Overview of Energy Storage Technology, Challenges, and Emerging Practices

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Pacific Northwest National Laboratory

Maine Energy Storage Commission Workshop

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Agenda

- Energy Storage Program Overview
- Technology and Trends
- Challenges to Energy Storage in Resource Planning
- Emerging Planning Practices for Energy Storage
- Overview of State-Level Policies on Energy Storage

Energy Storage Program Overview

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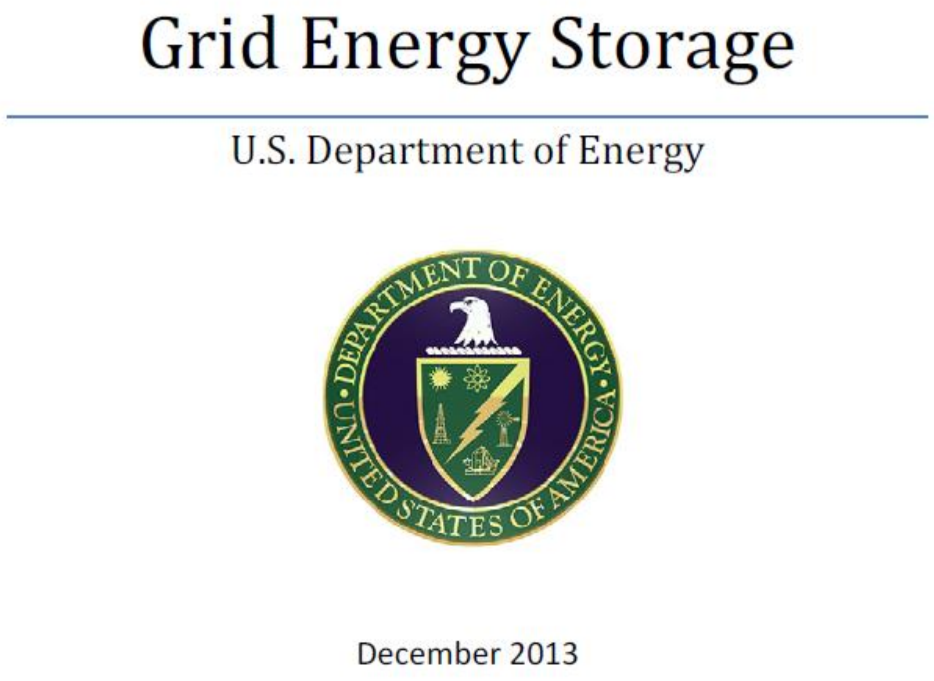
The Department of Energy's Grid Energy Storage report (2013) identified a four-pronged strategy to facilitate energy storage deployment:

- Cost-competitive energy storage technology development;
- Validated reliability and safety;
- Equitable regulatory environment; and
- Industry acceptance

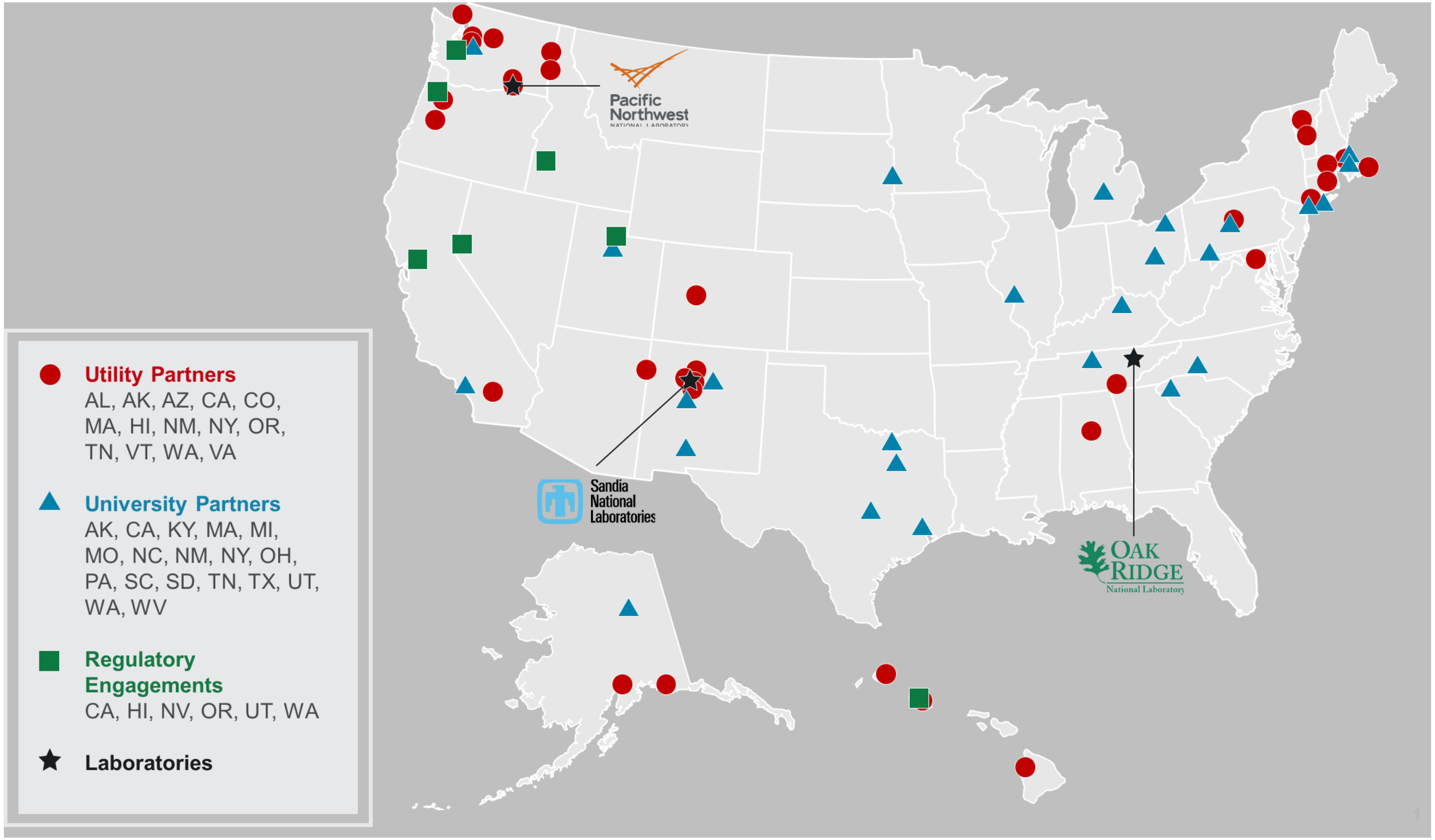

Grid Energy Storage

U.S. Department of Energy

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

December 2013

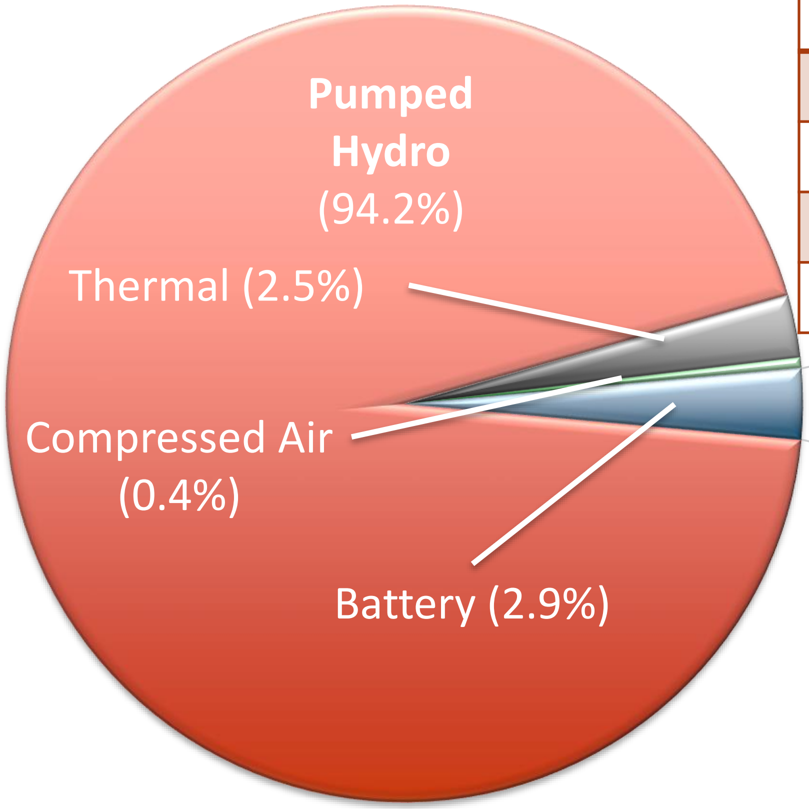
Energy Storage Program Engagements



Energy Storage Technologies and Trends

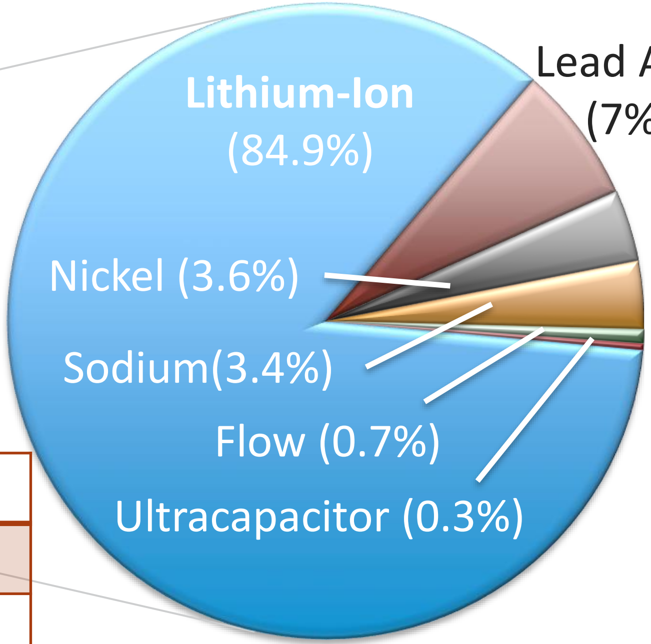
Current Installed Capacity – U.S.

Total Energy Storage Capacity



Pumped Hydro	24.5 GW
Battery	0.7 GW
Thermal	0.7 GW
Compressed Air	0.1 GW
Total	**26 GW**

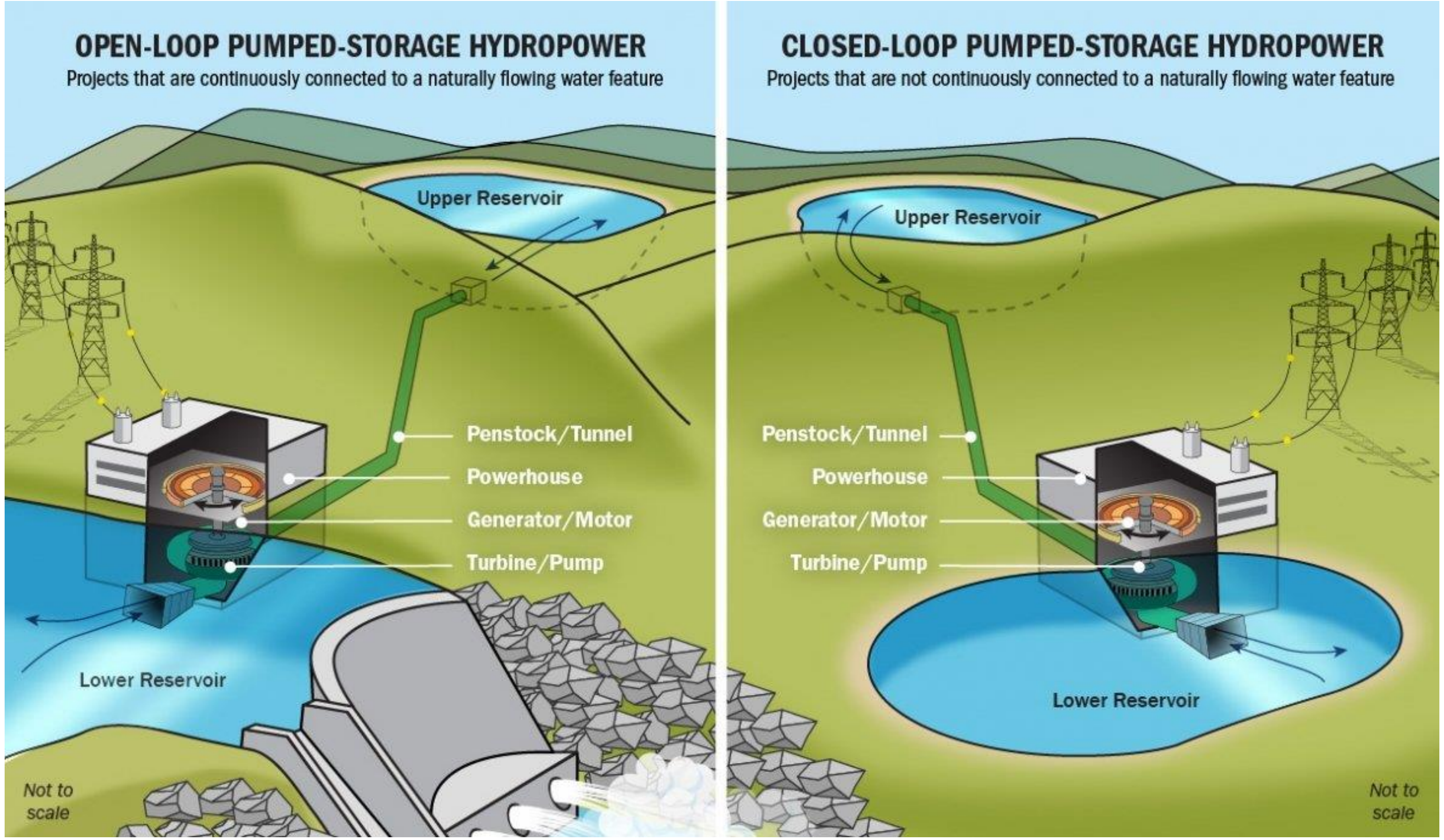
Total Battery Capacity



Lithium-Ion	631 MW
Lead Acid	52 MW
Nickel	27 MW
Sodium	26 MW
Flow	5 MW
Ultracapacitor	2 MW

Source: DOE Global Energy Storage Database, https://energystorageexchange.org/.

Pumped Storage - Overview

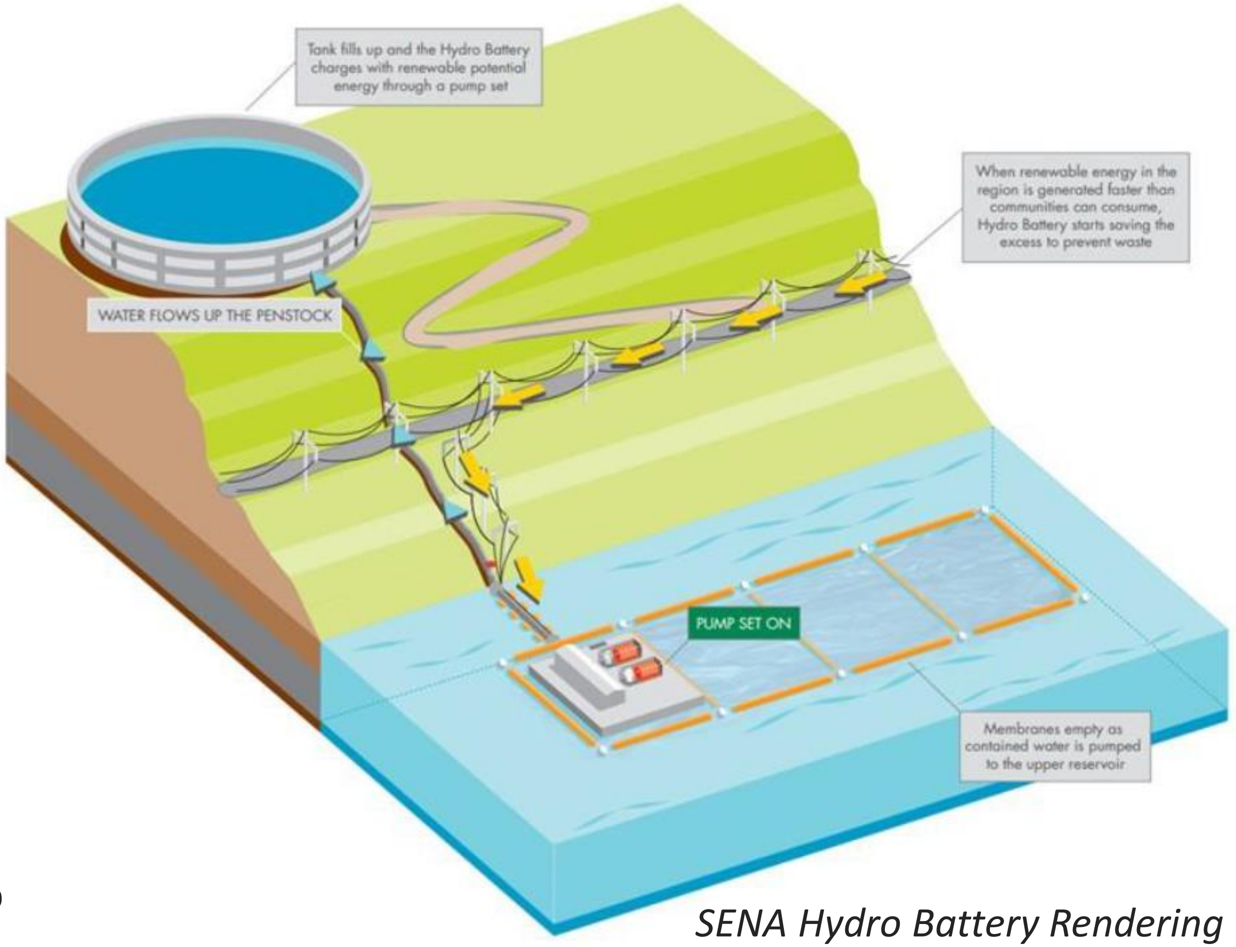


U.S. Department of Energy Water Power Technologies Office, https://www.energy.gov/eere/water/pumped-storage-hydropower.

- **Advantages**
  - Very long duration (hours/days)
  - Very high capacity (GW scale)
- **Challenges**
  - High capital costs
  - Permitting requirements
  - Geographic requirements
- **Key applications**
  - Arbitrage
  - Long-duration storage
  - Transmission

Pumped Storage – A Modular Approach

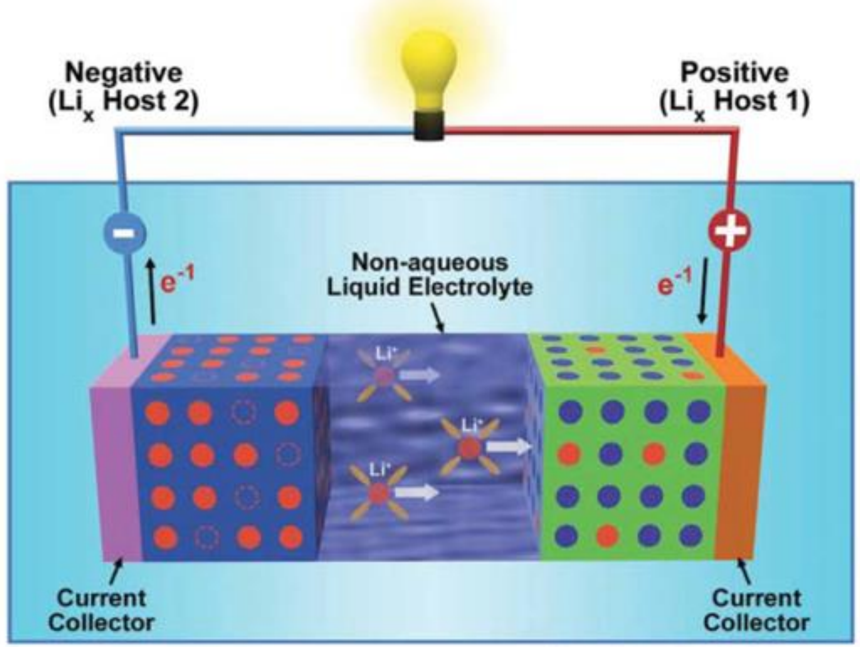
- Shell Energy North America (SENA) "hydro battery" – 5 MW (9 MW pumping capacity) / 30 MWh
- Four operating modes
  - Generating mode
  - Pumping mode
  - Spin reserve mode
  - Standby
- Can be configured as closed-loop or open-loop
- Upper reservoir: A lined corrugated steel tank with a 26.5 acre-foot (AF) operating volume
- Lower reservoir: A flexible sealed membrane floating in an existing body of water
- Penstock: A single 36 inch carbon steel pipe, which will deliver water between the reservoirs
- Generation and pumping efficiencies estimated at 84.49% and 79.55%, respectively
- Round trip efficiency estimated at 67.21%



SENA Hydro Battery Rendering

Batteries – Basic Terminology

- Electrochemical Cell: Cathode(+), Anode (-), and Electrolyte (ion conducting intermediate)
- Energy (kWh) = Voltage (V) difference between anode and cathode multiplied by amount of ion the electrodes are able to store - given as Ah of capacity
- Energy Density (Wh/kg or Wh/L): used to measure the energy density of battery.
- $/kWh = capital cost of the energy content of storage device.



Battery Technologies: Lithium-ion

- **Advantages**
  - High energy density
  - Moderate cycle life
  - Decreasing costs – Stationary applications benefit from EV demand
  - Multiple vendors
  - Fast response
  - High round-trip efficiency (80% range)

- **Challenges**
  - Reliance on rare-earth minerals
  - Safety
  - Performance/useful life dependent on usage

- **Key applications**
  - Short duration, high power (frequency response, spinning reserves, peak shaving)

SCE/Tesla 20MW -80MWh Mira Loma Battery Facility

SCE Tehachapi plant, 8MW - 32MWh.

Battery Technologies: Lead Acid

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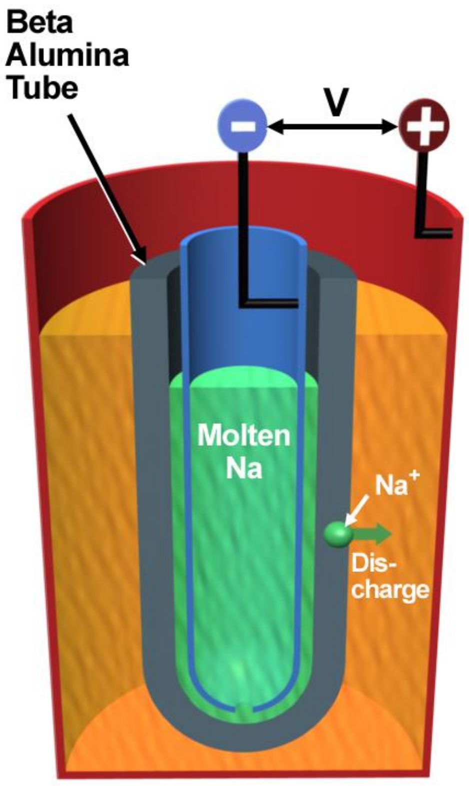
- **Advantages**
  - Low cost/multiple providers
  - Significant experience with the technology
- **Challenges**
  - Limited life (500 – 1,000 cycles)
  - Rapid degradation at deep discharge
  - Low energy density
  - Limited flexibility – overcharging/prolonged storage can ruin the chemistry
  - Recent advances are addressing many of these challenges
- **Key applications**
  - Arbitrage
  - Light-duty applications (car battery, emergency backup)

EastPenn Ultra Battery:
90% capacity at 20,000 cycles

Battery Technologies: Sodium Metal

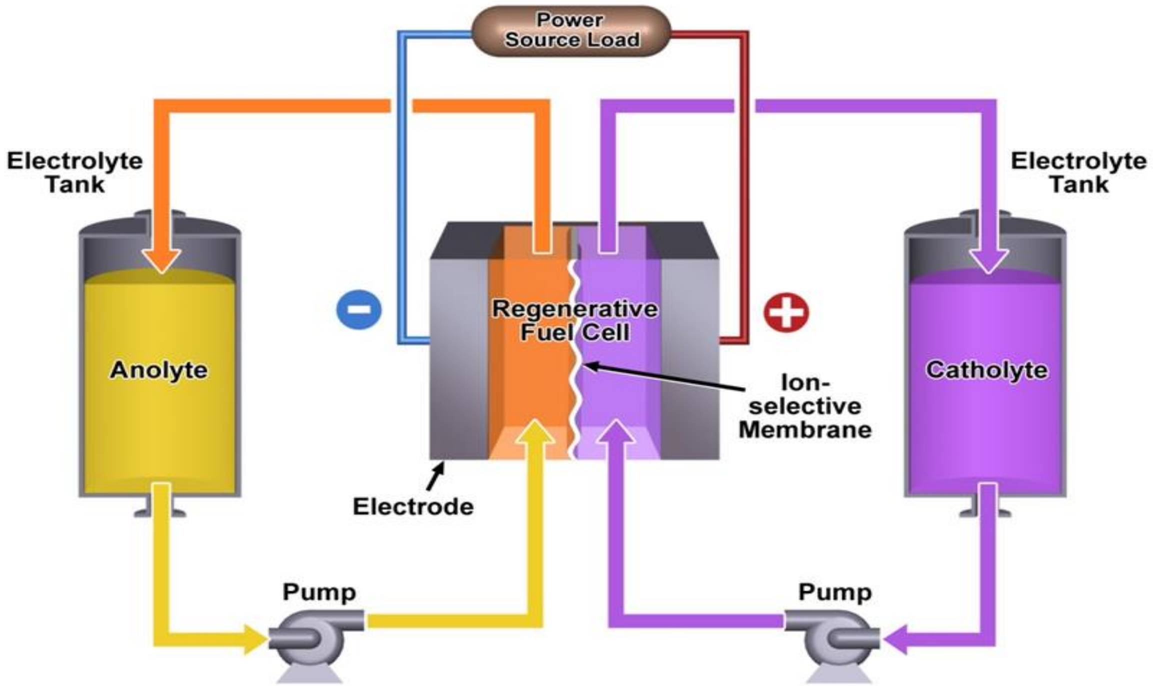
Sodium chemistries invert traditional battery structure, using a solid electrolyte and a semisolid (molten) anode

- **Advantages**
  - Low-cost, abundant materials
  - Good energy density
  - Long duration (4-6 hours)
- **Challenges**
  - Very high operating temperatures (300 – 350 degrees Celsius)
  - Potential for thermal runaway
- **Key applications**
  - Arbitrage
  - Capacity



Battery Technologies: Flow

- **Advantages**
  - Long life, deep cycling
  - Power/energy decoupling
  - High recyclability
  - Safe – no fire risk, weak acid
- **Challenges**
  - Limited experience
  - Complicated design
  - Lower energy density
  - Lower round-trip efficiency (60-70%)
- **Key Applications**
  - Ancillary services
  - Peak shaving
  - Arbitrage



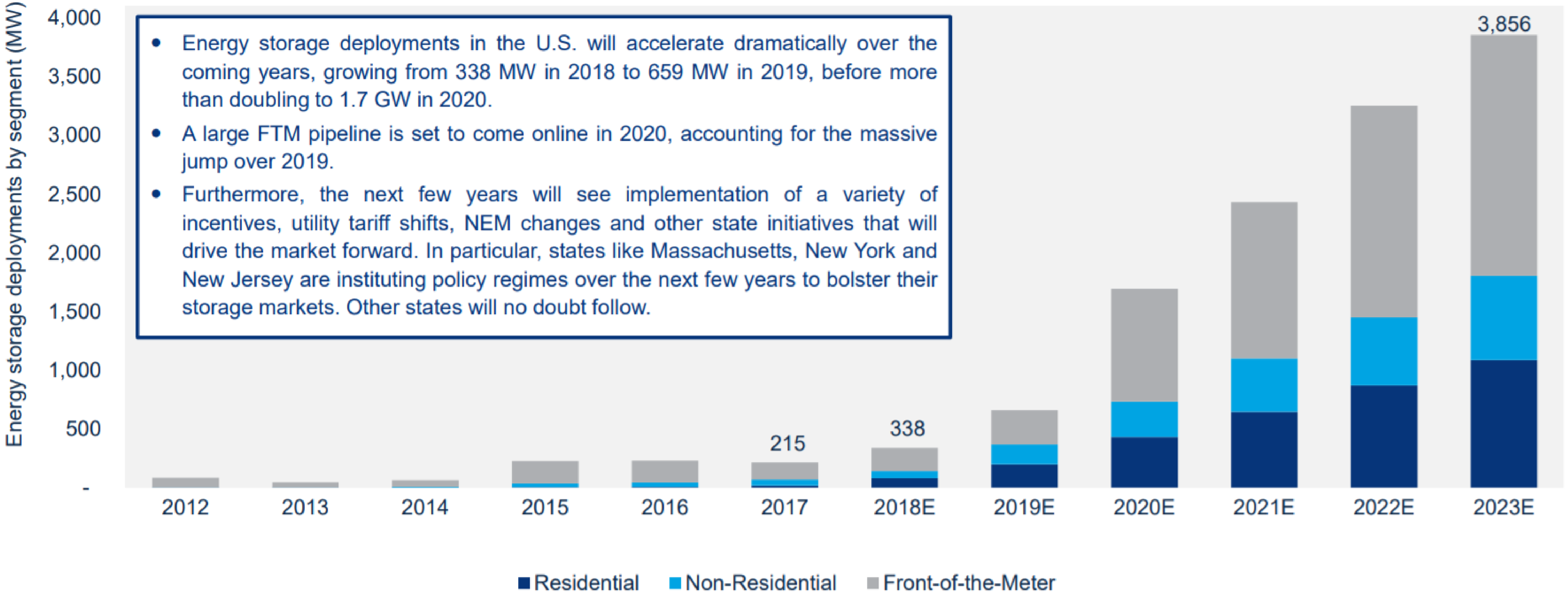
Basic flow battery schematic. Vanadium-based chemistries are most common, but other chemistries (iron, etc.) also exist.

DOE's Battery R&D Efforts

Conceptually, DOE-sponsored energy storage R&D is focused on developing technologies that rely on earth-abundant materials to reduce costs and environmental impacts

- Flow batteries: organic chemistries
  - Organic compounds have been proven in concept, but have poor energy density and limited cycle life
- Sodium batteries: reduced operating temperature; solid-state technologies
  - Recent breakthroughs have lowered operating temperature from 300°C to 110°C, but with limited cycle life
  - Solid-state batteries don't rely on molten sodium, but have very low energy density and very limited cycle life
- Metal-air batteries: improving rechargeability
  - Very early stage research; limited rechargeability (~5%) and limited cycle life (~200 cycles)
  - Abundant and semi-abundant materials (zinc, lithium); significantly reduced flammability

Installation Trends

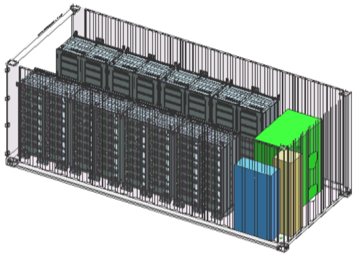


Source: Wood Mackenzie Power & Renewables, U.S. Energy Storage Monitor Q4 2018

Elements of Battery Energy Storage

Cell

- Storage device
- Battery Management & Protection (BMS)
- Racking
- $/KWh
- Efficiency
- Cycle life



Power Control System (PCS)

- Bi-directional Inverter
- Switchgear
- Transformer
- Interconnection
- $/KW

Energy management System (EMS)

- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability
- Monitoring
- $

Site Management System (SMS)

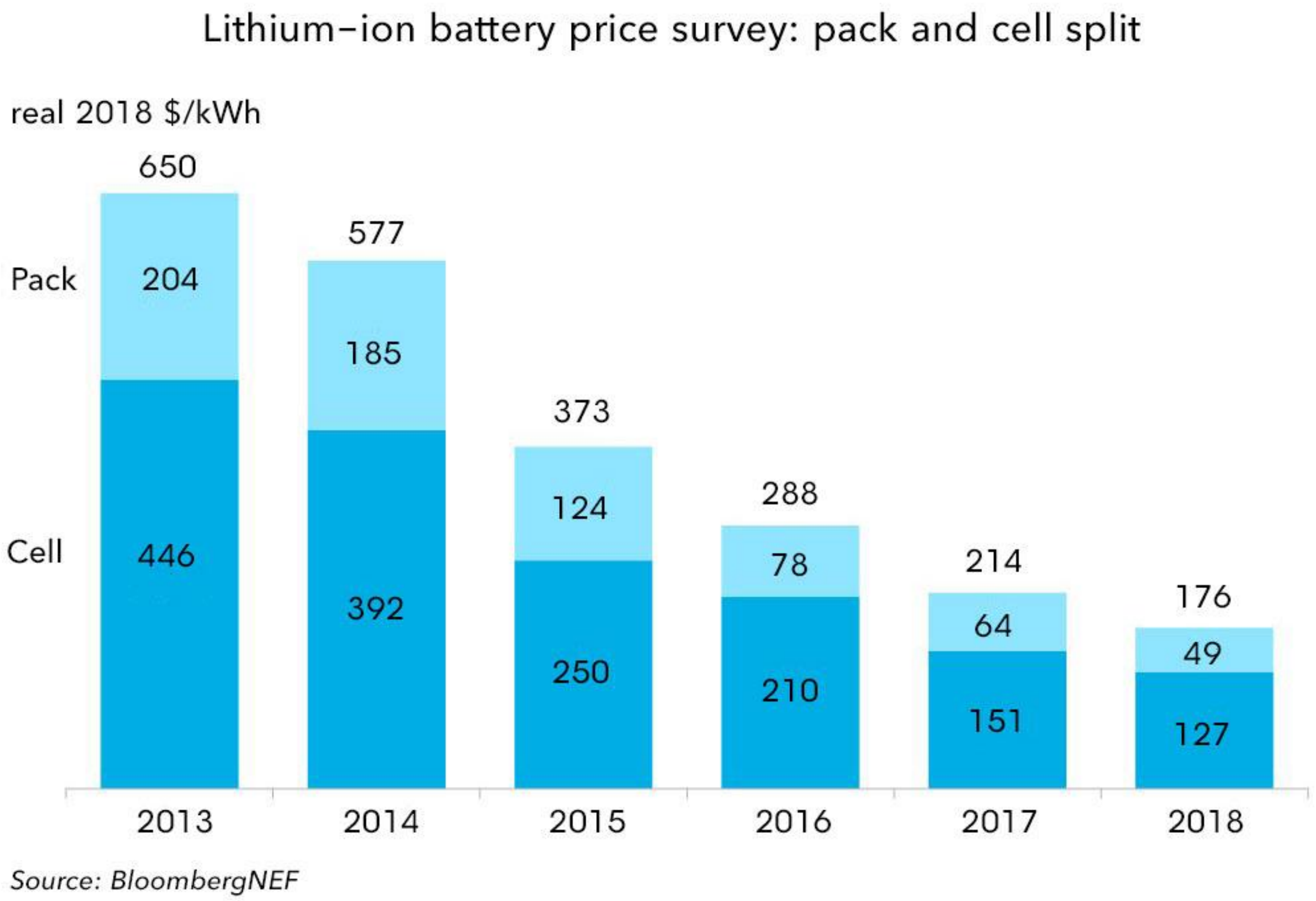
- DER control
- Synchronization
- Islanding
- Microgrid
- $

Balance of Plant

- Housing
- Wiring
- Climate control
- Fire protection
- Permits
- $

NOTE: All–in cost may be 4x higher than cell cost.

Lithium-Ion Price Trends



- When comparing prices for different systems, ensure that it is done on equal terms (cell, pack, installed)
- As cell and pack prices fall, balance of plant constitutes an increasing share of total system costs
- Balance of plant costs vary significantly by site; installed cost may be 4x or more the cell + pack cost

Current Cost Estimates - Batteries

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Table 4.3. Summary of Compiled Findings by Technology Type – BESS[(a)]

Parameter	Sodium Sulfur	Li-Ion	Lead Acid	Sodium Metal Halide	Zinc-Hybrid Cathode	Redox Flow
Capital Cost – Energy Capacity ($/kWh)	661 (465)	271 (189)	260 (220)	700 (482)	265 (192)	555 (393)
Power Conversion System ($/kW)	350 (211)	288 (211)	350 (211)	350 (211)	350 (211)	350 (211)
Balance of Plant ($/kW)	100 (95)	100 (95)	100 (95)	100 (95)	100 (95)	100 (95)
Construction and Commission Cost ($/kWh)	133 (127)	101 (96)	176 (167)	115 (110)	173 (164)	190 (180)
Total Project Cost ($/kW)	3,626 (2,674)	1,876 (1,446)	2,194 (1,854)	3,710 (2,674)	2,202 (1,730)	3,430 (2,598)
Total Project Cost ($/kWh)	907 (669)	469 (362)	549 (464)	928 (669)	551 (433)	858 (650)
O&M Fixed ($/kW-yr)	10 (8)	10 (8)	10 (8)	10 (8)	10 (8)	10 (8)
O&M Variable Cents/kWh	0.03	0.03	0.03	0.03	0.03	0.03
System Round-Trip Efficiency (RTE)	0.75	0.86	0.72	0.83	0.72	0.675 (0.7)
Annual RTE Degradation Factor	0.34%	0.50%	5.40%	0.35%	1.50%	0.40%
Response Time (limited by PCS)	1 sec	1 sec	1 sec	1 sec	1 sec	1 sec
Cycles at 80% Depth of Discharge	4,000	3,500	900	3,500	3,500	10,000
Life (Years)	13.5	10	2.6 (3)	12.5	10	15
MRL	9 (10)	9 (10)	9 (10)	7 (9)	6 (8)	8 (9)
TRL	8 (9)	8 (9)	8 (9)	6 (8)	5 (7)	7 (8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

Break down storage into comparable performance attributes:

- Round-trip efficiency (RTE)
- Lifespan
- Number of cycles
- Degradation rate
- Point of interconnection
- Response time
- Energy to Power ratio (E/P)

Balducci et al, *Energy Storage Technology and Cost Characterization Report*. http://energystorage.pnnl.gov/pdf/PNNL-28866.pdf.

Current Cost Estimates – Pumped Hydro

Parameter	Pumped Storage Hydropower [a]			
Capital Cost – Power ($/kW)	2,638[b]			
Power Conversion System ($/kW)	Included in Capital Cost			
Balance of Plant ($/kW)				
Construction and Commissioning ($/kW)				
Total Project Cost ($/kW)	2,640 [f]			
Total Project Cost ($/kWh)	165			
Operations and Maintenance (O&M) Fixed ($/kW-year)	15.9			
O&M Variable Cents/kWh	0.00025			
Round-Trip Efficiency (RTE)	0.8			
Annual RTE Degradation Factor				
Response Time		FS	AS	Ternary
	Spinning-in-air to full-load generation	5-70 s	60 s	20-40 s
	Shutdown to full generation	75-120 s	90 s	65-90 s
	Spinning-in-air to full load	50-80 s	70 s	25-30 s
	Shutdown to full load	160-360 s	230 s	80-85 s
	Full load to full generation	90-220 s	280 s	25-60 s
	Full generation to full load	240-500 s	470 s	25-45 s[g]

Parameter	Pumped Storage Hydropower [a]
Cycles at 80% Depth of Discharge	15,000
Life (Years)	>25
Manufacturing Readiness Level	9 (10)
Technology Readiness Level	8 (9)

Attributes are not equivalent to selection and do not provide the complete context:

- Scale
- Costs vs. risk
- Speed of response or duration of response
- Commissioning timeframe

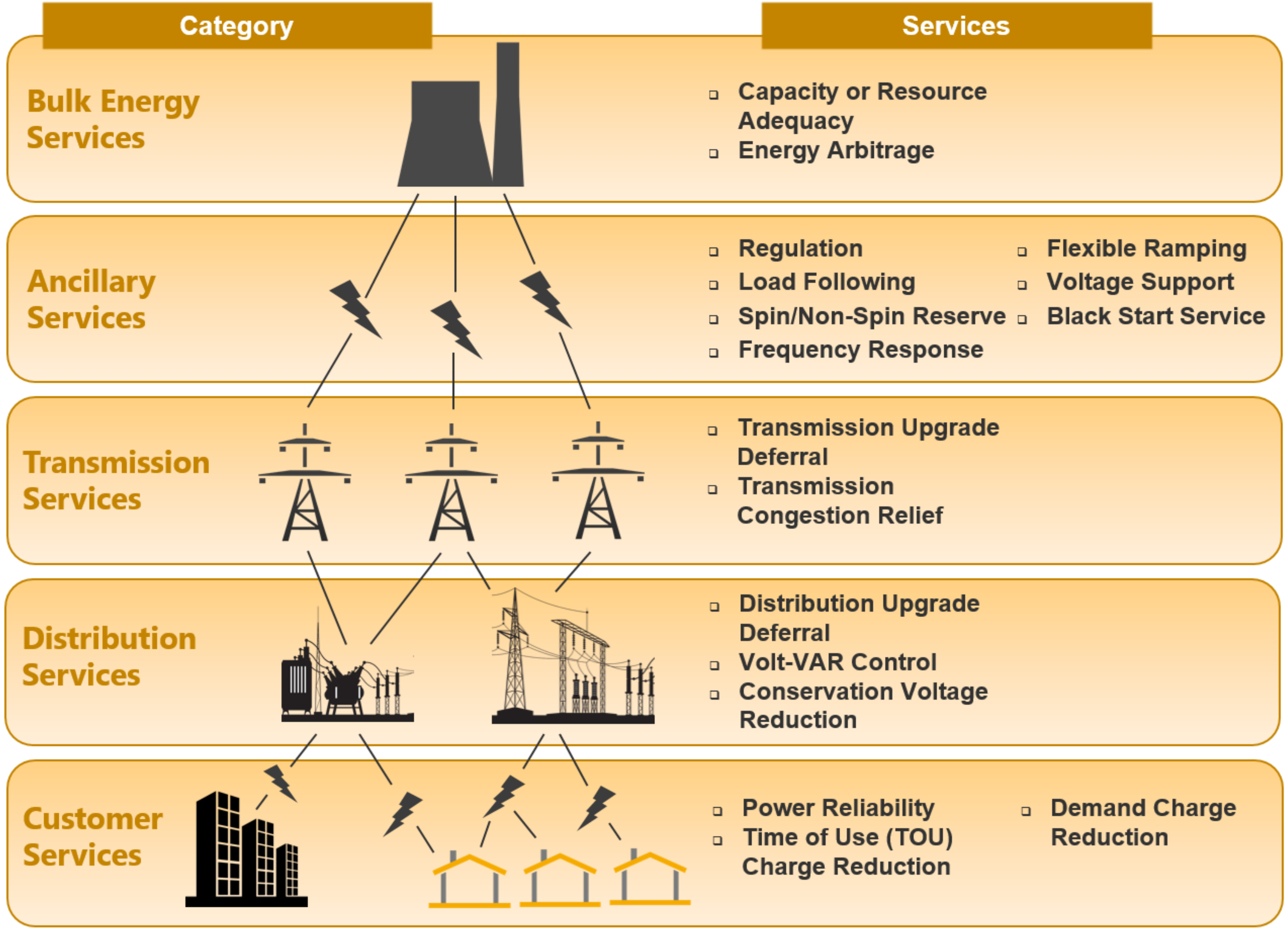
Challenges to Energy Storage in Resource Planning

The Planning Process

- Resource planning is an incredibly complex exercise
  - Load and generation must be kept in constant balance
  - Dozens of generators, market interfaces, fuel costs, changing load patterns (DG, EVs, etc.)
  - For each interval, solving the load/generation equation requires consideration of many complex variables
  - A 15-year plan looking at hourly intervals must solve for 131,400 data points

- As a result, resource plans make a number of simplifying planning assumptions
  - Hourly planning resolution
  - Substitution of robust reserve margins for ancillary services
  - Focus on generation only (no distribution planning, limited transmission planning)

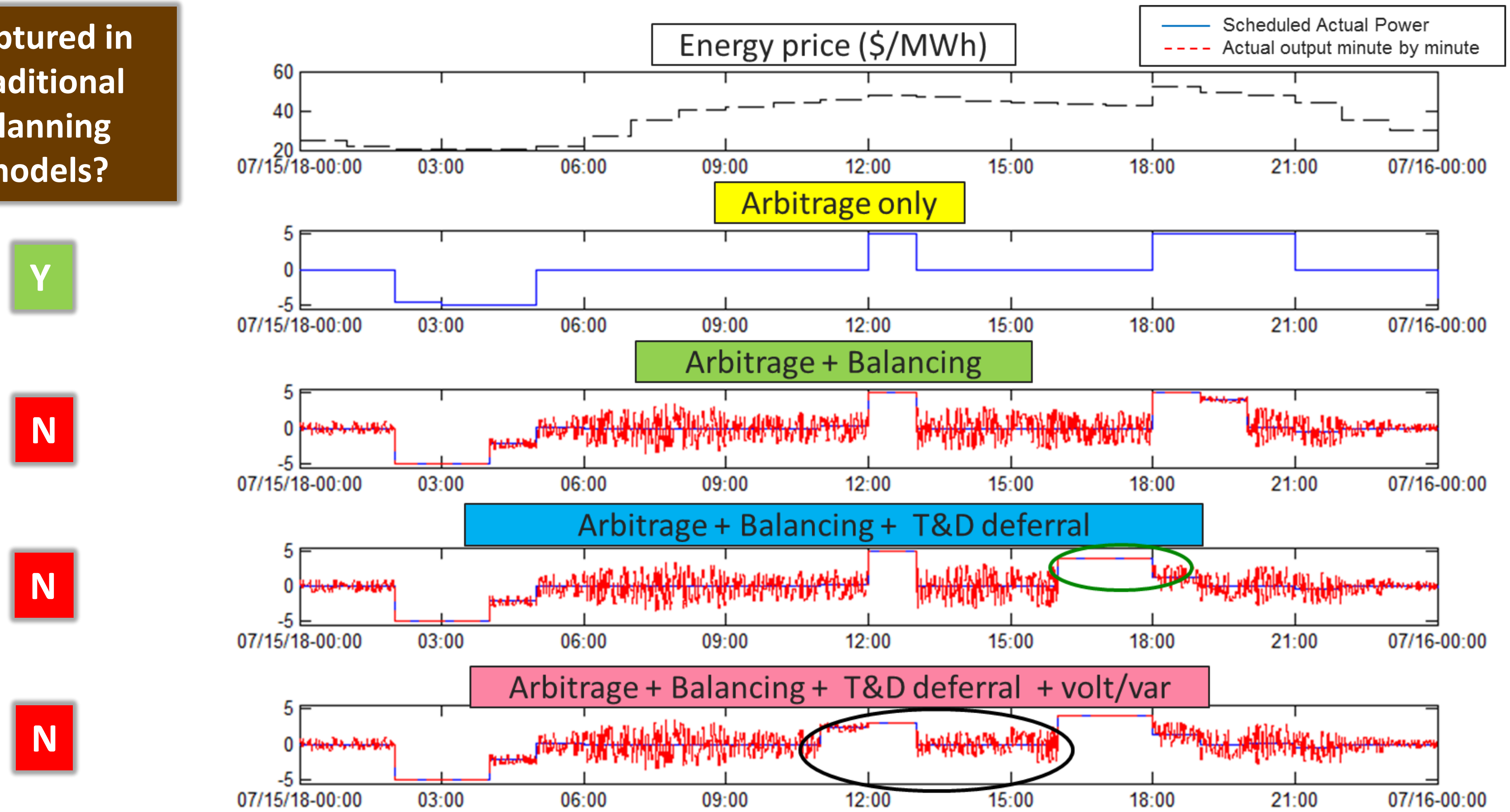
Taxonomy of Energy Storage Services



- Properly valuing energy storage is a complicated process of identifying and optimizing all value streams
- Storage can do a lot of things, but it can't do them all at once, and any time a service is selected, it comes with opportunity costs

Energy Storage Values and the Planning Process

Captured in traditional planning models?



Report: Energy Storage in IRPs

A recent PNNL report examined how 21 U.S. utilities are treating energy storage in integrated resource planning.

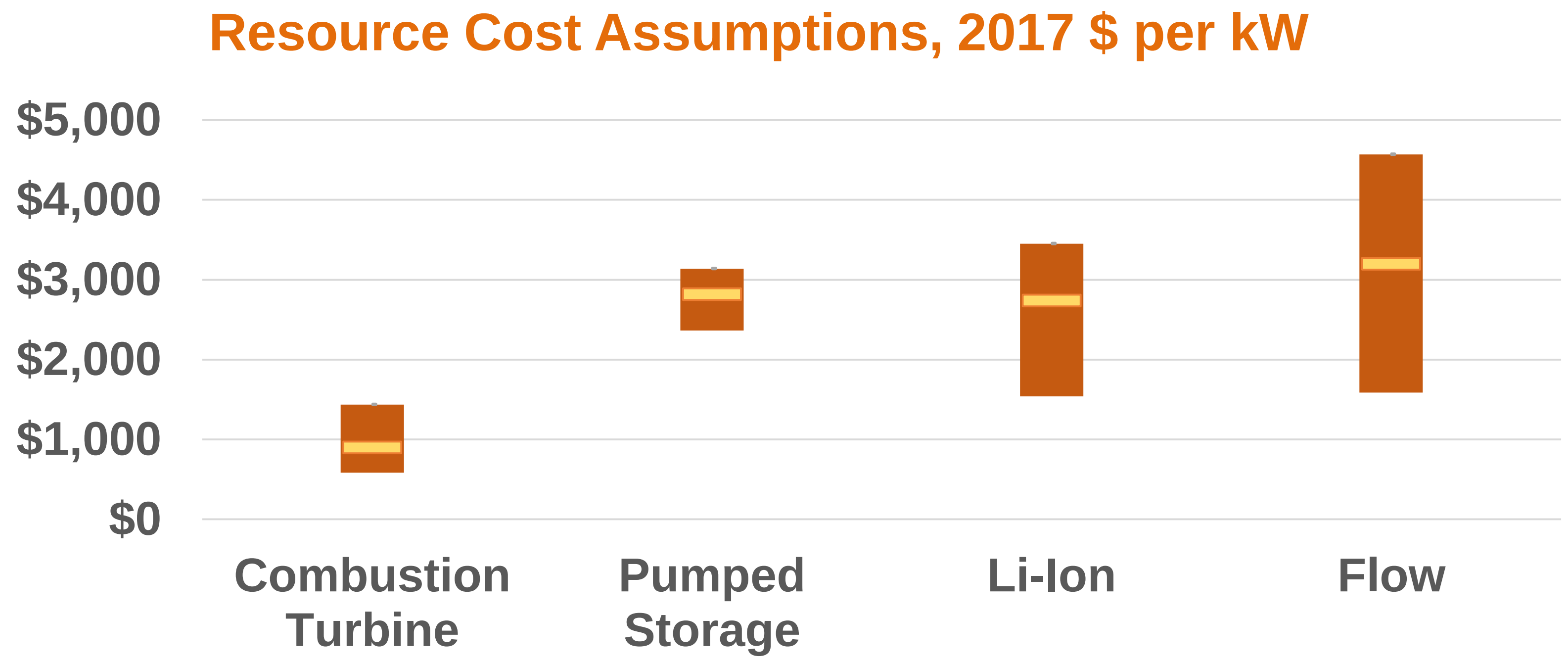
High level findings:

- **15 of the 21 IRPs included battery storage in their process. Of those:**
  - Eight plans did not select battery storage
  - Five plans selected batteries in their preferred portfolio
  - Two plans selected batteries in an alternate portfolio

- **10 of the 21 IRPs included pumped hydro storage in their process. Of those:**
  - Seven plans did not select pumped hydro
  - Two plans selected pumped hydro in the preferred portfolio (both expansions of existing facilities)
  - One plan selected pumped hydro in an alternate portfolio

Finding: Utilities Relatively Uncertain About Battery Costs

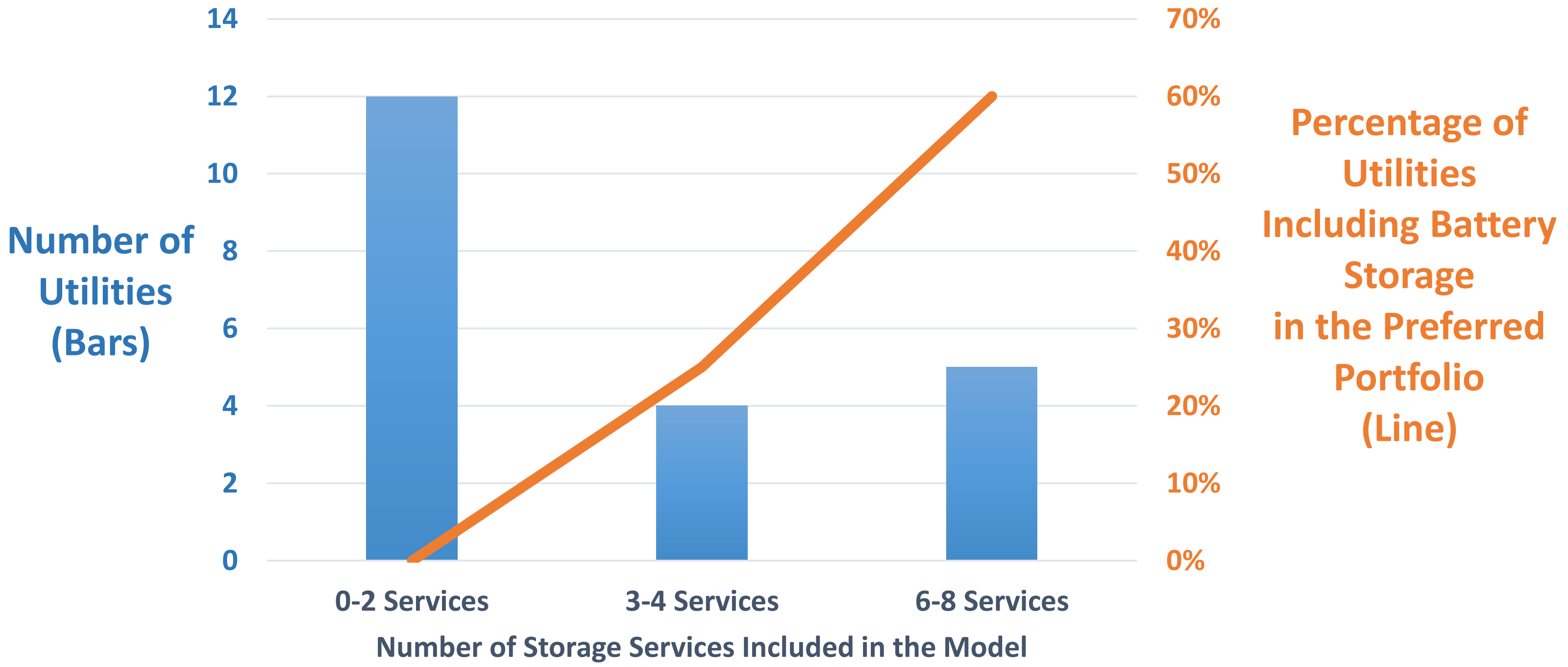
Cost assumptions for technologically mature resources such as combustion turbines and pumped storage tended to cover a smaller range than assumptions for less mature resources, such as lithium-ion and flow batteries:



Finding: More Services Lead to More Selections

As utilities account for more services provided by energy storage, the likelihood of storage being selected in the preferred portfolio increases:

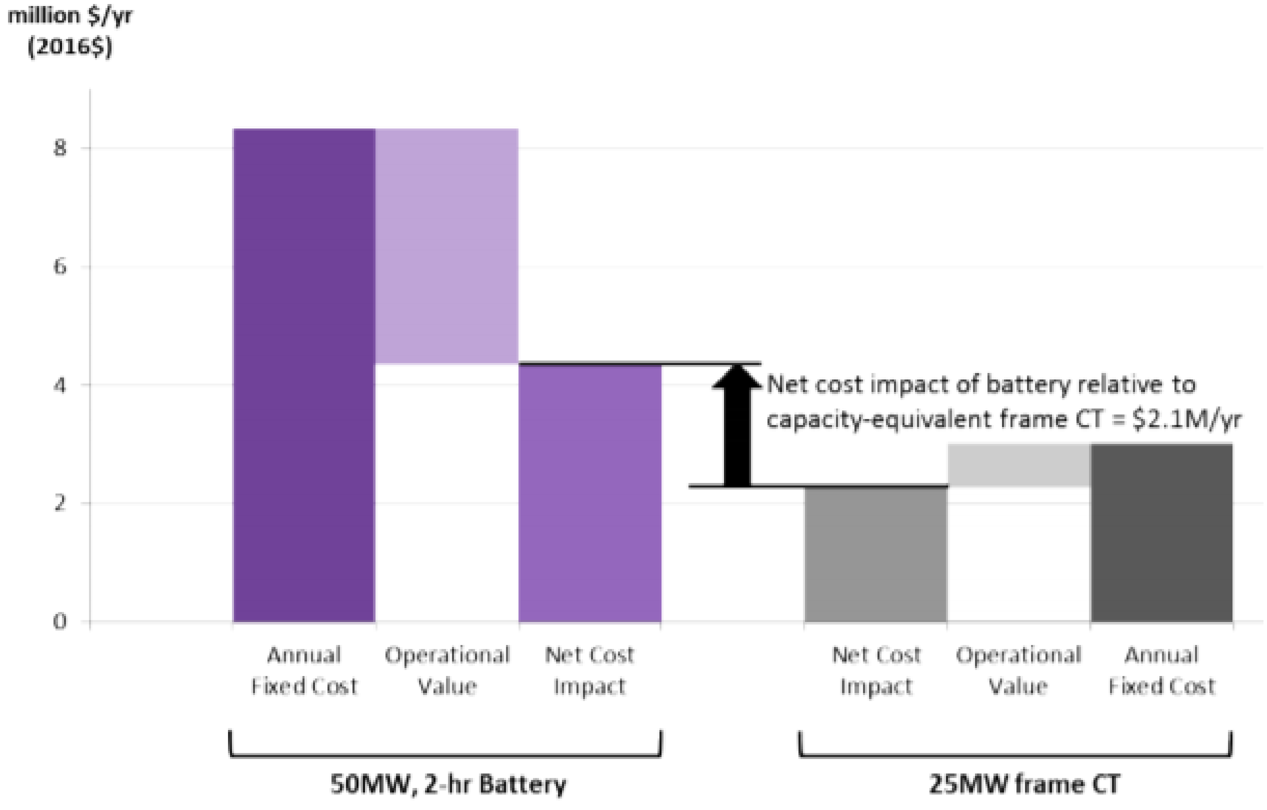
Percentage of Utilities Including Battery Storage in the Preferred Portfolio, by Number of Services Modeled



Emerging Planning Models

Net Cost Approach

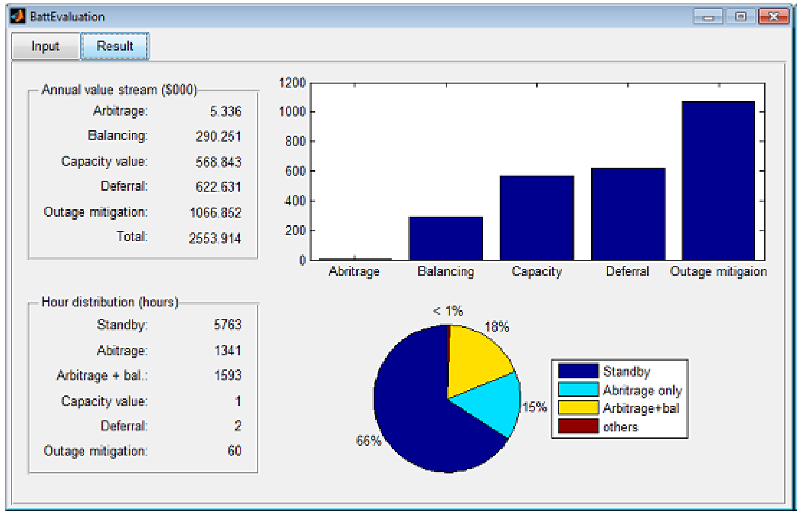
- An IRP model compares resources in terms of capital cost and hourly value
  - For storage, that's an apples-to-oranges comparison
  - Net cost uses an external model to capture non-IRP values of storage
  - Deducting those operational values from modeled storage cost → apples-to-apples

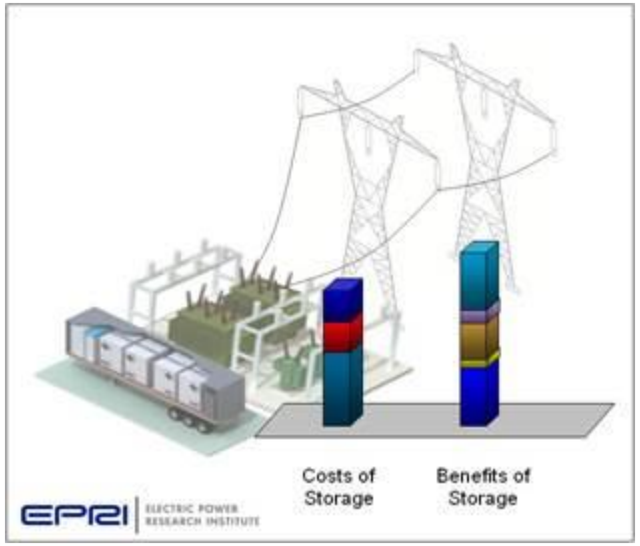


Portland General Electric 2016 IRP, p. 239

Net Cost Approach – Available Models

- Battery Storage Evaluation Tool (PNNL)
  - Free, non-exclusively licensed software
  - Conducts sub-hourly storage system optimization using user-input service values
  - Can be used to optimally size and site storage projects



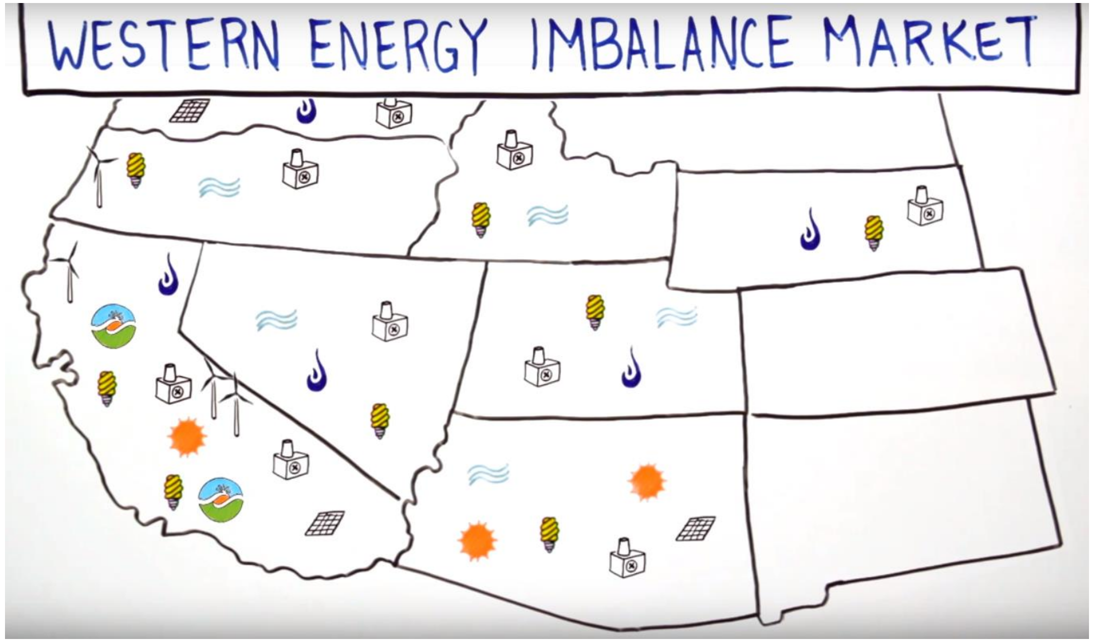


EPRI

- StorageVET (Electric Power Research Institute)
  - Free, open source software
  - Web-based interface
  - Flexible granularity and time horizons
  - Can directly compare storage to other resource options (i.e. combustion turbine)

Sub-Hourly Planning Models

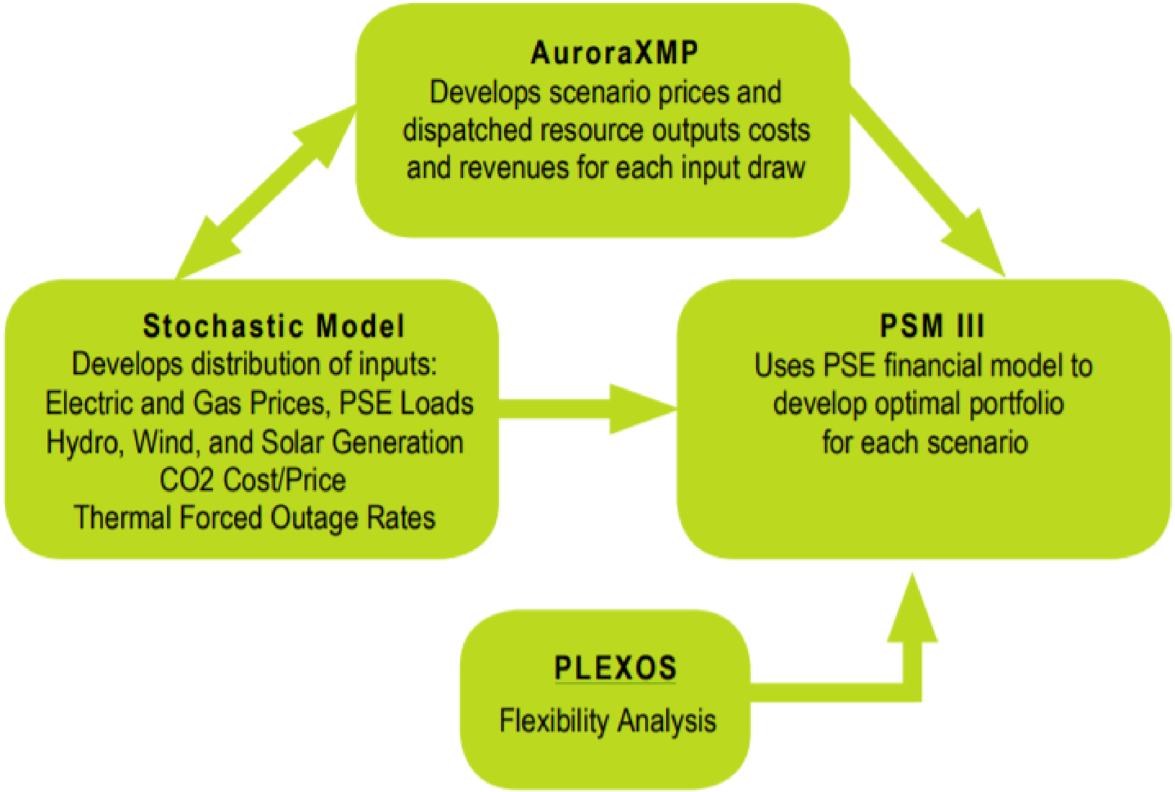
- At hourly granularity, many flexible and ancillary services are omitted
  - Frequency response is one of most universally valuable services, but it's measured in seconds
  - Under high DG penetration, load following may be measured in minutes as solar comes on and off with passing clouds
- Market operations moving toward sub-hourly transactions
  - FERC Order 825 requires regional market operators to clear markets at the same interval at which they are dispatched
  - Regional markets moving to 5- and 15-markets at varying paces
  - CAISO's Energy Imbalance Market offers granular market participation to non-market utilities
  - Granular system design/optimization of resources increasingly necessary to maximize revenue



CAISO

Sub-Hourly Planning Models: Puget Sound Energy

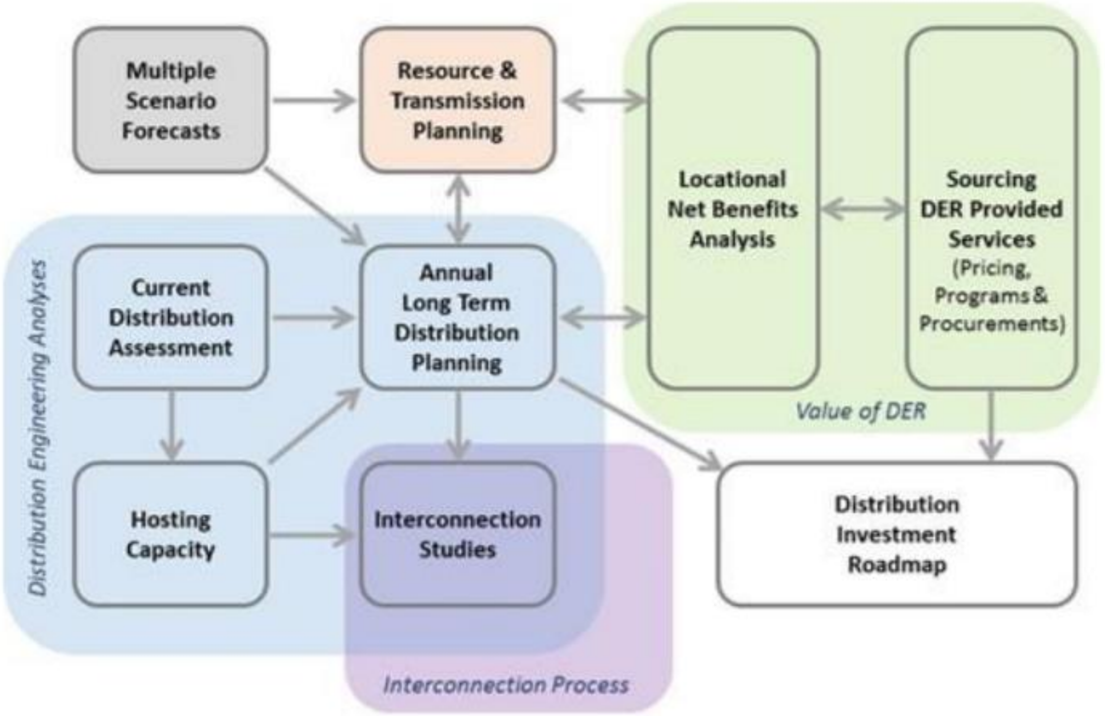
- Deploying a new resource planning model is a expensive and time-consuming process
  - Planning software is expensive
  - Utilities spend years training staff on model
- Puget Sound Energy developed a gradual transition for its 2017 IRP
  - Traditional (hourly) planning tools used to identify model inputs and portfolio selection
  - Once resource portfolio was selected, PSE used PLEXOS to compare it to a portfolio with storage at 5-min granularity
  - Result: 50 MW of storage by 2035 became 75 MW by 2024



Puget Sound Energy, 2017 IRP, pg. N-4.

Integrated Distribution System Planning

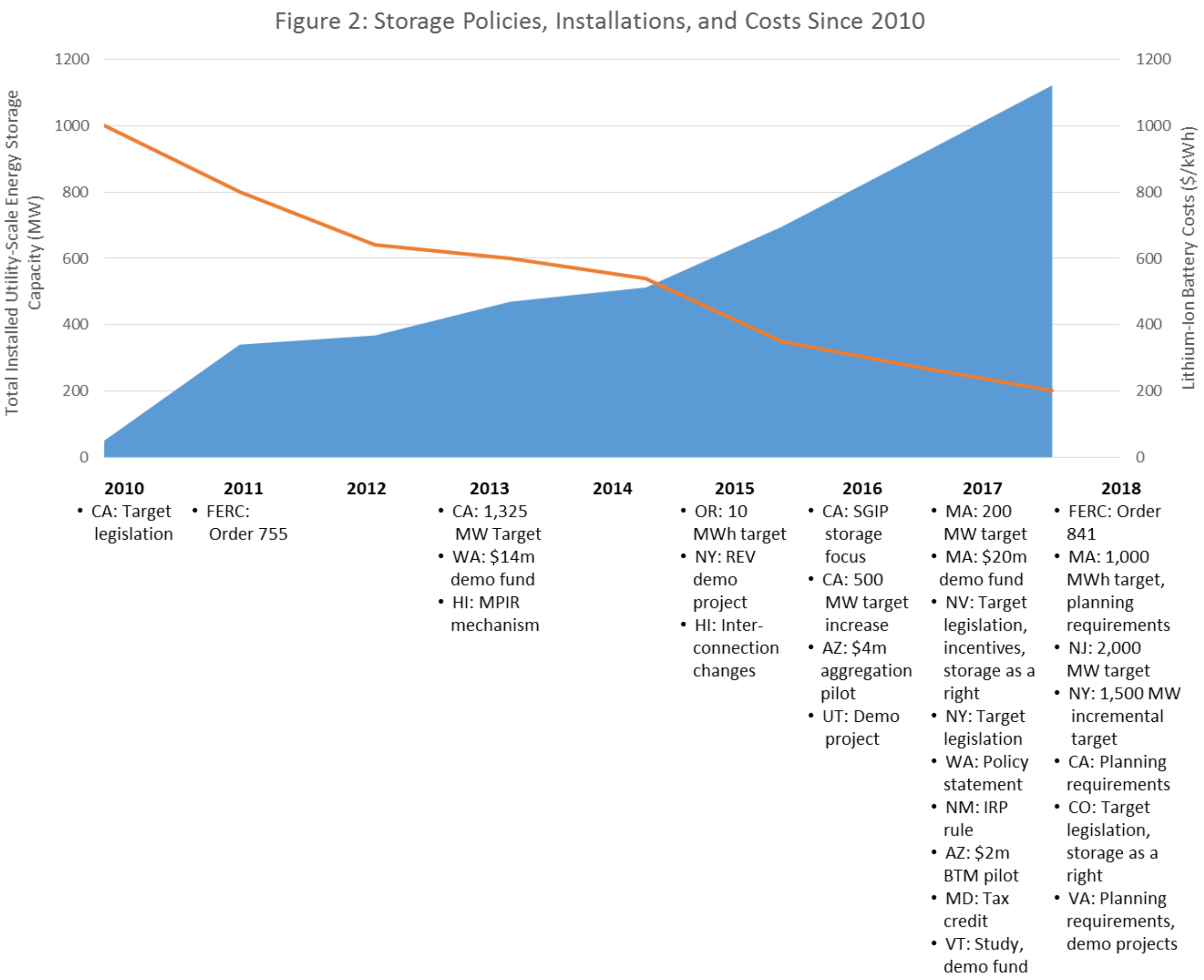
- Under the right circumstances, the benefits of transmission and distribution deferral can support a project on its own. But system-level IRP tool can't identify those constraints and those opportunities.
  - Punkin Center (APS)
  - Orcas Island (Orcas Island Power & Light in WA)
  - Brooklyn-Queens Demand Management Project (ConEd in NY)
- Additional values (volt/var optimization, resilience, outage mitigation, etc.) also best measured on locational basis
- Potential for local and system co-optimization
  - If local and system peaks align, resource may provide T&D deferral and capacity benefits
  - When resource not providing local benefits, can be dispatched to provide system benefits
  - IRP may identify need for storage, but can't identify optimal location



Integrated Distribution Planning, by Paul De Martini, ICF, for Minnesota Public Utilities Commission, August 2016

Overview of State-Level Policies on Energy Storage

Recent Energy Storage Policy Activity



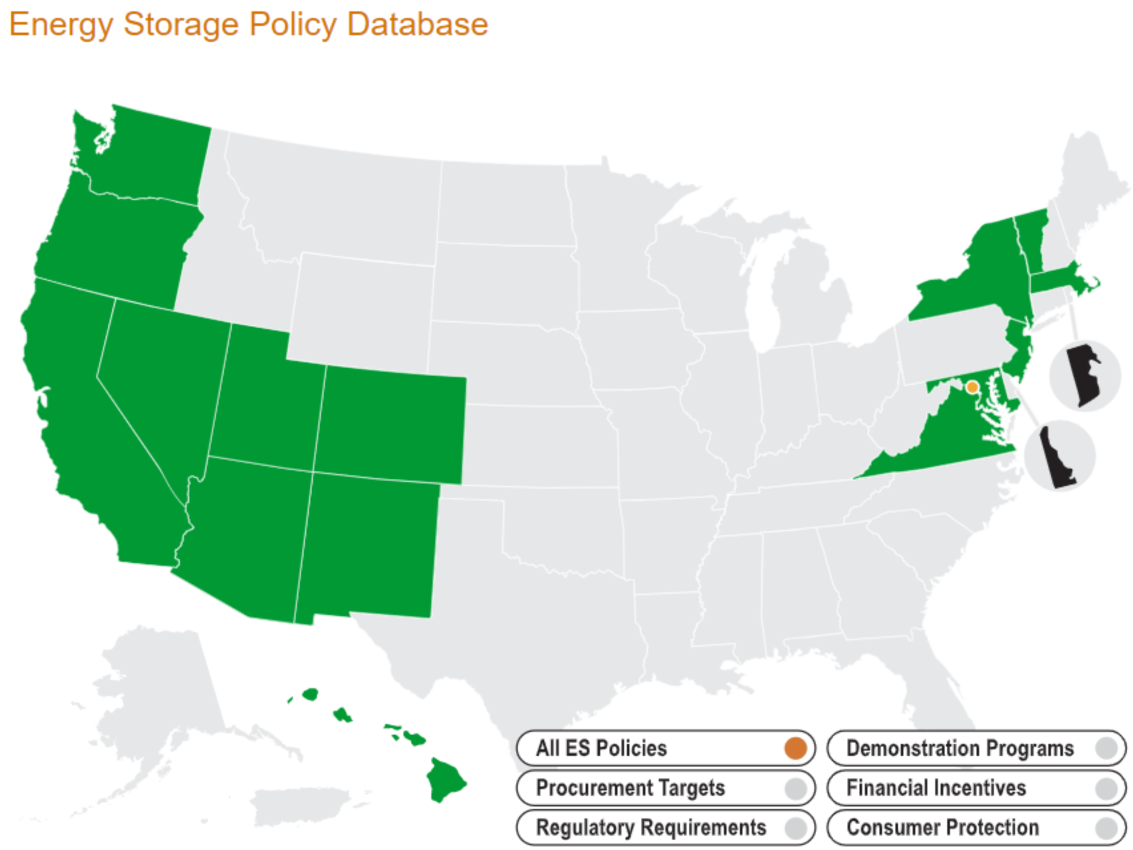
As energy storage costs (orange line) have fallen in recent years, the amount of new storage on the grid has rapidly increased (blue wedge), and state policy development has accelerated and differentiated.

The article explores the different types of polices that states are adopting, the drivers for different approaches, and early effects.

Report available at https://link.springer.com/article/10.1007/s40518-019-00128-1.

Energy Storage Policy Database

In recent years, several states have begun to identify and address barriers to energy storage. PNNL tracks these policies in an interactive database available at https://energystorage.pnnl.gov/regulatoryactivities.asp:



The policy database tracks five types of state-level energy storage policies, which were also explored in a recent journal article:

- Procurement targets
- Regulatory adaptation
- Demonstration programs
- Financial incentives
- Consumer protection

Procurement Targets

Generally adopted where a state identifies specific issues that energy storage is expected to address, and current practices that may prevent storage from adoption in the normal course of business. Currently adopted in seven states:

- **California:** 1,325 MW by 2020; 500 MW (distribution-connected) by 2020
- **Oregon:** 10 MWh by 2020
- **Massachusetts:** 200 MW by 2020; 1,000 MWh by 2025
- **New Jersey:** 600 MW by 2021; 2,000 MW by 2030
- **New York:** 1,500 MW by 2025; 3,000 MW by 2030
- **Nevada:** Pending
- **Colorado:** Pending

Regulatory Adaptation

Several states have adapted regulations to account for the unique capabilities of energy storage and other flexible, scalable technologies:

- **California:** CPUC adopts 11 rules covering energy storage in planning
- **Washington:** WUTC issues policy statement guiding storage modeling in IRPs
- **Hawaii:** HPUC changes to interconnection requirements encourage storage; streamlined proceedings for review of flexible resource investments
- **New Mexico:** NMPRC amends IRP rule to require storage analysis
- **Virginia:** Legislature requires distributed energy integration report
- **Maine:** Legislature creates nonwires alternative coordinator to make recommendations for non-wire investments in transmission and distribution systems
- Target legislation in OR, MA, NJ also requires PUC to develop processes for evaluating, siting storage

Demonstration Projects

Demonstration programs are state-directed initiatives in which the state authorizes, and often assists in funding, energy storage projects intended to assist utilities in gaining operational understanding of energy storage:

- **Massachusetts:** ACES program provides $20 million to 26 projects
- **New York:** REV initiative includes an open call for demonstration project proposals; four projects developed
- **Washington:** CEF provides $14.3 million for five demonstration projects
- **Virginia:** Legislation authorizes 40 MW of storage demonstration projects
- **Utah:** Legislation authorizes energy storage demonstration project
- **Maryland:** Legislation requires utilities to conduct demonstration projects testing various ownership models

Financial Incentives

Six states offer state-funded programs that provide incentives, either as direct payments or tax rebates, to customers who install energy storage:

- **California:** Self-Generation Incentive Program set aside $378M for customer-sited energy storage projects from 2017-2021
- **New York:** The New York State Energy Research and Development Authority provides multiple grant programs to support energy storage developments
- **Nevada:** Legislation expands solar incentive program to include energy storage
- **Arizona:** Regulators authorize $2M incentive program to assist large commercial customers in deploying behind-the-meter storage for peak management
- **Vermont:** Legislation makes storage eligible for Clean Energy Development Fund
- **Virginia:** Solar development authority expanded to include energy storage

Consumer Protection

Two states have adopted legislation that guarantees certain protections to customers who install energy storage:

- **Nevada**: Legislation establishes a right for customers to install energy storage in a timely manner, subject to reasonable standards
- **Colorado**: Legislation establishes a right for customers to install energy storage and directs the Colorado PUC to develop interconnection rules

Additional Resources

- PNNL Energy Storage (energystorage.pnnl.gov)
- Sandia National Laboratories (www.sandia.gov/ess/)
- DOE Global Energy Storage Database (www.energystorageexchange.org)
- Energy Storage Association (www.energystorage.org)


SANDIA REPORT

DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA

Sandia National Laboratories

Thank You!

Questions?

For any follow-up questions or to get more detailed information, please contact me at jeremy.twitchell@pnnl.gov or 971-940-7104.