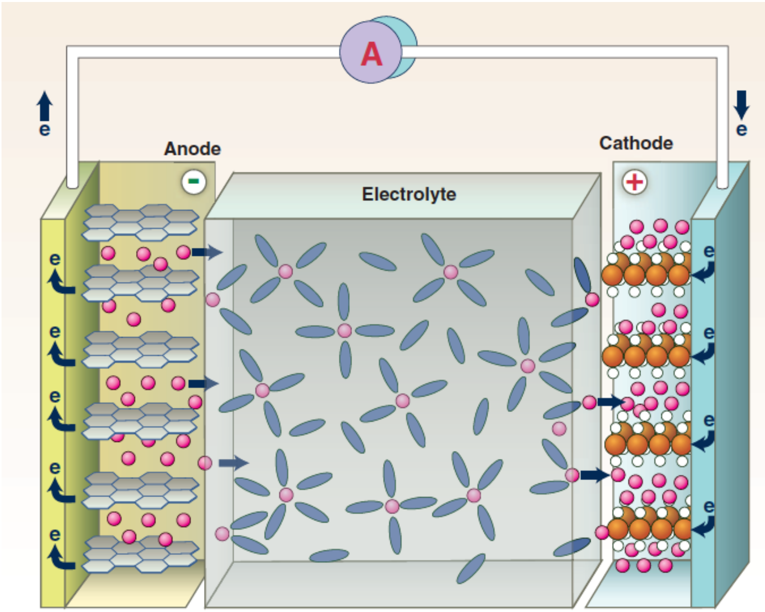
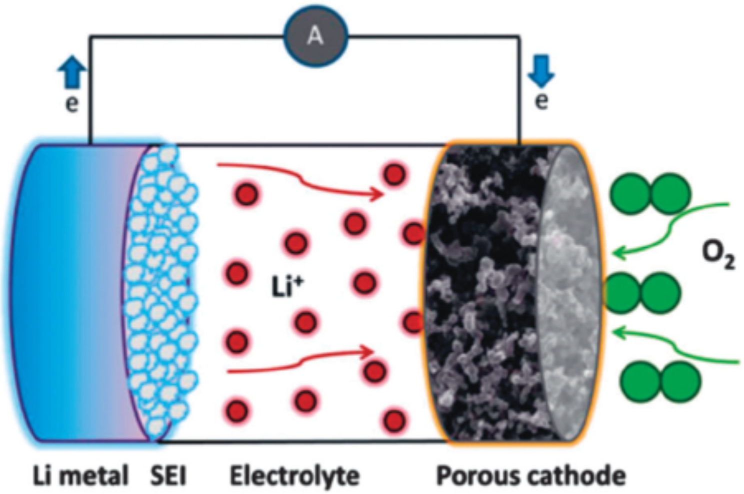
Electricity Storage in Batteries
- *Status and Perspectives*





Tejs Vegge

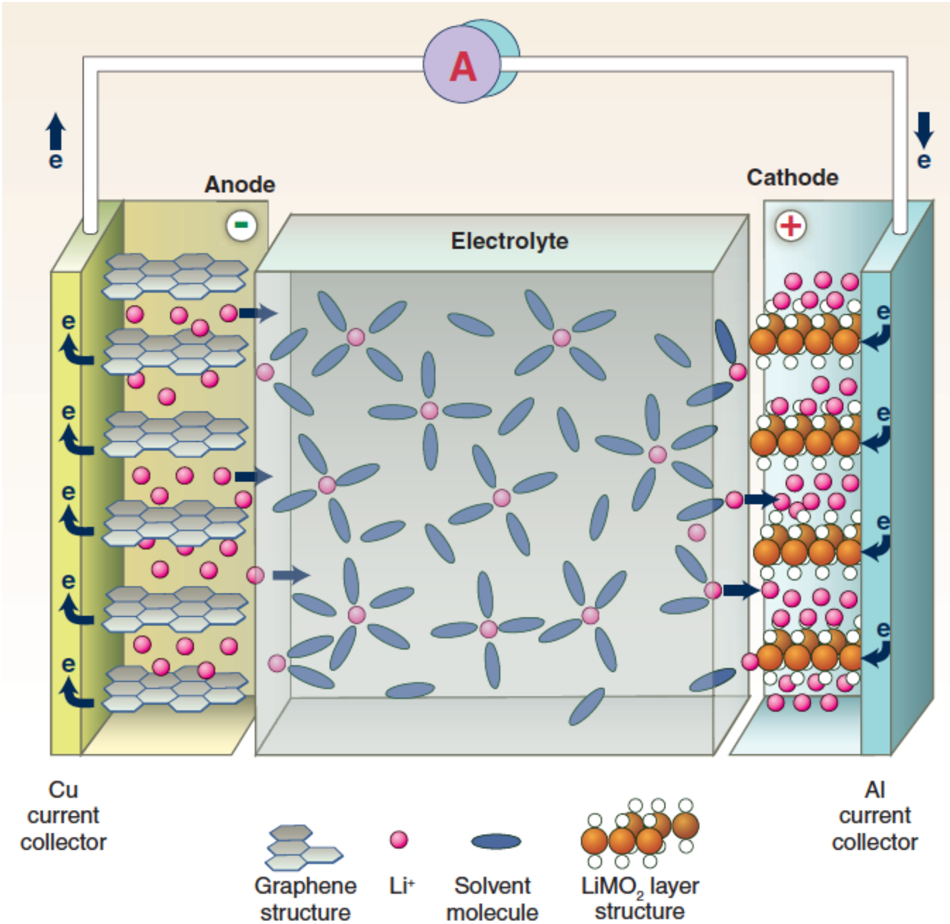
Atomic Scale Modeling and Materials

DTU Energy

DTU Energy
Department of Energy Conversion and Storage

A 60-second Guide to Batteries

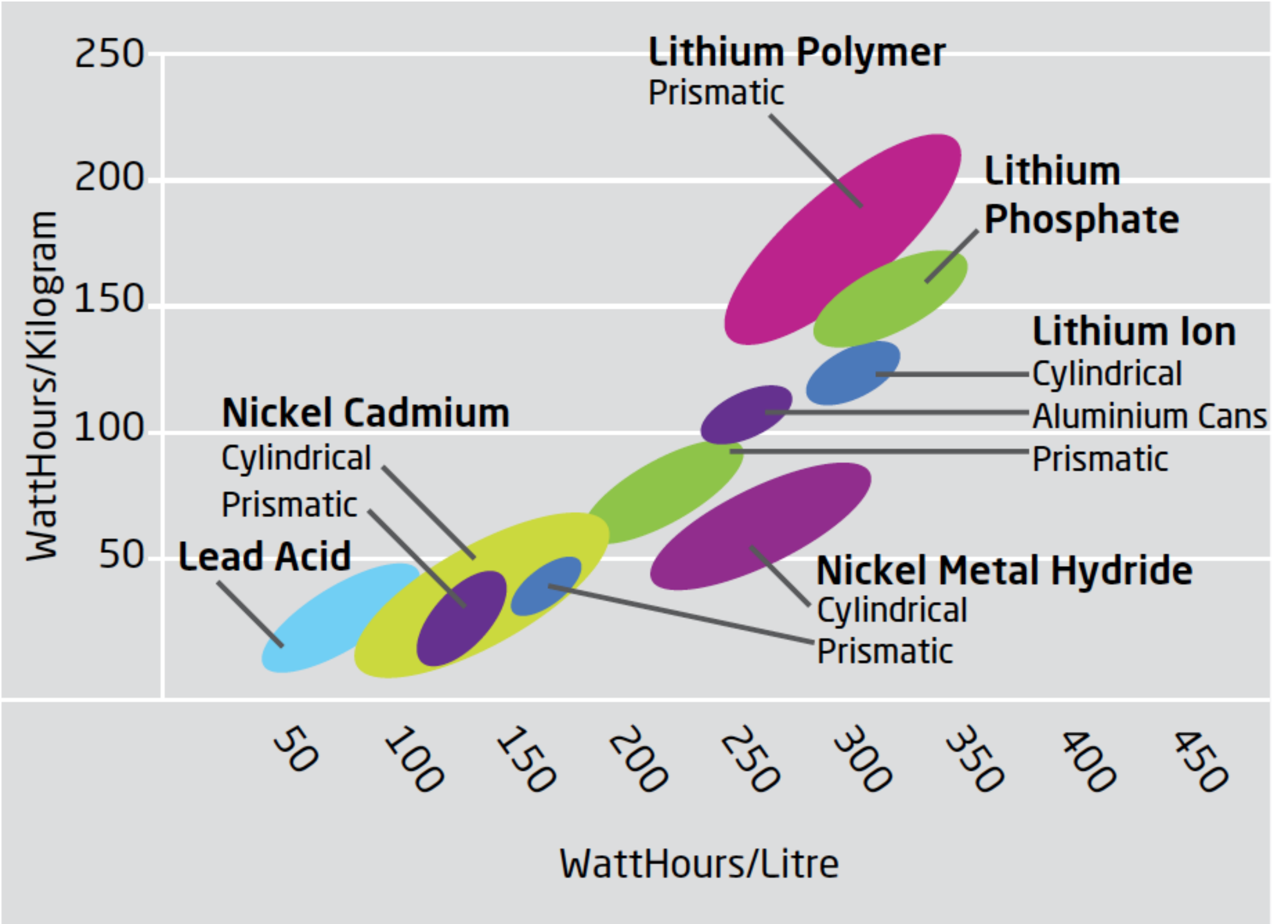
- Efficient electrochemical energy storage device
- Separation of electrons and ions
  - Negative electrode (anode)
  - Positive electrode (cathode)
- Primary batteries
- Secondary batteries
- Negative electrode in Li-ion
  - graphite Li_xC_6 (372 mAh/g)
- Positive electrode in Li-ion
  - $Li_{1-x}MO_2$ (120-170 mAh/g)
- Electrolytes
  - Li-salts: $LiPF_6/LiBF_4$ in solution
  - conducting polymers



Dunn, Kamath, Tarascon, Science 334, 928 (2011)

Specific Energy and Energy Density

- Specific energy remains very low compared to chemical fuels



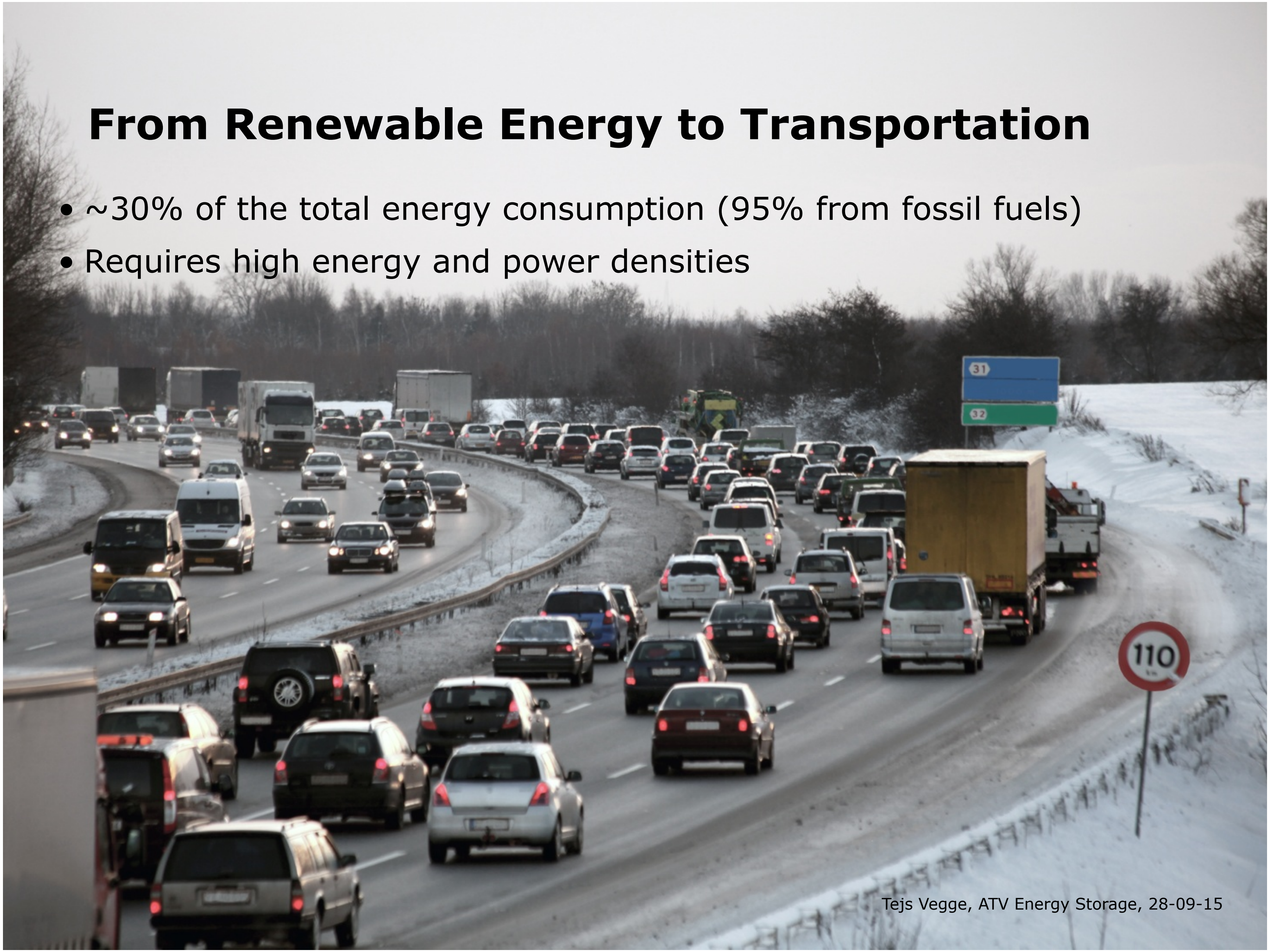
Vegge, Nordby and Edström, DTU Int. Energy Rep. (2014)

Battery Applications and Requirements

- Portable electronics
  - High specific energy (Wh/kg)
  - Fast charge
- Power tools
  - Medium power density (W/kg)
- Transportation
  - High power and energy density
  - Safety and durability
- Stationary / grid-scale storage
  - Cheap and earth-abundant
  - Efficiency and durability
  - Fast charge and discharge
- Different requirements for different applications
  - Cost is always an issue

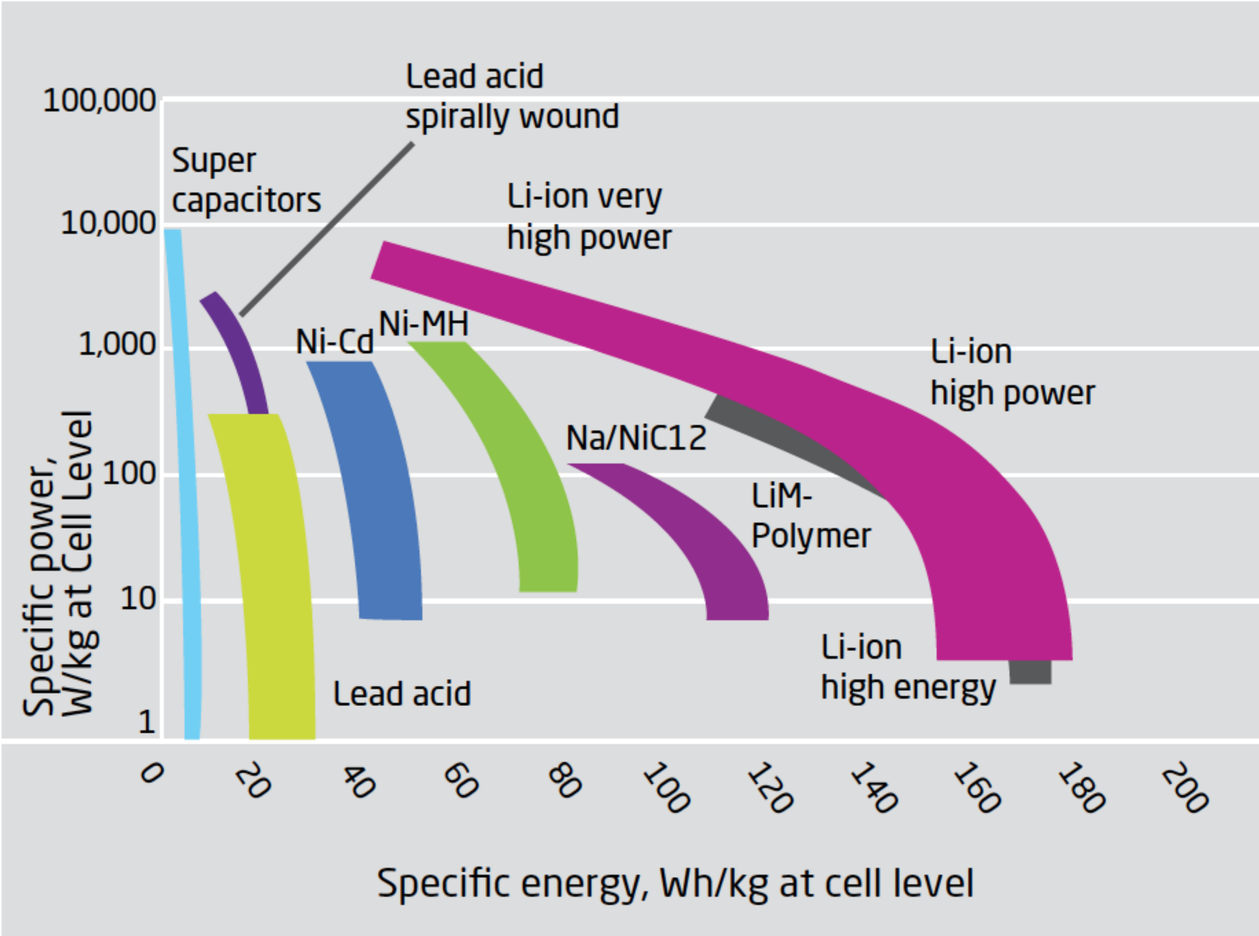
From Renewable Energy to Transportation

- ~30% of the total energy consumption (95% from fossil fuels)
- Requires high energy and power densities



Specific Energy and Specific Power

- Strong correlation between specific energy and power



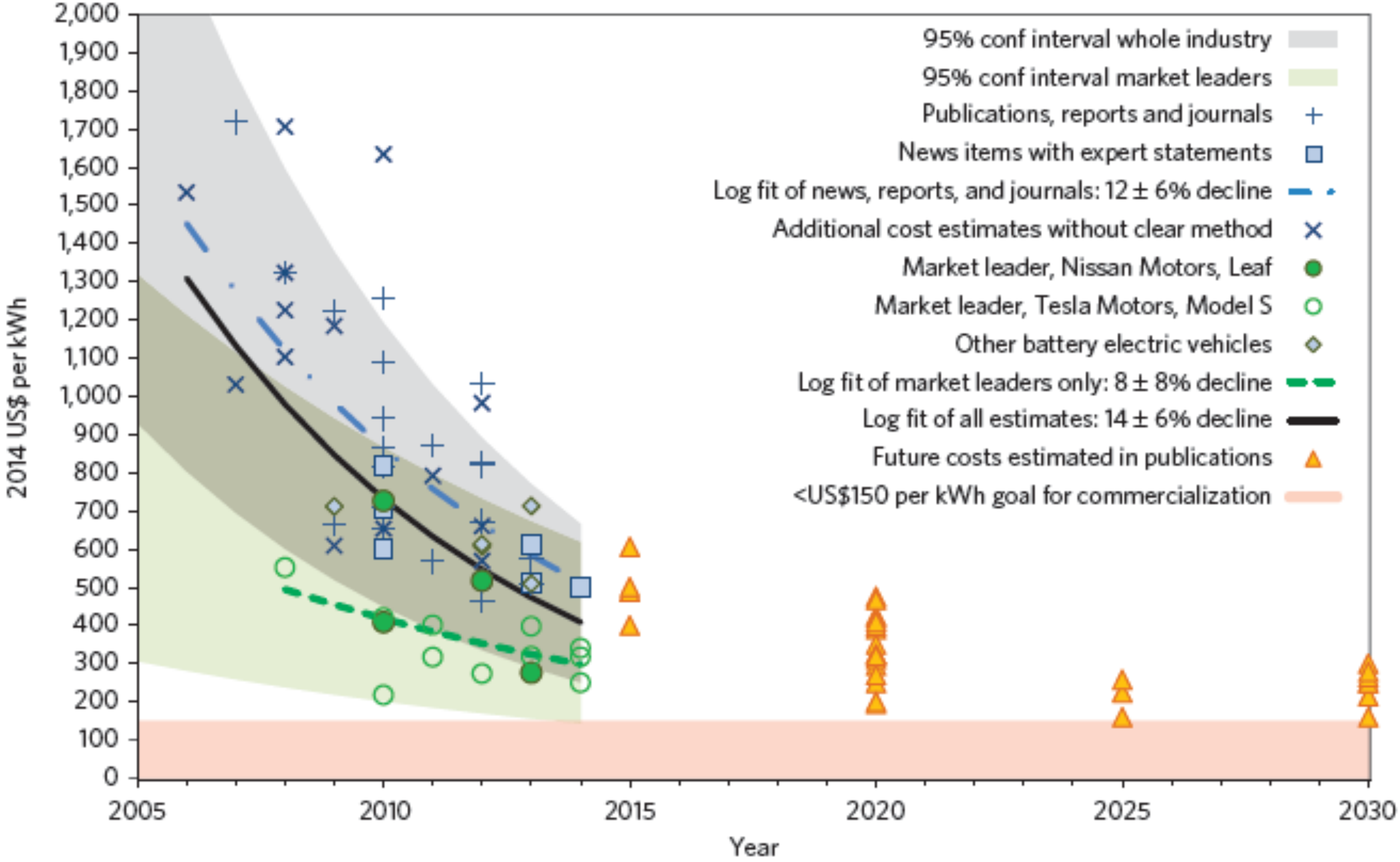
Vegge, Nordby and Edström, DTU Int. Energy Rep. (2014)

Are Batteries for Transportation already there?

- A Tesla S provides a range of 420-500 km
- The cost - without tax incentives – is very high

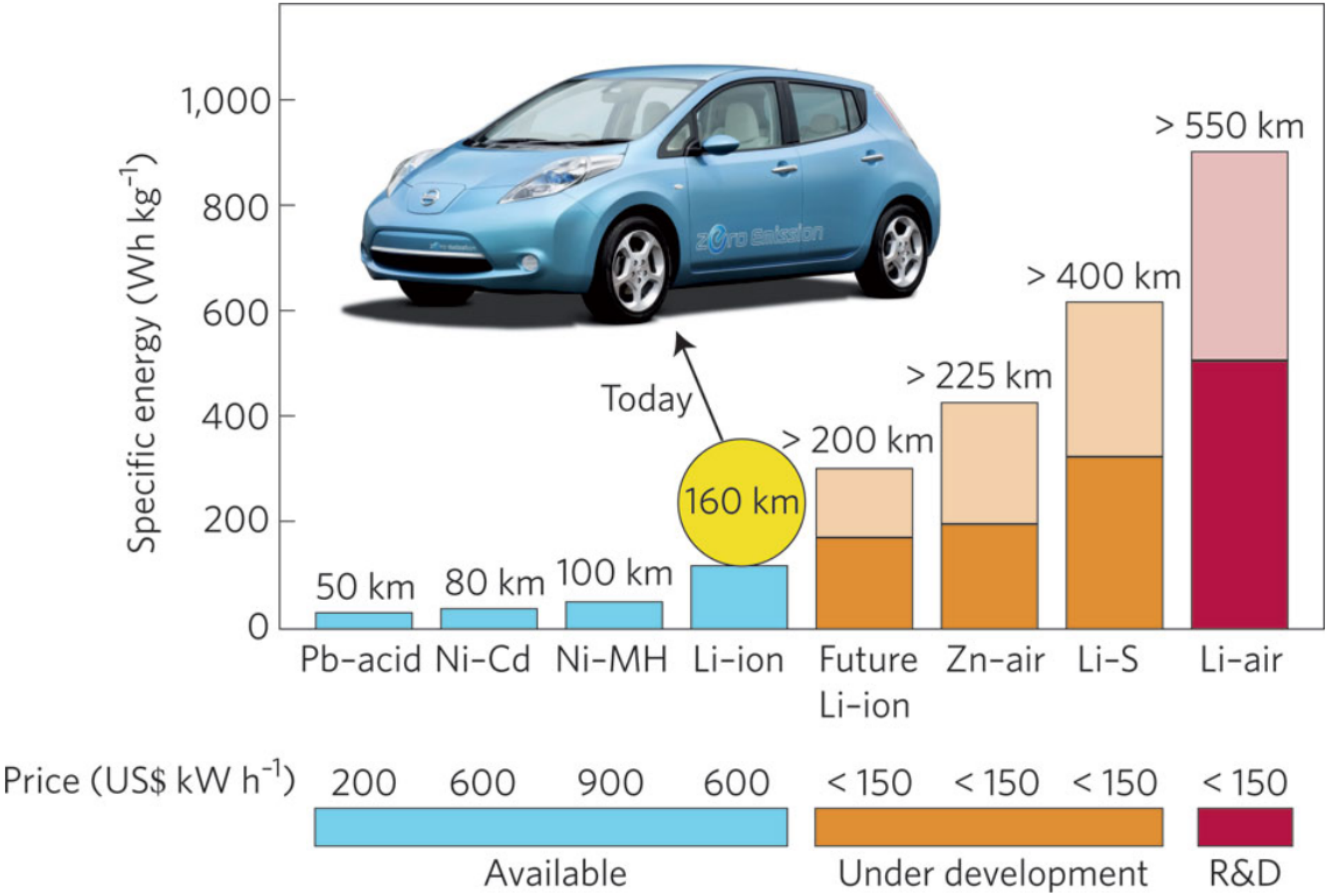
Tesla Motor (2015)

Cost of Li-ion Battery Packs for EV



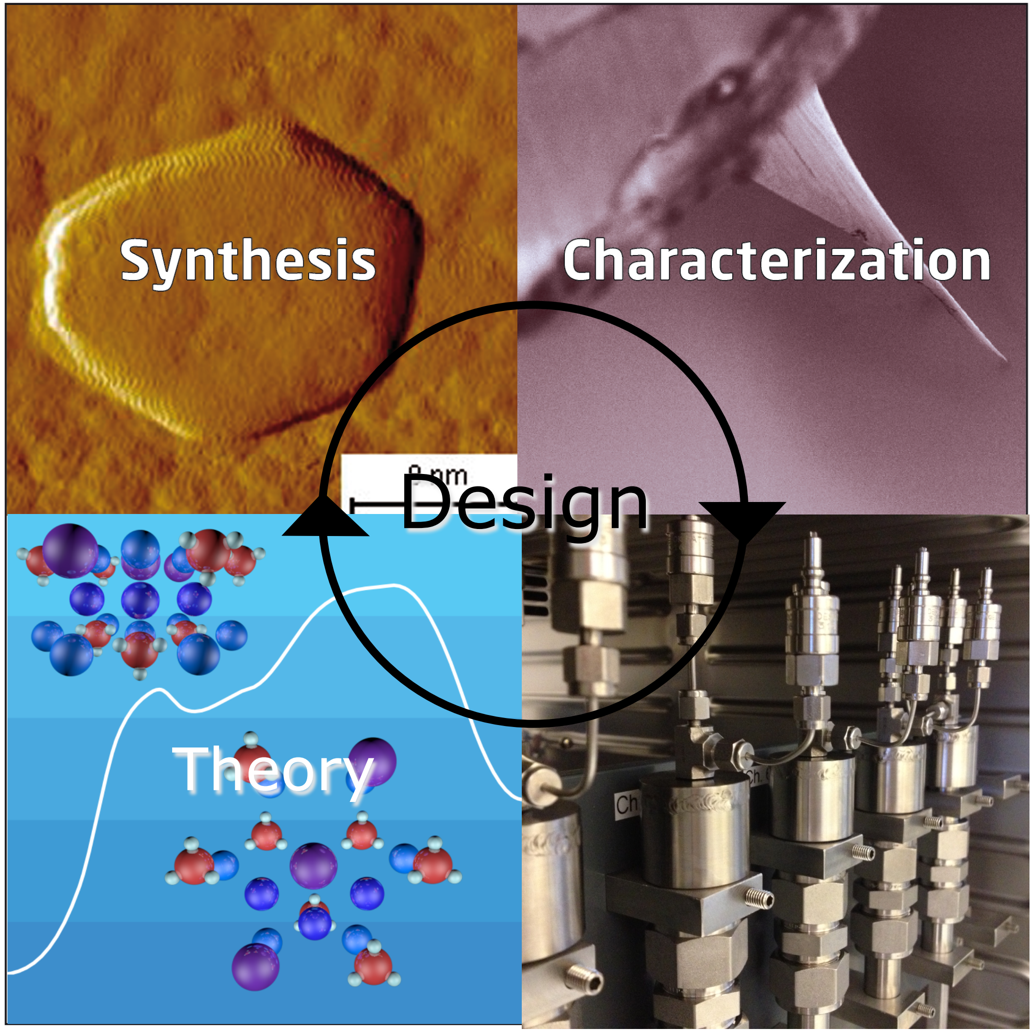
Nykvist and Nilsson, Nature Climate Change 5, 329 (2015)

Beyond Li-ion Batteries



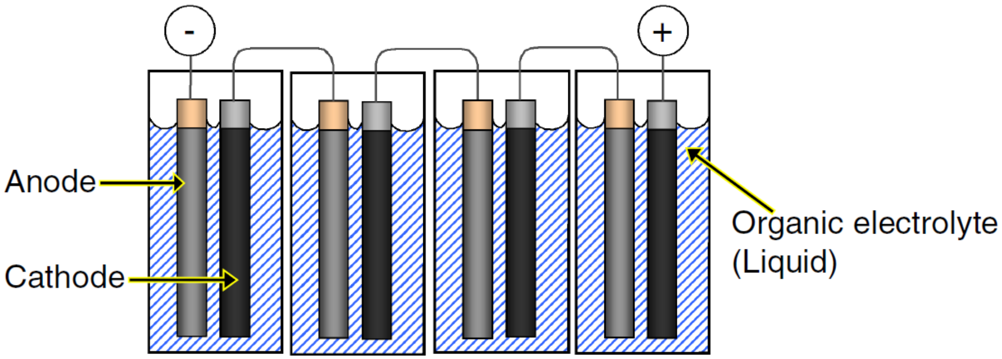
Bruce, Freunberger, Hardwick, Tarascon, Nature Materials 11, 19 (2012)

Design Loop for new Battery Materials

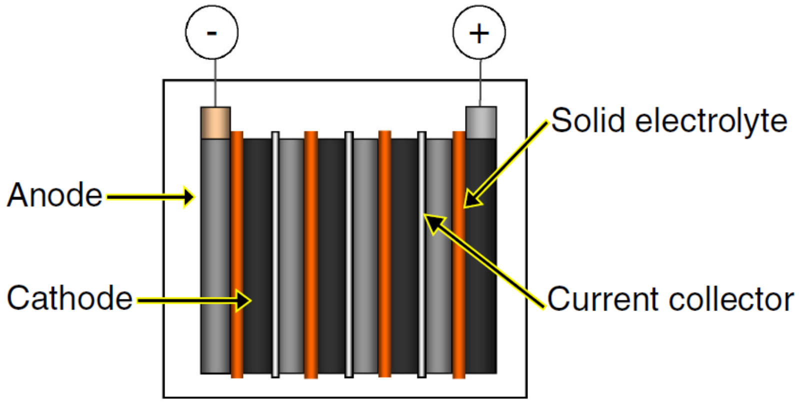


Solid-state Battery Electrolytes

- Improved energy and power density, e.g. lithium metal anode, high voltage cathodes and thinner electrolytes
- Safety is essential for transportation applications



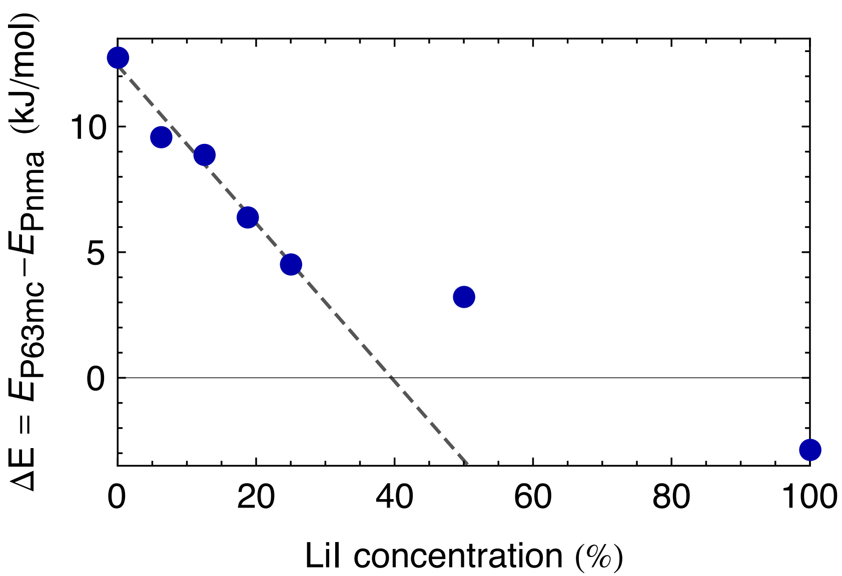
(A) Liquid type battery

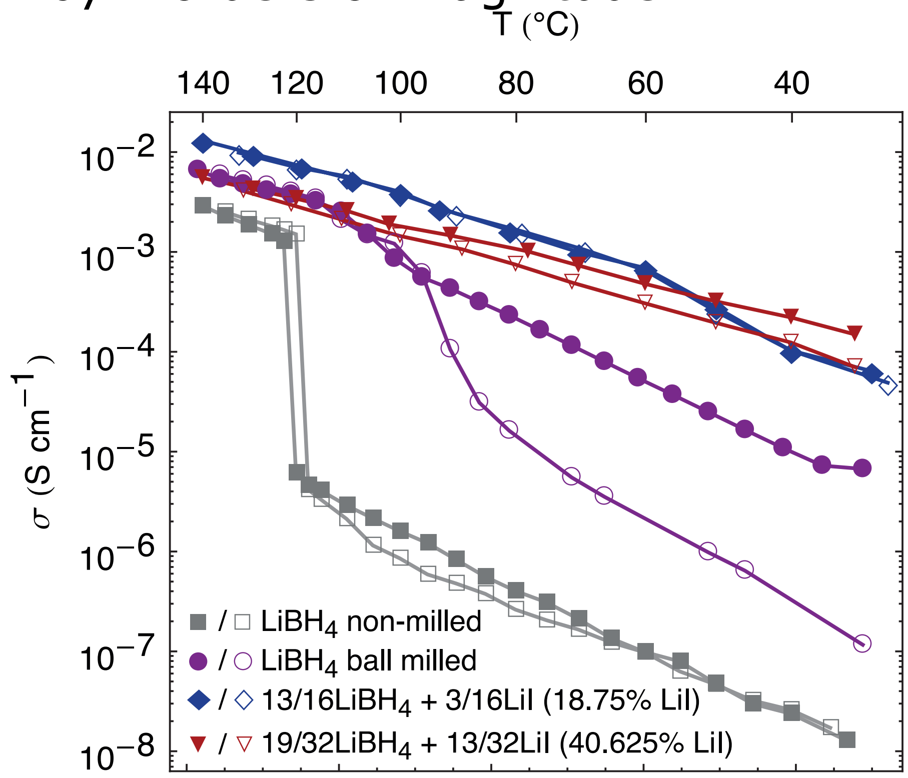


(B) All-solid-state battery

Designing Solid-state Li-battery Electrolytes

- The Li-ion conduction is generally too low at RT ($<10^{-2}$ S cm^{-1})
- Superionic Li-ion conduction in $LiBH_4$, but only above 110 °C
- Use calculations to identify substitutional elements and concentrations
- Enhances the RT Li-ion conduction by 4 orders of magnitude

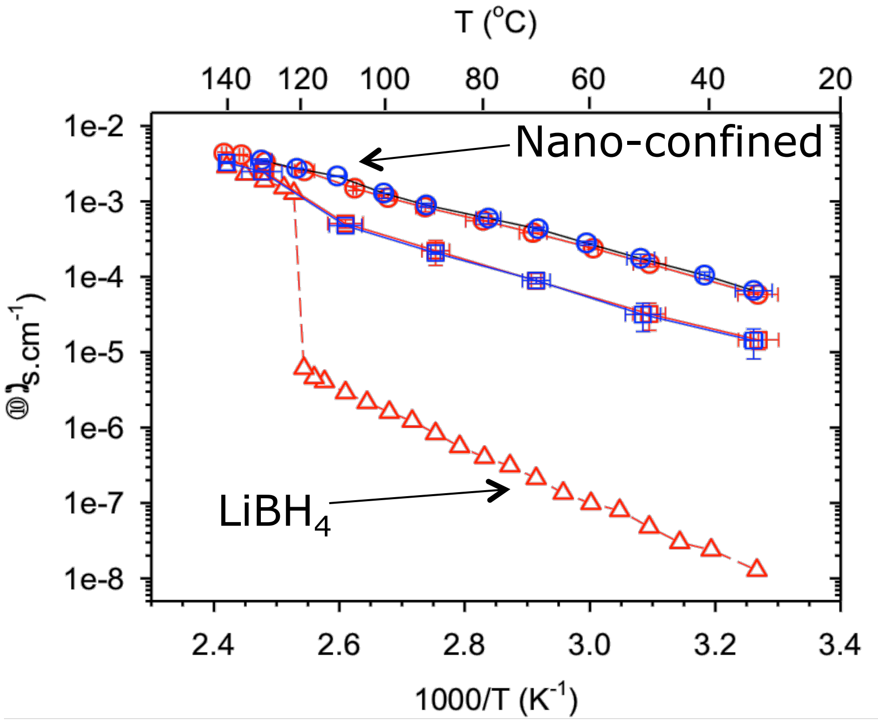


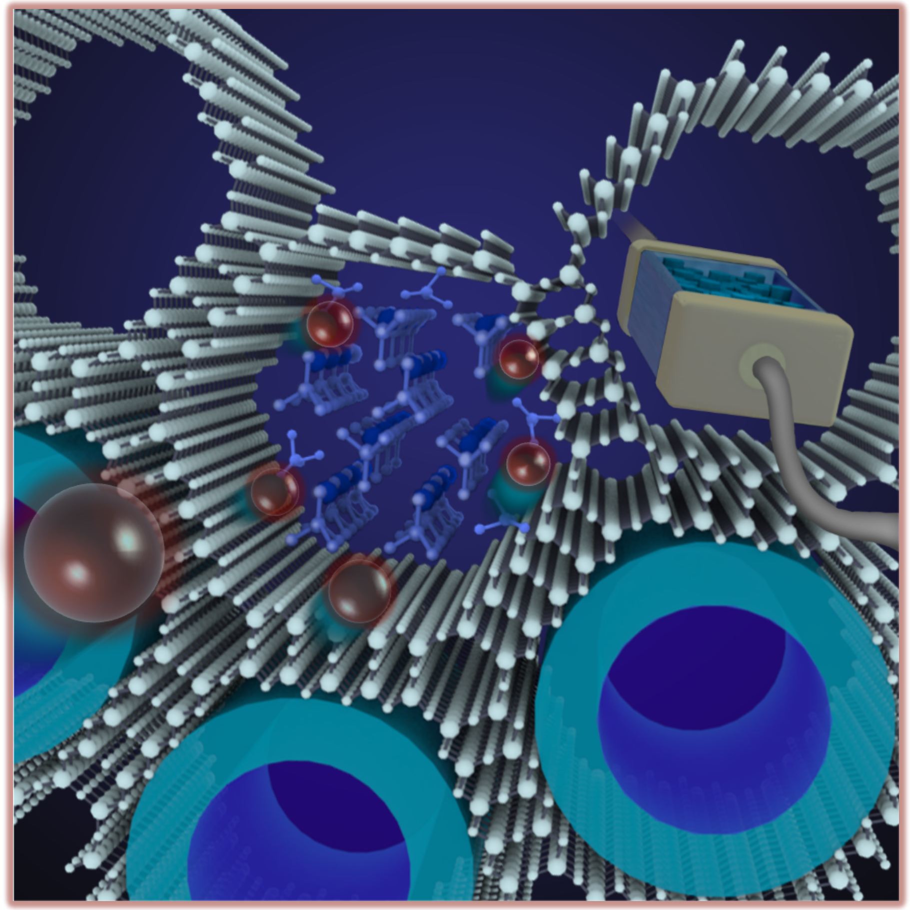


Matsuo, et al. JACS 131, 894 (2009) and Oguchi et al., Appl. Phys. Lett. 94, 141912 (2009)
Sveinbjörnsson, Mýrdal, Blanchard, Bentzen, Hirata, Mogensen, Norby, Orimo J. Phys Chem C 117, 3249 (2013)

Nano-confined Solid Electrolytes

- Nano-confining $LiBH_4$ yields high conductivity and improved stability

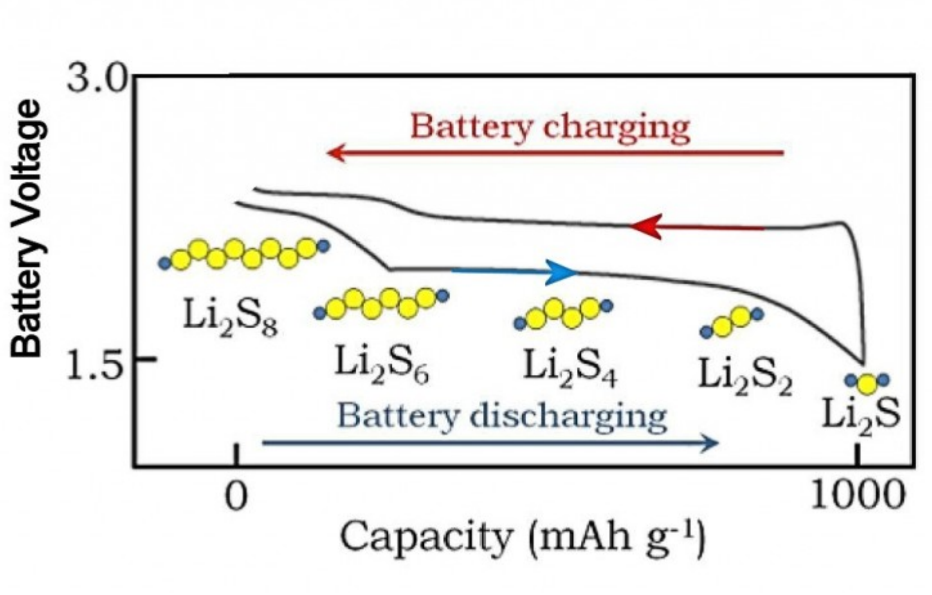


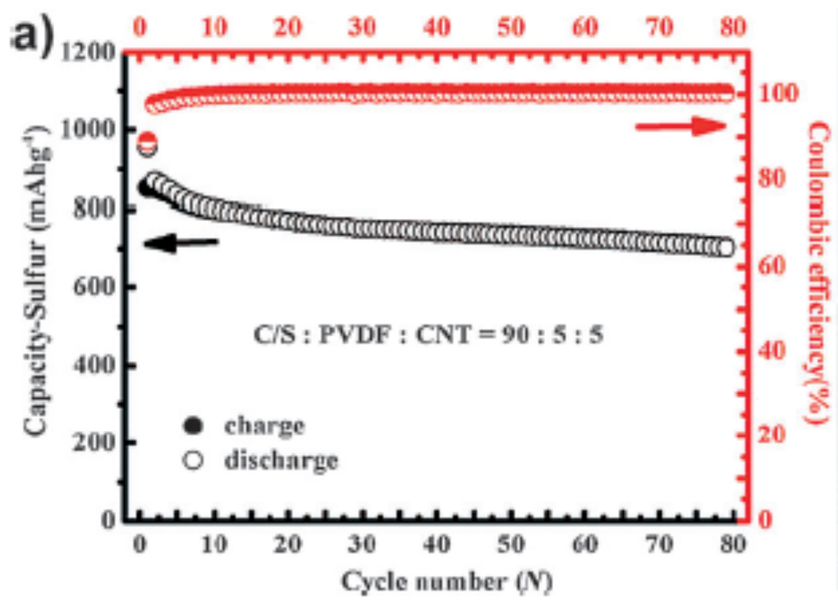


Blanchard, Nale, Sveinbjörnsson, Eggenhuisen, Verkuijlen, Suwarno, Vegge, Kentgens, de Jongh, Adv. Func. Mater. 25, 184 (2015)

Lithium-Sulfur (Li-S) Batteries

- Cheap and operational at room temperature (voltage ~2.1V)
- Li-S offers up to 4-600 Wh/kg (Sulfur: 1.672 mAh/g)
- Polysulfides, i.e. Li_2S_x, x=1-8, give poor ionic and electronic conductivity, shuttle effect, volume expansion
- Poor materials utilization, low DC-DC efficiency, limited cyclability

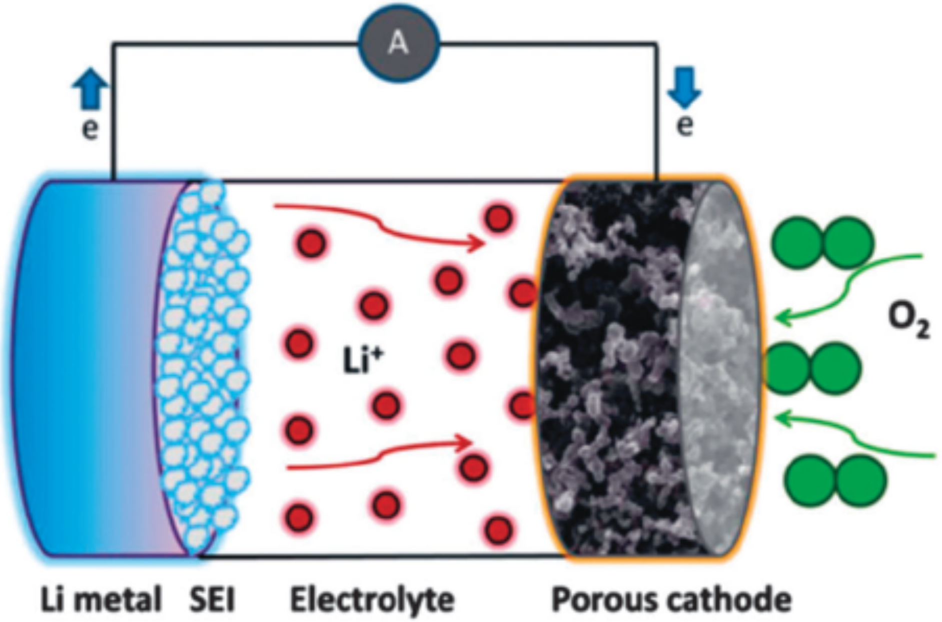


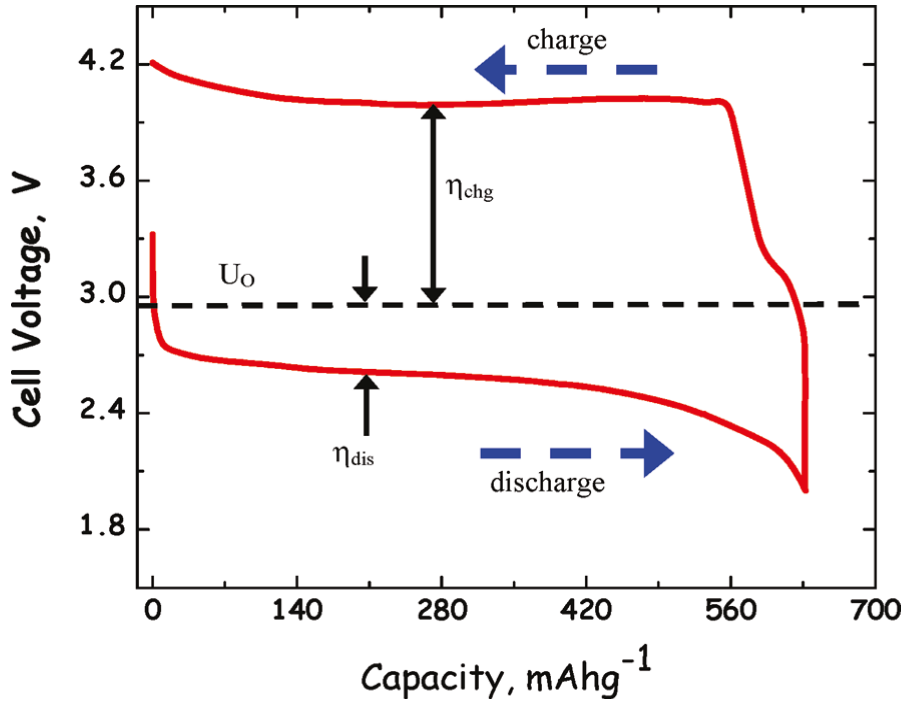


Yin et al., Angew. Chem. Int. Ed. 52, 13186 (2013)

Secondary Lithium-Air Batteries

- Between fuel cells and batteries: $2Li^+ + 2e^- + O_2(g) \leftrightarrow Li_2O_2(s)$
- High potential and fundamental challenges exist
  - Low efficiency and fast degradation
  - 'sudden death' of cells





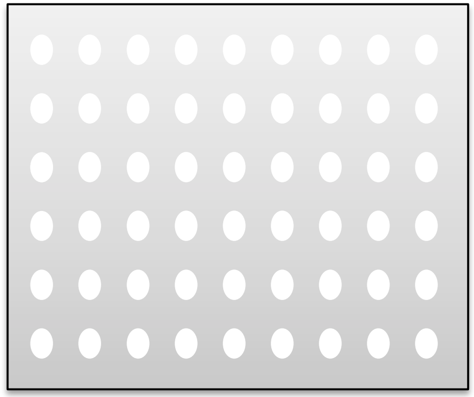
Girishkumar et al., J. Phys. Chem. Lett.1, 2193 (2010)

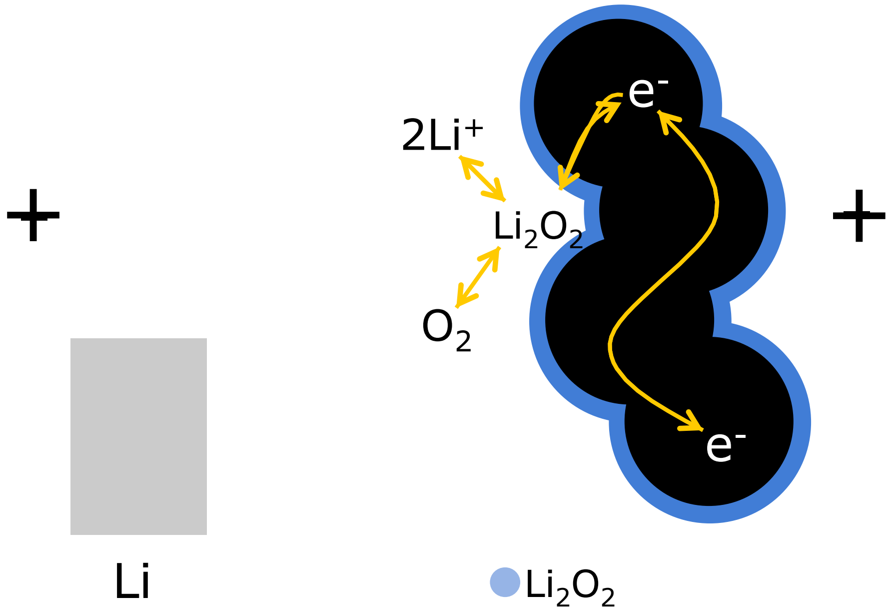
Younesi, Veith, Johansson, Edström, Vegge, Energy. Environ Sci. 8, 1905 (2015)

The Fundamentals of Li-Air Batteries

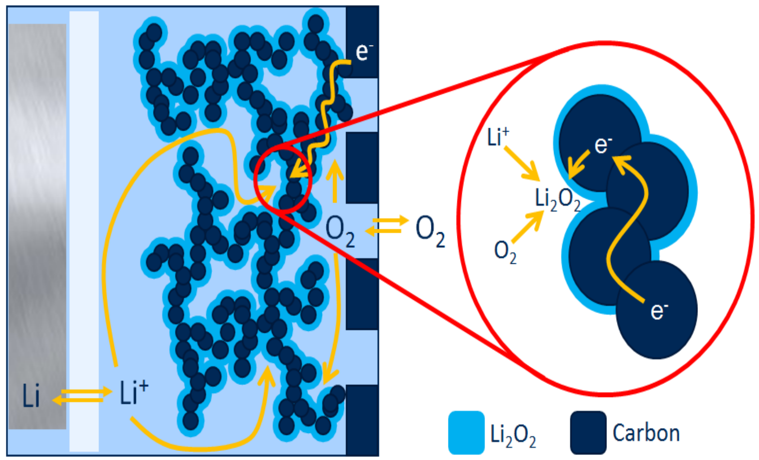
- Li-ion: intercalation in existing electrode structures
- Li-air: growth/depletion process
- Parasitic chemistry and degradation
- The cyclic stability must be improved

Li-ion





Li-air

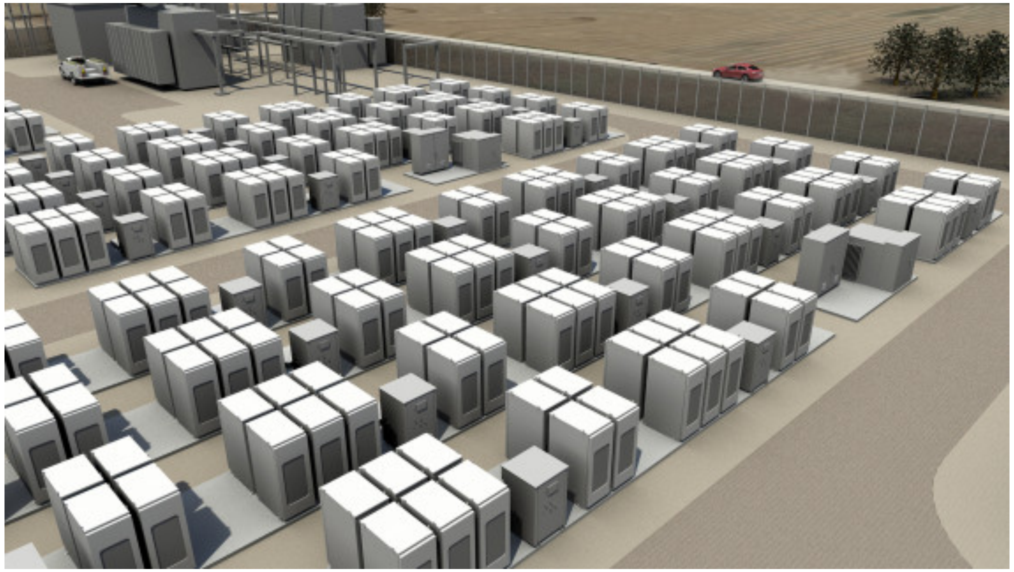


Højberg, Knudsen, Hjelm, Vegge, ECS Electrochem. Lett. 4, A63 (2015)

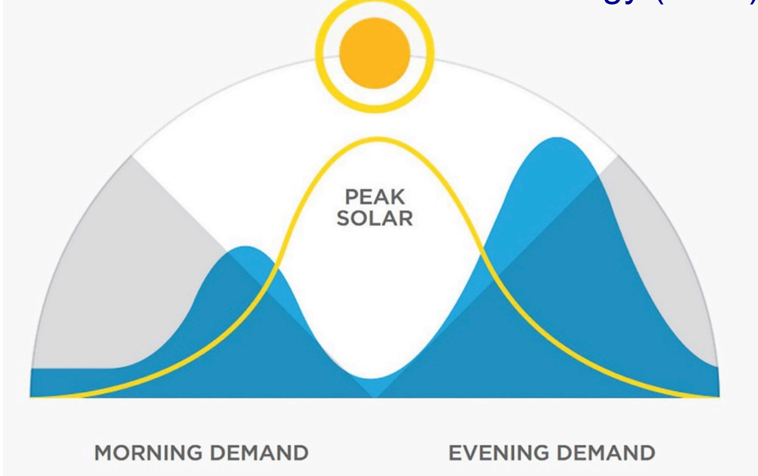
Højberg, McCloskey, Hjelm, Vegge, Johansen, Norby, Luntz, ACS Appl. Mater. Inter. 7, 4039 (2015)

Households and Grid-scale Storage

- Li-ion batteries may hold potential for household storage (internationally)
- Grid-scale storage opens for different battery technologies

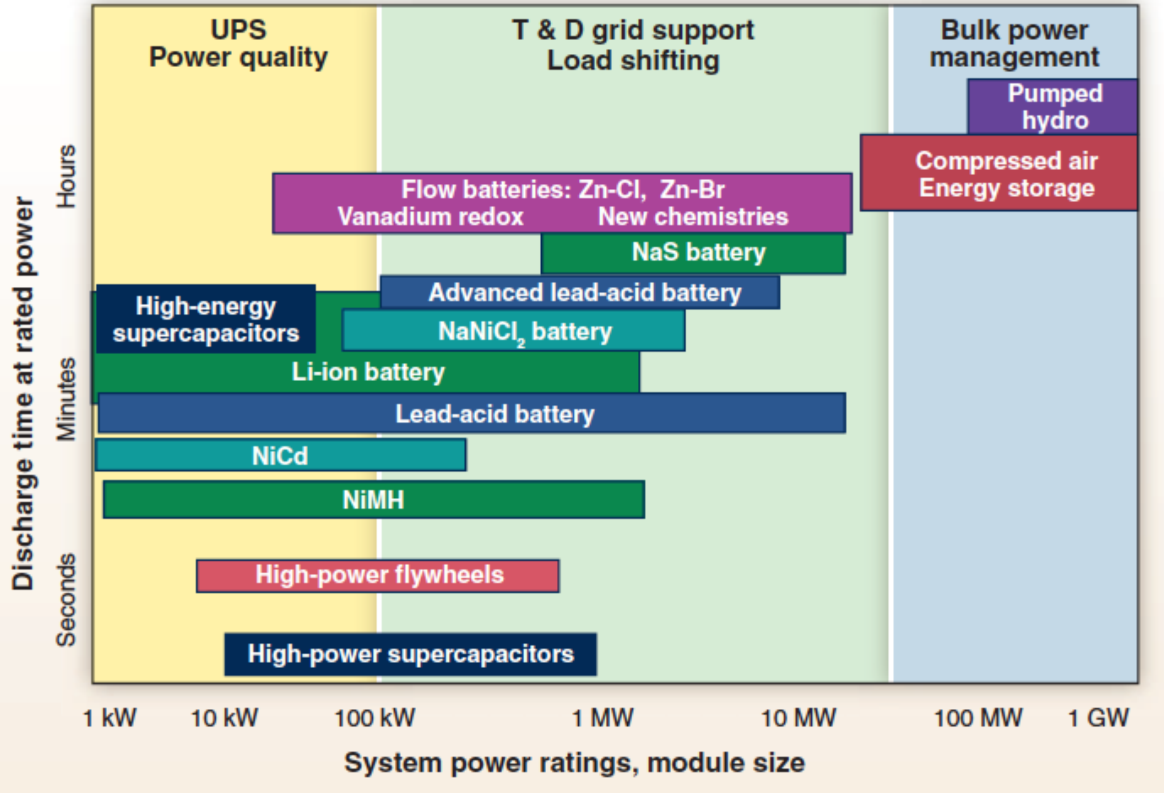


Tesla Energy (2015)



Battery Technologies for Grid-scale Storage

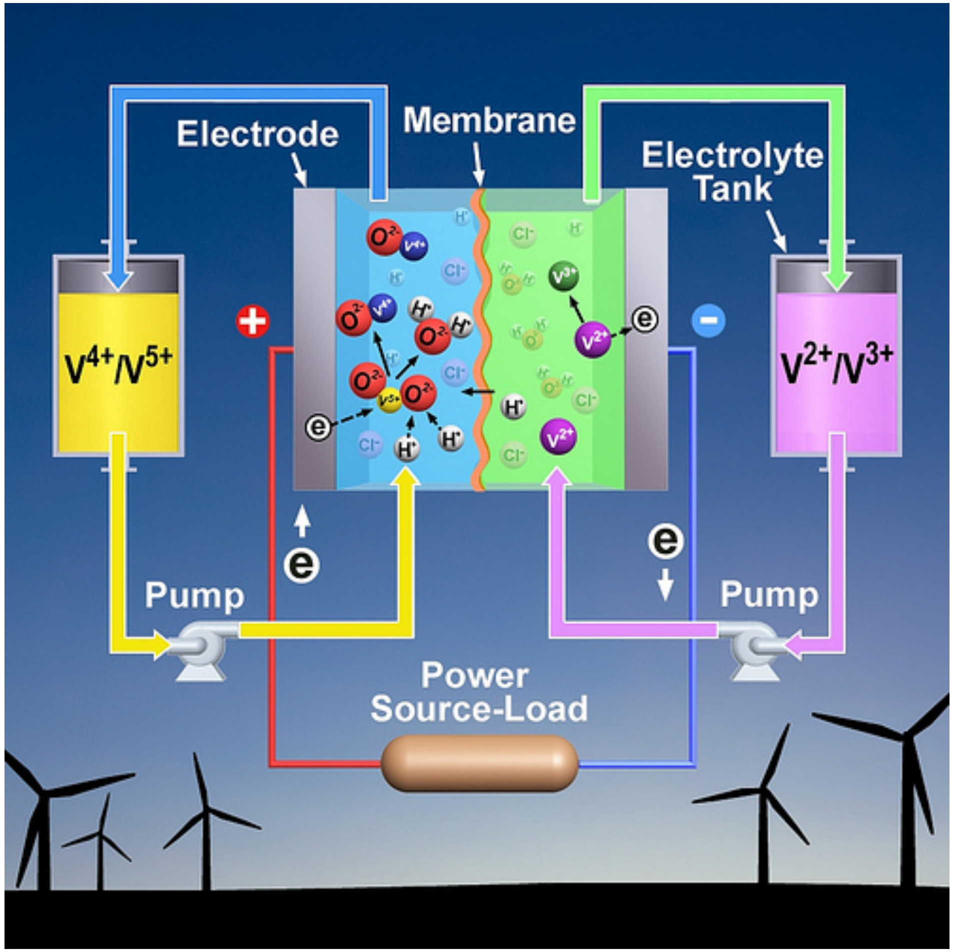
- Challenges for emerging technologies (Na-S, VRB, Na-$NiCl_2$, Li-ion)
  - Efficiency, price, scalability, cycle-life, charging rates, temperature
- Future technologies: Na-ion, Zn-Air, Ce-Zn, organic redox flox…



Dunn, Kamath, Tarascon, Science 334, 928 (2011)

Vanadium Redox Flow Batteries (VRB)

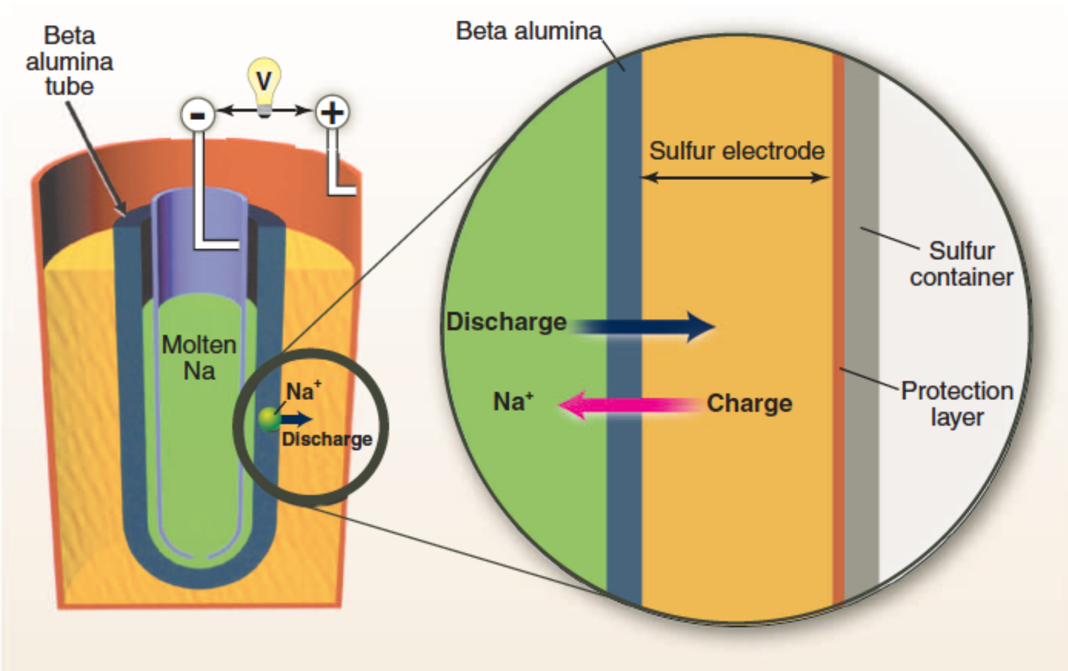
- Redox flow batteries separate the energy and power density
- The electrolytes are mechanically pumped
- The nominal VRB cell voltage is 1.4 V (1,26-1,6V)
- VRB operates at room temperature
- VRB offers 25-50 Wh/kg, high cycle life (>10.000) and 65-75% DC-DC efficiency
- High cost

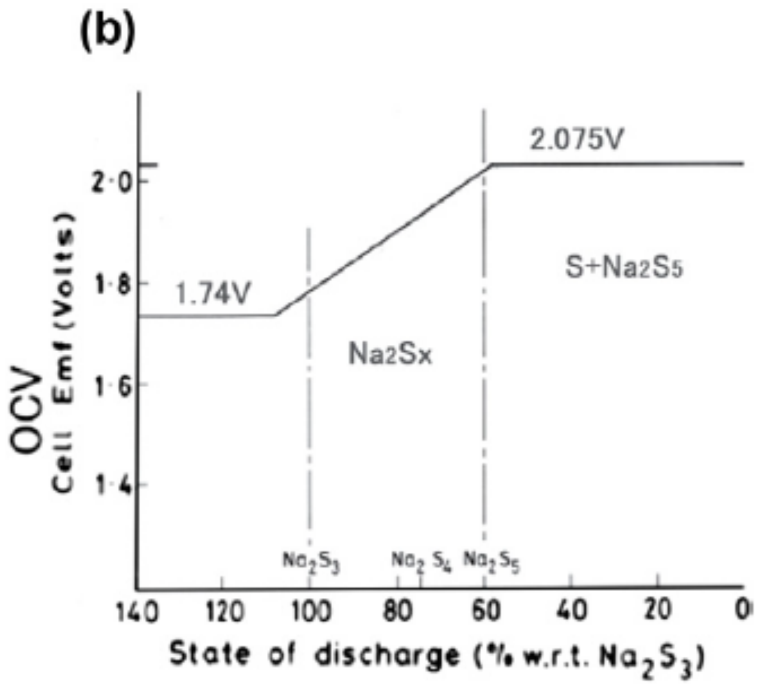


Wang, Luo, Li, Wei, Li and Yang, Adv. Funct. Mater. 23, 970 (2013)

Na-S Batteries

- The Na-S cell voltage is 1.7-2.1 V, but operates at 300-350 deg. C
- Na-S offers 100-140 Wh/kg and 80-90% DC-DC efficiency
- Medium cycle life (~4.000 cycles) and moderate cost

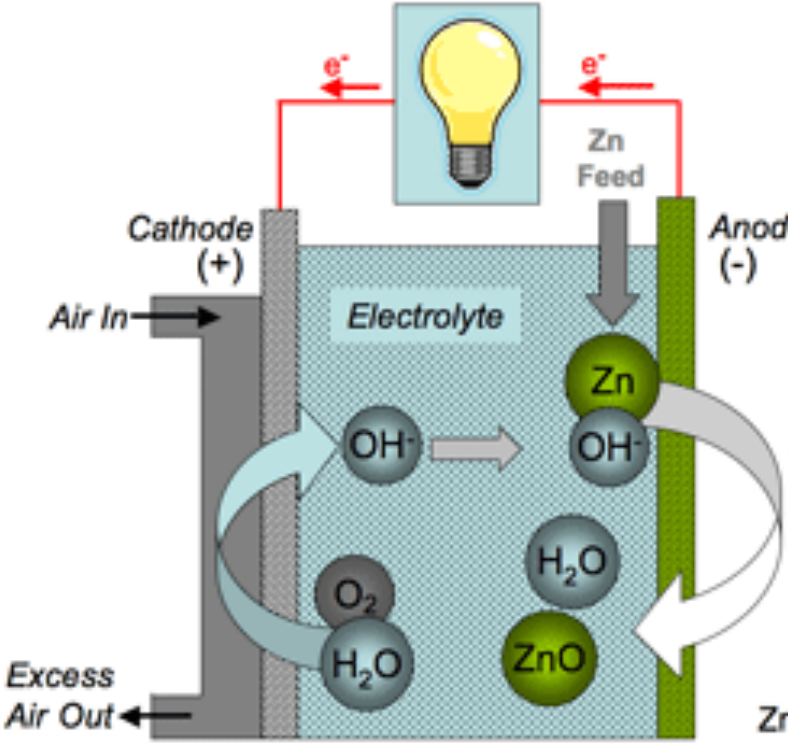




Dunn, Kamath, Tarascon, Science 334, 928 (2011)

Zinc-Air Batteries

- The Zn-air cell voltage is ~1.4 V and operates at RT
- Zn-air offers ~160 Wh/kg, but only ~50% DC-DC efficiency
- Low cost, but only moderate cycle life (~1.000 cycles)



Fuel Cell Reactions

Cathode: ½ O_2 + H_2O + 2e- → 2 OH-

Anode: Zn + 2OH- → ZnO + H2O + 2e-

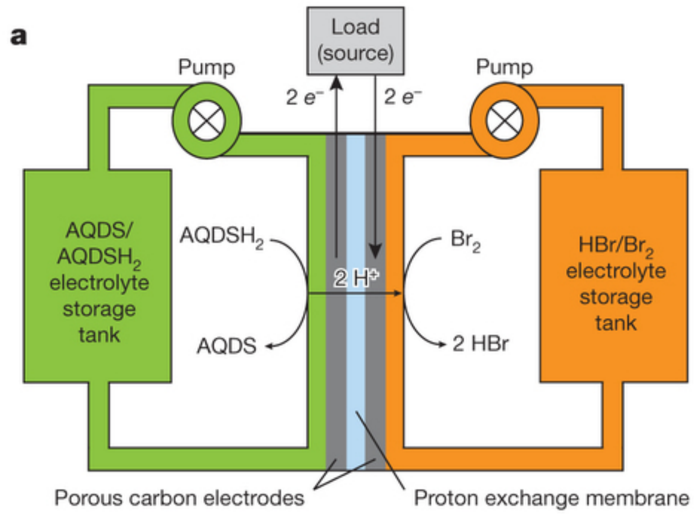
Overall Reaction: Zn + ½ O_2 → ZnO

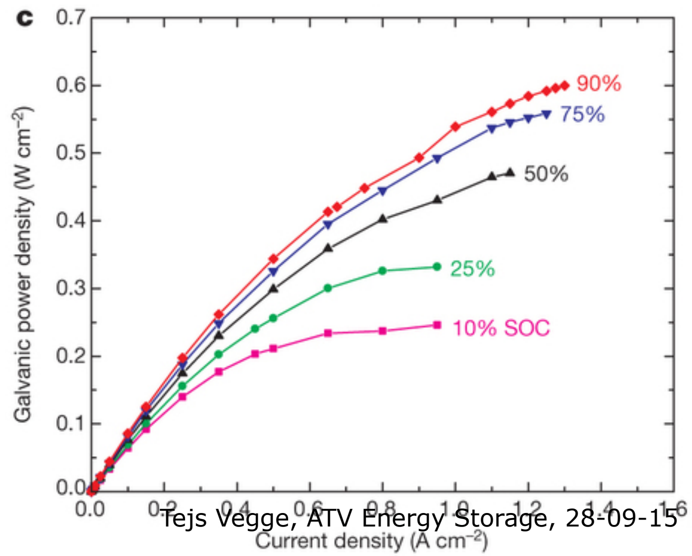
Zinc and air are fed to the fuel cell.
ZnO is removed by the flowing electrolyte.

Siahrostami, Tripković, Lundgaard, Jensen, Hansen, Hummelshøj, Mýrdal, Vegge, Nørskov, Rossmeisl, Phys. Chem. Chem. Phys. 15, 6416 (2013)

Organic Redox Flow Batteries (ORBAT)

- A redox flow battery using organic redox couples as electrolytes, e.g. ADQS quinone ($C_{14}H_8O_2$) and $ADQSH_2$ hydroquinone ($C_{14}H_8O_2H_2$)
- ORBATs have the potential to become very cost-competitive, but stability and performance must be improved
- The nominal cell voltage is ~1.0 V and it operates at room temperature
- Can be combined with Br_2-HBr for the positive electrolyte
- More research and development is needed





Huskinson et al., Nature 505, 195, 2014

Perspectives and Outlook

- Batteries will play an important role in a Danish and International transition to renewable energy, e.g. in the transportation sector and for short term grid-scale storage
- Penetration of the existing market for development and production of Li-ion batteries may prove very challenging
- A large-scale introduction of batteries for energy storage must rely on more earth-abundant materials
- The development of next generation battery technologies holds great potential for Danish companies, e.g. within battery materials and management, design and utilization of new battery technologies
- Substantial investments in fundamental battery research, materials development and implementation of new battery technologies is needed

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