Some Issues and Opportunities with the Integration of Solar and Wind Energy into a Smart Grid

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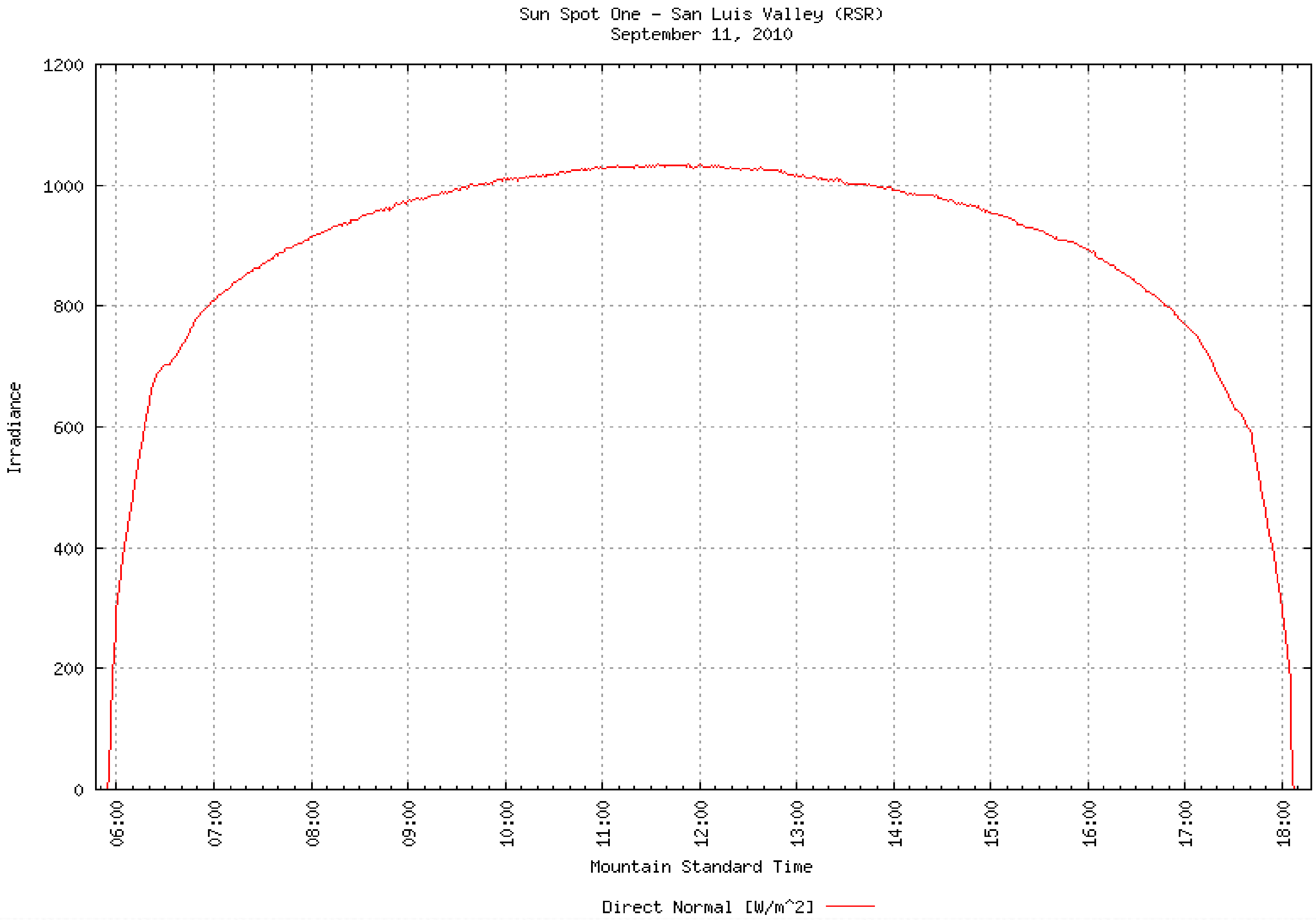
Introduction

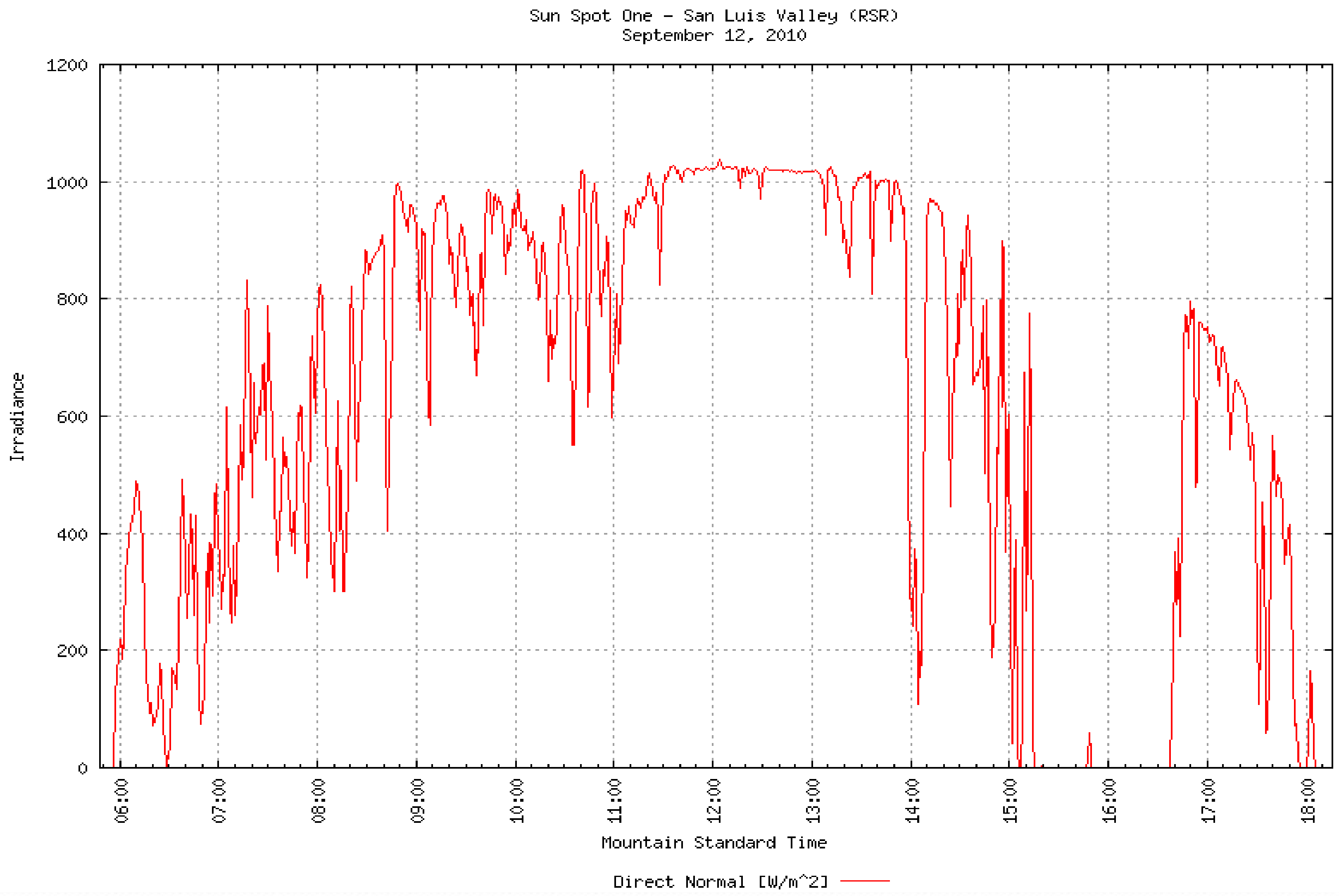
Obstacles to Integration of Wind and Solar Energy

1. The Variability of Wind, Solar and Hydroelectric Power and Mismatch to the Loads
2. The Integration and Control of a Large Number of Distributed Sources in to the Grid
3. Security and Privacy
4. Safety

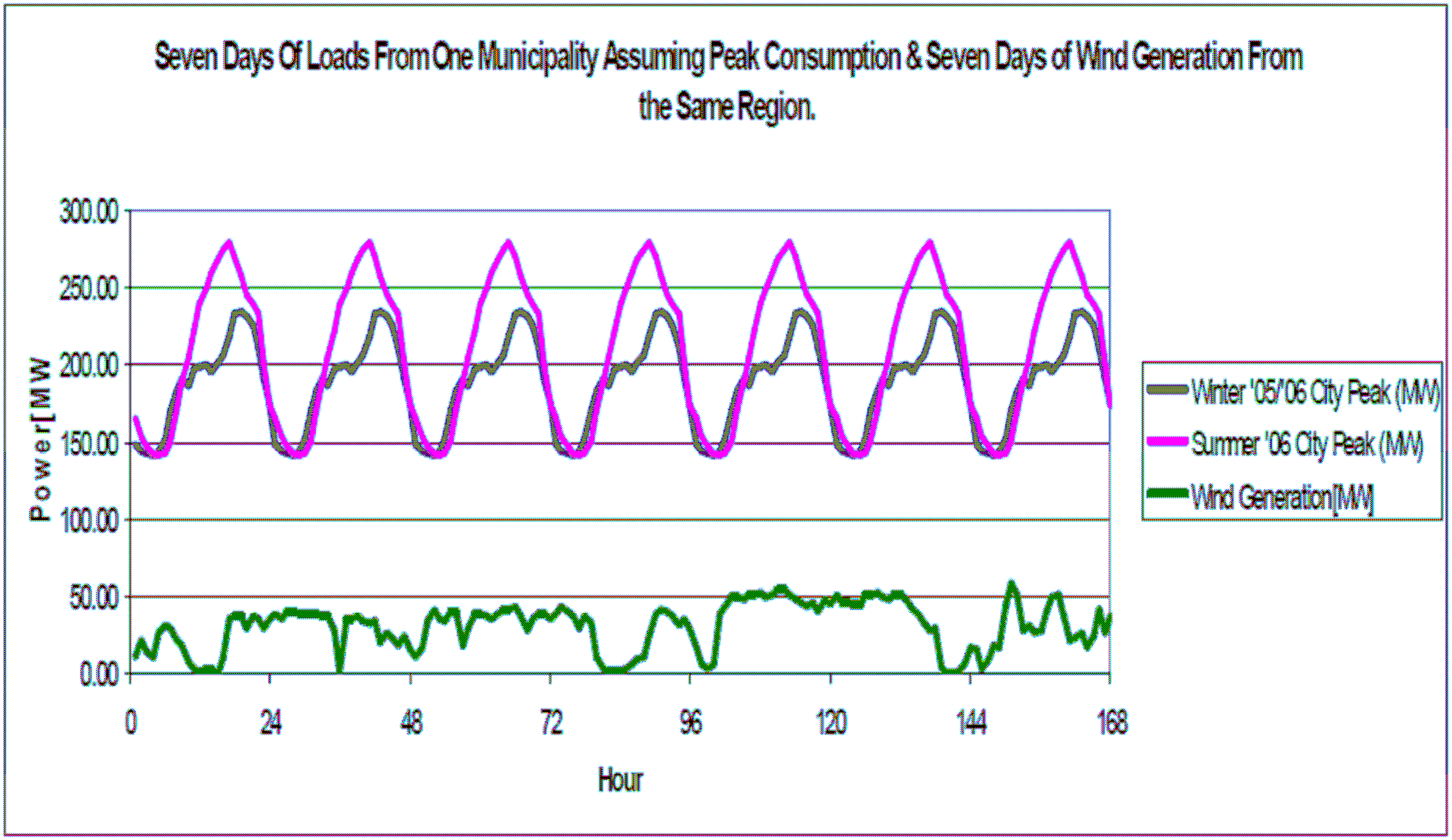
San Luis Valley Solar Data (09/11/2010) Good Day [1]



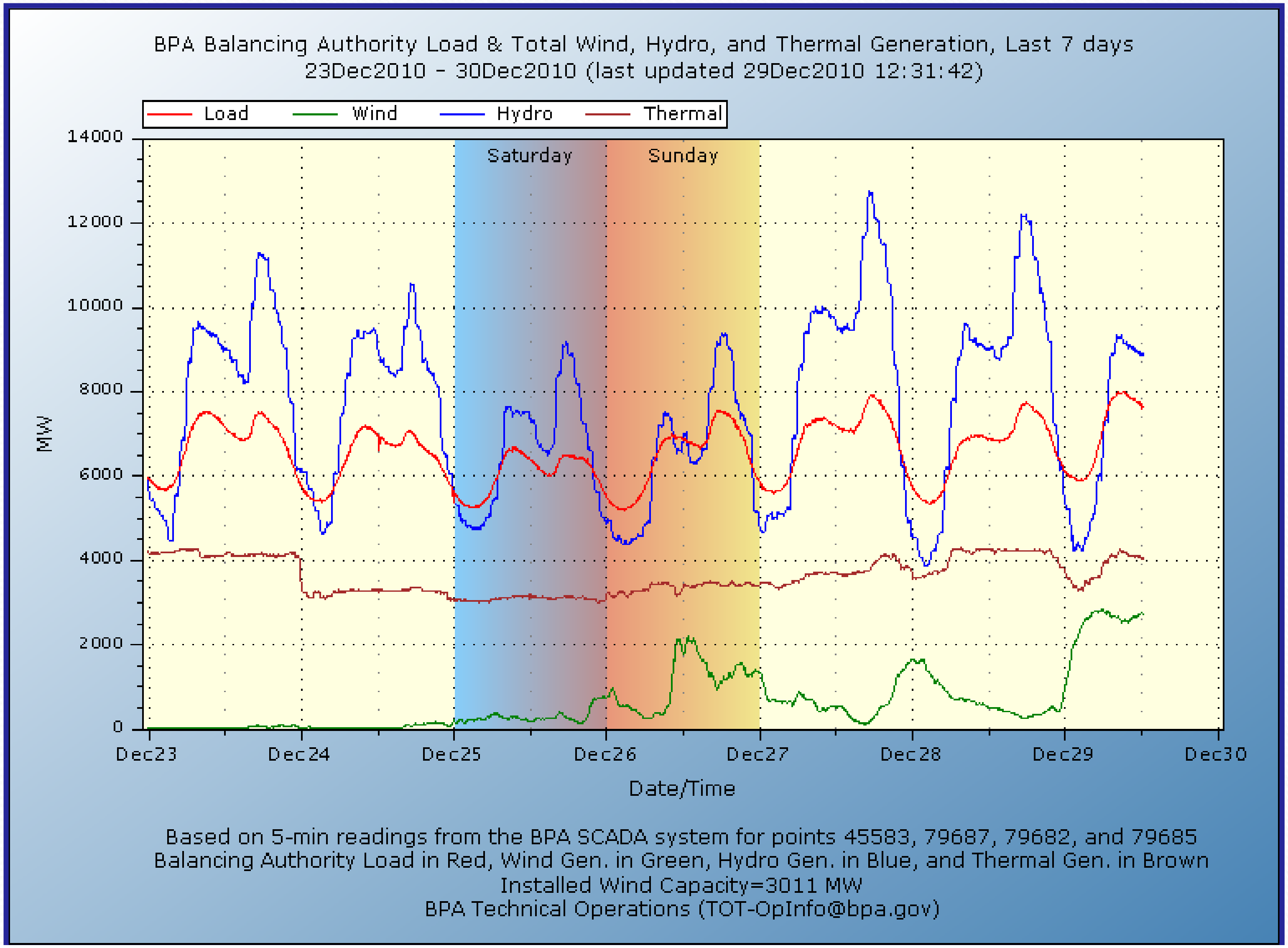
San Luis Valley Solar Data (09/12/2010) Bad Day [1]



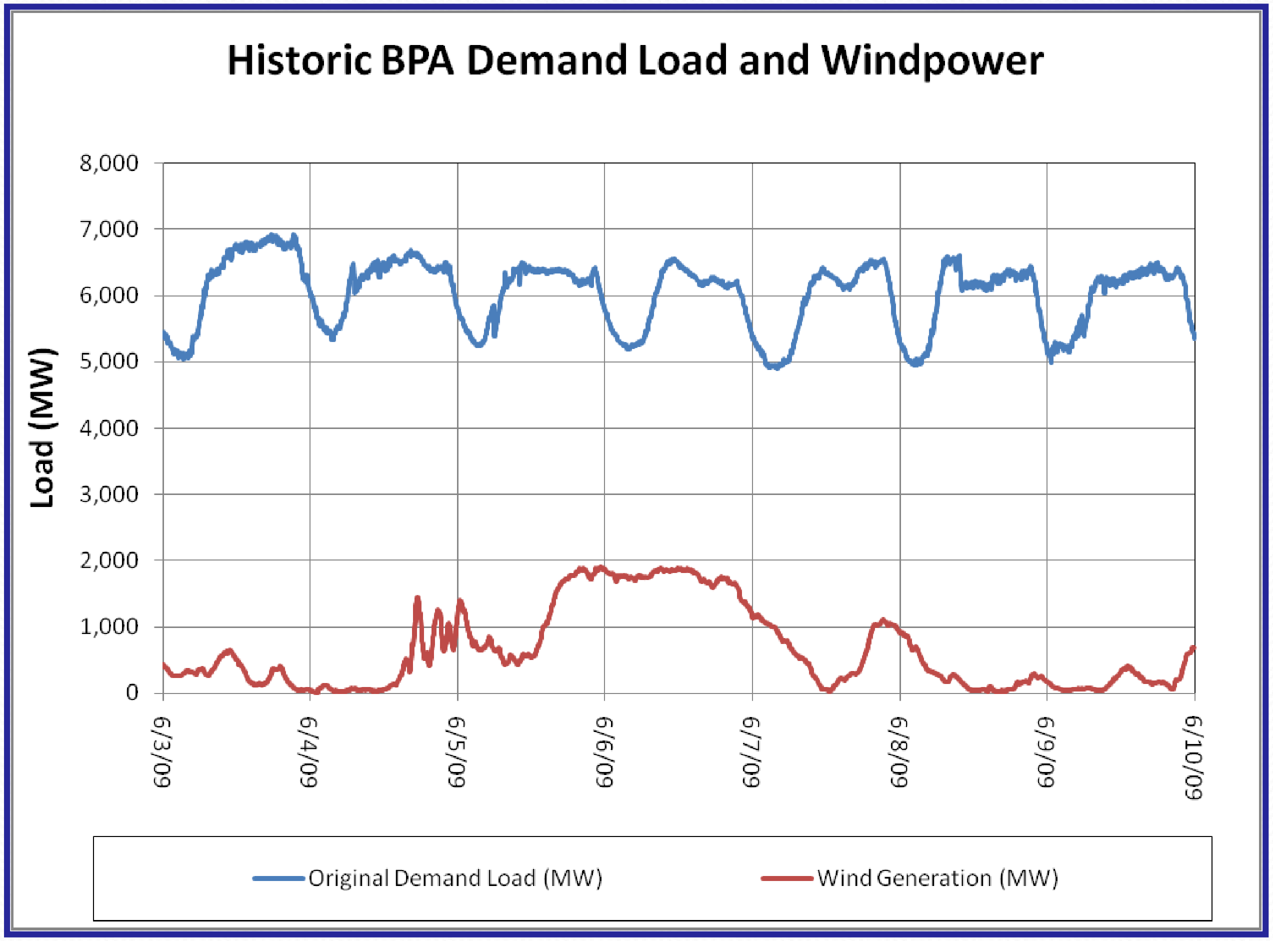
Intermittent Wind Generation



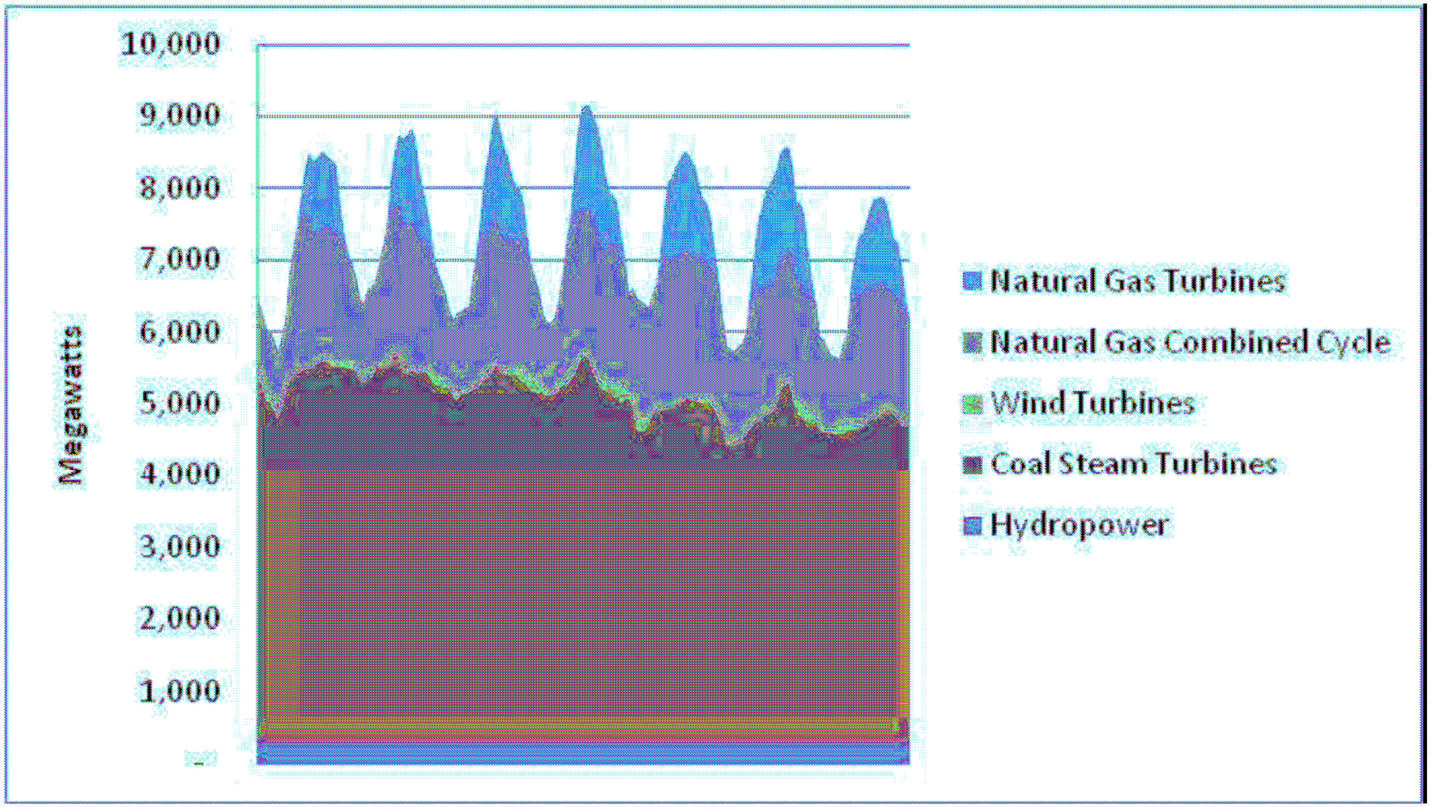
From Rick Miller HDR\DTA



Rick Miller HDR/DTA

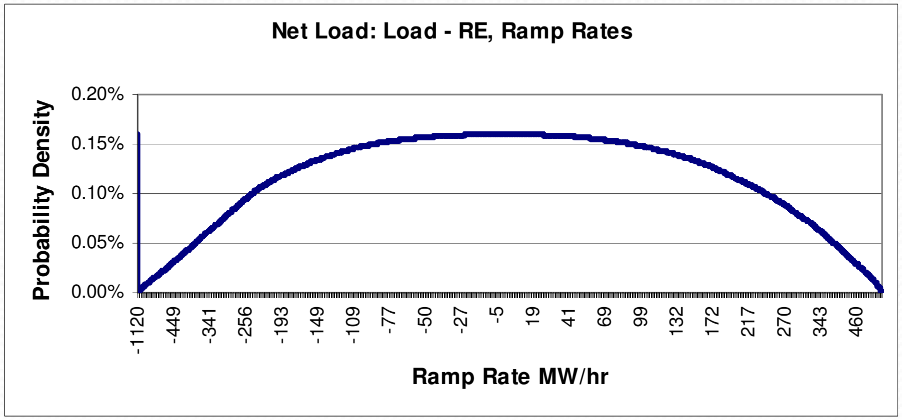


Energy Generation In Colorado



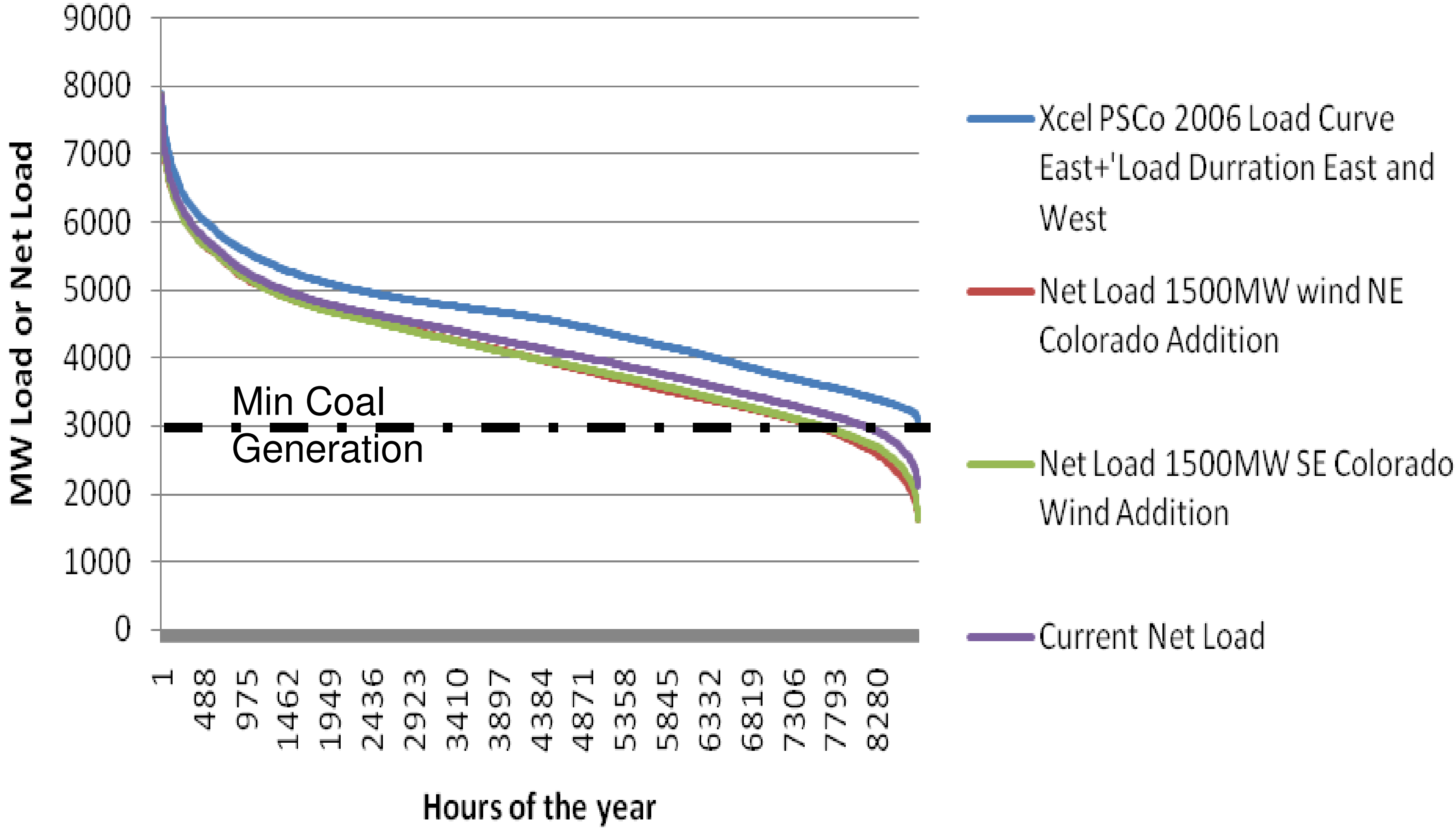
Matching Fossil Resources to the Net Loads In Colorado

Generation Resource Type	Rated Capacity [MW]	Ramp Up [MW/hr]	Ramp Down [MW/hr]
Coal sub-total[i]	*2834*	*322.58*	*-630.27*
Gas sub-total	*775*	*37.70*	*-65.75*
Ramp per (MW/hr)/MW avg.	**NA**	**.0998**	**-.1926**
Total	**3609**	**360.28**	**-695.02**
Extrapolated Total	**7,884 MW**	**786.82**	**-1,518.30**



Ramp Rate MW/hr	Number of Ramp Events	% of the year
-1000	1	0.01%
-900	2	0.02%
-800	2	0.02%
-700	26	0.30%
-600	72	0.82%
-500	178	2.03%
-400	317	3.62%
-300	434	4.95%
-200	603	6.88%
-100	1010	11.53%
0	1666	19.02%
100	1632	18.63%
200	1083	12.36%
300	769	8.78%
400	472	5.39%
500	284	3.24%
600	146	1.67%
700	44	0.50%
800	13	0.15%
900	5	0.06%
1000	1	0.01%

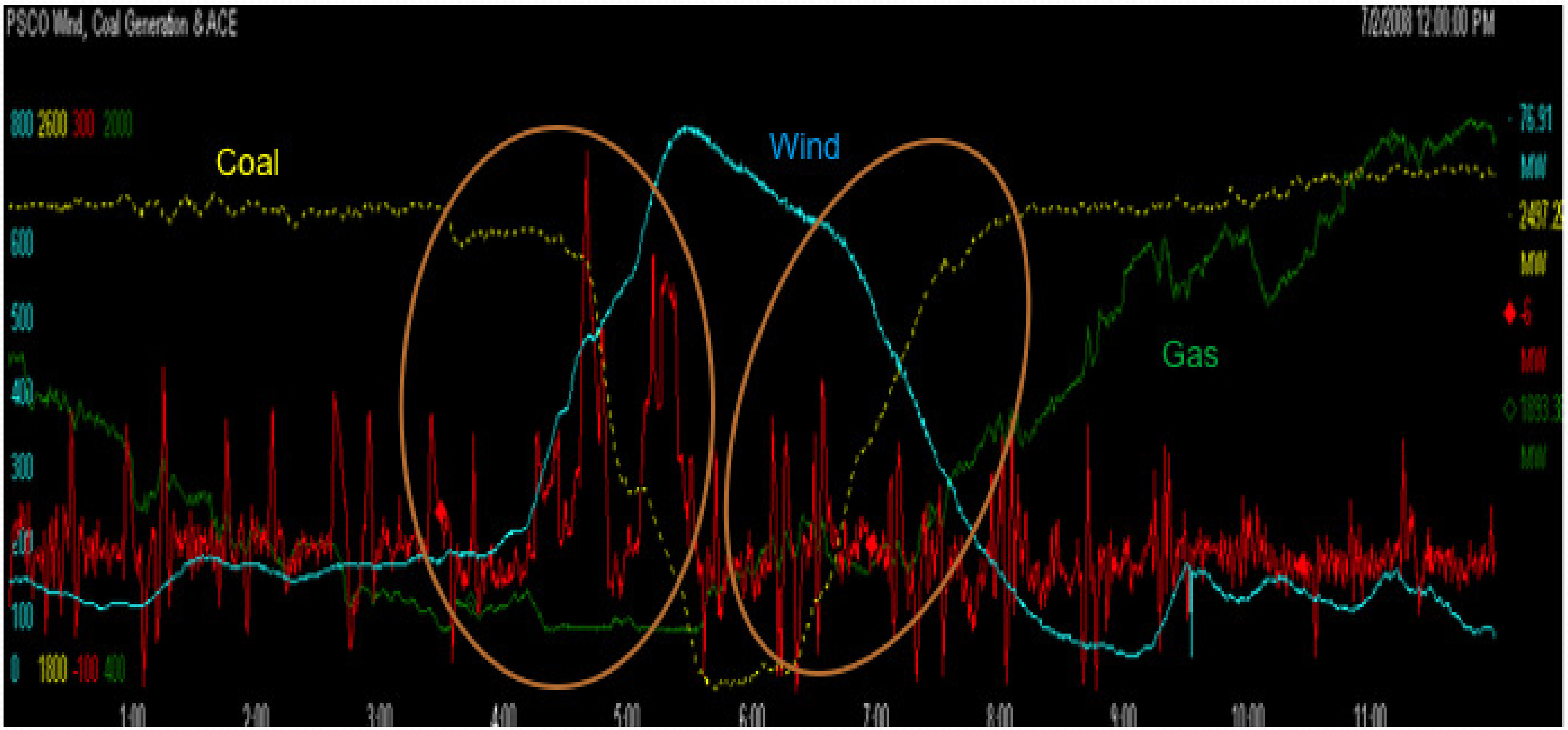
Xcel PSCo Load Duration Curve and Net Load Duration Curves



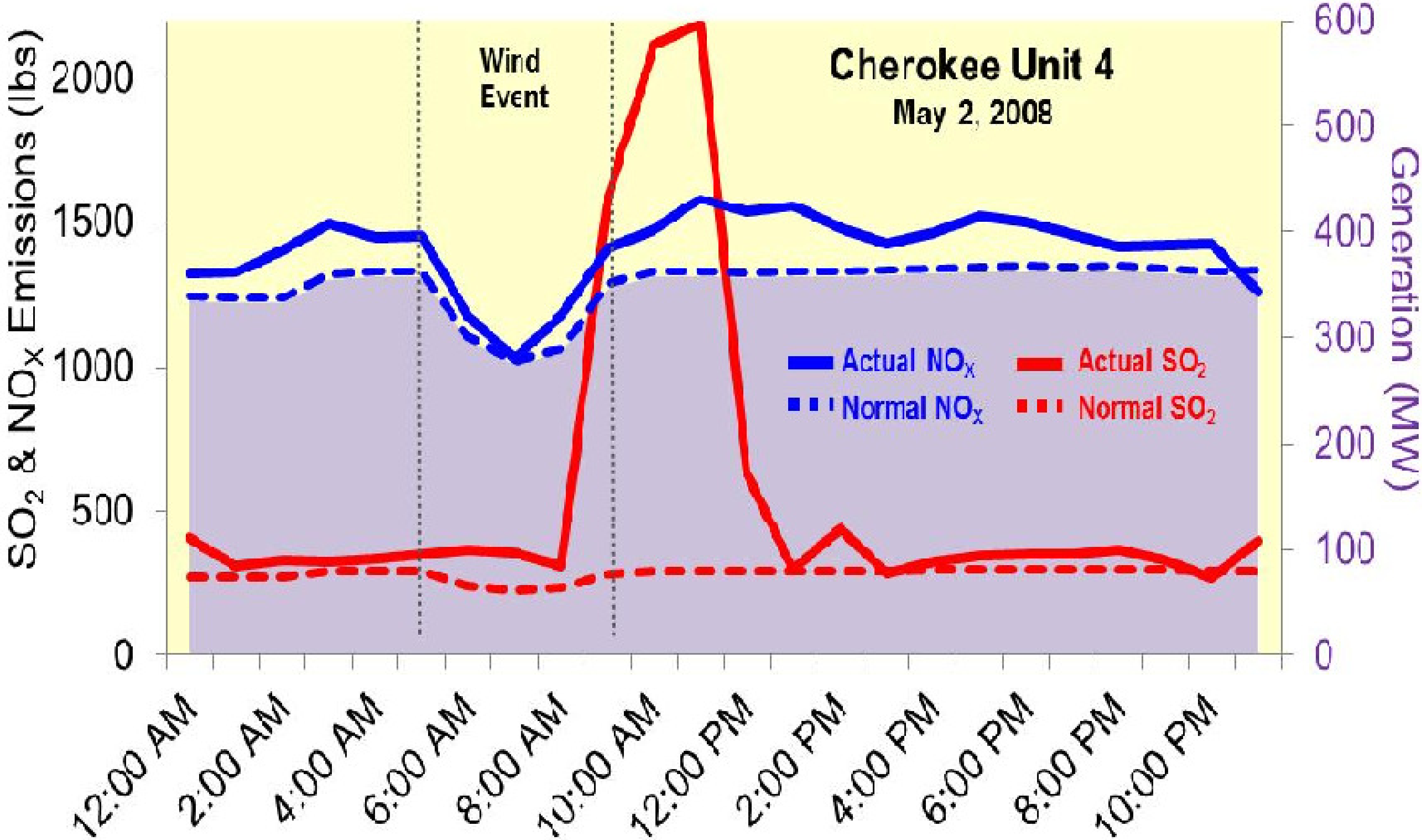
Case When Wind Energy Exceeds Capacity.

- Current Law Requires use of Wind Energy
- The wind energy may exceed the amount of gas fired energy that can be shut off and require the reduction of heat rate to coal fired plants
- This reduces electric power generation efficiency and increase emissions of SO_2, NO_x and CO_2
- It is expected to double the costs of maintenance.

Example of Wind Event and Response



Resulting Increase in SO_2, NO_x



Cost of Increasing Wind Energy Penetration

Gas Cost Impact of wind penetration with and without storage on Xcel's electric grid

Wind Penetration	10%	15%
$/MWH Gas Impact No Storage Benefits	$2.17	$2.52
$/MWH Gas Impact with storage benefits	$1.26	$1.45

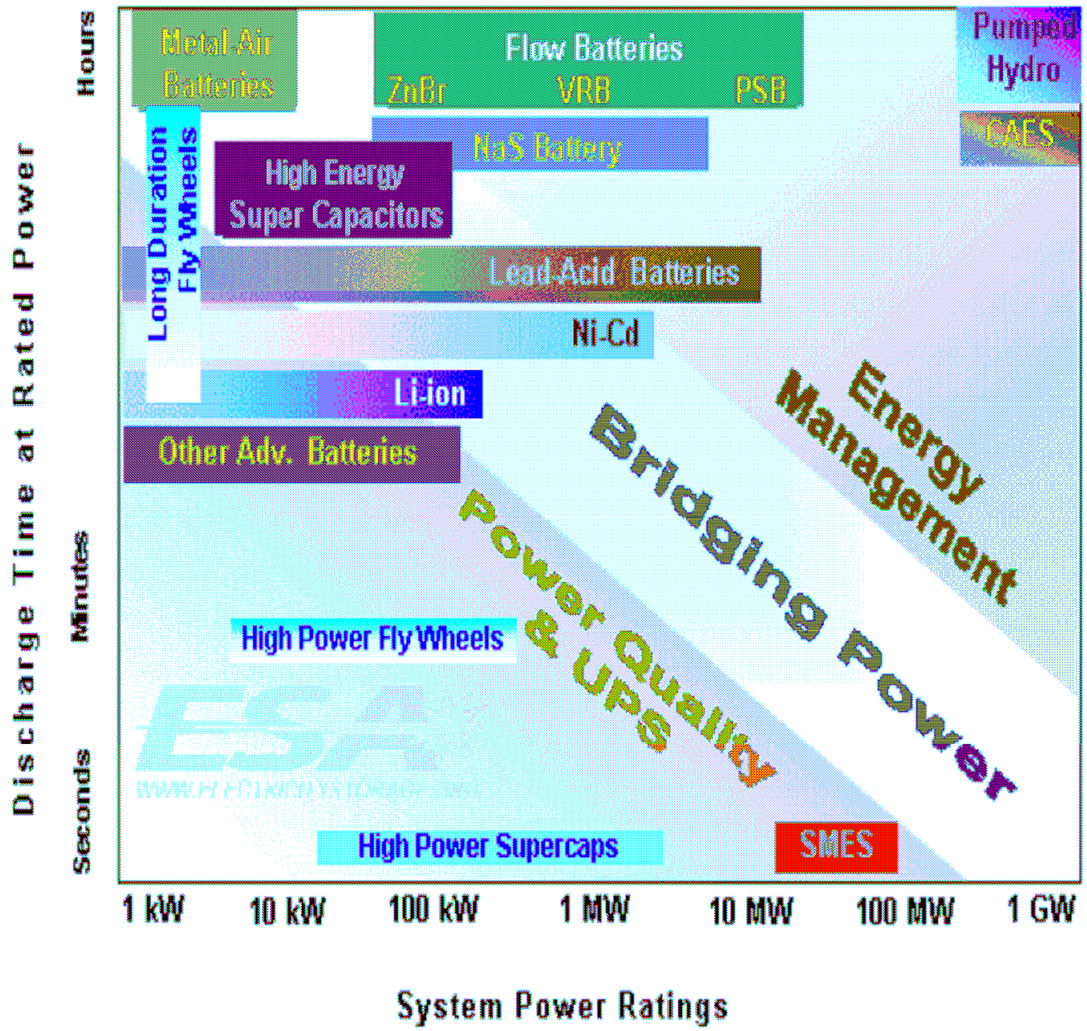
Cost Impact of increasing wind penetration on Xcel's electric grid

Wind Penetration	Electric Production Cost Impact	Gas Supply System Impact	Total
10%	$2.25	$1.26	$3.51/MWH
15%	$3.32	$1.45	$4.77/MWH
20%	$7.47	$2.10	$9.57/MWH

Approaches to Solving the Variability Issues.

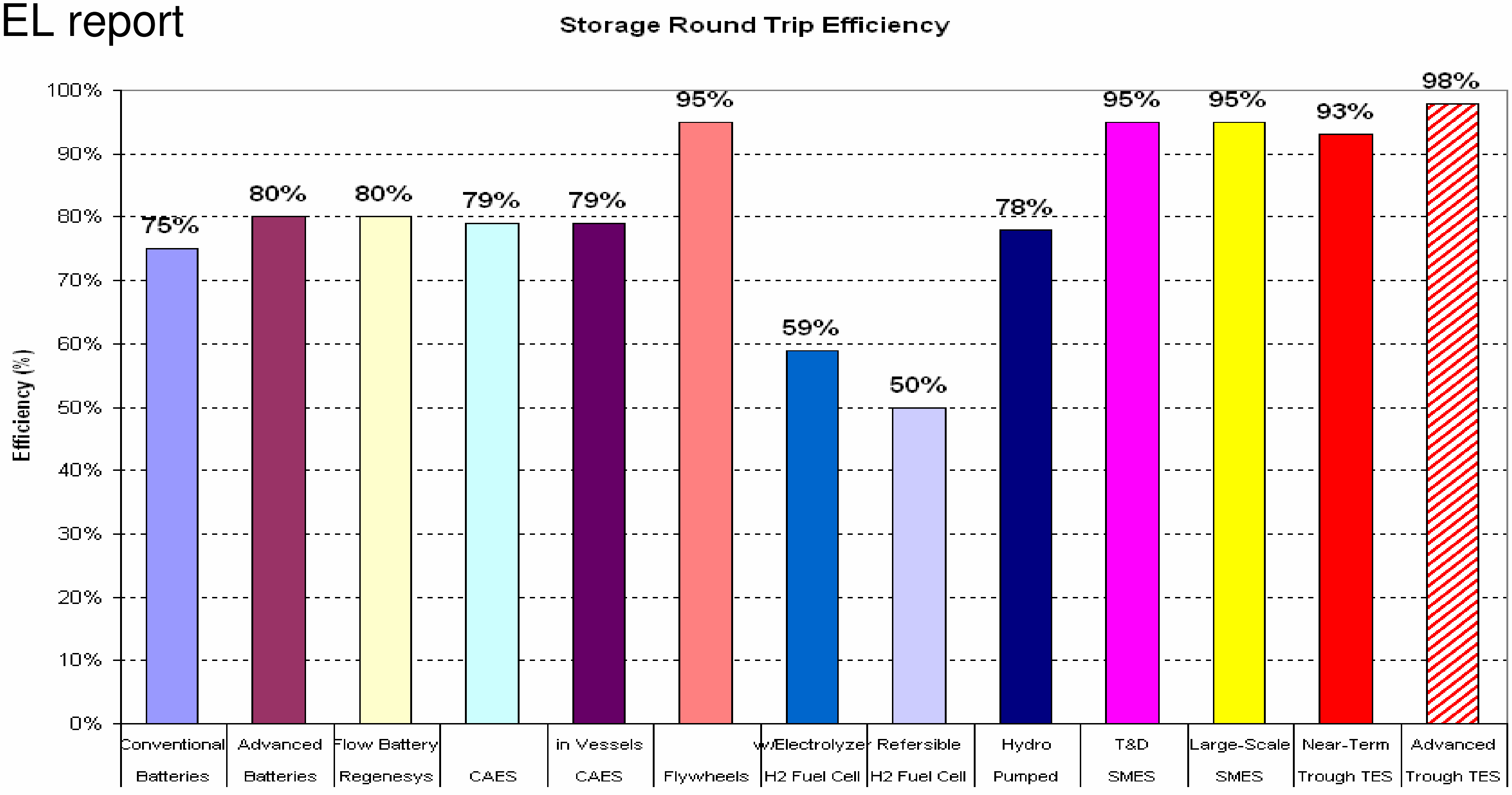
1. At low penetration grid spinning reserves.
2. Gas fired generators
3. Storage
   a. Batteries, super capacitors, fly wheels,
   b. Pumped Hydroelectric systems, CAES
4. Demand Response
5. Biomass, geothermal,

Energy Storage Systems



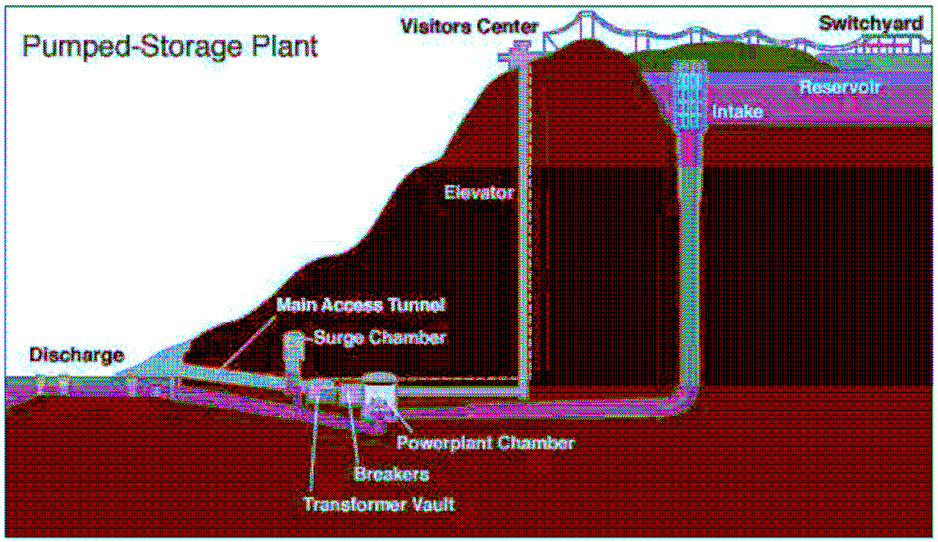
Comparison of efficiency of several energy storage technologies

NREL report



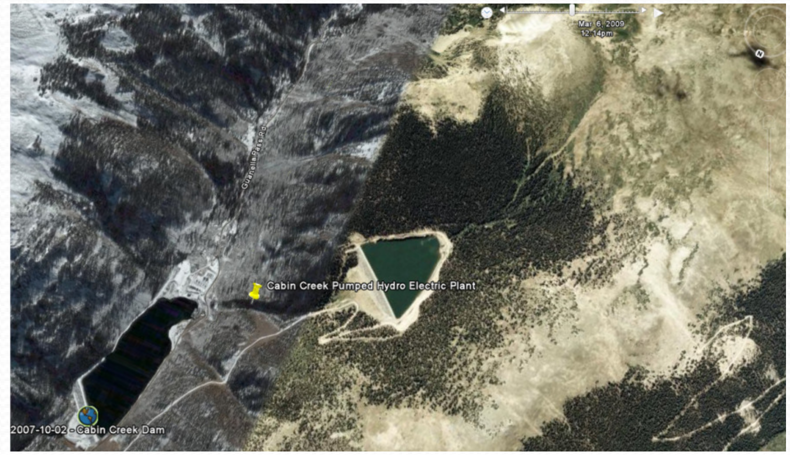
Pumped hydroelectric installation at Raccoon Mt

(TVA).

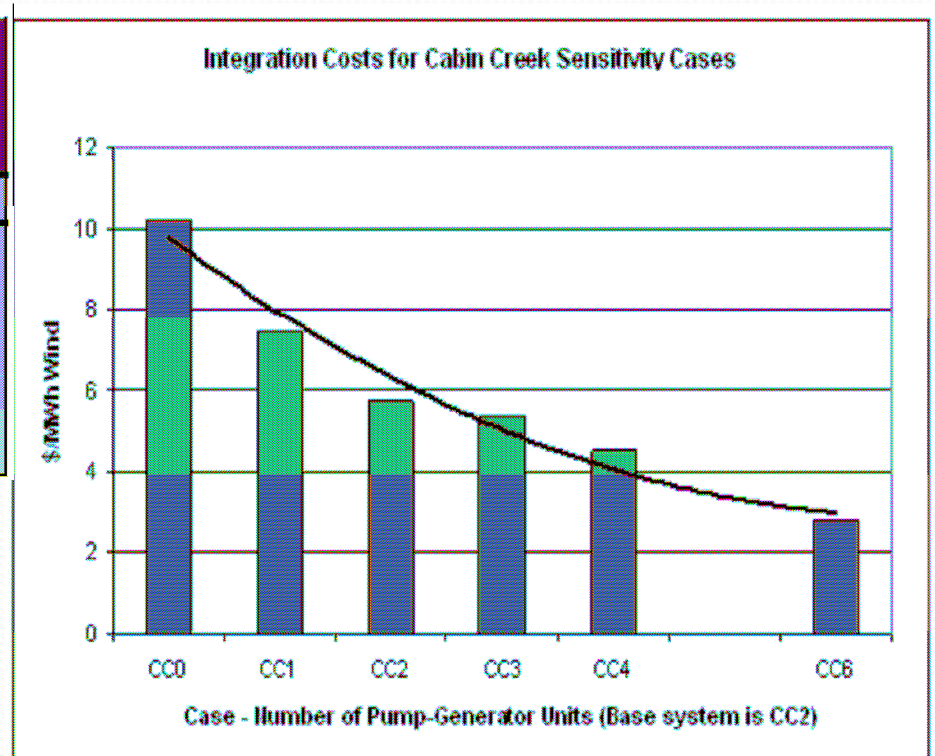


- Construction at Raccoon Mountain 1970-1978.
- The reservoir at the top of the mountain has 528 acres of water surface.
- Once the upper reservoir is full, the pumped-storage plant can provide 22 hours of continuous power generation.
- Generating capacity of Raccoon Mountain is 1,600 MW

Pumped Hydro Storage in Colorado



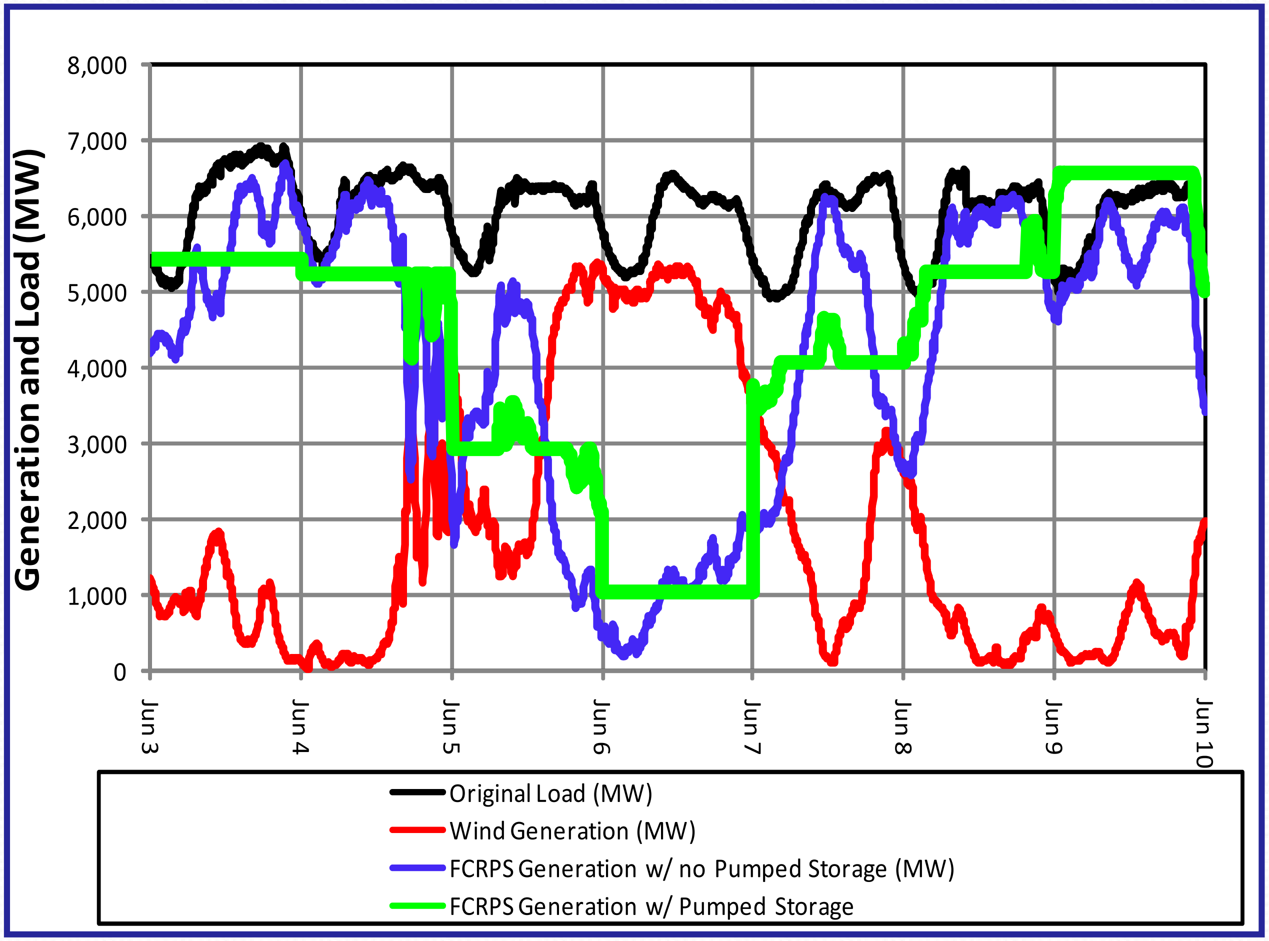
Case Name	Wind Integration Cost ($/MWh) ($5/MMBtu gas)
ase Case CC2 - 2 Cabin Creek Units	$5.75
:C0 - No Cabin Creek Units	$10.19
:C1 - 1 Cabin Creek Unit	$7.49
:C3 - 3 Cabin Creek Units	$5.34
:C4 - 4 Cabin Creek Units	$4.55
:C4 - 6 Cabin Creek Units	$2.78



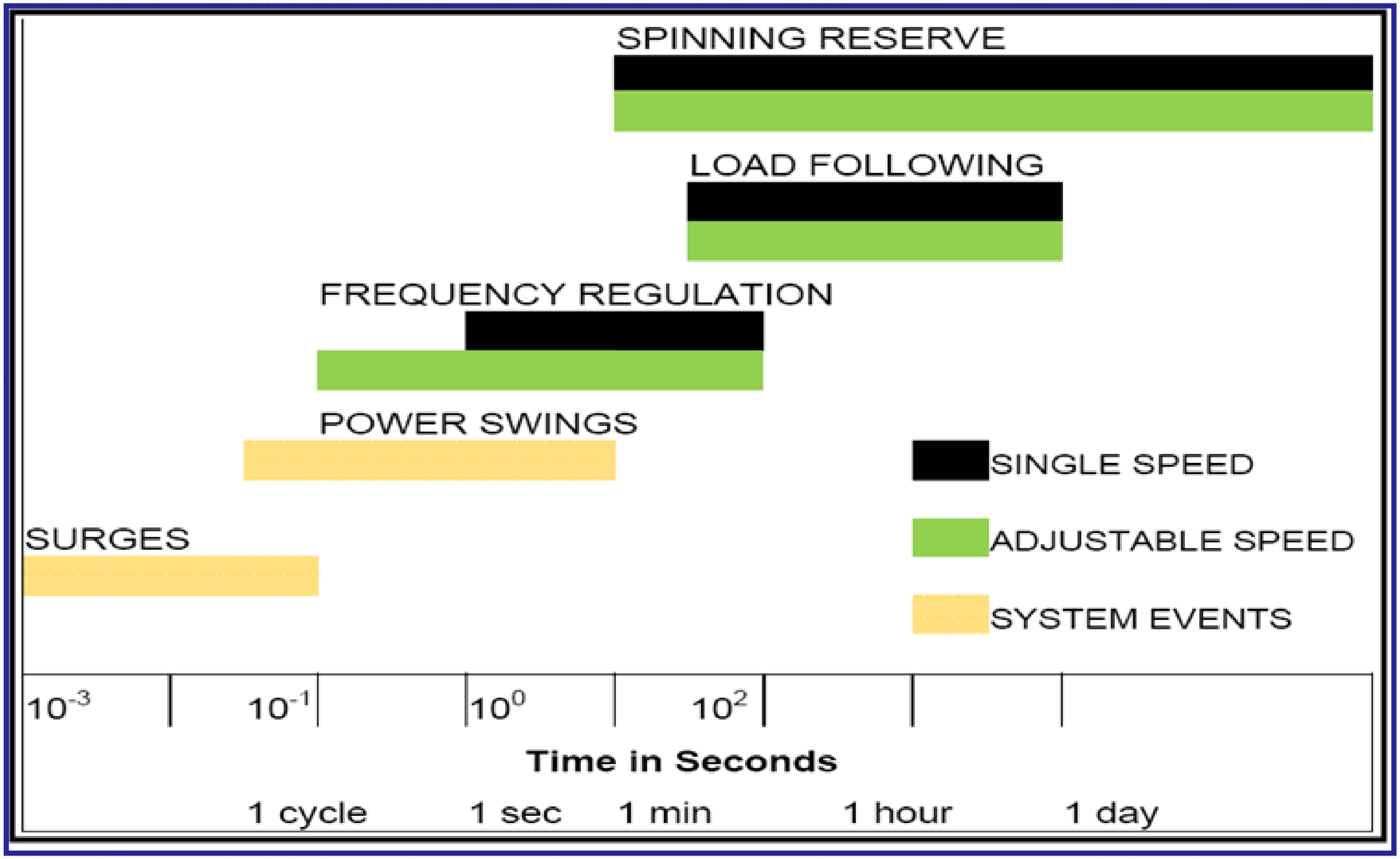
Wind Integration Study for Public Service of Colorado Addendum Detailed Analysis of 20% Wind Penetration

http://www.xcelenergy.com/SiteCollectionDocuments/docs/CRPWindIntegrationStudy.pdf

Historic BPA Load – Managing Reliability & Wind Integration with Pumped Storage Rick Miller HDR/DTA

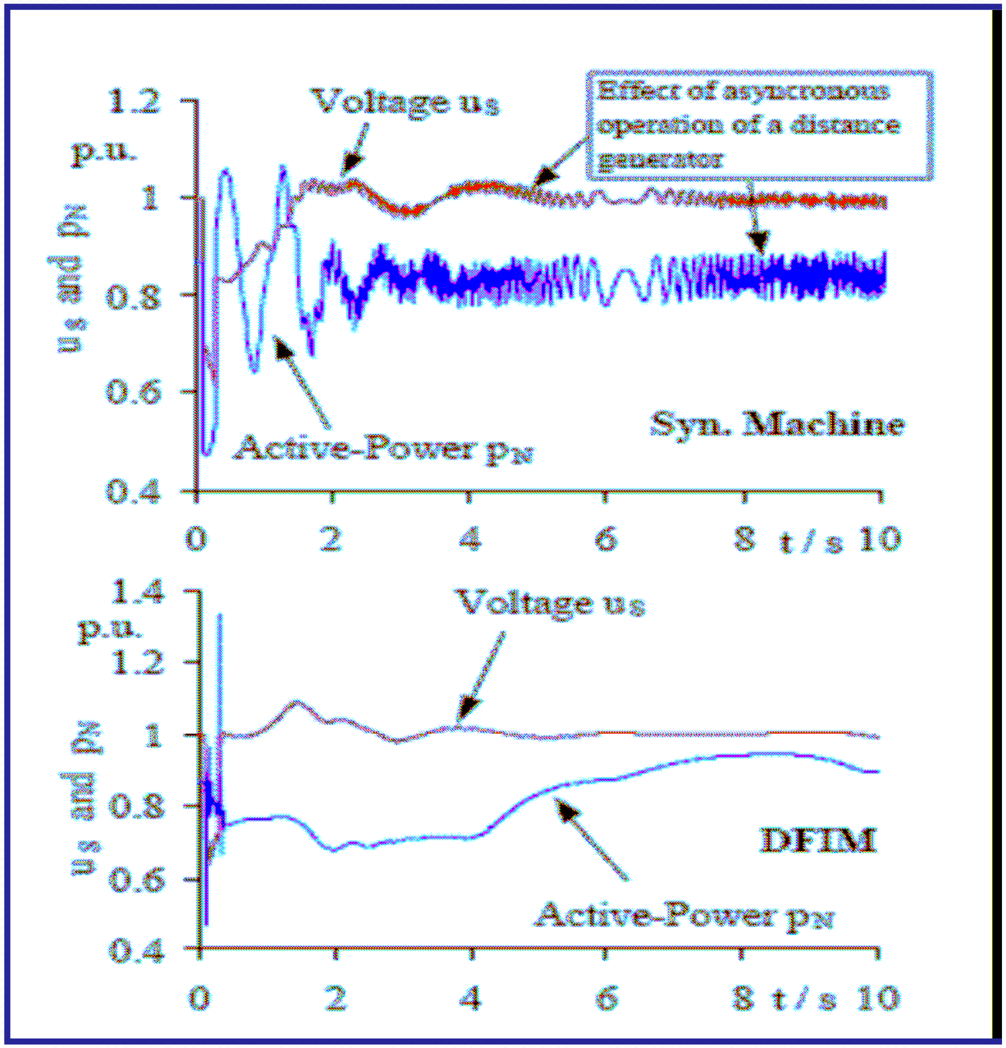


Adjustable Speed Pumped Storage
Fast Response Capabilities Rick Miller HDR/DTA

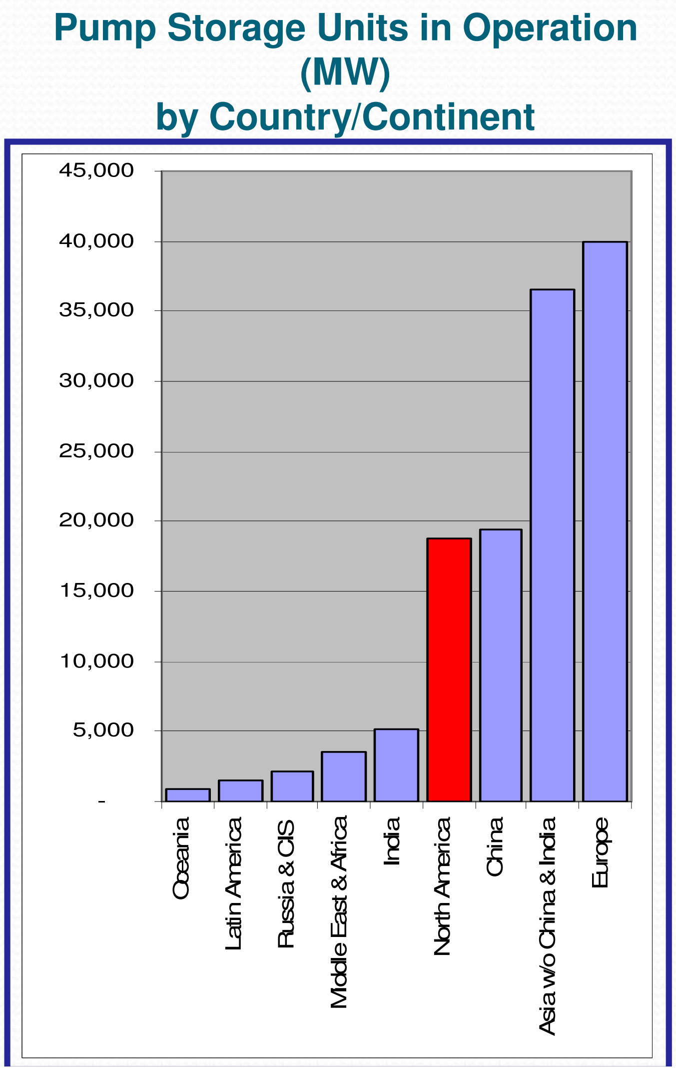


Adjustable Speed PS is a ‘fly wheel’
Rick Miller HDR/DTA

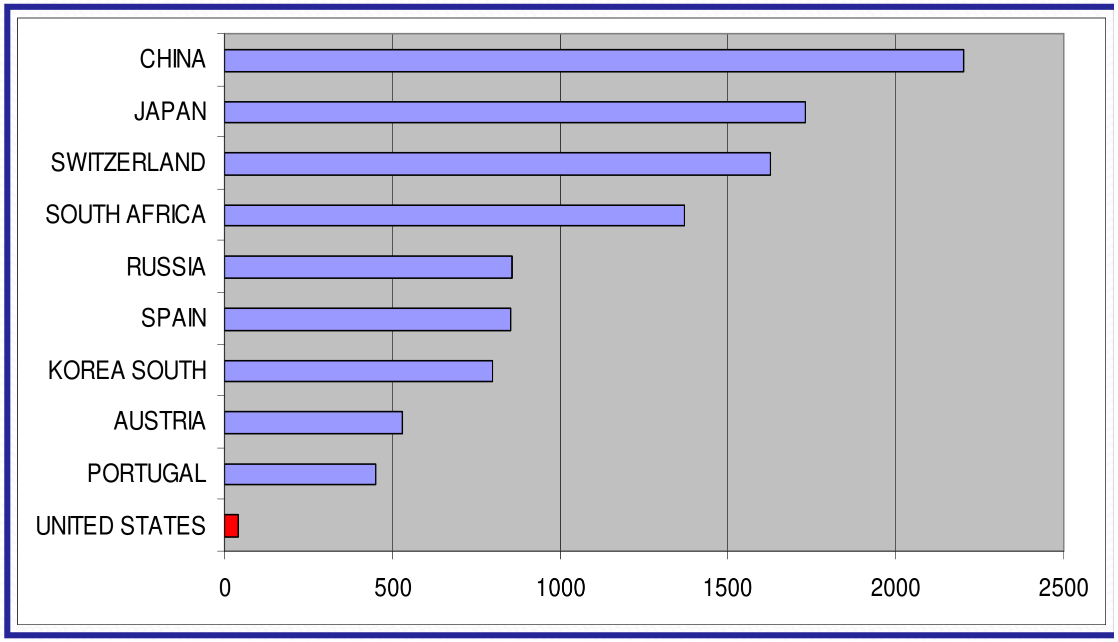
- **Adjustable Speed Pumped Storage Fast Response Capabilities**
- Utilize angular momentum stored in spinning rotor mass.
  - Rapid change of rotor speed
  - ≈ 150 Milli Seconds
  - Change speed and energy stored in rotating inertia: ωM = ωS +/- ωR
  - Control bulk power system power and frequency variations.

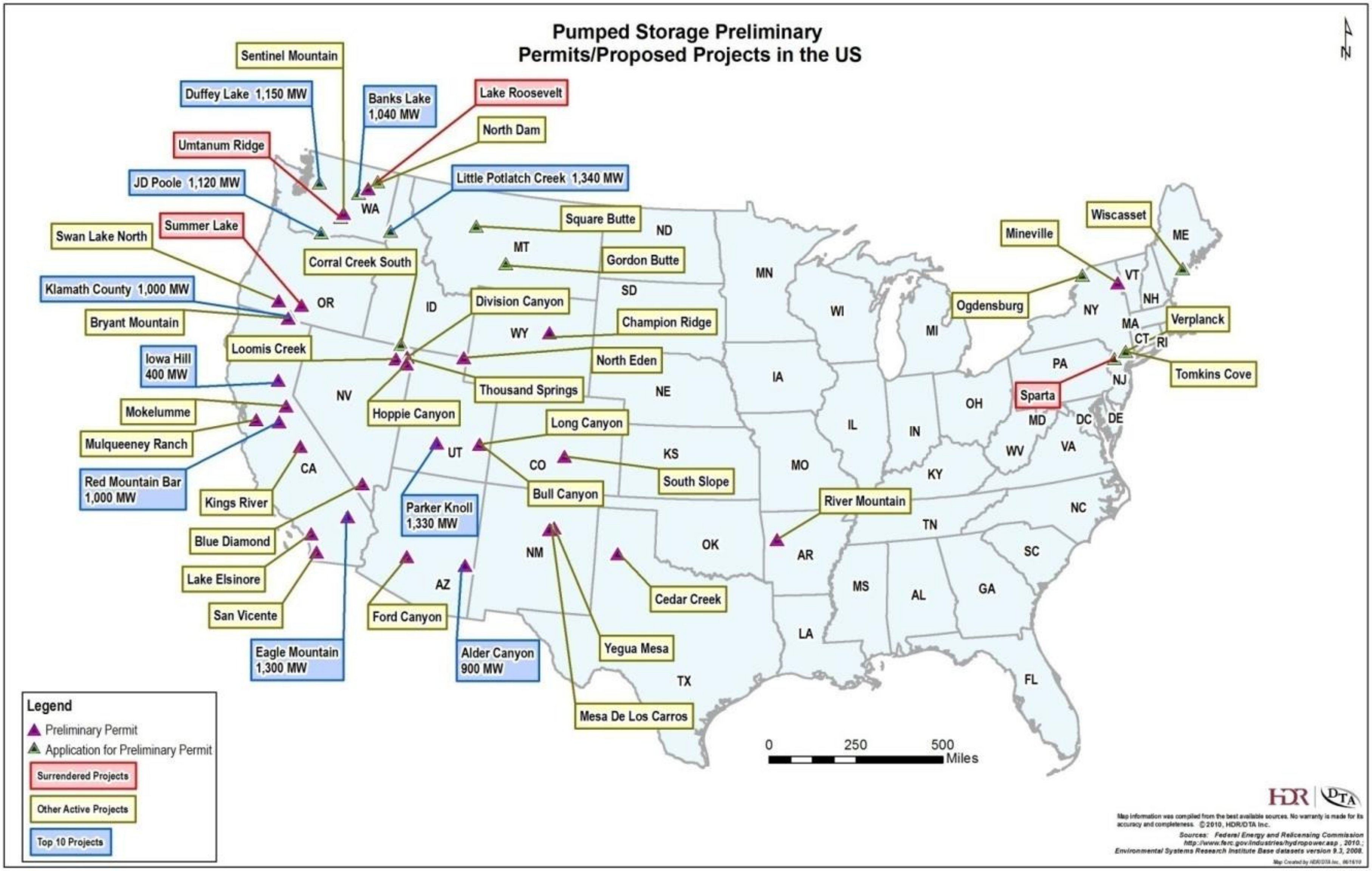


Snapshot of Pumped Storage Globally Rick Miller HDR/DTA



Pumped Storage Projects Under Construction (MW)





Pumped Storage Preliminary
Permits/Proposed Projects in the US
N
Sentinel Mountain
Duffey Lake 1,150 MW
Banks Lake 1,040 MW
Lake Roosevelt
North Dam
Umtanum Ridge
JD Poole 1,120 MW
Little Potlatch Creek 1,340 MW
Summer Lake
Swan Lake North
Corral Creek South
Square Butte
Gordon Butte
Klamath County 1,000 MW
Bryant Mountain
Division Canyon
Champion Ridge
Loomis Creek
North Eden
Iowa Hill 400 MW
Thousand Springs
Mokelumme
Hoppie Canyon
Long Canyon
Mulqueeney Ranch
Red Mountain Bar 1,000 MW
South Slope
Kings River
Bull Canyon
Parker Knoll 1,330 MW
River Mountain
Blue Diamond
Lake Elsinore
San Vicente
Ford Canyon
Cedar Creek
Eagle Mountain 1,300 MW
Alder Canyon 900 MW
Yegua Mesa
Mesa De Los Carros
Wiscasset
Mineville
Ogdensburg
Verplanck
Tomkins Cove
Sparta
WA
OR
CA
NV
ID
MT
WY
UT
CO
AZ
NM
ND
SD
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WV
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NY
MD
DC
DE
NJ
CT
RI
MA
VT
NH
ME
0 250 500 Miles
Legend
Preliminary Permit
Application for Preliminary Permit
Surrendered Projects
Other Active Projects
Top 10 Projects
Map information was compiled from the best available sources. No warranty is made for its accuracy and completeness. ©2010, HDR/DTA Inc.
Sources: Federal Energy and Relicensing Commission http://www.ferc.gov/industries/hydropower.asp , 2010.; Environmental Systems Research Institute Base datasets version 9.3, 2008.

Compressed Air Storage

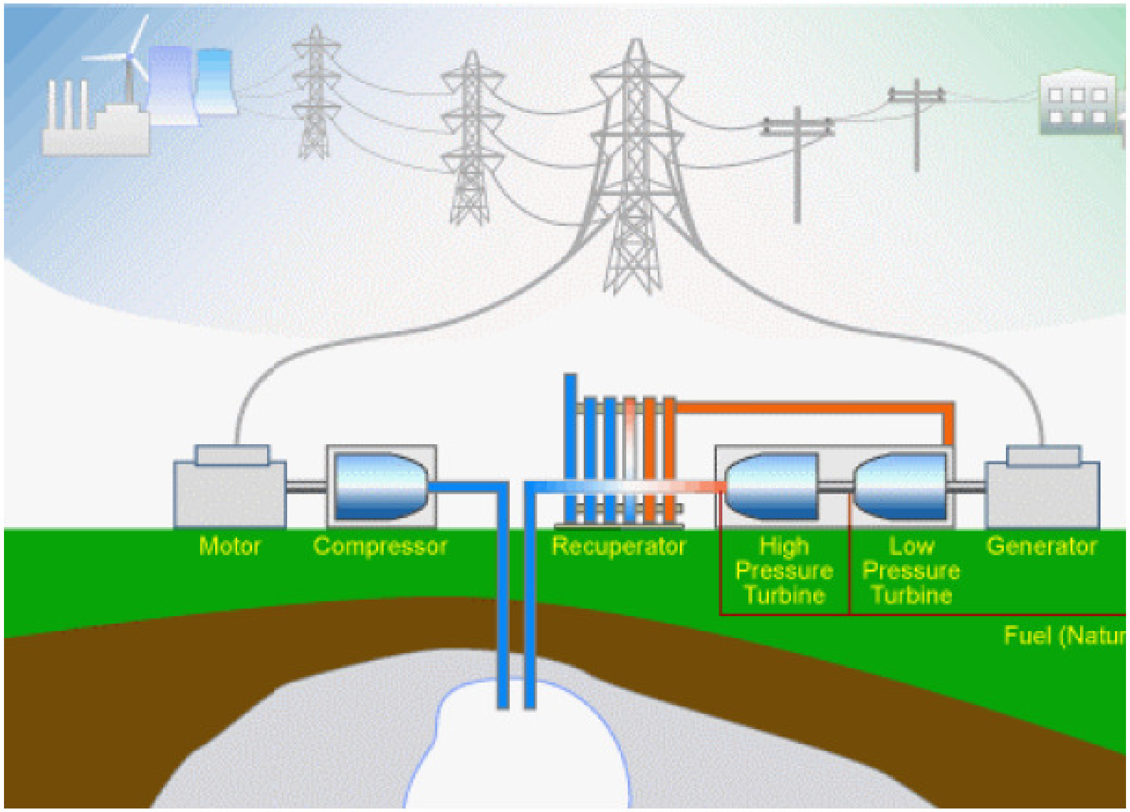
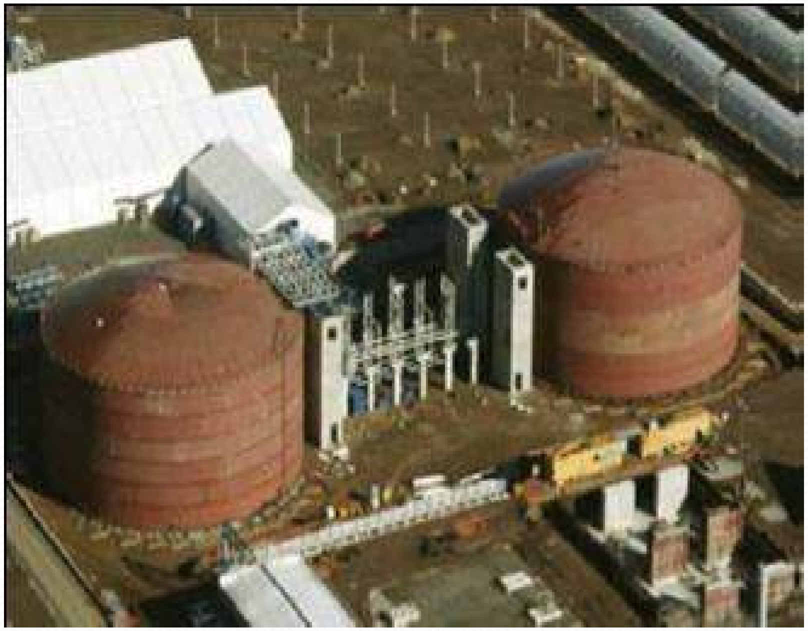
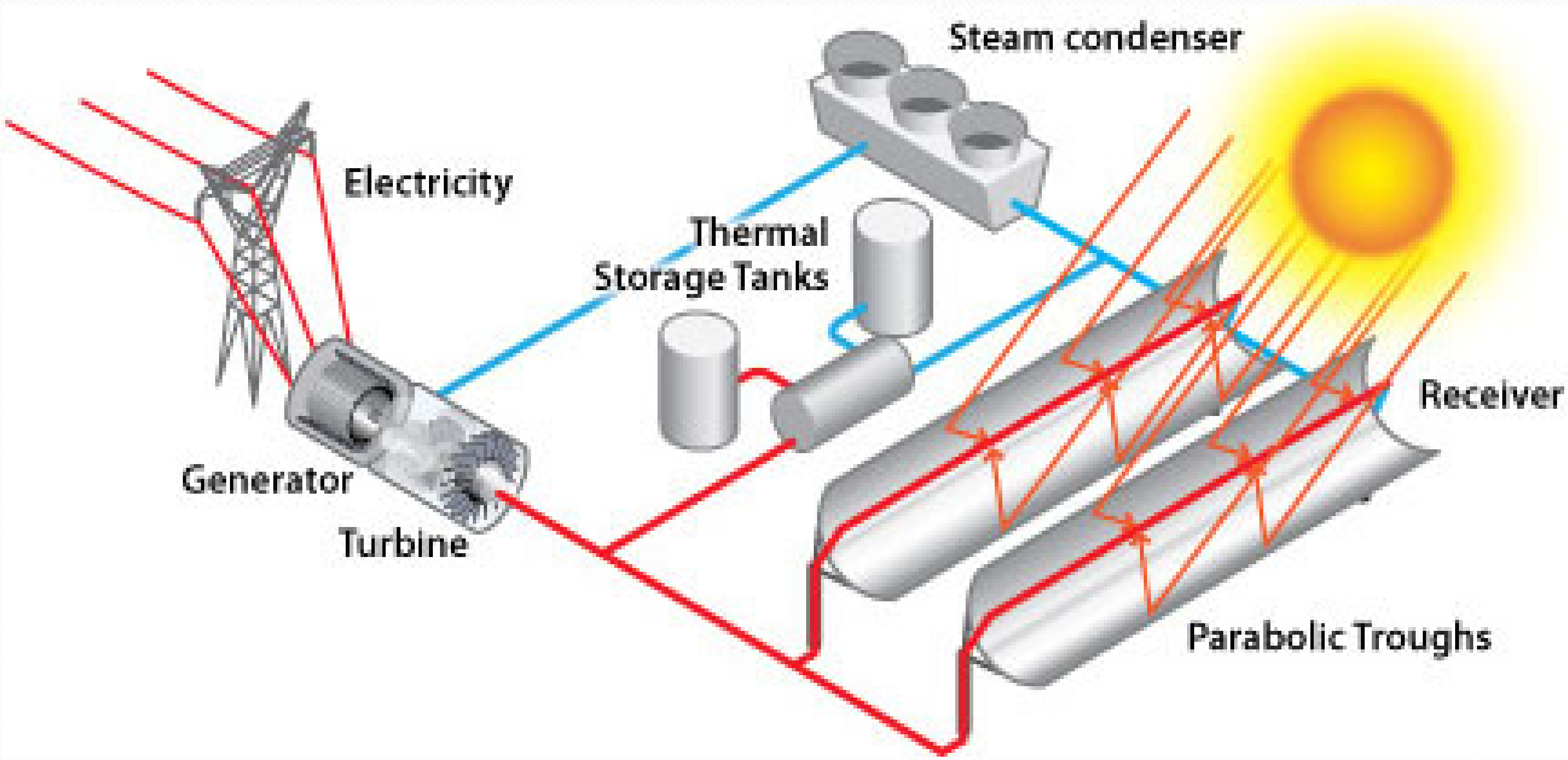


Figure 2: Generic diagram of CAES operation [16]

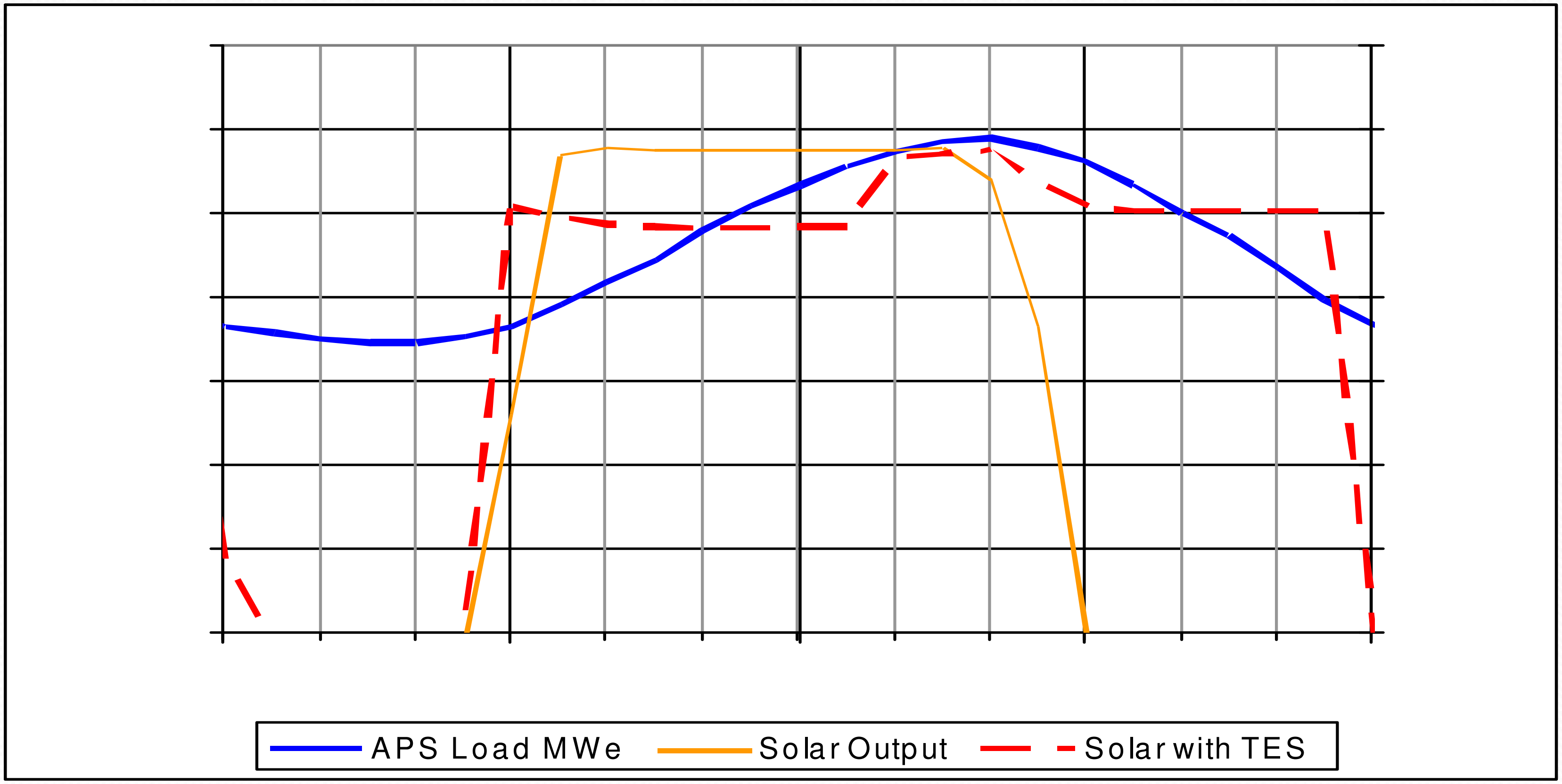
Solar Thermal Energy Storage



Typical layout of power plant with two-tank storage



Solar Energy with Thermal Storage



The cost per kilowatt-hour of concentrated solar thermal power is estimated by the US National Renewable Energy Laboratory (NREL) in Golden, Colorado, at about $0.17.

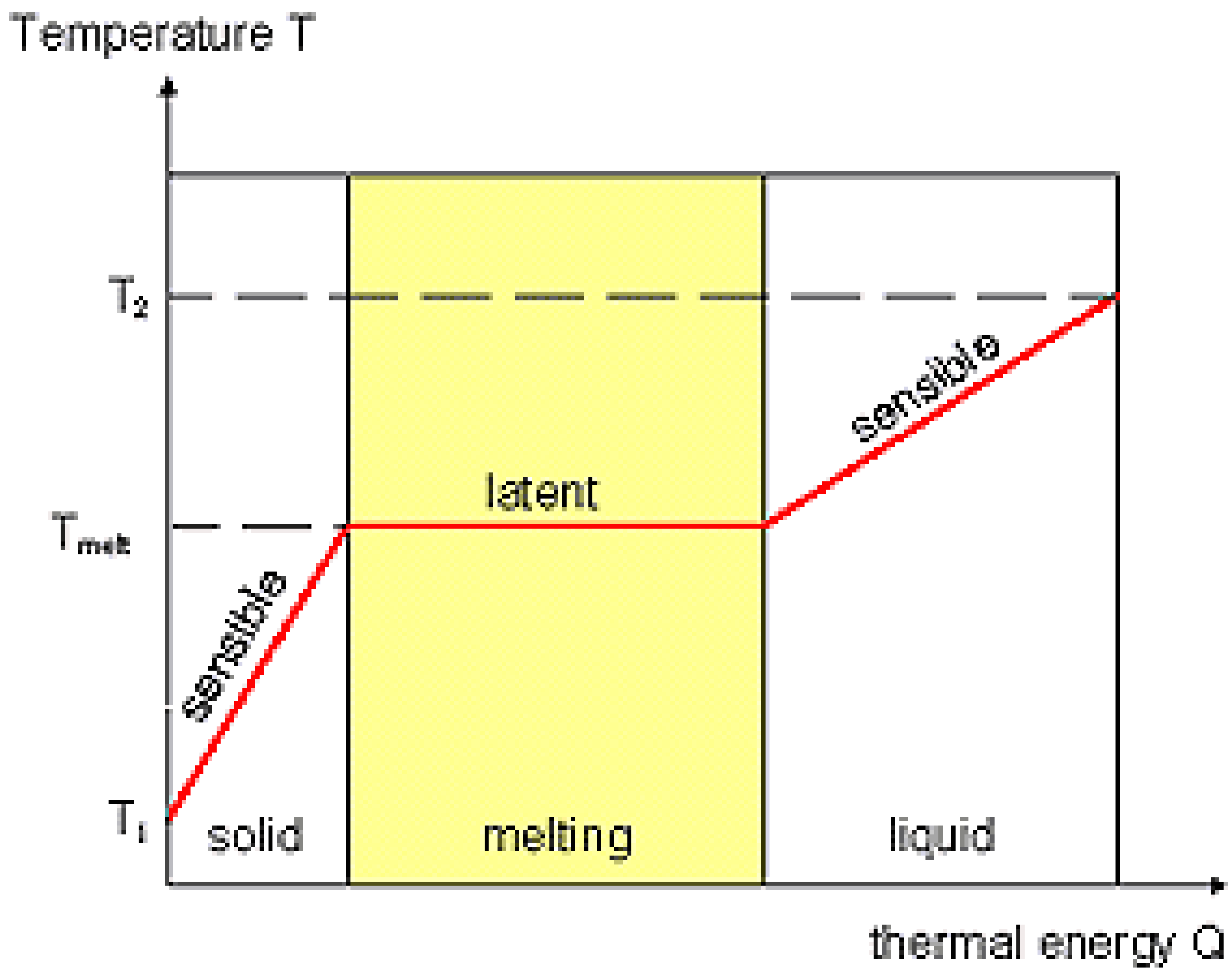
Thermal Storage

Thermal Energy may be stored

A. As *Sensible heat* – temperature change of storage material,

B. As *Latent heat* – isothermal phase change of storage material (melting, freezing, vaporization, fusion and crystallization)

C. As *Heat ofreaction (thermochemical)* – storage material undergoes a reversible thermochemical reaction



Temperature vs. Thermal Energy for a material undergoing a phase change

Physical Properties of Sensible Storage Materials

Storage Medium	Temperature		Average density	Average heat conduct-ivity	Average heat capacity	Volume specific heat capacity	Media costs per kg	Media costs per kWh_t
	Cold (°C)	Hot (°C)	(kg/m^3)	(W/mK)	(kJ/kgK)	(kWh_t/m^3)	($/kg)	($/$kWh_t$)
Solid media								
Sand-rock-mineral oil	200	300	1,700	1.0	1.30	60	0.15	4.2
Reinforced concrete	200	400	2,200	1.5	0.85	100	0.05	1.0
NaCl (solid)	200	500	2,160	7.0	0.85	150	0.15	1.5
Cast iron	200	400	7,200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7,800	40.0	0.60	450	5.00	60.0
Silica fire bricks	200	700	1,820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1,200	3,000	5.0	1.15	600	2.00	6.0
Liquid media								
Mineral oil	200	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil	250	350	900	0.11	2.3	57	3.00	43.0
Silicone oil	300	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts	250	450	1,825	0.57	1.5	152	1.00	12.0
Nitrate salts	265	565	1,870	0.52	1.6	250	0.70	5.2
Carbonate salts	450	850	2,100	2.0	1.8	430	2.40	11.0
Liquid sodium	270	530	850	71.0	1.3	80	2.00	21.0

(Source: Geyer 1991)

Physical Properties of Latent Storage Materials

Storage Medium	Temperature Cold (°C)	Temperature Hot (°C)	Average density (kg/m³)	Average heat conductivity (W/mK)	Average heat capacity (kJ/kgK)	Volume specific heat capacity (kWh_t/m^3)	Media costs per kg ($/kg)	Media costs per kWh_t ($/$kWh_t$)
Phase change media								
$NaNo_3$	308		2,257	0.5	200	125	0.20	3.6
KNO_3	333		2,110	0.5	267	156	0.30	4.1
KOH	380		2,044	0.5	150	85	1.00	24.0
Salt-ceramics ($NaCo_3$-$BaCO_3$/MgO)	500-850		2,600	5.0	420	300	2.00	17.0
NaCl	802		2,160	5.0	520	280	0.15	1.2
Na_2CO_3	854		2,533	2.0	276	194	0.20	2.6
K_2CO_3	897		2,290	2.0	236	150	0.60	9.1

(Source: Geyer 1991)

Thermochemical Storage Reactions

Reaction	ΔHº (kJ)	T' (K)
$NH_4F(s) \leftrightarrow NH_3(g) + HF(g)$	149.3	499
$Mg(OH)_2(s) \leftrightarrow MgO(s) + H_2O(g)$	81.1	531
$MgCO_3(s) \leftrightarrow MgO(s) + CO_2(g)$	100.6	670
$NH_4HSO_4(l) \leftrightarrow NH_3(g) + H_2O(g) + SO_3(g)$	337.0	740
$Ca(OH)_2(s) \leftrightarrow CaO(s) + H_2O(g)$	109.3	752
$BaO_2(s) \leftrightarrow BaO(s) + \frac{1}{2}O_2(g)$	80.8	1000
$LiOH(l) \leftrightarrow \frac{1}{2}Li_2O(s) + \frac{1}{2}H_2O(g)$	56.7	1000
$CaCO_3(s) \leftrightarrow CaO(s)\ CO_2(g)$	178.1	1110
$MgSO_4 \leftrightarrow MgO(s) + SO_3(g)$	287.6	1470

(Source: Wyman, year)

TES Options for Solar Thermal Power	Temp. (℃)	Storage Medium	Type
Small power plants and water pumps			
Organic Rankine	100	Water in thermocline tank or two tanks	sensible
	300	Petroleum oil in thermocline tank	sensible
Steam Rankine with organic fluid receiver	375	Synthetic oil with trickle charge	sensible
Dish mounted engine generators (buffer storage only)			
Organic Rankine	400	Bulk PCM with indirect HX	latent
Stirling and air Brayton	800	Bulk PCM with indirect HX	latent
Advanced air Brayton	1370	Graphite	sensible
		Encapsulated PCM	latent
Larger Power Plants (typically 3 - 8 hrs storage)			
Steam Rankine with organic fluid receiver	300	Petroleum oil in thermocline tank or two tanks, evaporation only	sensible
		Petroleum oil/rocks (dual medium) in thermocline tank	sensible
Steam Rankine with water-steam receiver	300	Petroleum oil in thermocline tank or two tanks, evaporation only	sensible
		Petroleum oil/rocks (dual medium) in thermocline tank	sensible
		Encapsulated PCM with evaporative HX	latent
		Bulk PCM with indirect HX	latent
		Bulk PCM with direct HX	latent
		Pressurized water above ground or underground	latent
	540	Molten draw salt in thermocline tank or two tanks, superheat	sensible
		Air/rocks	sensible
		Bulk PCM with direct HX, evaporation stage	latent
		Solid or liquid decomposition, evap stage	thermochemical
Steam Rankine w/ molten draw salt receiver	540	Molten draw salt in thermoline tank or two tanks	sensible
Steam Rankine with liquid metal receiver	540	Liquid sodium in one tank, mixed, buffer only	sensible
		Liquid sodium in two tanks	sensible
		Air/rocks	sensible
Brayton with gas-cooled reciever	800	Refractory or cast-iron chequirworks in pressure vessel	sensible
		Bulk PCM with indirect HX	latent
		Solid or liquid decomposition	thermochemical
Brayton with liquid-cooled receiver	800	VHT molten stalt in two tanks	sensible
		VHT molten salt/refractory (dual medium) in thermocline tank	sensible
	1100	Bulk glassy slag, liquid and solid bead storage, direct HX	sensible & latent

Batteries

1. Lead Acid
2. Metal Hydride
3. Li –Ion
4. Na S
5. Vanadium Redox –Flow

	Lead-acid	NaS	Li-ion	Vanadium redox
Chemistry Anode Cathode Electrolyte	Pb PbO_2 H_2SO_4	Na S β-alumina	C $LiCoO_2$ Organic solvent	$V^{2+} \leftrightarrow V^{3+}$ $V^{4+} \leftrightarrow V^{5+}$ H_2SO_4
Cell Voltage Open circuit Operating	2.1 2.0-1.8	2.1 2.0-1.8	4.1 4.0-3.0	1.2
Specific Energy & Energy density Wh/kg Wh/L	10-35 50-90	133-202 285-345	150 400	20-30 30
Discharge Profile	Flat	Flat	Sloping	Flat
Specific Power W/kg	Moderate 35-50	High 36-60	Moderate 80-130	High 110
Cycle life, cycles	200-700	2500-4500	1000	12,000
Advantages	Low cost, good high rate	Potential low cost, high cycle life, high energy and good power density, high energy efficiency	High specific energy and energy density, low self discharge, long cycle life	High Energy, high efficiency, high charge rate, low replacement costs
Limitations	Limited energy density, Hydrogen evolution	Thermal management, safety, durable seals, freeze-thaw durability	Lower rate (compared to aqueous system)	Cross mixing of the electrolytes

NaS Battery

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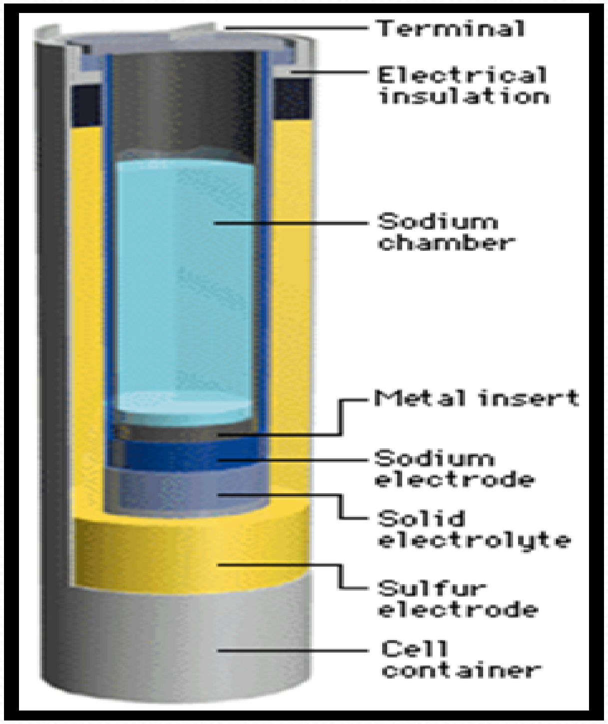
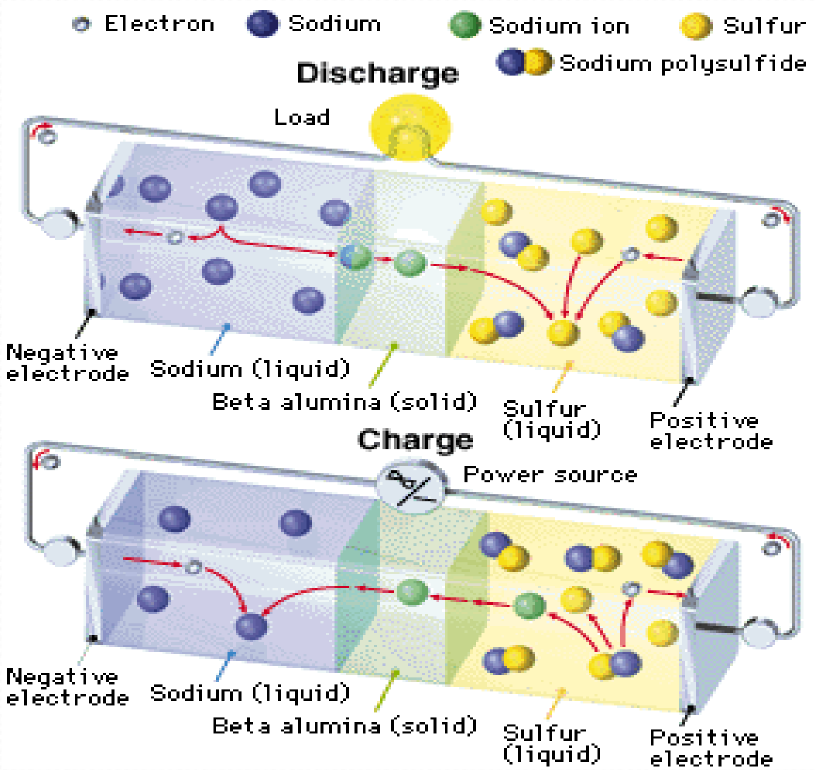


NaS Battery Cell

Diagram of electron and ion motion during discharge and charge cycles.

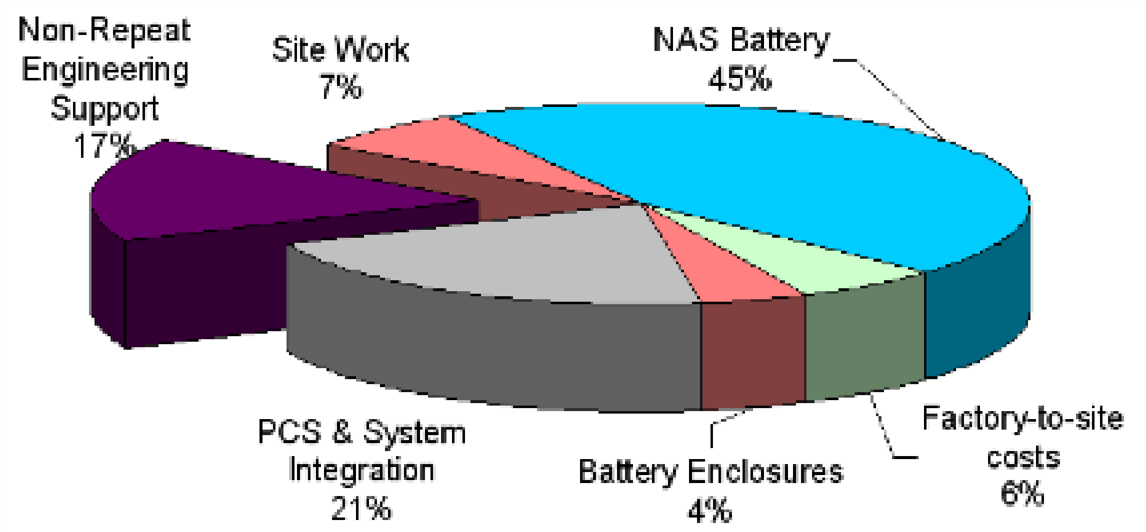


(Courtesy of NGK)

NaS Batteries

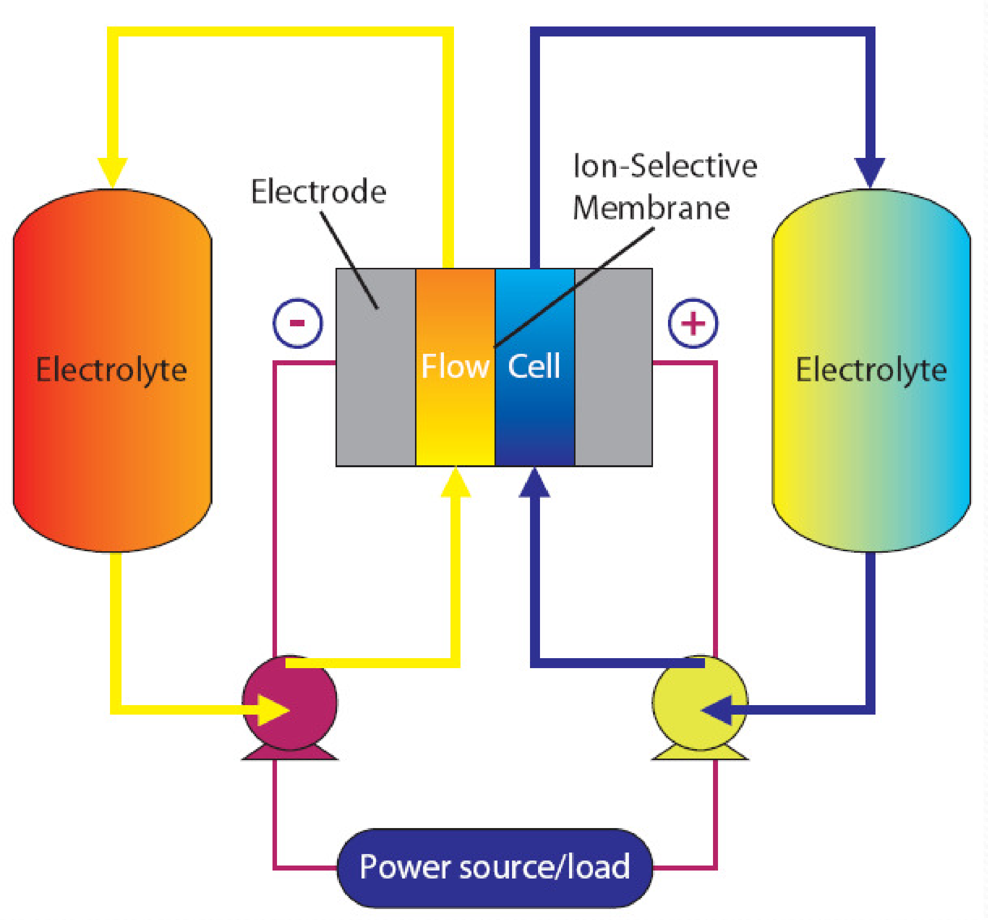
Twenty NaS Batteries installed in four enclosures

NaS Battery Costs

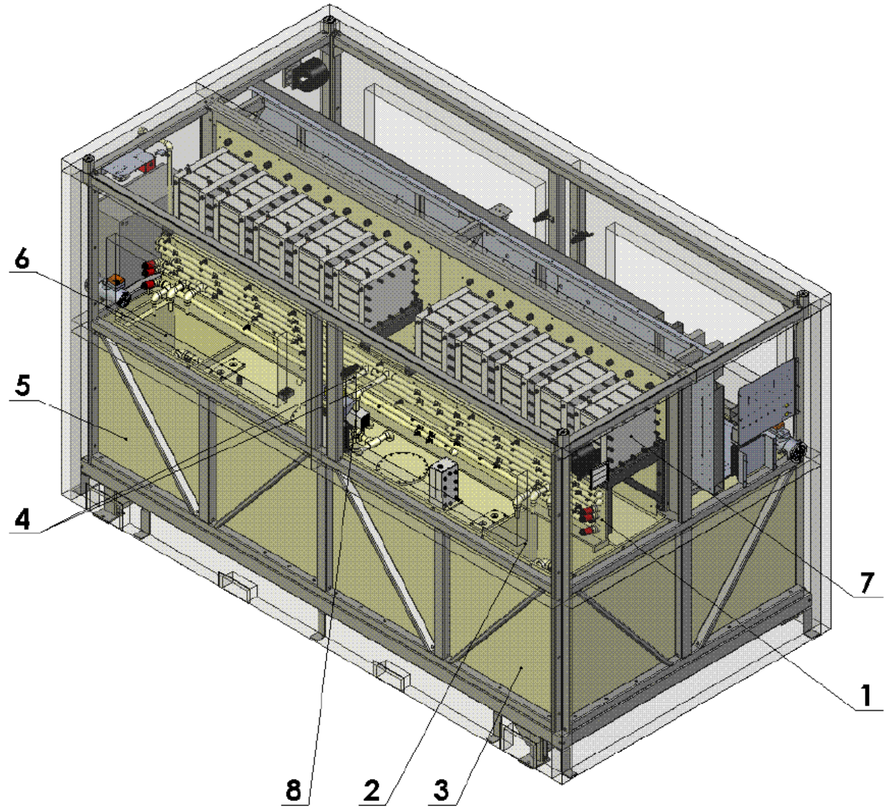


Major cost components for an installed NaS-based DESS

Vanadium Redox Battery



Vanadium Redox Battery



1. *Fluid lines*
2. *Positive electrolyte pumps*
3. *Positive electrolyte tank*
4. *Return lines*
5. *Negative electrolyte tank*
6. *Negative electrolyte pumps*
7. *Stacks (also called cell stacks or modules)*
8. *Rebalance valve.*

FB10/100 Fluid, thermal, safety system.

Source : html://www.cellstrom.com

Capital Costs for Energy Storage

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

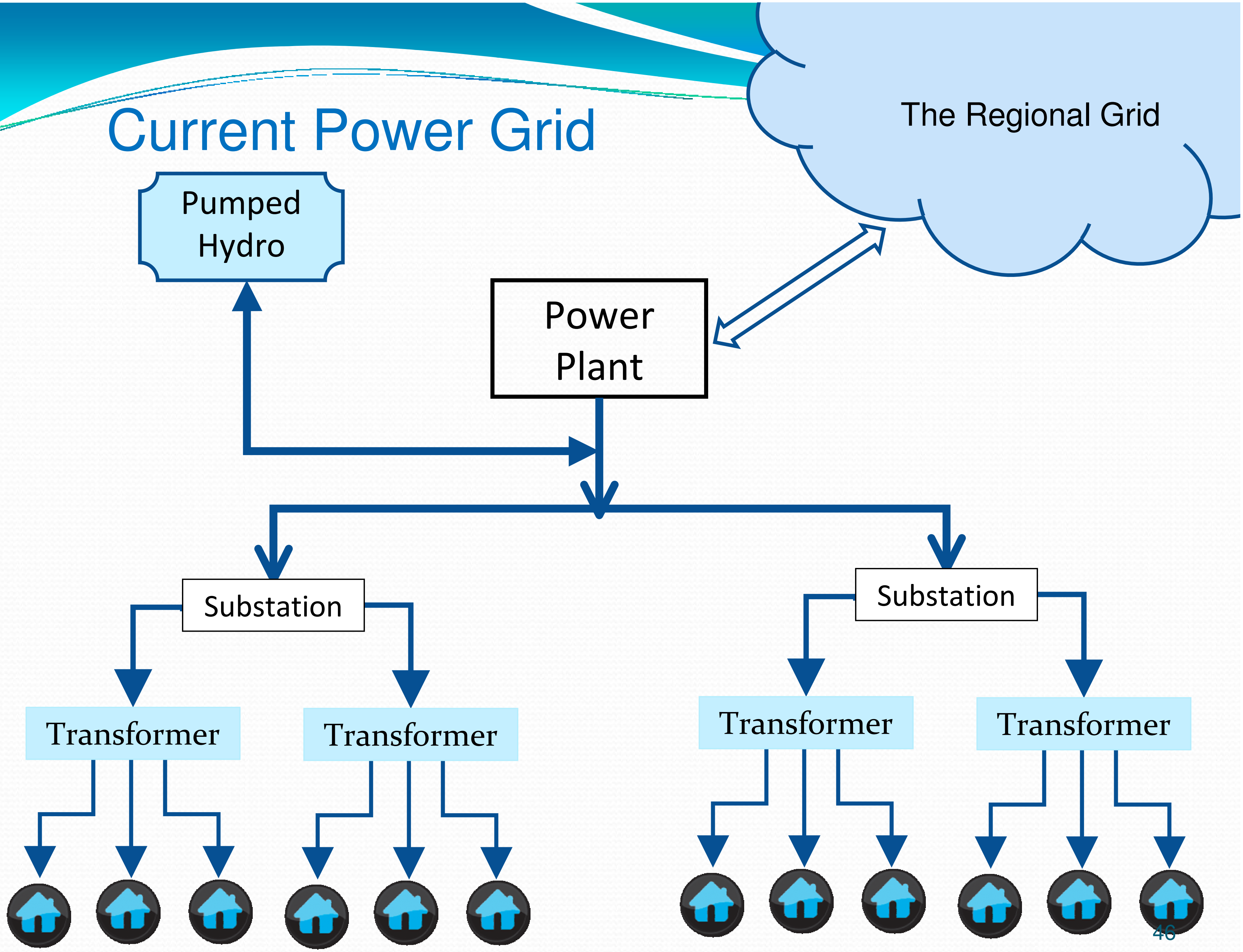
Mobile Battery and Supercapacitor Costs

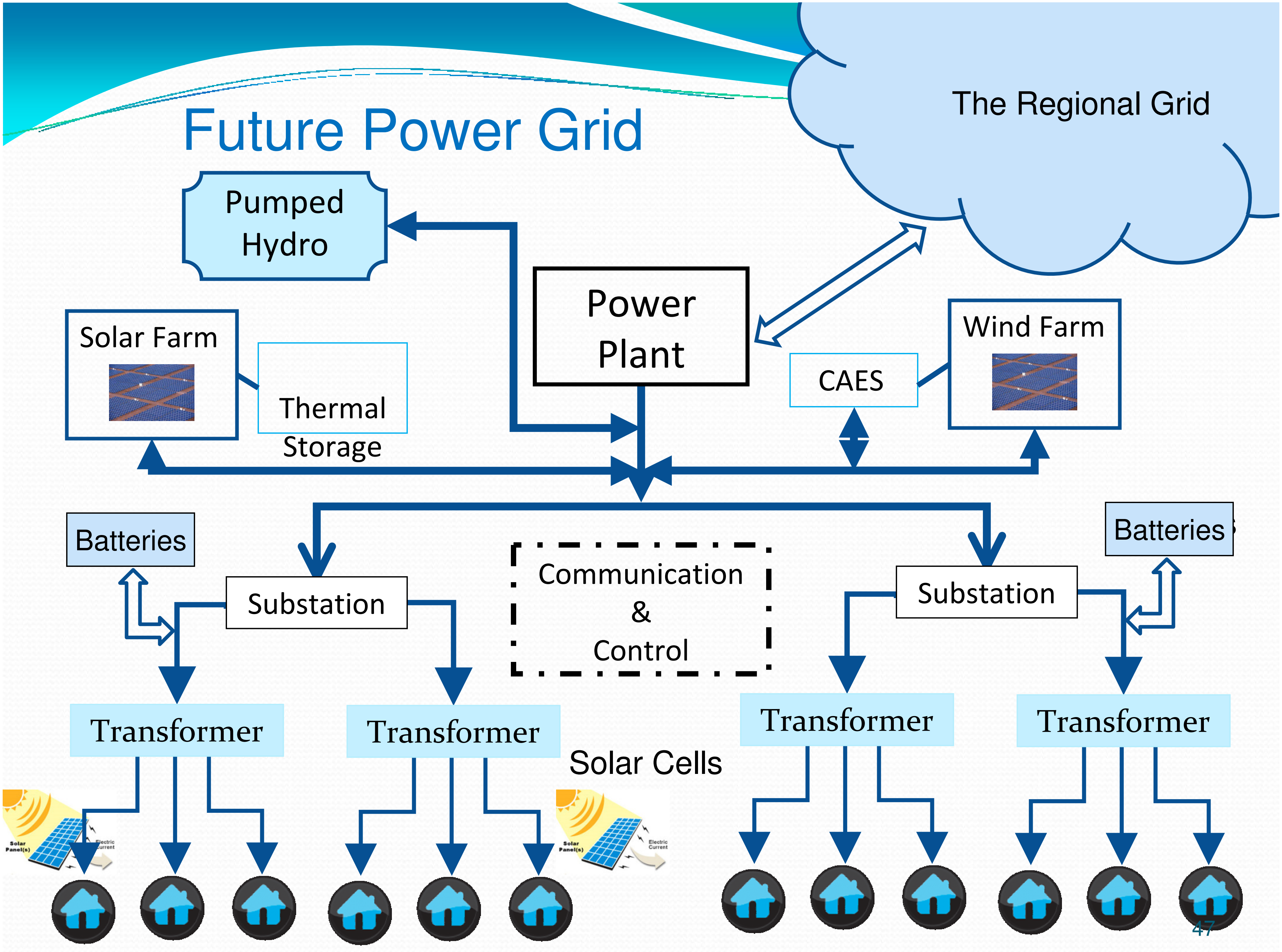
		Capacity Price		*Energy Density*
1. Lead Acid	≈	\$215/KWh	≈	25 Wh/Kg
2. NiM	≈	\$3500/KWh	≈	43 Wh/Kg
3. Li ion	≈	\$1250/KWh	≈	300 Wh/Kg
4. Supercapacitors			≈	4 Wh/Kg

When does Storage Pay ?

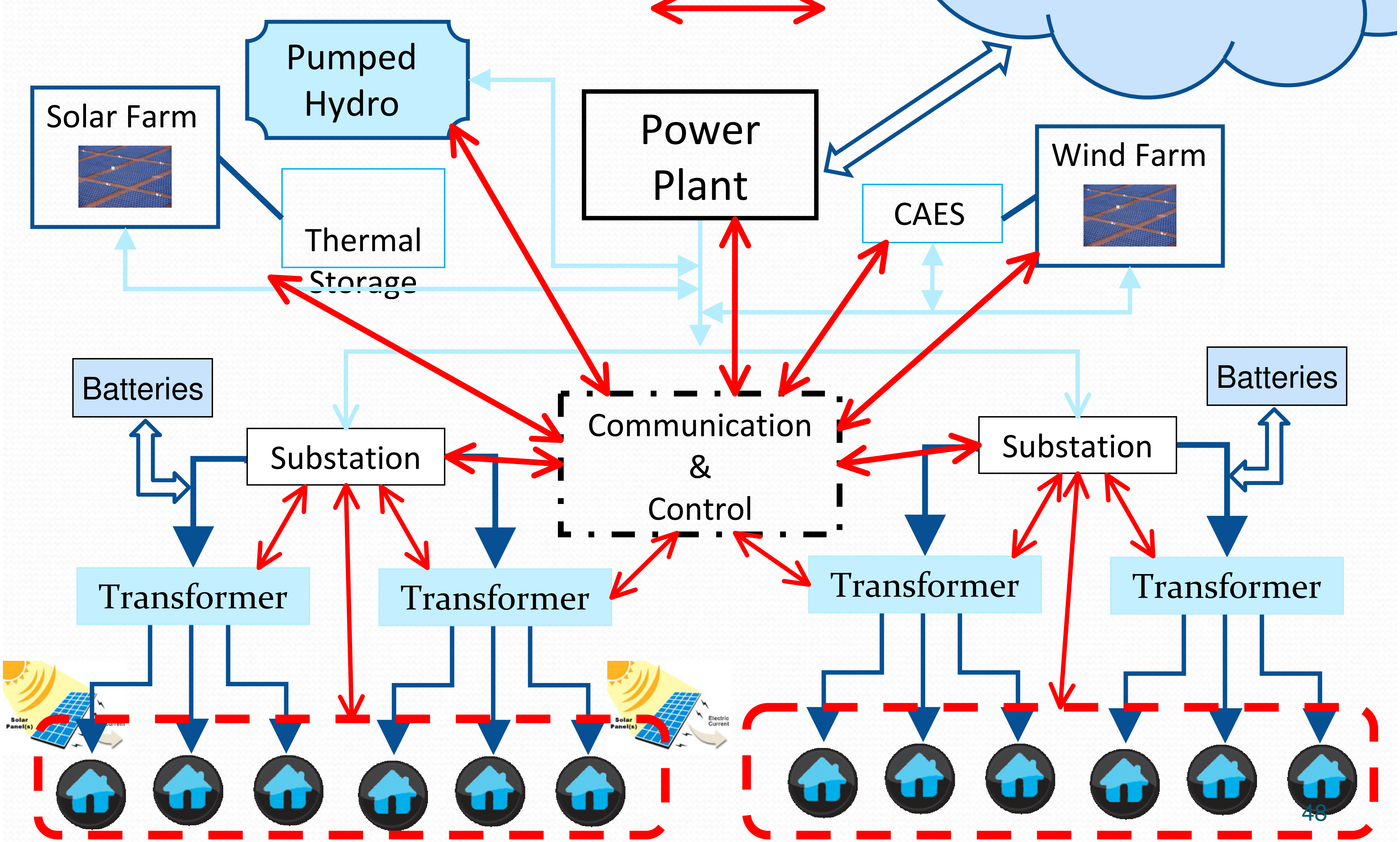
1. It depends on the details, however estimates are in the range of 15% wind energy penetration
2. Thermal Storage seems to pay almost always for large solar thermal systems.

Current Power Grid




Future Power Grid
The Regional Grid
Pumped Hydro
Power Plant
Solar Farm
Thermal Storage
CAES
Wind Farm
Batteries
Substation
Communication & Control
Substation
Batteries
Transformer
Transformer
Solar Cells
Transformer
Transformer

Future Power Grid Communications



Smart Grid Advantages

- Reduced Maintenance Costs, Time to Locate, Manage and Repair Faults
- Mobile Work Force Management
- Automatic Meter Reading
- Demand Response
- Time of Day Pricing, "Smart Homes" Expected reduction in power used approximately 10%

Table S.1. Potential Reductions in Electricity and CO_2 Emissions in 2030 Attributable to Smart Grid Technologies

Mechanism	Reductions in Electricity Sector Energy and CO_2 Emissions[a]	
	Direct (%)	Indirect (%)
Conservation Effect of Consumer Information and Feedback Systems	3	-
Joint Marketing of Energy Efficiency and Demand Response Programs	-	0
Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings	3	-
Measurement & Verification (M&V) for Energy Efficiency Programs	1	0.5
Shifting Load to More Efficient Generation	<0.1	-
Support Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles	3	-
Conservation Voltage Reduction and Advanced Voltage Control	2	-
Support Penetration of Renewable Wind and Solar Generation (25% renewable portfolio standard [RPS])	<0.1	5
Total Reduction	**12**	**6**

(a) Assumes 100% penetration of the smart grid technologies.

Smart Grids Issues

- More than 50 manufactures
  - The communications systems are not compatible.
- Multiple communications systems
- Public, Wireless, Wire-line, Optical Fiber
- Private, Broadband Over the Power Lines, Optical Fiber
- Need for Standards, 17 Standards Committees

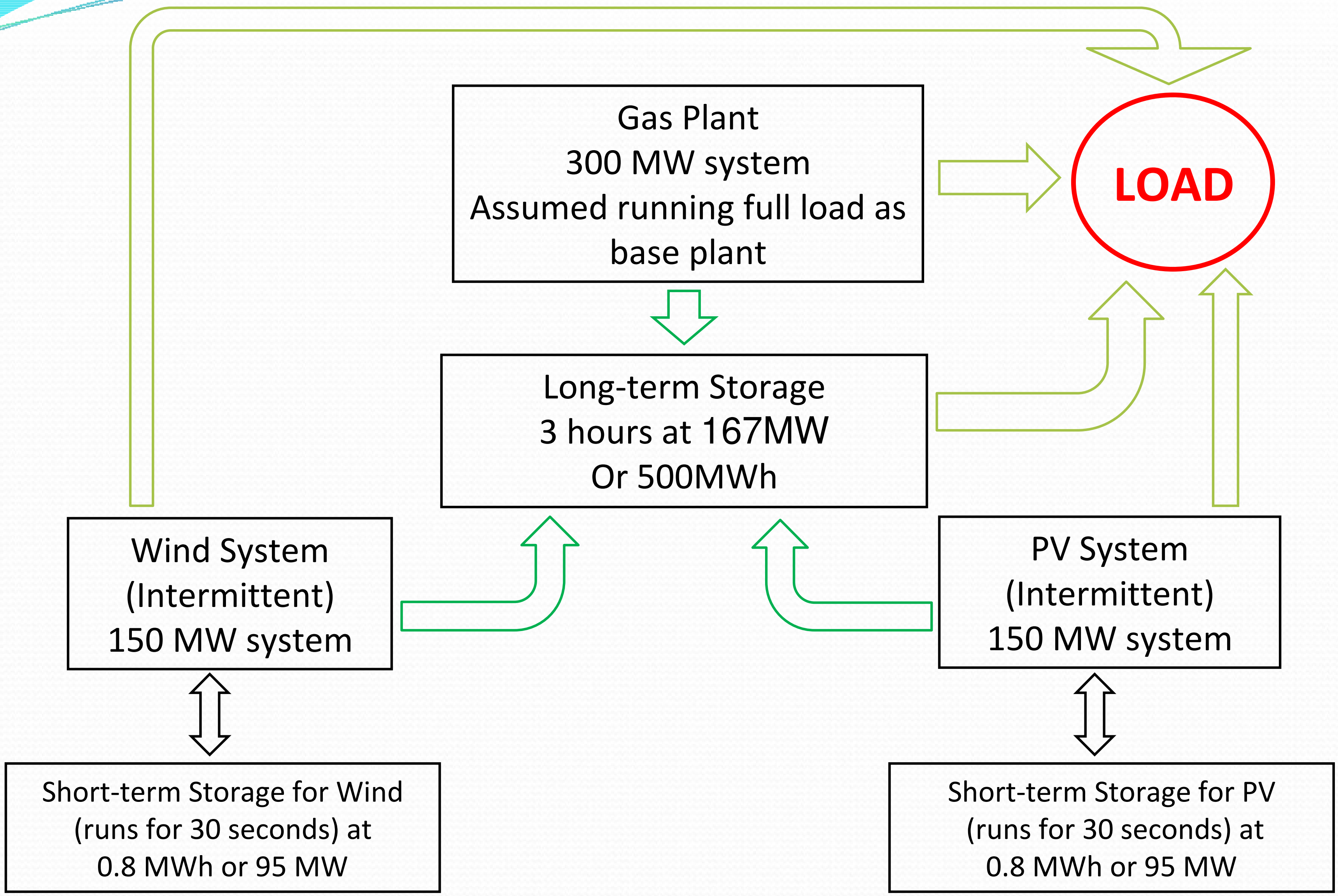
Control Problems

1. Voltage Control
2. Frequency Control
3. Two Way Power Flow
4. Generation of Harmonics
5. Power system Oscillations and Grid Stability
6. Setting up a Communications for a Smart Grid.
7. Security of the Controls.

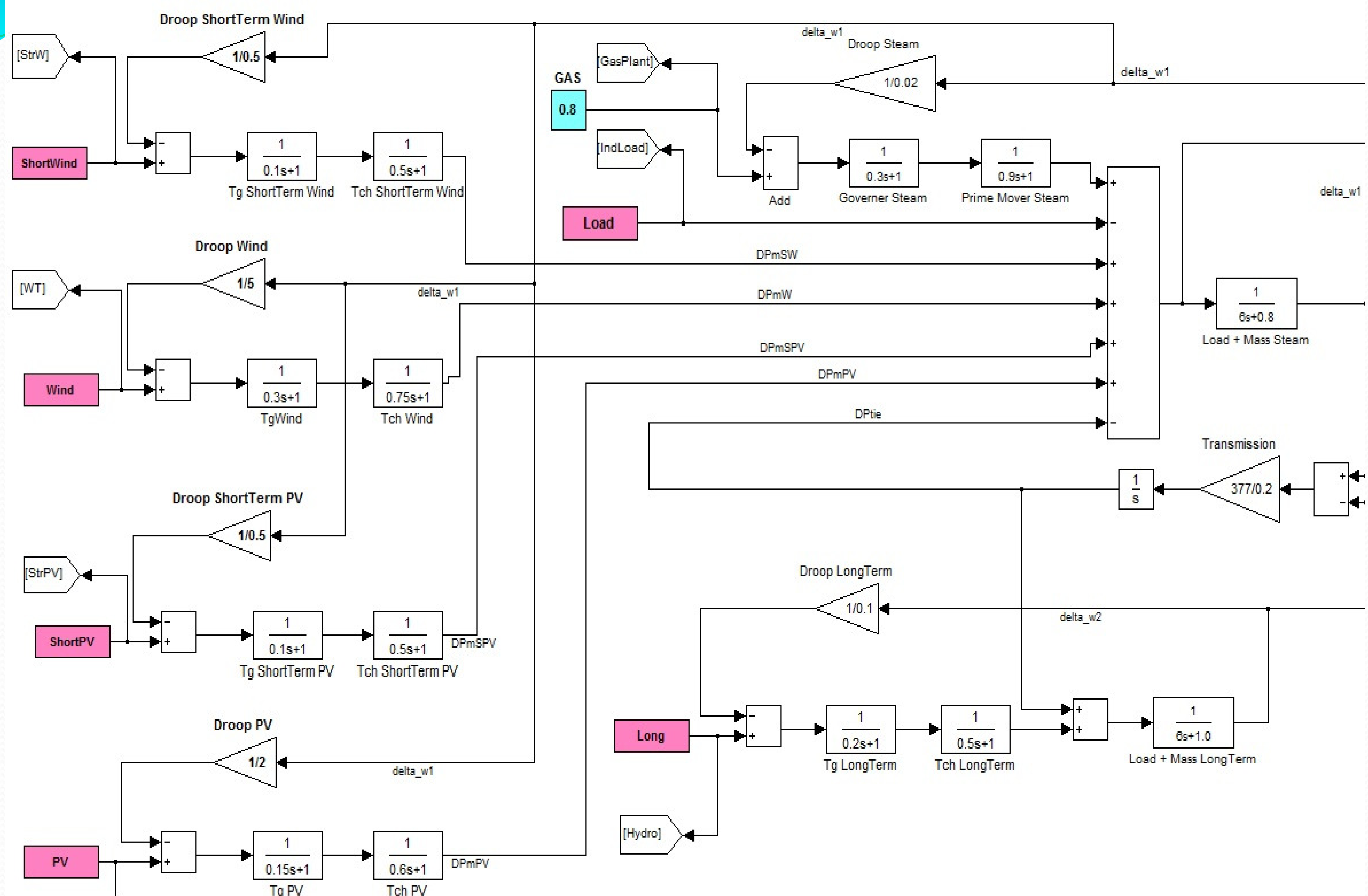
Frequency Response of Interconnected Systems

- IMPORTANT QUESTIONS:
  1. What response times of storage system causes frequency oscillations?
  2. How large frequency oscillations due to fluctuating wind & solar?
  3. What time constants causes unstable systems?
- Simulate Interconnected System with 6 plants:-
  - A gas plant ~300 MW
  - A wind-powered system ~150 MW
  - A solar/PV-powered system ~150 MW
  - Two short-term storage systems (Wind & PV each) ~0.8MWh discharge rate & discharge time = 0.5 minute
  - A long-term storage system e.g. pumped hydro ~500MWh discharge rate & discharge time = 180 minutes (3 hrs)

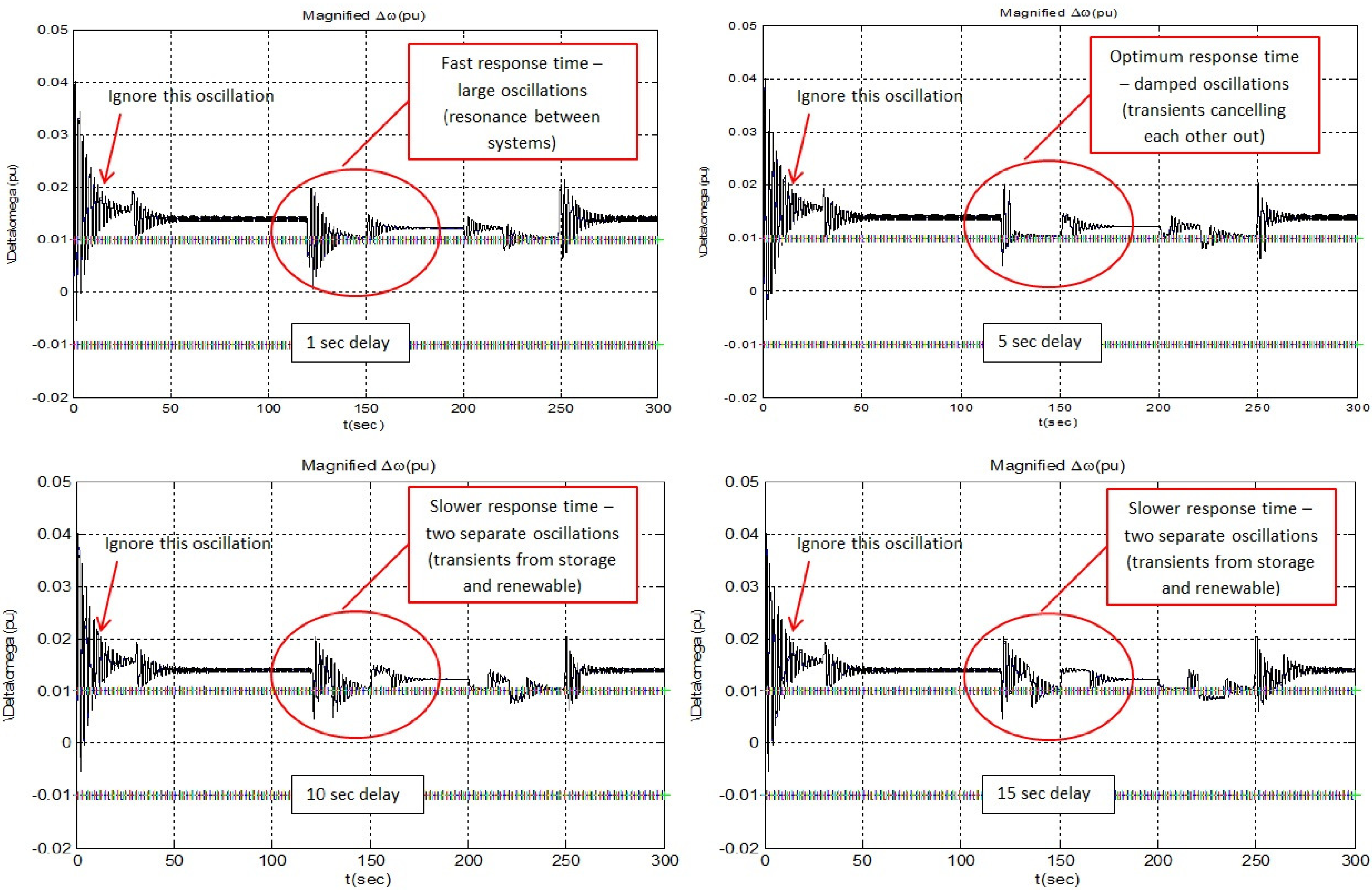
Outline of Interconnected System



Interconnected System with Six Generating Systems:

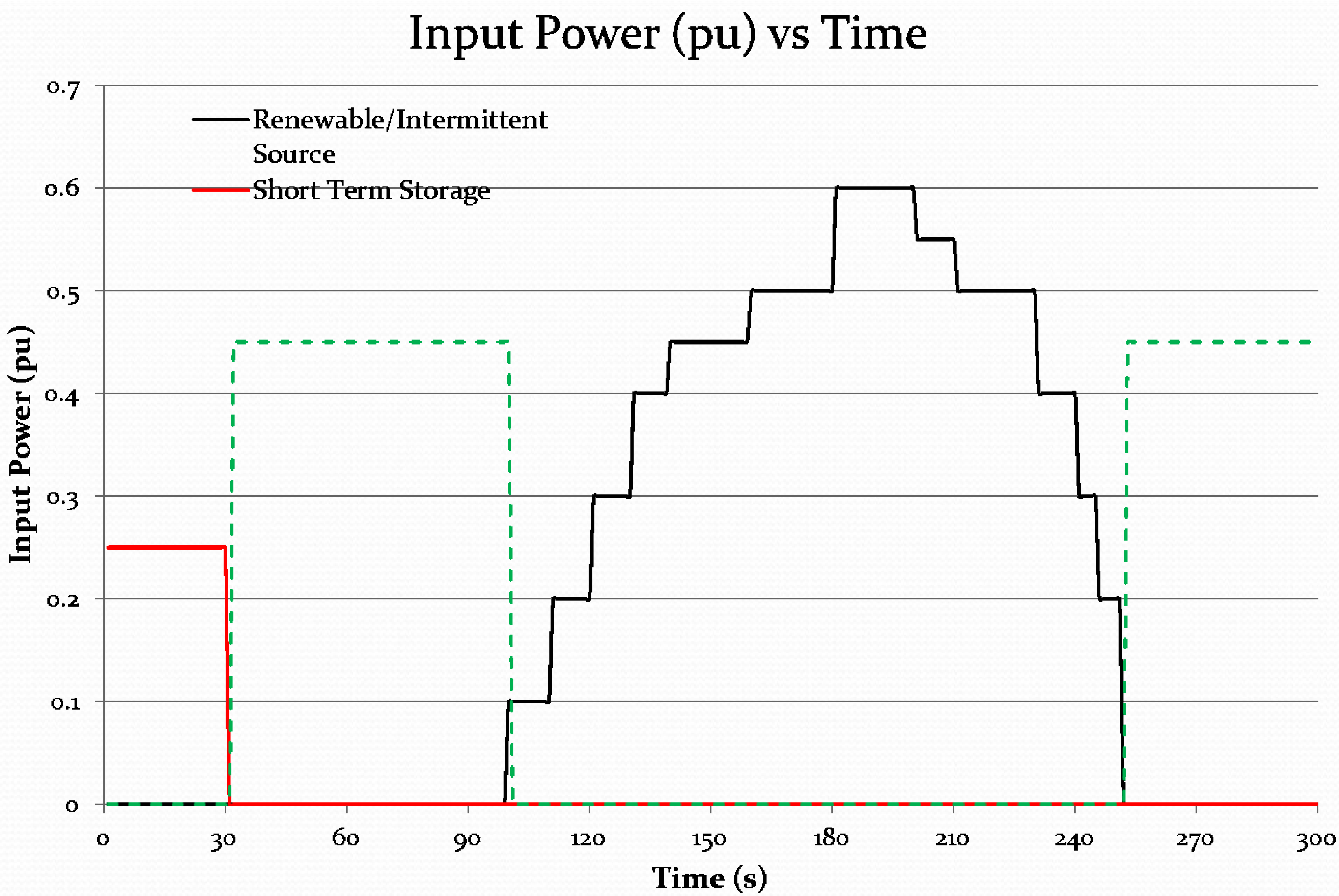


Question 1: Response times ⟵⟶ Frequency Oscillations in System

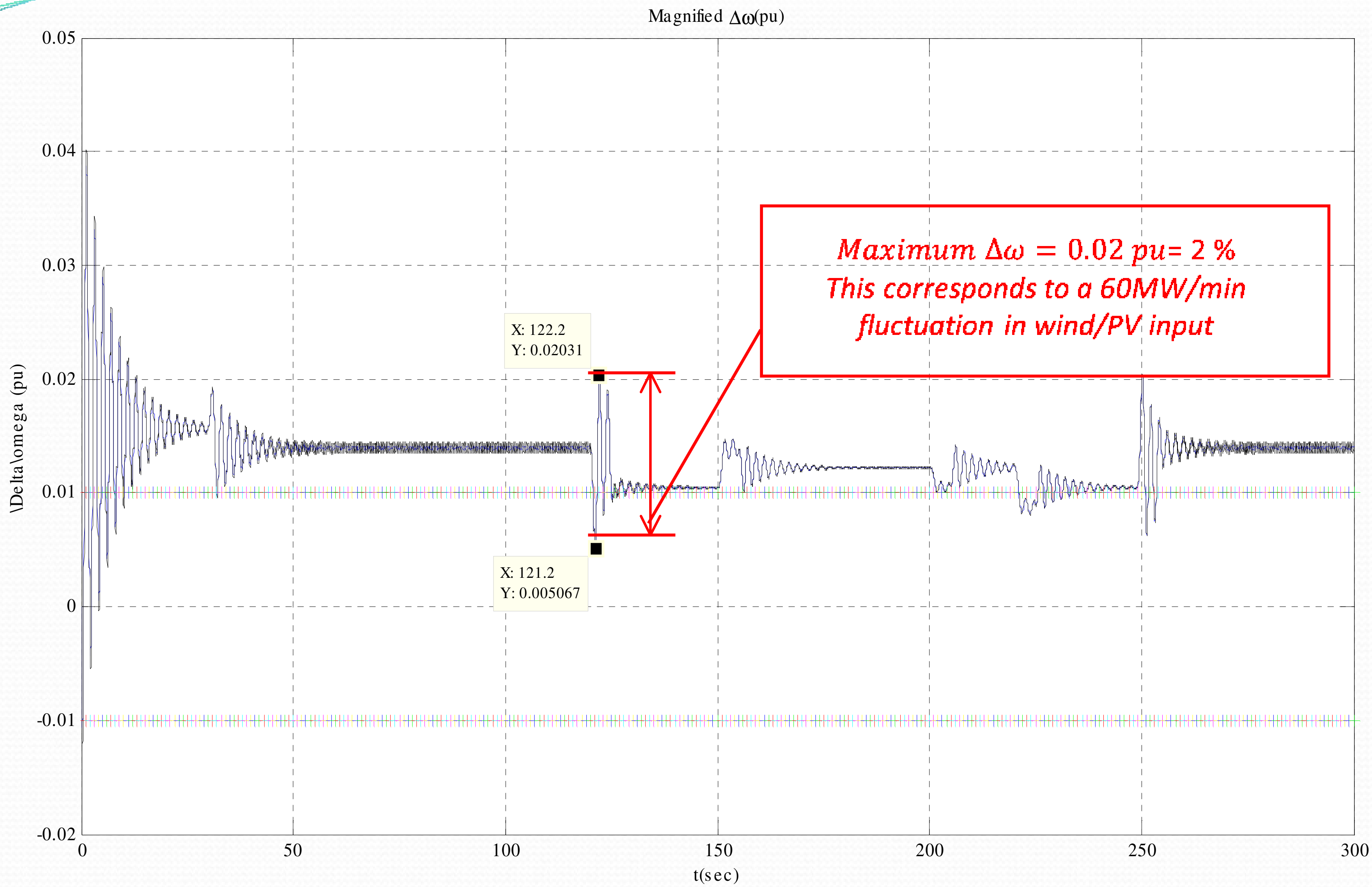


The response time is the time it takes for the short-term storage to replace power drop in wind/PV

Question 2: Frequency Oscillations ↔ Fluctuating Wind/PV



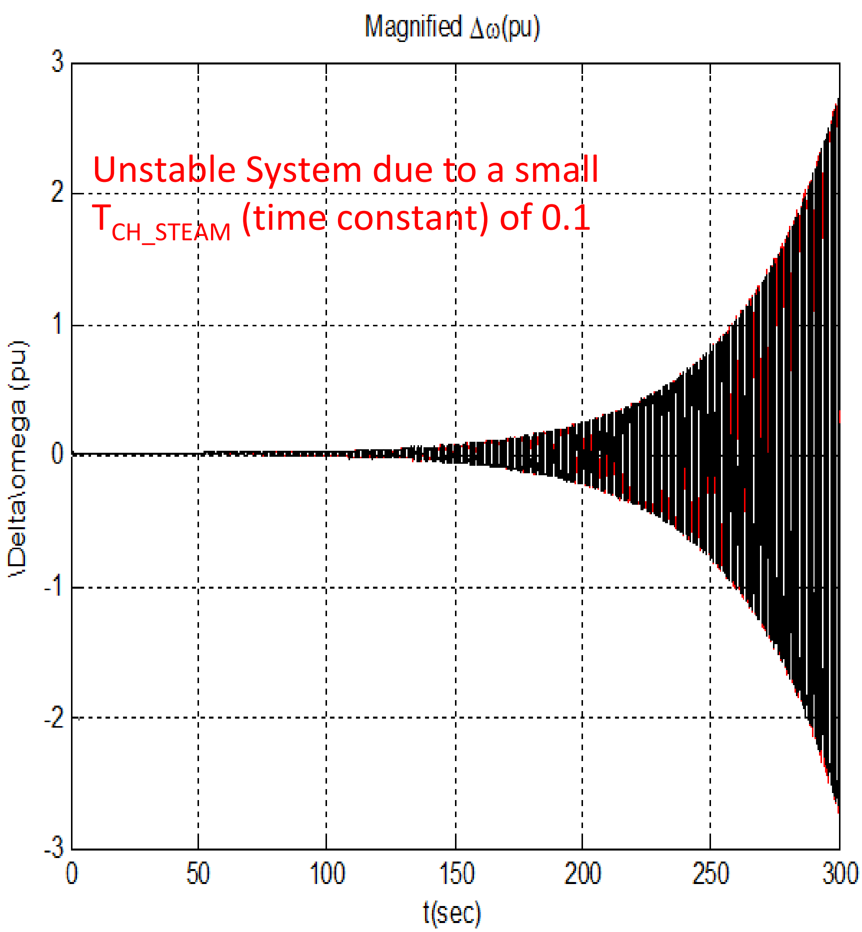
Question 2: Max frequency oscillations <—> Fluctuating Wind/PV

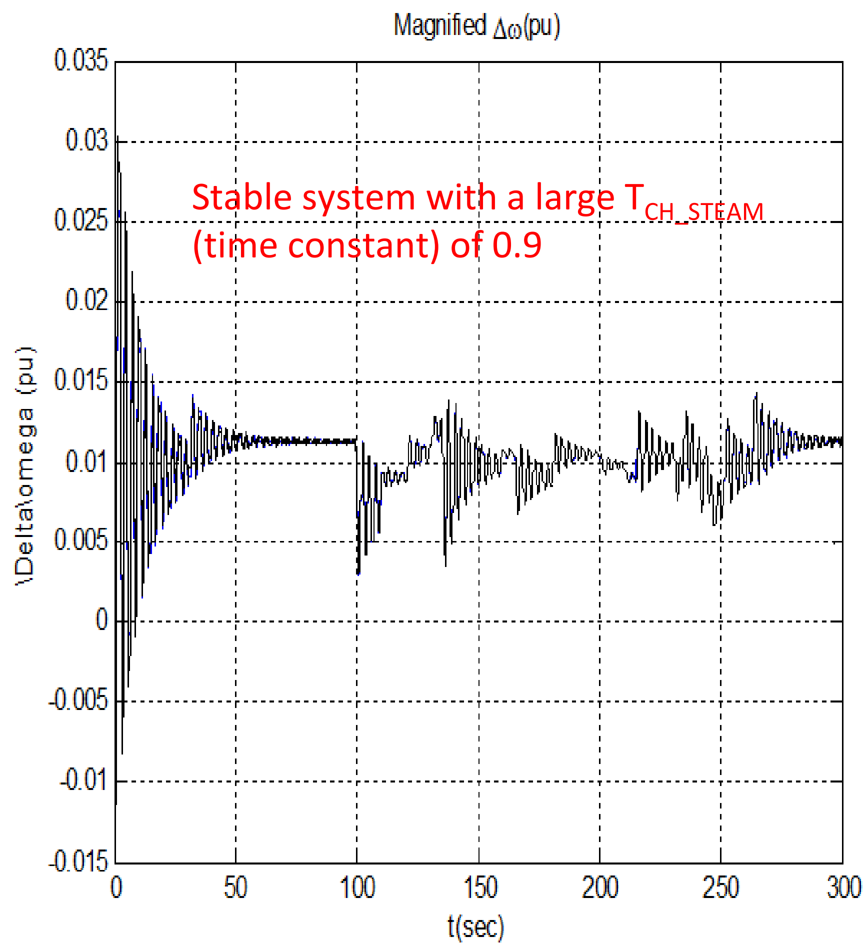


Maximum $\Delta\omega = 0.02\ pu$ = 2 %
This corresponds to a 60MW/min fluctuation in wind/PV input

**Note that the 0 p.u. on y-axis ($\Delta\omega_{system}$) corresponds to 60 Hz.*

Question 3: Unstable systems <—> Changing Time Constants





τ_{CH} is known as the charging time constant , i.e. the time constant that determines how fast the prime mover drives the generator.

$$\frac{d\Delta P_{valve}}{dt} = \frac{\Delta P_{valve} - \Delta P_{mechanical}}{\tau_{CH}}$$

Security Issues

1. You do not want an enemy or a hacker to shut down the electrical grid.
2. Multiple levels of security are needed.
   a. Both physical and electronic security are needed.
   b. Each point of access is a potential point of entry to the system.
3. The system needs to be continuously up graded.
4. You need to be able to locate faults and isolate regions from many new distributed sources.

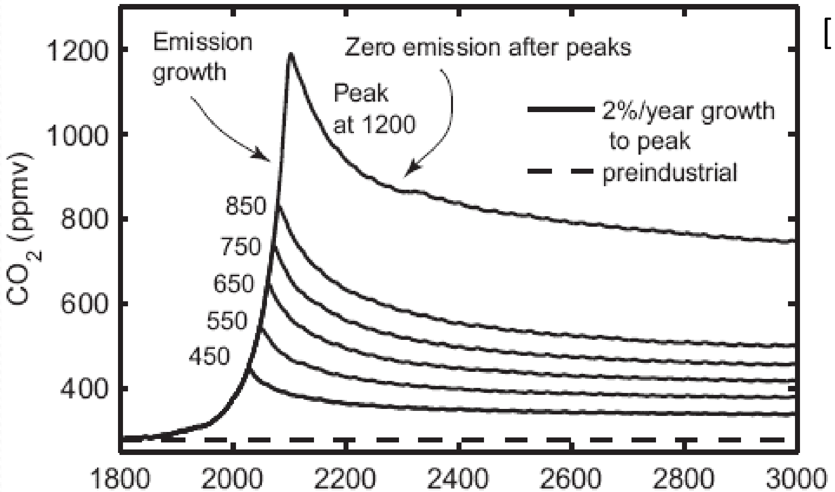
Grid and Cyber Security

1. The present systems are not Secure.
2. Electronic Systems can be hacked
   a. If there is access to the Internet there is world wide access to your system.
   b. If there is Wireless access it is easier to access.
   c. If your system is programmed by someone who wants to cause damage.
   d. If you have a malicious employee or a corruptible one

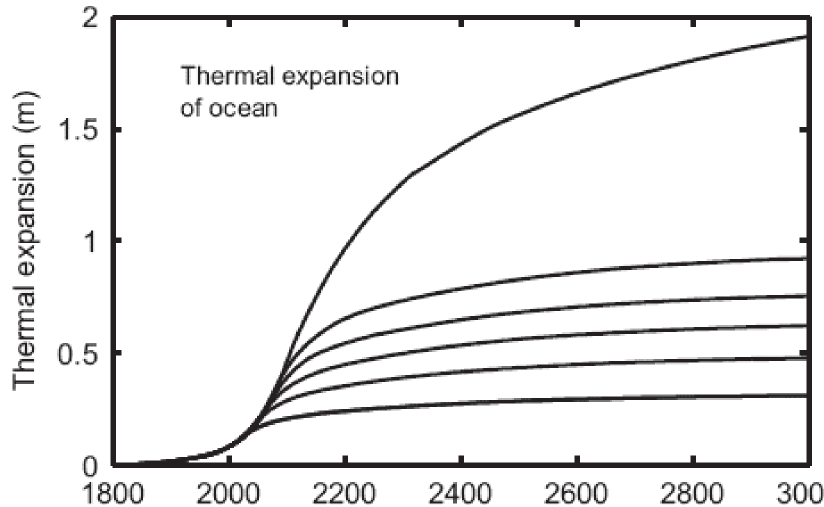
Levels of Security

1. The security level should be multilevel
2. It should increase with the level of potential damage and the risk that some one will try to do the damage.
3. Systems for control of substations, power plants, network element monitoring etc. should be physically isolated from communication systems with customers.
4. Customer communication systems at smart homes should be isolated from each other to avoid cascading.
5. Physical security is important as is having key employees that can be trusted and limiting access to those who need to be there.
6. Security Systems need to be continuously up graded and reviewed.

Carbon & the Electric Utility Sector



[1]



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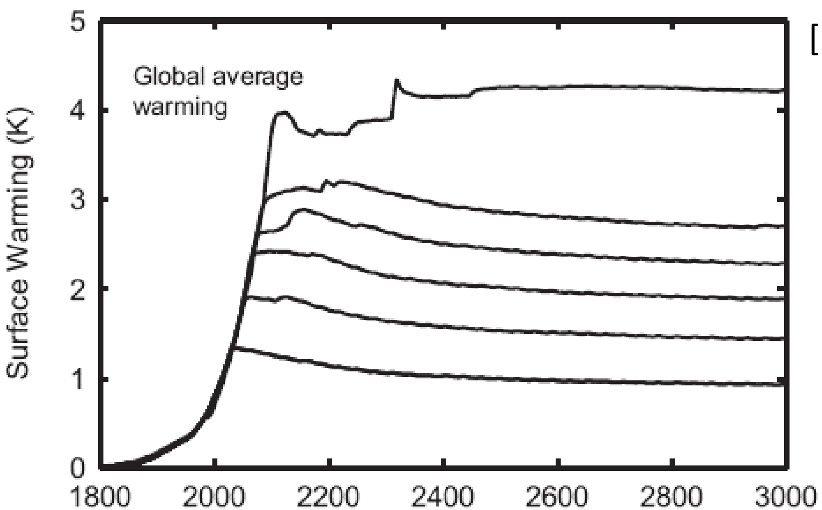

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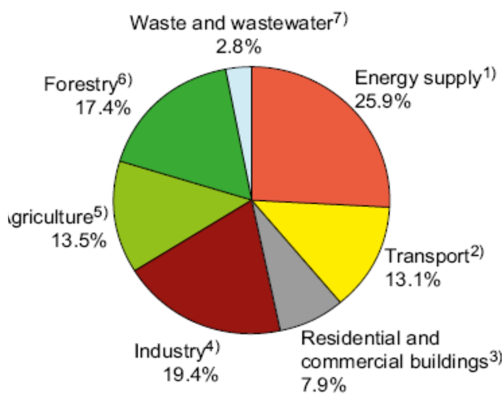


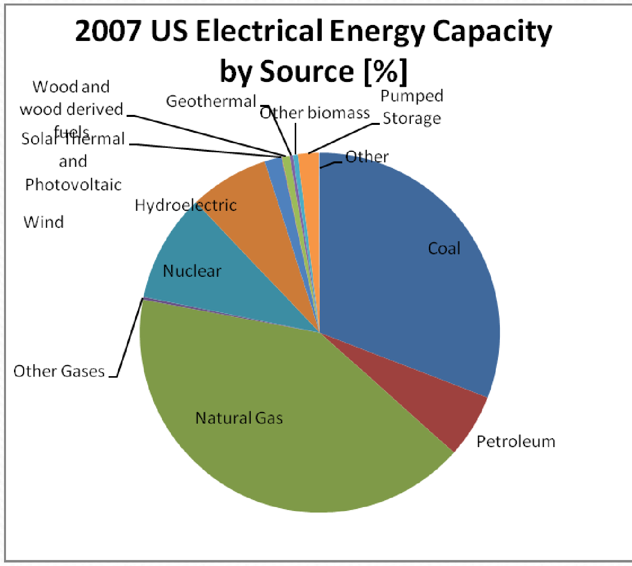
igure TS.2b: *GHG emissions by sector in 2004 [Figure 1.3b].*

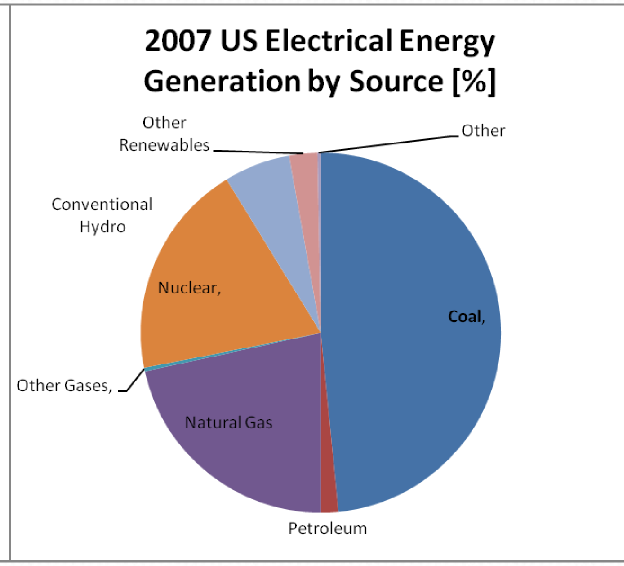
In the U.S. about **41%** of anthropogenic CO_2 emissions were attributed to the combustion of fossil fuels for the generation of electricity in 1998.[2]

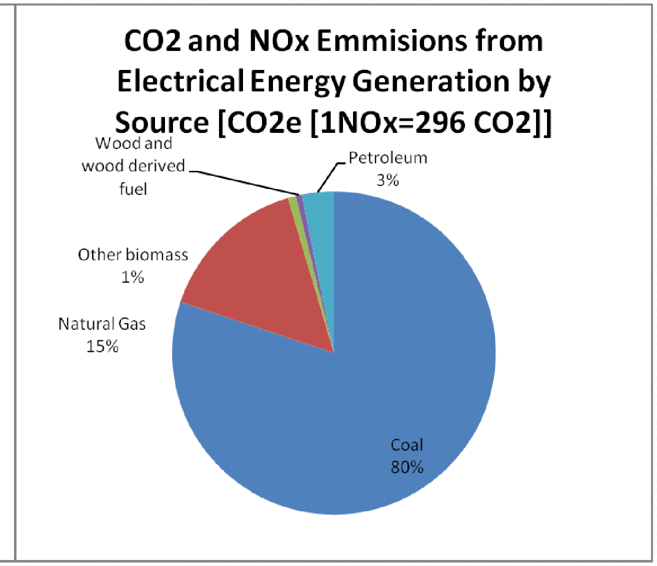
[1] Susan Solomon, Plattner. G, Knutti. R, Friedlingstein. (December 2008). Irreversible climate change due to carbon dioxide emissions. Proceedings National Academy of Science. 10.1073/pnas.0812721106 PNAS February 10, 2009 vol. 106 no. 6 1704-1709

[2] Carbon Dioxide Emissions from the Generation of Electric Power in the United States. (2000). US DOE & EPA. http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html#N_7_#N_7_

High (>20%) Penetration of RE is Critical







Fuel Source	Traditional to RE Fuel Switch Energy to GHG Reduction Ratio
Natural Gas	0.71
Petroleum	2.02
Coal	1.65

Annual US Electric Utility CO_2e Reduction by RPS Energy %