Northwest **Power** and **Conservation** Council

July 5, 2017

MEMORANDUM

TO: **Power Committee**

FROM: **Massoud Jourabchi**

SUBJECT: **Report on Life-cycle of Batteries**

BACKGROUND:

Presenters: Massoud Jourabchi

Summary: Council staff has been following emerging technologies and mobility trends for the past 7 years. Today's mobile world is energized by more and more batteries of various shapes, sizes and chemistries. In this presentation we will discuss life-cycle of predominant battery types from their inception to manufacturing processes and end-of-life options.

Relevance: Impact on load forecast and behind-the-meter storage.

Workplan: Tracking emerging trends and markets

Background: Today's global society is hooked on mobility. What could be done yesterday only in a fixed location, now can be done while mobile. Every day billions of mobile devices rely on battery technologies to power them. For every battery type and chemistry that becomes commercialized, there are many batteries that do not go beyond laboratory settings. What might be beyond lithium? We will discuss; where the raw materials for battery components come from, how the batteries are made, what are trends in their costs and capabilities, what causes their failure and what are the recycling, remanufacturing and repurposing options currently available.

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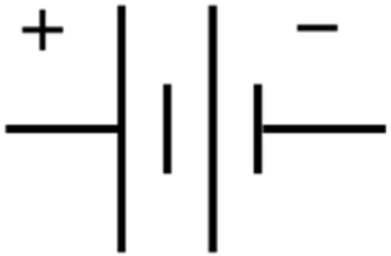


Life-cycle of Batteries

July 11, 2017

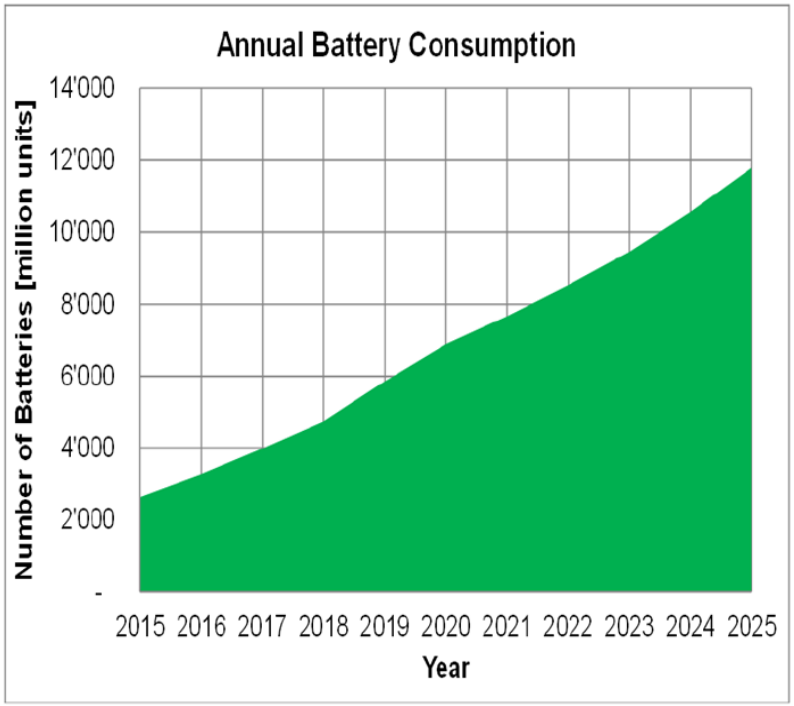
Massoud Jourabchi

In this presentation

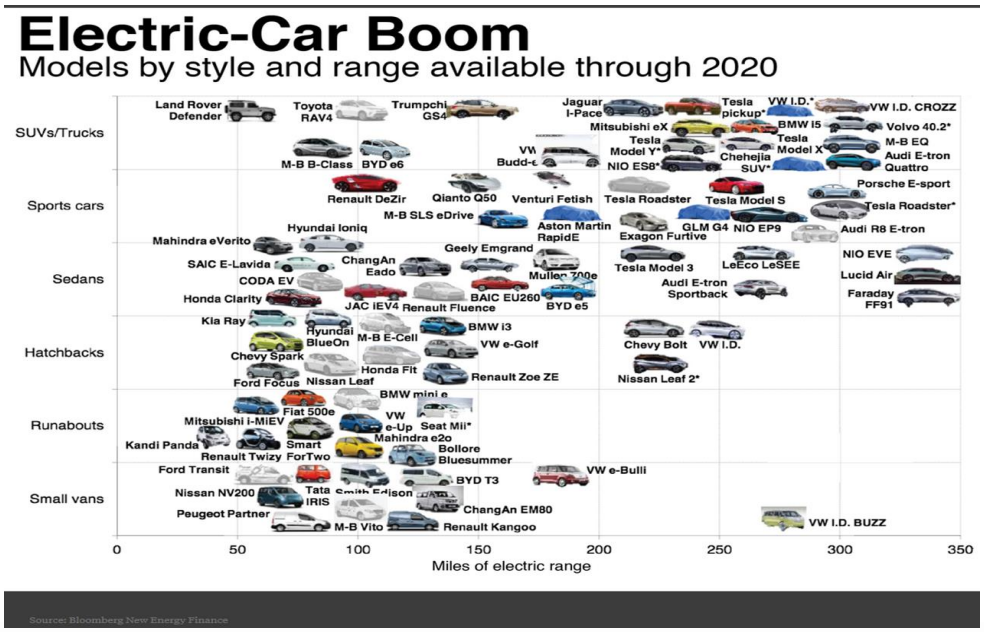
- Why we are doing this presentation?
- What is a battery and what are types of batteries?
- Dominate battery types
- Life cycle of Lithium-ion class of batteries
  - Row material (when and how much)
  - Processing
  - Market conditions (Supply, demand and prices)
  - How battery life is defined (depends on applications)
  - End-of-life options
- Next generation of batteries

Rapid increase in demand for batteries

Figure 18: Estimates for worldwide annual battery consumption related to Io

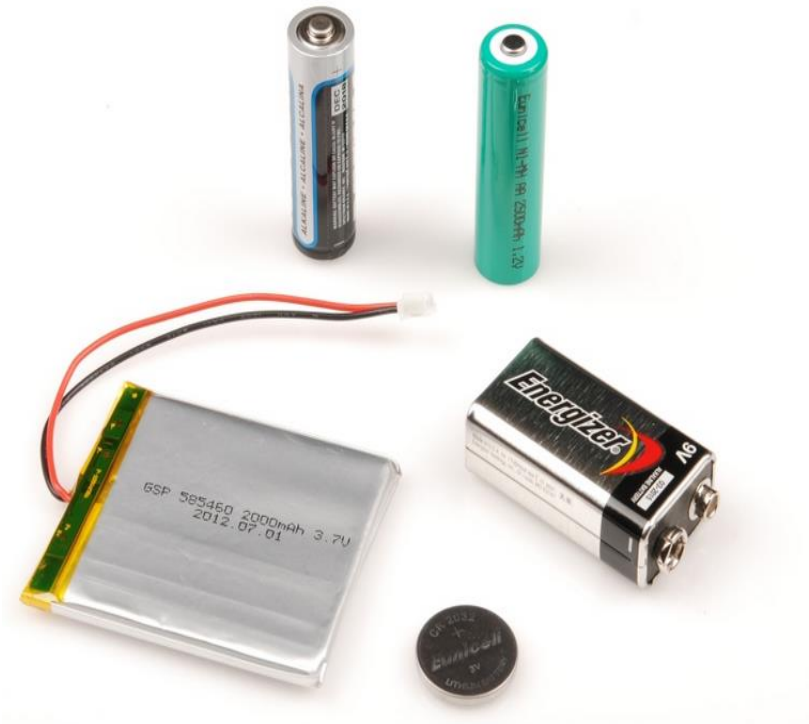


- Demand for Mobile applications
- Internet of Things
- Electric Vehicles
- RPS and intermediacy of renewables

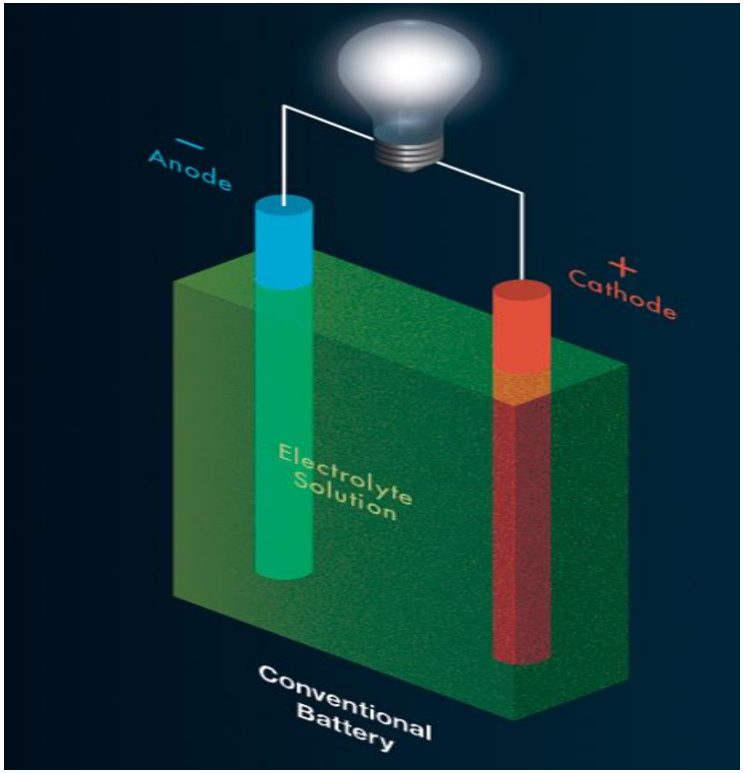


What is a battery?

Conventional batteries



Three Basic Elements

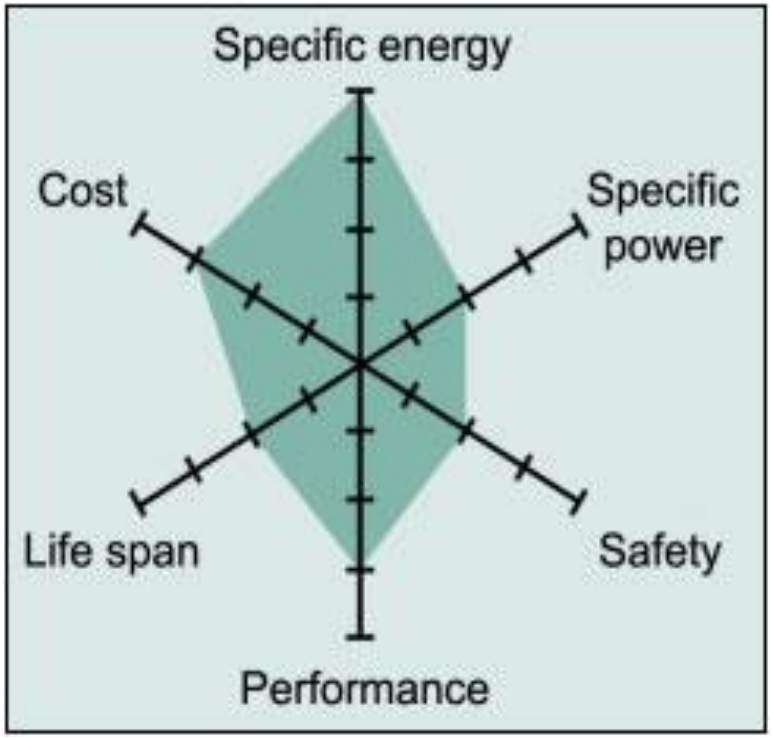


Role of Battery Architecture

Attributes of a battery

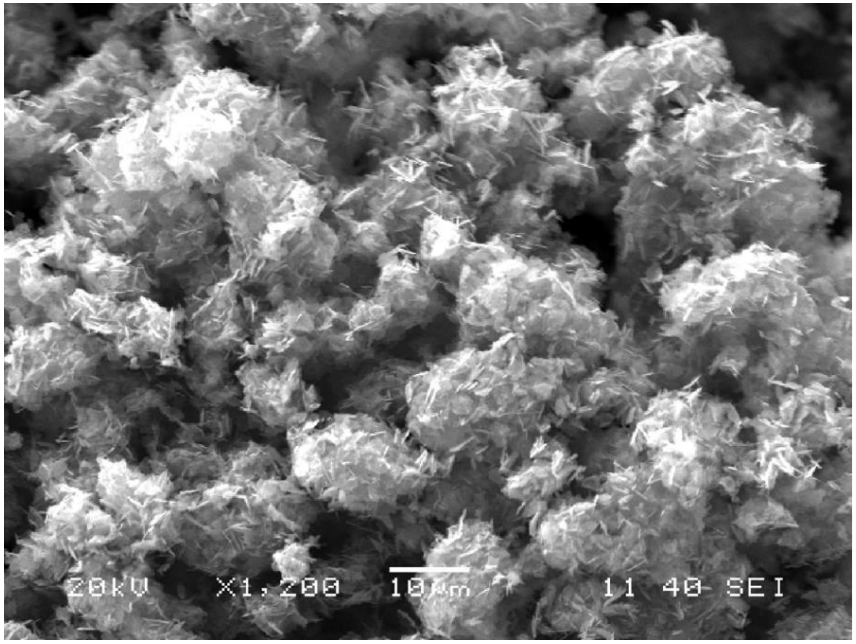
Attributes of a good battery

- **High specific energy**
- **High specific power**
- **Affordable price**
- **Long life**
- **High Safety**
- **Wide operating range**
- Low Toxicity
- Fast charging
- Low self-discharge

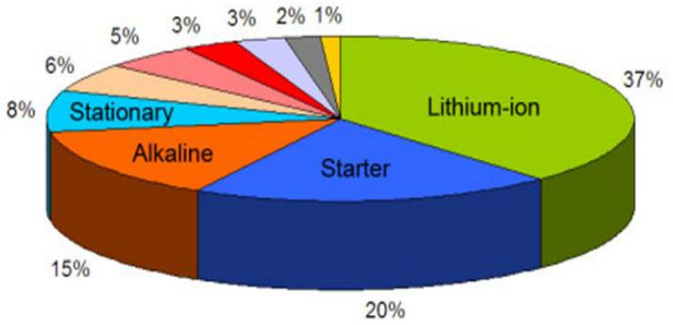


Dominate Types of Battery

Flakes of lithium manganese phosphate can serve as electrodes for batteries.



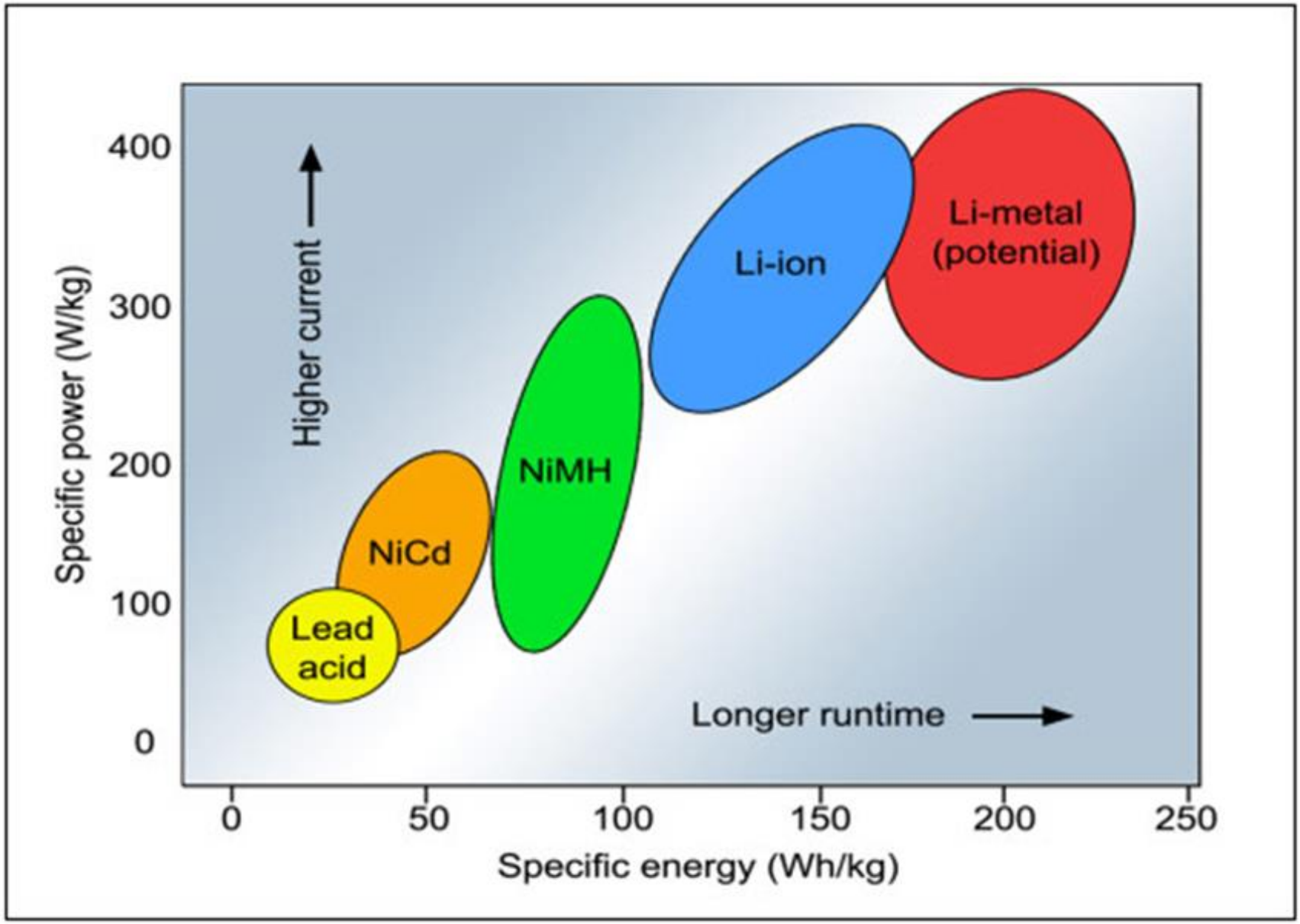
Photograph by the Pacific Northwest National Laboratory



Revenue contributions by different battery chemistries

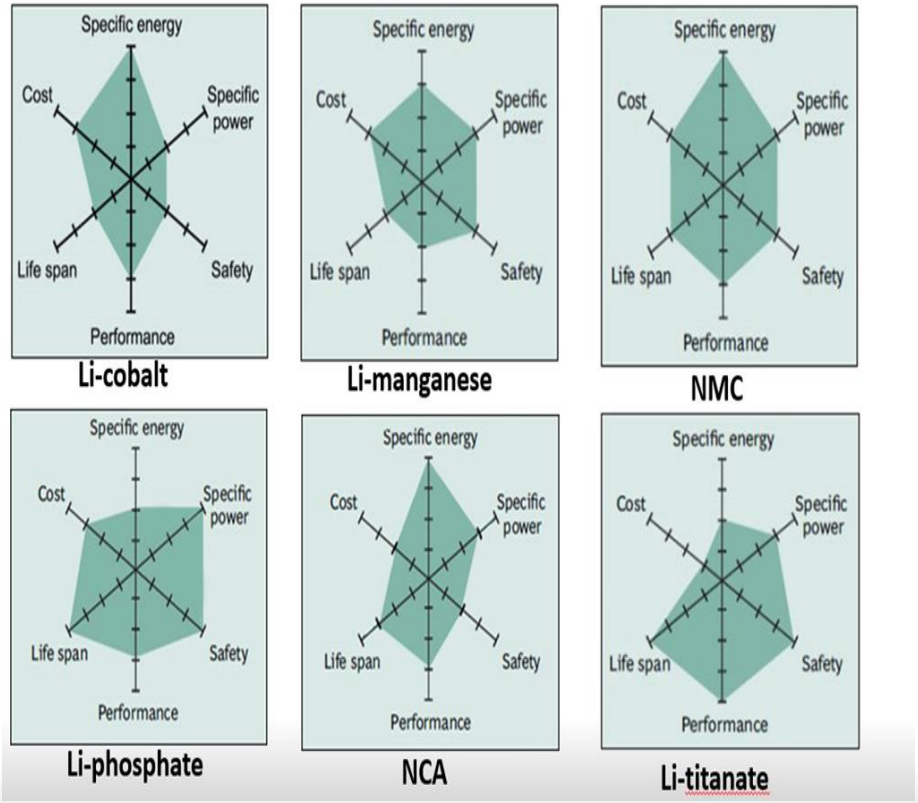
- 37% **Lithium-ion**
- 20% **Lead acid, starter battery**
- 15% **Alkaline, primary**
- 8% **Lead acid, stationary**
- 6% **Zinc-carbon, primary**
- 5% **Lead acid, deep-cycle**
- 3% **Nickel-metal-hydride**
- 3% **Lithium, primary**
- 2% **Nickel-cadmium**
- 1% **Other**

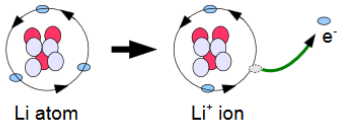
Source: Frost & Sullivan (2009)


Specific power (W/kg)
400
300
200
100
0
Higher current
Li-metal (potential)
Li-ion
NiMH
NiCd
Lead acid
Longer runtime
0
50
100
150
200
250
Specific energy (Wh/kg)

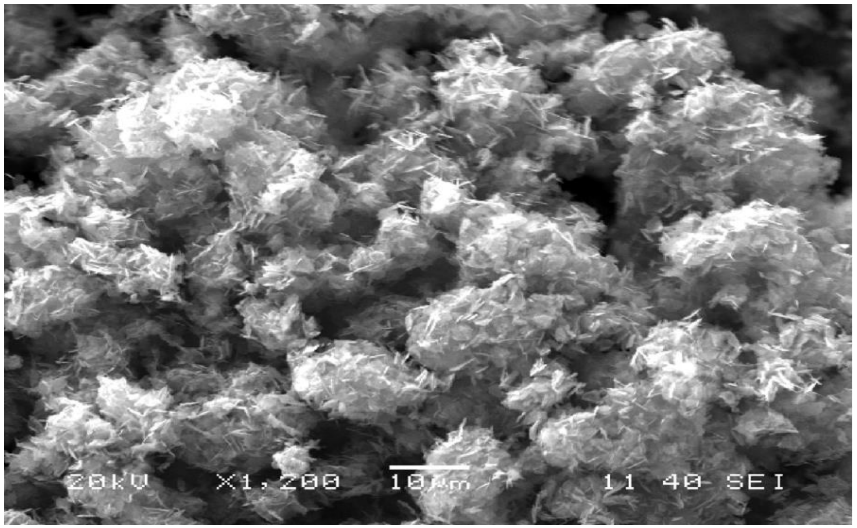
Various Types of Lithium-ion Battery

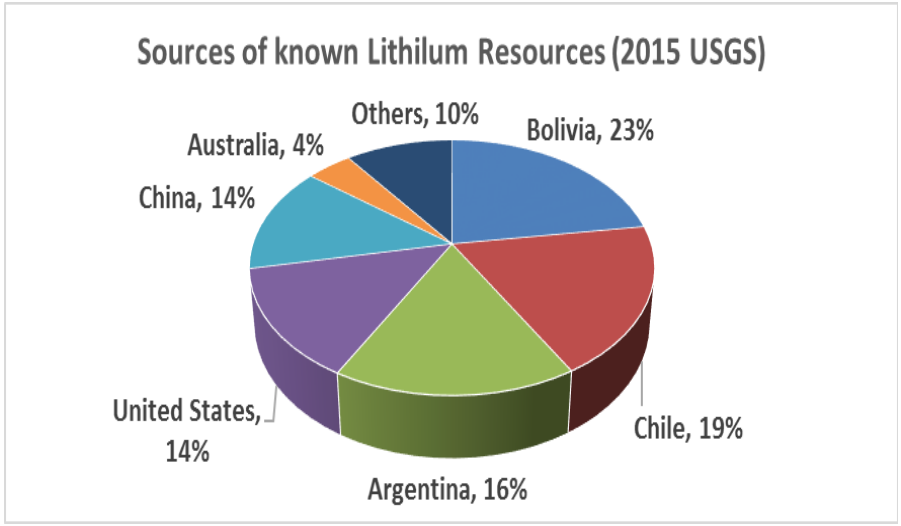
- Lithium cobalt ($LiCoO_2$)
- Lithium Manganese ($LiMn_2O_4$) (LMO) used for most EVs (leaf, volt)
- Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) NMC
- Lithium Iron Phosphate ($LiFePO_4$)
- Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) NCA
- Lithium Titanate ($Li_4Ti_5O_{12}$)





Life-cycle of Lithium



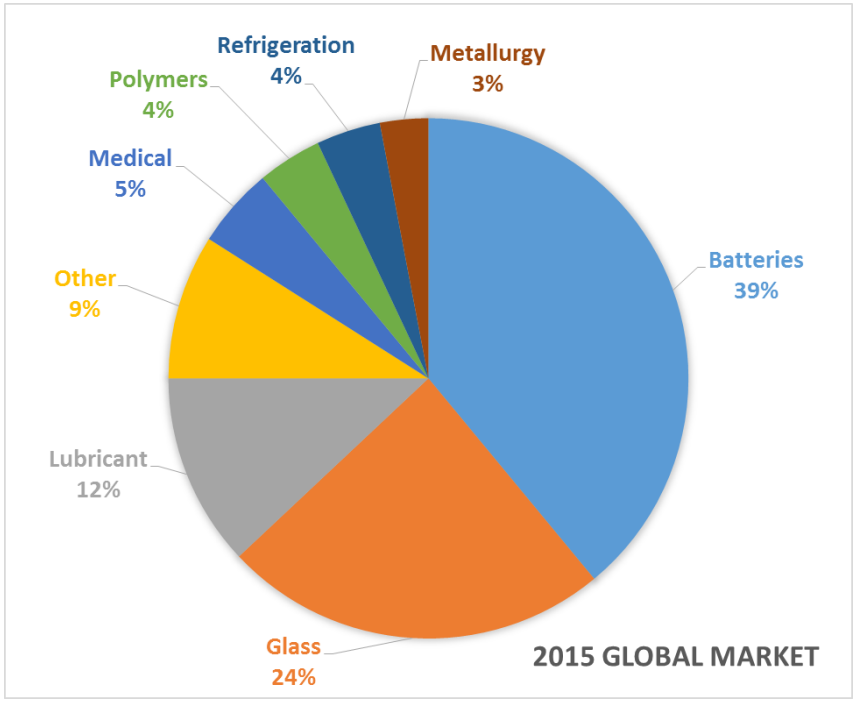


Brine Triangle

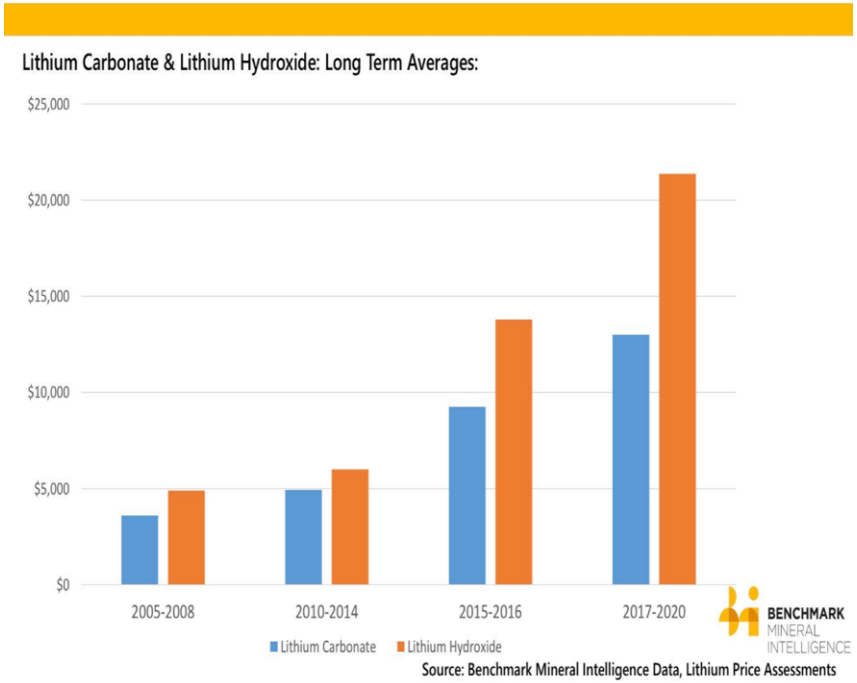
Lithium is often found in salt flats, such as this one in Salar del Hombre Muerto in northwestern Argentina, when water repeatedly evaporates from a shallow lake, leaving behind a crusty layer of salt minerals. **Photograph by Danita Delimont — Getty Images/Gallo Images**

Demand For Lithium and Cost

Uses



Cost of different types of Li



Amount of lithium carbonate in different devices

SMARTPHONE
3 grams

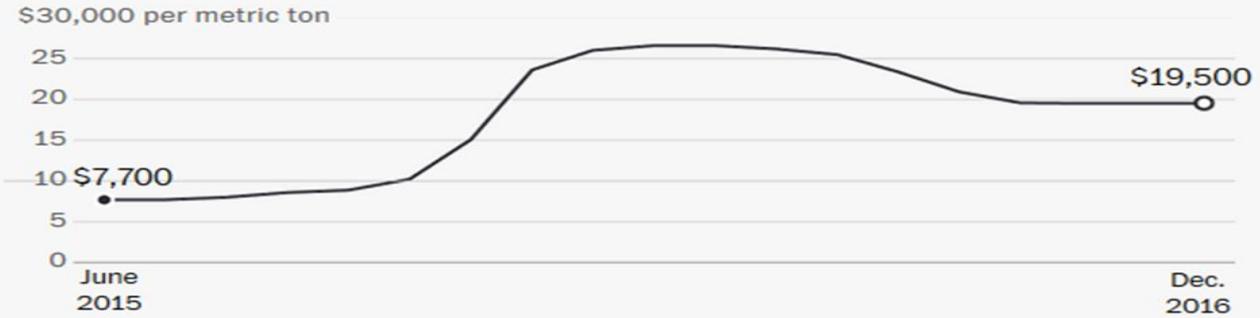
LAPTOP
1 ounce

TYPICAL HYBRID CAR
3.5 pounds

TYPICAL ELECTRIC CAR
44 pounds

TESLA 85-KWH MODEL
112 pounds

Lithium carbonate spot prices since June 2015



Source: Industrial Minerals, part of Metal Bulletin Group

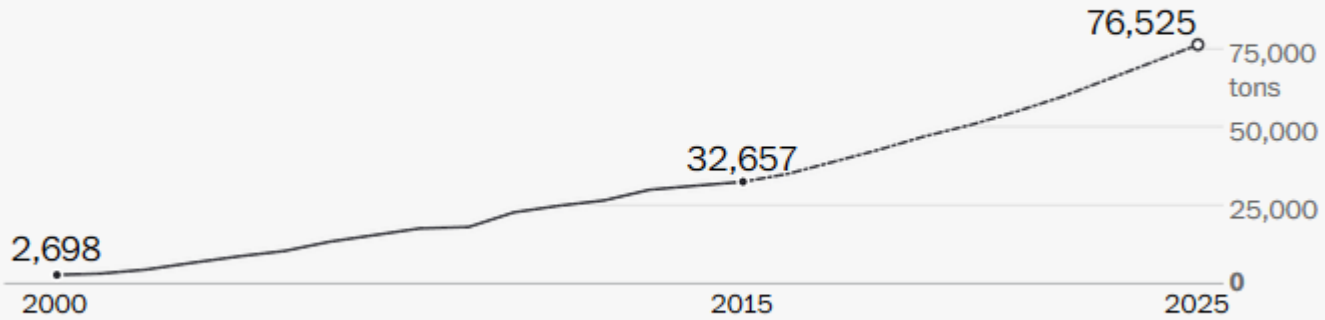
Amount of cobalt in different devices

SMARTPHONE
5 to 10 grams

LAPTOP
1 ounce

TYPICAL ELECTRIC CAR
10 to 20 pounds

Cobalt demand for lithium-ion batteries is expected to double by 2025



Source: Christophe Pillot, Avicenne Energy

U.S. Graphite Demand

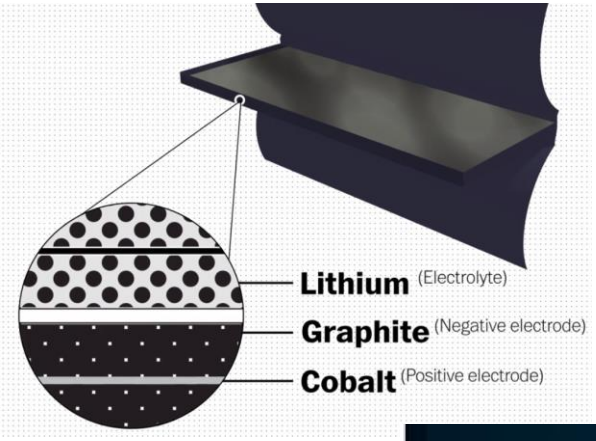
The U.S. is **100%** import-dependent for graphite[1]

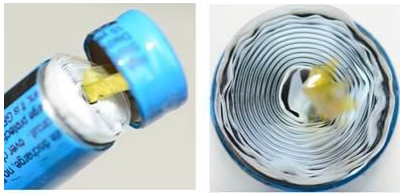
Reliance

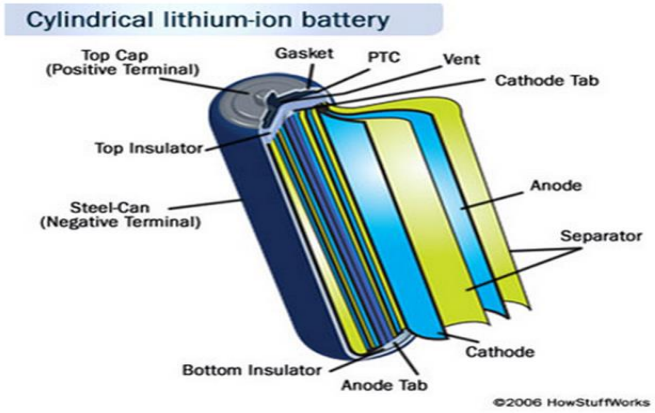
- The U.S. imported $45.2MM Natural Graphite in 2013[2]. There was not **a single oz. produced in the United States.**
- *"Right as foreign oil becomes less of a national concern, our foreign mineral dependence has taken its place as insidious thread to America's security, growth and competitiveness."* – The American Mineral Security Act of 2015
- The European Union has included Natural Graphite on its Critical Raw Materials (CRMs) list. These combine high economic importance with a high risk associated with their supply.

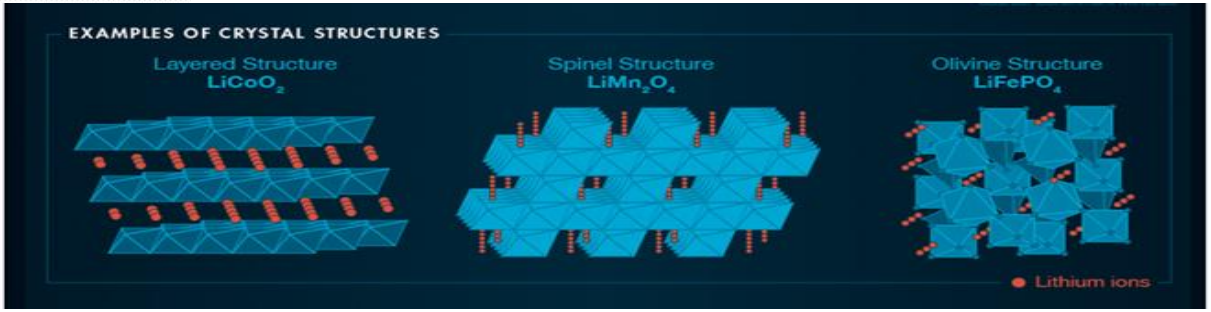
[1] **Source:** *US Geological Survey* [2] *United States Geological Survey Mineral Resources Program*

Chemical composition and architecture of the battery defines it's capability and characteristics



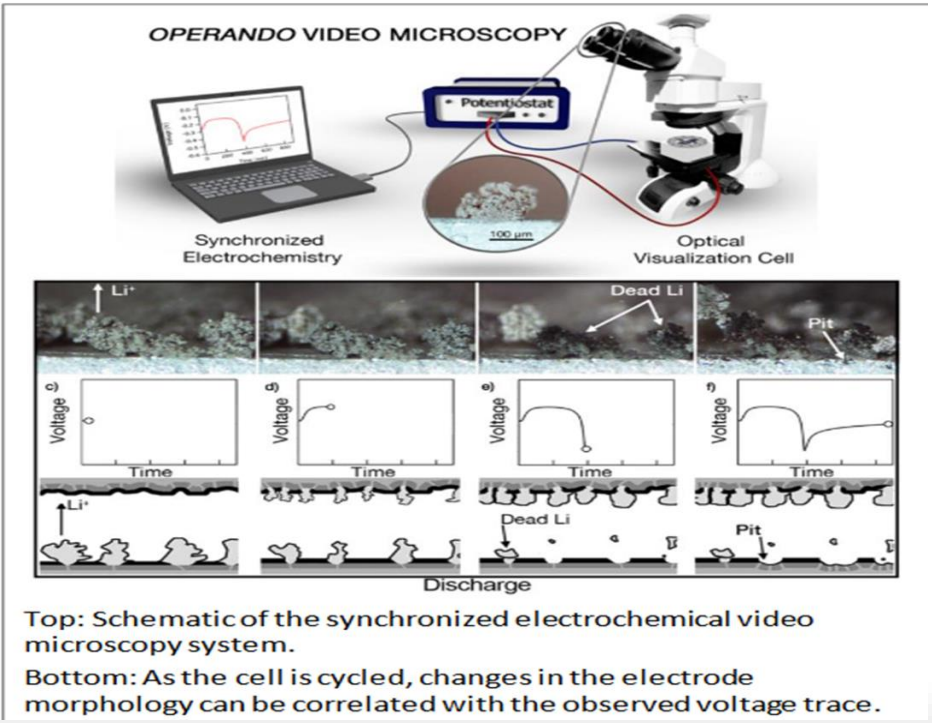






service life of a battery

- Cell oxidation
- Number of cycles
- Elevated temperatures



Top: Schematic of the synchronized electrochemical video microscopy system.

Bottom: As the cell is cycled, changes in the electrode morphology can be correlated with the observed voltage trace.

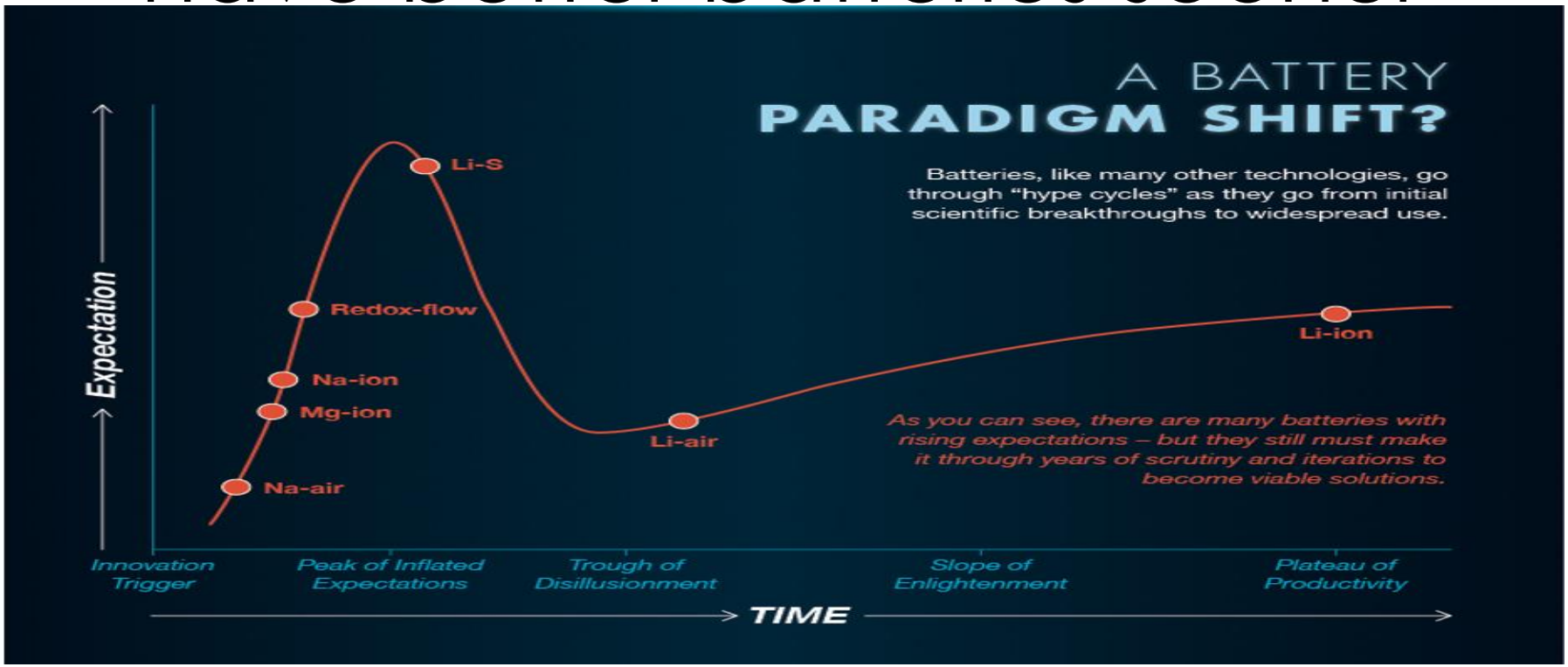
Tesla P100D battery module cooling loops [Credit: Jason Hughes]

Cooling system of Tesla Motors 18650 Cell battery system

Options for end-of life (3Rs)
Remanufacturing, Repurposing, Recycling for EVs

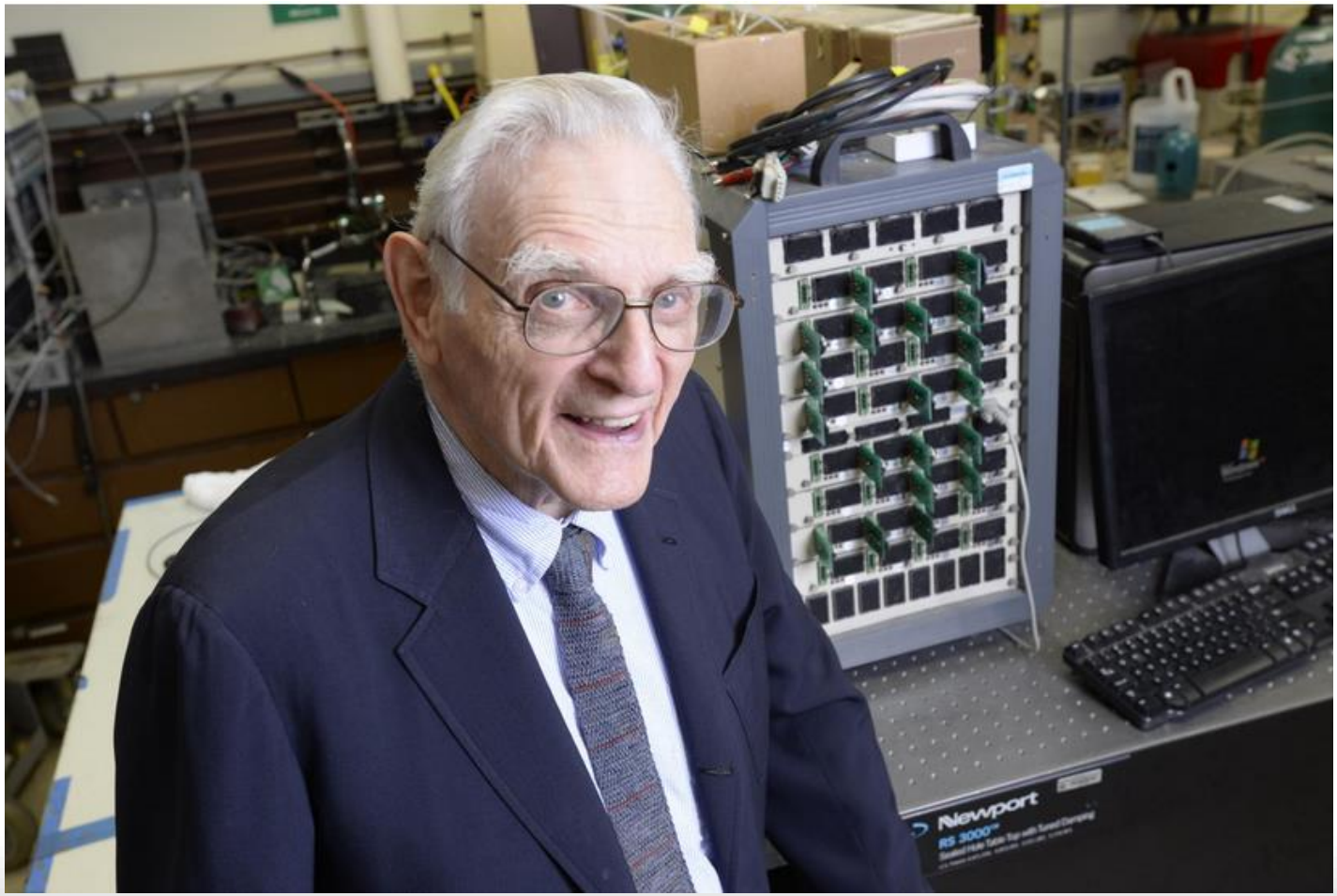
Used Chevrolet Volt batteries are helping keep the lights on at the new General Motors Enterprise Data Center at its Milford Proving Ground in Milford, Michigan. Five Volt batteries work with an adjacent solar array and two wind turbines to help supply power to the data center's administrative offices. (Photo by John F. Martin for General Motors)

Post Lithium and Why we do not have better batteries sooner



Adopted from visualcapitalist.org

Father of Modern Battery



There is a wide range of battery options for stationary battery here is one example

Aquion batteries are made of common, safe materials. These features make AHI batteries simple to manufacture, safe, sustainable, inexpensive, robust, and abuse-tolerant.

Aqueous Hybrid Ion (AHI™) Chemistry

PROS	CONS
Low cost, multiple suppliers	Lower conductivity than alternatives
Low cost, multiple suppliers	Lower specific capacity than alternatives
Low cost	None
Proprietary material specific to AHI battery, tolerant to partial state-of-charge cycling	Lower energy density than alternatives
Not flammable, toxic, or caustic, natural overcharge protection, lower cost and greater conductivity than organic solvent alternatives	Lower energy density than alternatives

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Summary

- Fast growing demand for batteries of various capabilities, will undoubtedly increase pressure on supply.
- Improvements in battery performance will be gradual.
- Most likely batteries used in mobile applications will be repurposed for stationary backup applications.