SAND2009-2571P

Energy Storage

ENG 300

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Electrical Energy Storage and Distributed Resources
Sandia National Laboratories

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

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What is Energy Storage?

Energy Storage Mediates Between

Variable Sources and Variable Loads

Without storage, energy generation must equal energy consumption

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Why Store Energy?

1. Economic advantage using predictable price swings
   – Natural gas storage
   – Pumped Hydro electricity storage
2. Improve asset utilization
   • Balance generation and load to minimize capital costs
   • Performance when you want it
   • Strategic hedge against unpredictable interruptions in supply
   • Strategic petroleum reserve
   • UPS

How is energy stored currently?

- Oil
  - Strategic Petroleum Reserve
  - Storage Tanks
- Natural Gas
  - Underground Storage reservoirs
  - Pipelines
- Thermal Energy
  - Thermal Mass/Adobe
  - Ice
- Electric Energy Storage
  - Pumped Hydro
  - Batteries/UPS
  - CAES

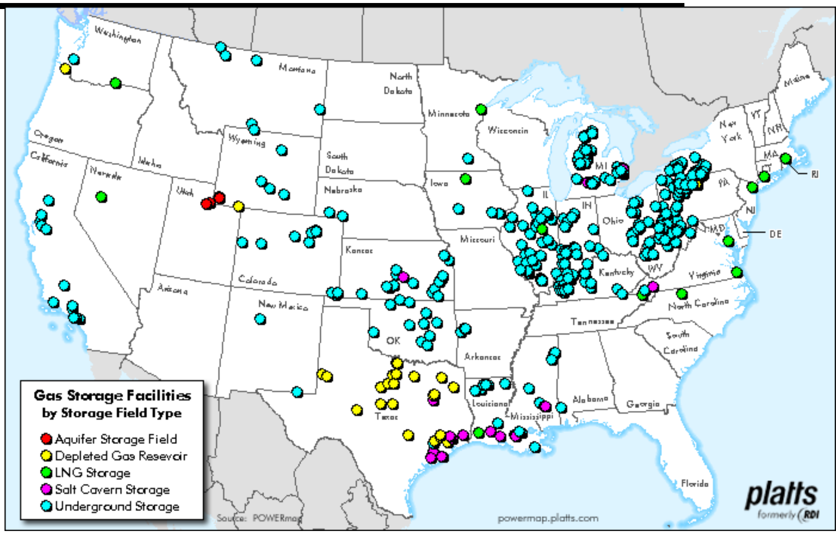
Oil Storage

- Strategic Petroleum Reserve
  - Underground salt caverns
  - Louisiana and Texas gulf coast
  - 665 million bbls, 40 days supply
  - Strategic Application
  - Funded by Federal Govt.
  - Reserves held for National Emergency

- Storage tanks
  - Asset utilization application
  - Balance refinery output/distribution system/demand

Natural Gas Storage

- Underground caverns, aquifers and depleted natural gas fields
- Dispersed across nation
- Reserves built during summer
- Reserves drawn during winter
- Levels demand/supply imbalance



Without storage, supply infrastructure would have to be sized for meet peak winter demand

Thermal Energy Storage

- Passive solar building
  - Large thermal mass
- Ice
  - Ice generated over night, provides cooling during day

- Solar thermal
  - Power tower system stores energy in hot oil or in phase change salts

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Electricity Storage - History

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Early History

- 1780’s modern battery begins "animal electricity" by Luigi Galvani

- 1799 Volta invented the modern battery

- 1836 batteries were adopted by industry for use in stationary devices, particularly in telegraph networks

1880s Private DC systems

- Lead-acid batteries original solution for night-time load
- Value of electricity storage in batteries
  - turn off generators during low-load periods
  - absorb excess electricity from generators for sale later
- The hydroelectric development of Niagara Falls in 1896.
  - Tesla and AC

1st US large-scale energy storage (31MW) in 1929 at Connecticut Light & Power Rocky River Plant

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History of Electricity Storage Industry

Initial Enthusiasm
1980s-mid 1990

Drivers

- Limited flexibility steam plants (no CTs)
- Projected nuclear builds
- Fuels Act (no gas)

- Rise of merchant generators
- Focus "cheap" natural gas for baseload and load following
- Limited nuclear build out

Results

Initial Storage Build Out

- Conventional pumped hydro: ~20 GW
- CAES: 110 MW Alabama project co-funded by EPRI
- Other (<100 MW total): A few batteries, SMES, mostly for local power quality issues

Storage efforts abandoned

- Pumped Hydro sites gone
- Exotic technologies remain costly

ATREIDES CAPITAL, LLC Building Value Building Companies

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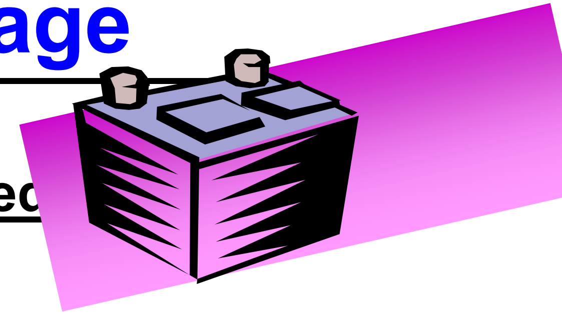
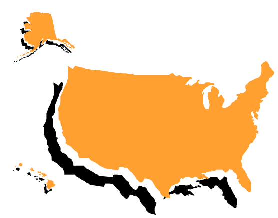
Electrical Energy Storage



Percentage of generated electricity that is stored

- **Japan 15%**
- **Europe 10%**
- **USA 2.5%**



Why Electricity Storage ?

"Power systems have become so **complex** that they exceed man's ability to react to them. They must be designed to give people **adequate time** to manage failure."

- Bruce Nussbaum

Business Week, September 8, 2003

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Benefits of Energy Storage

Generation:

- Spinning Reserve
- Capacity Deferral
- Area/Frequency Regulation
- Load Leveling
- Renewables Support

Transmission & Distribution:

- Line and Transformer Deferral
- Stability
- Voltage Regulation

Renewable Support:

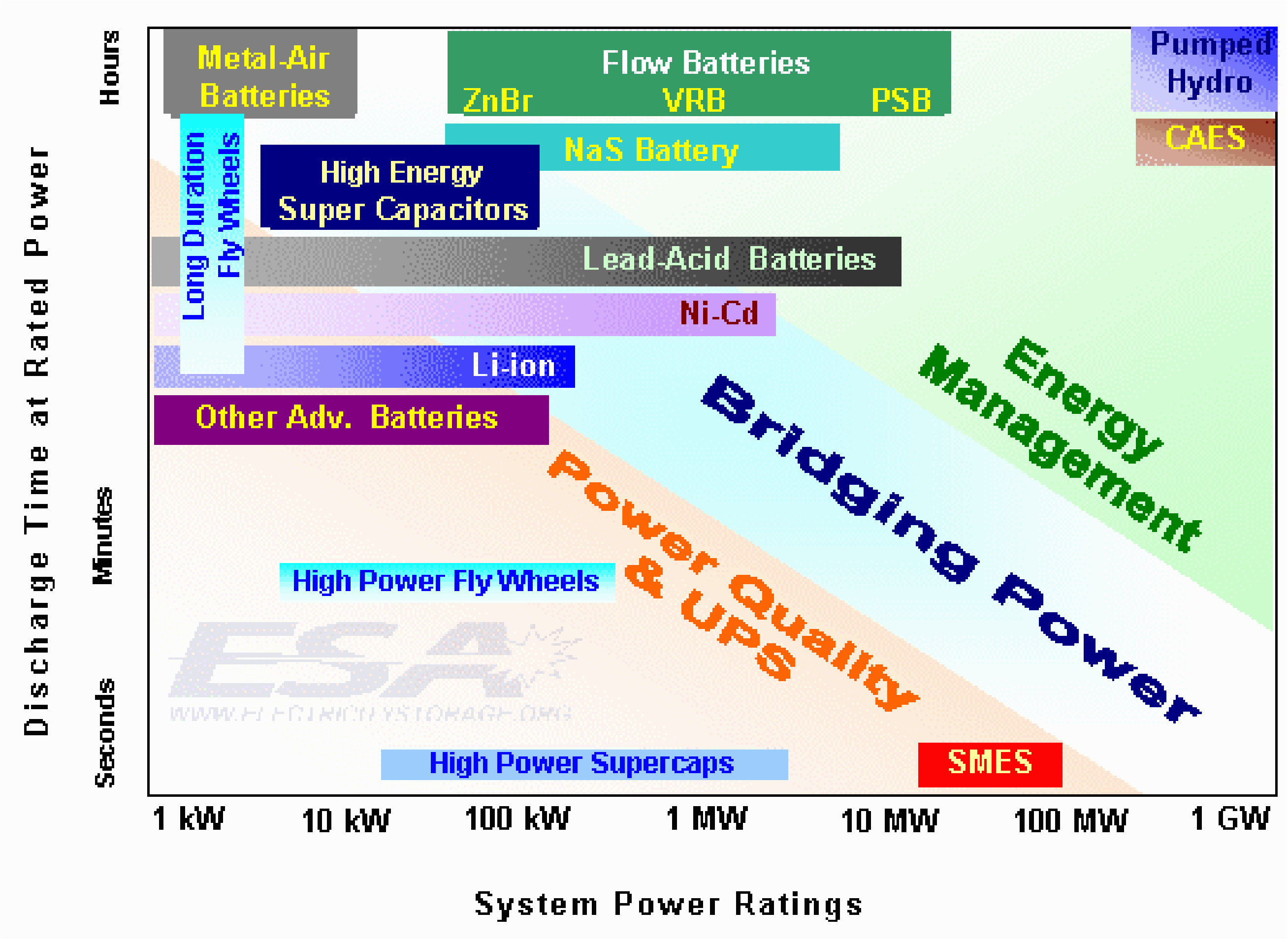
- Time Shifting generation
- Control and Integration
- Reserve

End-Use:

- Power Quality/Reliability
- Peak Load Reduction
- Distributed Generation Support

	POWER Applications		ENERGY Applications
LOAD	**PQ, Digital Reliability**	**DER Support for Load Following**	**Peak Shaving to Avoid Demand Charges**
GRID	**Voltage Support, Transients**	**Dispatchability for Renewables, Village Power**	**Mitigation of Transmission Congestion, Arbitrage**
	seconds	**minutes**	**hours**

Range of Storage Technologies Available



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Energy Storage Provides Grid Security

Improve T&D stability

‘Blackouts’ and ‘brownouts’

Maintain quality power and reliability

Local Supplies of Reactive Power Are Essential to Maintaining Voltage Stability…(from storage devices…)

Final Report on the August 14, 2003 Blackout in the United States and Canada, April 2004

Typical "Regulation" Profile

ISO Goal:

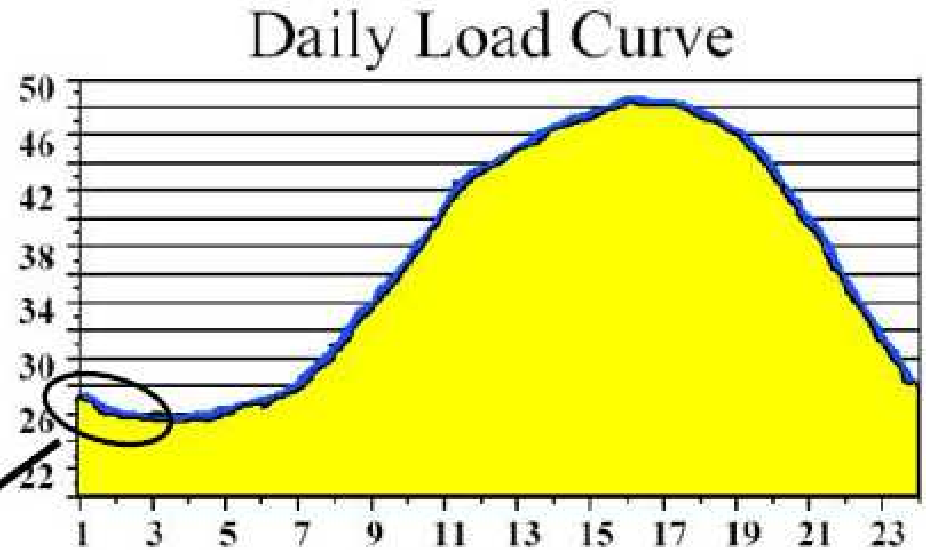
Load = Power Generated

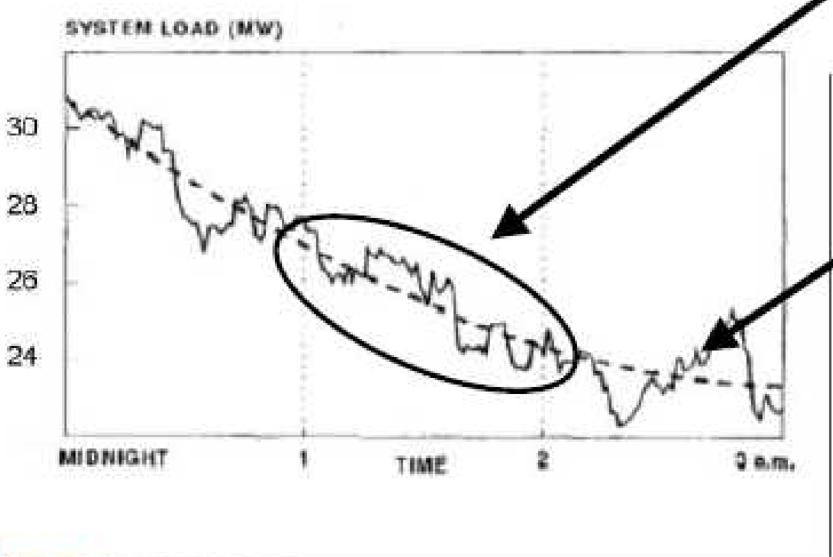
Power < Load:

– Frequency drops under 60 Hz.

Power > Load:

– Frequency rises over 60 Hz.

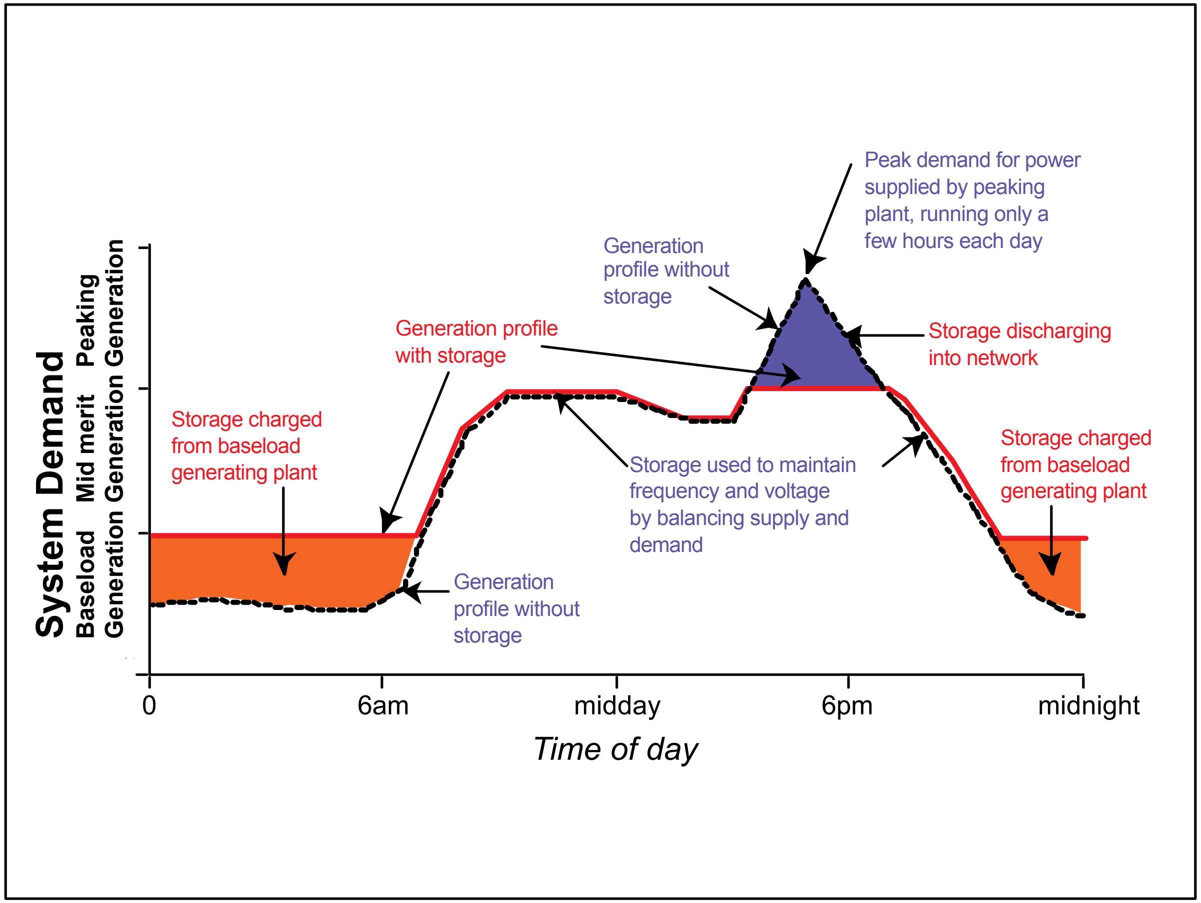




Short term variation

- ~ 1% of daily load
- Managed via regulation
- Fluctuation is net zero

Peak Shaving with Utility Support



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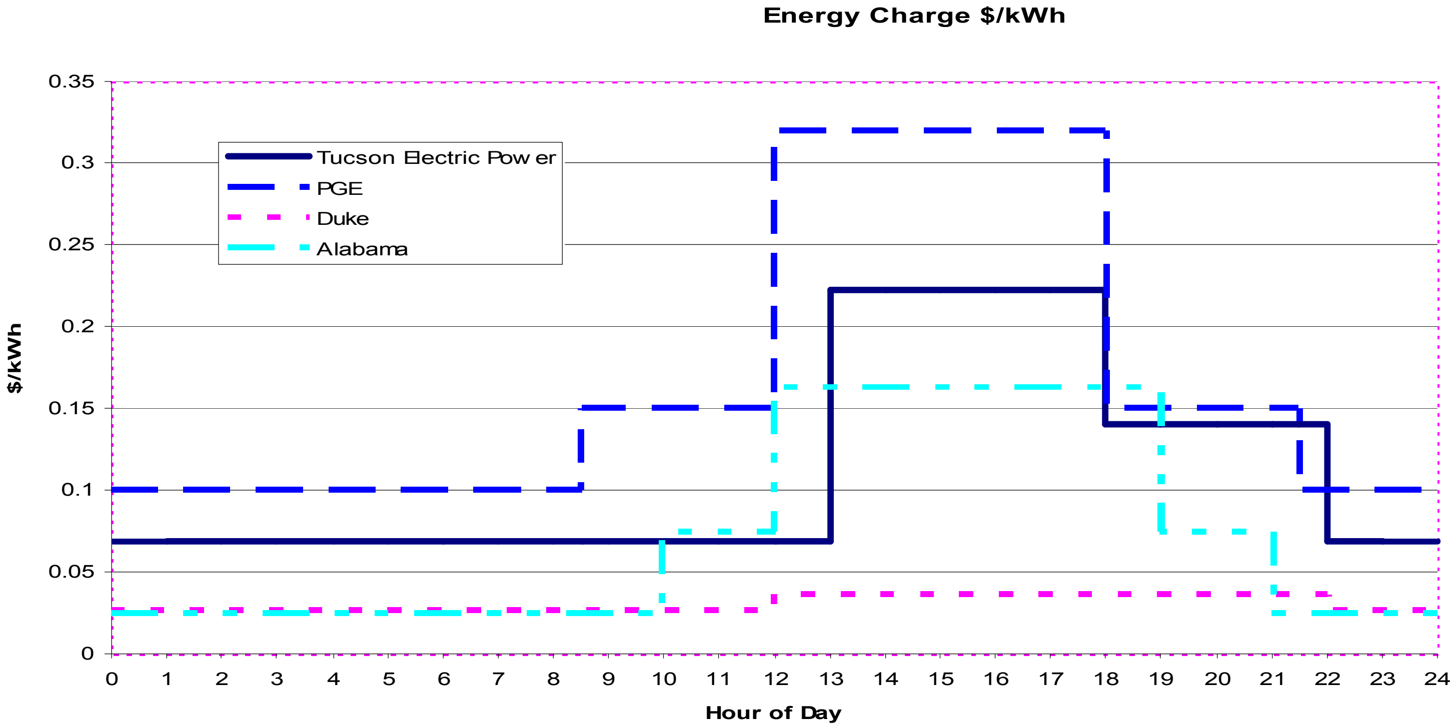
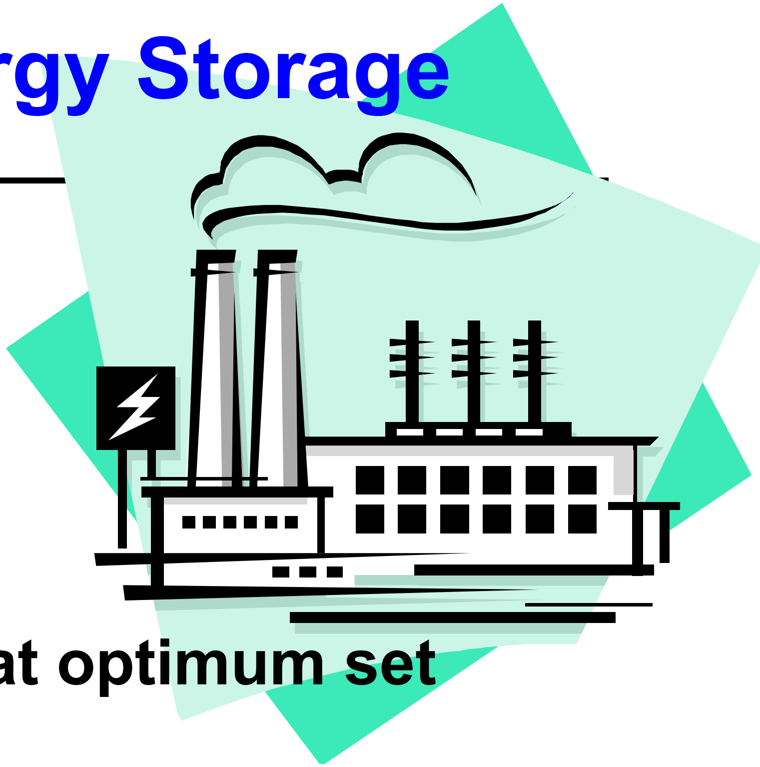
Benefits Are Utility Dependent

Time of Day Rate Structure Varies Greatly
Benefit Is Dependent On Variability

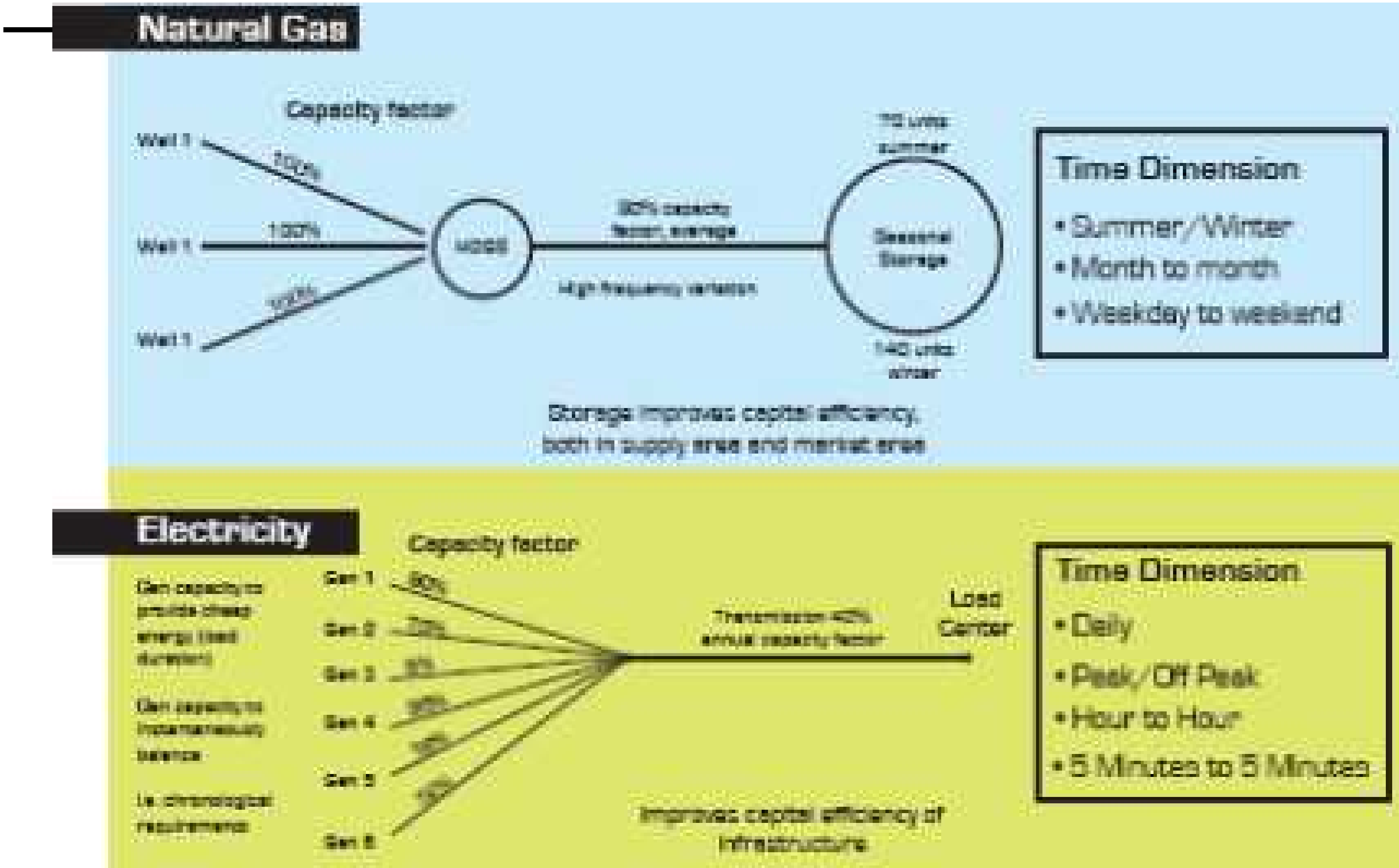


Fossil Fuels and Energy Storage



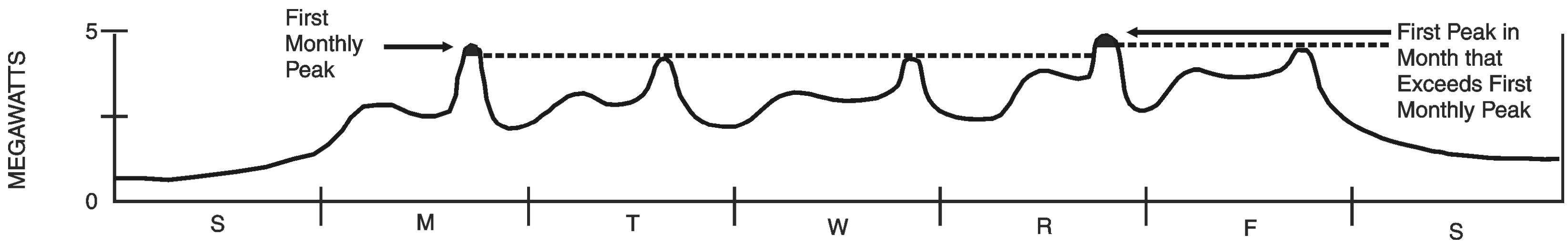
- Enhance asset utilization
- Defer upgrades
- Operate Fossil fuel generators at optimum set point– reduce emissions

Storage as Part of a Transmission System



Customer - Peak Shaving

- Utility charges a “peak demand charge” based on the highest power drawn during the month
- With experience, peak shaving can be tailored to fit storage system capacity



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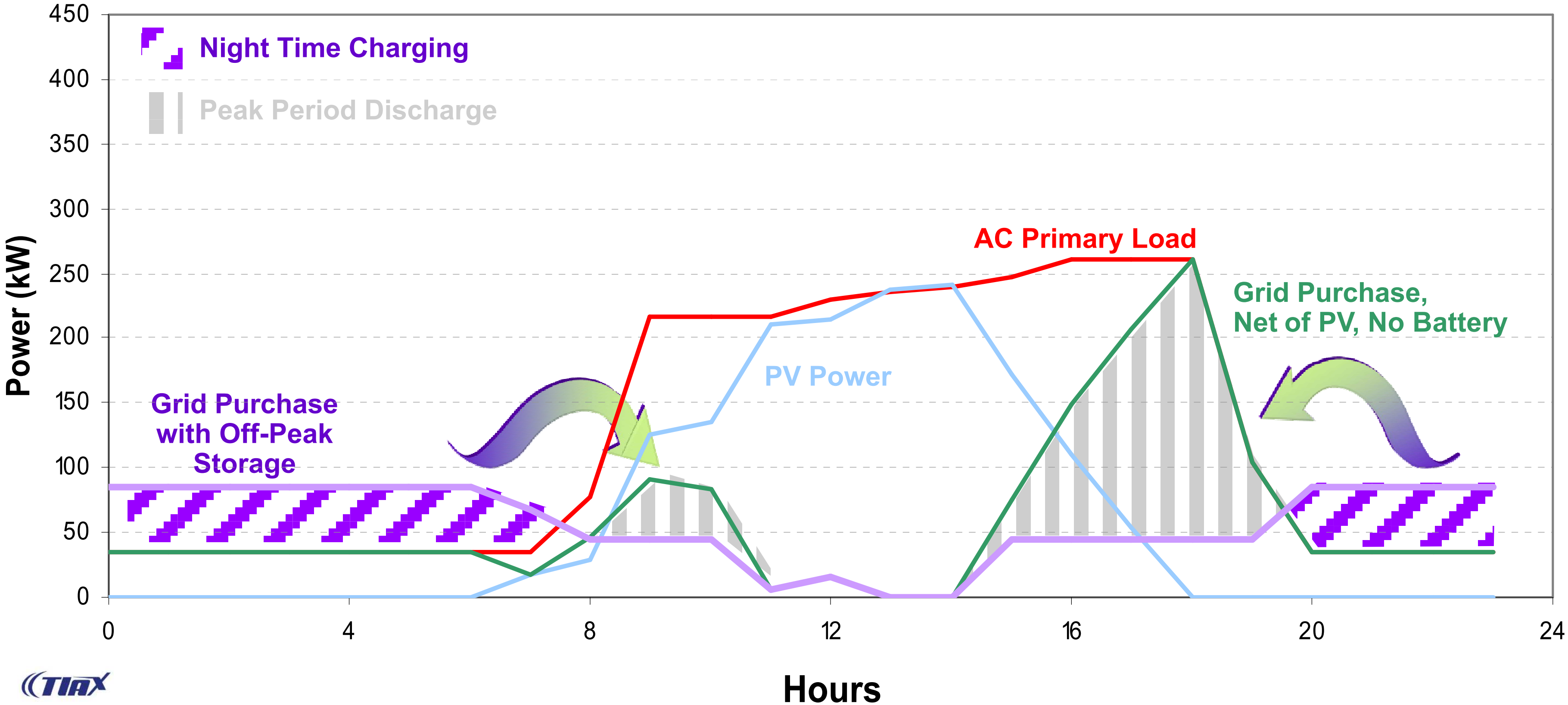
Customer Services



TIAX

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Storage Enables

Increased value of Renewables & DG

- Use more renewables –reduce need for fossil plants
  - for regulation and spinning reserve
  - minimize transmission congestion

- Operate Fossil fuel generators at optimum set point
  - reduce emissions

•Enhance reliability and power quality

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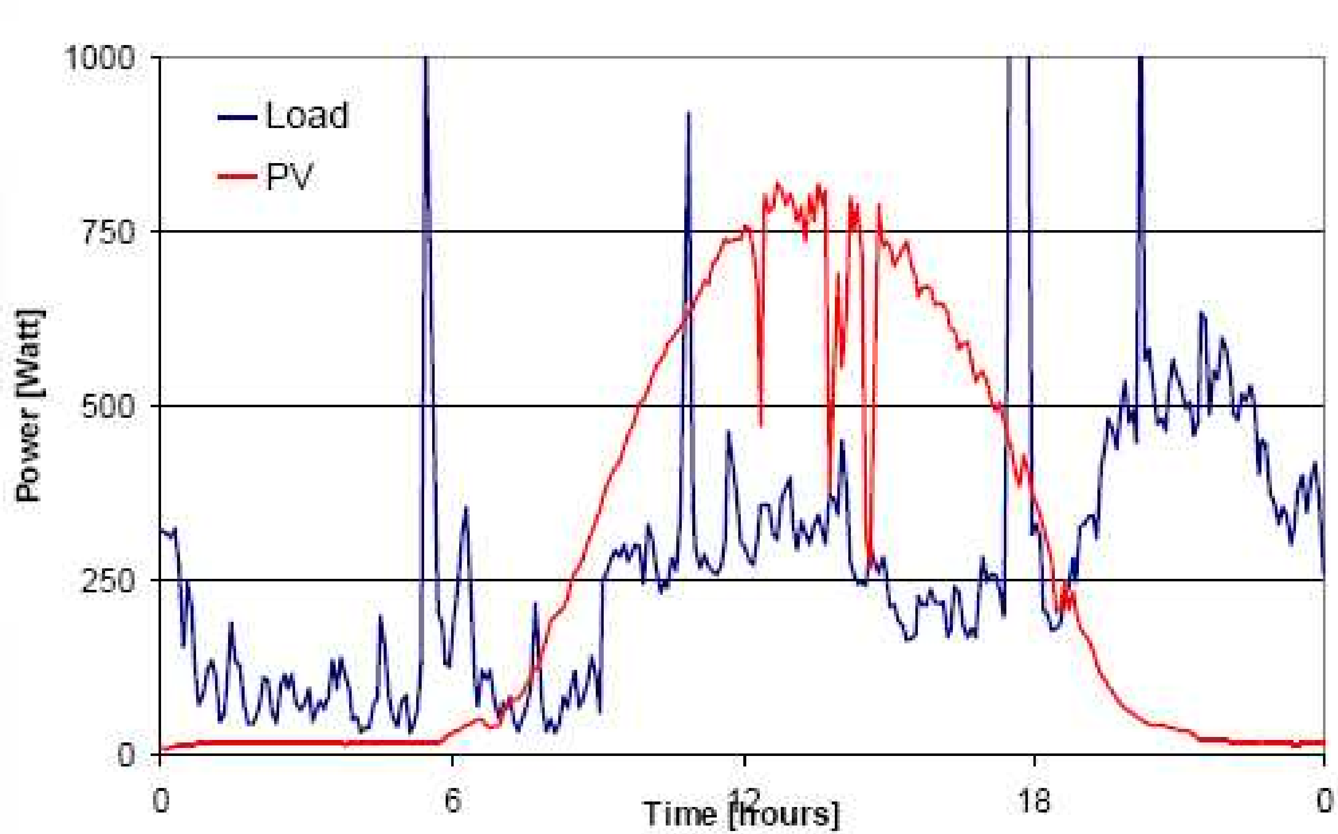
Typical Load Profile

(Example, solar)



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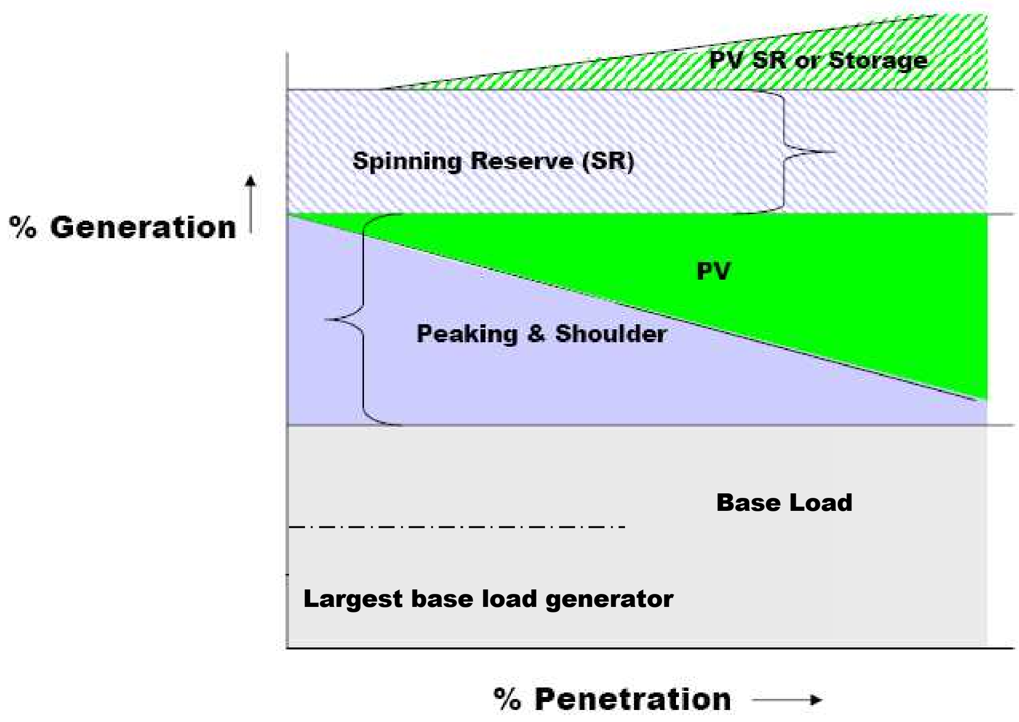
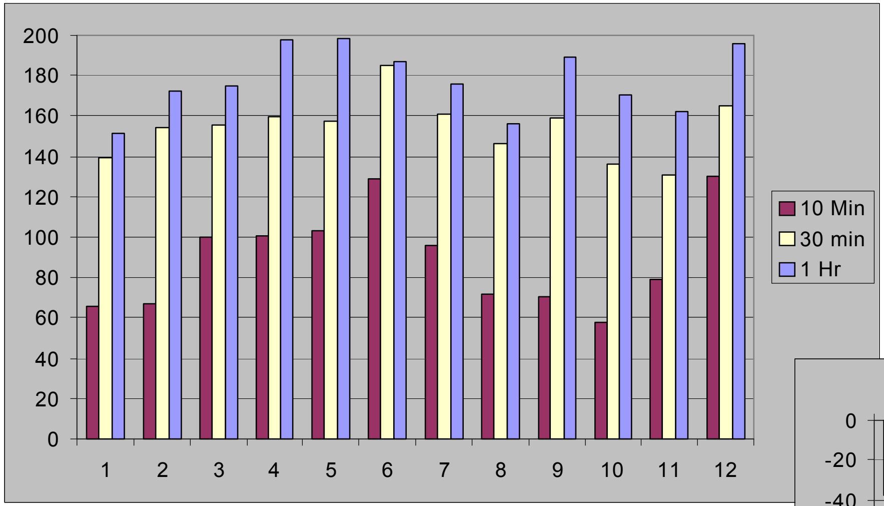
Need for Energy Storage in High-penetration PV Systems



Maximum Up Ramps and Down Ramps

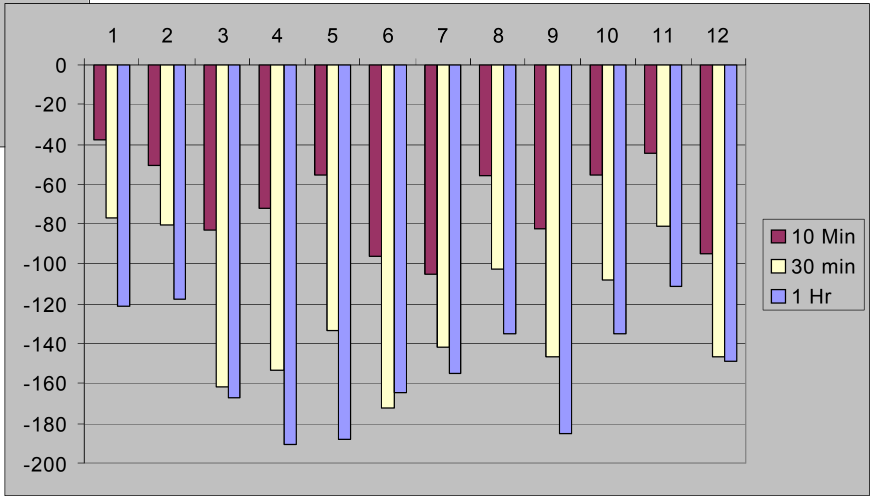
New Mexico Wind Energy Center
(by month)



MW Up Ramps

Up ramps --- back down generation

Down ramps---chasing them with fossil assets.



MW Down Ramps

Pricing Problems

Time Period	7x16 Average	7x8 Average	Number of negative intervals	Max. Price	Number of Instances	Minimum Price	Number of instances
2006	$57.41	$39.35	75	$1,003	1	($950)	1
2007	$57.18	$42.19	338	$1,534	1	($999)	3
Jan 2008	$52.82	$47.30	248	$1,500	2	($86)	1
Feb 2008	$54.04	$46.02	214	$1,500	2	($77)	1
March 2008	$43.60	$11.38	933	$2,303	2	($1,938)	1

Unusual pricing behavior

High Volatility

ATREIDES CAPITAL, LLC Building Value Building Companies

Source: ERCOT

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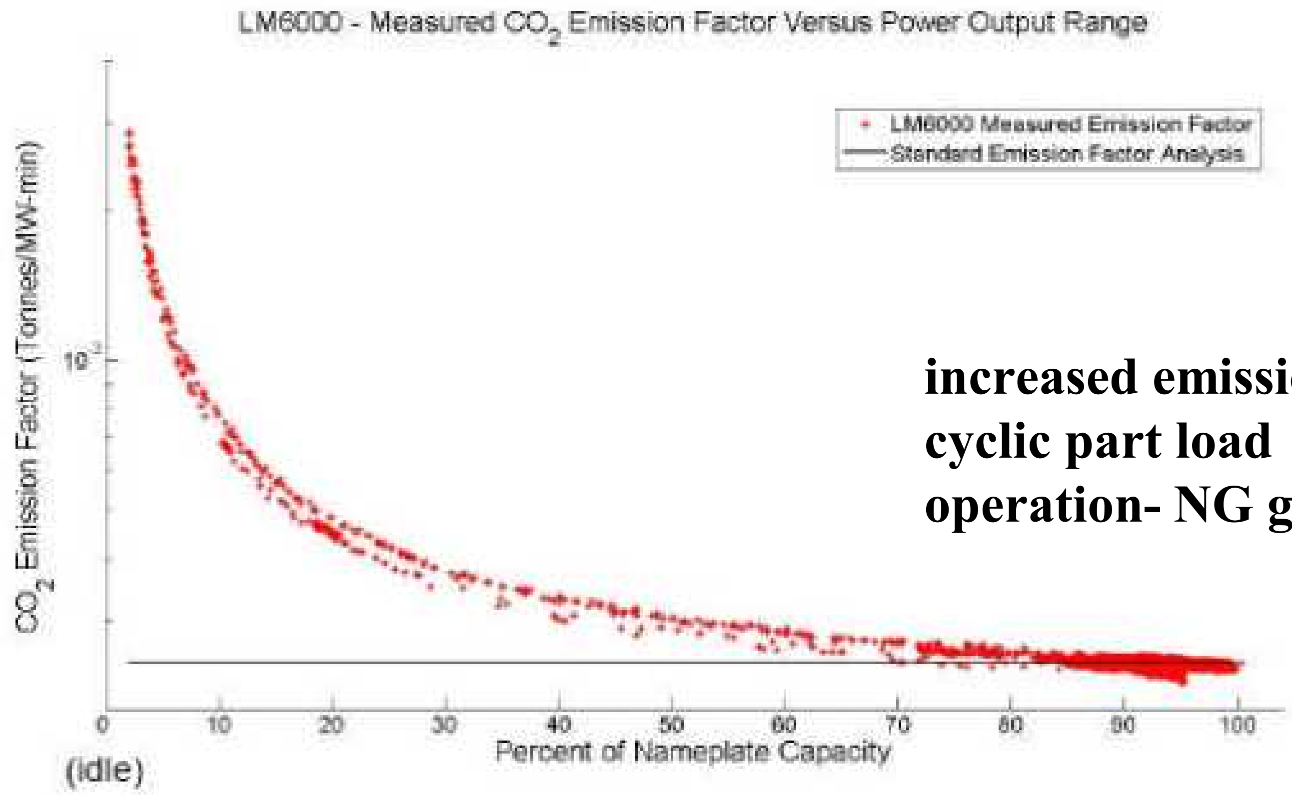
Environmental Concerns

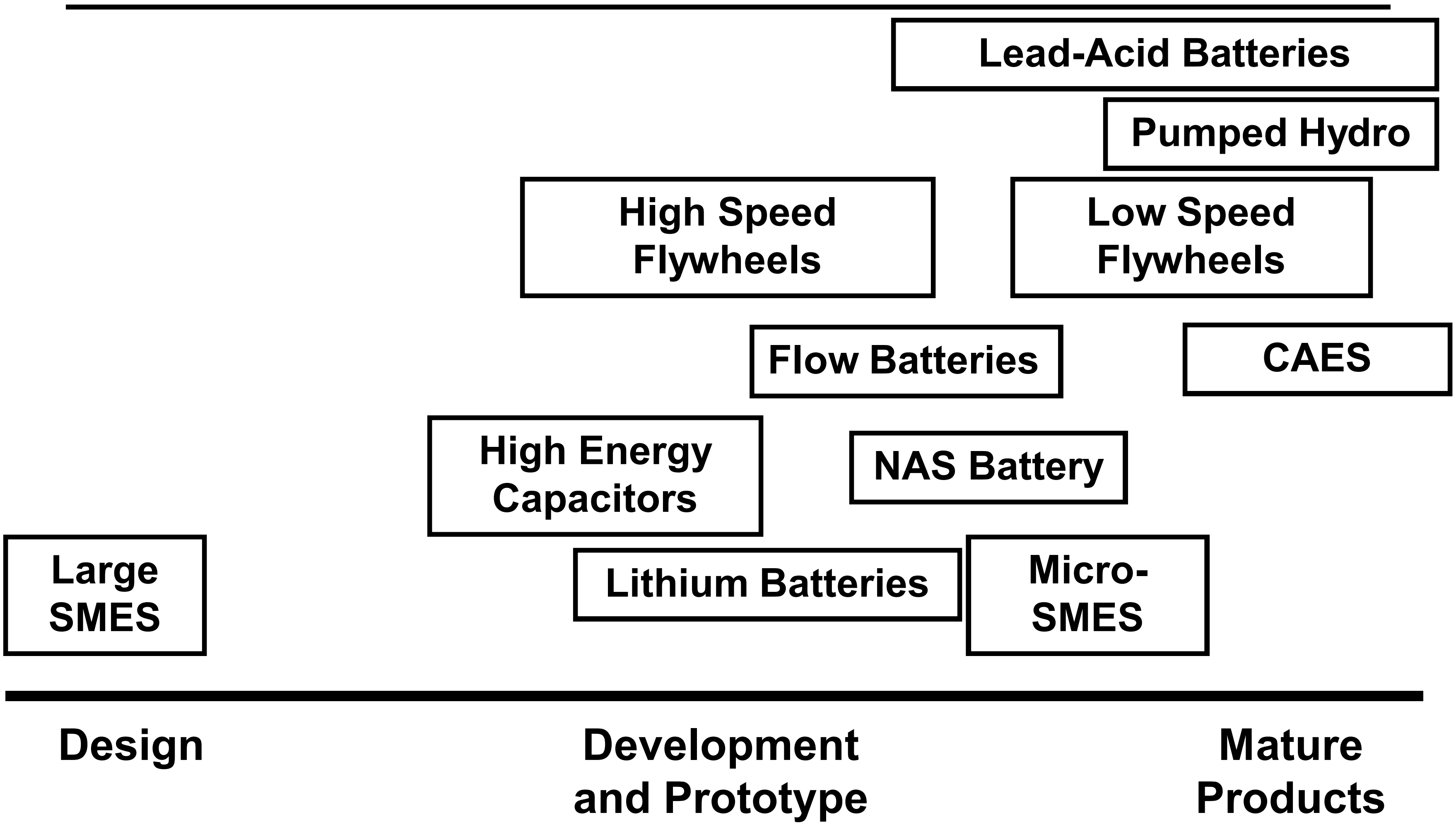


increased emissions for cyclic part load operation- NG generator

Source: EPRI/DOE Handbook of Energy Storage for Transmission and Distribution Applications - Wind Supplement update 2009

CO2-equivalent GHG Emission Rates for Alternative Baseload Power Systems (kgCO2/MWh)				
IGCC-V	IGCC-C	Wind/CAES	Wind/Gas	NGCC
829	132	86.5	224	440

Commercial Maturity of Storage Technologies



Lead Acid Batteries

- **Conventional**
- **Low cost**

Critical Load Backup/ Energy Management
Lead Smelter: Battery Recycling
Near Los Angeles, CA
5 MW, 3.5 MWH VRLA Battery

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Advanced Batteries

Hybrid LA-Supercap and PbC

- lead acid battery positive electrode
- supercapacitor negative electrode made of activated carbon.

Pb-Ca grid alloy instead of Pb-Sb alloy, improving the corrosion-resistance of the positive grid.

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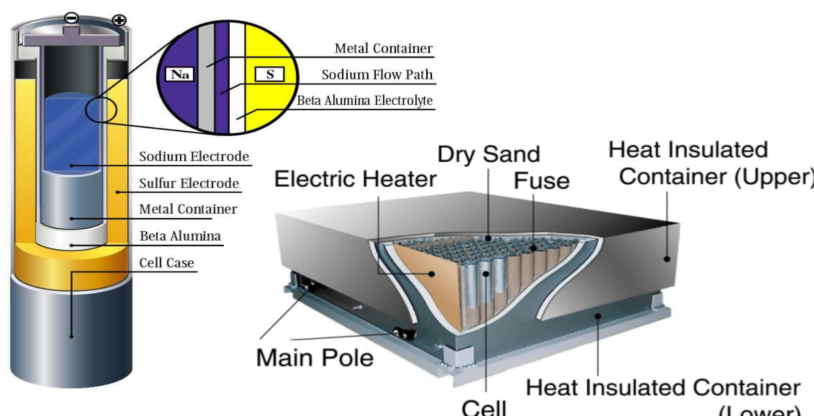
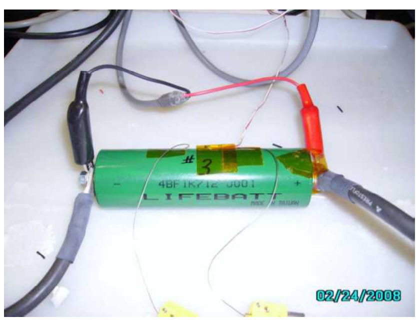
Sodium Sulfur (NAS)

First Commercial use of NAS battery in the US.
(serving an office Building)

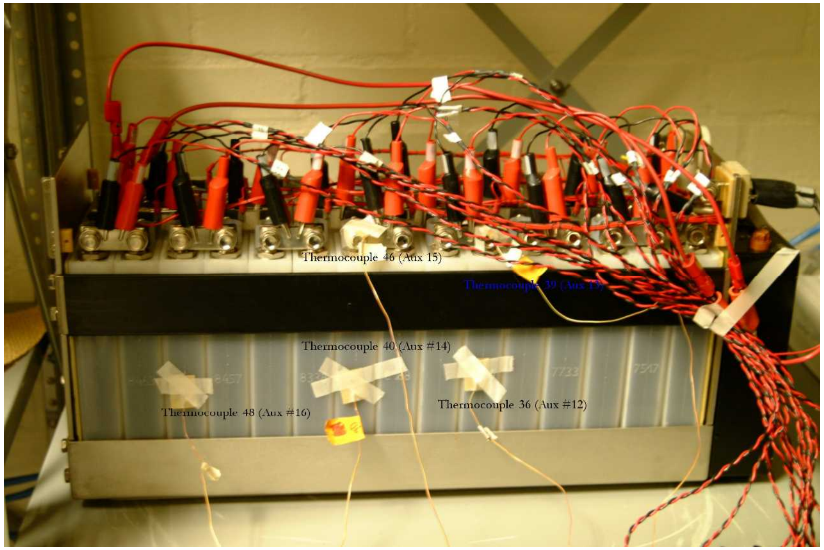


LiFe

- Safer than traditional Li-ion
- High power density
- Lower cost than traditional Li-ion
- Lower energy density than other Li-ion technologies



Non-Battery Electricity Storage - Electrochemical Capacitors

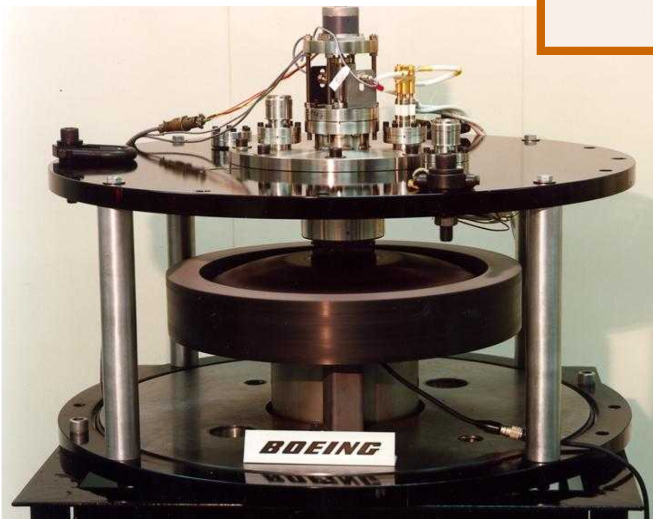


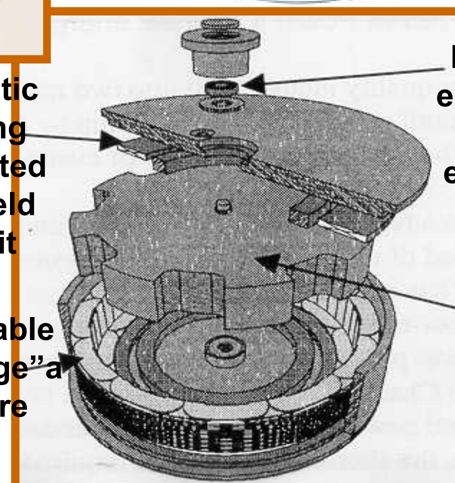
- All high power applications
  - Transmission stability
  - Power quality
  - Distributed resource support

Non-Battery Electricity Storage - Flywheels

Low Speed – PQ

High Speed - development





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Flow Batteries

- **Vanadium Redox**
- **Zinc Bromine**

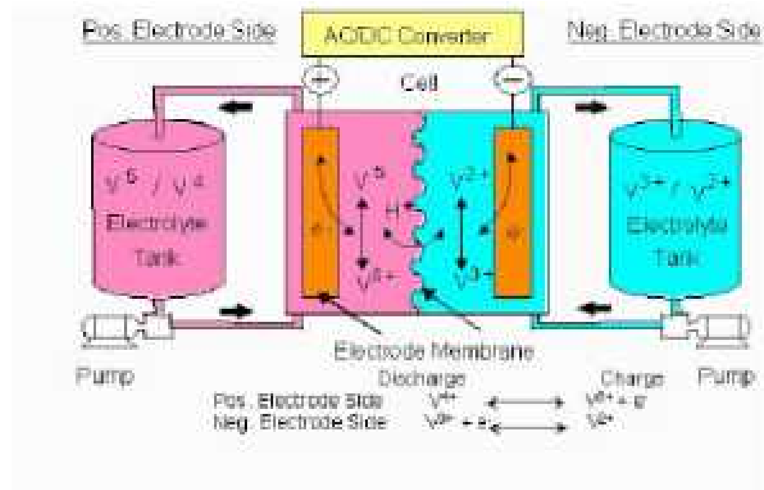
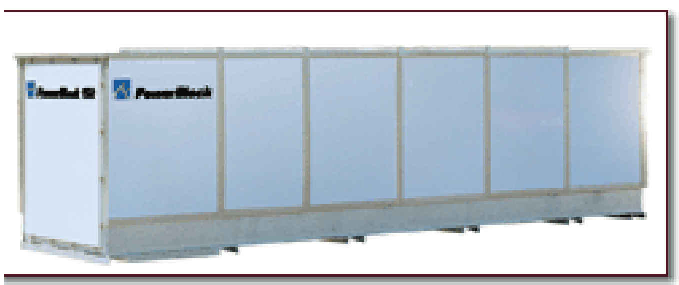
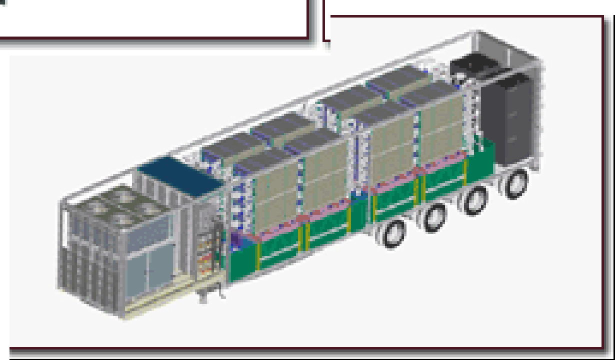


Photo Courtesy of Sumitomo Electric Industries, Ltd. (SEI) – Copyright 2001





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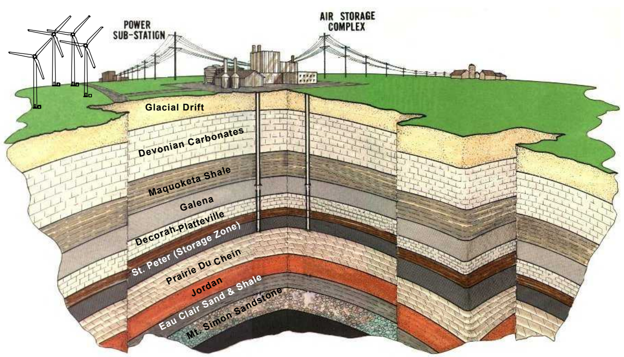
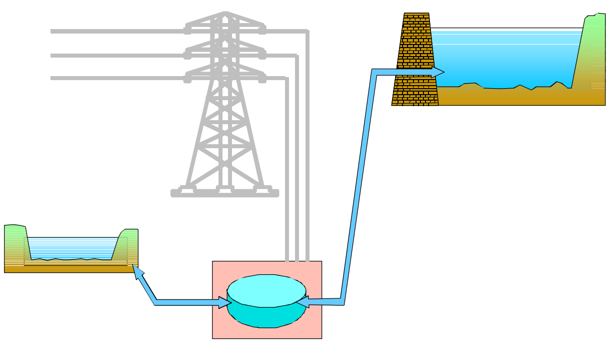
Large Scale Energy Storage

- Pumped Hydro
- CAES





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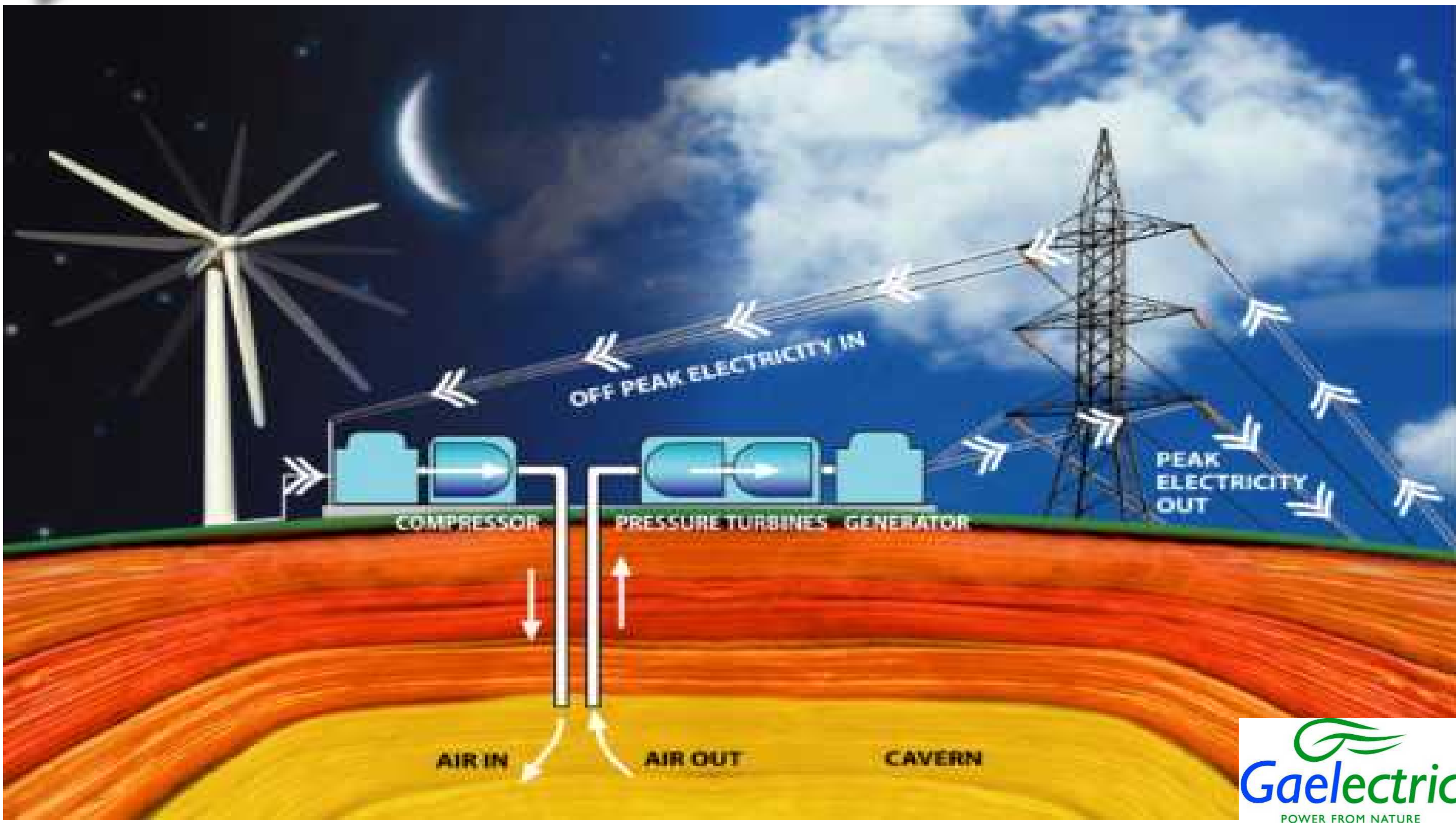
How CAES Works



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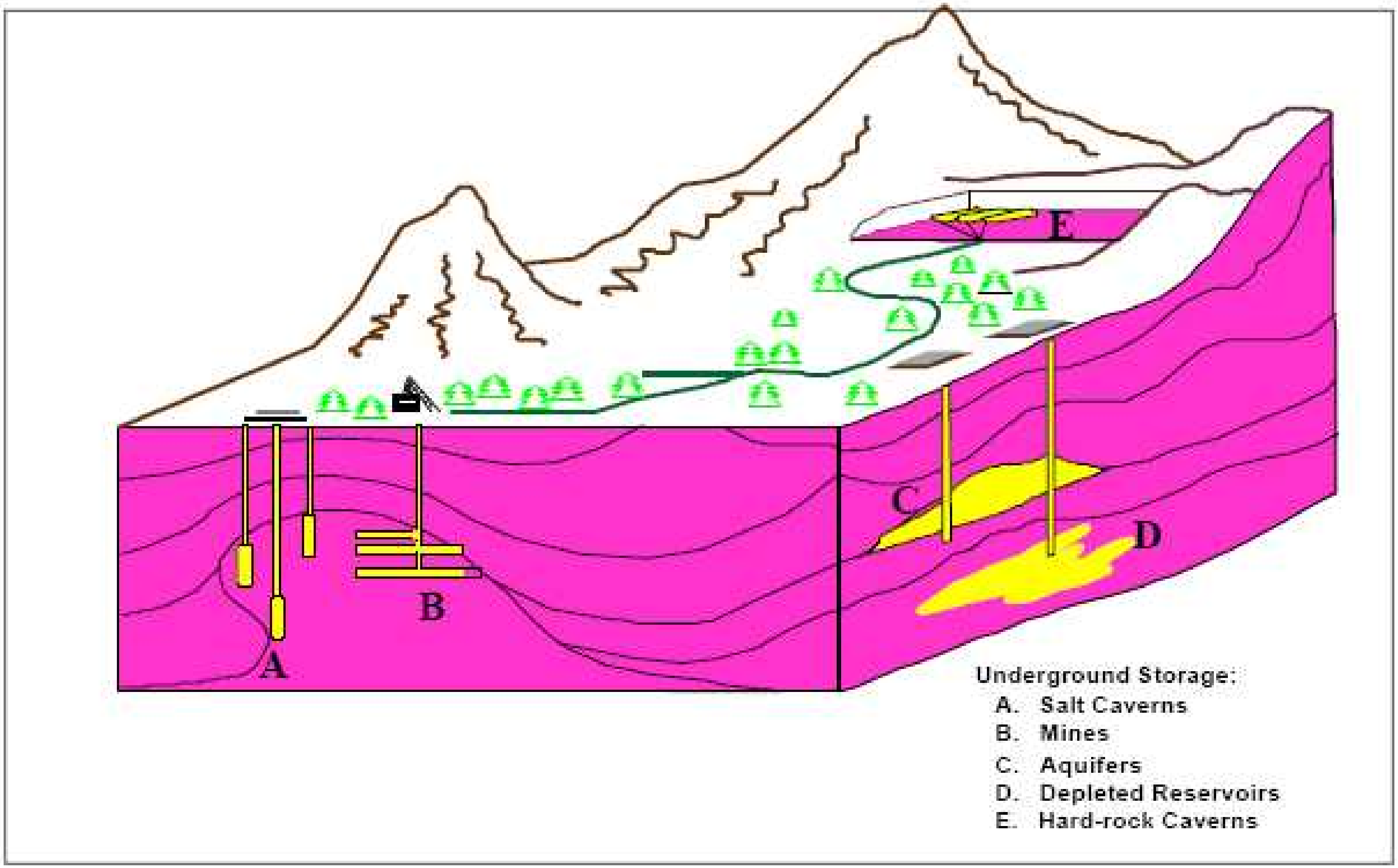
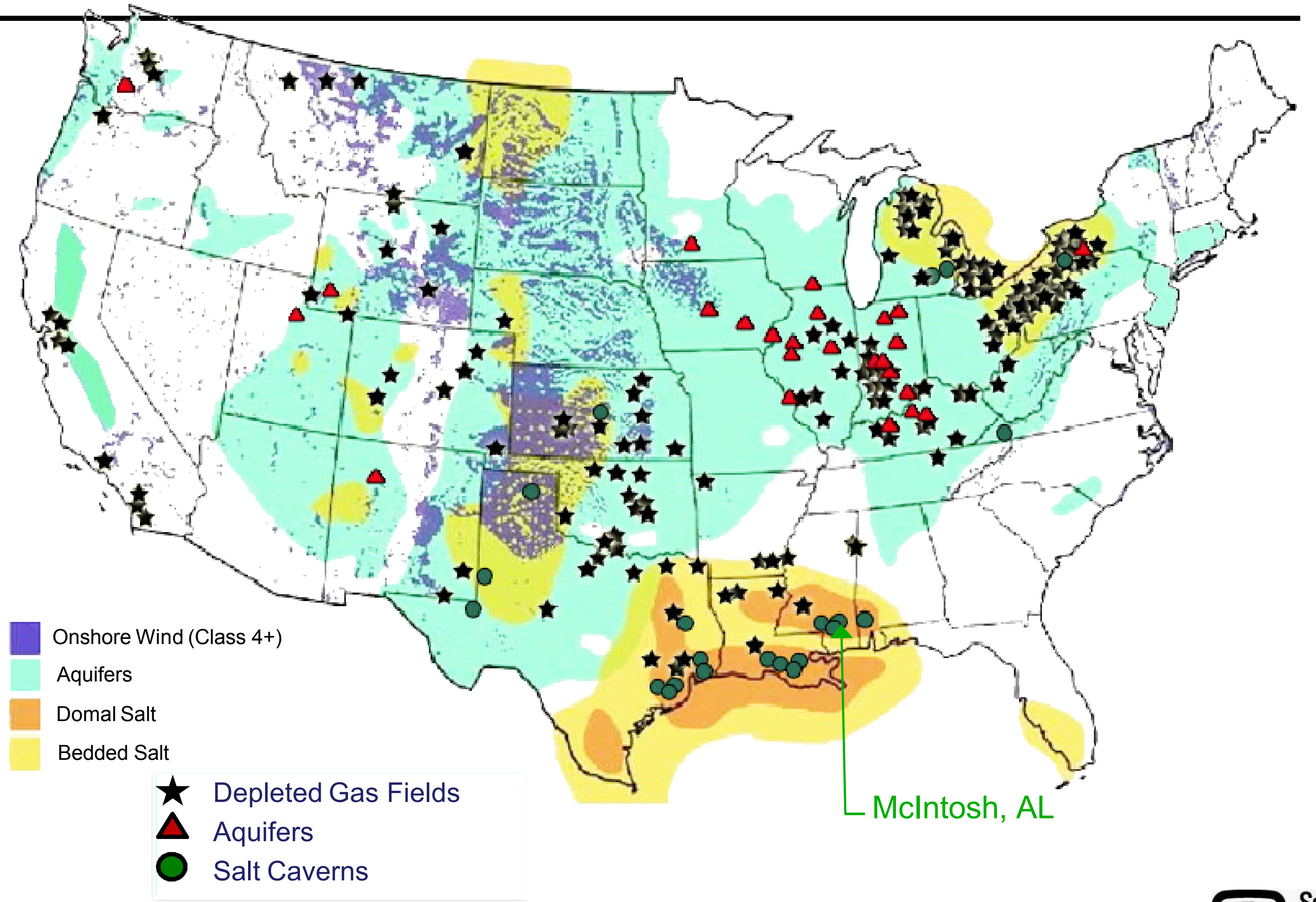
Types of Underground Storage



Source: PB-KBB Inc. Recreated by Energy Information Administration, Office of Oil and Gas.

Geologic Formations and Wind Regimes Potential for CAES



Energy Information Agency EIA; Succar & Williams, PEI- 2008

Large Scale Energy Storage Capital Costs Comparisons[1, 2]

Technology	Capital Cost: Capacity ($/kW)	Capital Cost: Energy ($/kWh)	Hours of Storage	Total Capital Cost ($/kW)
CAES (300MW)	580	1.75	40	650
Pumped Hydroelectric (1,000MW)	600	37.5	10	975
Sodium Sulfur Battery (10MW)	1720-1860	180-210	6 - 9	3100-3400
Vanadium Redox Battery (10MW)	2410-2550	240-340	5 - 8	4300-4500

[1] EPRI-DOE, "Handbook of Energy Storage for Transmission and Distribution Applications"

[2] EPRI-DOE, "Energy Storage for Grid Connected Wind Generation Applications"

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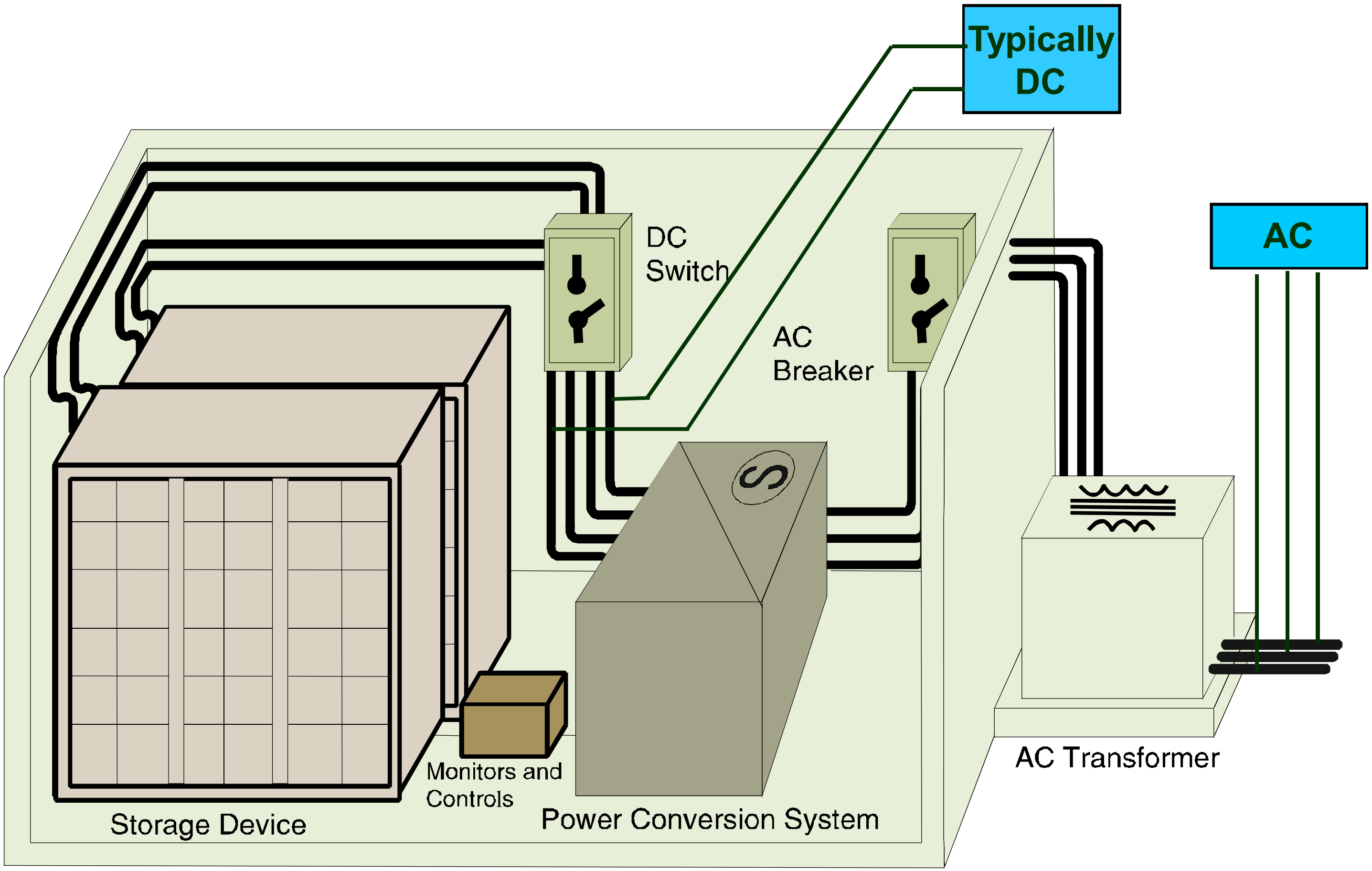
Storage System Capacity Capital Costs

Technology	Current Cost ($/kWh)	10-yr Projected Cost ($/kWh)
Flooded Lead-acid Batteries	$150	$150
VRLA Batteries	$200	$200
NiCd Batteries	$600	$600
Ni-MH Batteries	$800	$350
Li-ion Batteries	$1,333	$780
Na/S Batteries	$450	$350
Zebra Na/NiCl Batteries	$800 [1]	$150
Vanadium Redox Batteries	20 kWh=$1,800/kWh; 100 kWh =$600/kWh	25 kWh=$1,200/kWh 100 kWh=$500/kWh
Zn/Br Batteries	$500	$250/kWh plus $300/kW [2]
Lead-carbon Asymmetric Capacitors (hybrid)	$500	<$250
Low-speed Flywheels (steel)	$380	$300
High-speed Flywheels (composite)	$1,000	$800
Electrochemical Capacitors [3]	$356/kW	$250/kW

SAND2008-4247

[1] €600/kWh
[2] The battery system includes an integrated PCS; the PCS price will vary with the rated system output.
[3] Electrochemical capacitors are power devices used only for short-duration applications. Consequently, their associated costs are shown in $/kW rather than $/kWh.

Electricity Energy Storage System



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Power Electronics

- Power Electronic System is 25-60% of system cost
- Power Electronic Systems do not have the desired reliability
- Power Conversion from storage to/from desired output contributes significantly to system size, complexity and design tradeoffs

Emitter
Turn-Off
Thyristor

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Barriers to Energy Storage

- Technical
  - System Design
  - Operating Data
- Institutional
  - New Technology Risk
  - Existing Rate Structures
  - Utility Interdepartmental Roles
  - Few System Suppliers

- Market
  - Cost
  - Market Size Uncertainty
  - Utility/Customer Awareness
  - Unquantified Benefits

Electric Energy Storage R&D

- US Department of Energy
  - Sandia National Labs
- California Energy Commission (CEC)
- New York Energy Research and Development Authority (NYSERDA)
- Electricity Storage Association (ESA)
- EPRI
- Universities

DOE Energy Storage Program

Develop advanced electricity storage technologies, in partnership with industry, for modernizing and expanding the electric supply.

This will improve the quality, reliability, flexibility and cost effectiveness of the existing system

Sandia has led the DOE Energy Storage Program since its establishment in the early 1970's

NYSERDA/DOE PROJECT

1MW/7.2 MWh NGK NAS Battery

Provides off peak power to Natural Gas Compressors at Long Island NG Refueling Station for 220 Busses

- **Relieves LIPA Peak Load,**
- **Eliminates Night Shift at Plant**

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CEC/DOE Energy Storage
PROJECTS

450 kW Ultra-Capacitors to provide Wind Smoothing and Backup Power for the Palmdale, CA Water Treatment Plant 1.25 MW Microgrid (Maxwell)

100 kW / 25 kWh Flywheel for Grid Frequency Regulation (Beacon Power)

Rail Application - *High-Speed Flywheel Demonstration*

2.5 MW/30sec FESS

NYPA/LIRR

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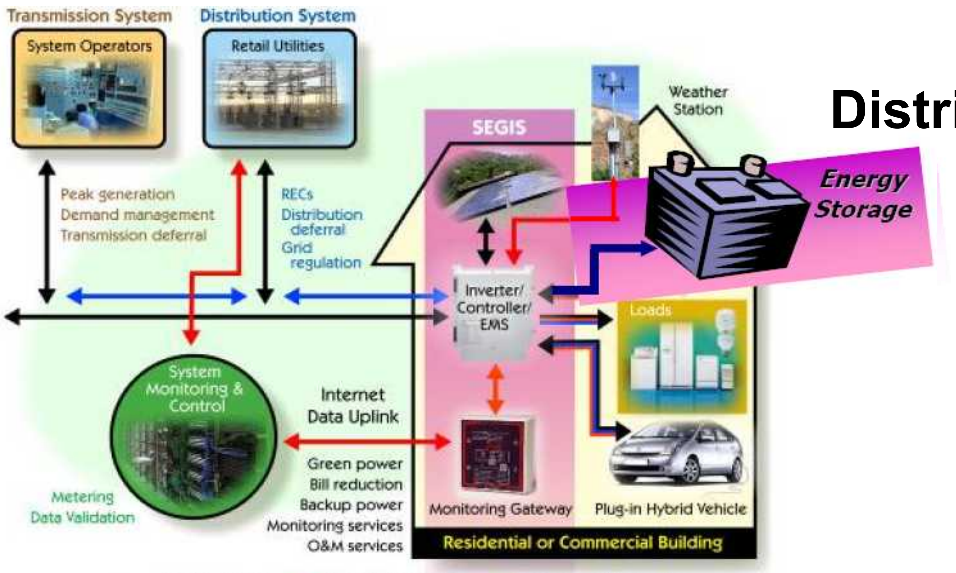
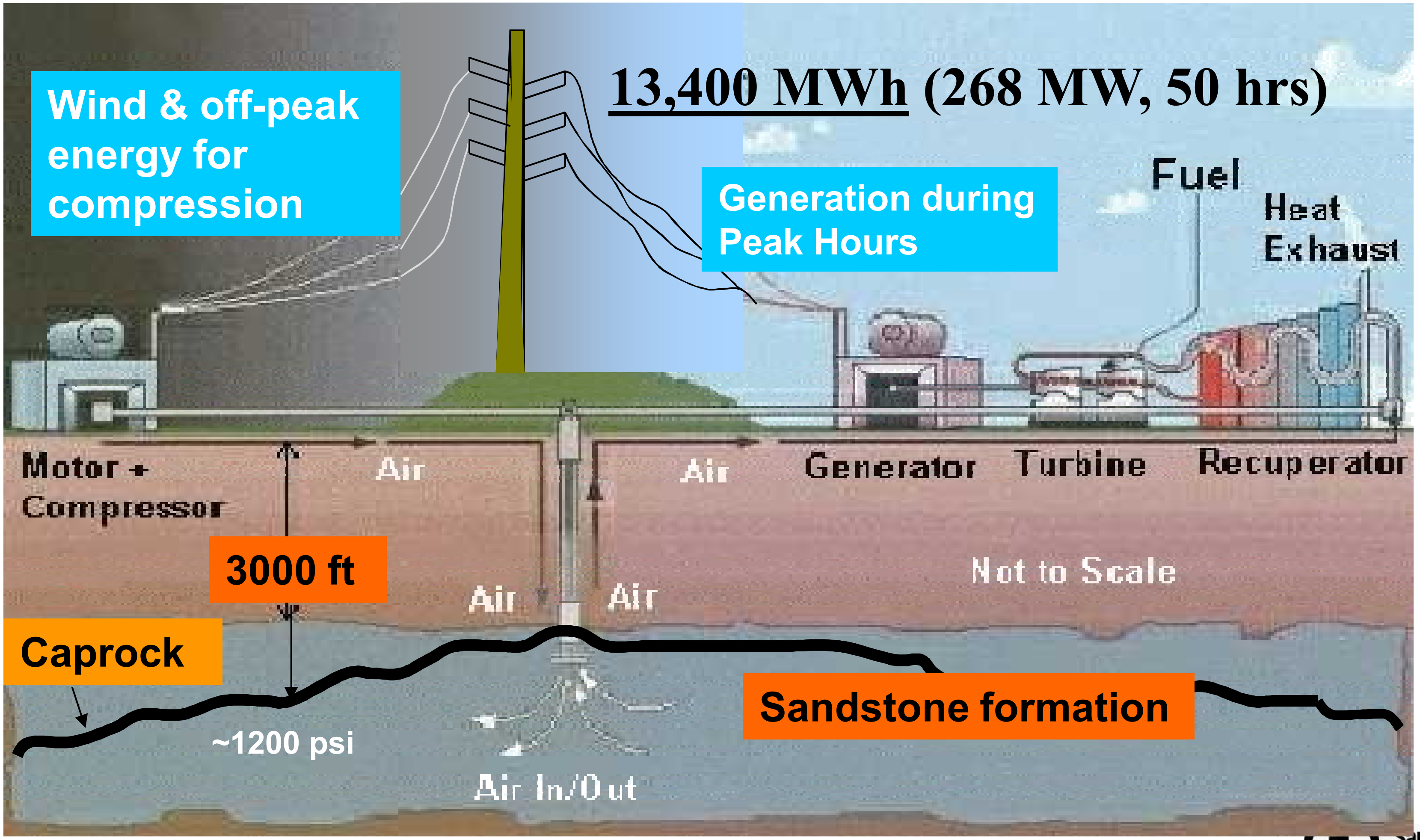
Solar Energy Grid Integration Systems – Energy Storage (SEGIS-ES)



Distribution-scale PV up to 100 kW

- Residential
- Small Commercial
- Micro-grids

Develop Storage Technologies based on current state-of-the-art for use with grid-tied PV systems



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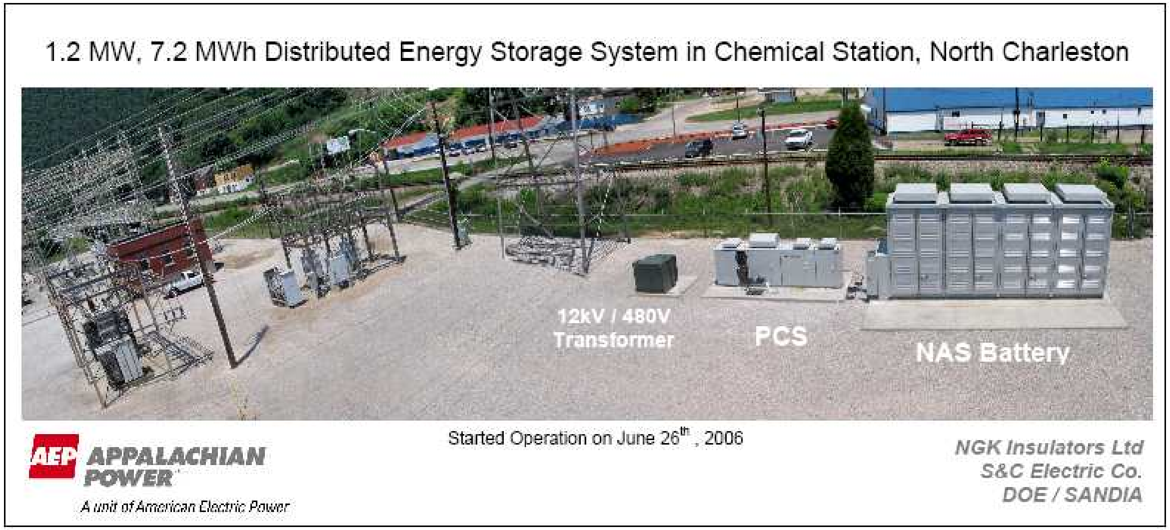
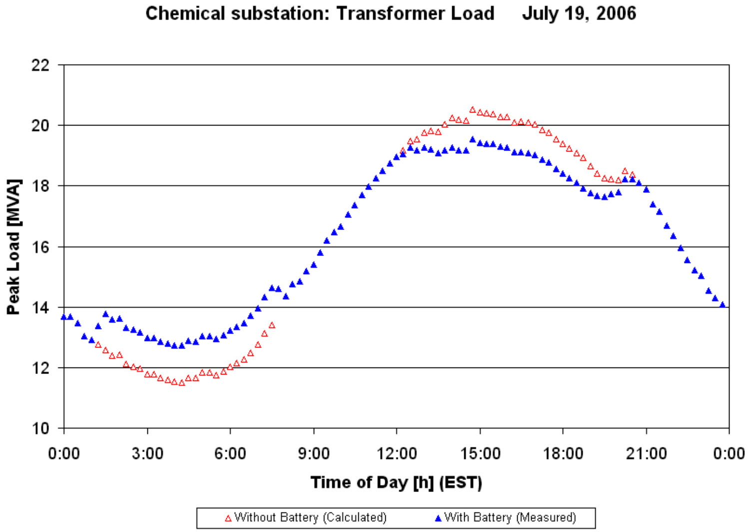
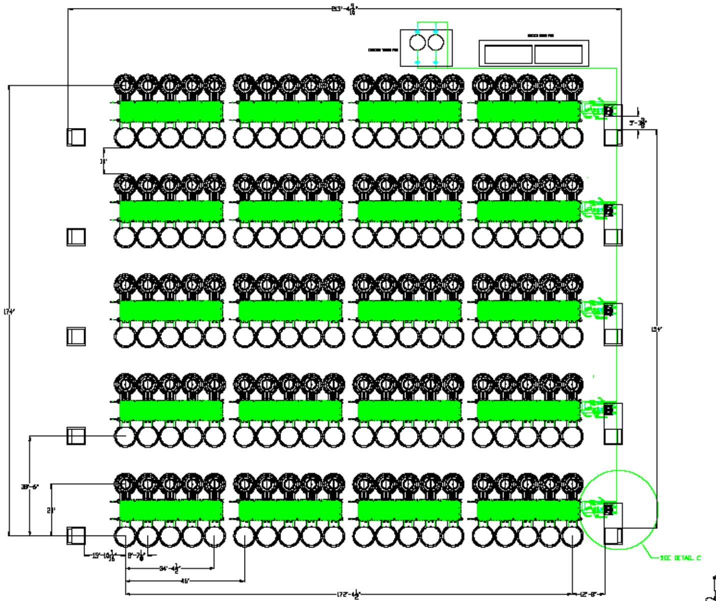
NAS Battery for Substation Support

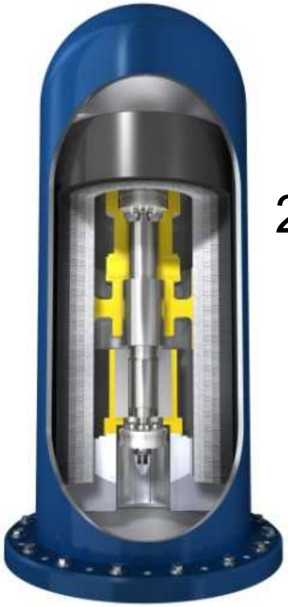




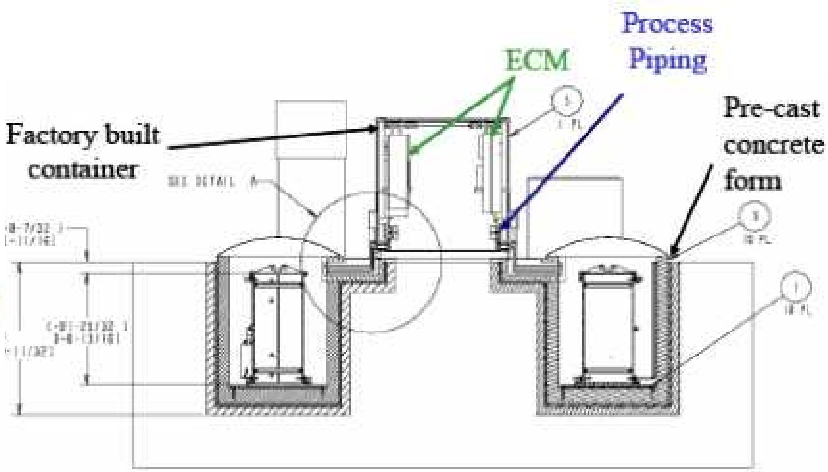
- Backup during Peak Load
- Defers Upgrade
- Potential Arbitrage Benefits

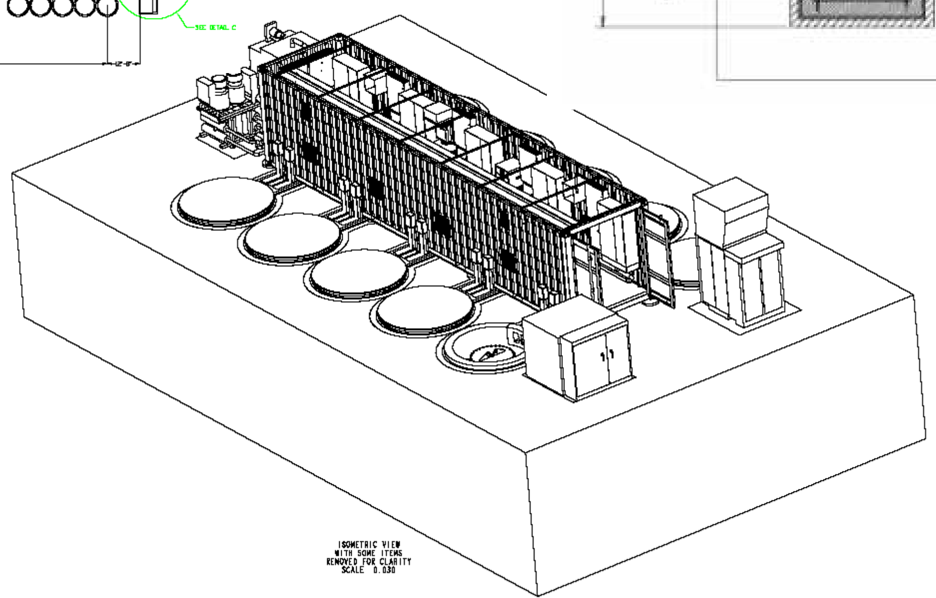
20 MW FESS Plant





25 kWh





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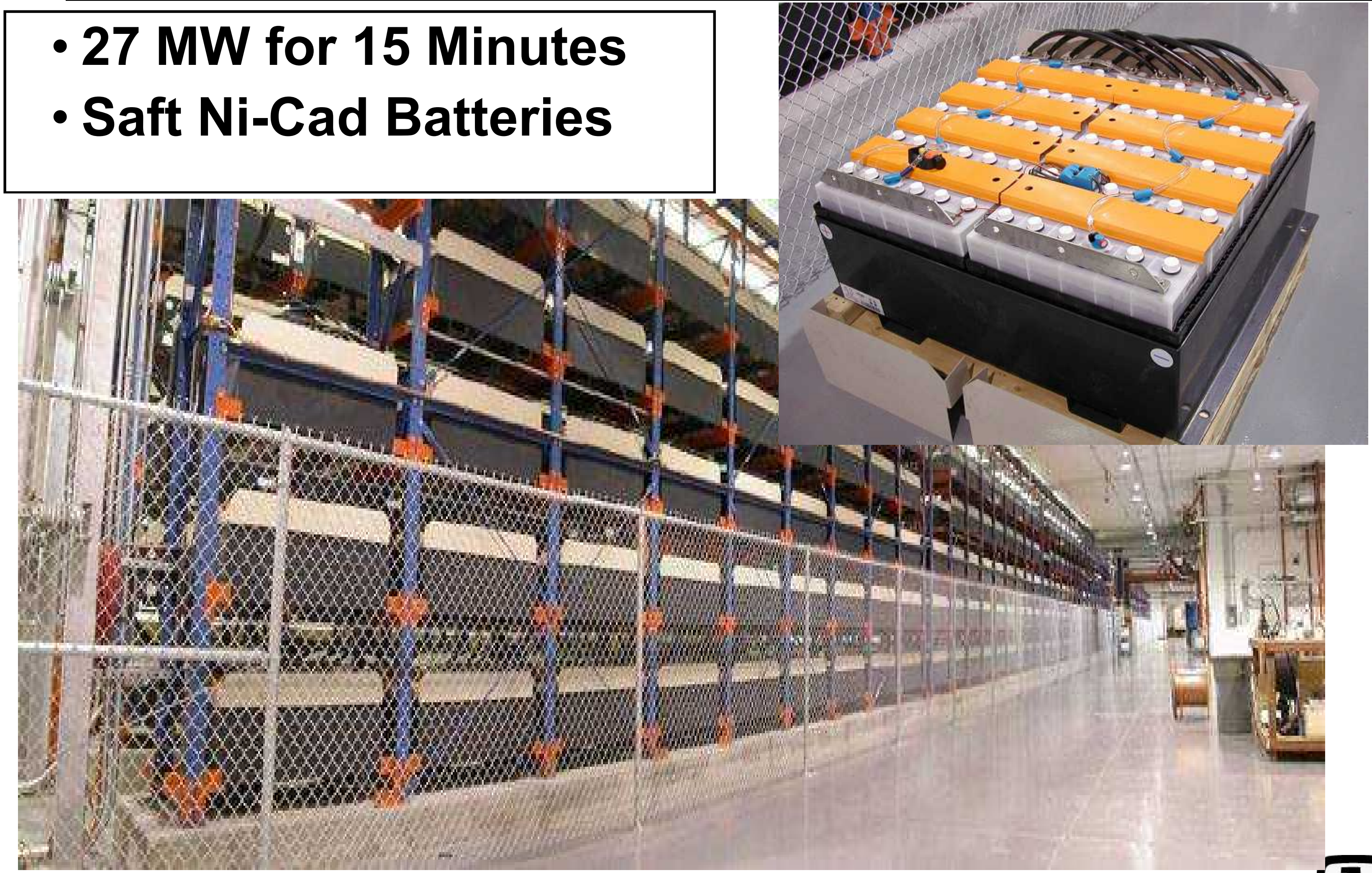
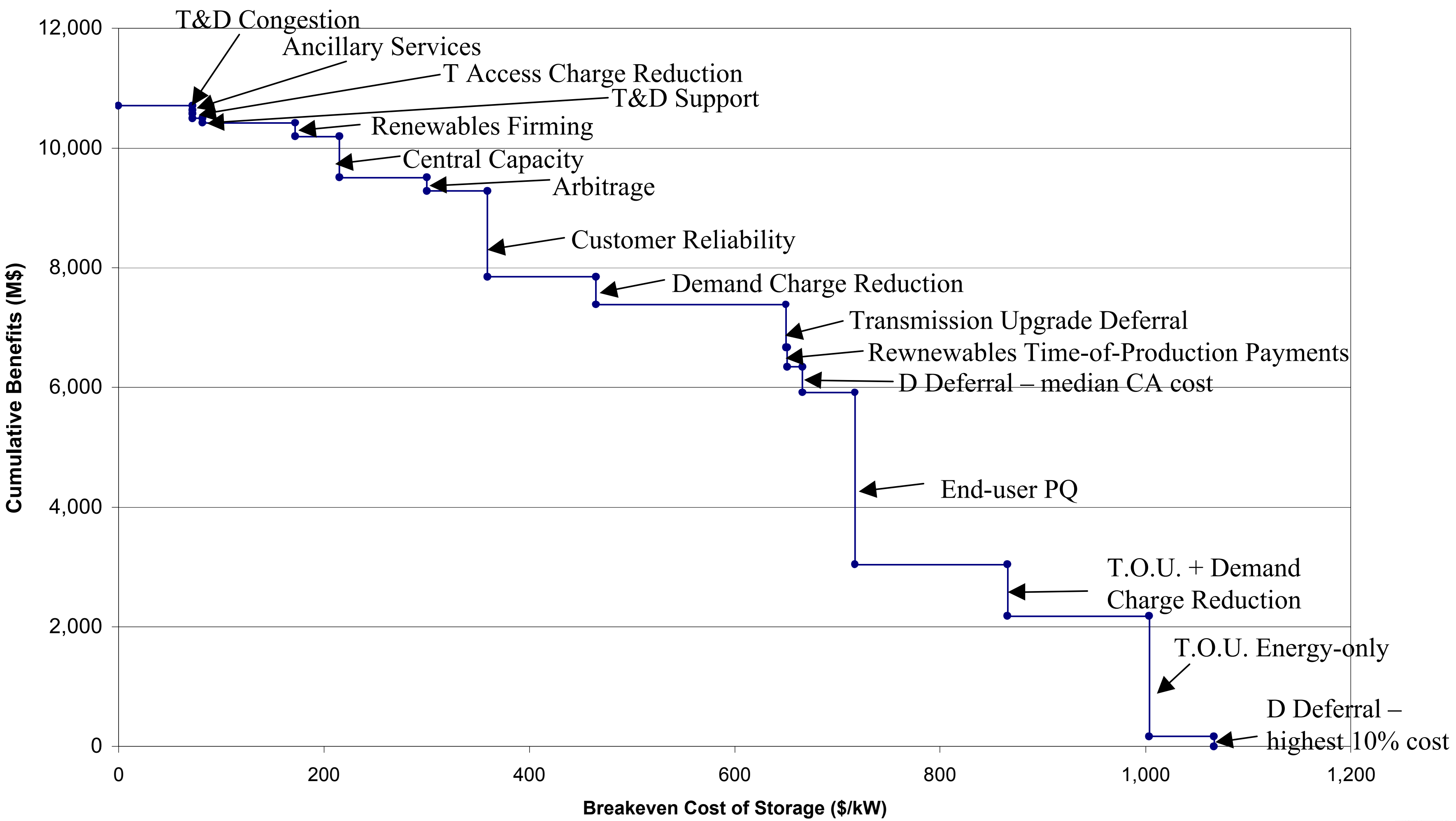
Golden Valley Battery Energy Storage System (BESS)

- 27 MW for 15 Minutes
- Saft Ni-Cad Batteries



California Storage Benefits



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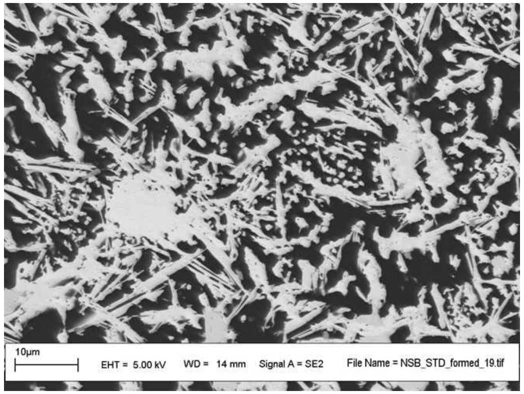
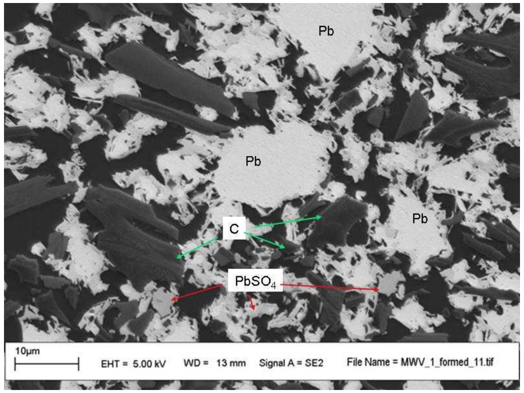
Development of Lead/Carbon Devices

- MeadWestvaco is developing several new classes of carbon material for energy storage
- Collaboration with Wisconsin Public Service Co. to evaluate utility markets
- Collaboration with Northstar Batteries to build lead carbon batteries
- Evaluation of batteries for hybrid vehicles, motive power, and frequency regulation by Sandia, MeadWestvaco and ETA Using Both Testing and Specialized Analytical Methods





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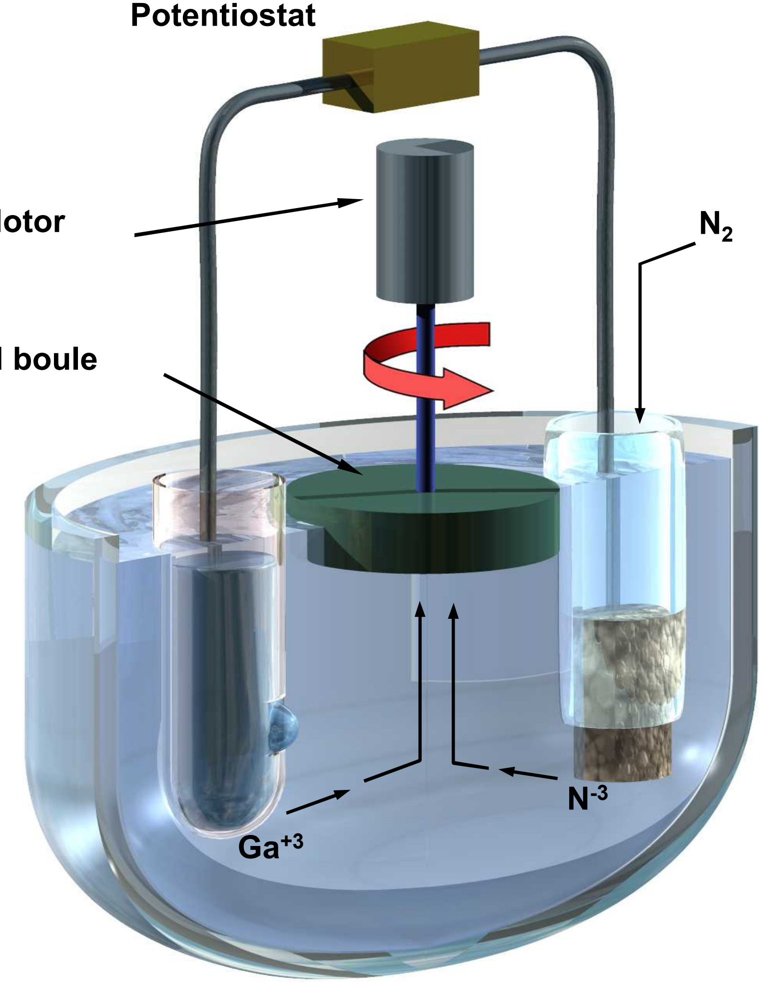
New Growth Technique: Electrochemical Solution Growth (ESG)



Use salt flow to deliver precursors

Increase growth rate through flux of reactants (increase spin rate)

- Half-reaction 1:
  - $1/2N_2 + 3e^- \rightarrow N^{-3}$
  - N^{-3} concentrations ~12 mole %
- Half-reaction 2:
  - $Ga \rightarrow Ga^{+3} + 3e^-$
  - Ga^{+3} equilibrium concentrations ~1 mole %

Precursors can be replenished as they are consumed
Advantage: Continuous, isothermal or steady-state growth

U.S. Patent filed April 11, 2005

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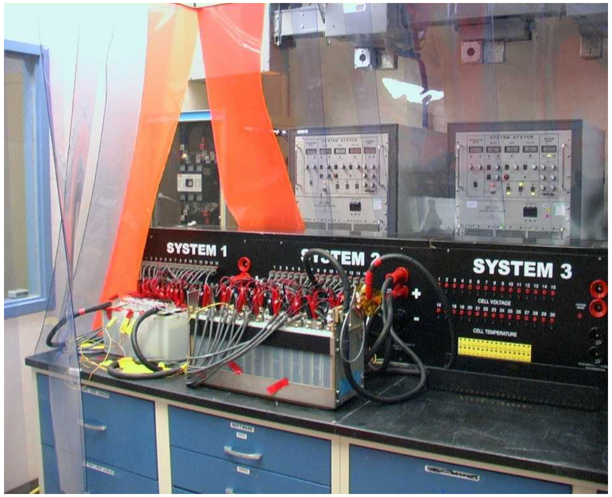
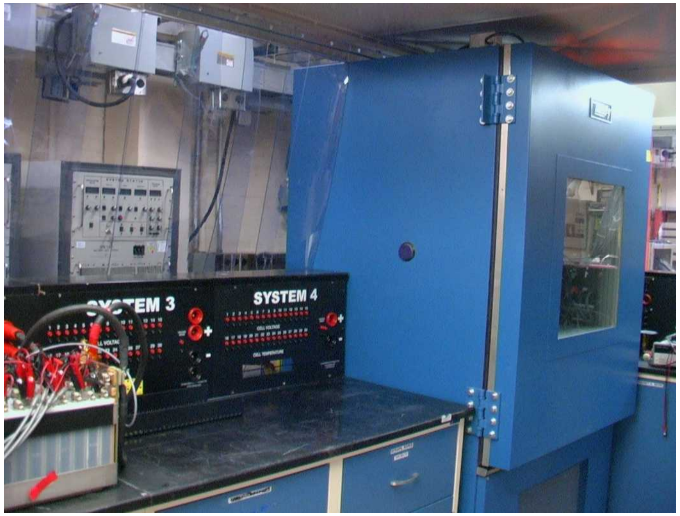
Sandia Test Activities

- EC Supercap testing
- Battery Testing
- Abuse Testing





Distributed Energy Technology Laboratory (DETL)

- fully instrumented, configurable, controlled, utility-interconnected test bed
- interactions of multiple, distributed sources of various technologies

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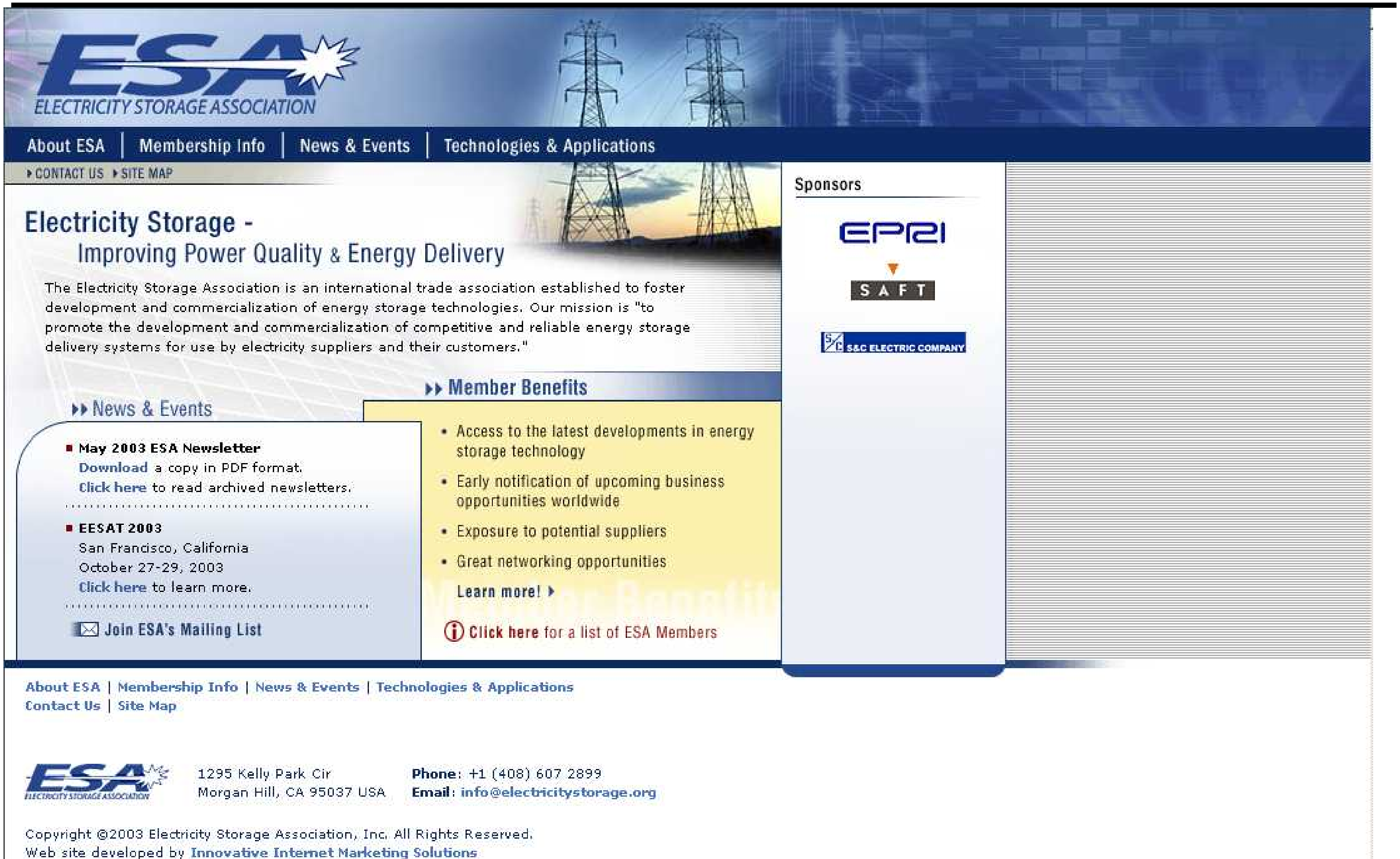
Electricity Storage Association www.electricitystorage.org



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Energy Storage Websites

- DOE Home Page
  - http://www.oe.energy.gov/storage.htm
- DOE/Sandia Energy Storage Program
  - http://www.sandia.gov/ess/
- Electricity Storage Association
  - http://www.electricitystorage.org/
- EESAT Conference
  - http://www.sandia.gov/eesat

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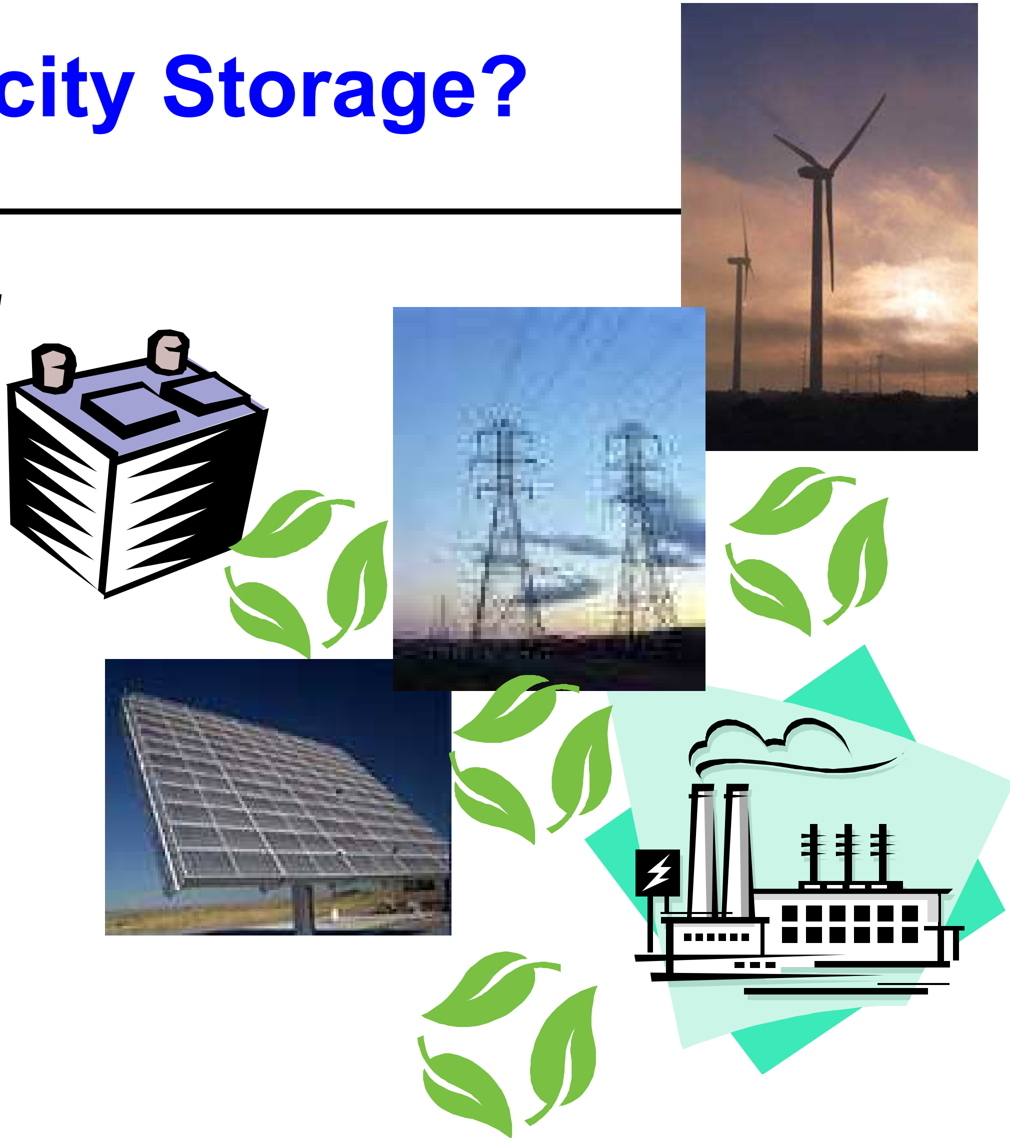
Why Electricity Storage?

Electricity Storage Enables

- **Better system-wide asset utilization**
- **Enhanced reliability / power quality**
- **Increases value of Renewables and DER**
- **To Reduce Greenhouse Gas Impacts**



Energy Storage

Questions?

Thank You...

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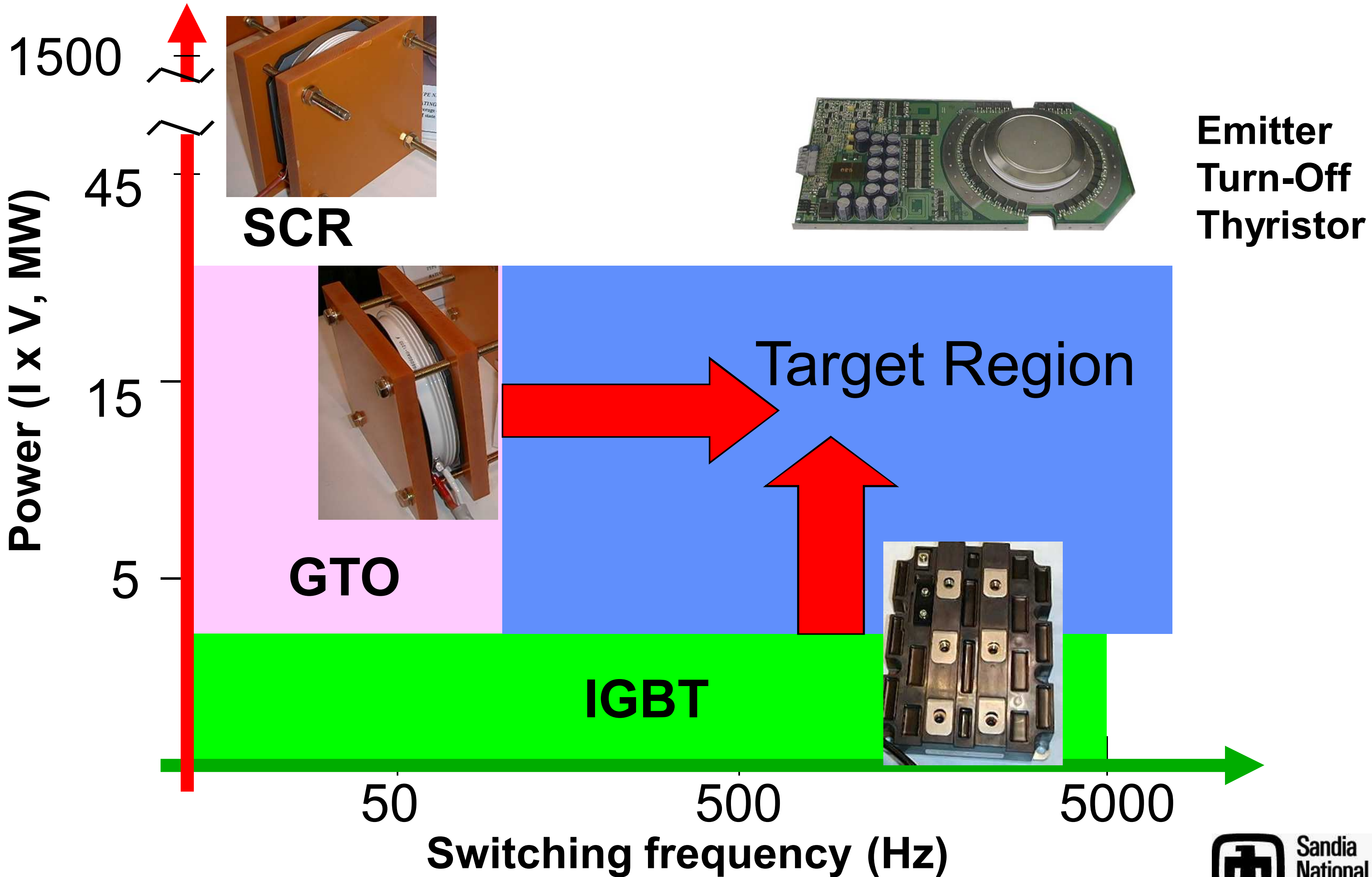
Power Electronic Devices (High Power)



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Electric Vehicle – Stationary Systems

Technical and Economic feasibility of Applying Used EV Batteries in Stationary Applications, Cready et. al., SAND2002-4084

http://infoserve.sandia.gov/sand_doc/2002/024084.pdf