Grid-Scale Energy Storage

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Presented by:

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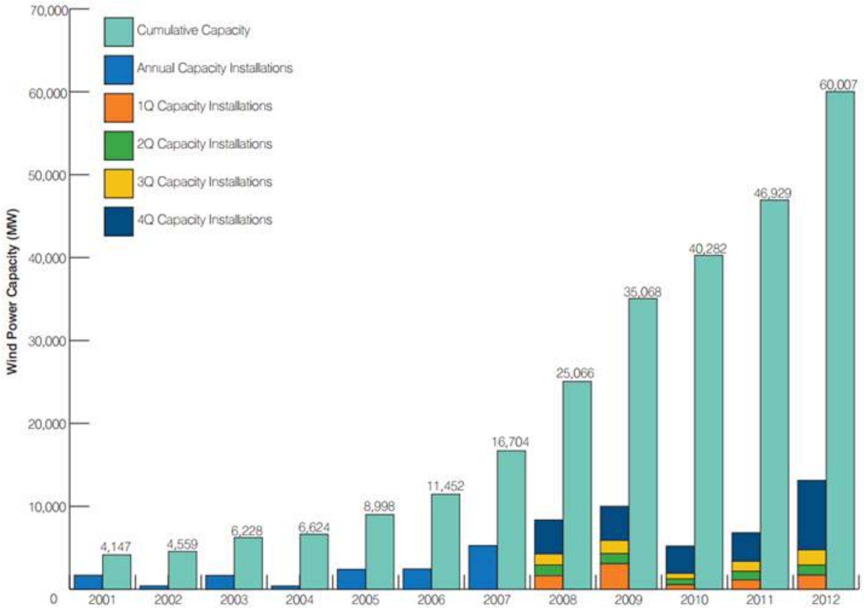
With the Advance of Renewable Energy Sources, Energy Storage Is Becoming Increasingly Important

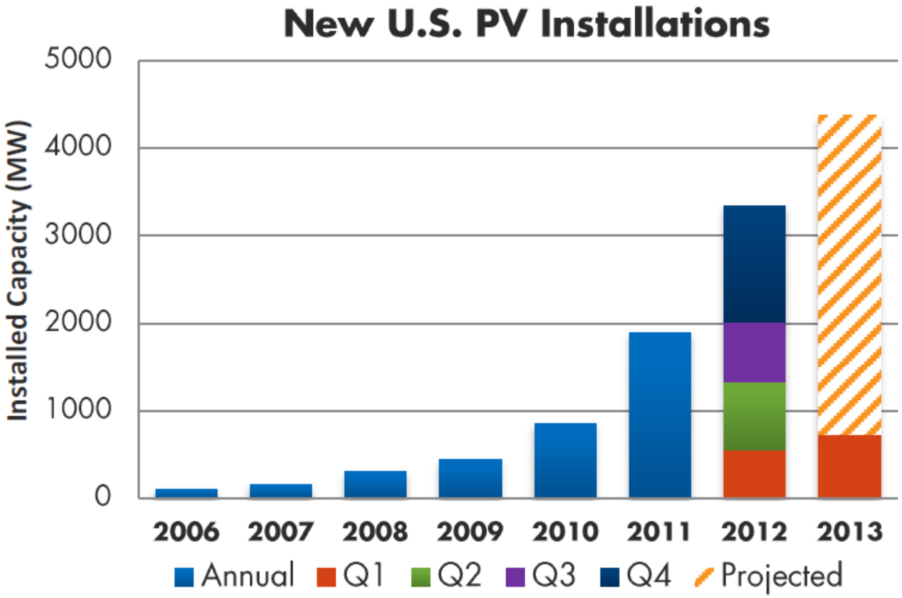
- Energy storage is not a new concept for electric utilities
- Although extremely desirable, wider deployment of energy storage has been limited by the economics/costs and available locations
- Pumped-storage hydro (PSH), large hydro reservoirs, and a few pilot compressed air energy storage (CAES) plants were the main way to store energy
- Small quantities of energy 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, and to facilitate better use and functionality of smart grid technologies

Drivers for Energy Storage: Recent Growth in Wind and Solar



Wind capacity is now over 60 GW

Source: AWEA 2013

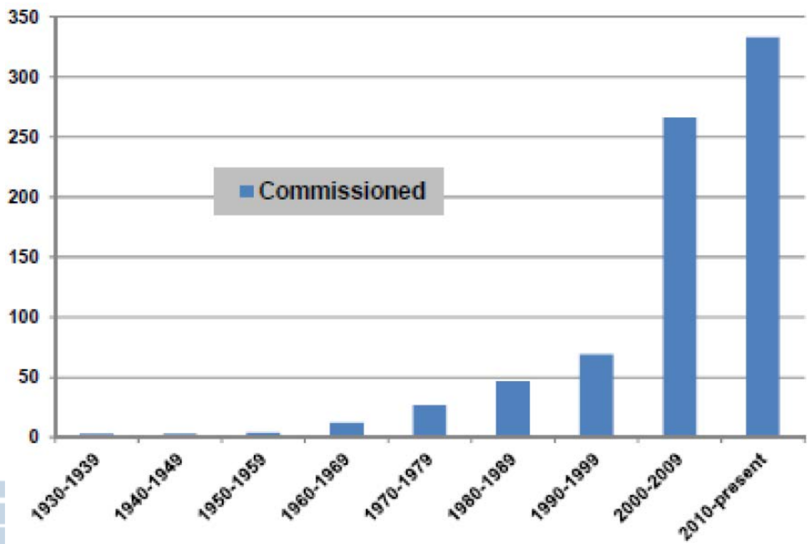


Solar PV is now about 8.5 GW

Source: SEIA 2013

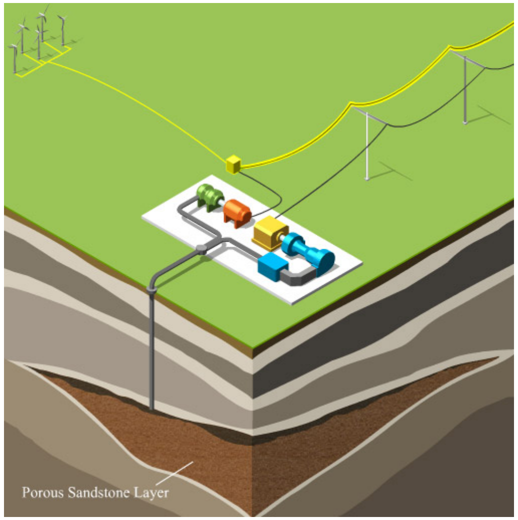
Worldwide energy storage projects by decade

Source: Pike Research 2012



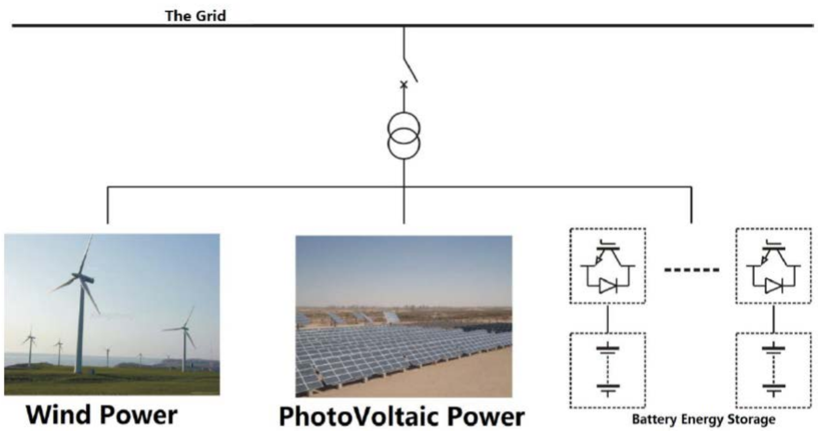
Main Categories of Storage Technologies

- **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.



There are a Variety of Energy Storage Applications

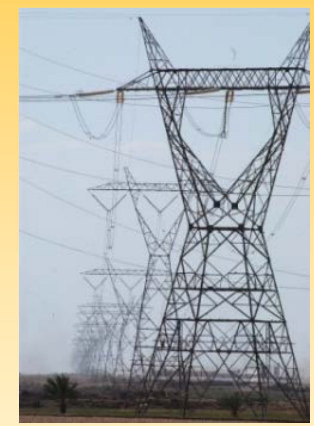
- System storage (e.g., PSH, CAES, large-scale battery storage
  - Currently about127 GW of PSH in the world, of which:
    - 40 GW in European Union
    - 22 GW in the United States
  - Many utilities are building new PSH capacity
    - 1,200 MW Alto Tamega in Portugal,
    - 760 MW Venda Nova 3 in 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

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

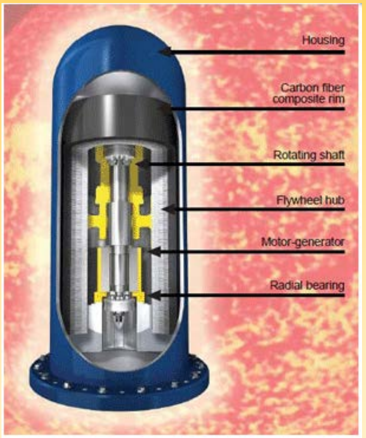
- **Generating capacity**
  - Peaking capacity (e.g., pumped-hydro storage)
- **Energy arbitrage**
  - Load shifting and energy management (load-leveling, time-shift, price arbitrage)
- **Ancillary services**
  - Frequency regulation
  - Operating reserves (spinning, non-spinning, supplemental)
  - Voltage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

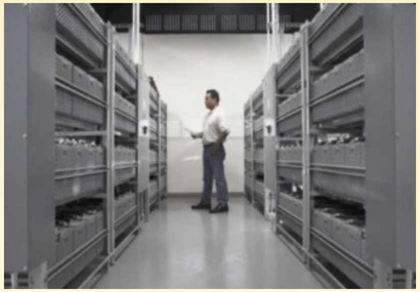


Energy Storage Can Provide Services at all Levels of the Power System Value Chain (cont'd)

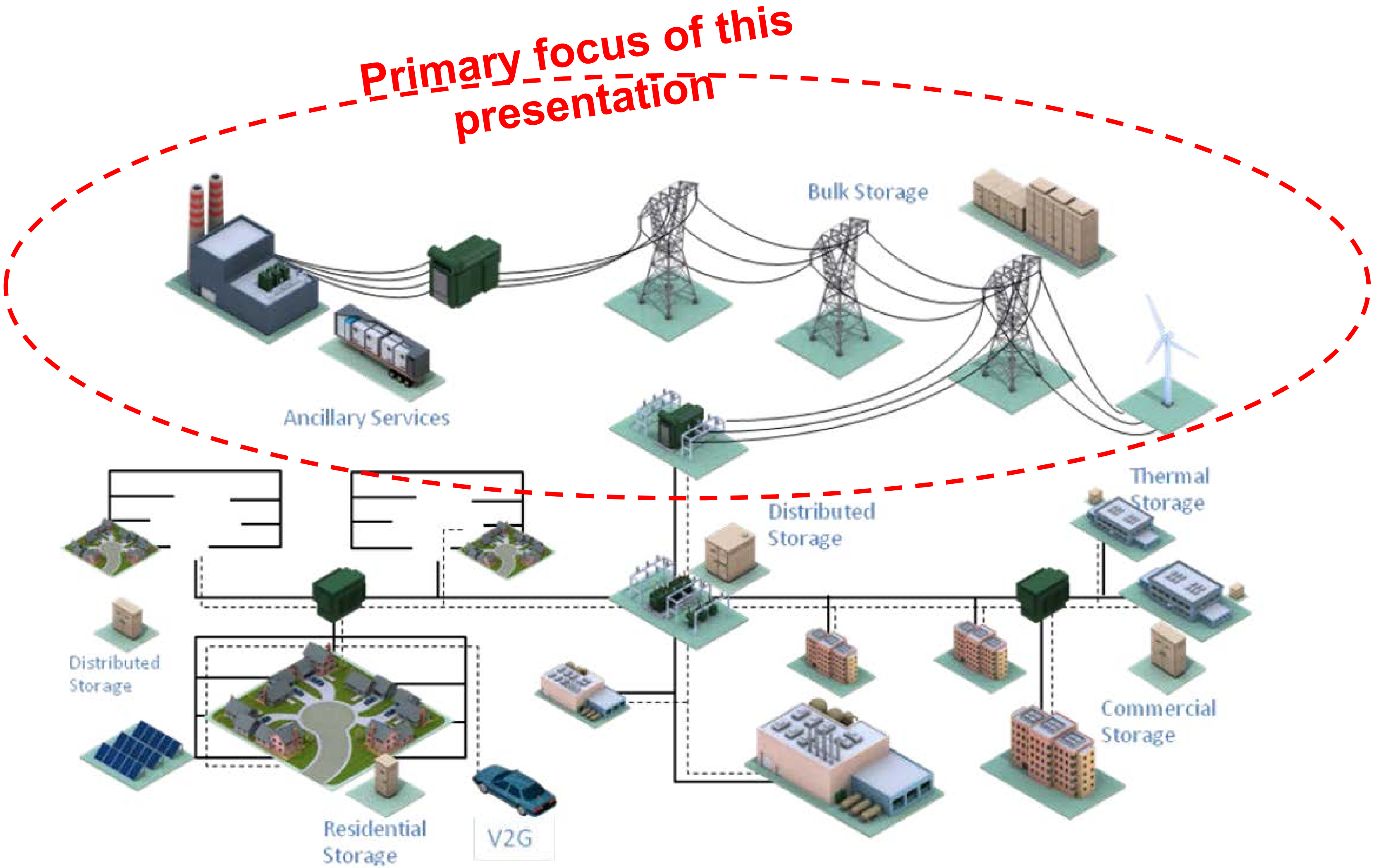
- **Integration of variable energy resources (VER)**
  - Capacity firming
  - Renewable energy time-shift
  - Renewable energy integration (power quality, ramping, and flexibility reserves)
- **Utility customer**
  - Time-of-use energy cost management
  - Capacity charge management
  - Improved power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

* Depending on the plant mix in the system



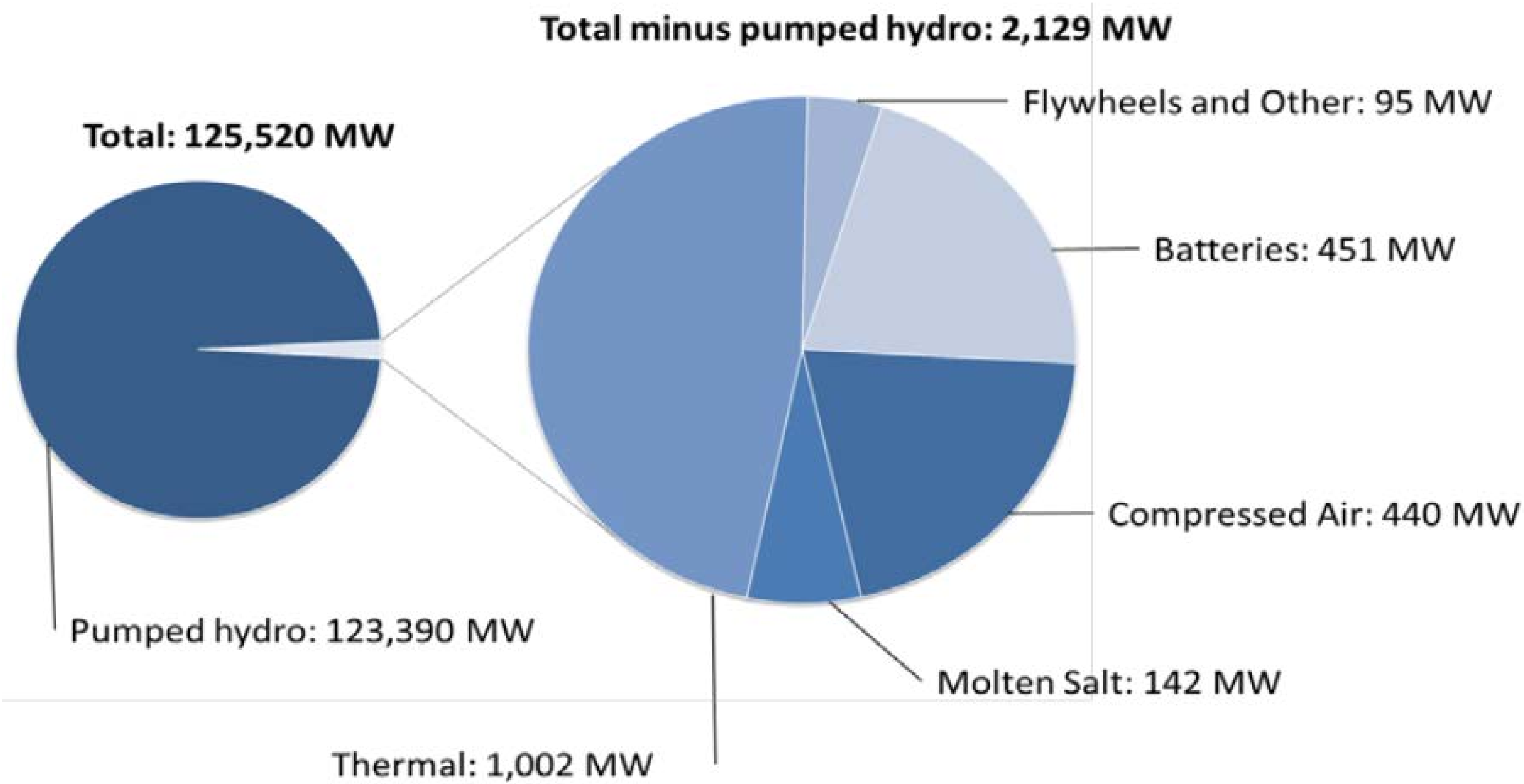


Applications of Energy Storage Systems on the Grid



Source: DOE Electricity Advisory Committee - 2012 Storage Report

2011 Worldwide Grid-Scale Energy Storage Capacity



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

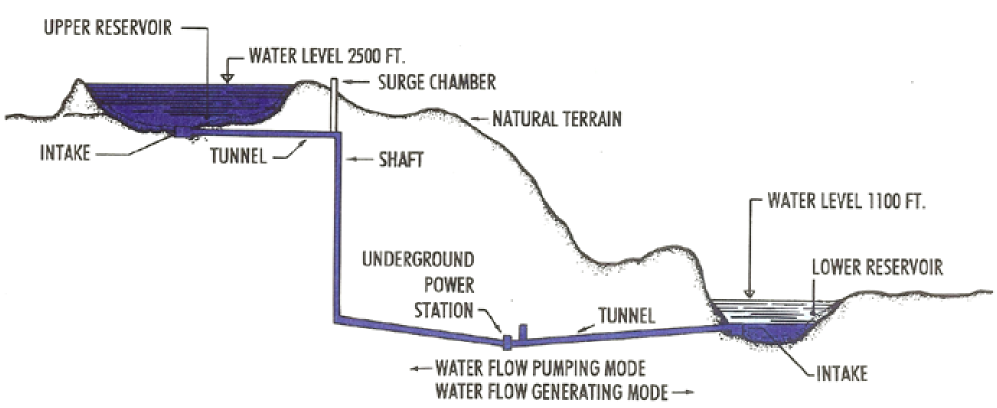
2011 Energy Storage Capacity in the United States

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

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

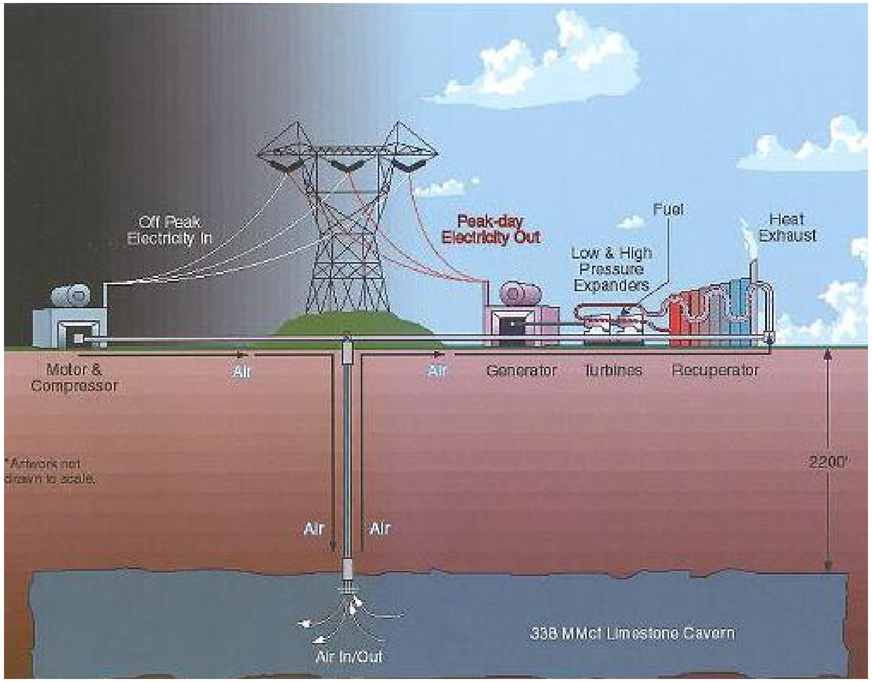
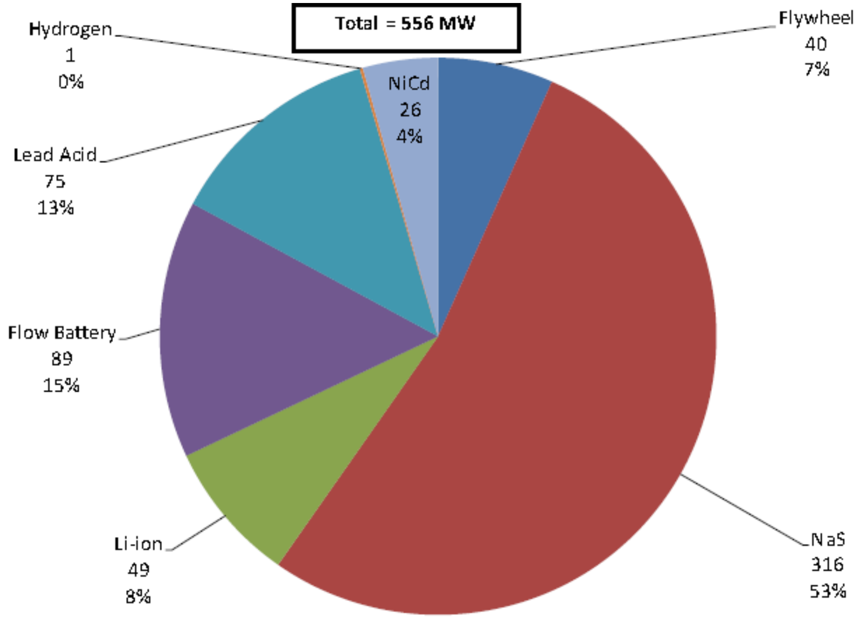


Photo by CAES Development Company

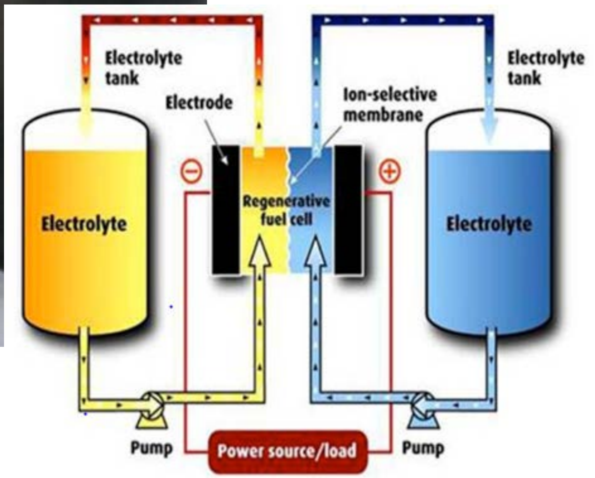
Batteries

- Various chemistries
- Most applications in Japan (typically NaS batteries)
- Li-ion increasing market share



Source: PIKE Research 2012

Source: VRB Power Systems



Flow battery

Photo by AEP

NaS (sodium-sulfur) battery

Flywheels

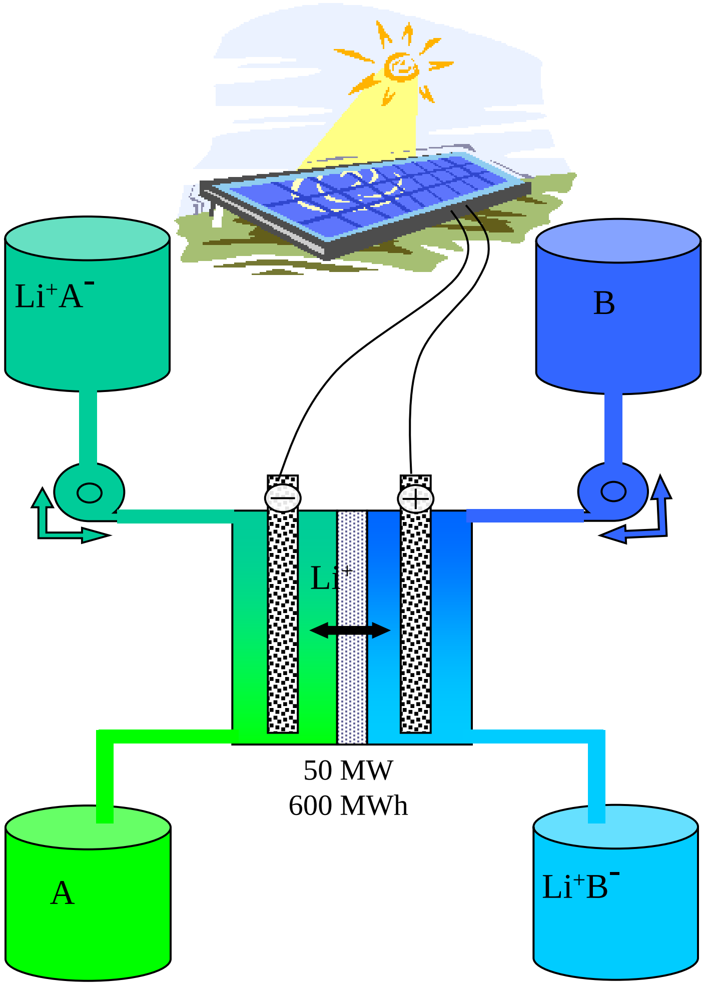
Photo by Beacon Power

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

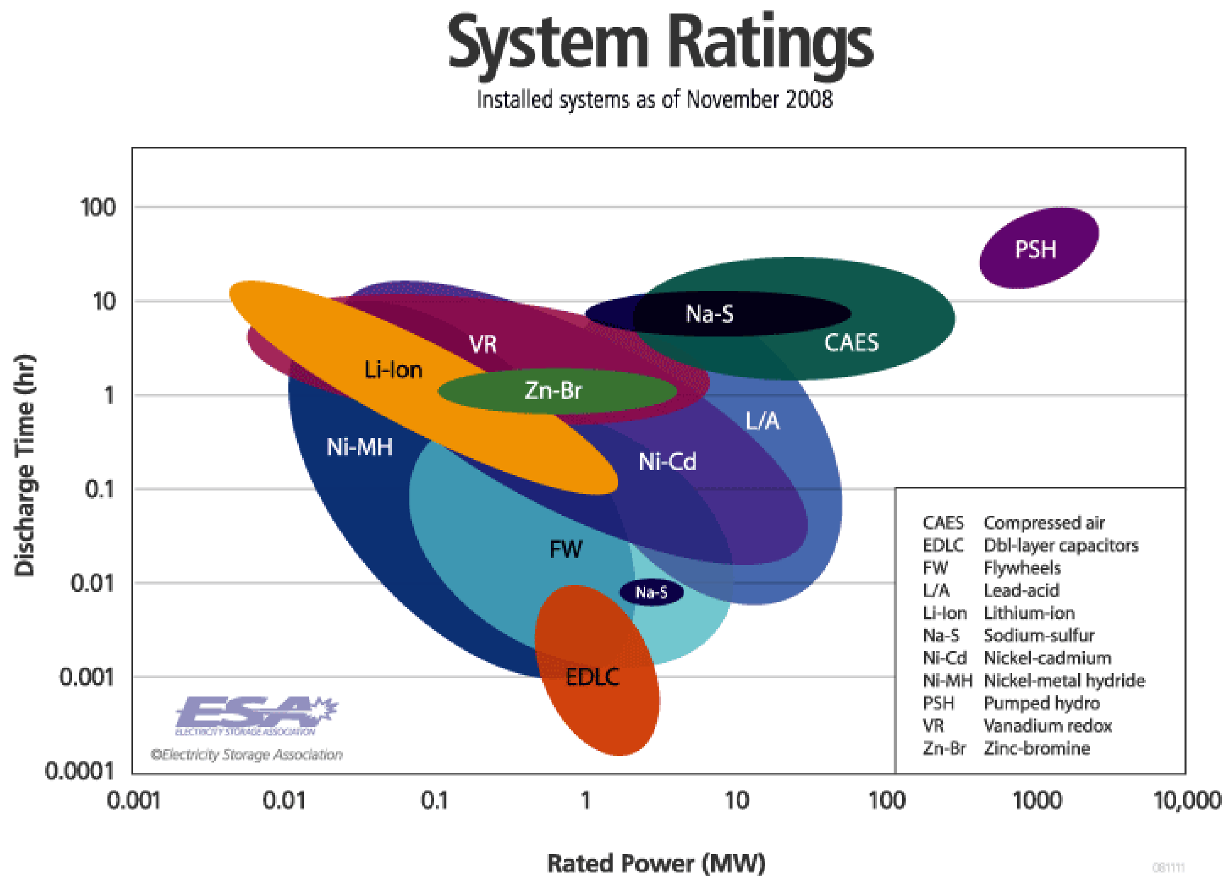
- A new type of flow-battery for large-scale utility applications



Simplified schematic of a flow battery used for load leveling. Shown for generic species A and B with lithium ions as the ions 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.

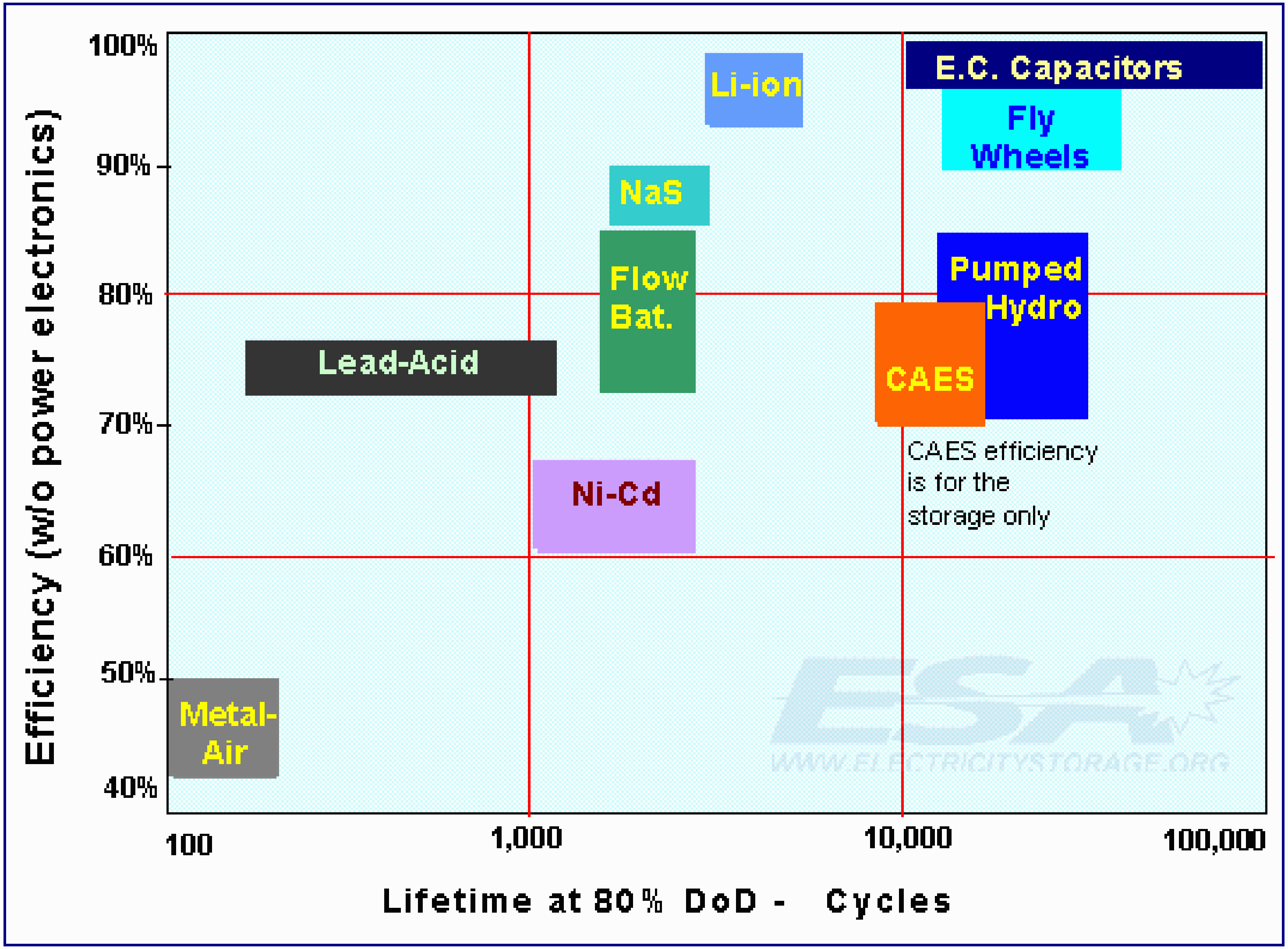
Requirements for Energy Storage

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



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

Cycle Efficiency of Energy Storage Technologies



Cost and Performance Characteristics of Energy Storage Technologies

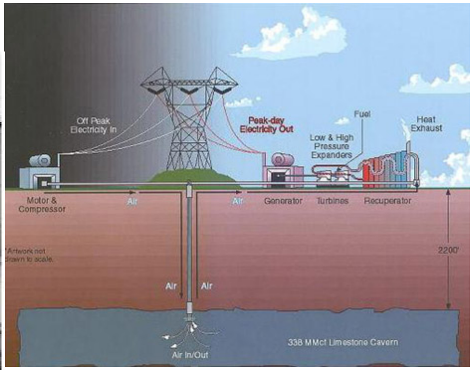
	Lead-acid batteries	Li-Ion batteries	NaS batteries	Flow batteries	Fly-wheels	Pumped hydro	Large-scale CAES
Applicable grid system size [kW/MW]	≤10 MW	≤10 MW	≥100 MW	25 kW–10 MW	100 kW–200 MW	Mostly ≥200 MW	≥500 MW
Lifetime [years]	3–10	10–15	15	Cell stack: 5–15; Electro-lyte: 20+	20	25+	20+
Lifetime [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

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

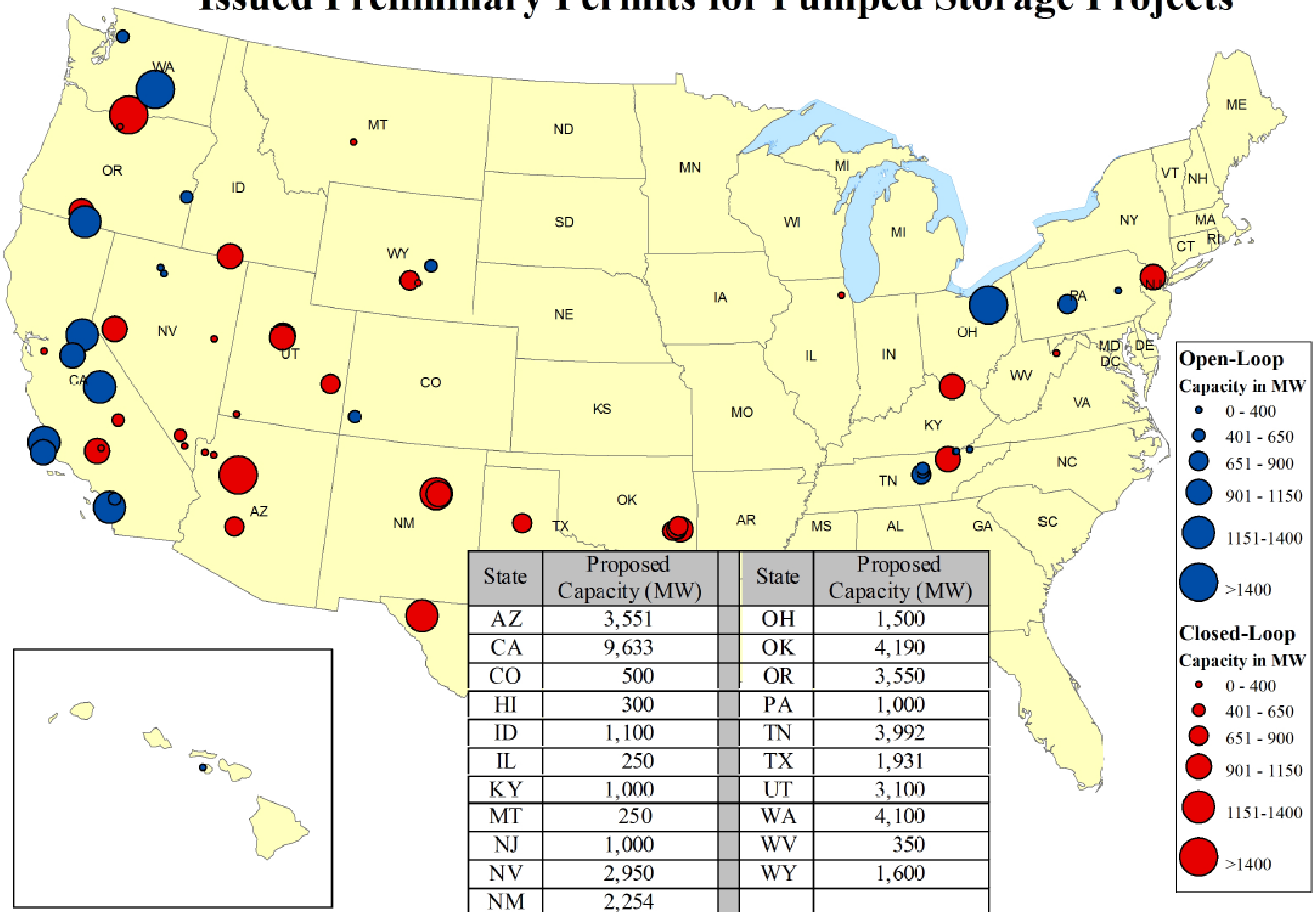
- Flywheels, super-capacitors, SMES, and other storage technologies with the short-term power output (minute time scale)
  - Regulation service
  - Spinning reserve, etc.

- 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.



Will there be Enough Energy Storage Available?

Issued Preliminary Permits for Pumped Storage Projects

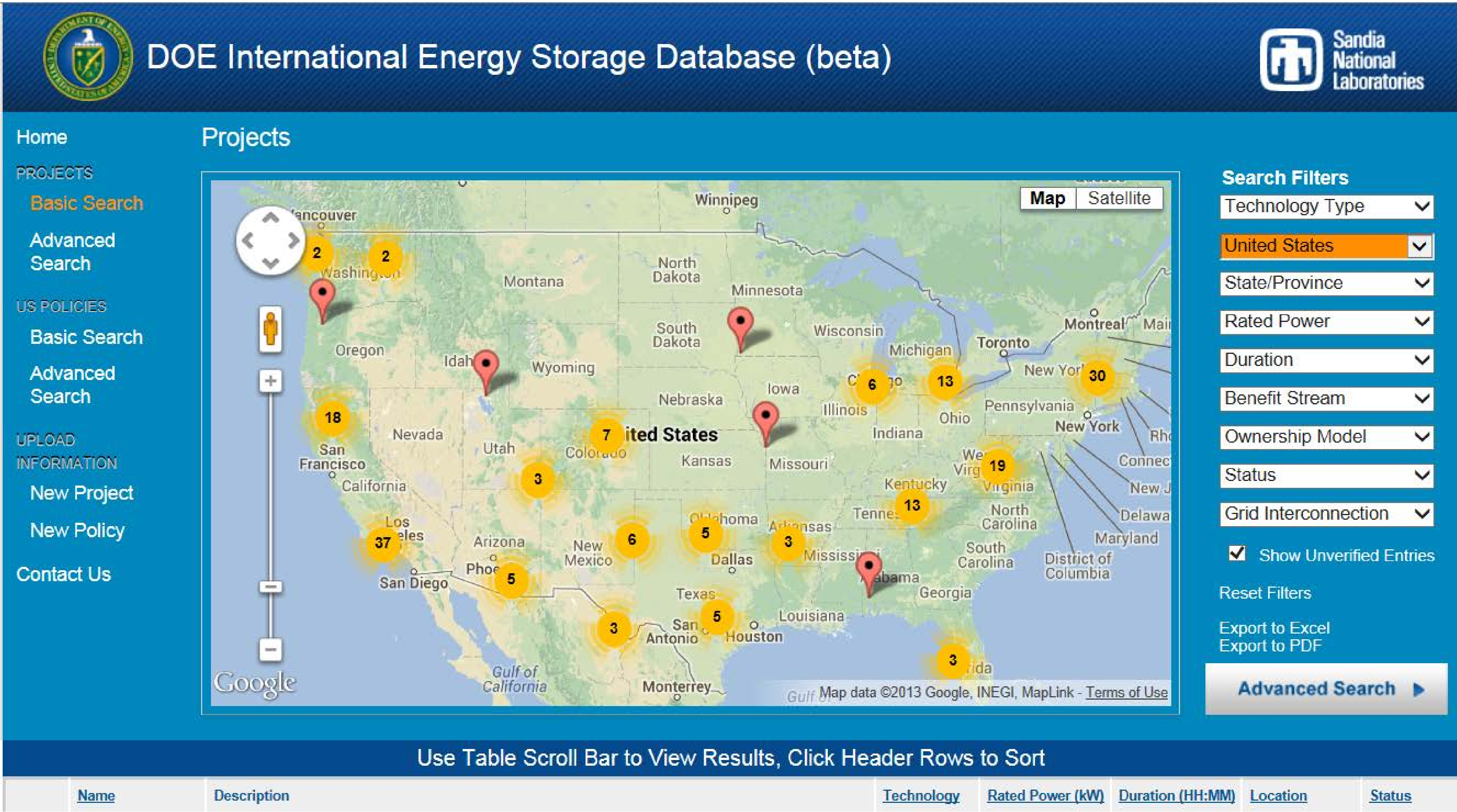


State	Proposed Capacity (MW)	State	Proposed Capacity (MW)
AZ	3,551	OH	1,500
CA	9,633	OK	4,190
CO	500	OR	3,550
HI	300	PA	1,000
ID	1,100	TN	3,992
IL	250	TX	1,931
KY	1,000	UT	3,100
MT	250	WA	4,100
NJ	1,000	WV	350
NV	2,950	WY	1,600
NM	2,254		
TOTAL CAPACITY			48,101 MW

Note: Preliminary determination of open- vs. closed-loop classification based on preliminary permit application.

Source: FERC Staff, August 1, 2013

New DOE Database Tracks Energy Storage Projects



Source: http://www.energystorageexchange.org

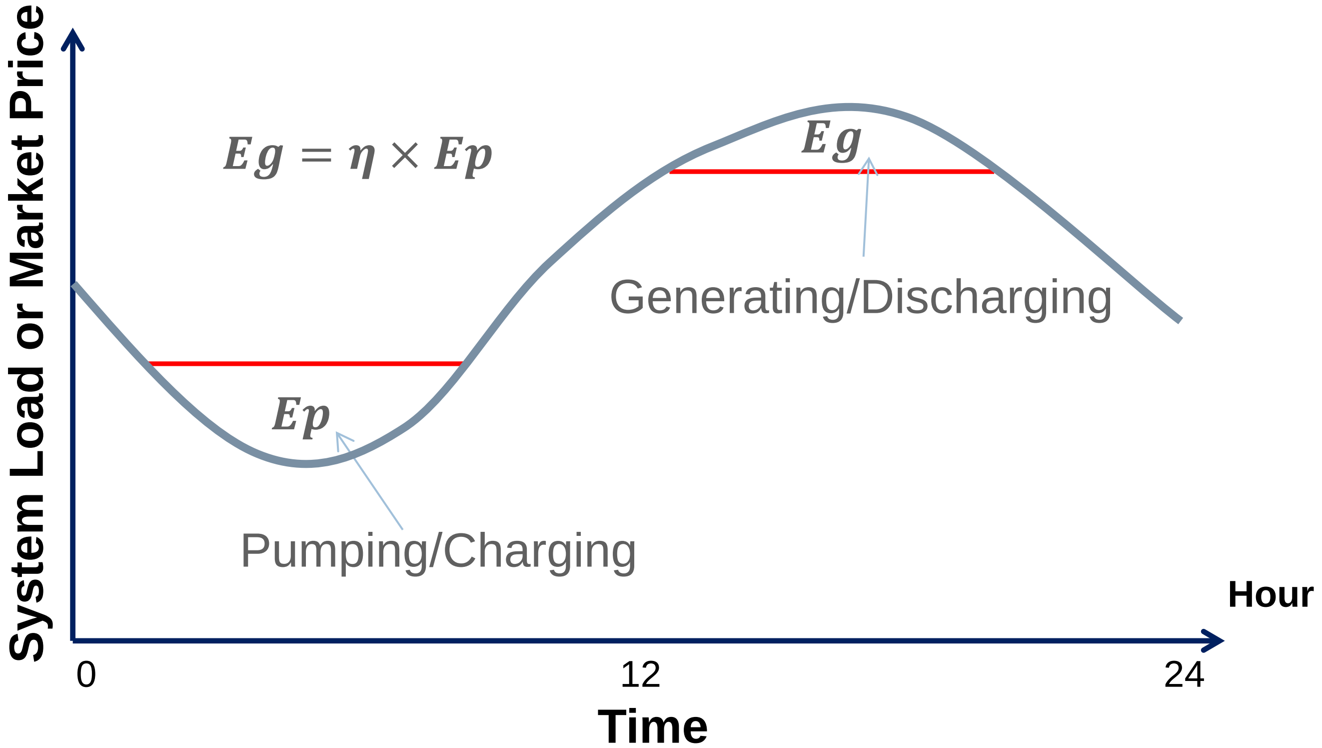
Value of Energy Storage in Utility Systems

Three main components:

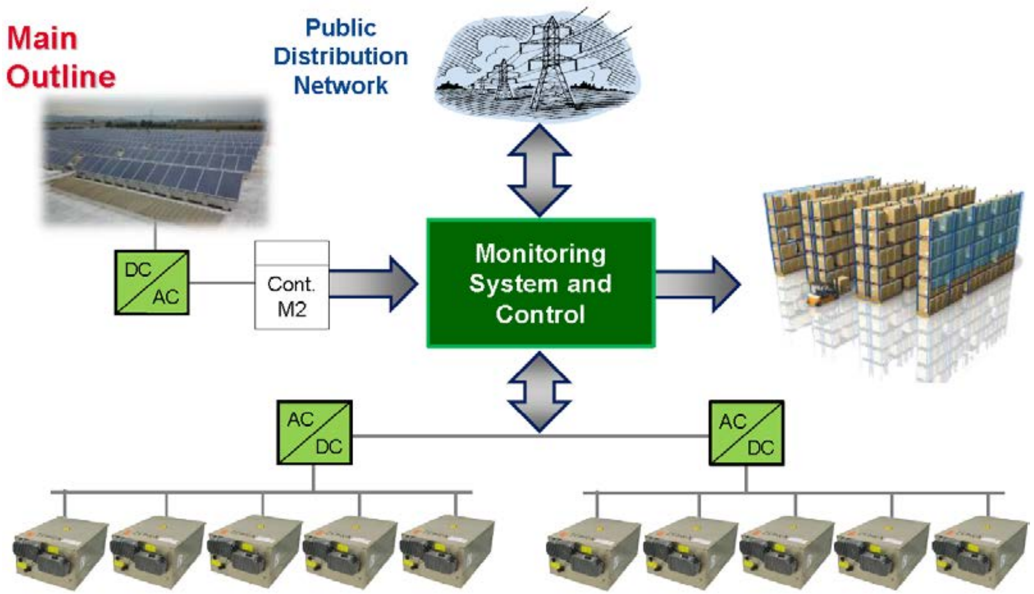
- Energy/price arbitrage (wholesale energy market)
- Ancillary services (reserves market)
- Portfolio effects (lower system operating costs, better integration of VER, reduced cycling of thermal units, increased system reliability, etc.)

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



Firming up and time shifting of solar generation

Source: FIAMM 2012

Ancillary Services

- Energy storage can also provide valuable ancillary services

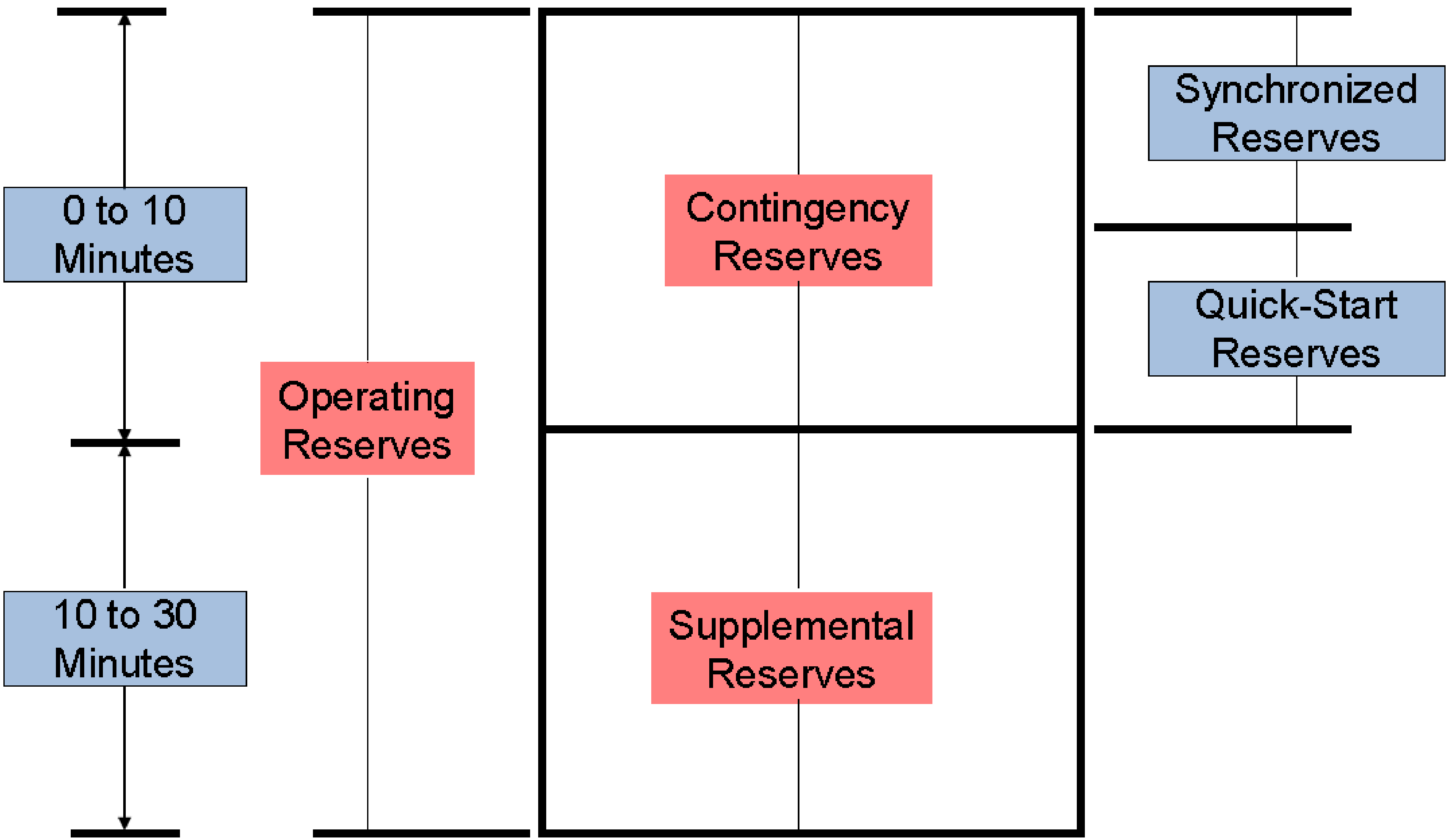
- Ancillary services are those necessary to support the generation, transmission, and distribution of electricity from producers to end-users.

- 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

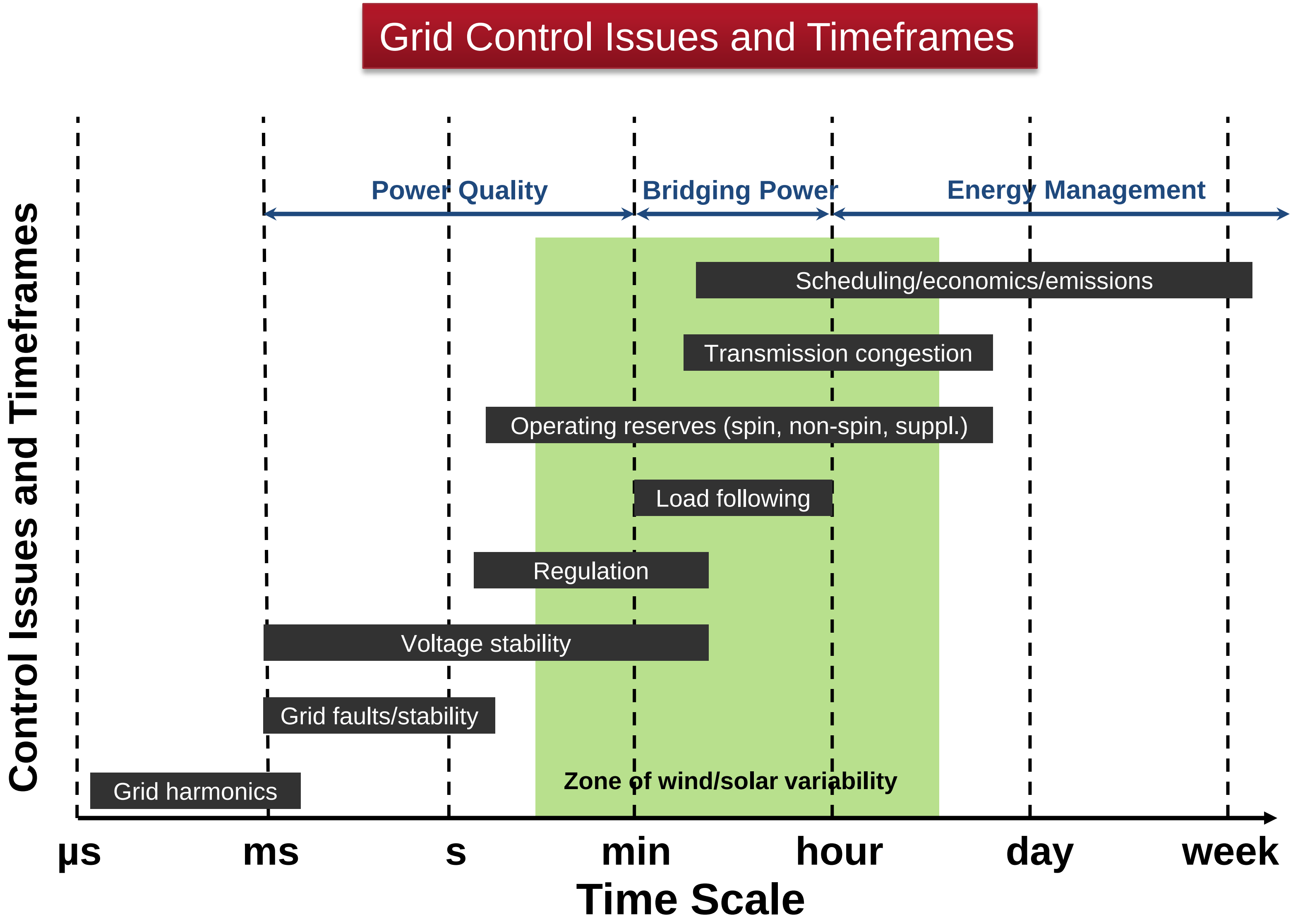
Energy Storage Provides Fast Response in Case of Unit Outages

Operating Reserves



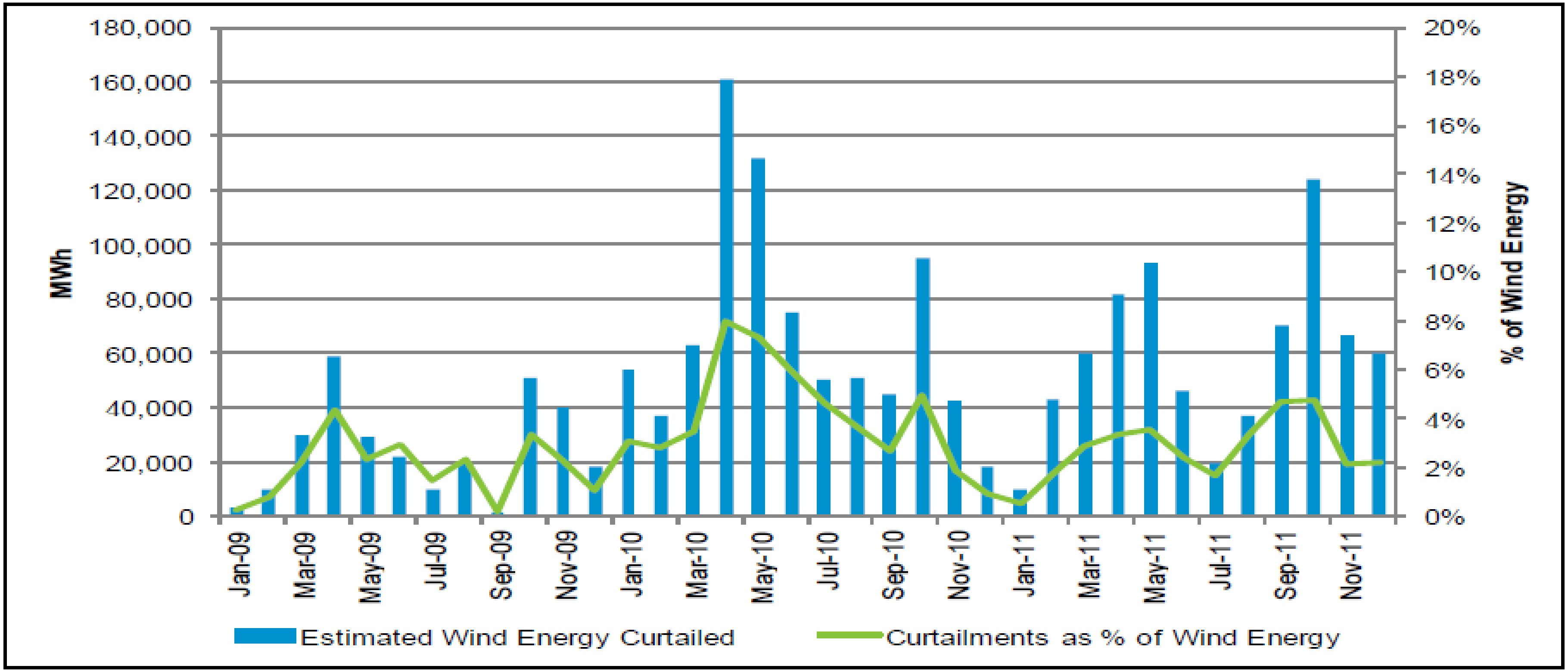
Source: PJM, 2012

Energy Storage Helps Grid Integration of Variable Energy Resources



Storage can Reduce Curtailments of Variable Energy Resources

- Curtailments of wind generation in MISO (January 2009 - December 2011)



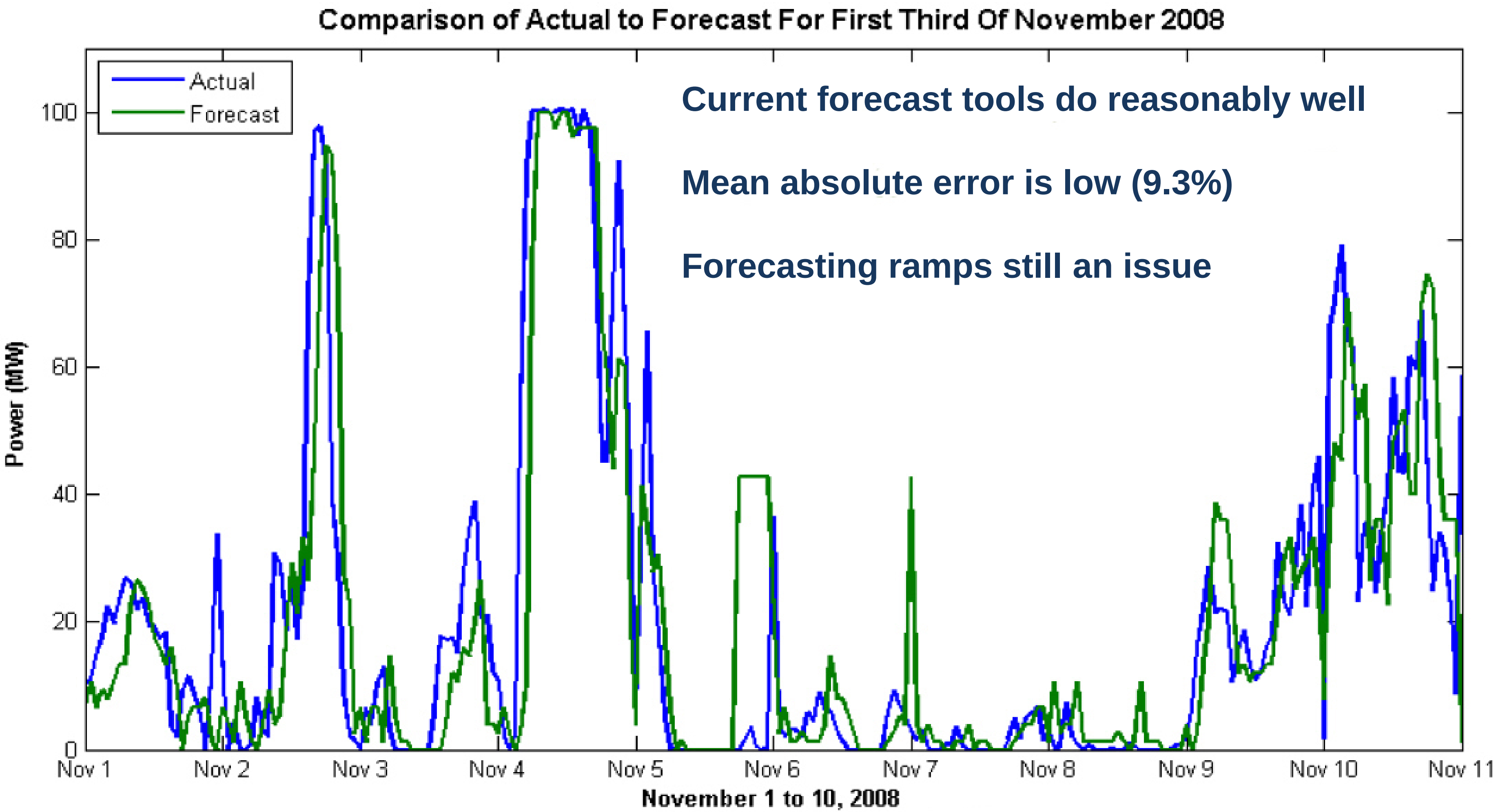
Source, MISO, 2012.

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 are the optimal locations for storage?
  - What type of storage is best to use with wind farms?
  - System storage or paired with VER projects?

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



Current forecast tools do reasonably well

Mean absolute error is low (9.3%)

Forecasting ramps still an issue

Source: Iberdrola, 2009

Hydropower Has a Key Role in the 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

- Mature technologies, commercially widely available

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

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

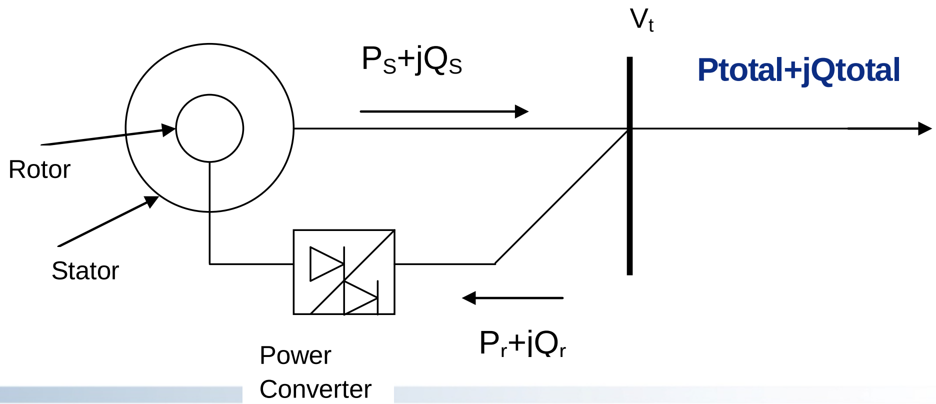
- CH and PSH plants provide ancillary services at much <u>lower cost</u> than thermal generating units

Currently, PSH Plants 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 and correct the control area intertie exchanges

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

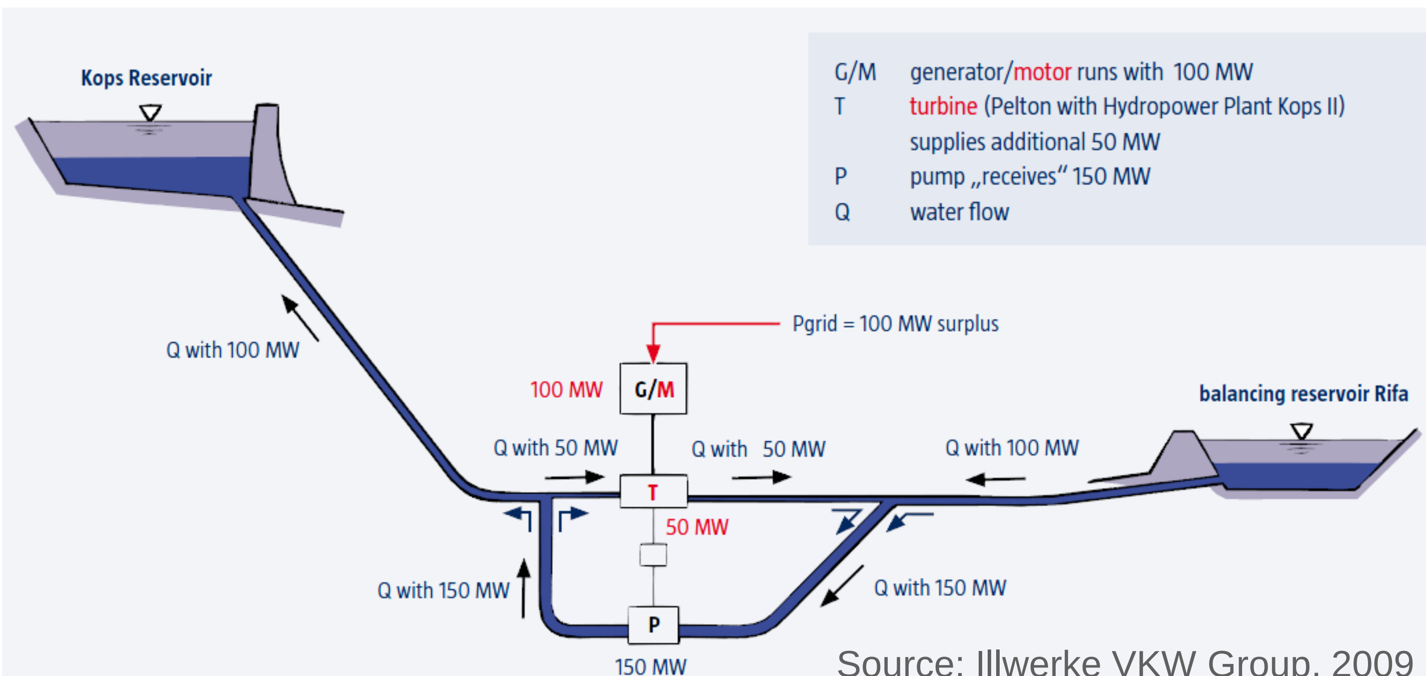


Additional Benefits of Adjustable Speed PSH (Compared to Conventional Fixed Speed PSH)

- More flexible and efficient operation in generation mode
  - Minimum unit power output as low as 20%
  - Increased efficiency and lifetime of the turbine at partial loads by operating at optimal speed
- Frequency regulation capabilities also available in the pumping mode
- Decoupled control of active and reactive power (electronically)
  - Provides more flexible voltage support
- Improved dynamic behavior and stability of power system
  - Improved transient stability in case of grid faults (e.g., short circuit faults in the transmission system)
  - Reduced frequency drops in case of generator outages
- Better compensation of variability of renewable energy sources
  - More flexible and quicker response in generating (turbine) mode
  - Variable power in pumping mode to counterbalance variability of wind
  - Excellent source of frequency regulation during the off-peak hours

Ternary PSH Technology Provides for Extraordinary Flexibility in the Pumping Mode

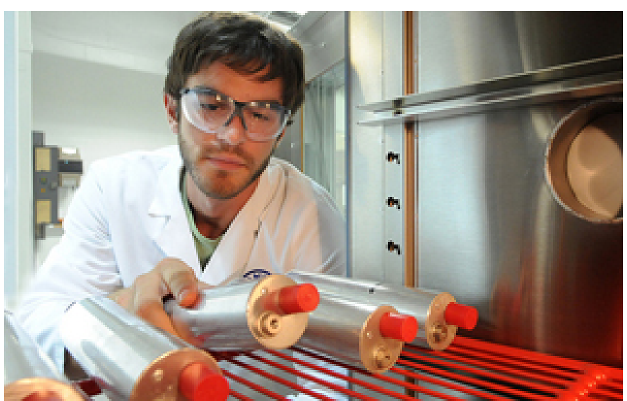
- Kops 2 (3x150 MW) PSH plant in Austria has implemented ternary pump-turbine arrangement
- Turbine and pump are connected with a mechanical clutch (pump can be separated during the generation mode to increase efficiency)
- During the pumping, the power taken from the grid can be supplemented by the 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

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



DOE Energy Innovation Hub for Advanced Batteries and Energy Storage

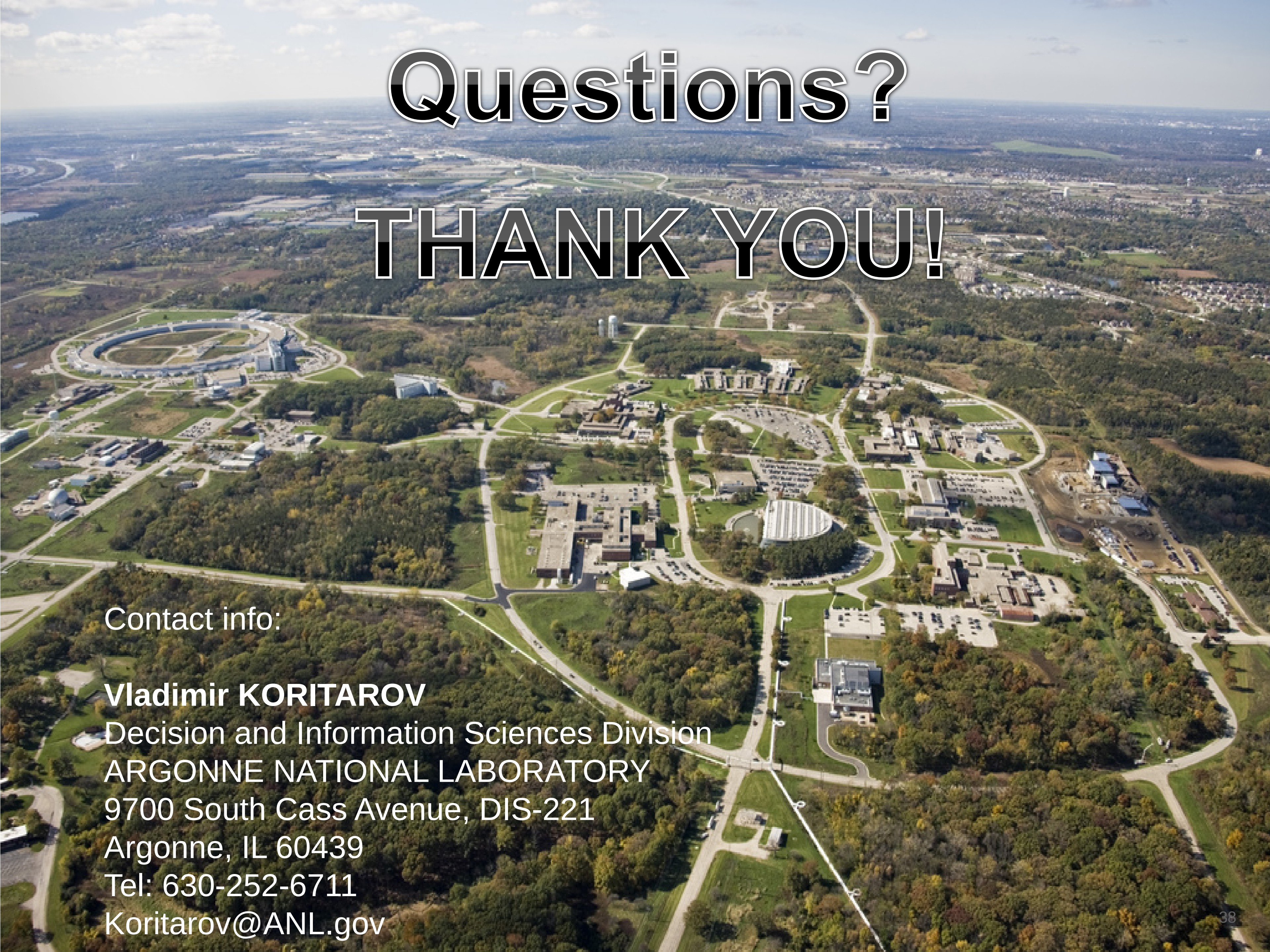
U.S. DEPARTMENT OF ENERGY | Office of Science

JCESR (Joint Center for Energy Storage Research) is a DOE Energy Innovation Hub, funded through the Basic Energy Sciences office of DOE, and led by Argonne National Laboratory

JCESR Goals: 5-5-5

Transformational technology goals:

- 5 times greater energy density → beyond Li-ion
- 1/5 cost
- within 5 years



Questions?

THANK YOU!

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