Electrical Energy Storage Technologies and Applications Workshop

Grid-Scale Energy Storage

Presented by
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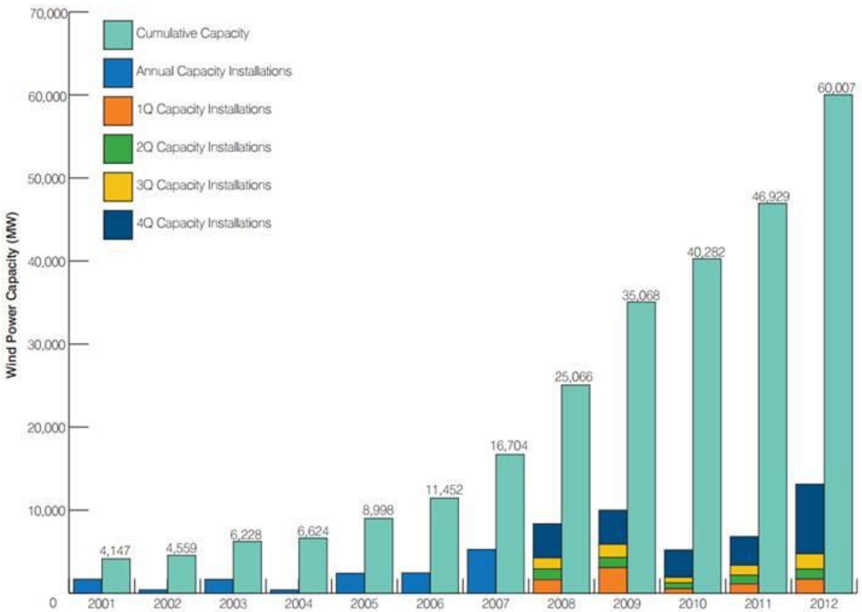
About the Lecturer…

- Vladimir Koritarov is Deputy Director of the Center for Energy, Environmental, and Economic Systems Analysis at Argonne National Laboratory
- Before joining Argonne in 1991, worked 8 years as power system planner in the Union of Electric Power Industry of Yugoslavia (JUGEL)
- Extensive experience in modeling and simulation of energy and power systems in the U.S. and abroad

With the Advance of Renewable Energy Sources, Energy Storage Is Becoming Increasingly Important

- Energy storage is not a new concept for electric utilities
- Although extremely desirable, wider deployment of energy storage has been limited by the economics/costs and available locations
- Pumped-storage hydro (PSH), large hydro reservoirs, and a few pilot compressed air energy storage (CAES) plants were the only way to store energy
- Small quantities of electricity were also possible to store in batteries and capacitors
- Large-scale implementation of energy storage (both system and distributed) is considered to be the key for enabling higher penetration (e.g., >20%) of variable generation sources, such as wind and solar
- Energy storage is also expected to contribute to more efficient and reliable grid operation, as well as to reduced emissions from the power sector

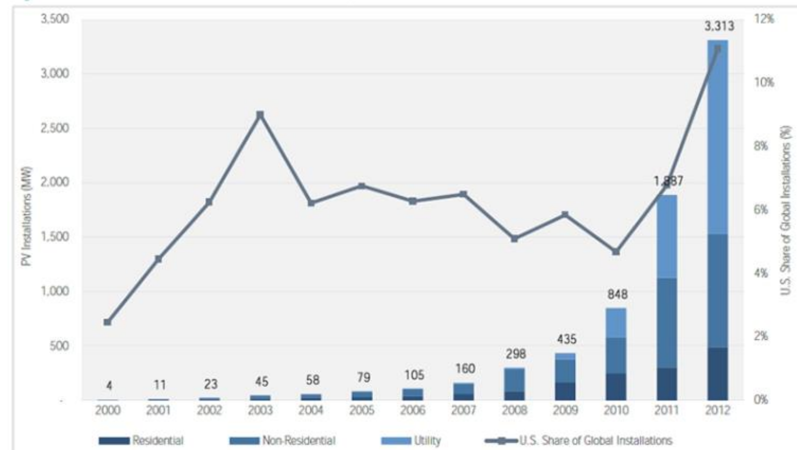
Drivers for Energy Storage: Recent Growth in Wind and Solar



Wind capacity is now over 60 GW

Source: AWEA 2013

Figure 2.1 U.S. PV Installations and Global Market Share, 2000-2012



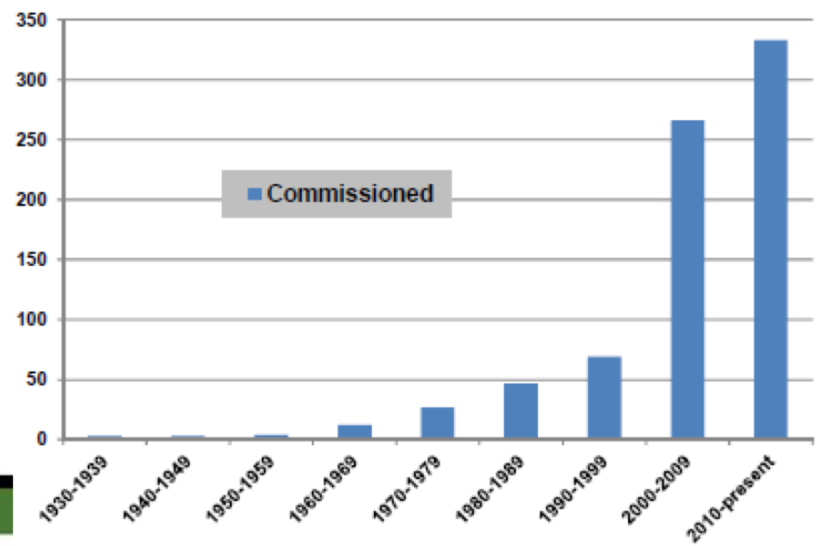
Installations (MWdc)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Residential	1	5	11	15	24	27	38	58	82	164	246	302	488
Non-Residential	2	3	9	27	32	51	67	93	200	213	336	826	1,043
Utility	0	3	2	3	2	1	0	9	16	58	267	760	1,781
Total Installations	4	11	23	45	58	79	105	160	298	435	848	1,887	3,313

Solar PV is now about 7.7 GW

Source: SEIA 2013

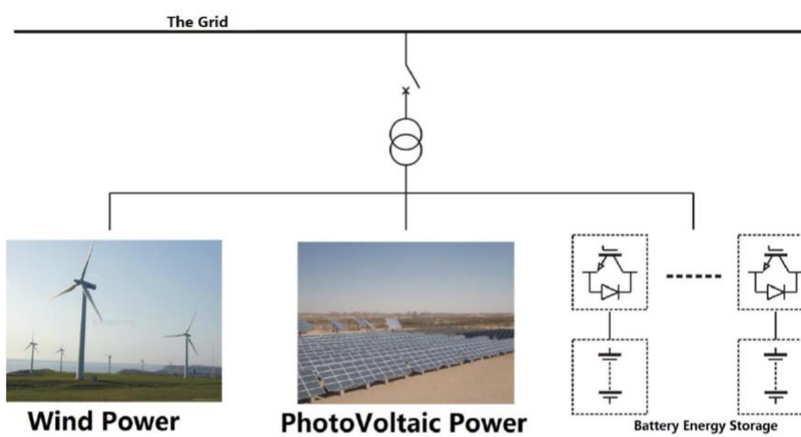
Worldwide energy storage projects by decade

Source: Pike Research 2012



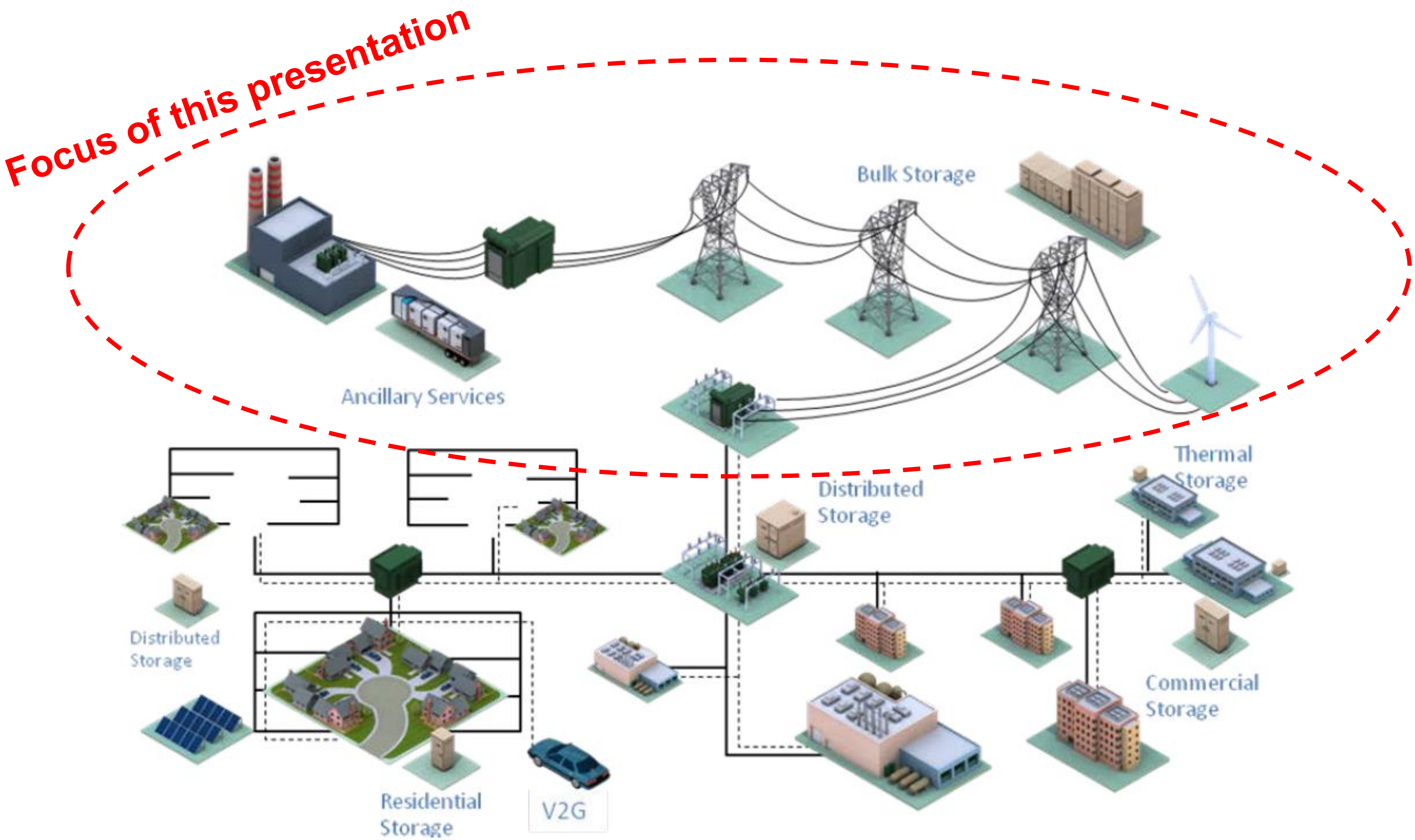
There are a Variety of Energy Storage Applications

- System storage (e.g., PSH, CAES, large-scale battery storage
  - Currently 127 GW of PSH in the world, of which:
    - 40 GW in European Union
    - 22 GW in the United States
  - Many utilities are building new PSH capacity
    - 1,200 MW Alto Tamega in Portugal,
    - 760 MW Venda Nova 3 in Portugal,
    - 852 MW La Muella 2 in Spain, etc.
- Renewable energy support (e.g., energy storage combined with wind or solar)
- Distributed energy storage (demand-side storage, customer installations, PHEV & EV batteries, etc.)



Source: Wanxiang 2011

Applications of Energy Storage Systems on the Grid



Source: DOE Electricity Advisory Committee - 2012 Storage Report

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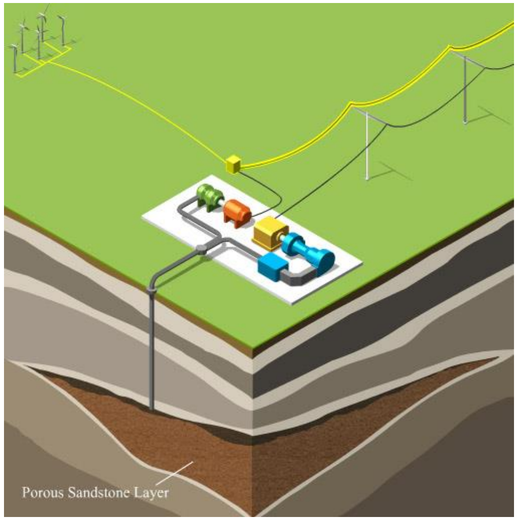
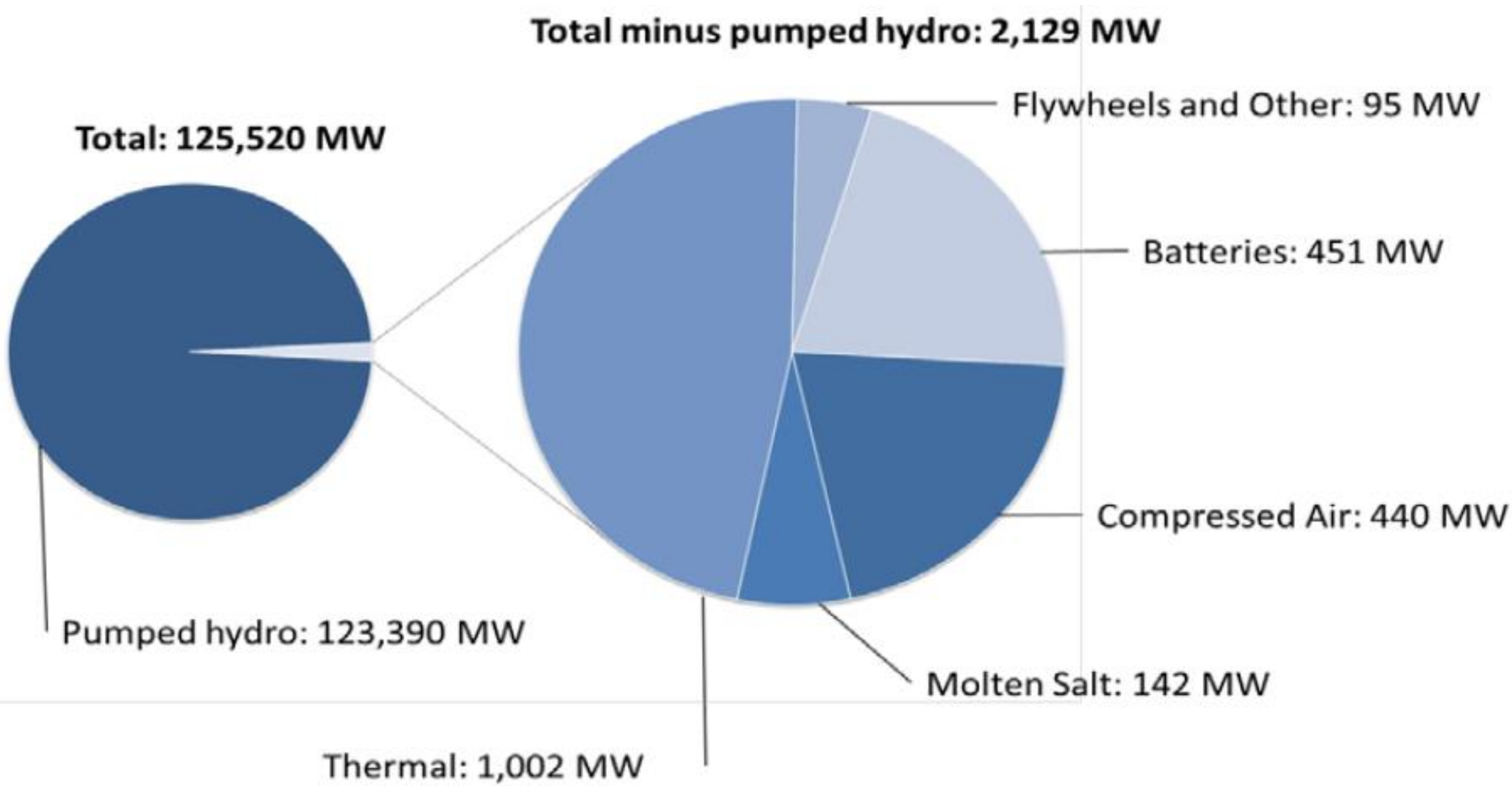
Main Categories of Storage Technologies

- **Mechanical**
  - Pumped-Storage Hydro
  - Compressed air energy storage (surface and underground)
  - Flywheels
- **Electrochemical**
  - Lead-acid (L/A) batteries
    - Flooded L/A batteries
    - Valve-regulated lead-acid (VRLA) batteries
  - Sodium-sulfur (NaS) batteries
  - Lithium-ion (Li-ion) batteries
  - Flow batteries
    - Sodium bromide sodium polysulfide
    - Zinc bromine (Zn/Br)
    - Vanadium-redox (V-redox)
  - Super-capacitors
  - Superconducting magnetic energy storage (SMES)
  - Hydrogen (as storage medium)
- **Thermal**
  - Molten salt, sensible heat, phase change materials, etc.



2011 Worldwide Grid-Scale Energy Storage Capacity



Source: U.S. DOE EAC Energy Storage Report 2011

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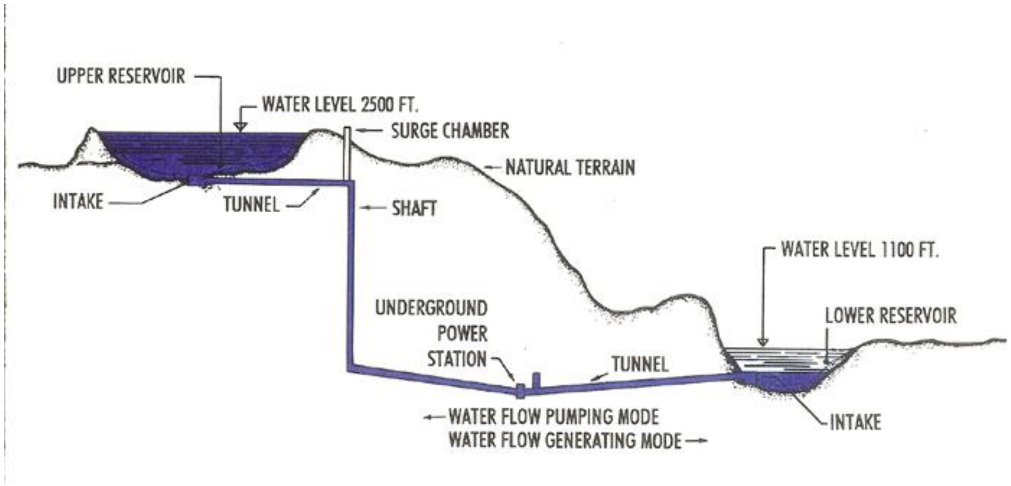
2011 Energy Storage Capacity in U.S.

Storage Technology Type	Capacity (MW)
Pumped Storage Hydro	22,000
Compressed Air	115
Lithium-ion Batteries	54
Flywheels	28
Nickel Cadmium Batteries	26
Sodium Sulfur Batteries	18
Other (Flow Batteries, Lead Acid)	10
Thermal Peak Shaving (Ice Storage)	1,000
TOTAL	**23,251**

Source: U.S. DOE EAC Energy Storage Report 2011

Pumped Storage Hydro

- Mature commercial technology
- Large capacity up to 1-2 GW
- Large energy storage (8-10 hours or more)
- Fixed and adjustable speed units



Source: Electric Power Group

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Compressed-Air Energy Storage

- Two existing pilot projects:
  - Huntorf, Germany (290 MW) built in 1978
  - McIntosh, Alabama (110 MW) in 1991
- Compressed air is stored under pressure (>1000 psi) underground:
  - Salt domes,
  - Aquifers,
  - Depleted gas/oil fields,
  - Mined caverns, etc.
- Compressed air is used to power combustion turbines
- Increased efficiency of electricity generation compared to regular CTs
- Lower capital costs than pumped hydro storage
- Above-ground CAES more expensive

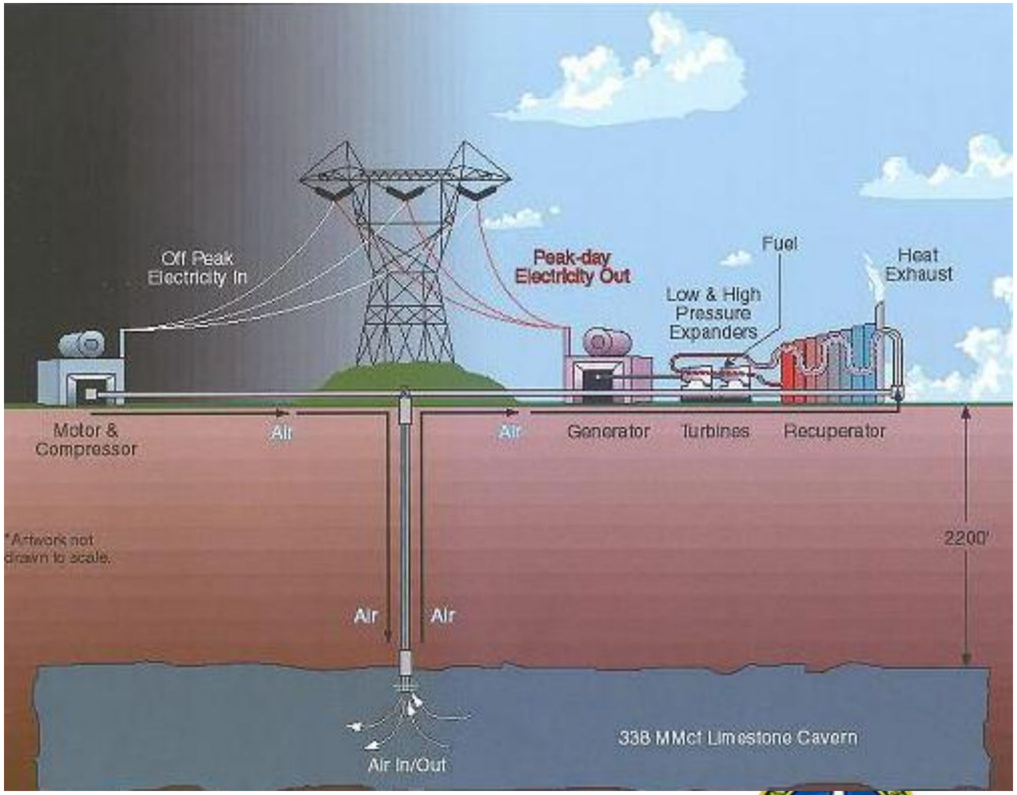

Photo by CAES Development Company

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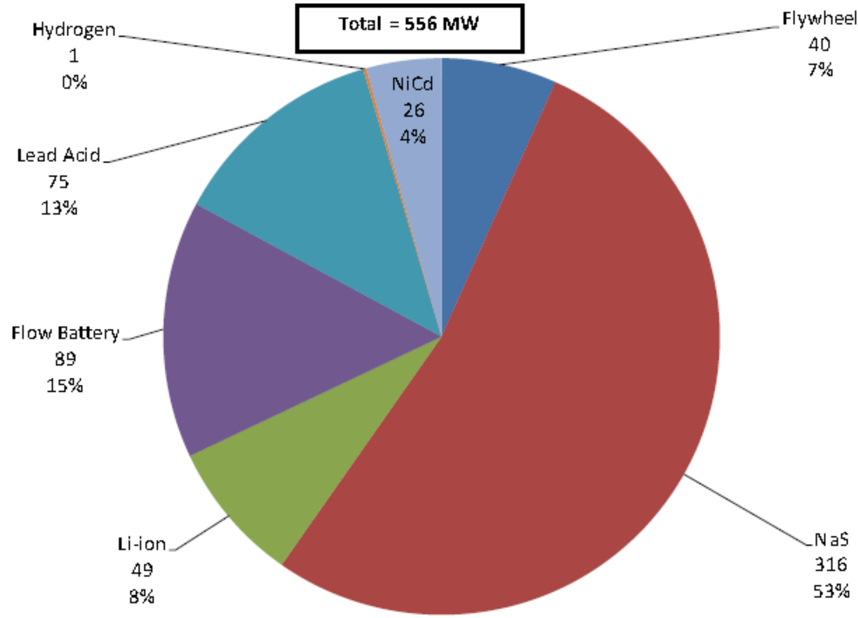
Batteries

- Various chemistries
- Most applications in Japan (typically NaS batteries)



Source: PIKE Research 2012

Source: VRB Power Systems

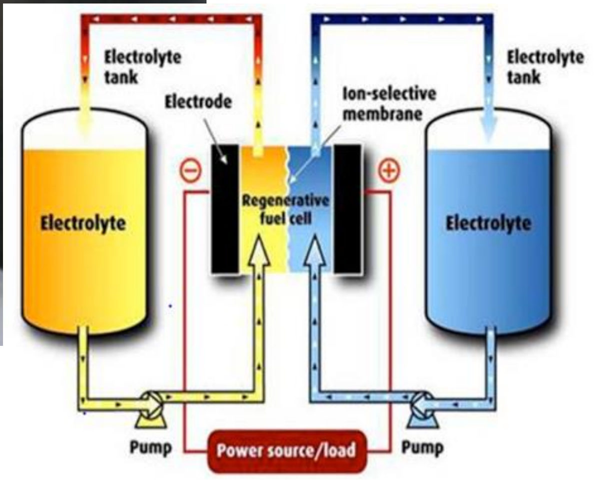


Photo by AEP

Flywheels

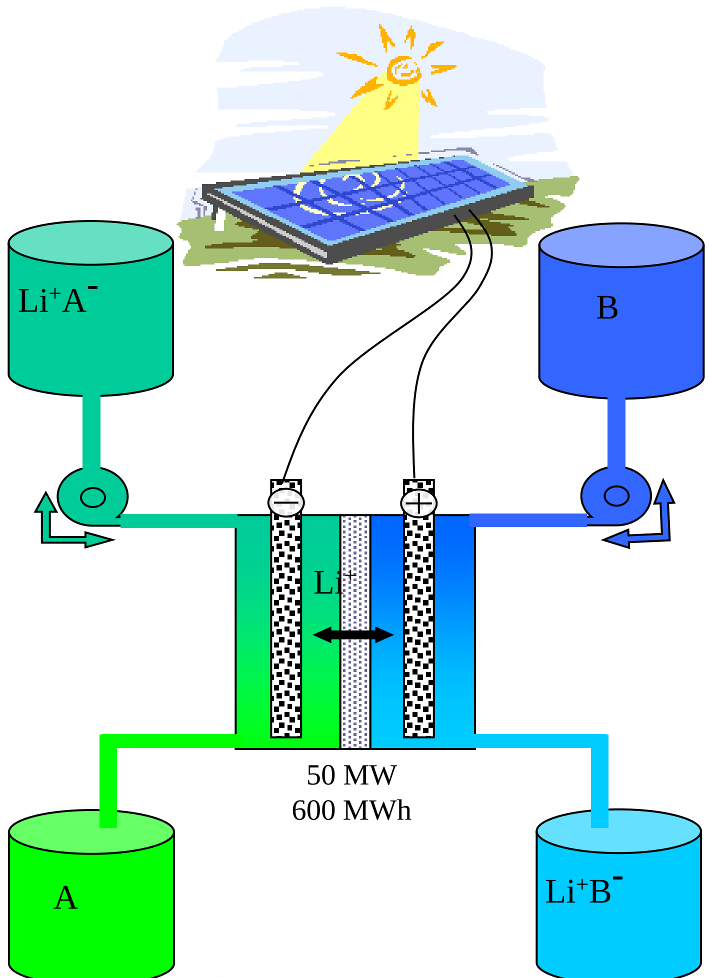
Photo by Beacon Power

2-MW flywheel storage
in ISO-NE
(Source: Beacon Power)

20-MW flywheel plant in Stephentown, NY
(Source: U.S. DOE)

New Technologies: Non-Aqueous Flow Battery

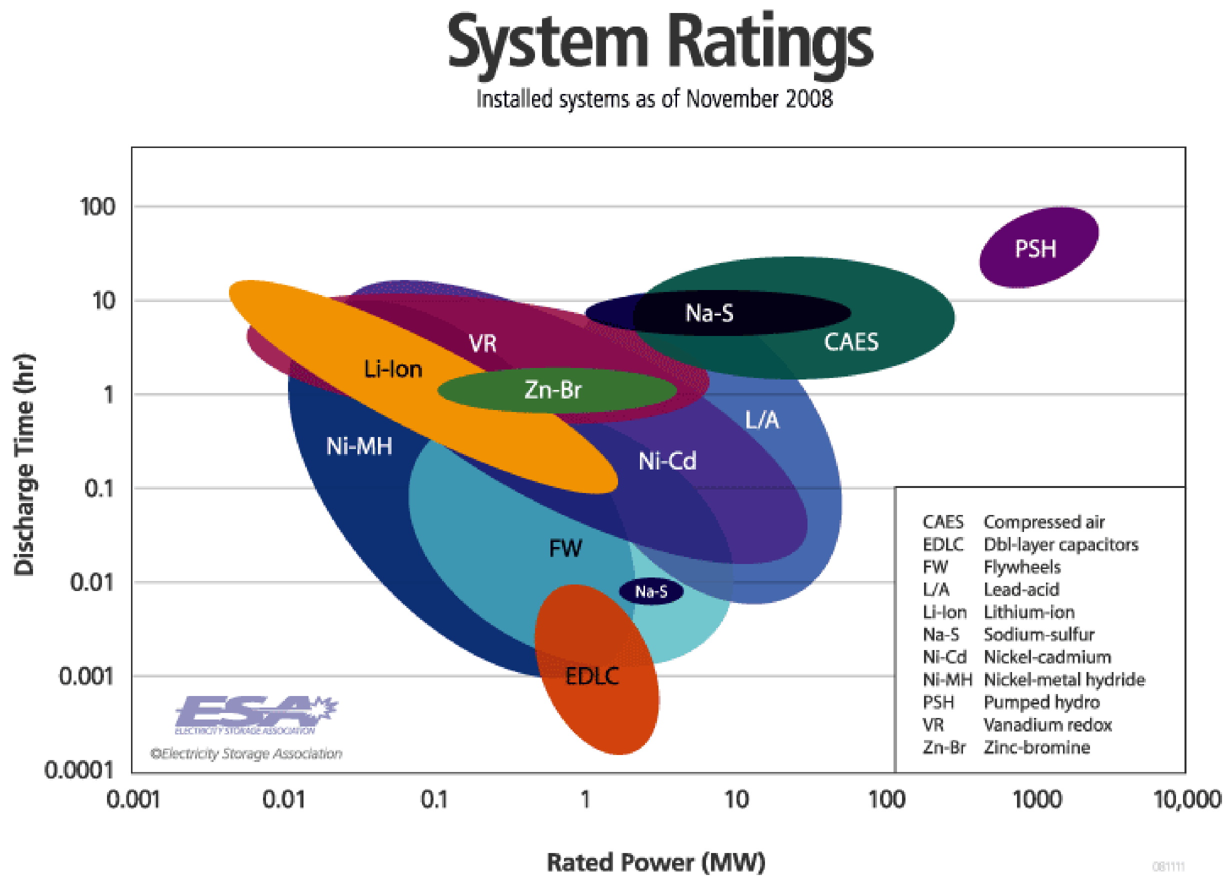
- A new type of flow-battery for large-scale utility applications



Simplified schematic of a flow battery used for load leveling. Shown for generic species A and B with lithium ions as the ion exchanged across the separator (other cations or anions could be used instead). If 1 Molar solutions are assumed, each storage tank would be ~11,000 m^3 (30-m diameter by 15-m high) for a 50 MW/600 MWh system and could easily be sited on five acres.

Requirements for Energy Storage

- Energy density
- High power output
- Cycle efficiency
- Cycling capability
- Operating lifetime
- Capital cost



Source: Electricity Storage Association (www.electricitystorage.org)

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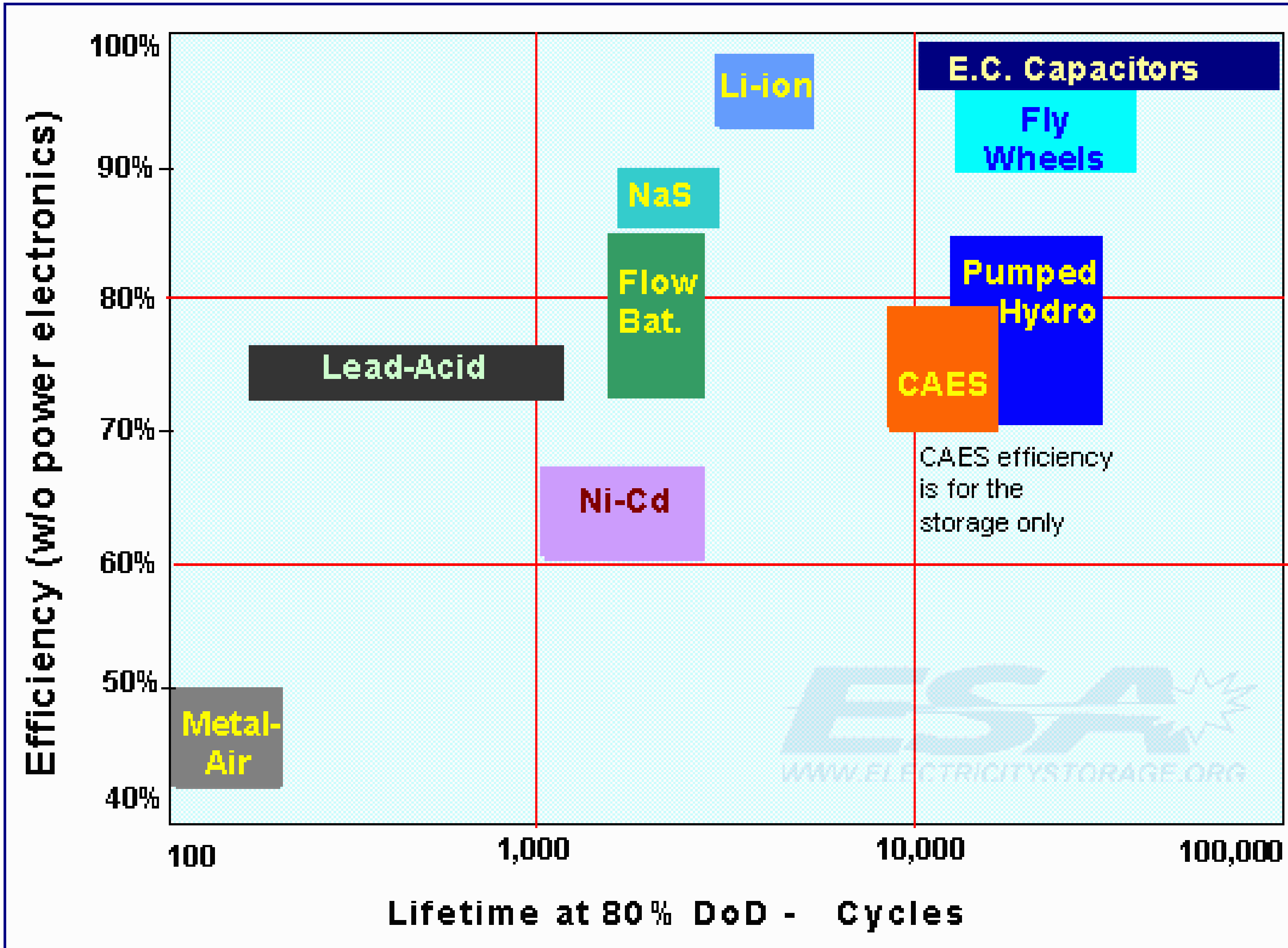
Cycle Efficiency of Energy Storage Technologies



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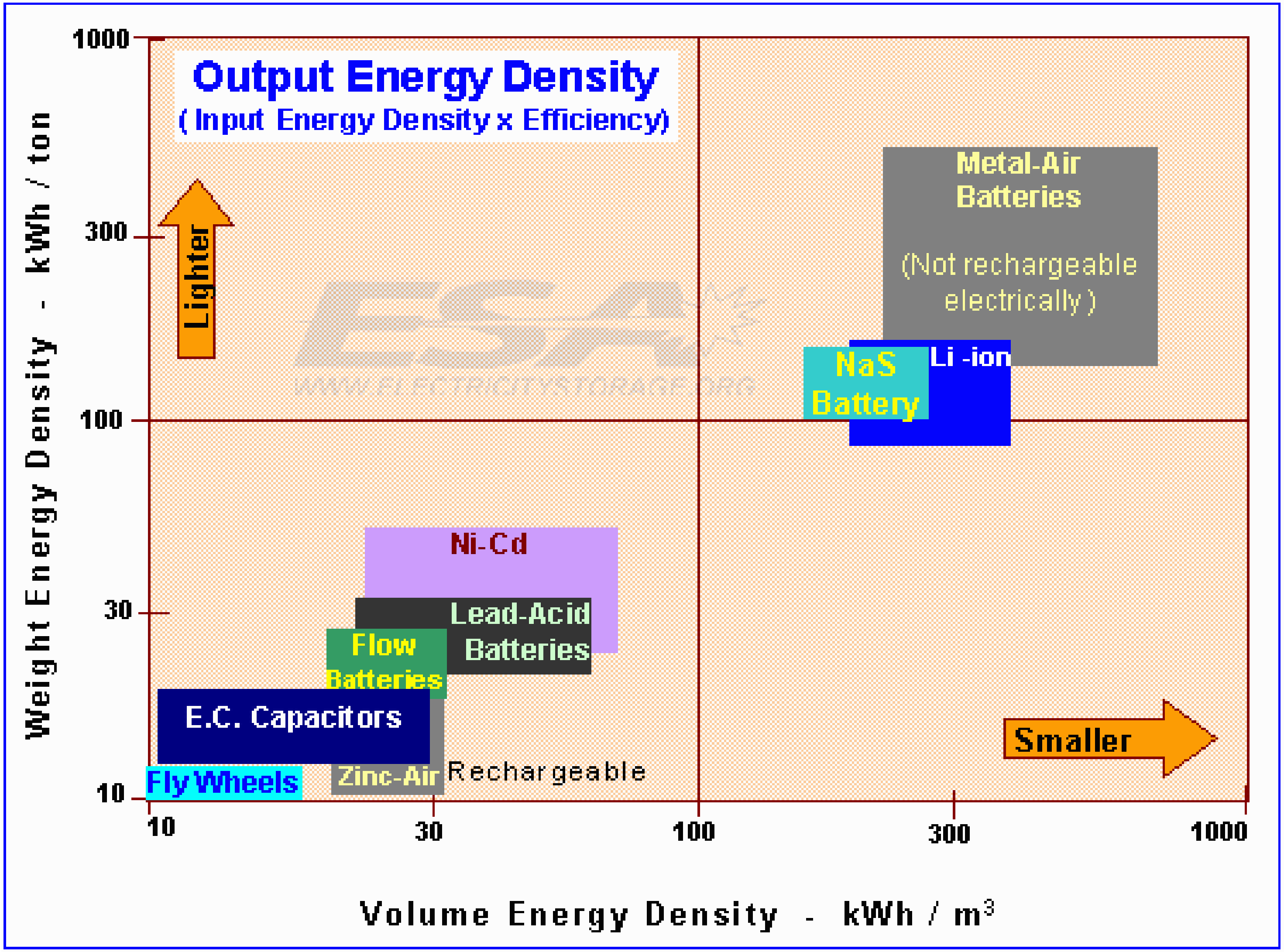
Size and Weight of Energy Storage



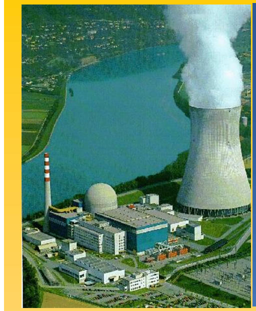
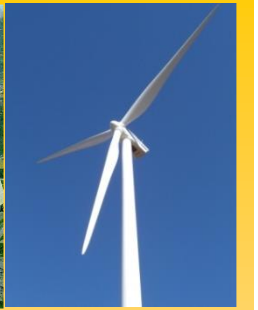
Cost and Performance Characteristics of Energy Storage Technologies

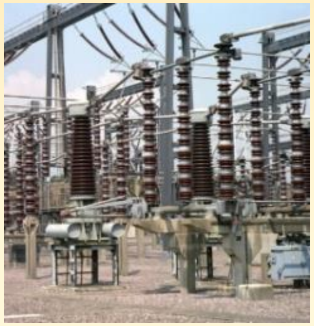
	Lead-acid batteries	Li-Ion batteries	NaS batteries	Flow batteries	Fly-wheels	Pumped hydro	Large-scale CAES
Applicable grid system size [kW/MW]	≤10 MW	≤10 MW	≥100 MW	25 kW–10 MW	100 kW–200 MW	Mostly ≥200 MW	≥500 MW
Lifetime [years]	3–10	10–15	15	Cell stack: 5–15; Electro-lyte: 20+	20	25+	20+
Lifetime [cycles]	500–800	2,000–3,000	4,000–40,000	Cell stack: 1,500–15,000	>100,000	>50,000	>10,000
Roundtrip efficiency [%]	70%–90%	85%–95%	80%–90%	70%–85%	85%–95%	75%–85%	45%–60%
Capital cost per discharge power [$/kW]	$300–$800	$400–$1,000	$1,000–$2,000	$1,200–$2,000	$2,000–$4,000	$1,000–$4,000	$800–$1,000
Capital cost per capacity [$/kWh$_{cap}$]	$150–$500	$500–$1,500	$125–$250	$350–$800	$1,500–$3,000	$100–$250	$50–$150
Levelised cost of storage [$/kWh$_{life}$]	$0.25–$0.35	$0.30–$0.45	$0.05–$0.15	$0.15–$0.25	N/A	$0.05–$0.15	$0.10–$0.20
Annual operating costs [$/kW-yr]	$30	$25	$15	$30	$15	$5	$5

Source: IRENA, May 2012

Energy Storage Can Provide Services at all Levels of the Power System Value Chain

- **Generating capacity**
  - Peaking capacity (e.g., pumped-hydro storage)
- **Energy arbitrage**
  - Load shifting and energy management (load-leveling, time-shift, price arbitrage)
- **Ancillary services**
  - Frequency regulation
  - Operating reserves (spinning, non-spinning, supplemental)
  - Voltage support
- **Grid system reliability**
  - Transmission stability support
  - Transmission congestion relief
  - T&D upgrade deferral
  - Substation backup power



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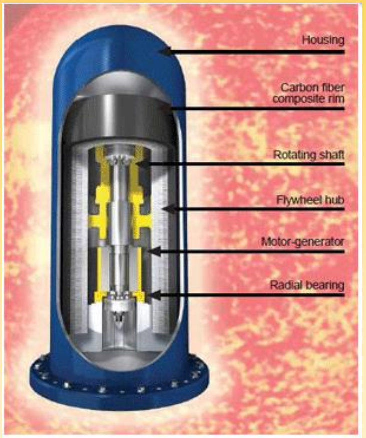
Energy Storage Can Provide Services at all Levels of the Power System Value Chain (cont'd)

- **Integration of variable energy resources (VER)**
  - Capacity firming
  - Renewable energy time-shift
  - Renewable energy integration (power quality, ramping, and flexibility reserves)
- **Utility customer**
  - Time-of-use energy cost management
  - Capacity charge management
  - Improved power quality and reliability
- **Environmental benefits***
  - Reduced fossil fuel consumption
  - Reduced environmental emissions

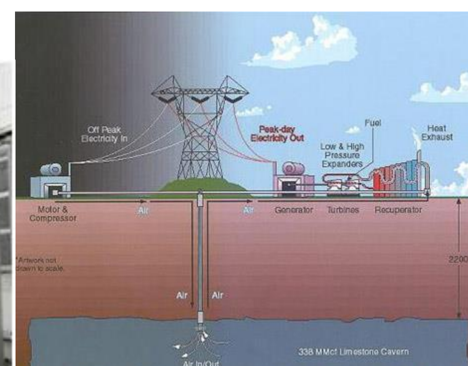
* Depending on the plant mix in the system



Operating Characteristics of Energy Storage Technologies Determine their Suitability for Different Applications

- Flywheels, super-capacitors, SMES, and other storage technologies with the short-term power output (minute time scale)
  - Regulation service
  - Spinning reserve, etc.

- NaS batteries, flow batteries, hydrogen fuel cells, CAES, pumped storage can provide several hours of full capacity:
  - Load shifting / energy management
  - Electricity generation
  - T&D deferral, etc.



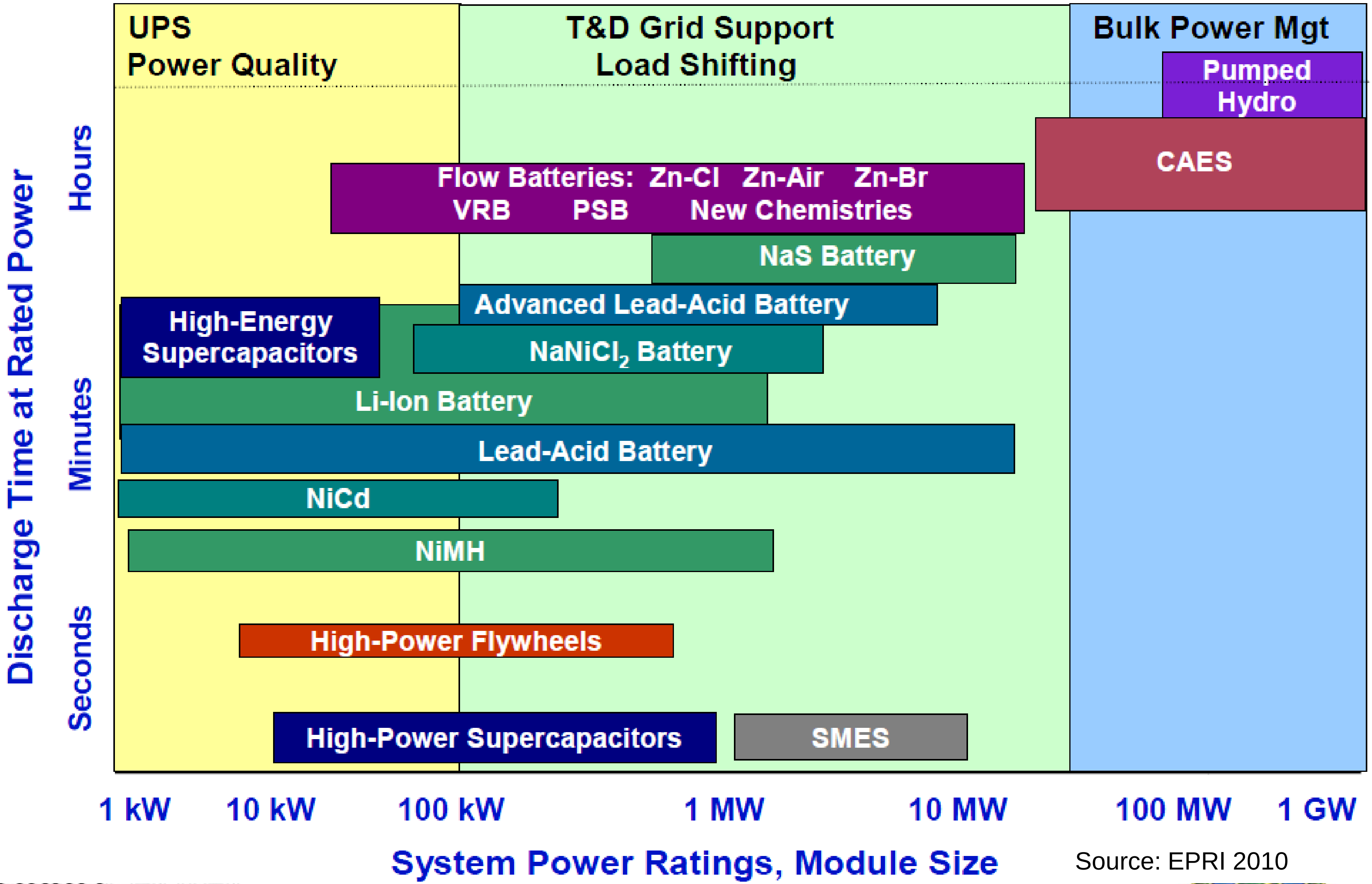
Technology Characteristics and Applications

Storage Technology	Main Advantage (Relative)	Disadvantage (Relative)	Power Application	Energy Application
High-speed Flywheels (FW)	High Power	Low Energy Density	●	
Electrochemical Capacitors (EC)	Long Cycle Life	Very Low Energy Density	●	
Traditional Lead Acid (TLA)	Low Capital Cost	Limited Cycle Life	●	○
Advanced LA with Carbon Enhanced Electrodes (ALA-CEE)	Low Capital Cost	Low Energy Density	●	●
Sodium Sulfur (Na/S)	High Power and Energy Density	Cost and Needs to Run at High Temperatures	●	●
Lithium-ion (Li-ion)	High Power and Energy Density	Cost and Increased Control Circuit Needs	●	◐
Zinc Bromine (Zn/Br)	Independent Power and Energy	Medium Energy Density	◐	●
Vanadium Redox (VRB)	Independent Power and Energy	Medium Energy Density	◐	●
Compressed Air Energy Storage (CAES)	High Energy, Low Cost	Special Site Requirements		●
Pumped Hydro (PH)	High Energy, Low Cost	Special Site Requirements		●

● Fully capable and reasonable ◐ Reasonable for this application ○ Feasible but not quite practical or economical NONE Not feasible or economical

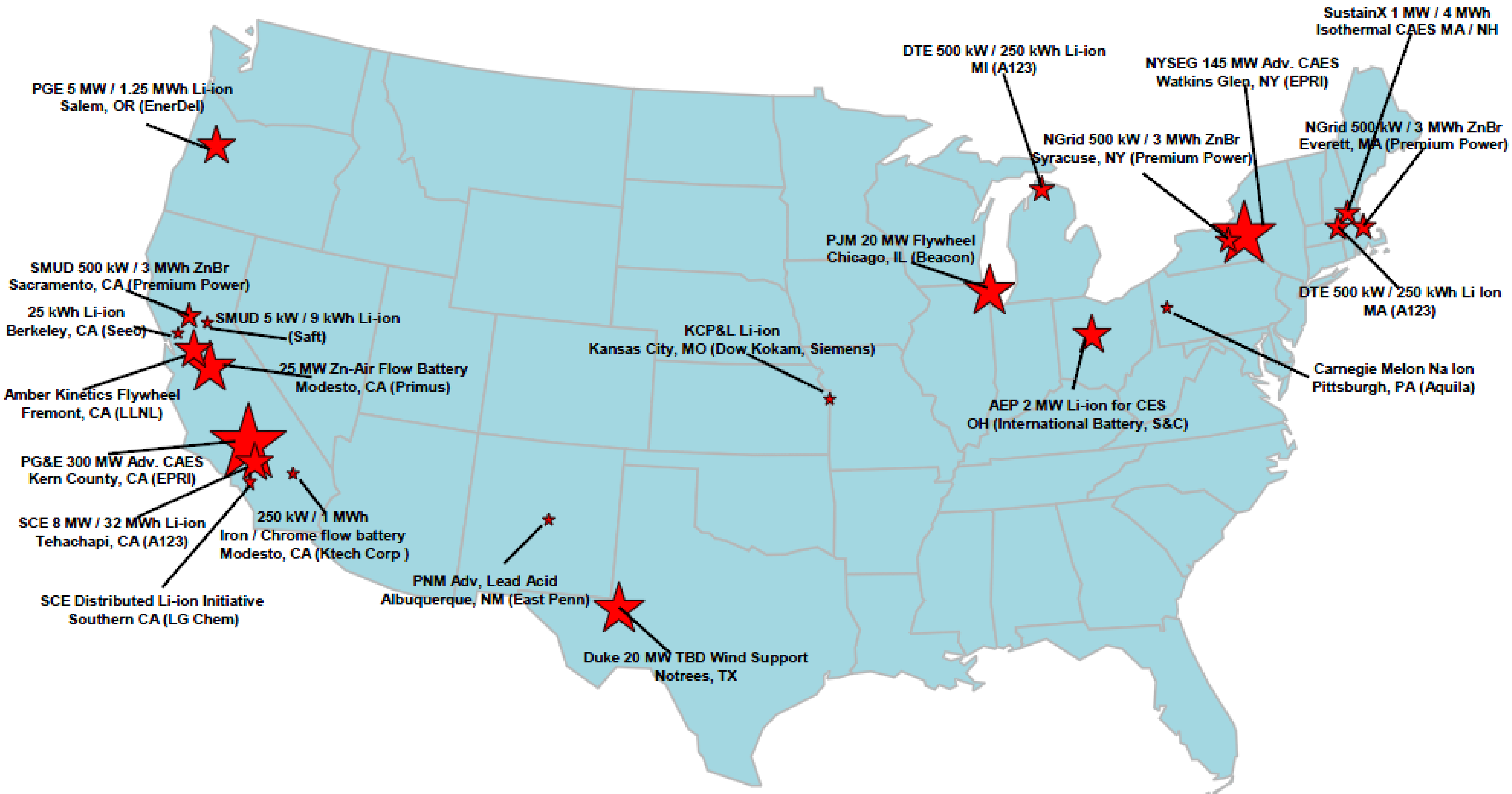
Source: ESA

Positioning of Energy Storage for Utility Applications



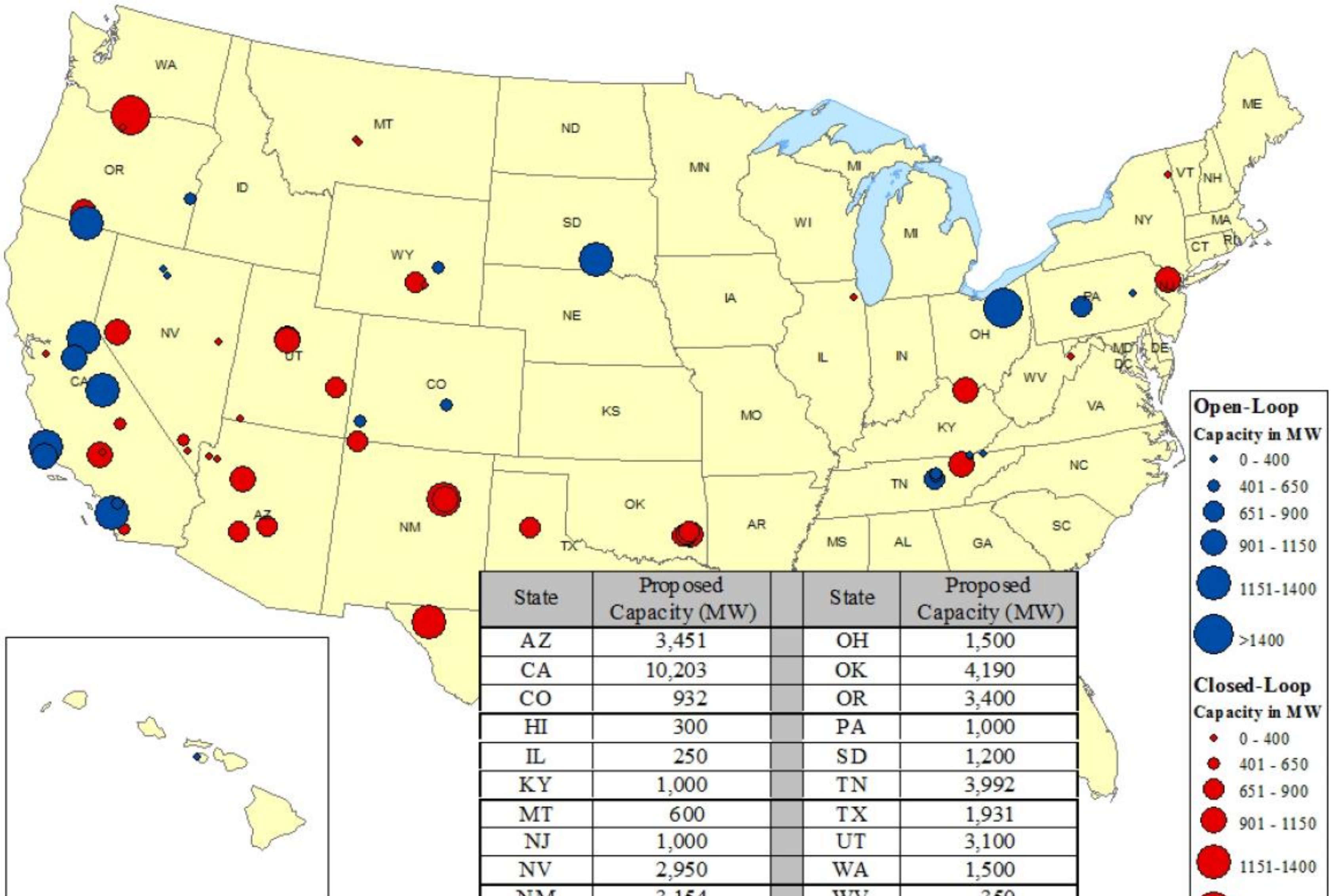
Source: EPRI 2010

Some Energy Storage Projects in U.S. Utilities



Source: EPRI 2010

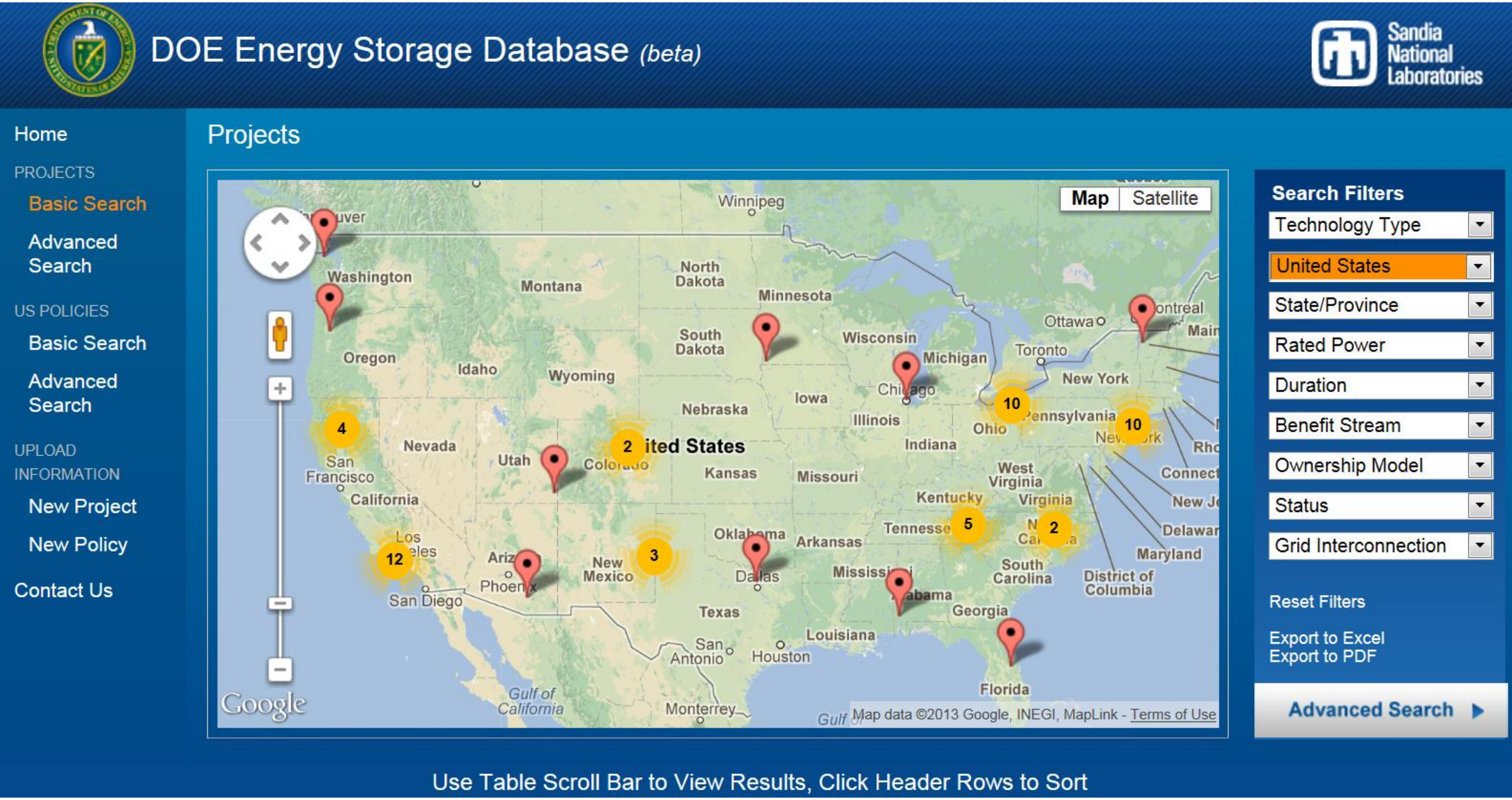
Issued FERC Permits for New PSH in the U.S.



State	Proposed Capacity (MW)	State	Proposed Capacity (MW)
AZ	3,451	OH	1,500
CA	10,203	OK	4,190
CO	932	OR	3,400
HI	300	PA	1,000
IL	250	SD	1,200
KY	1,000	TN	3,992
MT	600	TX	1,931
NJ	1,000	UT	3,100
NV	2,950	WA	1,500
NM	3,154	WV	350
NY	270	WY	1,600
TOTAL CAPACITY			47,873 MW

Source: FERC Staff, January 1, 2013

New DOE Database Tracks Energy Storage Projects



Source: http://www.energystorageexchange.org

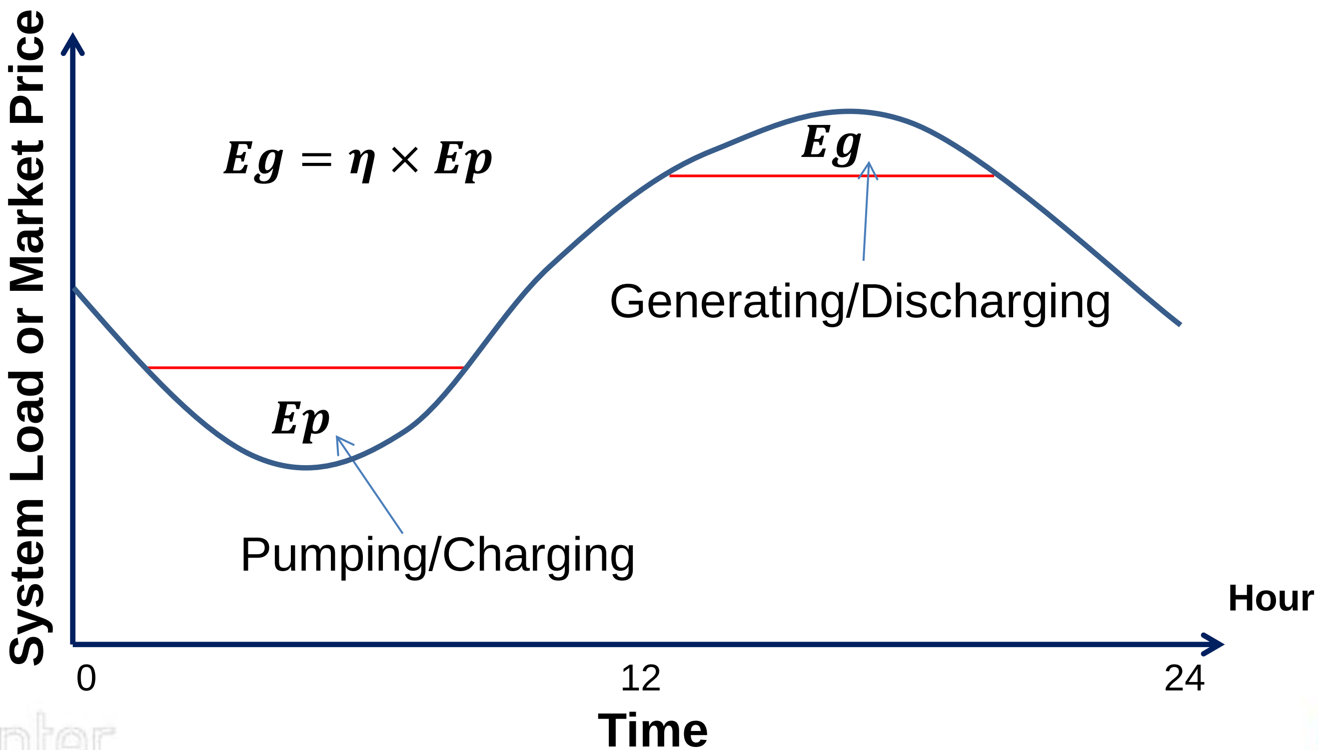
Value of Energy Storage in Utility Systems

Three main components:

- Energy/price arbitrage (wholesale energy market)
- Ancillary services (reserves market)
- Portfolio effects (lower system operating costs, better integration of VER, reduced cycling of thermal units, increased system reliability, etc.)

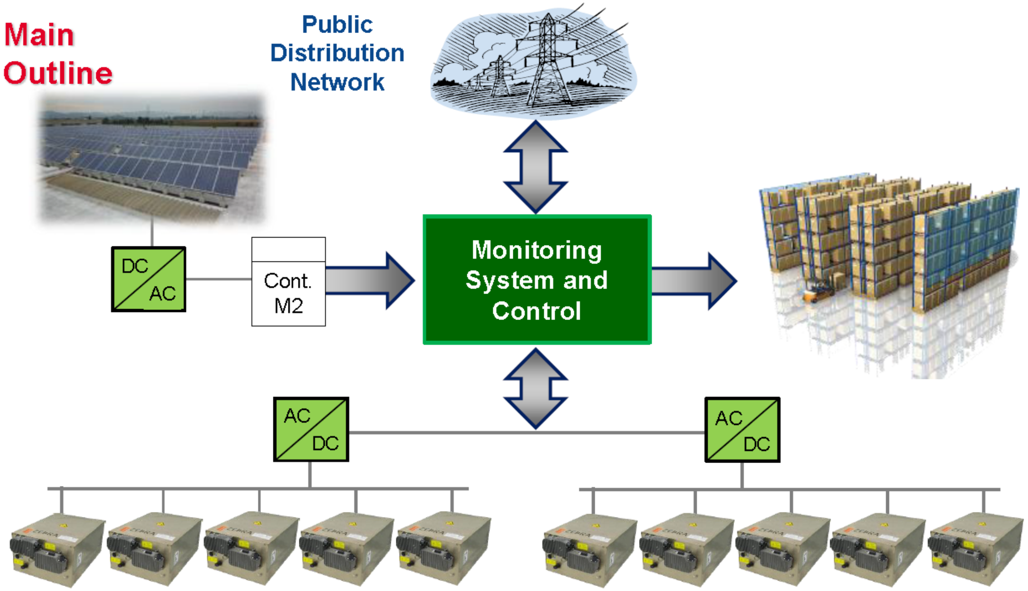
Energy/Price Arbitrage

- Energy storage is net consumer of energy
- Economic operation is based on price differential between peak and off-peak prices/costs



Renewable Generation Energy Management

Main Outline



Firming up and time shifting of solar generation

Source: FIAMM 2012

Energy Storage Can Also Provide Valuable Ancillary Services

- Ancillary services are those necessary to support the generation, transmission, and distribution of electricity from producers to end-users.

- In this context, ancillary services deal primarily with:
  - Control of power generation
  - Grid stabilization, and
  - Integration of variable energy resources (VER), such as wind and solar

- Energy storage is very fast and flexible, which makes it ideal for provision of many ancillary services

Why Do We Need Ancillary Services?

- System operators in electric utilities or ISO/RTOs perform two key tasks:
  - Balance the system generation and load in near-real-time
  - Maintain voltages and power flows through transmission grid within the operating criteria
- To perform these tasks, the system operator needs ancillary services
- Ancillary services provide for secure and reliable system operation
- Ancillary services are used by the "power system", not electricity consumers

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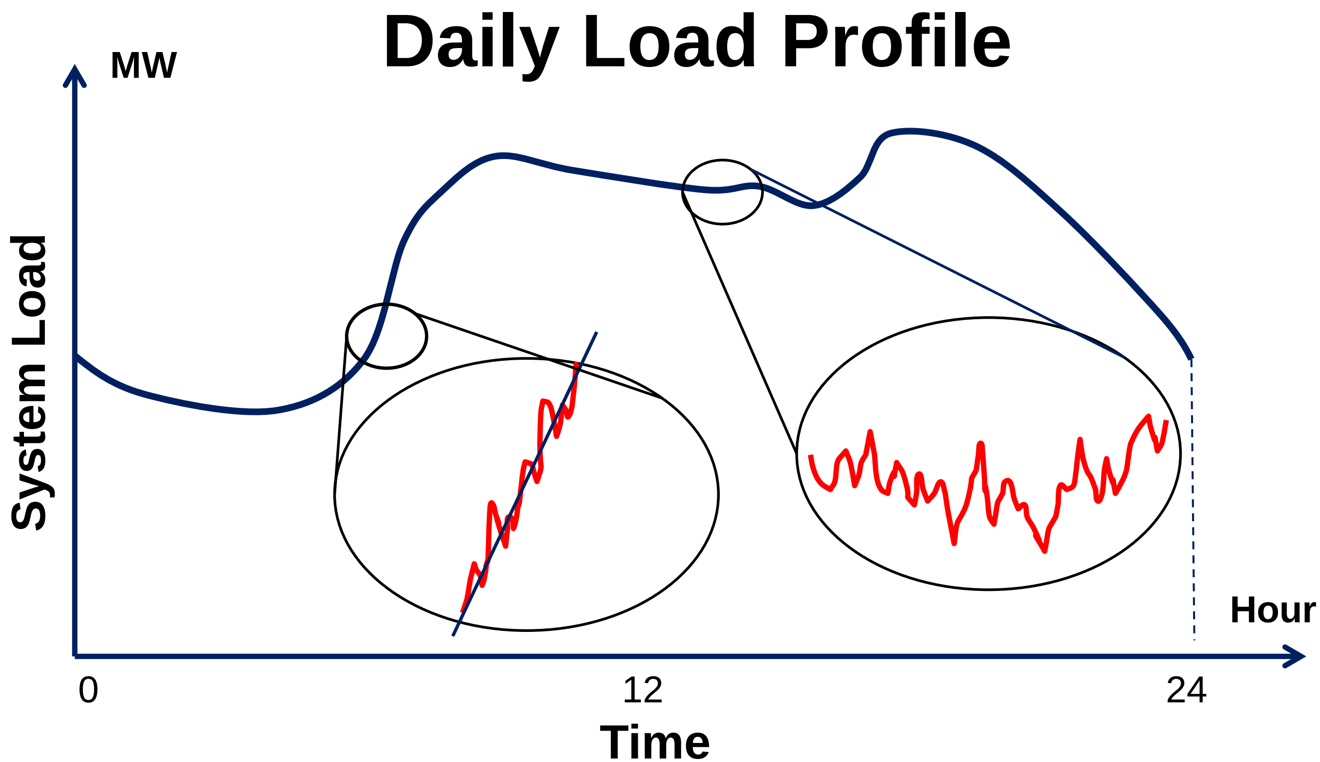
Main Types of Ancillary Services

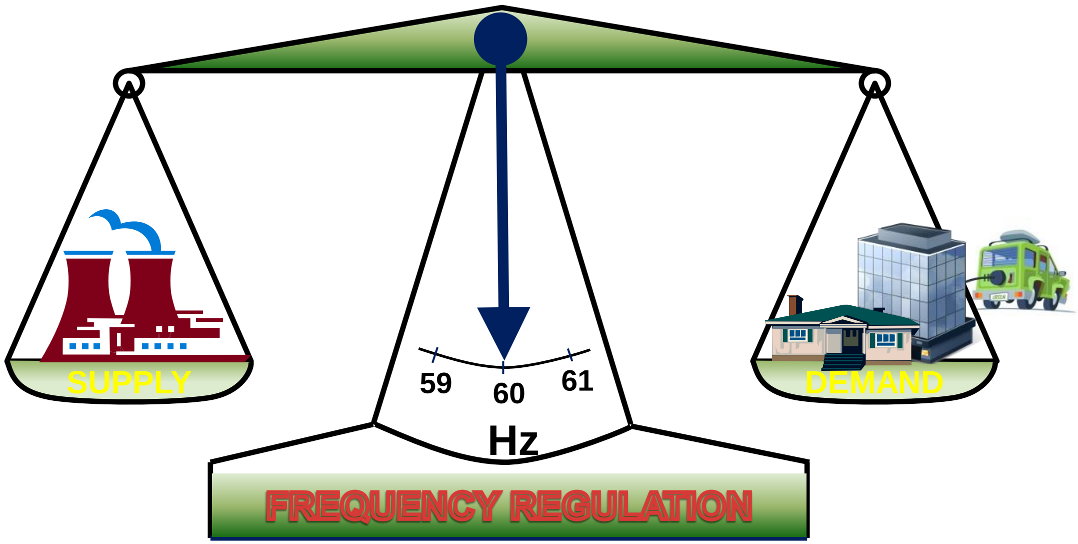
- **Frequency Regulation** (seconds to minutes) – Adjusts power output of generating unit to oppose small deviations in system frequency, as instructed by Automatic Generation Control (AGC)
- **Load following** (minutes to hours) – Adjusts generating unit power output or load to follow longer-term (hourly) changes in system demand (ramping requirements)
- **Voltage control** – provide voltage support for the system
- **Spinning reserve** (full response in 10 minutes) – rapid increase in generation or reduction in load in response to system contingencies (e.g., unit outages)
- **Non-spinning reserve** (full response in 10 minutes)– rapid start and delivery of power of a unit not synchronized to the system in response to system contingencies
- **Supplemental** (response in 10-30 minutes) reserve – Generating units or reduction in load dispatched to replace those providing spinning reserve
- **Black start capability** – To restart the power system after a blackout

Regulation and Load Following



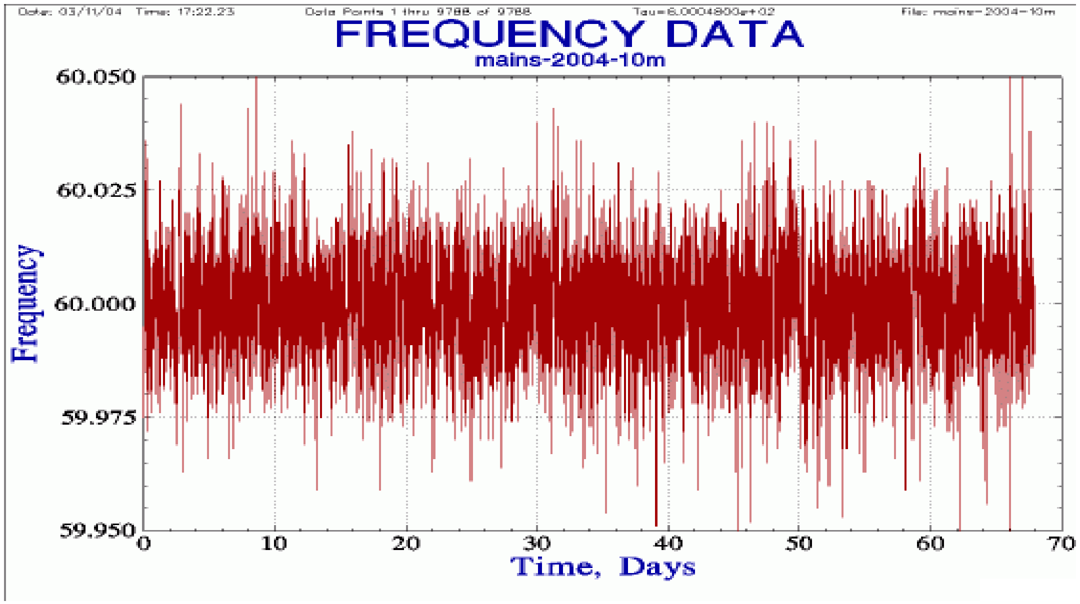
- Regulation is a zero-energy service that compensates minute-to-minute fluctuations in system load and generation of variable energy resources
- Load following compensates for slower and predictable changes in load from hour to hour

Frequency Regulation Is About Balancing Electricity Supply and Demand

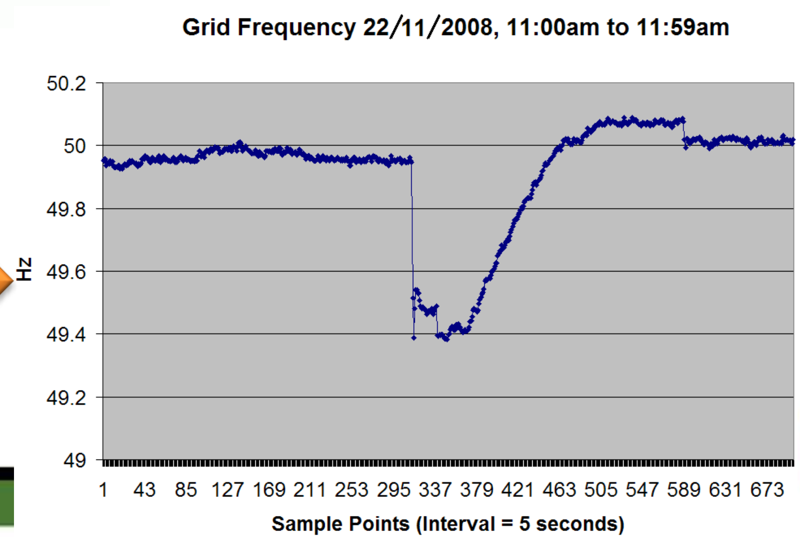


- Any power grid during operation must always maintain a balance between the supply and demand
- If the demand increases faster than the supply, the system frequency tends to decrease (and vice versa)
- The goal of system operators is to keep the system frequency within a narrow range around 60 Hz (50 Hz in Europe)

Frequency in Power Systems Constantly Fluctuates



In case of generating unit or transmission outages, the frequency drop may be significant (Ireland, 11/22/2008)



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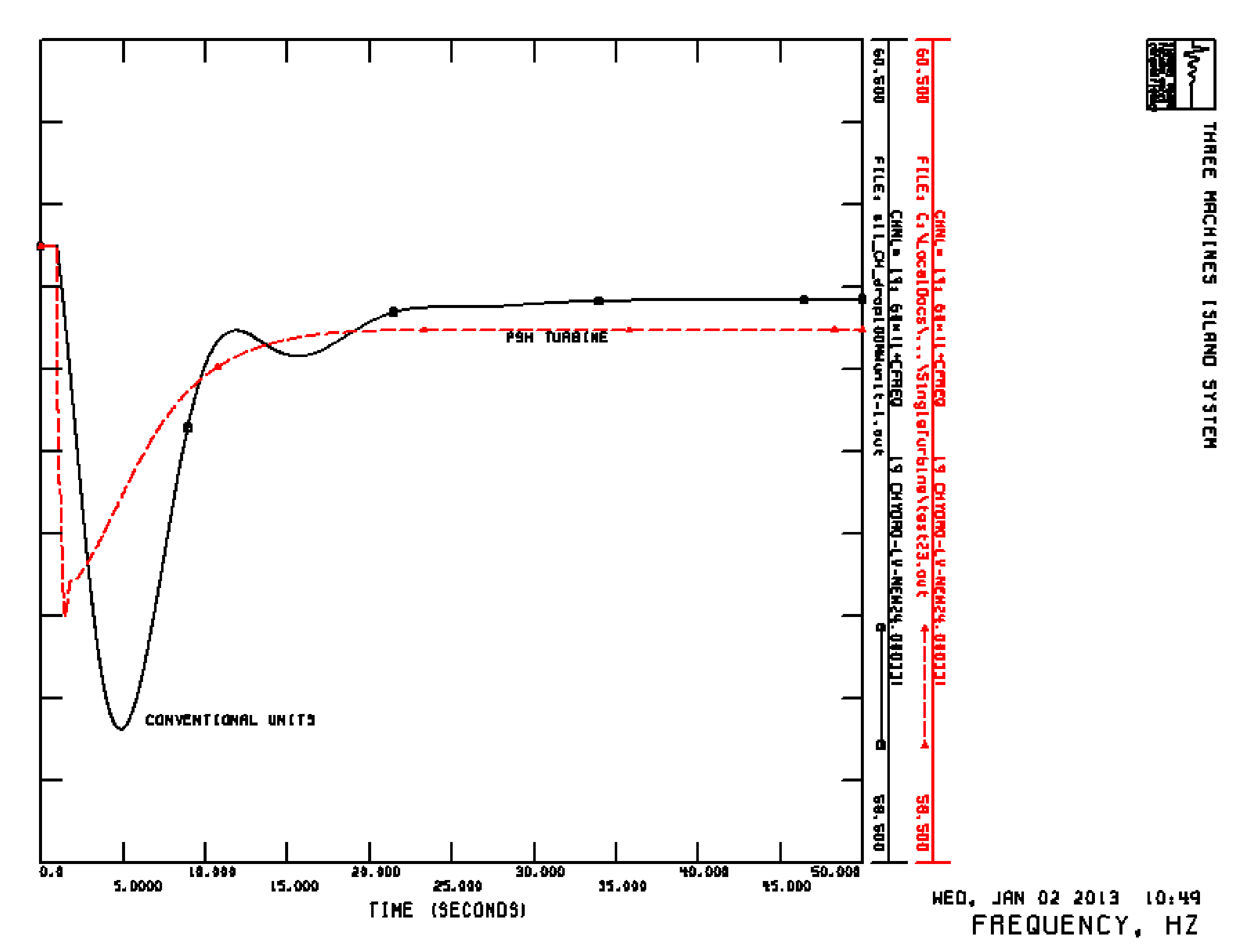
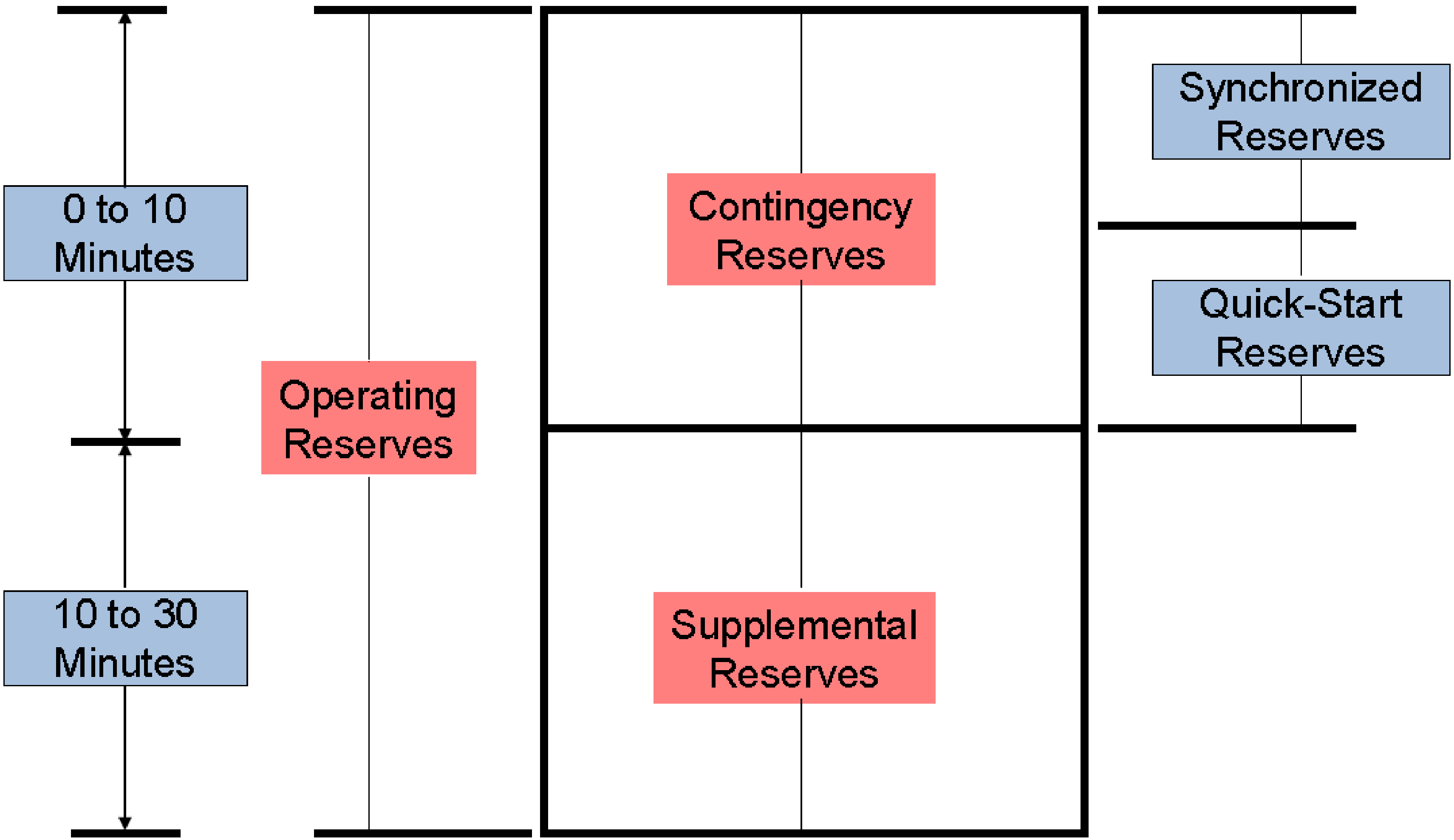
Energy Storage Provides Fast Response in Case of Unit Outages

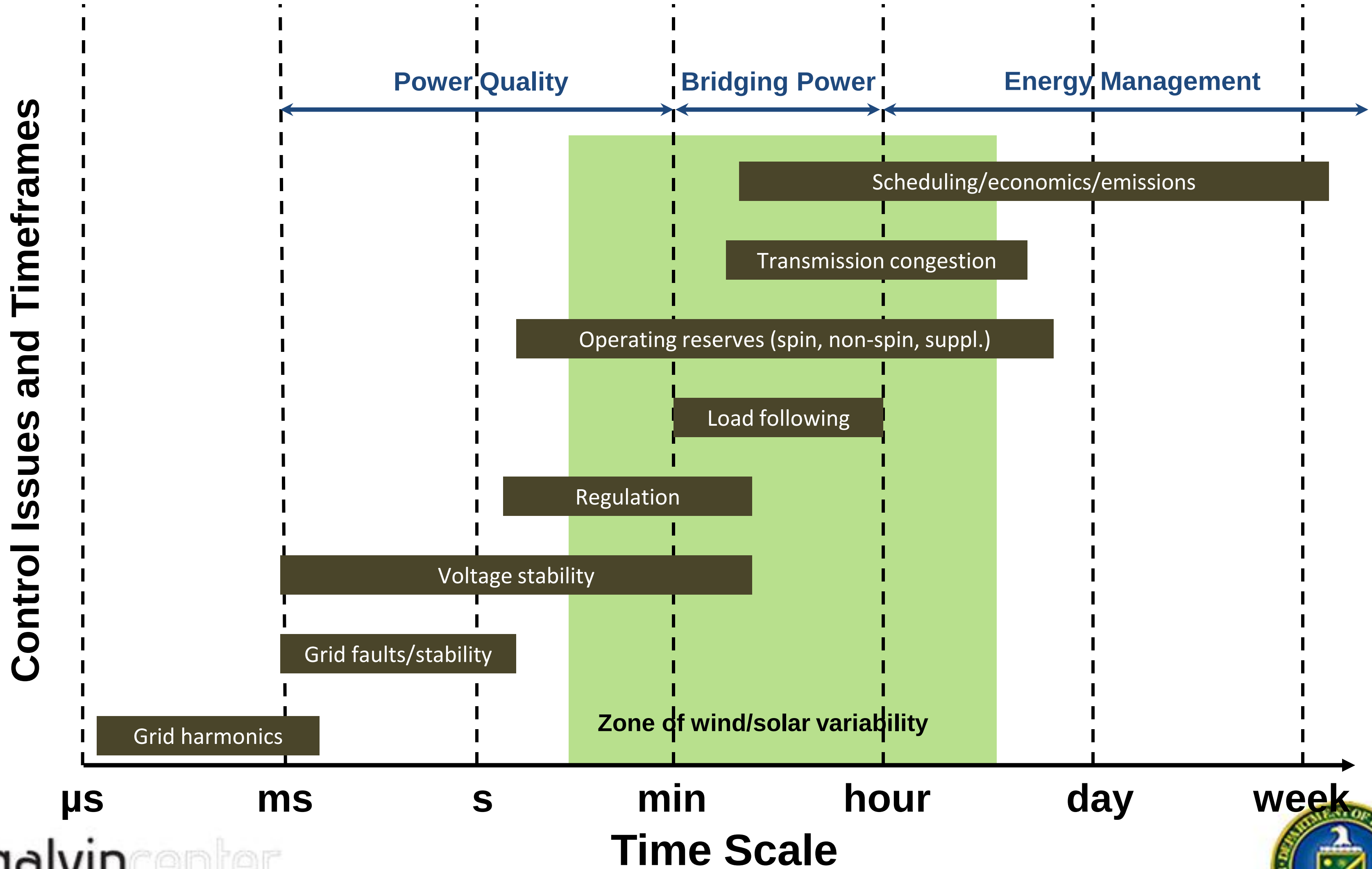


Energy Storage Provides Operating Reserves



Source: PJM, 2012

Grid Control Issues and Timeframes



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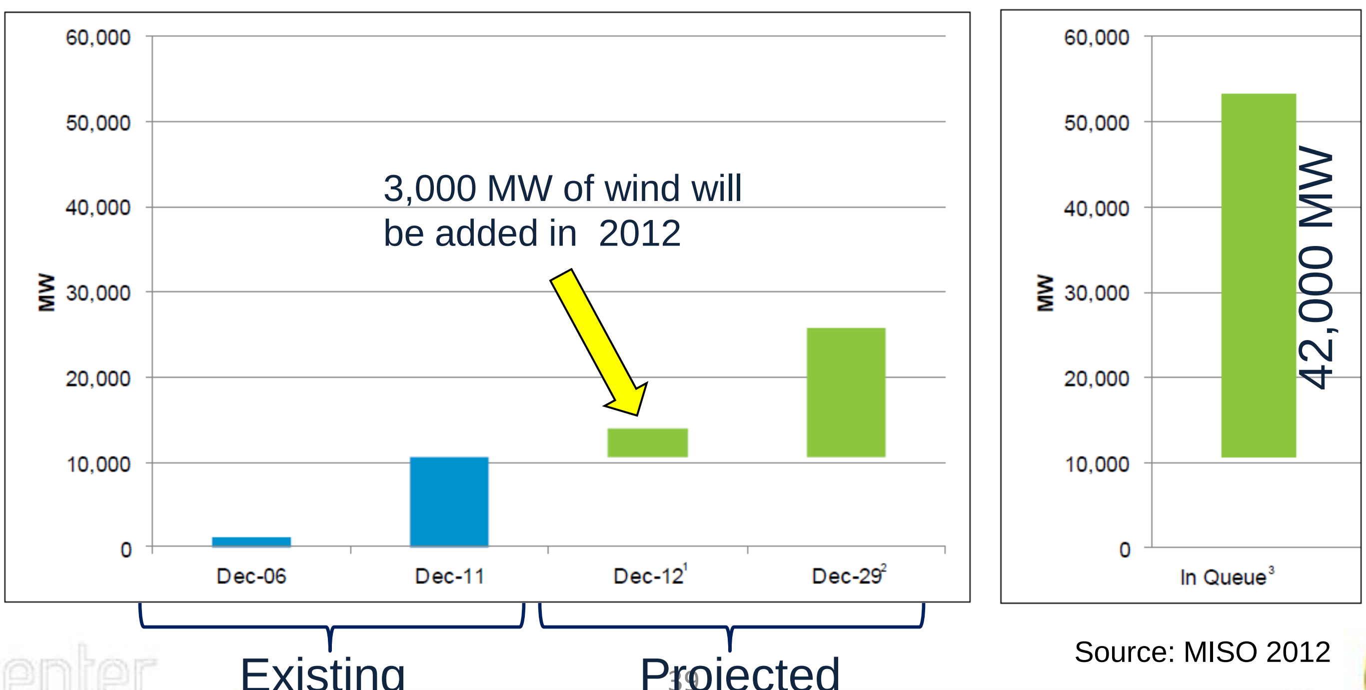
Grid Integration of Renewable Energy Sources

- Wind generation growth in Midwest ISO: 10 times between 2006 and 2011
- Wind variability creates operational problems:
  - Requires manual curtailments (wind cannot be dispatched down automatically during congestion events)
  - Surplus wind generation during light load periods (may cause de-committing of conventional generating units)
  - Requires larger operating reserves (costs more to operate the system)



Source: MISO 2012

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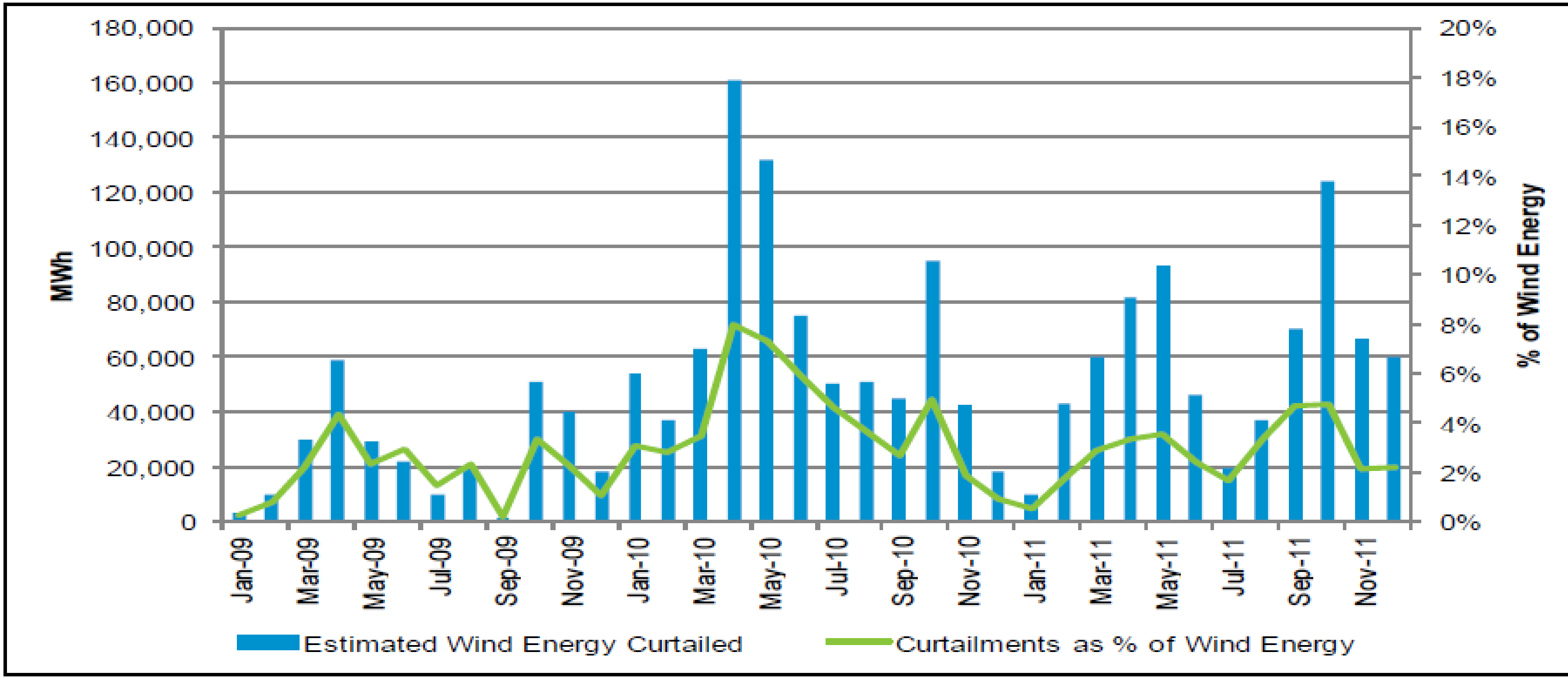
Storage can Reduce Curtailments of RE

- Curtailments of wind generation in MISO (data as of December 2011)



Source, MISO, 2012.

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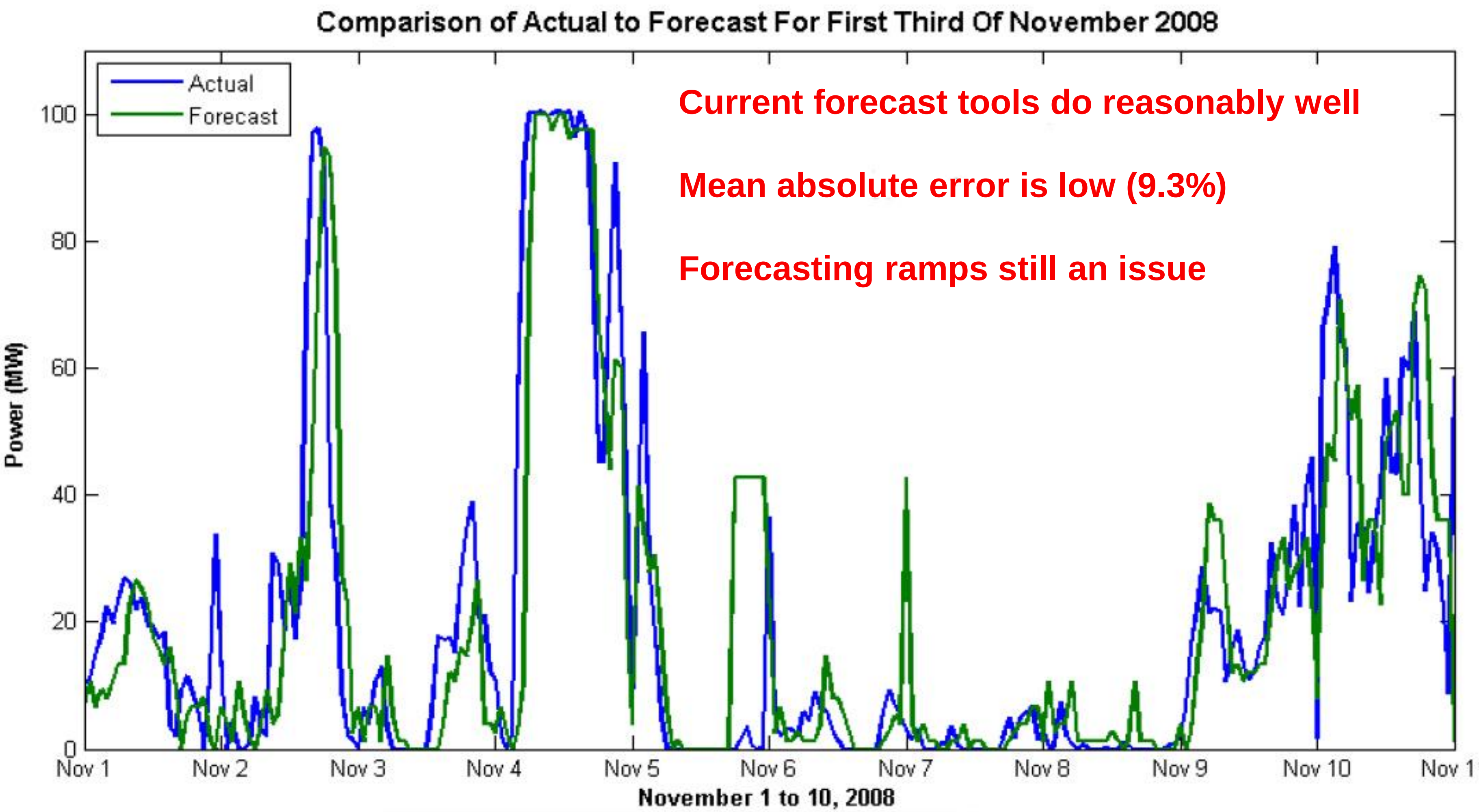
Large Wind Integration will Require Significant Use of Energy Storage

- Energy storage, either as system storage or coupled with wind farms, would provide for:
  - Firming of VER capacity
  - Time-shifting of VER electricity generation
  - Reduced ramping of conventional units
  - Lower reserve requirements, etc.

- Questions:
  - What is the optimal amount of storage?
  - What type of storage is best for use with wind farms?
  - System storage or paired with VER projects?

Source: AES Energy Storage LLC

Advanced Wind Forecasting Helps Reduce Uncertainty, Energy Storage Will Help Manage Variability



Source: Iberdrola, 2009

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Hydropower Plays Significant Role in Integration of Variable Generation Resources

- Hydropower plants, both conventional hydro (CH) and pumped-storage hydro (PSH) plants, are well-suited to provide a number of ancillary services

- CH and PSH plants are characterized by fast and flexible operation with quick starts and excellent ramping capabilities
  - often, the plant operation is constrained not by technical limits of the equipment, but by environmental considerations

- In the pumping mode, PSH plants create system load which can be used to accommodate excess generation of VER and reduce their curtailments

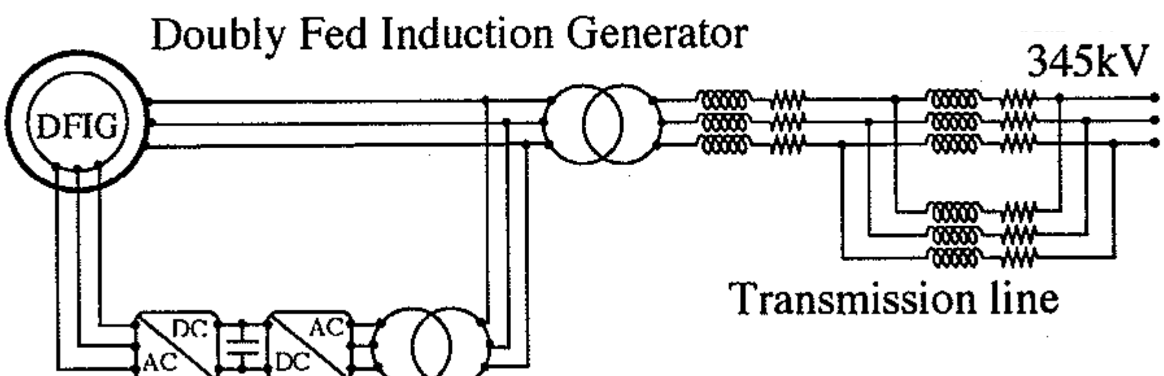
- In contrast to thermal generating units, CH and PSH plants provide ancillary services at much lower cost

PSH Plants can Provide a Variety of Services

- Load shifting (energy arbitrage)
  - Increases efficiency of system operation by:
    - Increasing the generation of base load units
    - Reduces the operation of expensive peaking units
- Contingency reserve (spinning and non-spinning)
  - Provides large amount of quick contingency reserve (e.g., for the outages of large nuclear and coal units)
- Regulation reserve
  - Helps maintain system frequency at a narrow band around nominal system frequency by balancing supply and demand
- Load following
  - Provides a quick-ramping capacity
- Energy imbalance reduction
  - Compensates the variability of wind and solar power

New Adjustable Speed PSH Provide Even More Flexibility

- Adjustable speed PSH are doubly fed induction machines (DFIM)
- The rotors of DFIM drives are equipped with three-phase windings and fed via frequency converter
- The actual mechanical speed is the result of superposition of both rotor and stator rotating magnetic fields and is controlled by frequency converter
- The units can vary the speed (typically up to 10% around the synchronous speed)
- It is possible to adjust the speed to actual water head, which increases turbine efficiency
- Active and reactive power can be controlled electronically and separately
- The units are able to operate in partial load pumping mode



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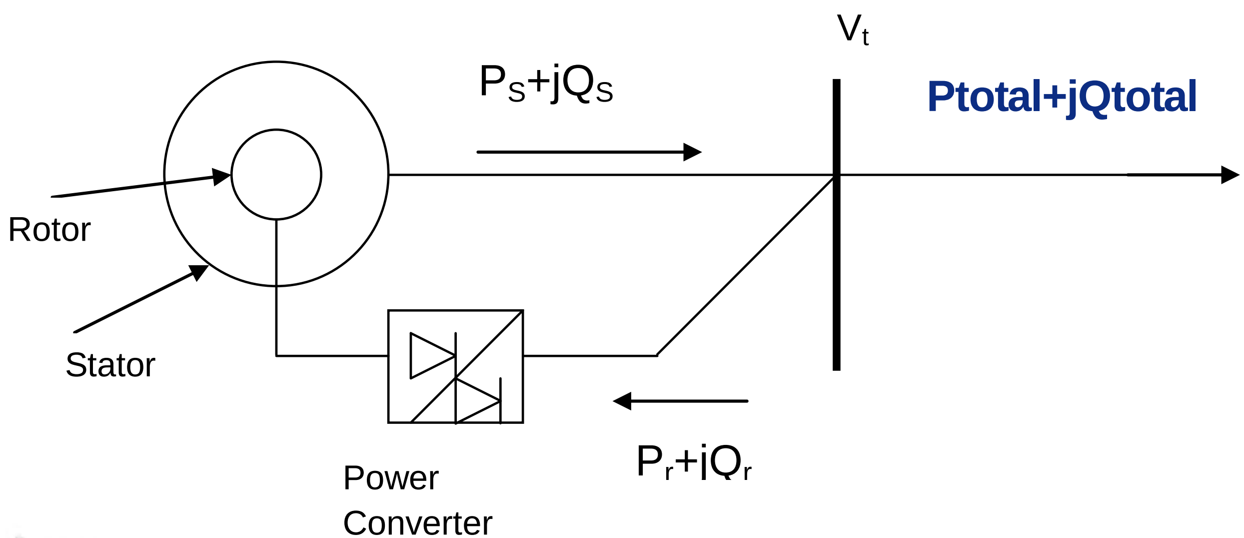
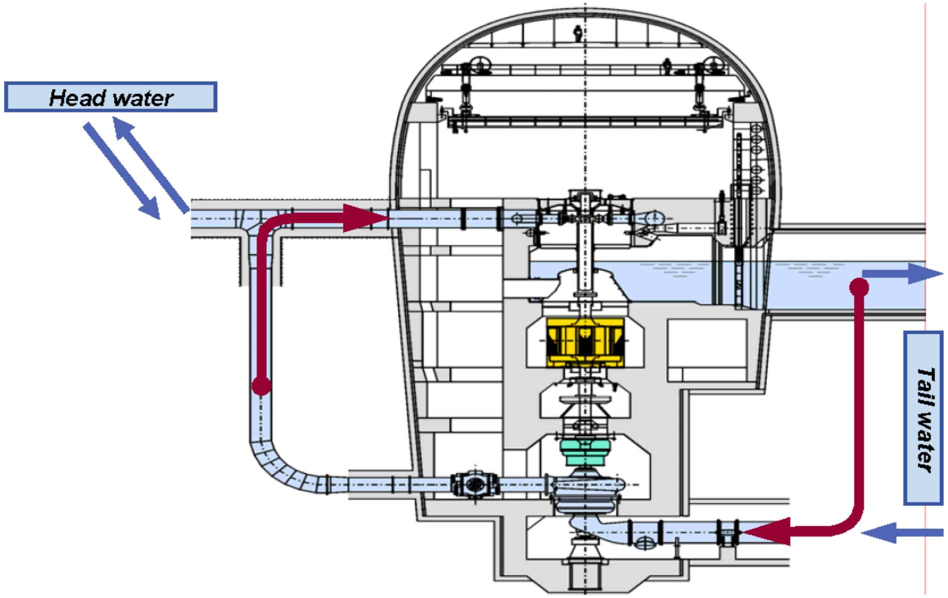
Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines

- Basics of DFIM operation:
  - The stator of the machine is connected to the system.
  - The rotor of the machine is connected to the machine terminals through a power converter.
  - The power converter can control the voltage, current, and frequency in the rotor circuit, and hence the machine power and reactive power



Ternary Pumped Storage Units

- A ternary pumped storage system consists of a separate turbine and pump on a single shaft with an electric machine that can operate as either a generator or motor
- The ternary plant can simultaneously operate both the pump and turbine, referred to as a "hydraulic short circuit"
- This ability provides for greater flexibility in plant's operation



Source: F. Spitzer and G. Penninger, Pumped Storage Power Plants—Different Solutions for Improved Ancillary Services through Rapid Response to Power Needs, HydroVision 2008, July 2008.

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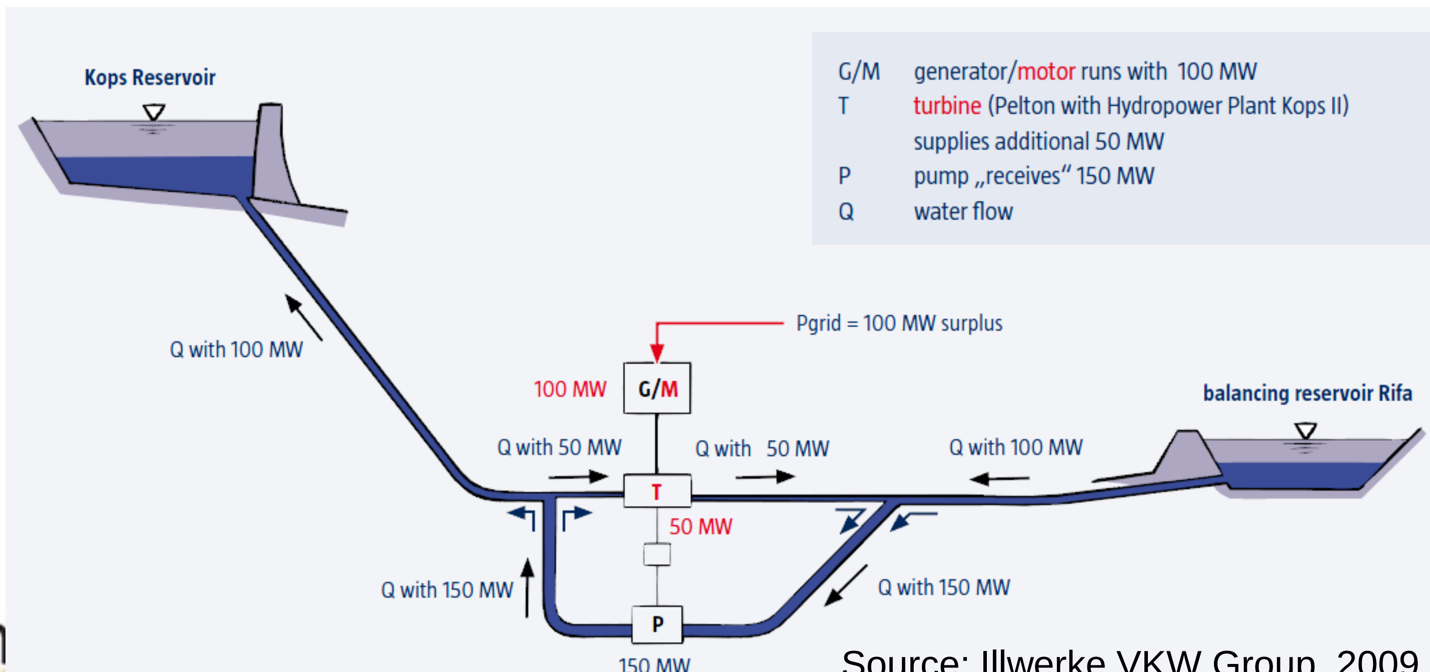
Ternary PSH Technology

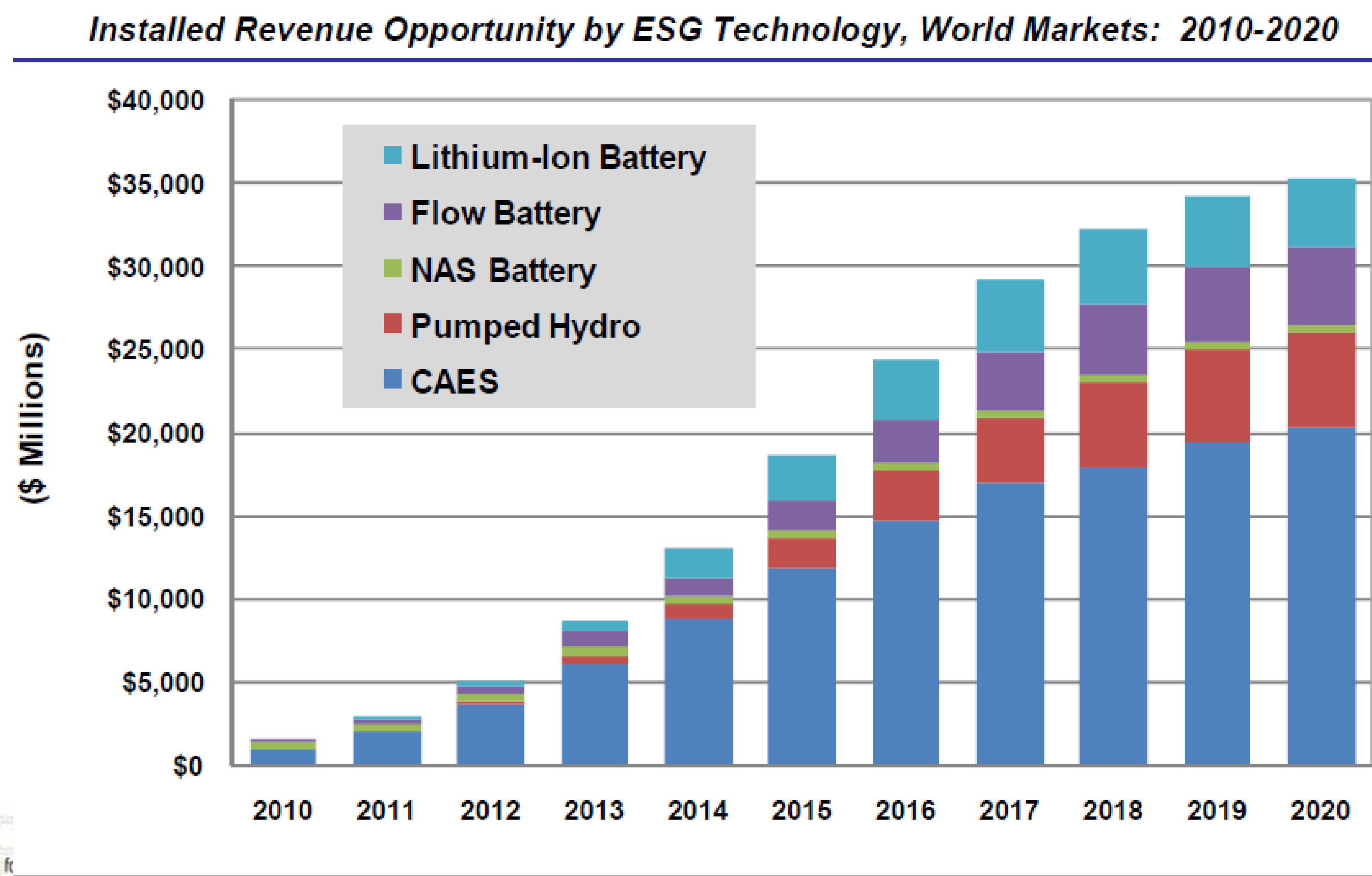
- Kops 2 PSH plant (3x150 MW) in Austria has implemented ternary pump-turbine arrangement
- Turbine and pump are connected with a mechanical clutch (pump can be separated during the generation mode to increase efficiency)
- During the pumping, the power taken from the grid can be supplemented by the power produced by the hydro turbine (“hydraulic short circuit”)
- This provides for flexibility in regulating the pumping power needs from the grid



Source: Illwerke VKW Group, 2009

Some Projections Show Substantial Market for Energy Storage Technologies

- Pike Research forecasts that total energy storage market will grow from $1.5B in 2010 to about $35B in 10 years (that's 37% average annual growth rate!)



(Source: Pike Research)

Potential Market Barriers to Widespread Storage Deployment

- Cost of the technology
- Risk of cost recovery
- Lack of adequate market rules
- Understanding the role and benefits of storage
- How to assess the value of storage in a given application
- Inadequate planning and operation (methods, training, software tools, etc.)

R&D Needs for Battery Storage Technologies

- **Increase power and energy densities**
- **Extend lifetime and cycle-life**
- **Decrease charge-discharge cycle times**
- **Ensure safe operation**
- **Reduce costs**

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In Conclusion, Energy Storage is the Key for Large-Scale Integration of Renewable and other Variable Sources

- Energy storage provides opportunity for better management of variable resources:
  - Capacity firming
  - Renewable energy time-shift
  - Renewable energy integration (regulation, ramping, load following, operational reserves)
- Energy storage will improve power system efficiency, stability, and reliability
- Energy storage can provide valuable ancillary services
  - With large ramp-up in wind, the need for regulation and spinning reserve will increase
  - The importance of storage, both system and distributed, will also increase
- On the consumer side, energy storage provides opportunity for:
  - Price arbitrage
  - Improved power quality and reliability of supply
- Energy storage will also facilitate better use and functionality of smart grid technologies

Questions?

Thank You!

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