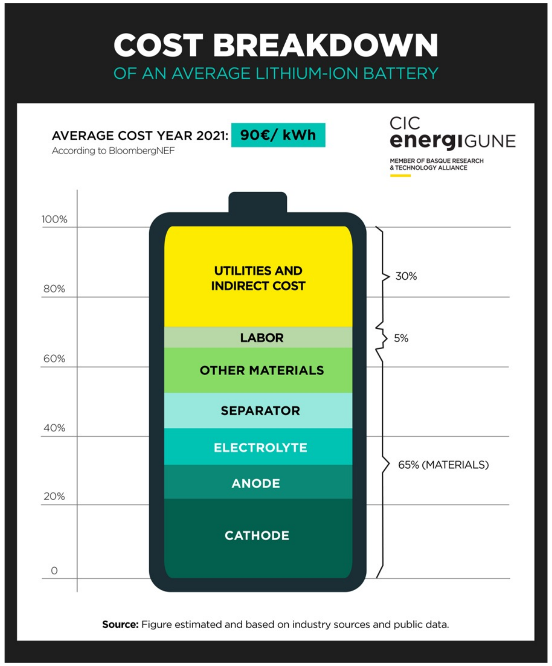
- A Tesla model 3(Y) provides a range of up to ~600(500) km
- The cost has been dropping rapidly over the last year!
- Cheaper alternatives are on the raise…

Tesla Motors (2023)

Developments in Li-ion battery prices

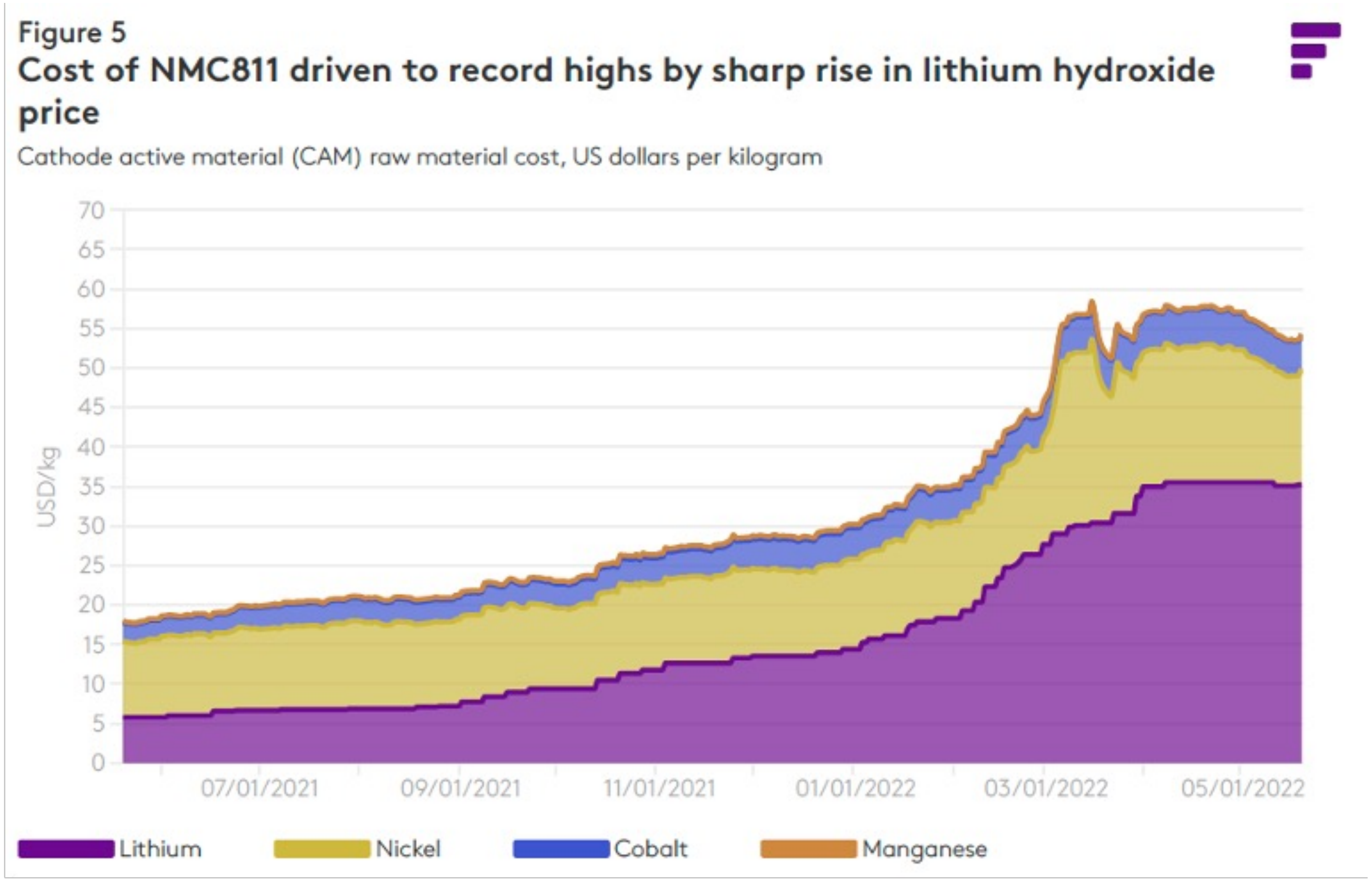
- The relative cost reduction has been going down over the last years
- The development has stagnated, and prices went up by +7% in 2022





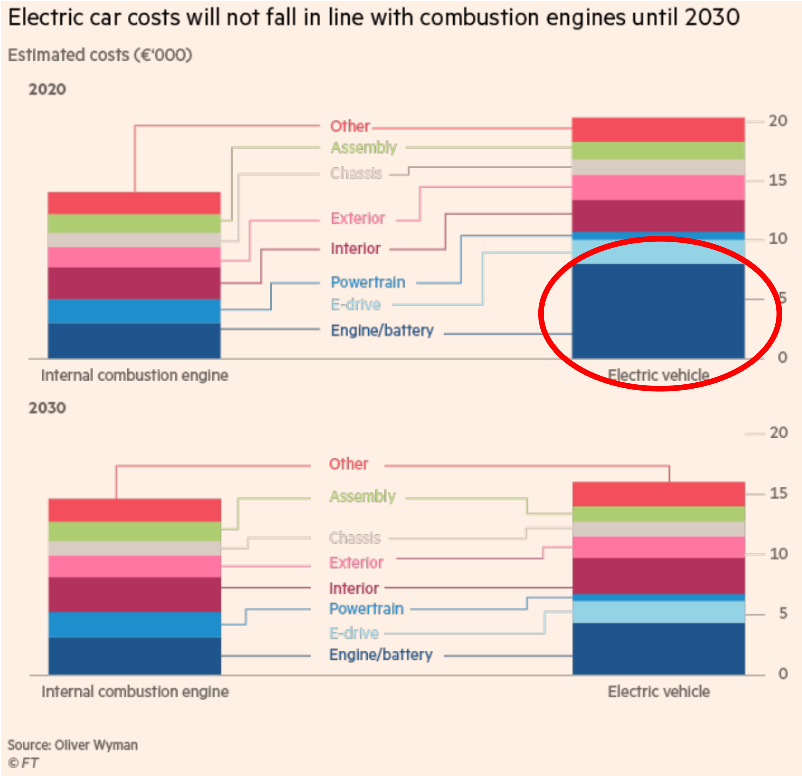
BloombergNEF (2023)

Lithium, nickel, cobalt and graphite demand and supply could be critical



A materials supply and cost challenge for EVs

Increased materials cost and supply constrains



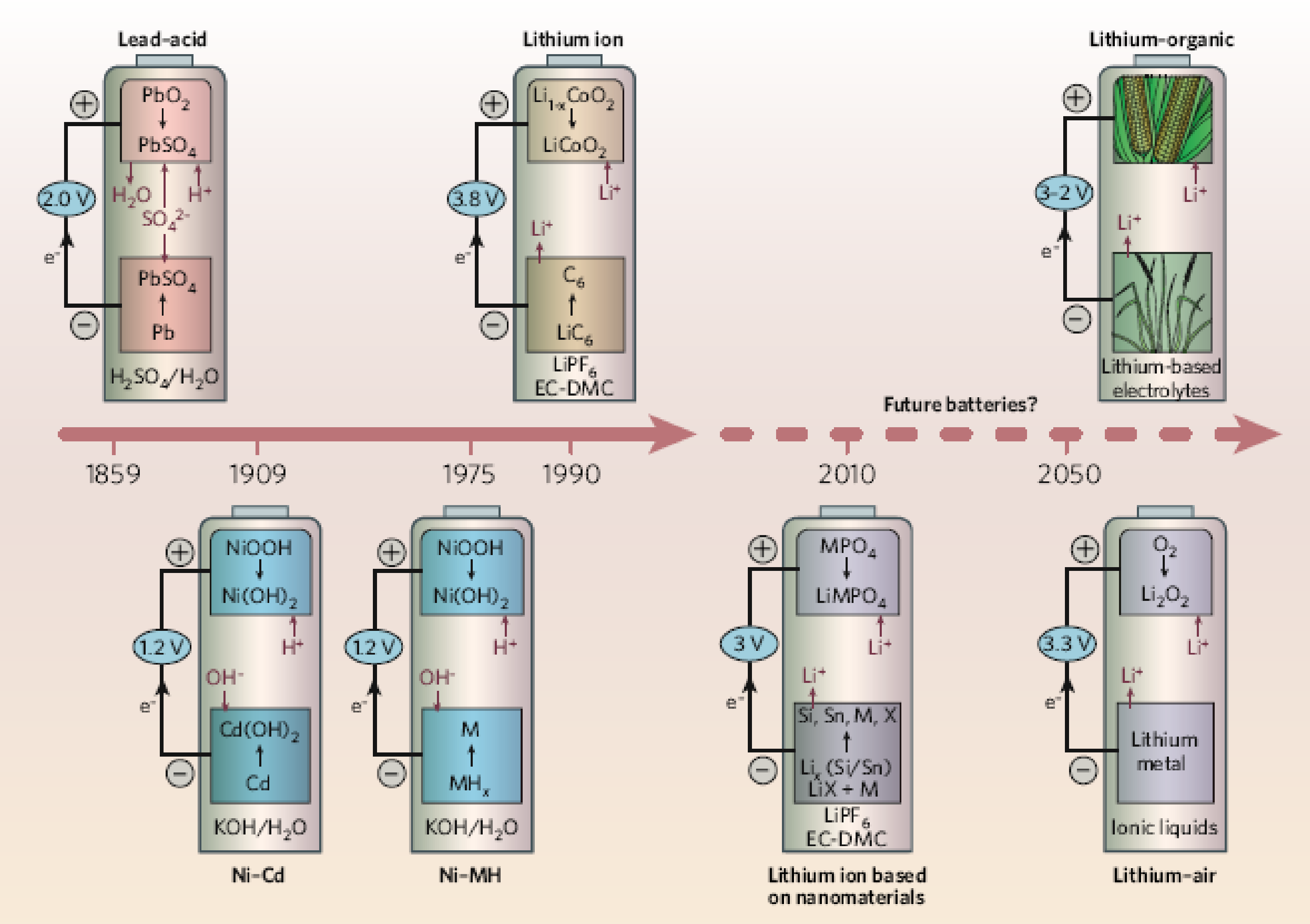
TOP 20 BEST SELLING ELECTRIC CARS IN 2021 AND THE RISE IN PRICE OF THE GRAPHITE, LITHIUM, COBALT AND MANGANESE USED IN THEIR BATTERIES

	Model	Sales	C ($)	Li ($)	Ni ($)	Co ($)	Mn ($)	Per Car 2021 ($)	Per Car 2020 ($)
1.	Tesla Model 3	418.7K	18.4M	393.6M	255.6M	72.7M	1.6M	1,772	847
2.	Wuling Hongguang MINI	343.7K	3.2M	62.2M	12.1M	15.6M	2M	277	108
3.	Tesla Model Y	327.3K	16.3M	372.4M	313.2M	94.1M	3.2M	2,442	1,237
4.	Volkswagen ID.4	102.8K	5.8M	129.4M	106.9M	46.7M	6.5M	2,873	1,445
5.	BYD Han EV	76.6K	5.1M	87.1M	-	-	-	1,204	342
6.	Volkswagen ID.3	67.8K	3.3M	74.7M	58.9M	27.1M	4.5M	2,486	1,236
7.	Changan BenBen e-Star	66.1K	1.6M	38.8M	17.9M	23.1M	3M	1,280	587
8.	Renault Zoe	65.7K	2.7M	62M	48.6M	22.4M	3.9M	2,124	1,054
9.	Chery eQ1	64.9K	1.7M	37.2M	14.3M	18.6M	2.4M	1,143	507
10.	Kia Niro	59.2K	2.5M	60.3M	40.6M	43.7M	3.8M	2,550	1,253
11.	Great Wall ORA Euler R1	55.4K	1.4M	34M	17.1M	22.1M	2.9M	1,397	651
12.	Hyundai Kona	55K	2.3M	55.4M	37.3M	40.2M	3.5M	2,520	1,239
13.	Nissan Leaf	55K	2.1M	54.4M	30.6M	39.6M	5.1M	2,398	1,140
14.	Roewe Clever EV300	53.6K	1.1M	26.3M	16.2M	14.3M	2.5M	1,128	538
15.	Xpeng P7	53.1K	3.1M	67.4M	46.7M	29.5M	3.2M	2,822	1,378
16.	BYD Qin Plus	49.2K	2.5M	42.4M	-	-	-	913	259
17.	Ford Mustang Mach-E	49.1K	3.2M	73.3M	57.4M	26.5M	4.6M	3,361	1,669
18.	GAC Aion S	46.6K	2.1M	51.4M	26.3M	33.8M	4.4M	2,530	1,182
19.	Hozon Neta V	44.4K	1.2M	27.8M	14.2M	14.4M	2.2M	1,349	624
20.	Audi e-tron Quattro	43.6K	2.8M	67.3M	45M	48.7M	4.3M	3,861	1,895

Source: **Adamas Intelligence** Battery Capacity & Battery Metals Tracker Registrations light duty vehicles in 100+ countries Jan to end-Nov 2021 Graphite, Lithium Carbonate Equivalent (LCE), Cobalt Sulphate (100% basis), Nickel Sulphate (100% basis) prices: **Benchmark Mineral Intelligence** Dec 2021/2020. Manganese Sulphate (100% basis): Asian Metal Dec 2021/2020

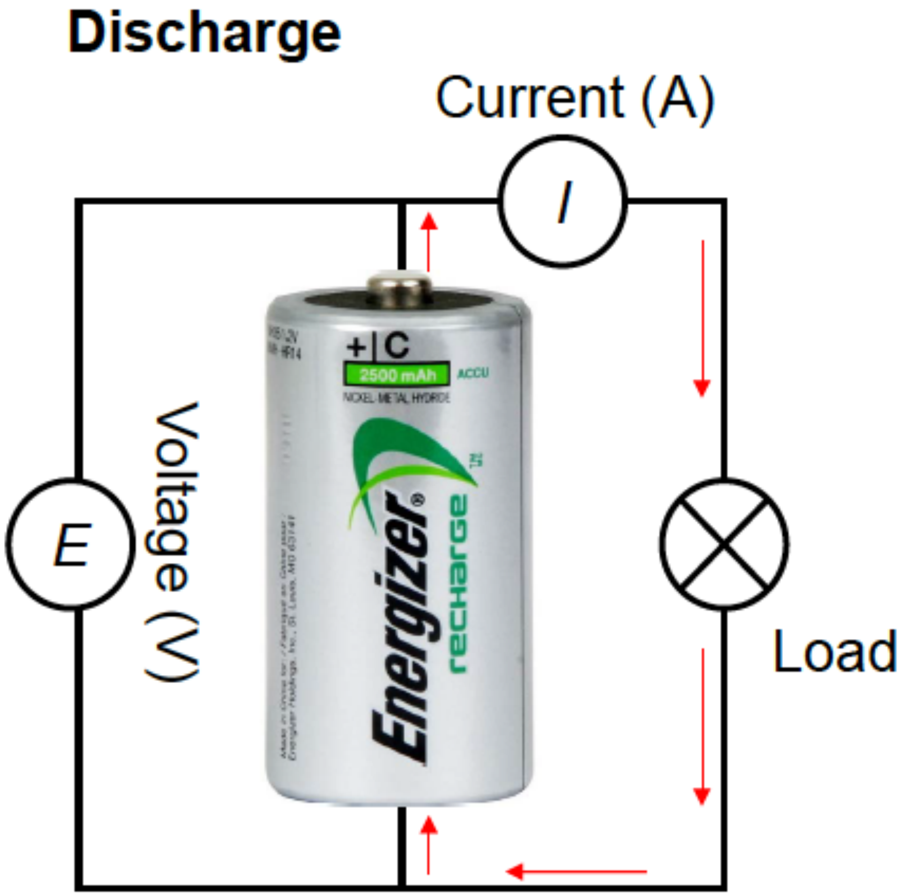
MINING [DOT] COM EV METAL INDEX

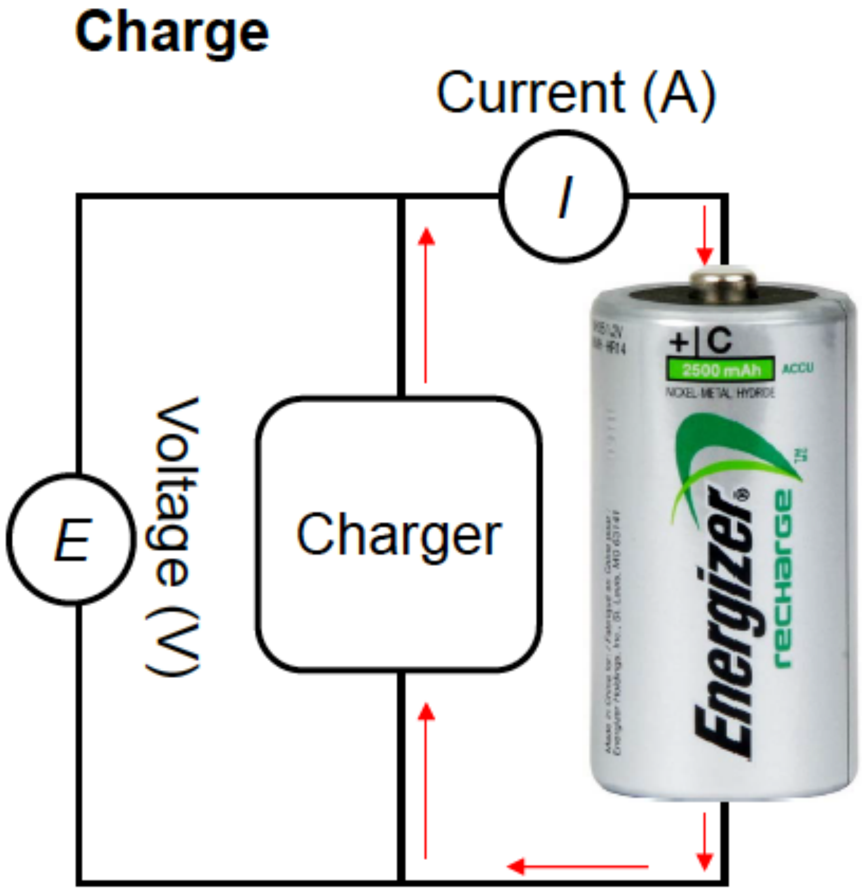
150 Years of Battery Development



Armand and Tarascon, Nature 451, 652 (2008)

Potential, current and energy

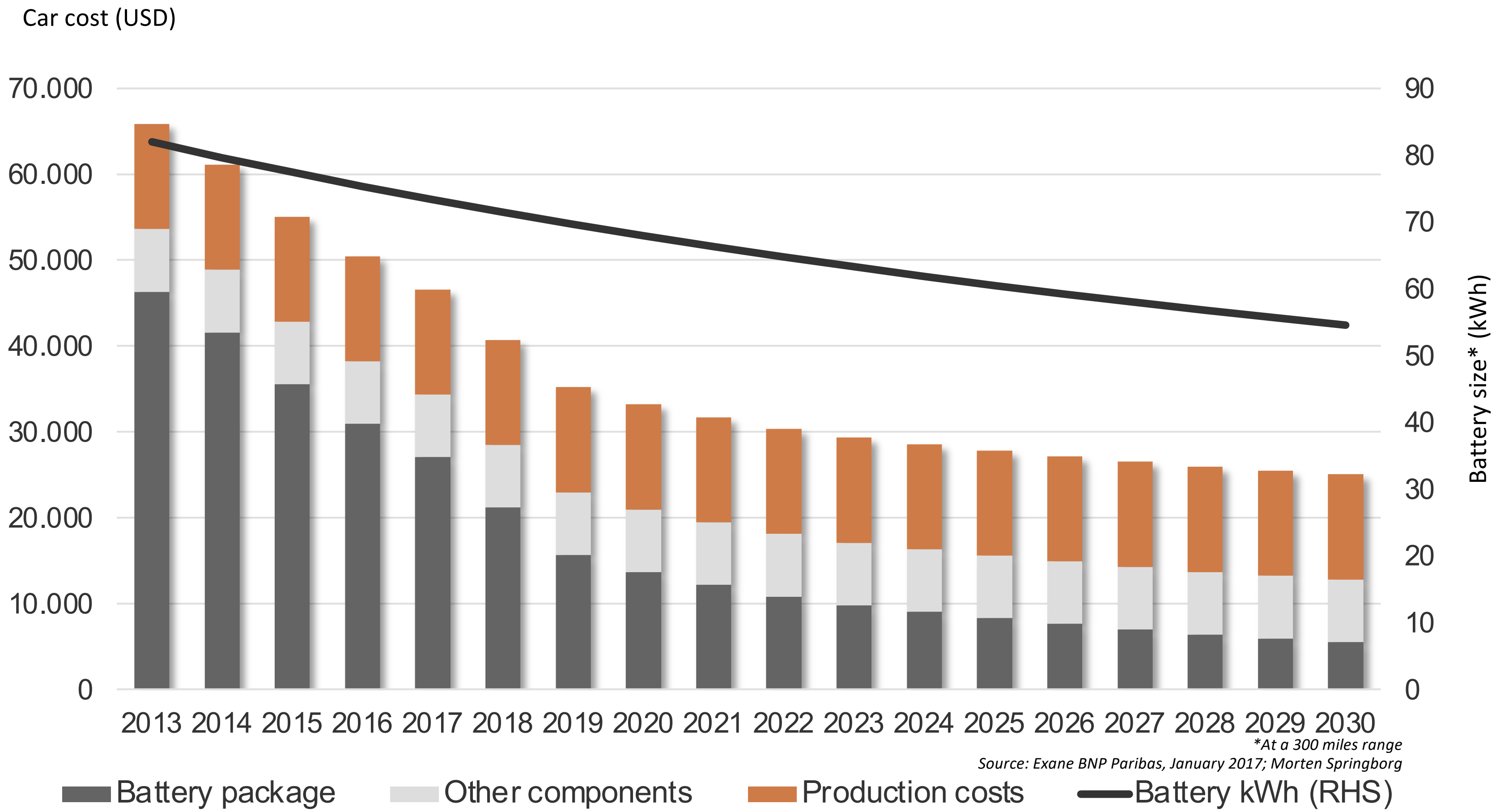




Power (W): $P = I \cdot E$ (current · voltage)
Energy (J): $W = I \cdot E \cdot t$ (current · voltage · time)
Charge (C): $Q = I \cdot t$ (current · time)

Which are the key parameters?

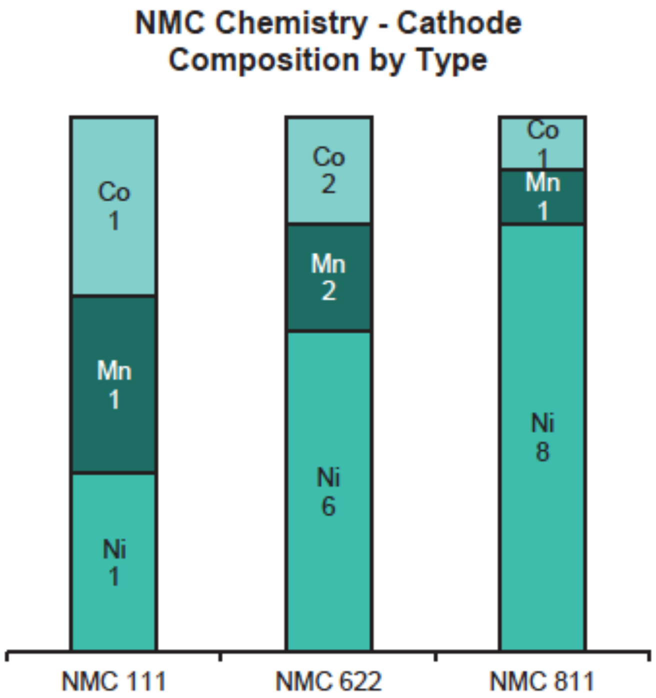
E-mobility: EV cost breakdown

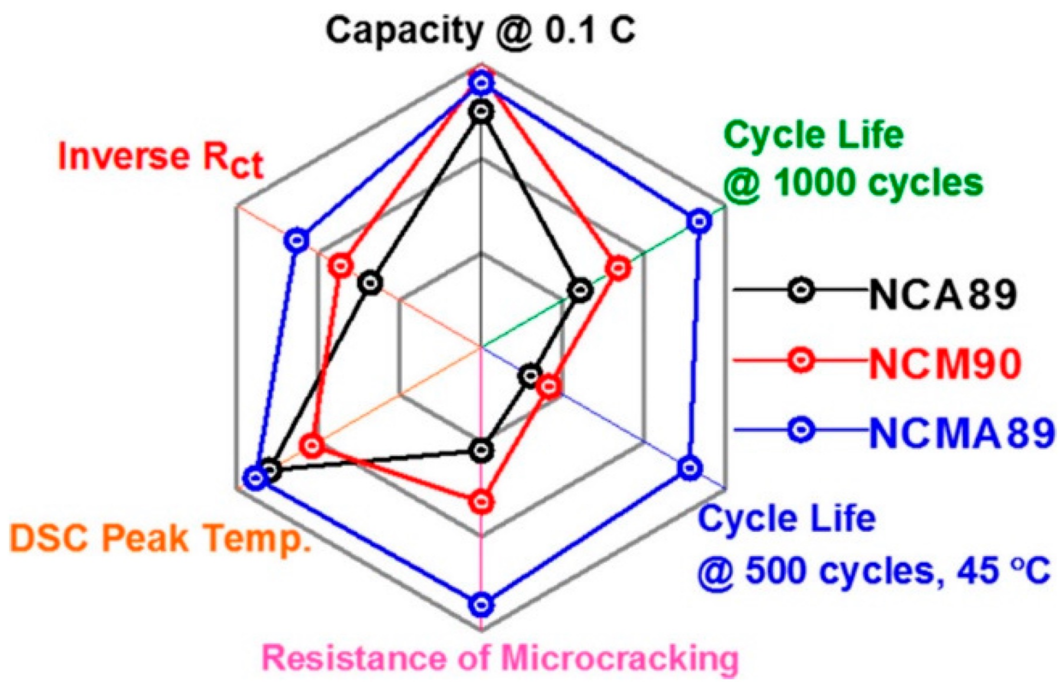


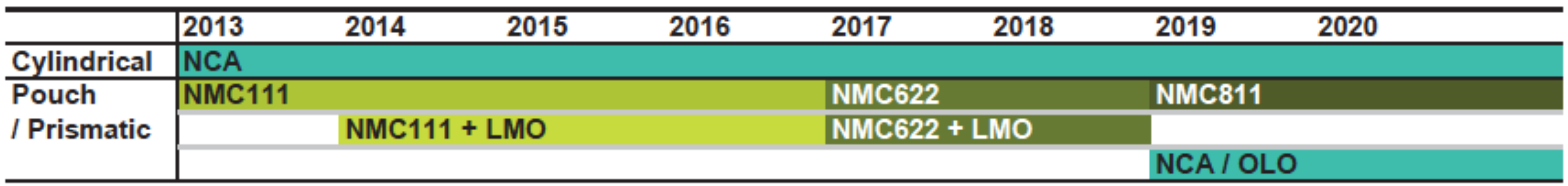
Developments - largely a question of scale…

Next generation NMC/NCA batteries

- ”Old” chemistries like $LiFePO_4$ are resurfacing







Source: SNE Research and Bernstein analysis.

Myung et al., ACS Energy Letters 2, 196 (2017)

Production of battery materials

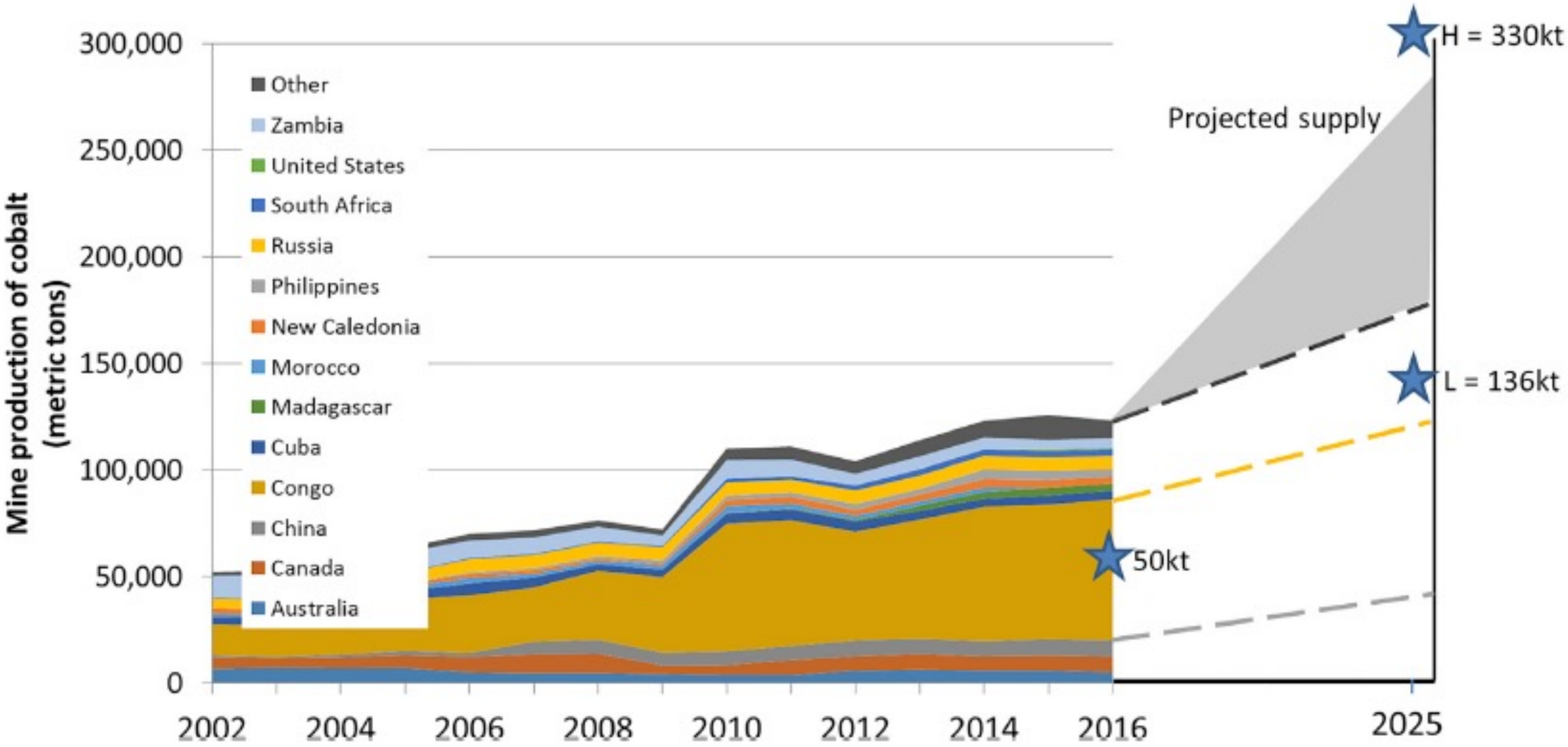
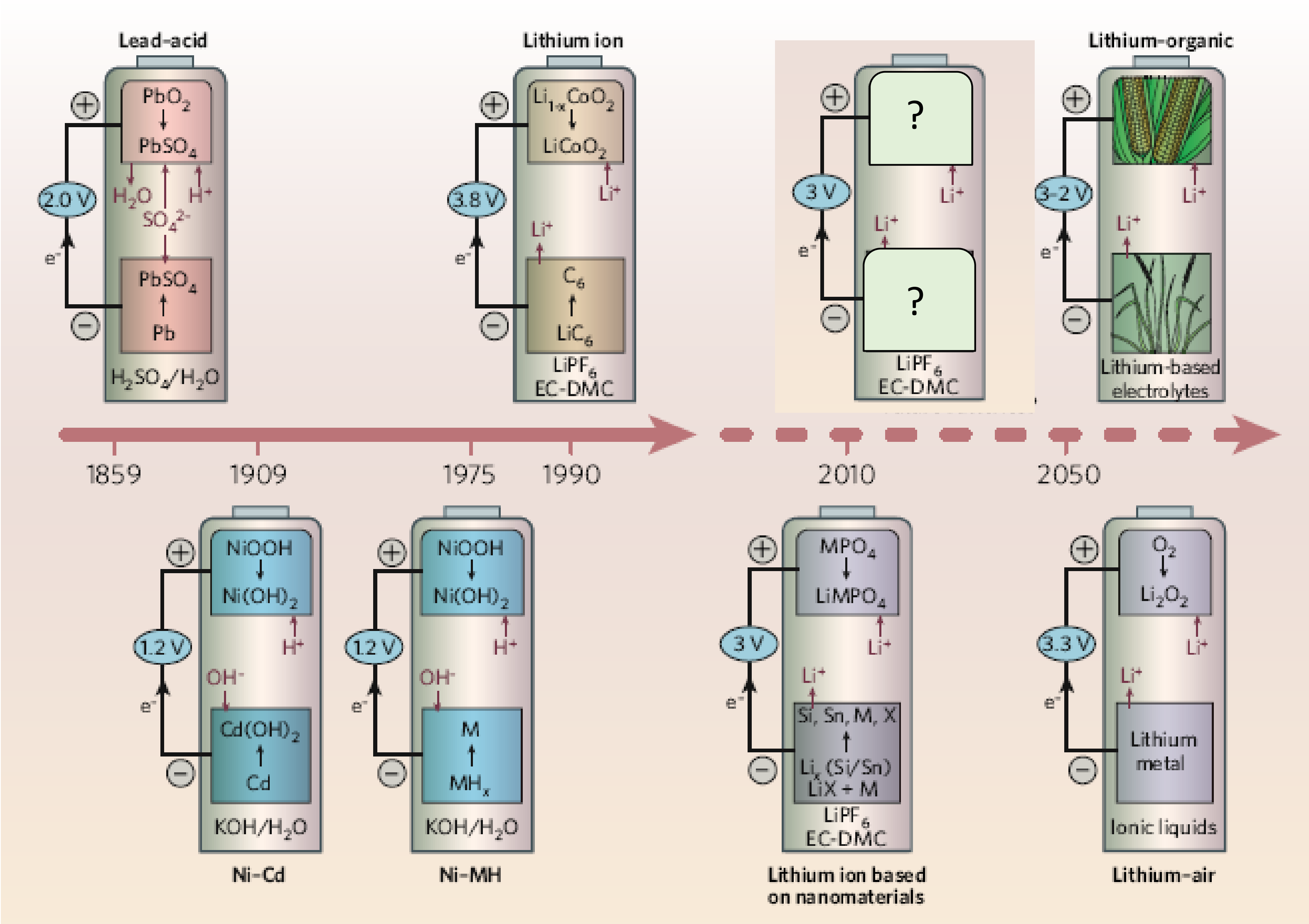


Figure 4. Cobalt Use in LIBs Including Historic Supply Broken Down by Country and Projected Supply Overlaid with Current and Projected Demand
Stars show the demand in tonnes in 2016 and the L and H scenarios in 2025. Dashed lines show supply projections based on published capacities and capacity expansions. Shaded supply shows linear growth in supply.

Olivetti, Ceder, Gaustad, Fu, Joule 1, 229–243 (2017)

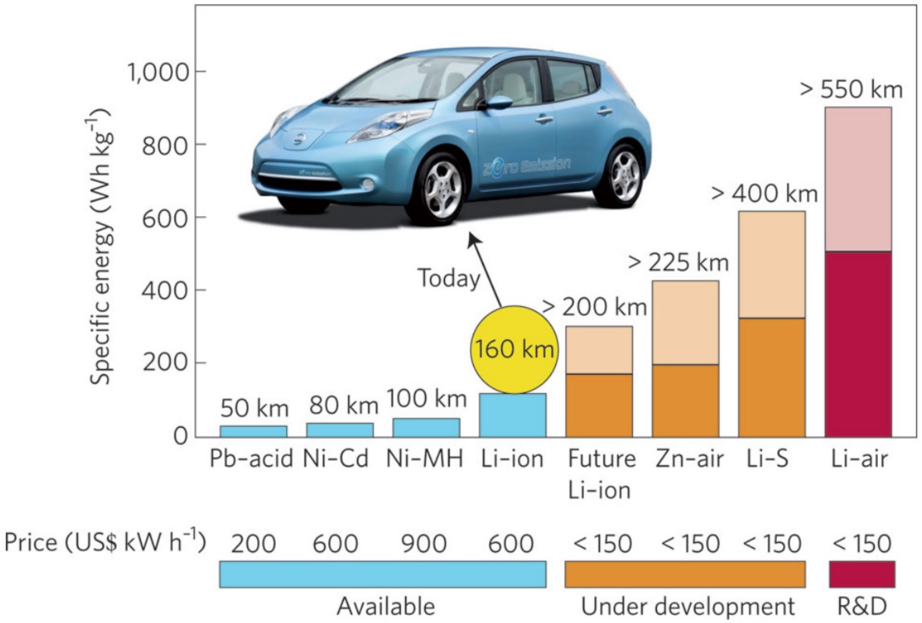
Future battery chemistries

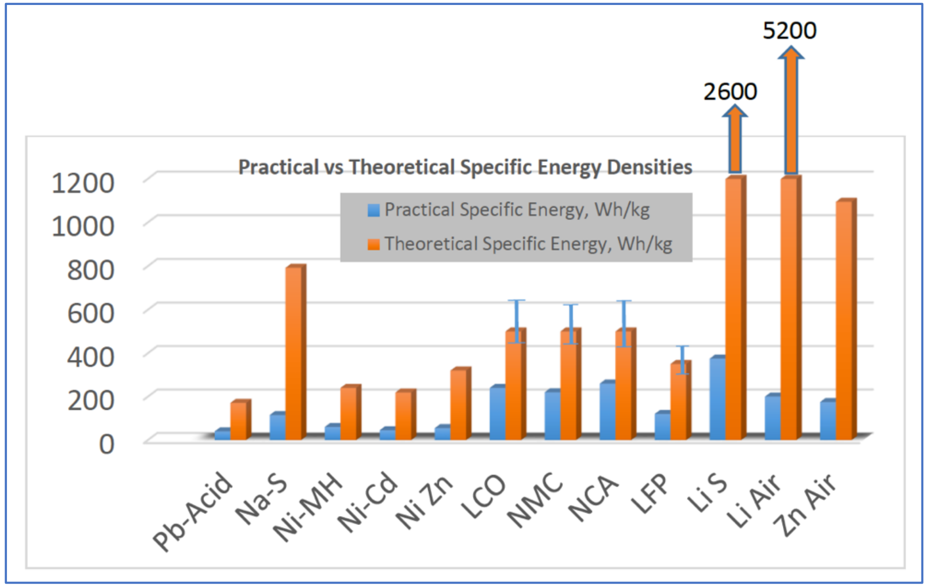


Armand and Tarascon, Nature 451, 652 (2008)

Electrifying the automotive industry

- Disruption calls for new battery concepts, e.g., for compact cars



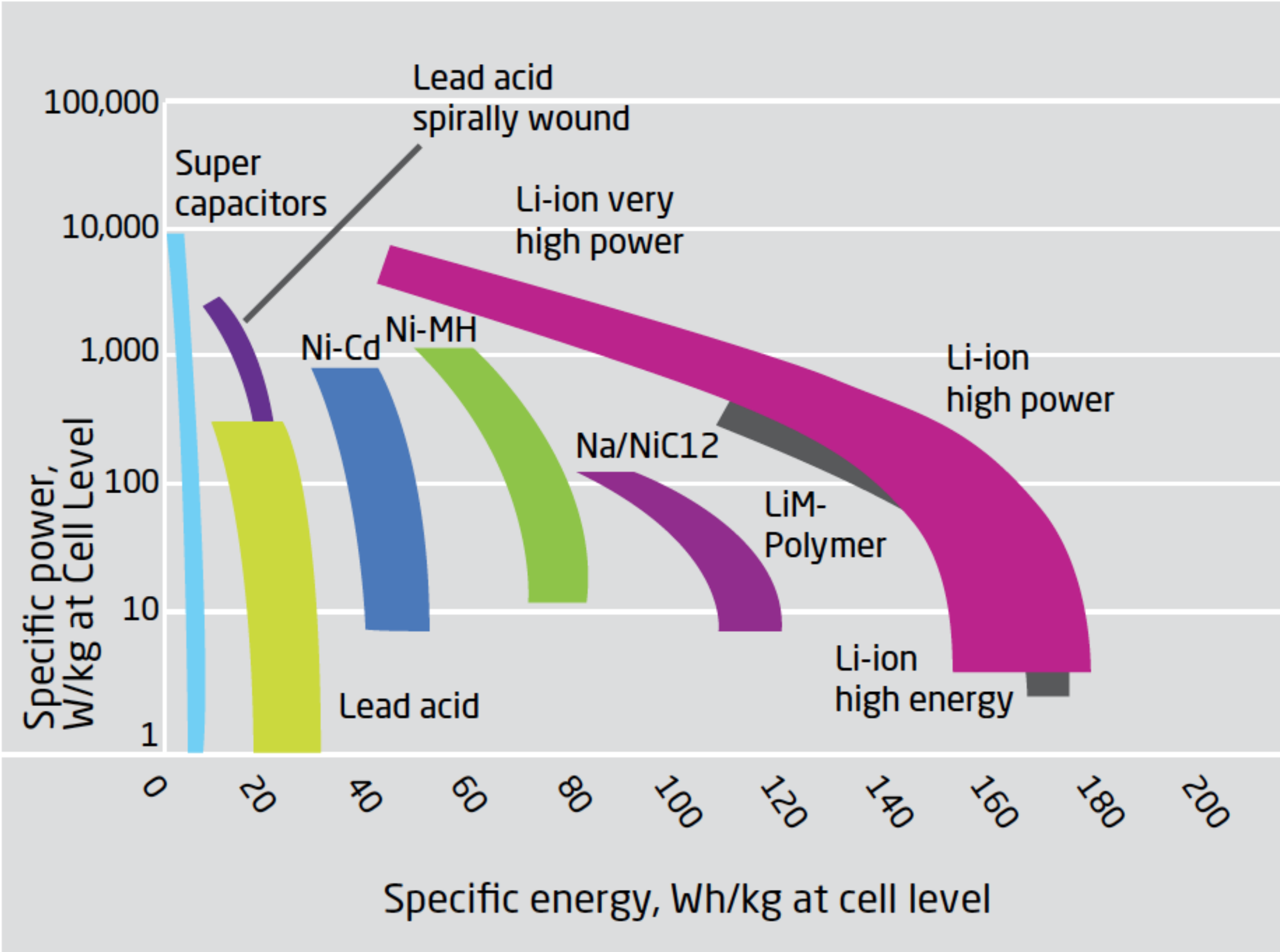


Bruce, Freunberger, Hardwick, Tarascon, Nature Materials 11, 19 (2012)

Edström, Dominko, Fichtner, Otuzewski, Perraud, Punckt, Tarascon, Vegge, Winter, BATTERY 2030+ Roadmap (2020)

Specific Energy and Specific Power

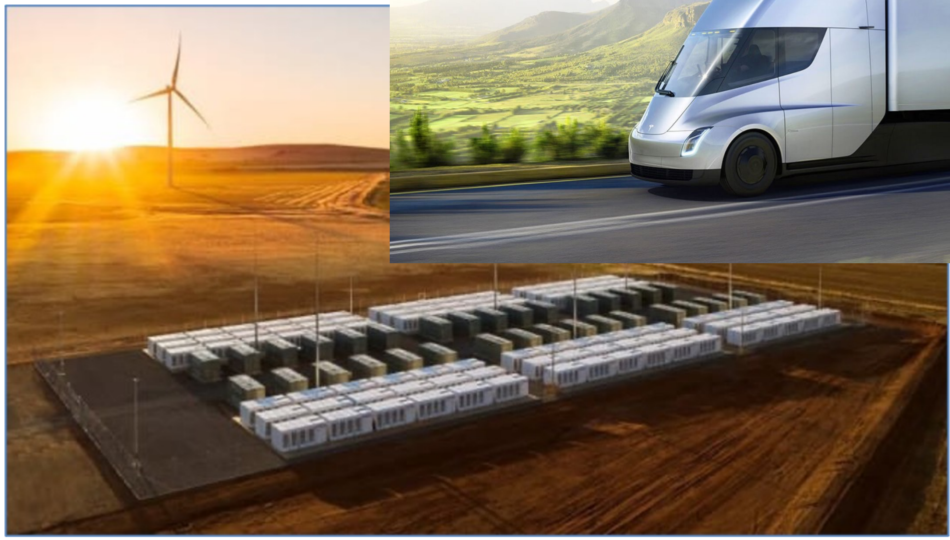
Strong correlation between specific energy and specific power



Vegge, Nordby and Edström, DTU International Energy Report (2014)

Emerging battery markets

- Stationary storage and heavy transport
- Challenges: high power, ultra-fast charging, high energy density, and high durability



Source: Wright Electric

Battery-based heavy transport?

- Can you name some key battery challenges here?
- 1st Delivery of Tesla's class 8 truck in December 2022
- 500-miles, dual-motor, charging to 70% in 30 min. (1MW)

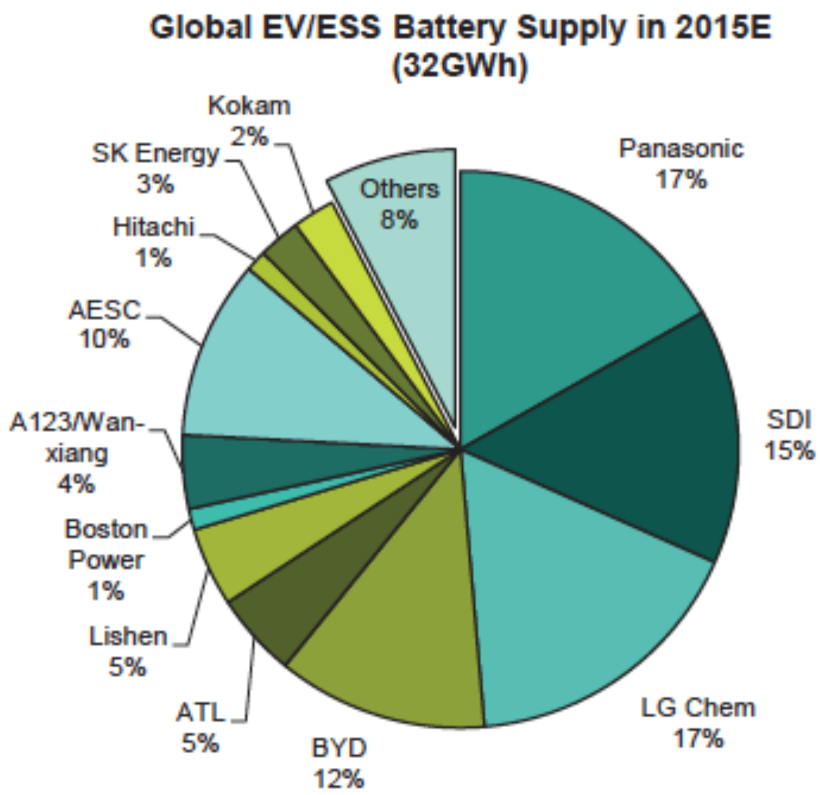
Battery-based heavy transport?

- And here?
- 4 MWh batteries and 57 ton; Each trip uses about 1,175 kWh
- Recharged when docked at 10.5 MW (10.5 kV, 600 Ampere) for 6 minutes in Denmark and 9 minutes in Sweden

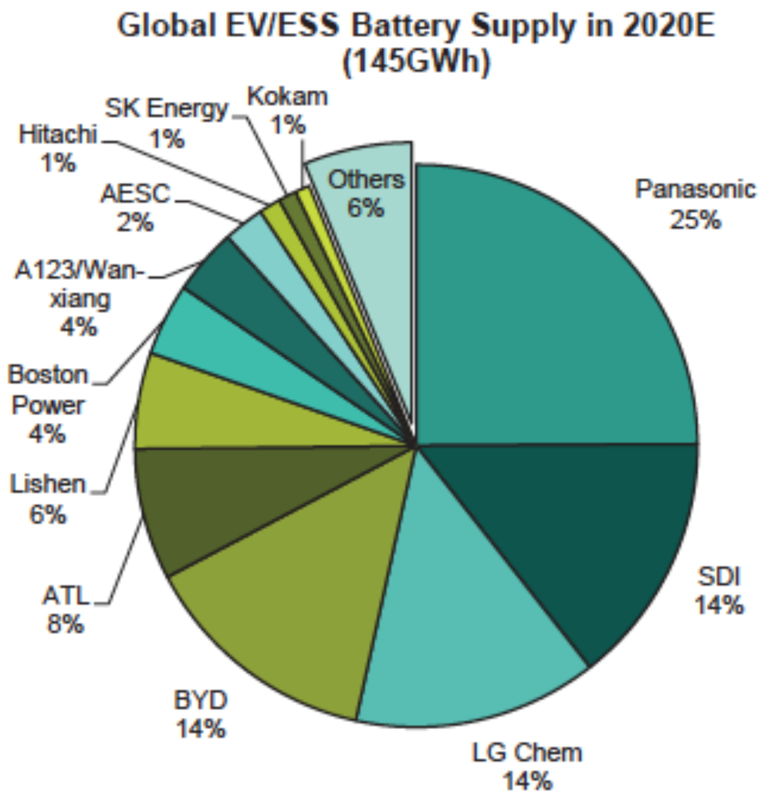
Battery-based heavy transport?

- Challenges?

Domestic European battery cell production?



Source: Gartner, and Bernstein estimates and analysis.



Source: Bernstein Asia Strategy team.

Domestic European battery cell production

- Identifying and/or creating a European advantage/edge
- Scalable and sustainable, low-carbon footprint batteries
- Going beyond existing Li-ion technologies
- More about this later…