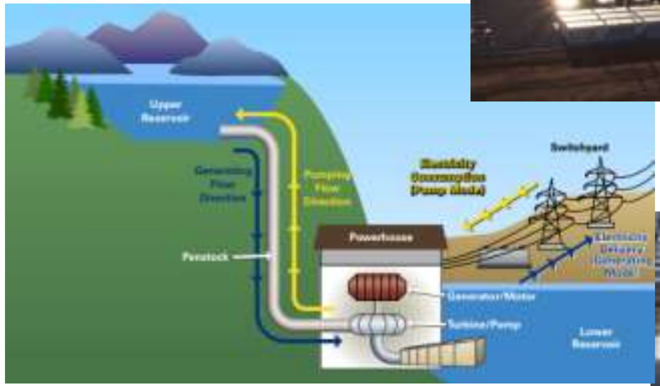
Grid-Scale Energy Storage Systems and Technologies



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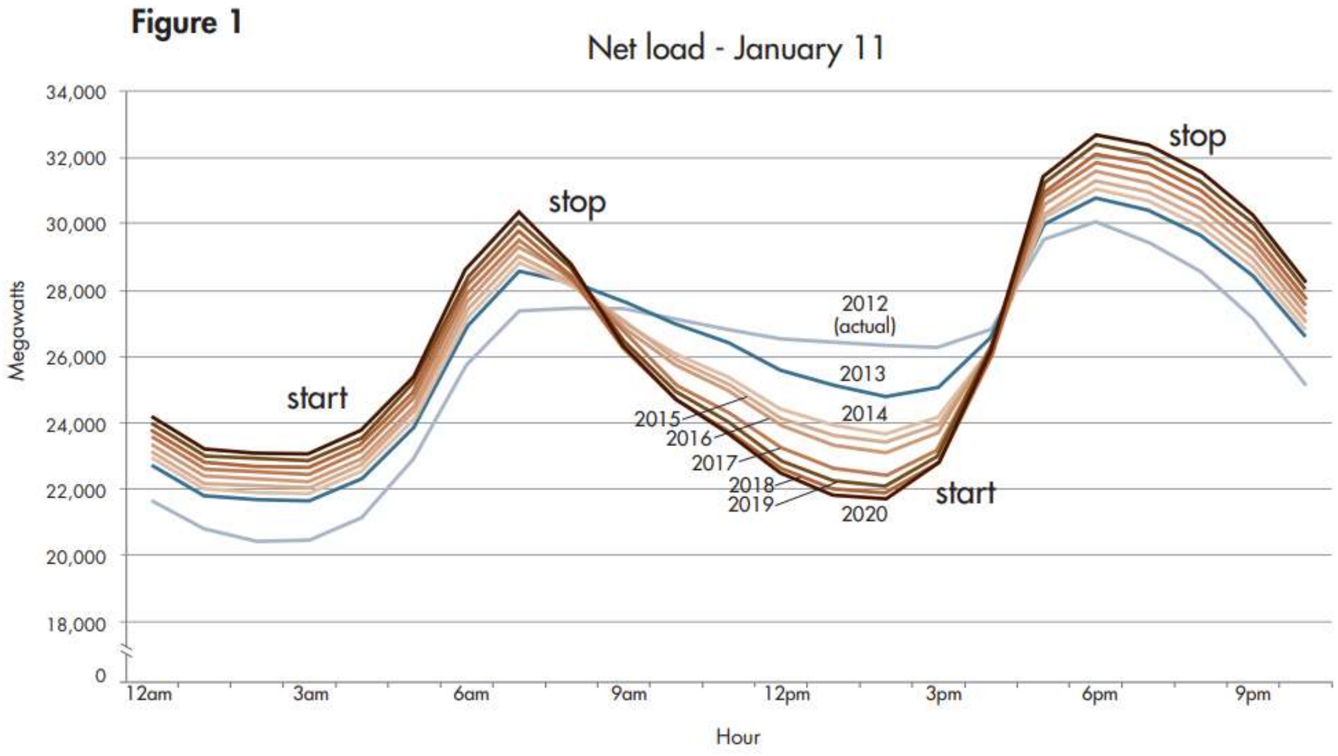
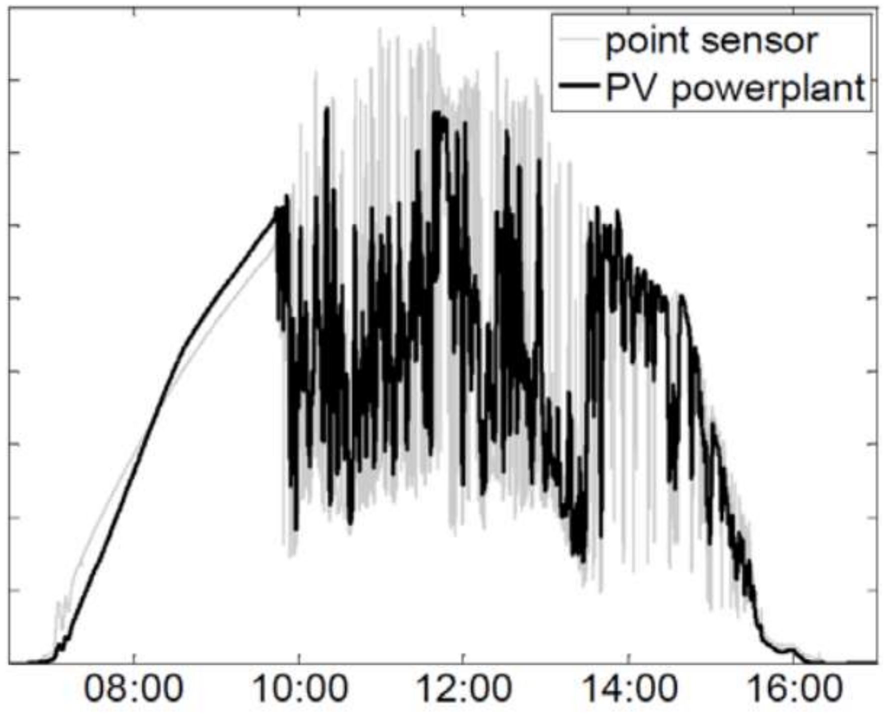
The Need for Energy Storage: Renewables



"Duck" Curve

Source: CAISO (2016)



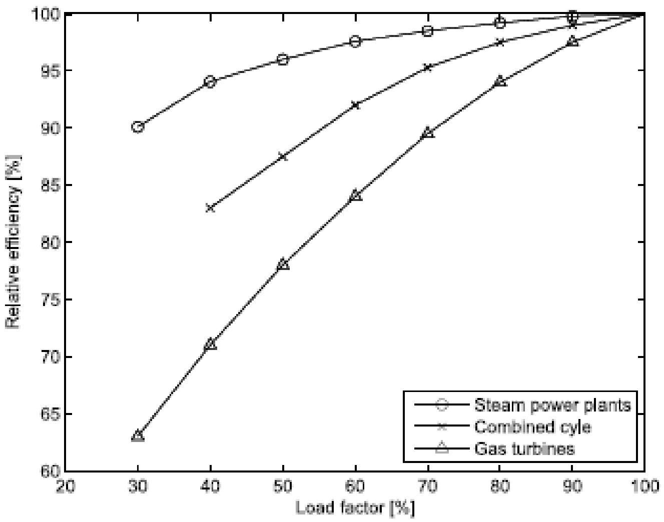
PV Plant Variability

Source: Byrne (2016)

Penetration of renewables into energy supply adds significant instantaneous, hourly, and seasonal variability while also displacing spinning reserve capacity

The Need for Energy Storage: Fossil/Nuclear

- Baseload generation technologies have poor transient capability
- Reduced off-design performance



Efficiency Penalty at Reduced Load

Image Source: Van den Bergh and Delarue (2015)

Technology	Design Point Plant Efficiency	Hot Startup Time (h)
Simple-Cycle Gas Turbines	35-40%	0.16
NG Combined-Cycle Turbine	56-60+%	2
IG Combined-Cycle Turbine	38-44%	6-8
Pulverized Coal - Steam	37-43%	3
Nuclear Steam	30-33%	24

Data Sources: Van den Bergh and Delarue (2015)
Gonzalez-Salazar *et al* (2017)
EIA 2017 Data, https://www.eia.gov/electricity/annual/html/epa_08_02.html, (2019)

Energy Storage Technology Overview

- Battery Storage
  - Solid-State Batteries
  - Flow Batteries
- Mechanical Storage
  - Pumped hydro
  - Gravitational
  - Compressed Air
  - Liquid Air
  - Flywheel
- Thermochemical Storage
  - Hydrogen
  - CO2 Phase Change
  - Synthesized Fuels
- Thermal Storage
  - Molten salt/refrigerant
  - Pumped thermal energy storage

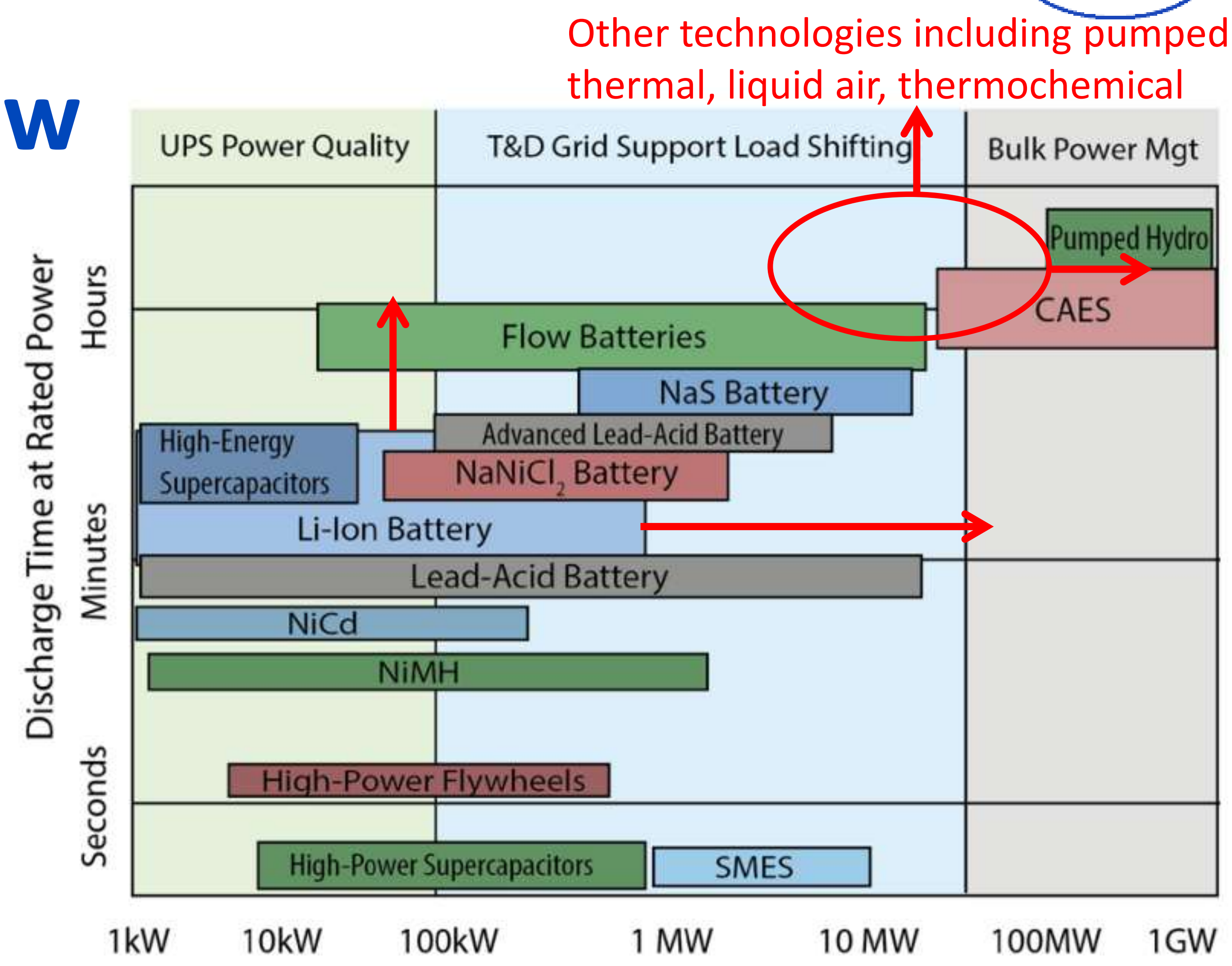
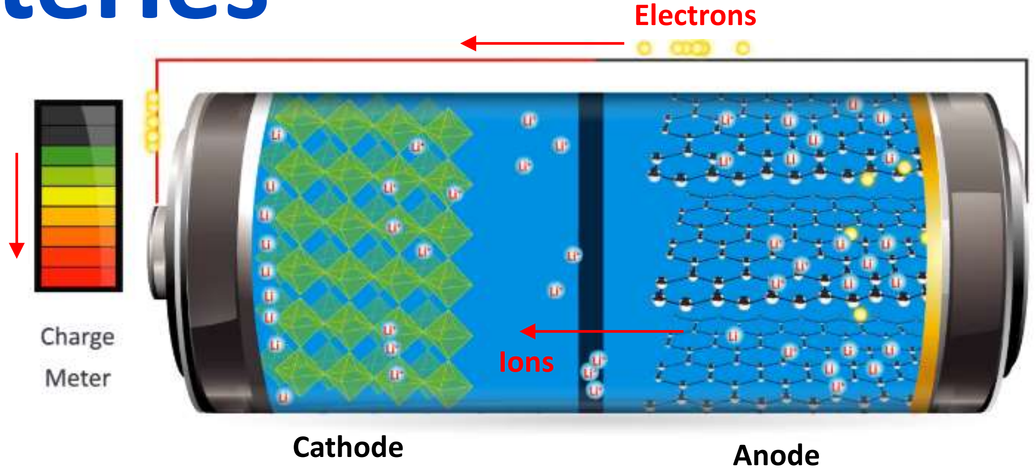


Image Modified From:
http://css.umich.edu/sites/default/files/U.S._Grid_Energy_Storage_Factsheet_CSS15-17_e2018.pdf

Battery ES: Solid-State Batteries

- Working Principles
  - Lithium ion movement between electrodes via electrolyte creates charge and electrical current
- Chemistries
  - Lead Acid and Li-ion are most popular
  - Sodium Sulfur, Zinc Hybrid, Sodium Nickel Chloride also considered
- Round-trip efficiency a function of charge/discharge profile
  - 65-75% for 30-min discharge
  - 75-85% for 2-hour discharge
  - Up to 97%



https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work

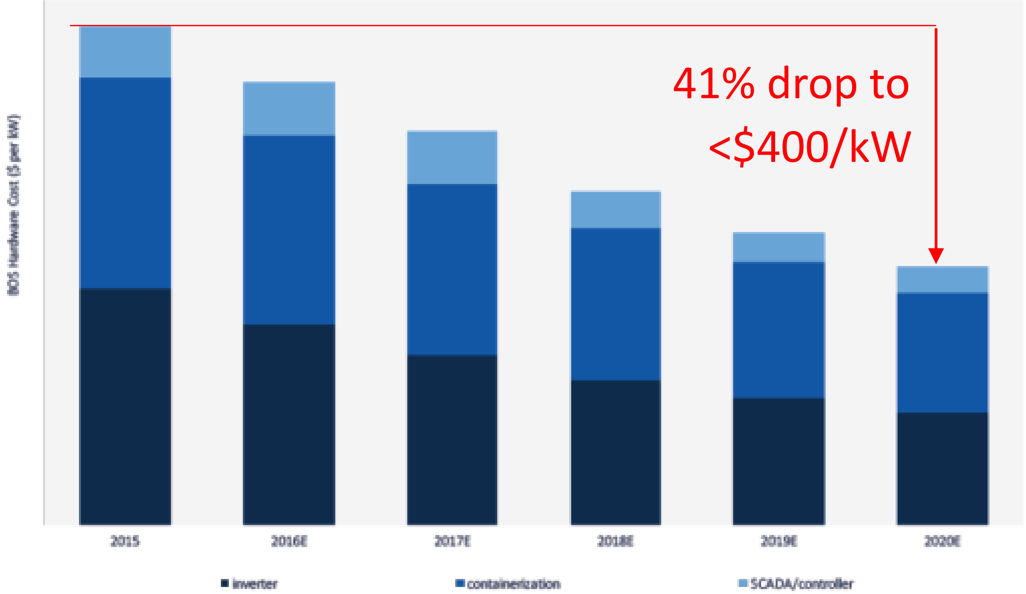
Tesla 100 MW/129 MWh Powerpack

https://electrek.co/2018/09/24/tesla-powerpack-battery-australia-cost-revenue/

Data Source: https://www.energystoragenetworks.com/three-battery-types-work-grid-scale-energy-storage-systems/

Battery ES: Solid-State Batteries

- Turbomachinery Integration
  - Coupled to wind turbine (and PV) farms
  - Pairing with gas turbine peaker plants for improved response time/spinning reserve classification
- Current TRL
  - TRL 9, Many commercial options. Li-ion batteries have ~95% grid-scale market share
- Technology Gaps
  - Long-term durability
  - Scalable cost
  - Material availability (cobalt, others)
- R&D Activities
  - Cost reductions, longevity, power density improvements, battery system management, hazard assessment, abuse/environmental testing, re-use



Adapted from: GTM Research (2015)


Battery environmental and abuse testing

Data Source: https://www.energystoragenetworks.com/three-battery-types-work-grid-scale-energy-storage-systems/

The Problem with Solid-State Batteries

- Battery costs increase linearly with storage duration
  - Cannot separate power and energy
- Other grid-scale technologies decouple power block from storage duration
  - Higher intercept, lower slope

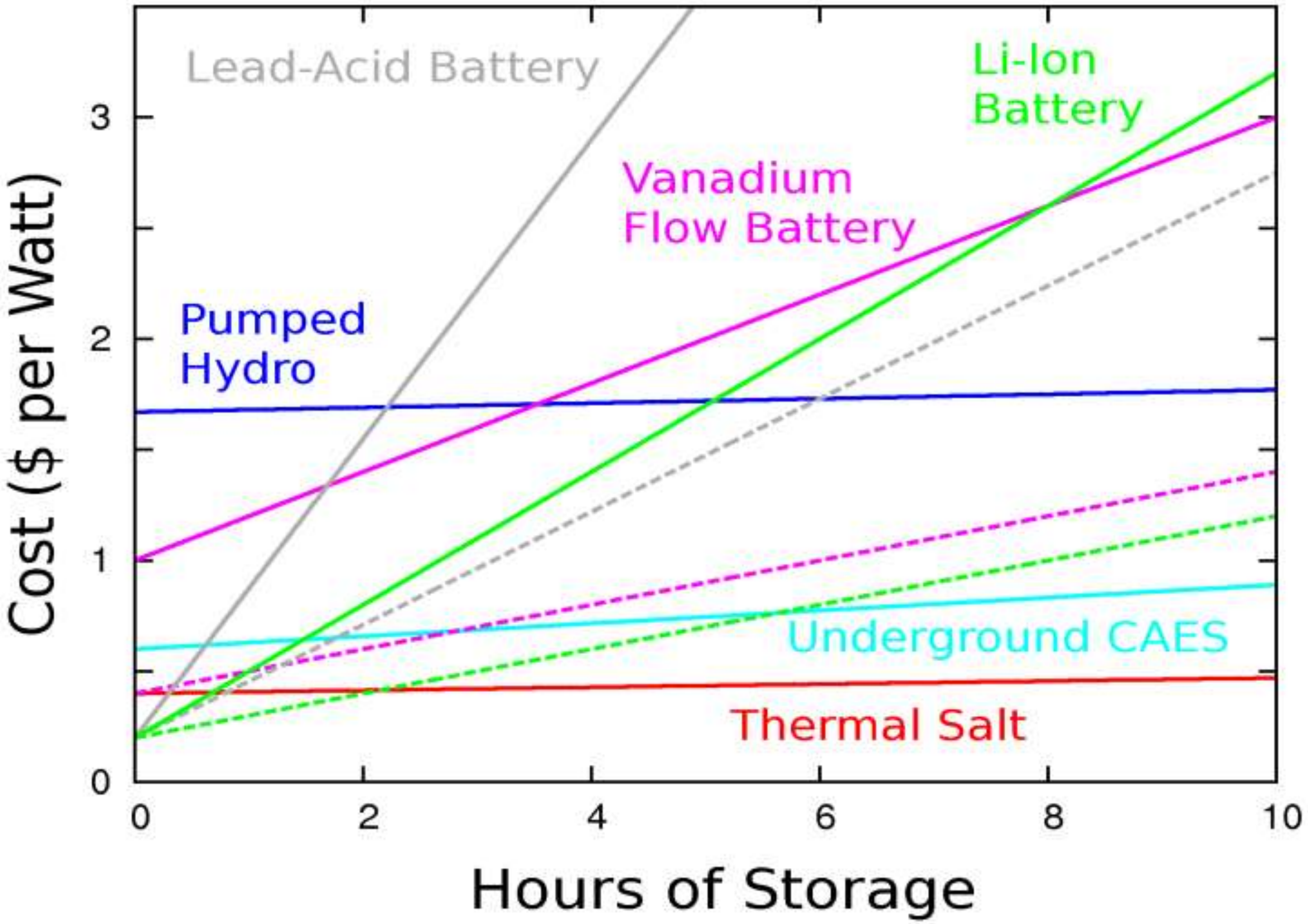
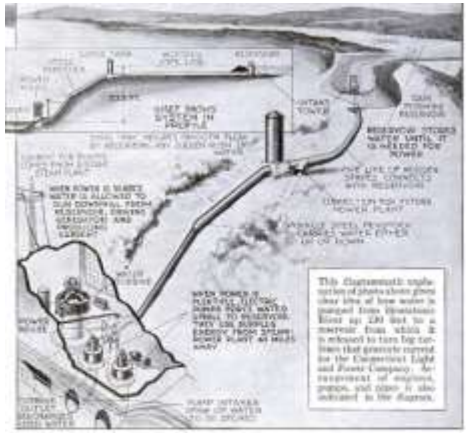


Image Source: Laughlin (2019)

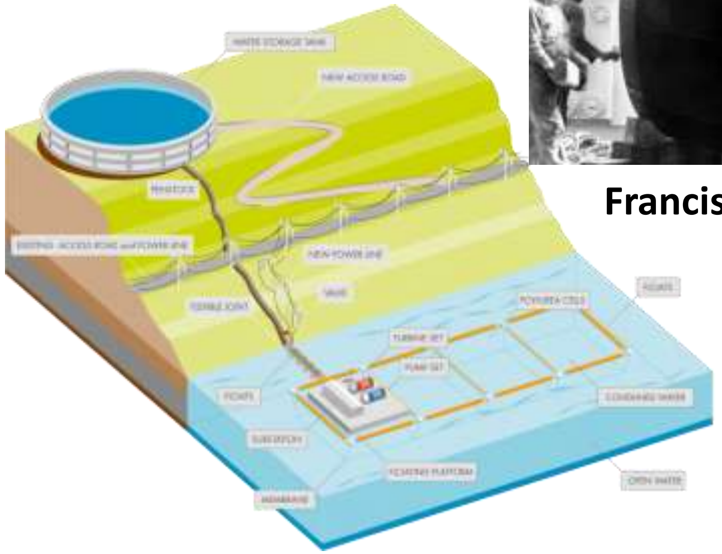
Mechanical ES: Pumped Hydro

- Current TRL
  - TRL 9, Decades of commercial experience
- Technology Gaps
  - Geography-specific concept -> siting limitations
- Expected Performance
  - 70-80%+ round trip efficiency (Energy Storage Association)
- R&D Activities
  - Subsurface/Subsea pumped hydro
  - Small modular PSH for cost-effectiveness
  - Variable speed/geometry pump/turbines



World's First PSH System, 1930

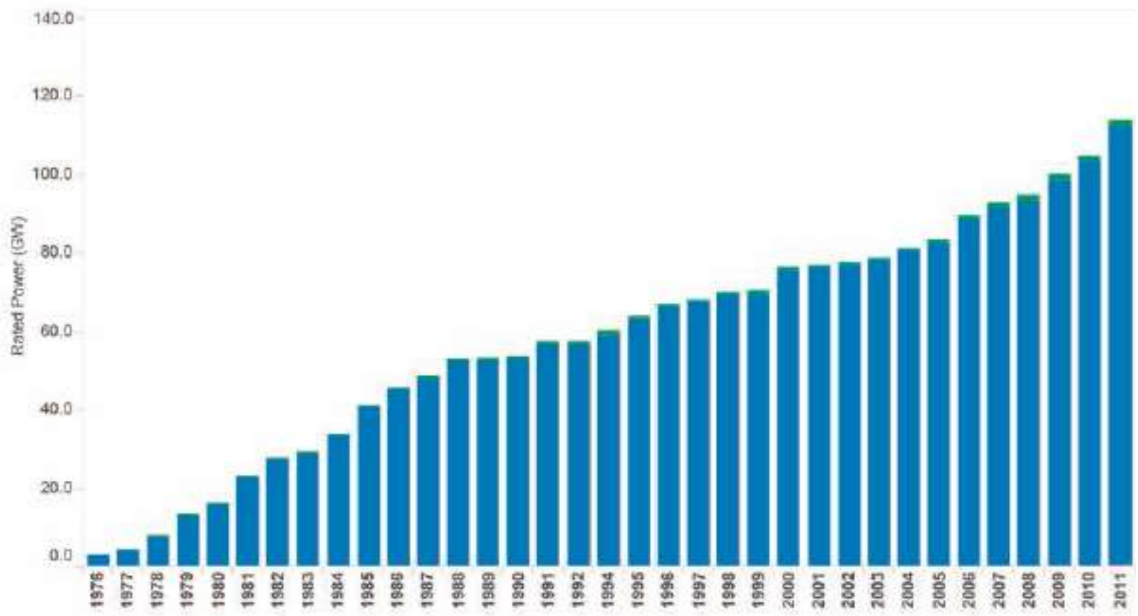
Francis Turbine Runner, 1942



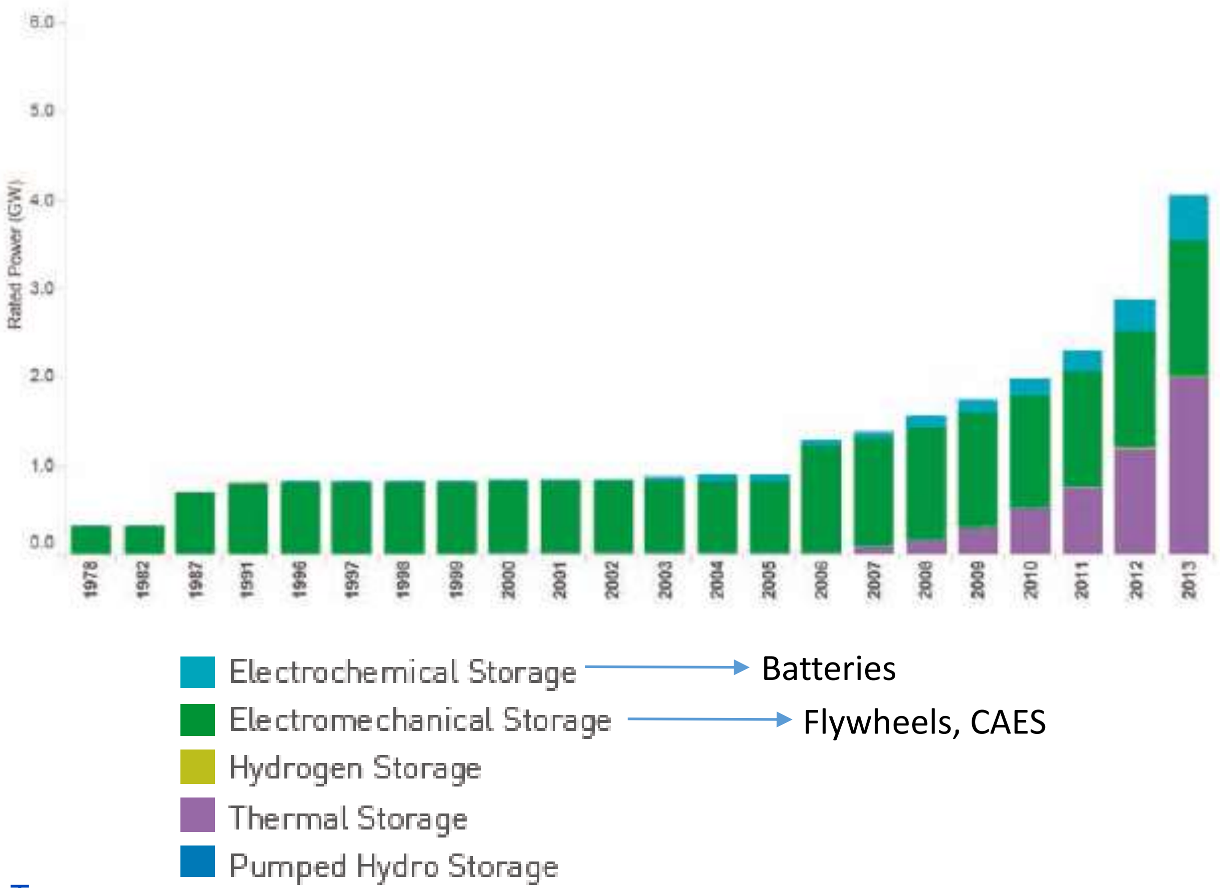
Shell Power 5 MW Hydro Battery

Global Energy Storage Timeline

Global Energy Storage Project Installations



Global Energy Storage Project Installations – excluding PHS



Data and Images from EASE/EERE (2017)

Global Energy Storage Technology Breakdown

Technology Types

Technology Type	Projects	Rated Power (MW)
Thermal Storage	220	3275
Electro-chemical	994	3301
Pumped Hydro Storage	351	183007
Hydrogen Storage	13	20
Liquid Air Energy Storage	2	5

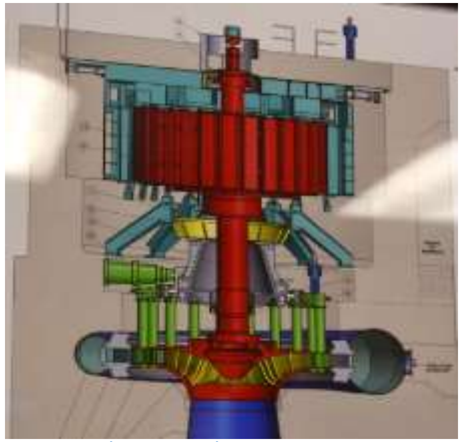
Pumped Hydro is Dominant Technology, Followed by Thermal (CSP) and Electro-Chemical (Battery)

Image Source: https://www.energystorageexchange.org/projects/data_visualization

Application – Pumped Hydro

- World's largest energy storage system at 3003 MW, 24 GWh
- Completed 1985
  - Six Francis pump-turbines from Voith-Siemens
- Water levels change 105/60 feet in upper/lower reservoirs
- Pumping/generating flow rates of 12.7/13.5 million GPM
- 79% RT Efficiency, 6 minute response

Bath County Pumped Storage Station (above) and turbine-generator (below)



Data source: https://www.dominionenergy.com/about-us/making-energy/renewable-generation/water/bath-county-pumped-storage-station

Image Sources: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world?v=preview https://www.bdtonline.com/news/the-quiet-giant-tells-the-story-pumped-hydroelectric-facility-tour/article_a921e92e-b6cd-11e7-81dd-733d166d4f37.html

Applications – Grid-Scale Solid-State Batteries

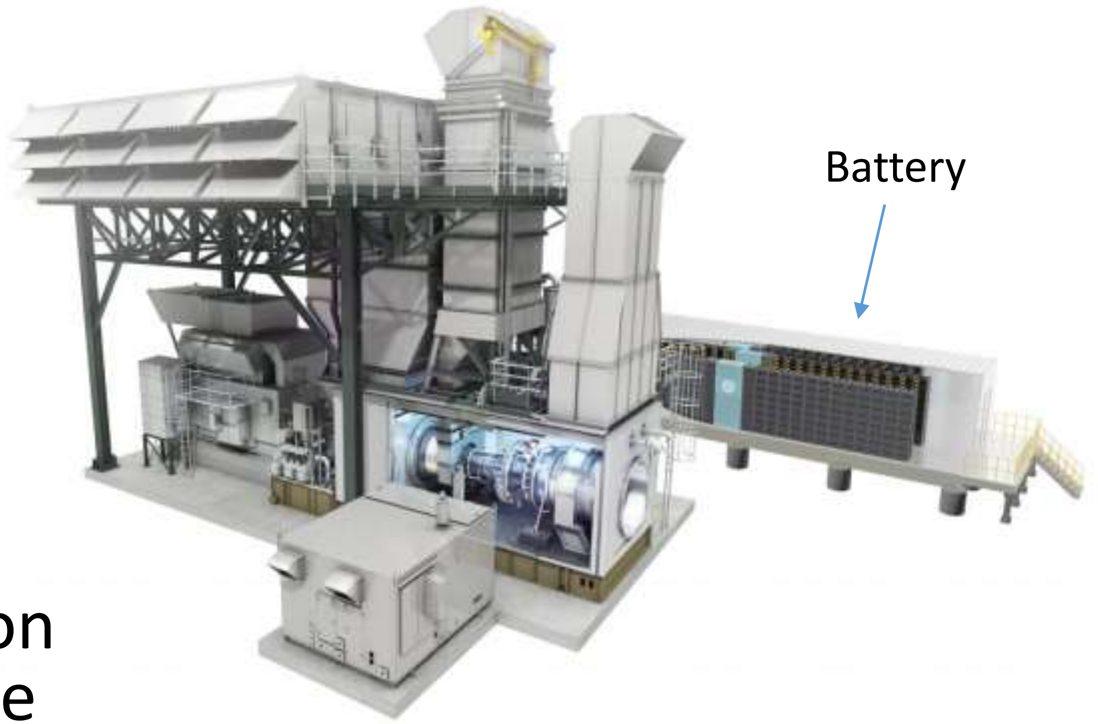
- Hornsdale Wind Farm Plus Power Reserve (AUS)
  - Li-ion, 100 MW, 129 MWh
  - Operational in December 2017
  - 70 MW / 10 min for grid stability
  - 30 MW / 3 hours for load shifting
  - 80% round-trip efficiency
  - <150 ms response

https://electrek.co/2018/09/24/tesla-powerpack-battery-australia-cost-revenue/

Data and Image sources:
https://reneweconomy.com.au/the-stunning-numbers-behind-success-of-tesla-big-battery-63917/
Aurecon (2018)

Application – Gas Turbine + Battery Storage

- Southern California Edison
- GE LM6000
  - 50 MW
  - 5 min ramp to full power
- Li-ion battery storage
  - 10 MW, 4.3 MWh
- Control system allows seamless transition from battery to turbine, enabling turbine stop during standby
- Online in April 2017



Data and Image sources:
https://www.ge.com/reports/batteries-included-hybrid-power-plants-let-californians-breathe-easy/
https://www.powermag.com/sce-ge-debut-battery-gas-turbine-hybrid-system-2/

Summary

- Batteries offer a cost-effective solution for near-term storage (e.g. minutes to < 2-3 hours)
  - Critical R&D needed for grid-scale adoption includes:
    - Further cost reductions and life improvement, energy density, and round-trip efficiency (at high rates) for all technologies
- Other technologies under development for cost-effective longer-term storage
  - Many promising longer-duration concepts under development (Advanced CAES, Pumped Thermal, Liquid Air, Hydrogen, others)
    - kW-scale demonstrators, MW-scale pilots
    - Turbomachinery improvements
    - Controls/system development
    - Integrated/hybrid systems with existing power plants

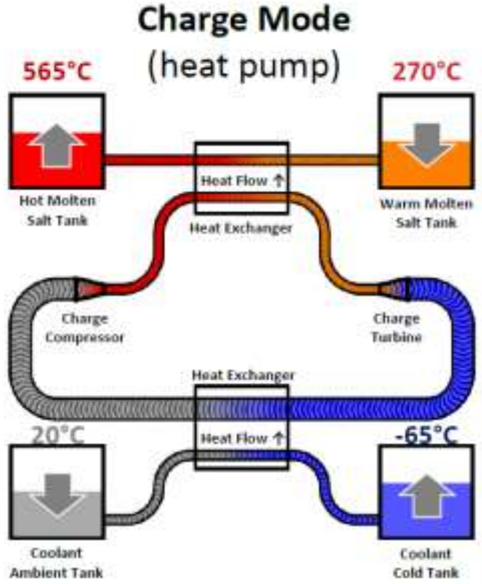


Image Source: Malta (2019) and Highview Power (2019)

Questions?