

# The Role of Energy Storage with Renewable Electricity Generation (Report Summary)



**Paul Denholm  
Erik Ela  
Brendan Kirby  
Michael Milligan**

**March 2010**

**NREL/PR-6A2-49396**

# Outline

---

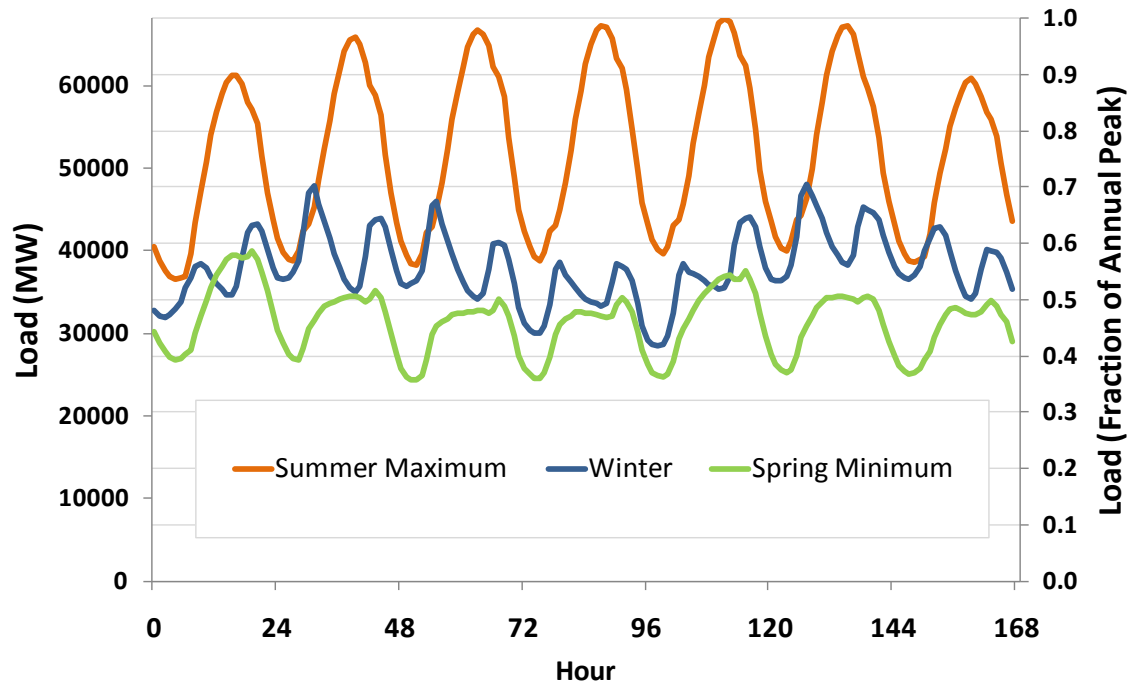
- Operation of the Electric Grid
- Electricity Storage in the Existing Grid
- Impacts of Renewables on the Grid and the Role of Enabling Technologies
- Storage and Flexibility Options for Renewable-Driven Grid Applications
- Conclusions

# Operation of the Electric Grid

---

- Supply must always meet demand
- Large hourly and season variations in electricity demand
- Operating reserve requirements to maintain system stability and reliability

# Large Demand Variability



Hourly electricity demand for three weeks in the ERCOT (Texas) Grid  
in 2005

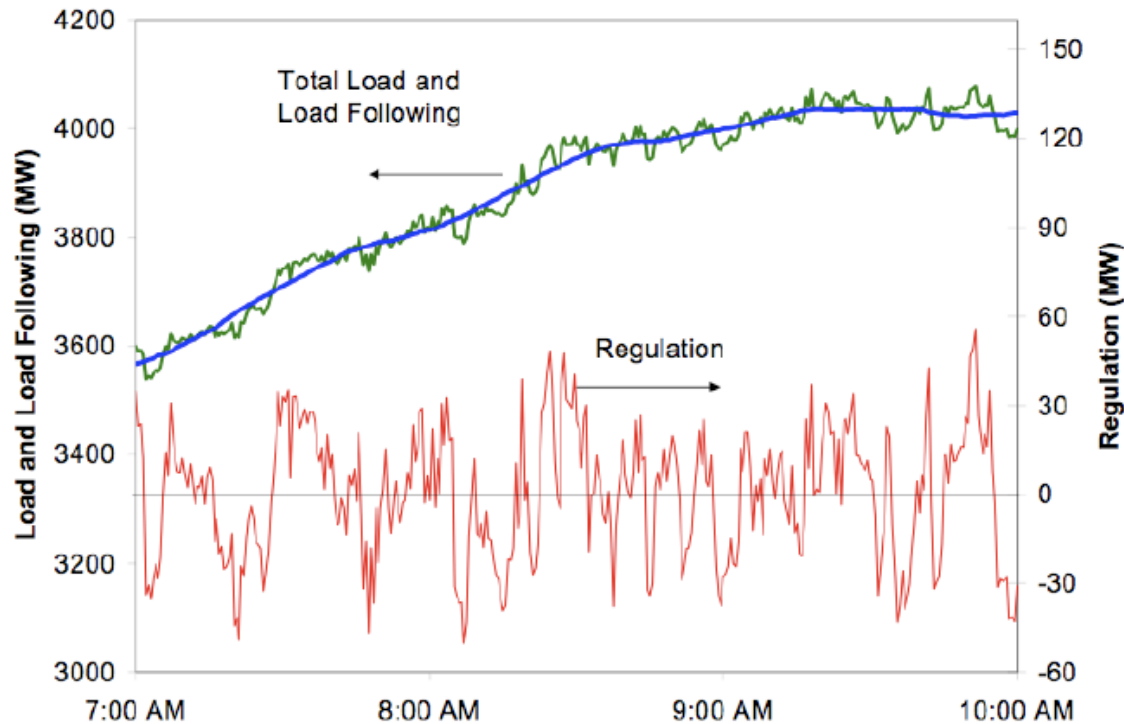
Requires multiple generator types: baseload, load-following  
(intermediate load and peaking)

# Reserve Requirements

---

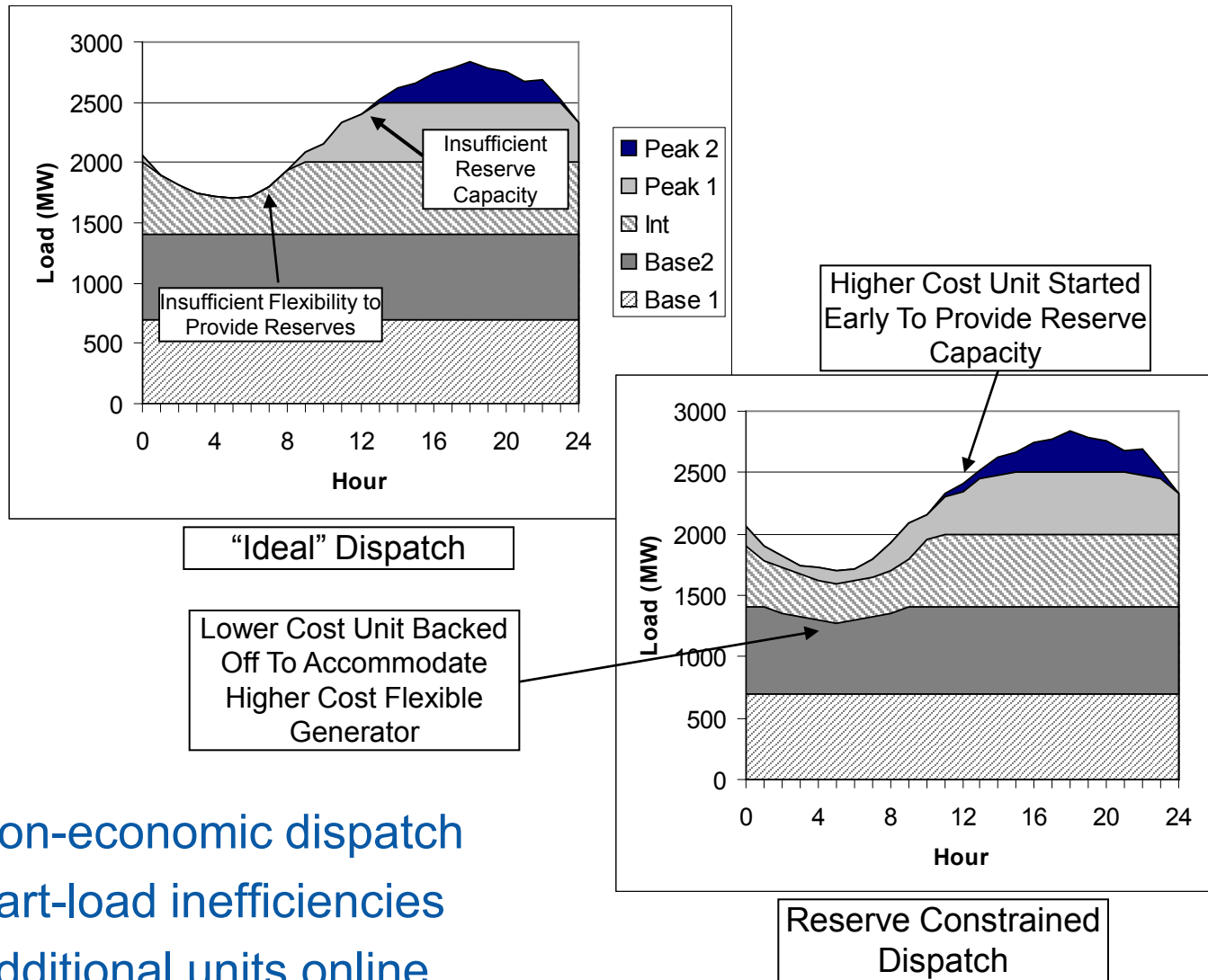
- Provides stable and reliable operation
- Not uniformly defined
- Frequency Regulation
  - Serves the random, rapid variation around the normal load
  - Highest value
- Contingency Reserve (often referred to as spinning reserves)
  - Quickly replaces a lost generator or transmission line
  - Infrequently called ~ 1x/week for about 10 minutes

# Frequency Regulation Requirements



System load following and regulation. Regulation (red) is the fast fluctuating component of total load (green) while load following (blue) is the slower trend

# Reserve Requirements Add Costs



- Non-economic dispatch
- Part-load inefficiencies
- Additional units online

# Energy Storage in the Existing Grid

---

- Historical motivations
- Renewed interest due to emergence of restructured markets
- Applications of energy storage

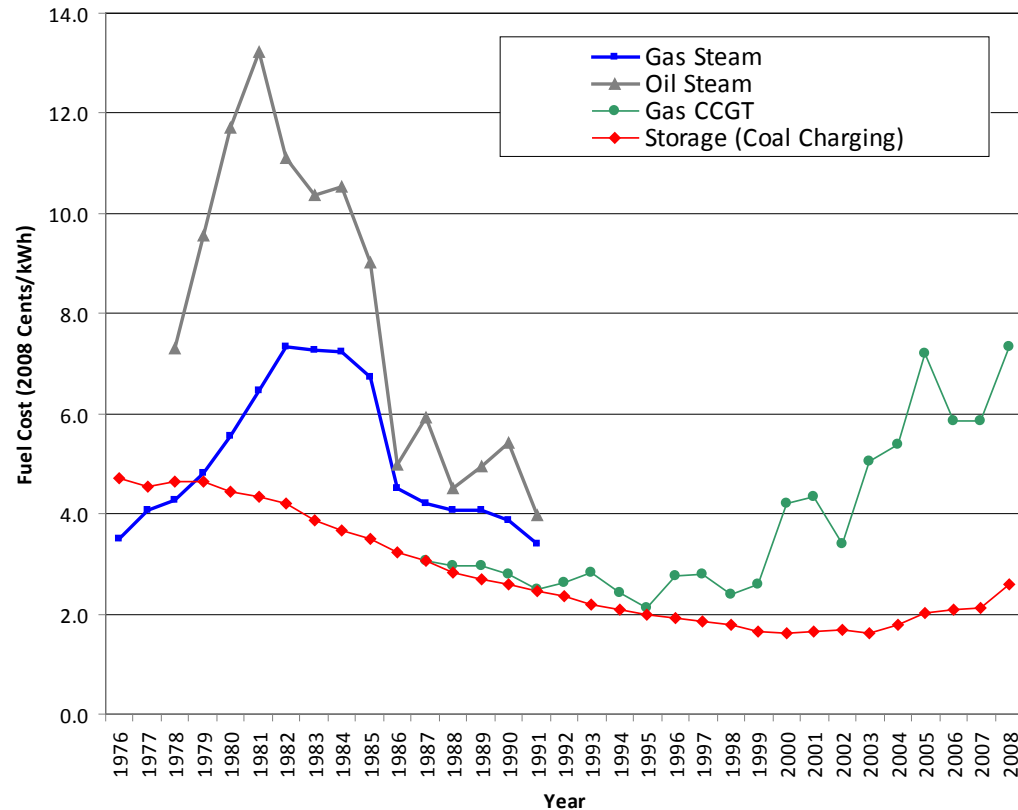
# Electricity Storage in the Existing Grid

## Historical motivations (pre-1980)

- Storage provides load following and reserves, while increasing use of low-cost baseload plants
- Limited options for peaking and intermediate load generation
  - Increasing cost of natural gas and oil
  - Restrictions on use of oil and natural gas (Power Plant and Industrial Fuel Use Act)
  - Low-efficiency oil and steam gas plants as opposed to today's efficient gas turbines
- Anticipated construction of many nuclear plants providing low cost (but inflexible) baseload energy

# Pumped Hydro

Was an attractive alternative to other load-following generators



Variable costs of storage are less than from oil or gas

Pumped hydro costs during this period (before 1980)  
are comparable to combined-cycle gas generators

# Limited Storage Built after 1980

---

- Collapse of oil and gas prices
- Repeal of fuel use act
- High-efficiency low cost gas turbines become available
- Storage development limited to ~20GW of pumped hydro storage, 1 CAES plant plus a few batteries and demonstration projects

# Revised Interest in Energy Storage

---

- Advances in storage technologies
- Increases in fossil fuel prices
- Energy markets
- T&D siting challenges
- Perceived need for storage with renewables

# Value of Storage in Restructured Markets

Historical Values of Energy Storage in Restructured Electricity Markets

Market Evaluated	Location	Years Evaluated	Annual Value (\$/kW)	Assumptions
Energy Arbitrage	PJM <sup>a</sup>	2002-2007	\$60-\$115	12 hour, 80% efficient device. Range of efficiencies and sizes evaluated <sup>[1]</sup>
	NYISO <sup>b</sup>	2001-2005	\$87-\$240 (NYC) \$29-\$84 (rest)	10 hour, 83% efficient device. Range of efficiencies and sizes evaluated.
	USA <sup>c</sup>	1997-2001	\$37-\$45	80% efficient device, Covers NE, No Cal, PJM
	CA <sup>d</sup>	2003	\$49	10 hour, 90% efficient device.
Regulation	NYISO <sup>b</sup>	2001-2005	\$163-248	
	USA <sup>e</sup>	2003-2006	\$236-\$429	PJM, NYISO, ERCOT, ISONE
Contingency Reserves	USA <sup>e</sup>	2004-2005	\$66-\$149	PJM, NYISO, ERCOT, ISONE

<sup>a</sup> Sioshansi et al. 2009

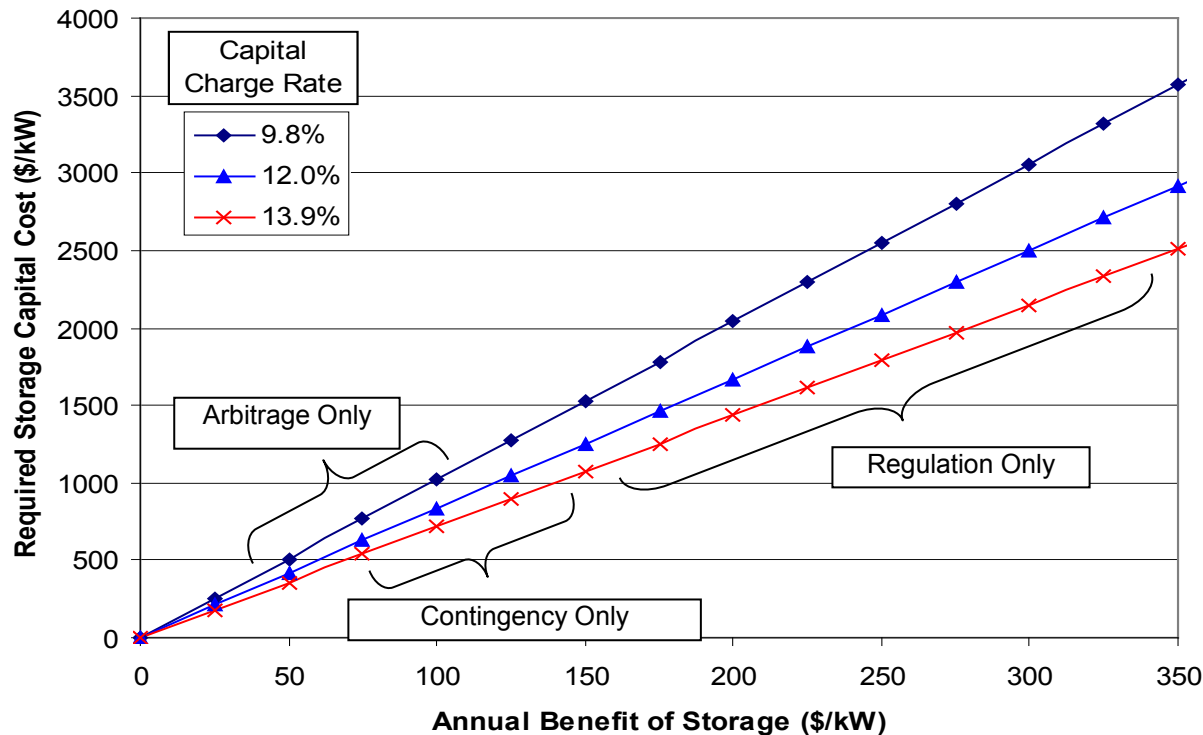
<sup>b</sup> Walawalkar et al. 2007

<sup>c</sup> Figueiredo et al. 2006

<sup>d</sup> Eyer et al. 2004

<sup>e</sup> Denholm and Letendre 2007

# Historical Value of Energy Storage in U.S. Markets



Relationship between total installed cost and annualized cost

Greatest value is frequency regulation – focus of many applications (flywheels, vehicle to grid). Arbitrage alone is generally insufficient to support most storage technologies, which are generally >\$1,000/kW

# Applications of Energy Storage

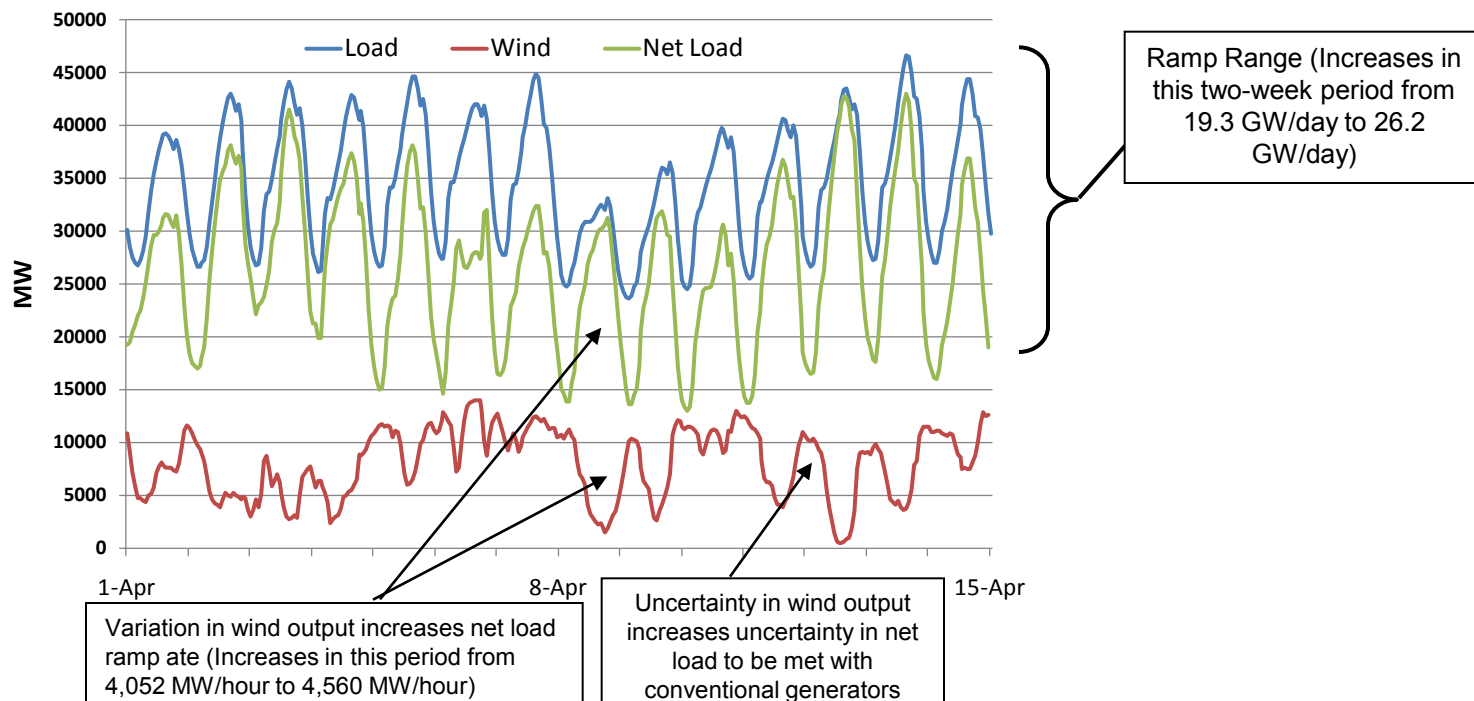
Application	Description	Timescale of Operation
<b>Load Leveling/ Arbitrage</b>	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Response in minutes to hours. Discharge time of hours.
<b>Firm Capacity</b>	Provide reliable capacity to meet peak system demand.	Must be able to discharge continuously for several hours or more.
<b>Operating Reserves</b>		
Regulation	Fast responding increase or decrease in generation (or load) to respond to random, unpredictable variations in demand.	Unit must be able to respond in seconds to minutes. Discharge time is typically minutes. Service is theoretically "net zero" energy over extended time periods.
Contingency Spinning Reserve <sup>[1]</sup>	Fast response increase in generation (or decrease load) to respond to a contingency such as a generator failure.	Unit must begin responding immediately and be fully responsive within 10 minutes. Must be able to hold output for 30 minutes to 2 hours depending on the market. Service is infrequently called. <sup>[2]</sup>
Replacement/ Supplemental	Units brought on-line to replace spinning units.	Typical response time requirement of 30-60 minutes depending on market minutes. Discharge time may be several hours.
<b>Ramping/Load Following</b>	Follow longer term (hourly) changes in electricity demand.	Response time in minutes to hours. Discharge time may be minutes to hours.
<b>T&amp;D Replacement and Deferral</b>	Reduce loading on T&D system during peak times.	Response in minutes to hours. Discharge time of hours.
<b>Black-Start</b>	Units brought online to start system after a system-wide failure (blackout).	Response time requirement is several minutes to over an hour. Discharge time requirement may be several to many hours. <sup>[3]</sup>
<b>End-Use Applications</b>		
TOU Rates	Functionally the same as arbitrage, just at the customer site.	Same as arbitrage.
Demand Charge Reduction	Functionally the same as firm capacity, just at the customer site.	Same as firm capacity. I
Backup Power/ UPS/Power Quality	Functionally the same as contingency reserve, just at the customer site.	Instantaneous response. Discharge time depends on level of reliability needed by customer.

# Impacts of Renewables on the Grid

---

- Storage is often perceived as “necessary” for renewables to achieve a large (>10%? >20%?) penetration.
- Renewables are seen as a source of value for storage
- Can renewables be used without storage?
- How do renewables impact the grid?

# Impacts of Renewables on the Grid

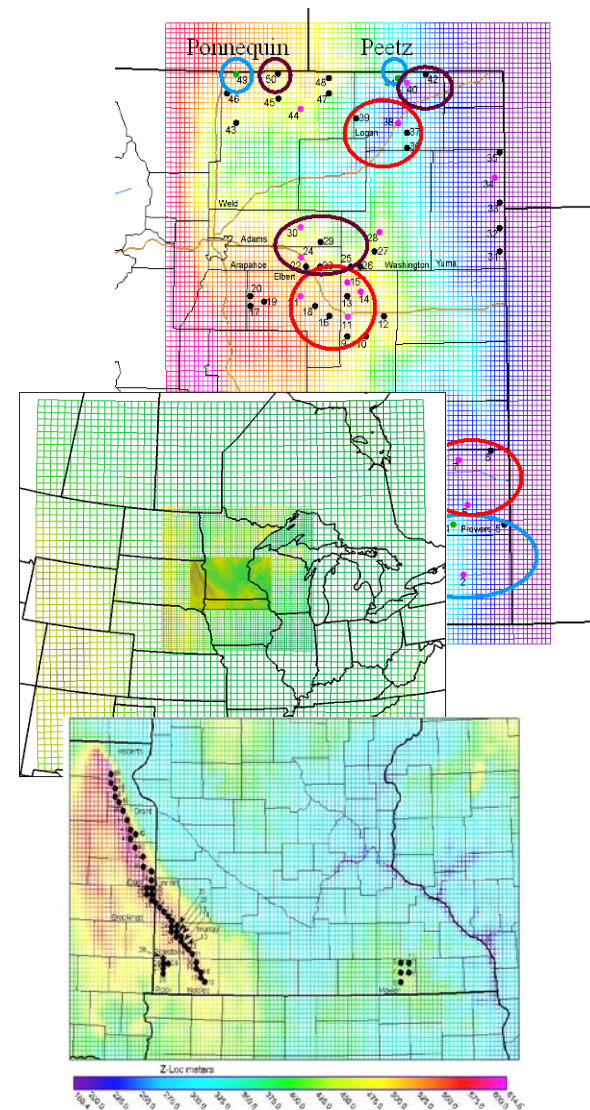


Four major impacts of variable generation (VG) on the grid:

- 1) Increased need for frequency regulation
- 2) Increase in hourly ramp rate
- 3) Increase in uncertainty of net load
- 4) Increase in ramp range

# Costs of Wind Integration

- Simulate system with and without solar and wind
  - Use unit commitment software includes existing generation mix, transmission system
  - Use lots of wind and solar simulations to consider spatial diversity
  - May involve substantial costs
- Evaluate costs of:
  - Additional regulation reserves
  - Additional load following
  - Wind uncertainty



# Costs of Wind Integration

Date	Study	Wind Capacity Penetration (%)	Regulation Cost (\$/MWh)	Load-Following Cost (\$/MWh)	Unit Commitment Cost (\$/MWh)	Other (\$/MWh)	Total Oper. Cost Impact (\$/MWh)
2003	Xcel-UWIG	3.5	0	0.41	1.44	Na	<b>1.85</b>
2003	WE Energies	29	1.02	0.15	1.75	Na	<b>2.92</b>
2004	Xcel-MNDOC	15	0.23	na	4.37	Na	<b>4.6</b>
2005	PacifiCorp-2004	11	0	1.48	3.16	Na	<b>4.64</b>
2006	Calif. (multi-year) <sup>a</sup>	4	0.45	trace	trace	Na	<b>0.45</b>
2006	Xcel-PSCo <sup>b</sup>	15	0.2	na	3.32	1.45	<b>4.97</b>
2006	MN-MISO <sup>c</sup>	36	na	na	na	na	<b>4.41</b>
2007	Puget Sound Energy	12	na	na	na	na	<b>6.94</b>
2007	Arizona Pub. Service	15	0.37	2.65	1.06	na	<b>4.08</b>
2007	Avista Utilities <sup>d</sup>	30	1.43	4.4	3	na	<b>8.84</b>
2007	Idaho Power	20	na	na	na	na	<b>7.92</b>
2007	PacifiCorp-2007	18	na	1.1	4	na	<b>5.1</b>
2008	Xcel-PSCo <sup>e</sup>	20	na	na	na	na	<b>8.56</b>

<sup>a</sup> Regulation costs represent 3-year average.

<sup>b</sup> The Xcel/PSCO study also examine the cost of gas supply scheduling. Wind increases the uncertainty of gas requirements and may increase costs of gas supply contracts.

<sup>c</sup> Highest over 3-year evaluation period. 30.7% capacity penetration corresponding to 25% energy penetration

<sup>d</sup> Unit commitment includes cost of wind forecast error.

<sup>e</sup> This integration cost reflects a \$10/MMBtu natural gas scenario. This cost is much higher than the integration cost calculated for Xcel-PSCo in 2006, in large measure due to the higher natural gas price: had the gas price from the 2006 study been used in the 2008 study, the integration cost would drop from \$8.56/MWh to \$5.13/MWh.

# Conclusions of Wind Integration Studies

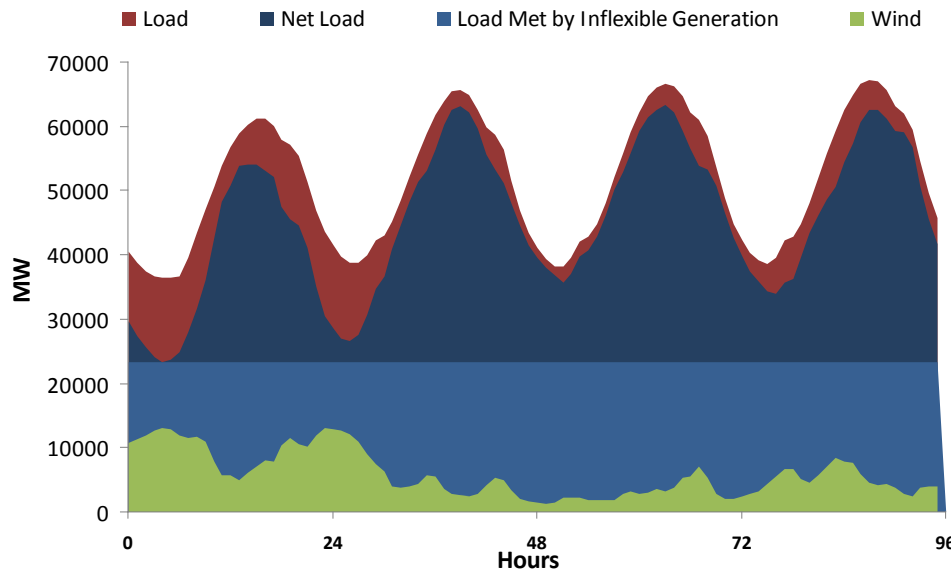
## (<30% Penetration)

- Challenges are unit commitment, regulation and load following
- Integration costs are modest (typically less than \$5/MWh)
- Increased variability can be accommodated by existing generator flexibility and other “low-cost” flexibility such as increased balancing area cooperation (balancing wind generation and load over larger areas to “share” the increased variability).
- Spatial diversity smooths aggregated wind output reducing short-term fluctuations to hour time scales
- Storage would “help” but is not needed, and the integration costs would not “pay” for currently expensive storage technologies.

# Limits to VG Penetration - Curtailment

- At high penetration, economic limits will be due to curtailment
  - Limited coincidence of VG supply and normal demand
  - Minimum load constraints on thermal generators
  - Thermal generators kept online for operating reserves
- Results from EWITS and WWSIS, along with other studies, indicate that beyond 30% VG, new sources of flexibility will be needed

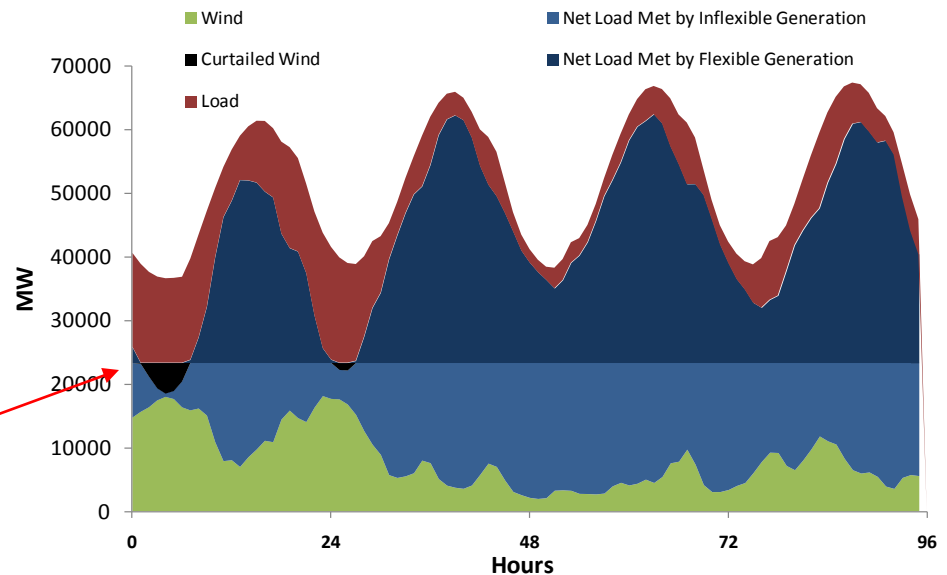
# High Penetration Limits



Dispatch with low VG penetration (wind providing 8.5% of load)

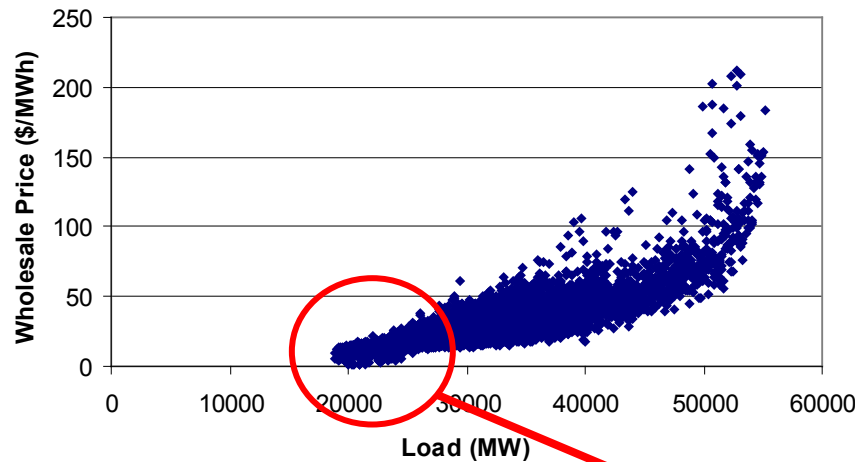
Dispatch with higher VG penetration (wind providing 16% of load)

Inflexible systems may be unable to accommodate large amounts of wind



# Current System Flexibility

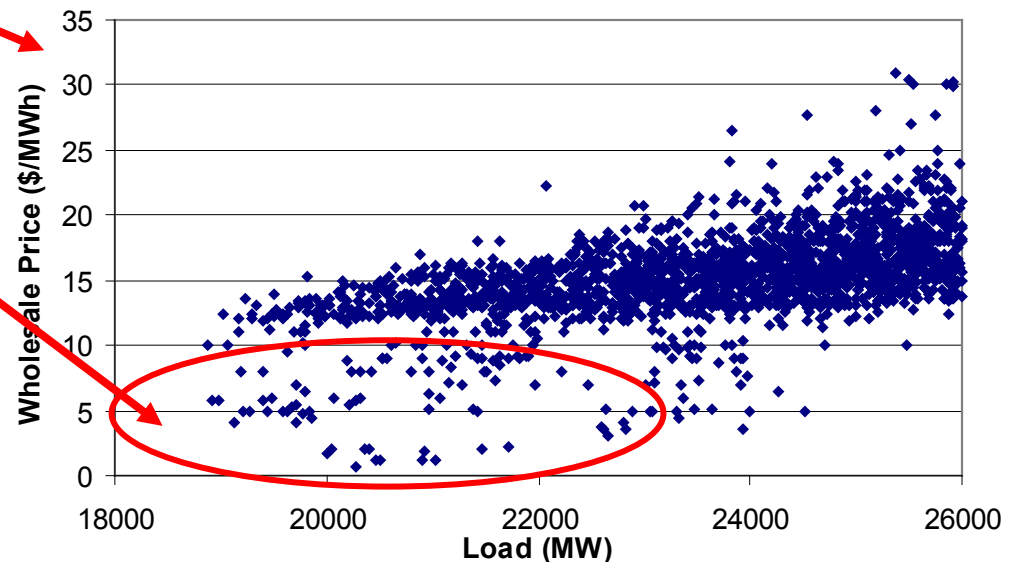
## Limited by Baseload Capacity



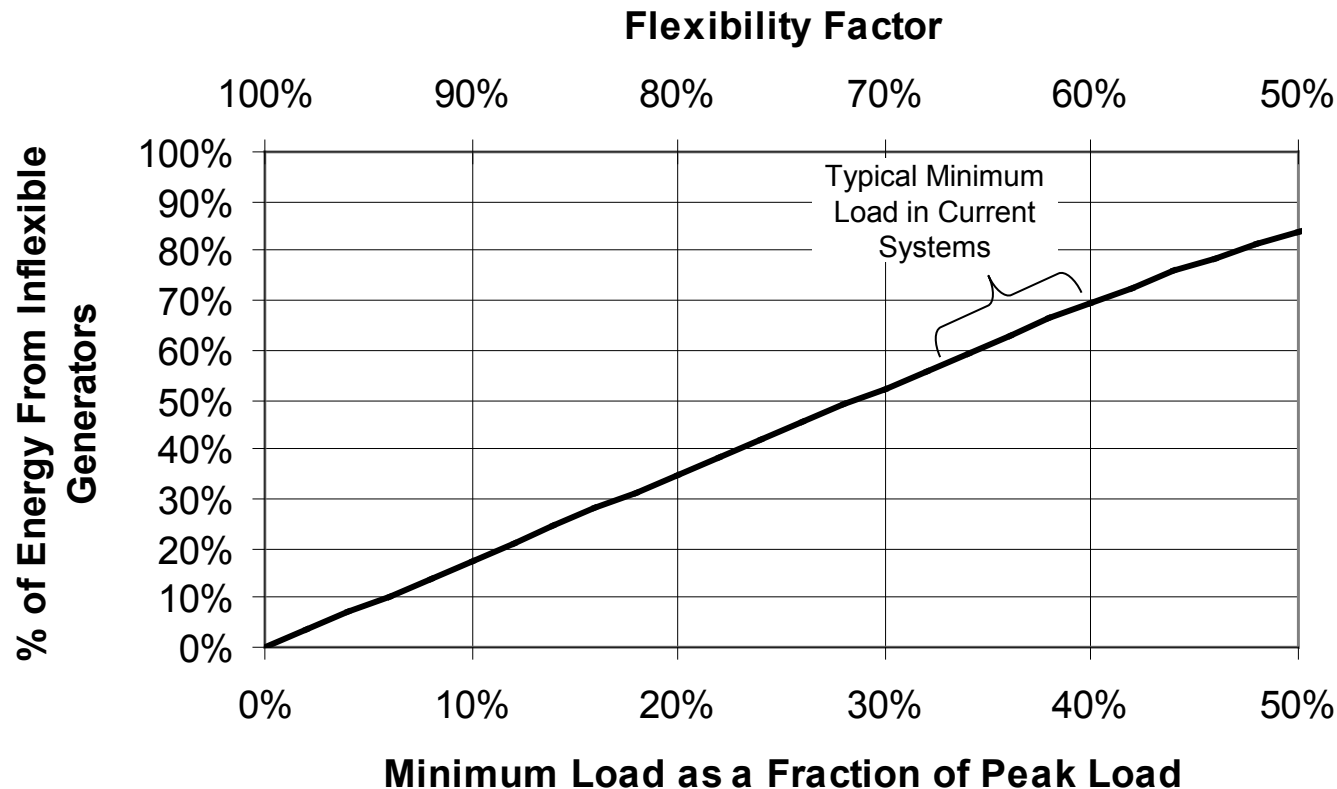
Price/Load Relationship in PJM

## Below Cost Bids

Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind may be curtailed under these conditions



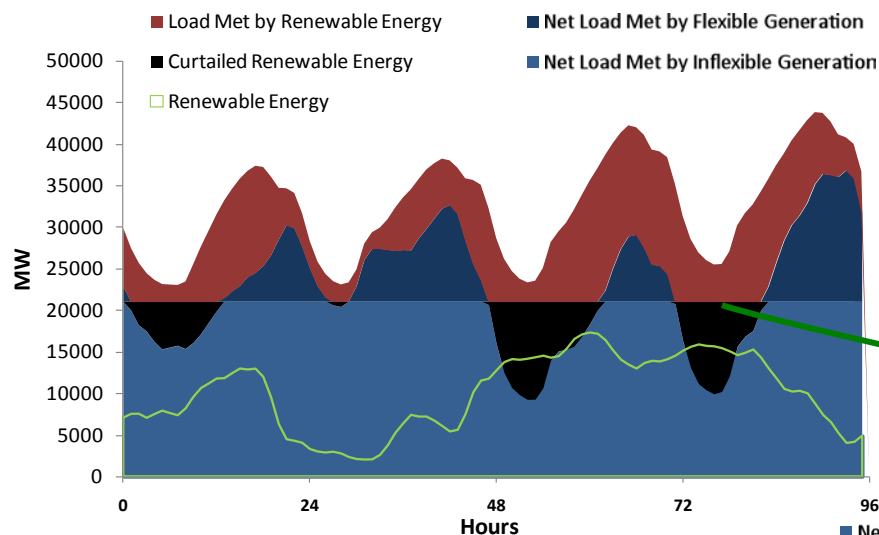
# Increased Flexibility is Required



At current minimum loads, baseload generators provide 60-70% of generation, leaving only 30%-40% for VG.

# Decreased Minimum Load

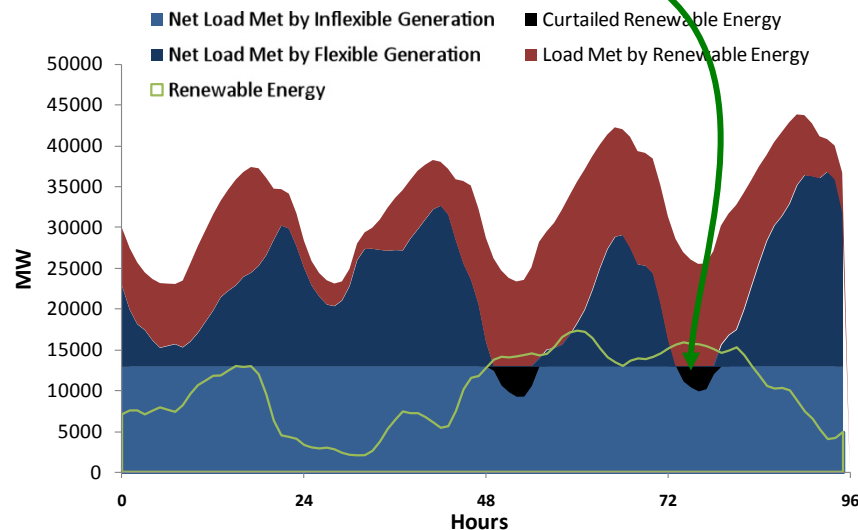
Needed to accommodate greater amounts of VG without significant curtailment



Inflexible System -  
Minimum Load of  
21 GW (65% FF)

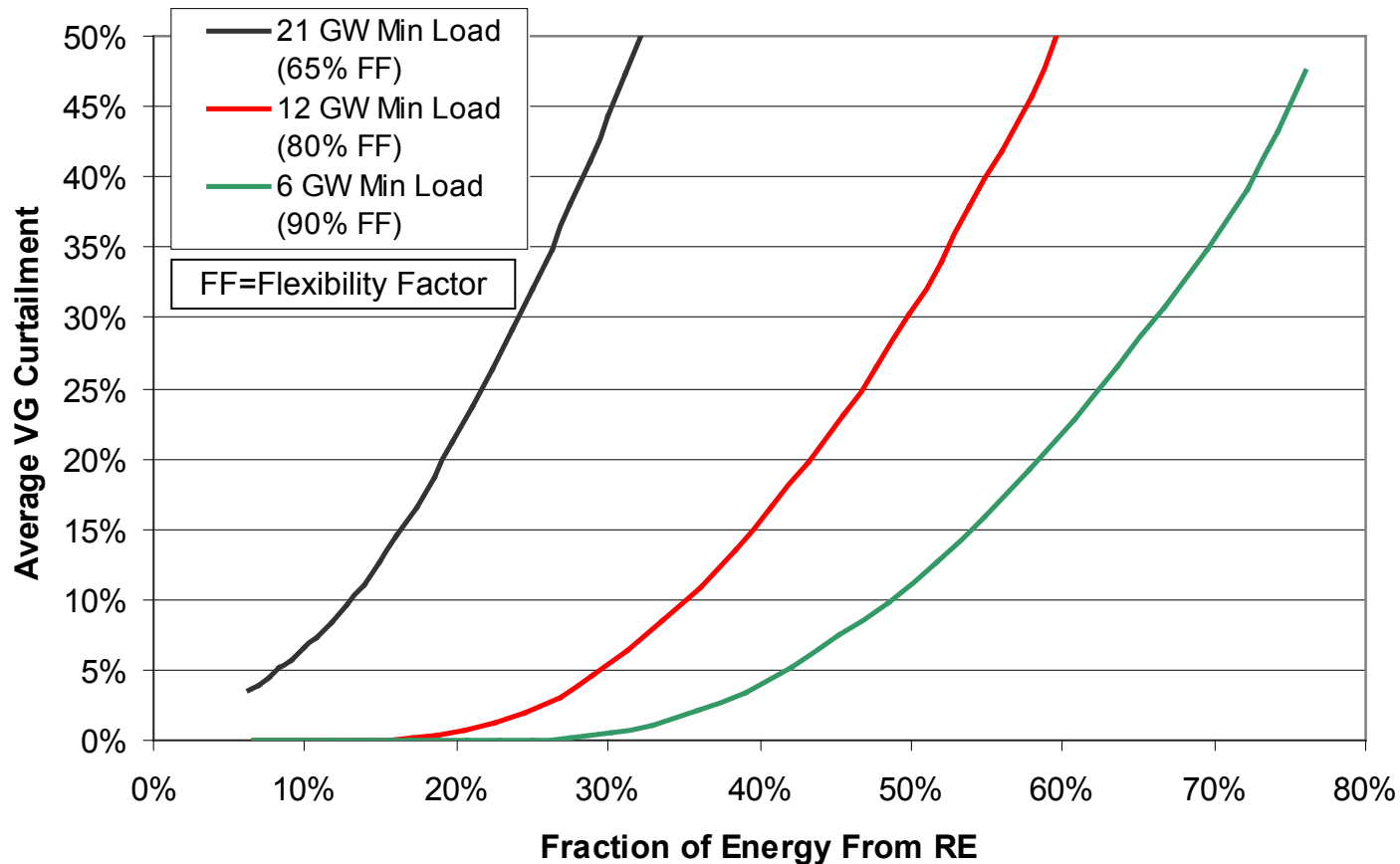
Decreased  
curtailment

More Flexible System  
-Minimum Load of  
13 GW (80% FF)



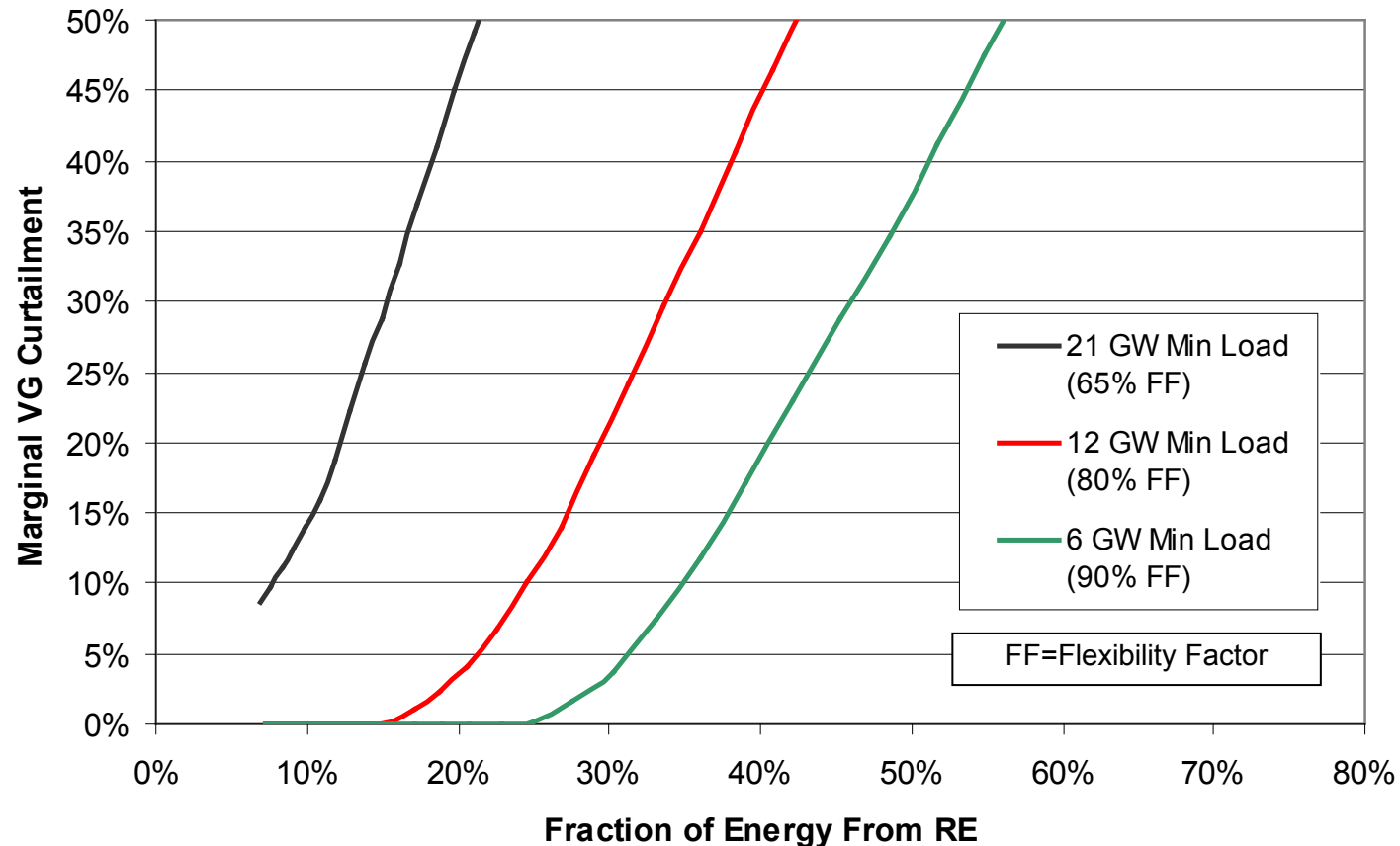
Simulations based on  
2005 load and weather

# Curtailment as a Function of Flexibility



Average curtailment rate as a function of VG penetration for different flexibilities in ERCOT

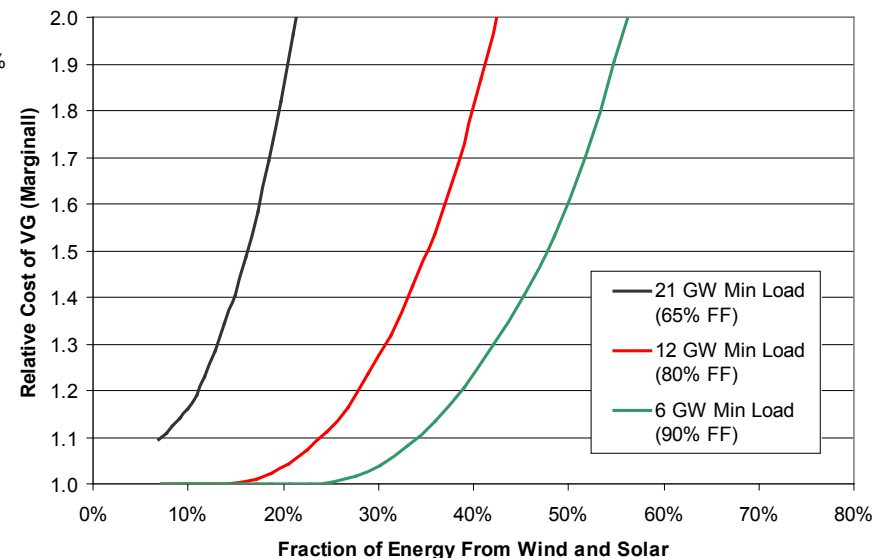
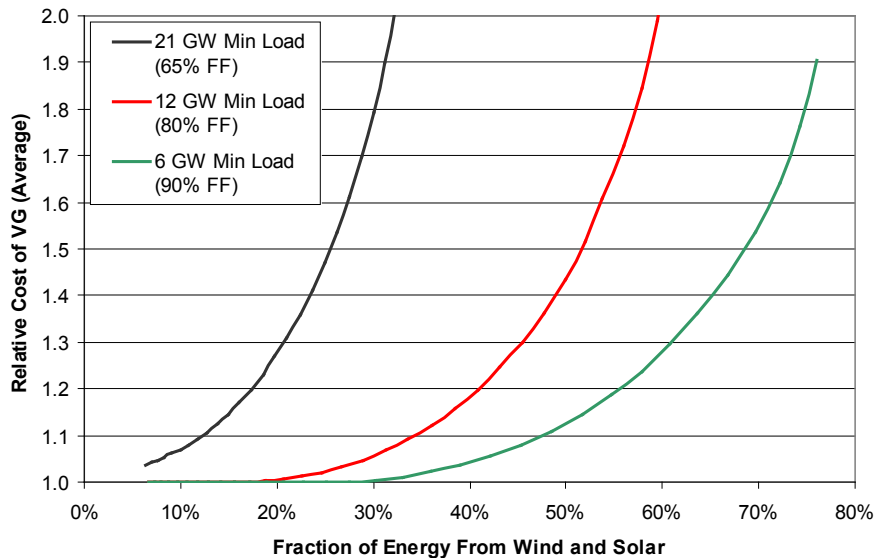
# Curtailment as a Function of Flexibility *(cont.)*



Marginal curtailment rate as a function of VG penetration for different system flexibilities in ERCOT (marginal curtailment is defined as the percentage curtailed as a function of the incremental penetration)

# VG Curtailment

## May Result In Unacceptably High Costs at High Penetration



Relative cost of VG – average (top chart) and marginal (bottom chart) – as a function of VG penetration for different system flexibilities in ERCOT

# Renewables-Driven Grid Applications

---

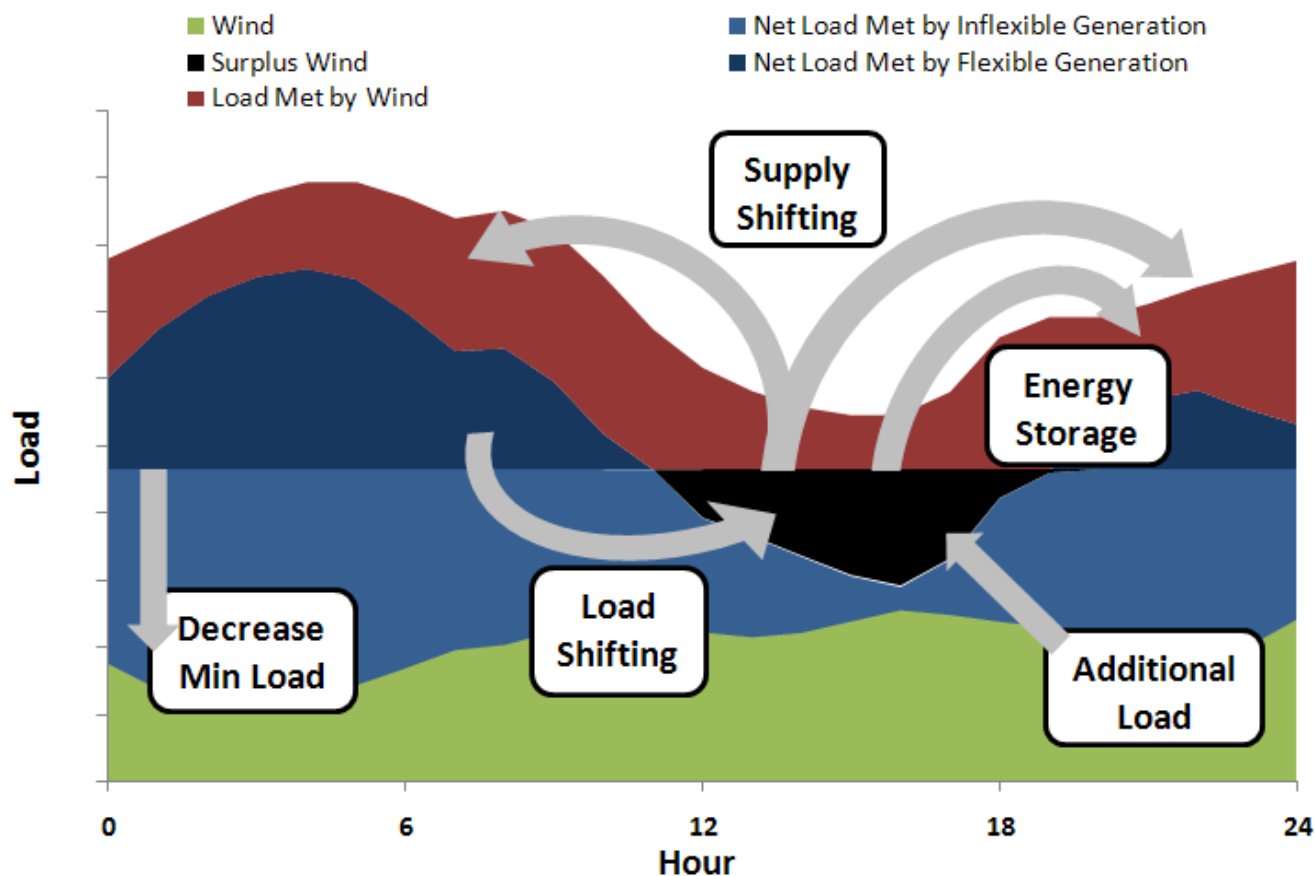
## Storage and Flexibility Options

- At high penetration of VG, additional flexibility is required
- What are the options?

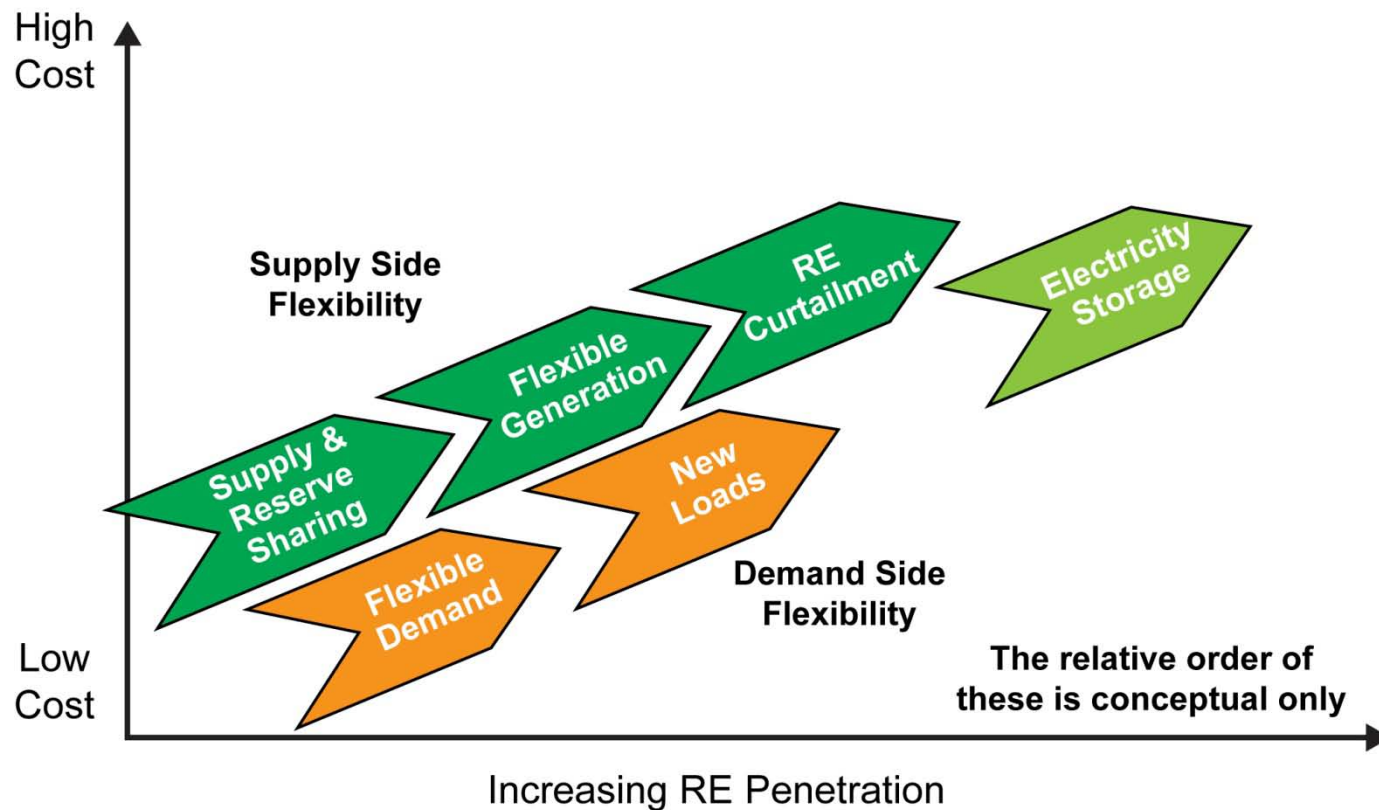
# Renewables-Driven Grid Applications

## Storage and Flexibility Options (*cont.*)

While storage provides an “obvious” answer to the problem of supply-demand coincidence, there are a number of options



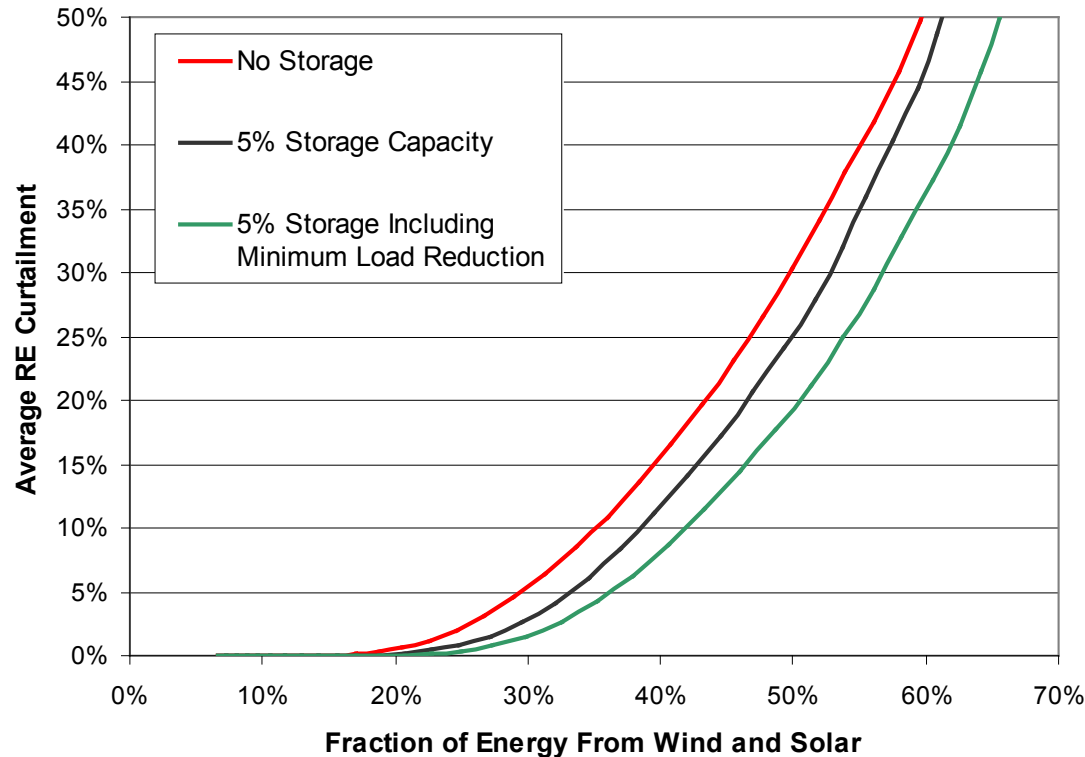
# Flexibility Supply Curve



The cost of all options has yet to be determined. Currently, energy storage is expensive and incurs the penalty of round-trip losses.

Based on an original by Nickell 2008

# Energy Storage Can Reduce VG Curtailment



FF=80% (12 GW min load)

Energy storage can reduce curtailment both by shifting otherwise unusable generation, and also increase system flexibility by providing reserves (reducing the need for partially loaded thermal generators) and replacing “must-run” capacity

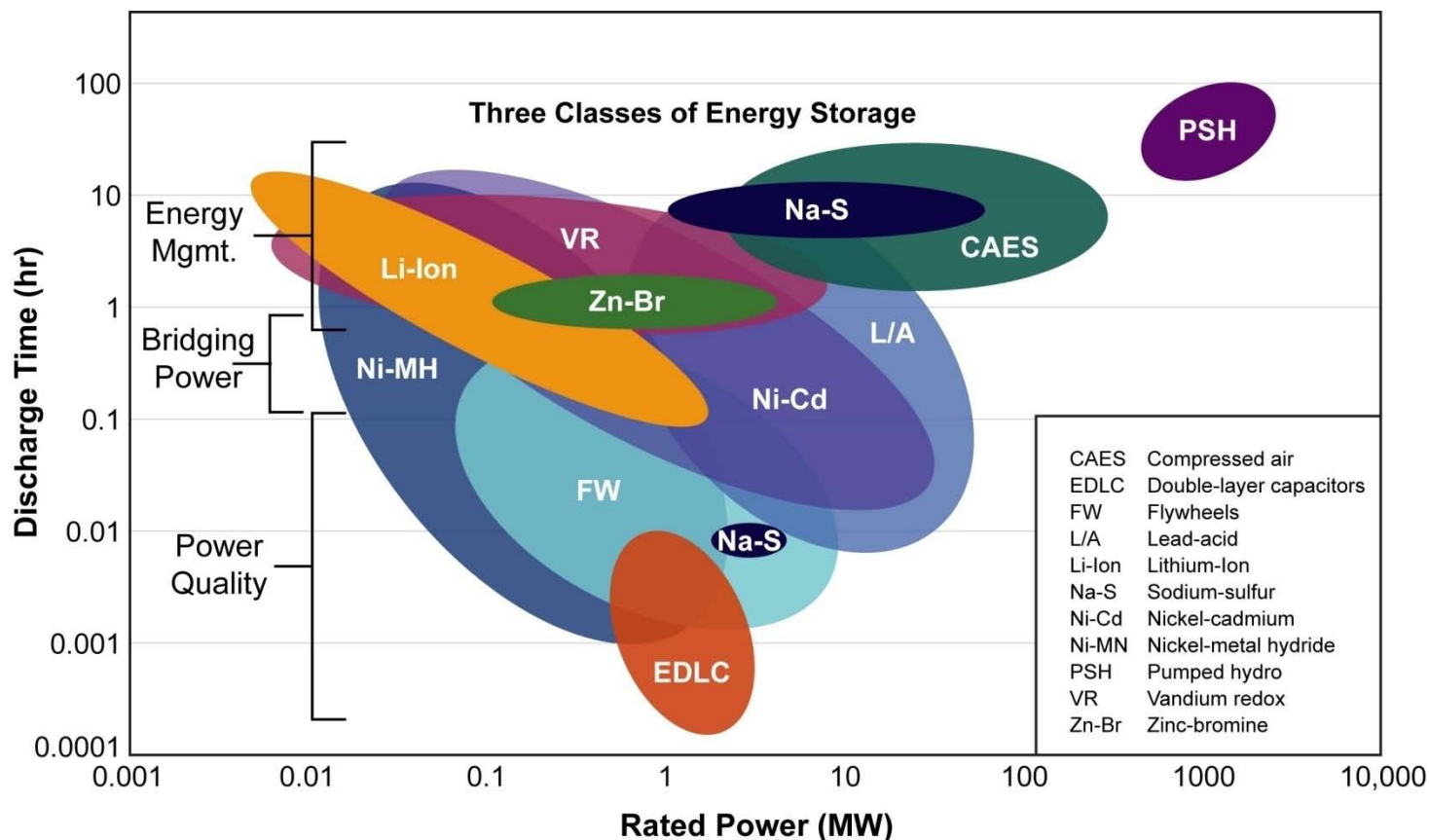
# Dedicated Renewable Storage?

- Dedicated renewable storage is generally a non-optimal use
- Could have scenarios where one storage device is charging while another is discharging simultaneously in the same system
- “Renewable specific” applications are already typically captured in grid operations

RE Specific Application	“Whole Grid” Application
Transmission Curtailment	Transmission Deferral
Time Shifting	Load Leveling/Arbitrage
Forecast Hedging	Forecast Error
Frequency Support	Frequency Regulation
Fluctuation Suppression	Transient Stability

# Storage Technologies

Common Name	Example Applications	Discharge Time Required
Power Quality	Transient Stability, Frequency Regulation	Seconds to Minutes
Bridging Power	Contingency Reserves, Ramping	Minutes to ~1 hour
Energy Management	Load Leveling, Firm Capacity, T&D Deferral	Hours



Not shown – thermal storage in end use and in CSP plants

# Caveats

---

- Efficiency
  - Not uniformly defined (should be AC-AC, but sometimes stated in terms of DC-DC, which doesn't capture conversion)
  - May not include parasitics
  - CAES (which uses natural gas) and thermal storage cannot be easily compared to pure electricity storage devices such as pumped hydro
- Cost
  - Many technologies have not been deployed as large scale, so costs are largely unknown
  - Commodity prices affect estimates from different years
  - Difficult to compare devices that offer different services (power vs. energy)

# Storage Devices for Power Quality

- Requires response time of seconds or less, discharge time of up to 10 minutes
- Flywheels
  - Currently targeted toward frequency
  - Regulation applications
- Capacitors
  - Limited deployment to date (low energy capacity)
- Superconducting Magnetic Energy Storage (SMES)
  - Limited deployment to date due to high cost and low energy density

# Storage Devices for Bridging Power

---

- Rapid response (seconds to minutes)
- Discharge time of up to 1 hour
- May also provide power quality services
- Several battery technologies
  - lead-acid
  - nickel-cadmium
  - nickel-metal hydride
  - lithium-ion

# Storage Devices for Energy Management

---

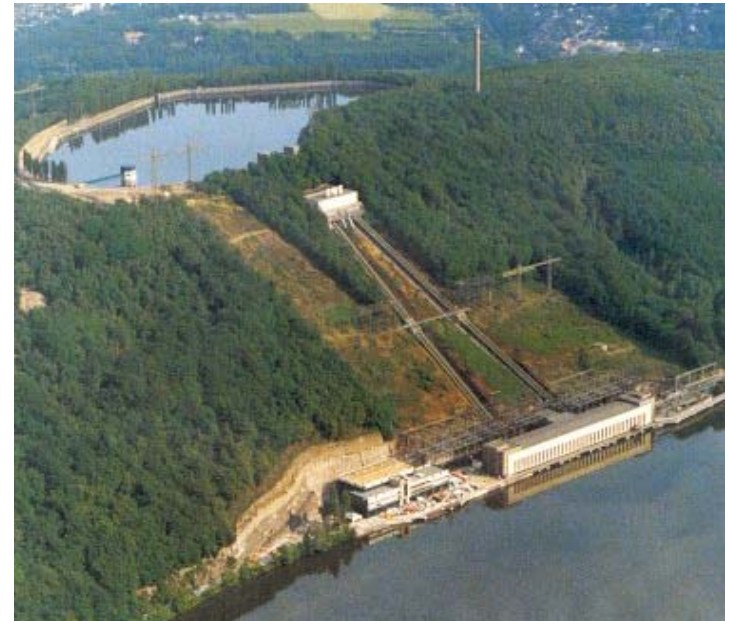
- Discharge time of several hours
- Some technologies also provide power quality and bridging power
- Would be the most important class of storage devices for decreasing VG curtailment
- High energy batteries
- Pumped hydro
- Compressed Air
- Thermal Storage

# High Energy Batteries

- High-temperature batteries
  - Sodium sulfur – the most widely deployed battery with more than 270 MW installed
  - Sodium-nickel chloride (early commercialization stage)
- Liquid electrolyte “flow” batteries
  - Feature separate power and energy components
  - All in the early commercialization stage
  - Vanadium redox
  - Zinc-bromine
  - Other chemistries being pursued

# Pumped Hydro Storage

- Only technology deployed on a gigawatt scale
  - ~20 GW in the U.S. at 29 sites
  - ~100 GW worldwide
- Installations in the U.S. range from <50 MW to 2,100 MW
- Can exceed 75% AC-AC round-trip efficiency
- Permitting is difficult and time-consuming, but ~ 30 GW of proposed new capacity in the U.S.



# Compressed Air Energy Storage (CAES)

- Hybrid technology that a gas turbine and burns natural gas
- Single point efficiency not easily defined
  - Better to use electricity energy ratio (0.6-0.8 kWh in per kWh out) and heat rate (4000-4300 BTU/kWh)
- Two sites – U.S. (110 MW) and Germany (270 MW)
- Alternative designs proposed including adiabatic (no fuel input)

Alabama CAES  
Plant (110 MW)



# Thermal Storage

---

- End-use thermal storage in buildings
  - Hot or cold
  - Very high round-trip efficiencies (near 100% in some applications)
  - Commercially available
- Thermal storage for CSP
  - Very high round-trip efficiency  
(stores energy before Carnot losses)
- Both applications are tied to a specific use and difficult to compare to more flexible storage technologies

# Electric Vehicles and Vehicle-to-Grid

---

- Potential valuable source of distributed storage
- More likely to be used for ancillary services than bulk energy shifting due to high battery cost
- Active area of research

# Conclusions

---

- The role of storage is an economic issue – does the value of storage exceed its benefits?
- Storage is undervalued in existing markets and it is still difficult to assess the true value and opportunities for energy storage in the current and future grid
- Renewables increase the value of storage, but the current grid can accommodate substantially increased amount of renewables with options that appear to be lower cost than new dedicated storage
- At penetrations of wind and solar that exceed 30%, increased curtailment will require new sources of grid flexibility
- New models and analysis will be required to evaluate the benefits of energy storage in the future electric grid.

# For More Information

---

Full Report:

Denholm, P.; Ela, E.; Kirby, B.; Milligan, M. (2010). Role of Energy Storage with Renewable Electricity Generation. NREL Report No. TP-6A2-47187.

Available at:

<http://www.nrel.gov/docs/fy10osti/47187.pdf>