The energy storage landscape: Feasibility of alternatives to lithium based batteries

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Harvard Energy Journal Club

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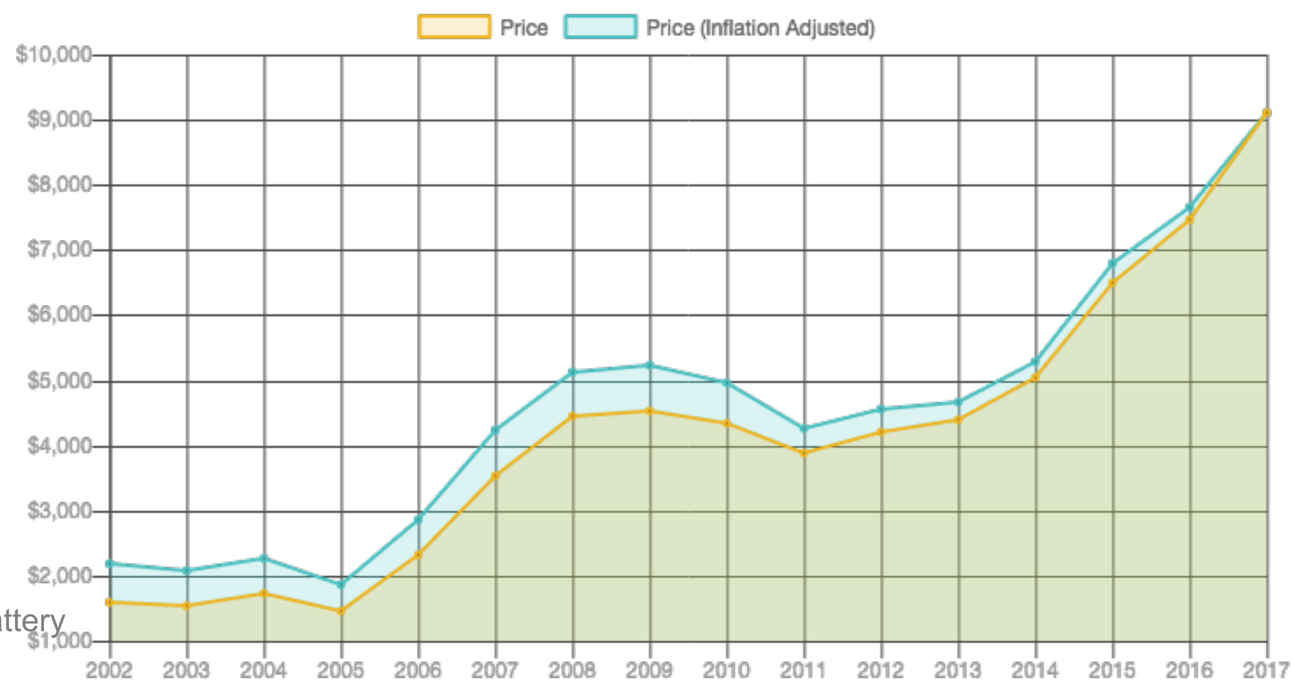
https://arstechnica.com/business/2017/04/washington-states-new-8-megawatt-hour-flow-battery-is-the-largest-of-its-kind/

Outline

- Lithium ion batteries
- Vanadium and other flow batteries
- Molten metal batteries
- Economics of utility-scale energy storage

Lithium Ion Batteries

- Energy Density: 250 – 676 W·h/L
- Specific Energy: 100 – 265 W·h/kg
- Specific Power: ~250 – 340 W/kg
- Consumer price: $400/kWh (~present cost of Tesla Powerpack)
- Nominal charging temperature range:
  5 to 45 °C (41 to 113 °F).
- Cycle durability: 400 – 1200 cycles
- Charge/discharge efficiency: 80-90% depending on battery age



https://en.wikipedia.org/wiki/Lithium-ion_battery
https://www.metalary.com/lithium-price/

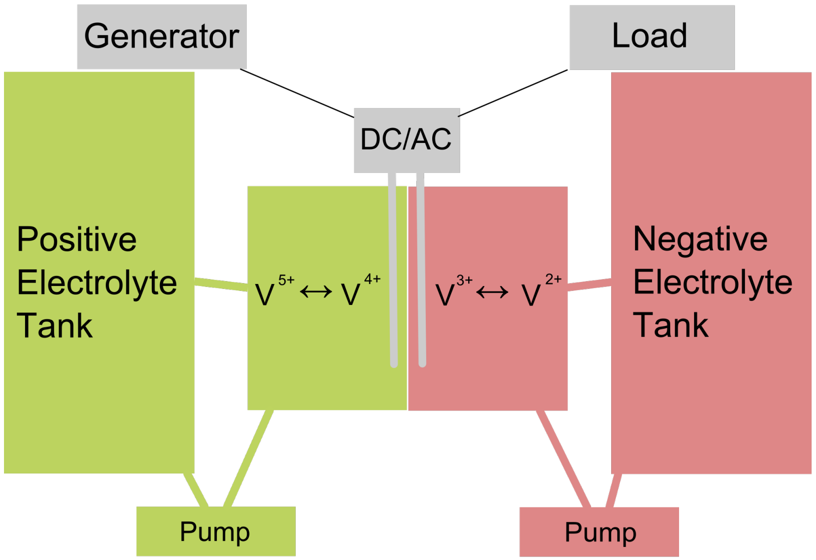
DOE energy storage goals

- Research and develop new technologies based on advanced materials and chemistries to meet the following AC energy storage system targets:
  - System capital cost: under $150/kWh
  - Levelized cost: under 10 ¢/kWh/cycle (i.e., economically scalable without subsidies)
  - System efficiency: over 80%
  - Cycle life: more than 5,000 cycles

Grid Energy Storage: U.S. Department of Energy, December 2013

Vanadium redox flow battery

- Positive half-cell contains VO_2^+ (V^{5+}) and VO^{2+} (V^{4+}) ions, negative half-cell contains V^{3+} and V^{2+} ions
- Half-cell reactions and potentials $E^{\varnothing}$ during discharge of battery:
  - Reduction rxn: $VO_2^+{}_{(aq)} + 2H^+{}_{(aq)} + e^- \rightarrow VO^{2+}{}_{(aq)} + H_2O(l)$, $E^{\varnothing} = 1.00$ V
  - Oxidation rxn: $V^{2+}{}_{(aq)} \rightarrow V^{3+}{}_{(aq)} + e^-$, $E^{\varnothing} = 0.26$ V
  - Potential of rxn under standard conditions = 1.26 V
- Fun fact: Can determine charge state by color of electrolyte solution.



https://en.wikipedia.org/wiki/Vanadium_redox_battery

Vanadium redox flow battery details

- Specific energy: 10 – 20 W·h/kg
  (~10 times less than Li-ion)
- Specific density: 15 – 25 W·h/L
  (10 – 45 times less than Li-ion)
- Cycle durability: >10,000 cycles
  (10 times greater than Li-ion)
- Charge/discharge efficiency: 75 – 80%
- Predicted lifetime: 20 – 30 years
- UniEnergy Technologies (UET) Uni.System: Optimal temperature operation range: -40°C to +50°C (-40°F to +122°F)
  Larger temperature range than Li-ion

- Vionx Energy: $400/kWh for a DC system (on par with Li-ion batteries)
- UET claims levelized cost can be reduced to 5¢/kWh over the life time of the system.

https://en.wikipedia.org/wiki/Vanadium_redox_battery

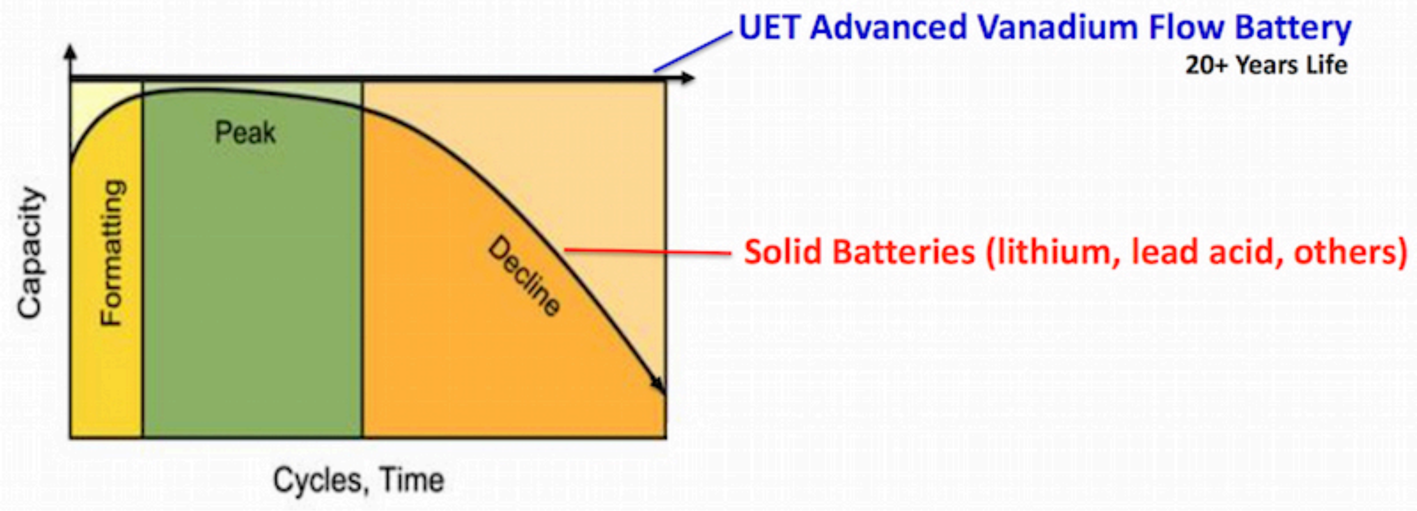
Vanadium redox flow battery characteristics

Pros:

- Theoretically unlimited energy capacity simply by using larger electrolyte storage tanks
- Large feasible operating temperature range: -40°C to +50°C (-40°F to +122°F)
- Can be completed discharged and fully charged without degradation like Li-ion batteries.

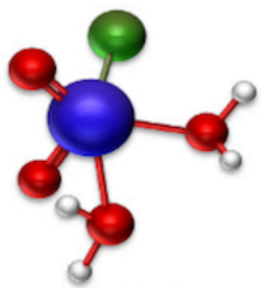
Cons:

- Low energy density compared to Li-ion.
  - Will not be used for portable energy storage.



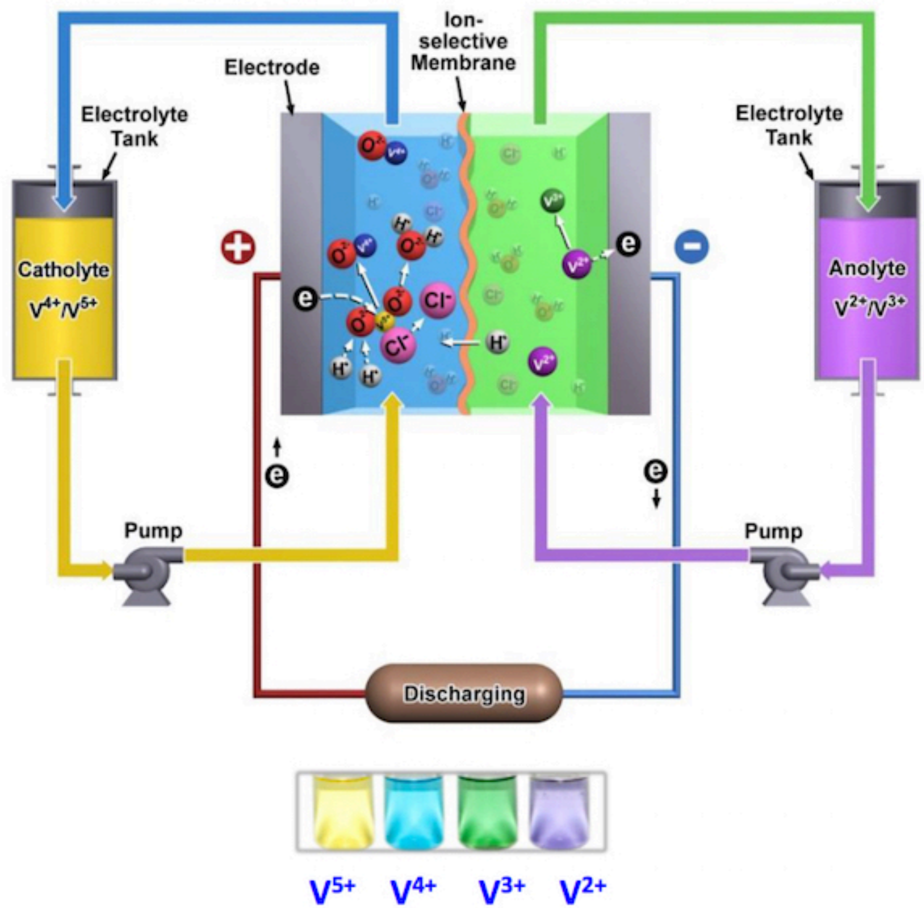
https://www.forbes.com/sites/jamesconca/2016/12/13/vanadium-flow-batteries-the-energy-storage-breakthrough-weve-needed/#2f23335a5bde

UniEnergy Technology (UET) Vanadium redox flow battery system design



$VO_2Cl(H_2O)_2$

When charged:
VO_2^+ (V^{5+})



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https://www.forbes.com/sites/jamesconca/2016/12/13/vanadium-flow-batteries-the-energy-storage-breakthrough-weve-needed/#7722f7835bde

UniEnergy Technology (UET) Vanadium redox flow battery system design

- Pacific Northwest National Laboratory developed a new vanadium chemistry that is used in UET flow batteries.

- Hydrochloric acid introduced into the electrolyte solution:
  - Almost doubling the storage capacity
  - Increasing the temperature range of operation from -40°C to 50°C (-40°F to 122°F)

https://www.forbes.com/sites/jamesconca/2016/12/13/vanadium-flow-batteries-the-energy-storage-breakthrough-weve-needed/#7722f7835bde

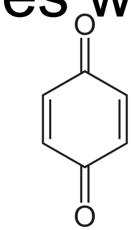
Utility scale vanadium flow battery systems

- March 2017: UET finished installation of a V-flow battery on the grid in Snohomish County in Washington state.
  - 2 MW, 8 MWh battery – currently the largest capacity **containerized** flow battery system in the world.
  - Can power ~1,000 homes for eight hours.
  - 20 connected shipping containers, each with its own module weighing 80,000 pounds each once filled with vanadium solution.
- Rongke, sister company of UET: Planning the largest V-flow battery in the world in Dalian, China, population 7 million.
  - 200 MW power and 800 MWh energy capacity to be completed in 2018.
  - Expected to peak-shave approximately 8% of Dalian's expected load in 2020.

https://arstechnica.com/business/2017/04/washington-states-new-8-megawatt-hour-flow-battery-is-the-largest-of-its-kind/
http://www.uetechnologies.com/news/71-200mw-800mwh-energy-storage-station-to-be-built-with-rongke-power-s-vanadium-flow-battery

Flow batteries cheaper than vanadium?

- Replace metals with multiple valence states with organic molecules that can hold different changes.
- Quinones – organic ring molecules with double-bonded oxygen. e.g 1,4-Benzoquinone



  – Roy G. Gordon, and Michael J. Aziz groups at Harvard.

- Still in research development phase.

http://www.wbur.org/bostonomix/2017/01/10/rhubarb-battery-storage

Molten metal batteries

Estimates:

- Specific energy: 100 – 200 W·h/kg
  (~on par with Li-ion)
- Specific density: 250 – 300 W·h/L
  (~on par with Li-ion)
- Cycle durability: >10,000 cycles predicted
  (xtimes greater than Li-ion)
- Charge/discharge efficiency: 80%
  - 20% inefficiency released as heat to keep system working at operating temperature of 900°C
- Predicted lifetime: ??

https://en.wikipedia.org/wiki/Molten_salt_battery

Molten metal batteries

- Ambri company developing commercial systems based on research done in Donald Sadoway group at MIT.

- The electrode and electrolyte layers are heated until they are liquid and self-segregate due to density and immiscibility.

  – 2015: High temp kept melting seals in system. Company laid off ¼ quarter of staff
  – Plan for commercialization within 2 years (2019).

http://www.wbur.org/bostonomix/2017/03/27/ambri-molten-battery

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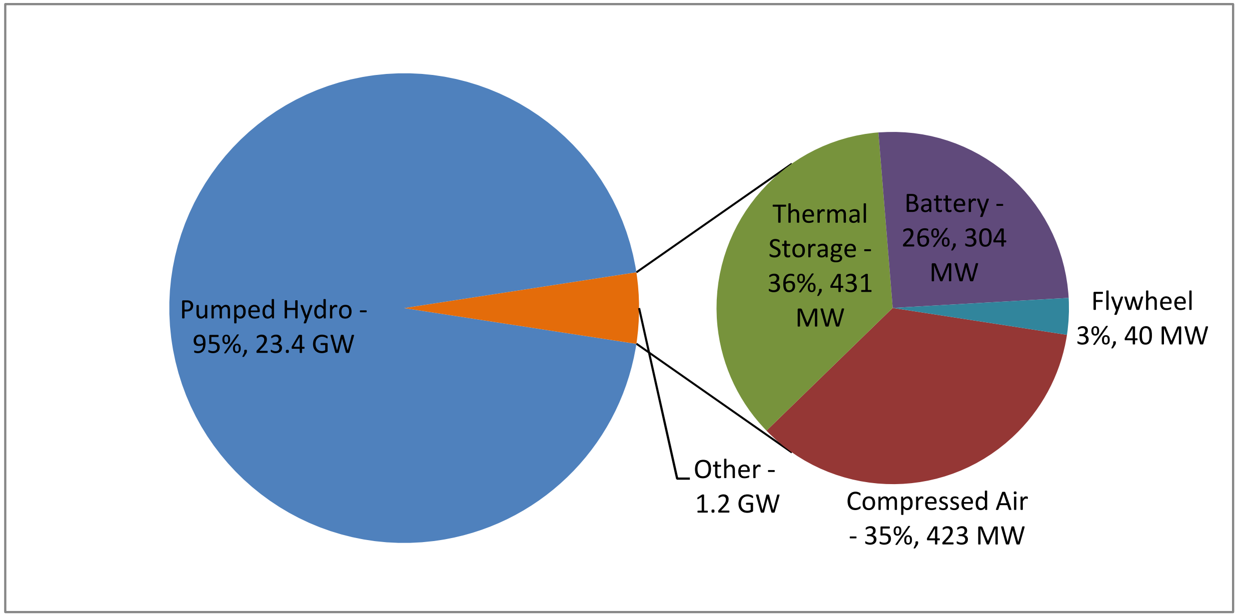
Current utility scale storage

Figure 1 – Rated Power of US Grid Storage projects (includes announced projects)



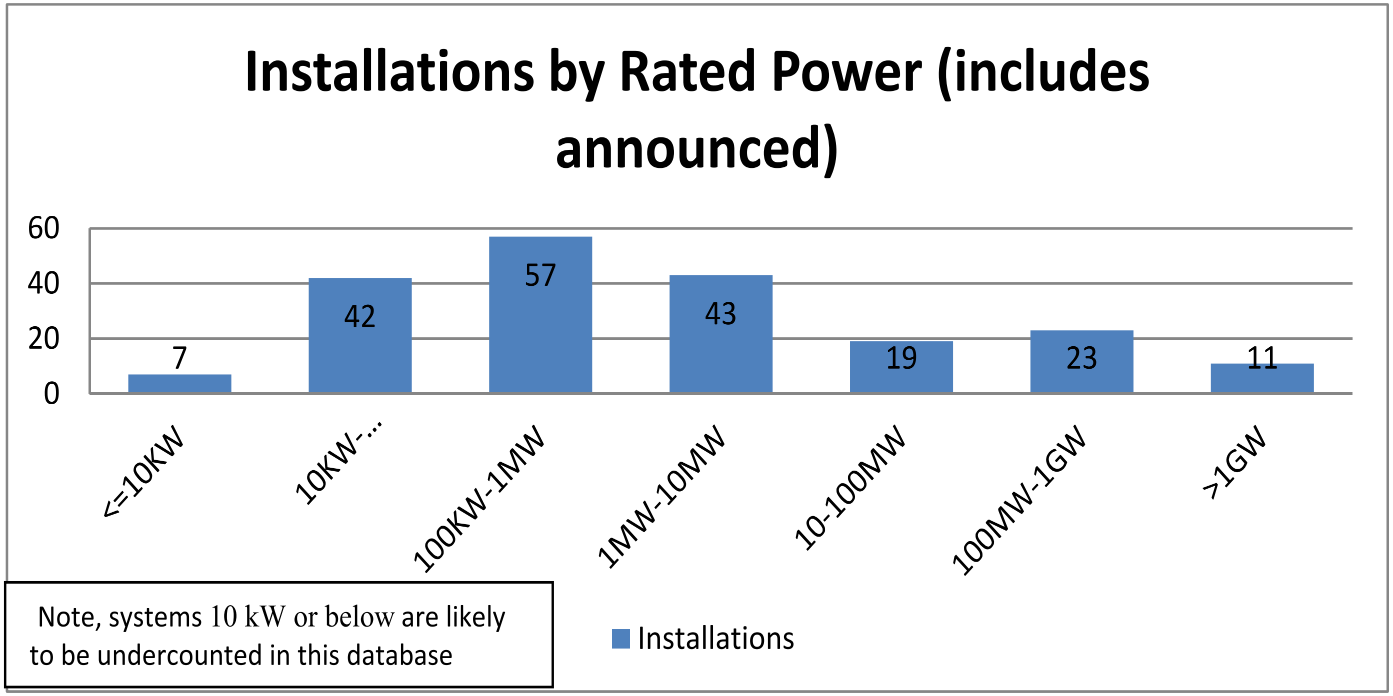
As of December 2013

- Total U.S. electricity summer capacity in 2014: 1,068.4 GW
- Average U.S. electrical power use in 2015: 466.6 GW

Grid Energy Storage: U.S. Department of Energy, December 2013
https://en.wikipedia.org/wiki/Electricity_sector_of_the_United_States

Current utility scale storage

Figure 2 – Number of US installations, grouped by capacity



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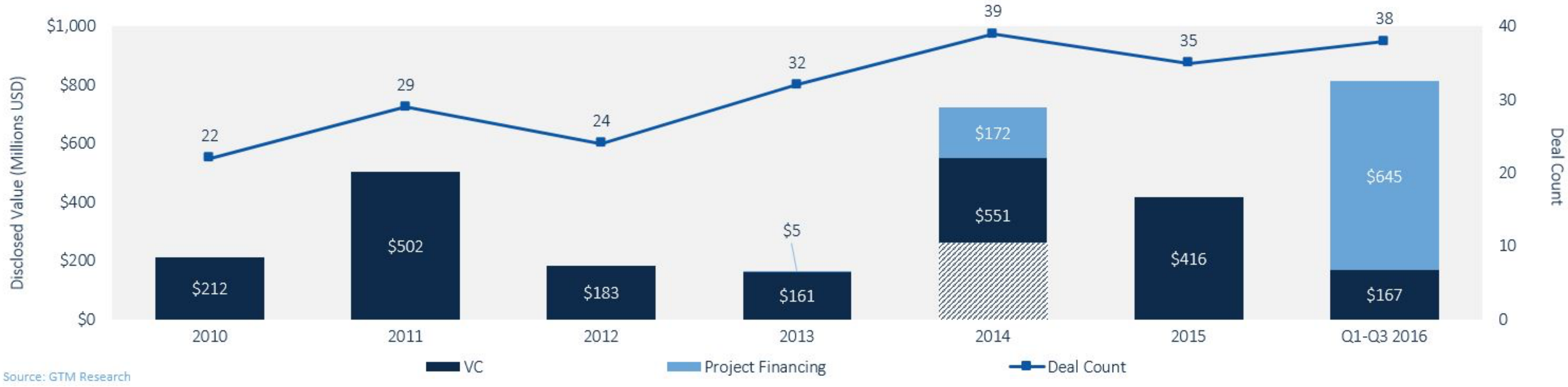
Investments in energy storage

Disclosed Corporate Investments in Energy Storage, 2010-Q3 2016 (Millions USD)



U.S. Annual Energy Storage Deployment Forecast, 2012-2021E (MW)

https://www.greentechmedia.com/articles/read/corporate-investments-in-energy-storage-at-660-million-in-q3-2016

Investments in energy storage

- Q3: U.S. deployed 16.4 MW of energy storage in Q3 2016
- 96.2% lithium-ion batteries.
- 86% behind-the-meter segment - residential and commercial deployments.

https://www.greentechmedia.com/articles/read/corporate-investments-in-energy-storage-at-660-million-in-q3-2016

Utility Scale Storage Requirements

- California: State law passed 2010, implementation 2013.
  - Requires California's three largest power generating utilities to contract for an additional 1.3 GW of energy storage power generation (meeting certain criteria) by 2020, coming online by 2024. Excludes pumped hydro.
- Oregon: State law passed 2015 requiring the state's main electricity providers, to have a minimum of 5 MWh of energy storage in service by January 1, 2020.
- The Massachusetts Department of Energy Resources (DOER) will adopt specific energy storage targets by July 1, 2017, and the targets would take effect by Jan. 1, 2020.

http://www.utilitydive.com/news/massachusetts-doer-will-set-energy-storage-mandate-targets-by-july/433138/
https://cleantechnica.com/2016/08/12/massachusetts-passes-3rd-us-energy-storage-mandate/

California storage projects announced or underway

- 3.1 GW total.
- 2.6 GW or 84% comes from projects not counted in the mandate, e.g. pumped hydro.

Infrastructure company AES completed array

Tesla completed array

Infrastructure company AES installing

Project Name	Technology Type	MW Output	Duration (Hrs)
Eagle Mountain Pumped Storage Project	Closed-loop Pumped Hydro Storage	1300	n/a
Lake Elsinore Advanced Pumped Storage	Closed-loop Pumped Hydro Storage	500	12.0
San Vicente Pumped Storage	Closed-loop Pumped Hydro Storage	500	8.0
PG&E Underground Compressed Air Energy Storage (CAES)	In-ground Compressed Air Storage	300	10.0
AES Alamitos Energy Storage Array	Lithium-ion Battery	100	4.0
Stem 85 MW Western Los Angeles Basin	Electro-chemical	85	n/a
AMS 50 MW Hybrid-Electric Buildings	Electro-chemical	50	n/a
Convergent 35 MW / 140 MWh - SCE	Lithium-ion Battery	35	4.0
Golden Hills - NextEra Energy	Lithium-ion Battery	30	2.0
SDG&E Escondido Substation - AES	Lithium-ion Battery	30	4.0
Ice Energy procurement from SCE's November 2014 LCR	Ice Thermal Storage	25.6	6.0
20 MW / 80 MWh - Energy Nuevo - Amber Kinetics	Flywheel	20	4.0
SDG&E / Hecate Energy Bancroft - (San Diego, CA)	Lithium-ion Battery	20	4.0
AltaGas Pomona Energy - SCE / Greensmith	Lithium-ion Battery	20	4.0
Aliso Canyon SCE Mira Loma Substation - Tesla	Lithium-ion Battery	20	4.0
10 MW - PG&E Molino Substation- Hecate Energy	Lithium-ion Battery	10	2.0
Kings County Energy Storage - PG&E Henrietta Substation	Zinc Air Battery	10	4.0
SDG&E El Cajon Substation - AES	Lithium-ion Battery	7.5	4.0
Riverside Public Utilities 5 MW Ice Energy Project	Ice Thermal Storage	5	6.0
Riverside Public Utilities 5 MW Ice Energy Project	Ice Thermal Storage	5	6.0
Western Grid Development - SCE	Lithium-ion Battery	5	4.0

http://www.renewableenergyworld.com/articles/2016/11/at-the-halfway-point-the-effect-of-california-s-energy-storage-mandate.html

Discussion Questions

- Will vanadium or other flow batteries surpass lithium ion as the utility scale grid storage? Is the Li-ion battery market too powerful and will push out flow batteries?

- Will the growth of renewables, in particular solar and wind energy, force commercial production of large scale storage?

- Does the levelized cost of renewables + storage need to be cheaper than peaker plants before storage grows significantly?

References – Links #1

Washington state’s new 8 megawatt-hour flow battery is the largest of its kind
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Massachusetts DOER will set energy storage mandate targets by July
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Massachusetts Passes 3rd US Energy Storage Mandate
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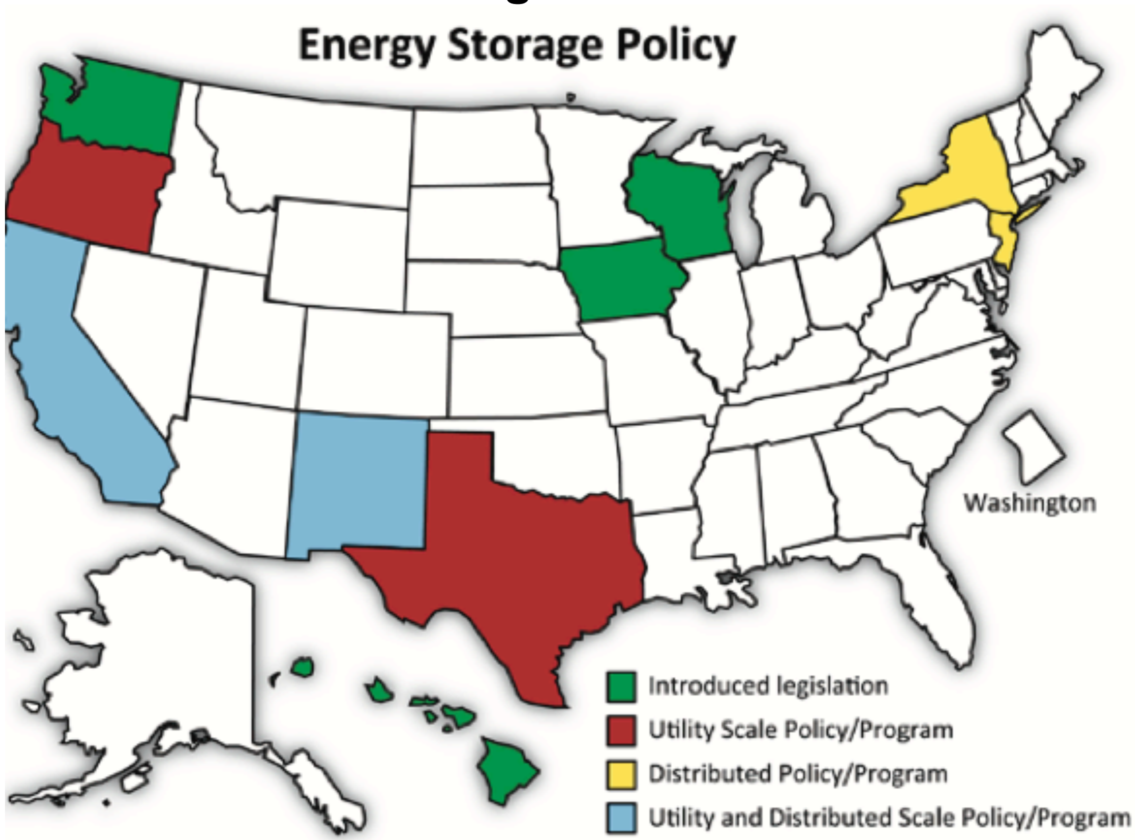
http://www.renewableenergyworld.com/articles/2016/11/at-the-halfway-point-the-effect-of-california-s-energy-storage-mandate.html

NREL: Issue Brief: A Survey of State Policies to Support Utility-Scale and Distributed-Energy Storage
http://www.nrel.gov/docs/fy14osti/62726.pdf

Utility and Distributed Storage Policies (not necessarily storage mandates)

As of August 2014



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