NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Economics of Energy Storage

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Today's Discussion

- Approaches to Valuation of Energy Storage
- Example Results for Energy and Ancillary Services
- Effects of Renewables
- Technical, Economic and Policy Challenges

Applications of Energy Storage

Application	Description	Timescale of Operation
Load Leveling/ Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Response in minutes to hours. Discharge time of hours.
Firm Capacity	Provide reliable capacity to meet peak system demand.	Must be able to discharge continuously for several hours or more.
Operating Reserves		
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[1]	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.[2]
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.
Ramping/Load Following	Follow longer term (hourly) changes in electricity demand.	Response time in minutes to hours. Discharge time may be minutes to hours.
T&D Replacement and Deferral	Reduce loading on T&D system during peak times.	Response in minutes to hours. Discharge time of hours.
Black-Start	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.[3]
End-Use Applications		
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.	nstantaneous response. Discharge time depends on level of reliability needed by customer.

Valuation Approaches

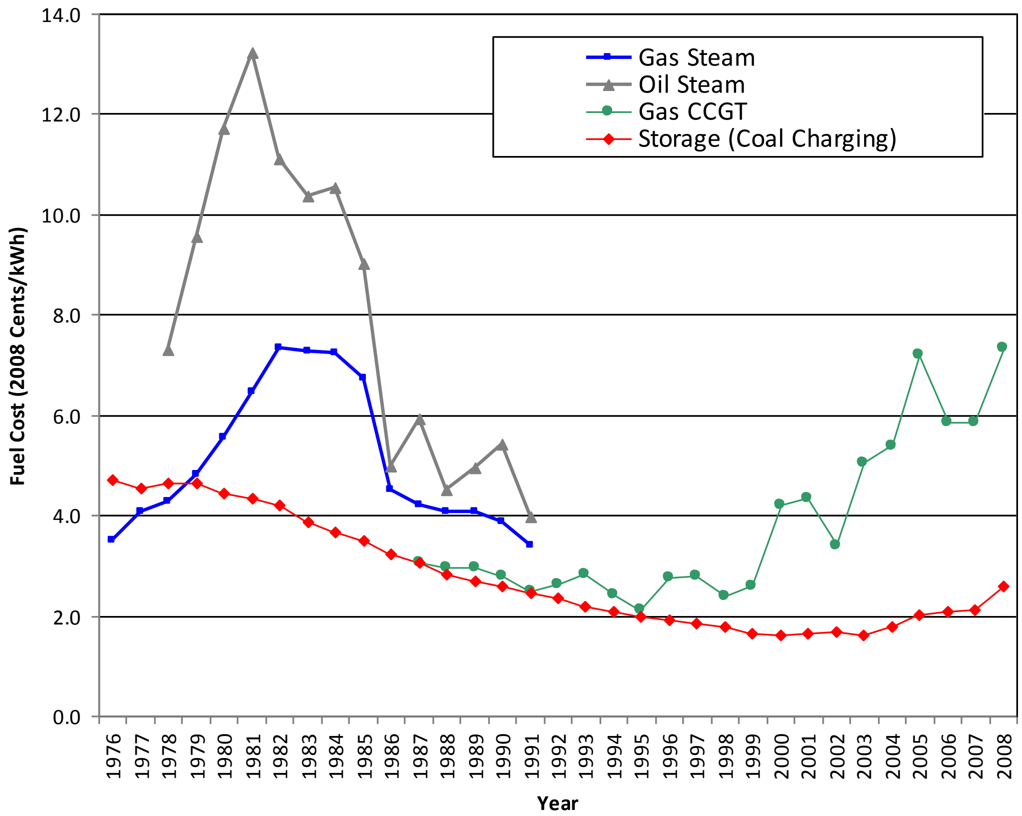
- Value in Traditional Integrated Resource Planning
- Value in Using Historical Market Data
- Full Value in System Planning and Operation

Historical Planning of Storage

- Storage as part of the resource planning process
- Compares a new storage plant to an alternative generation resource (oil or gas fired steam plant)
  - Assume approximately equivalent performance (capacity factor, grid services etc)
  - Assume low cost charging from coal or nuclear power
  - Assume 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

Pumped Hydro

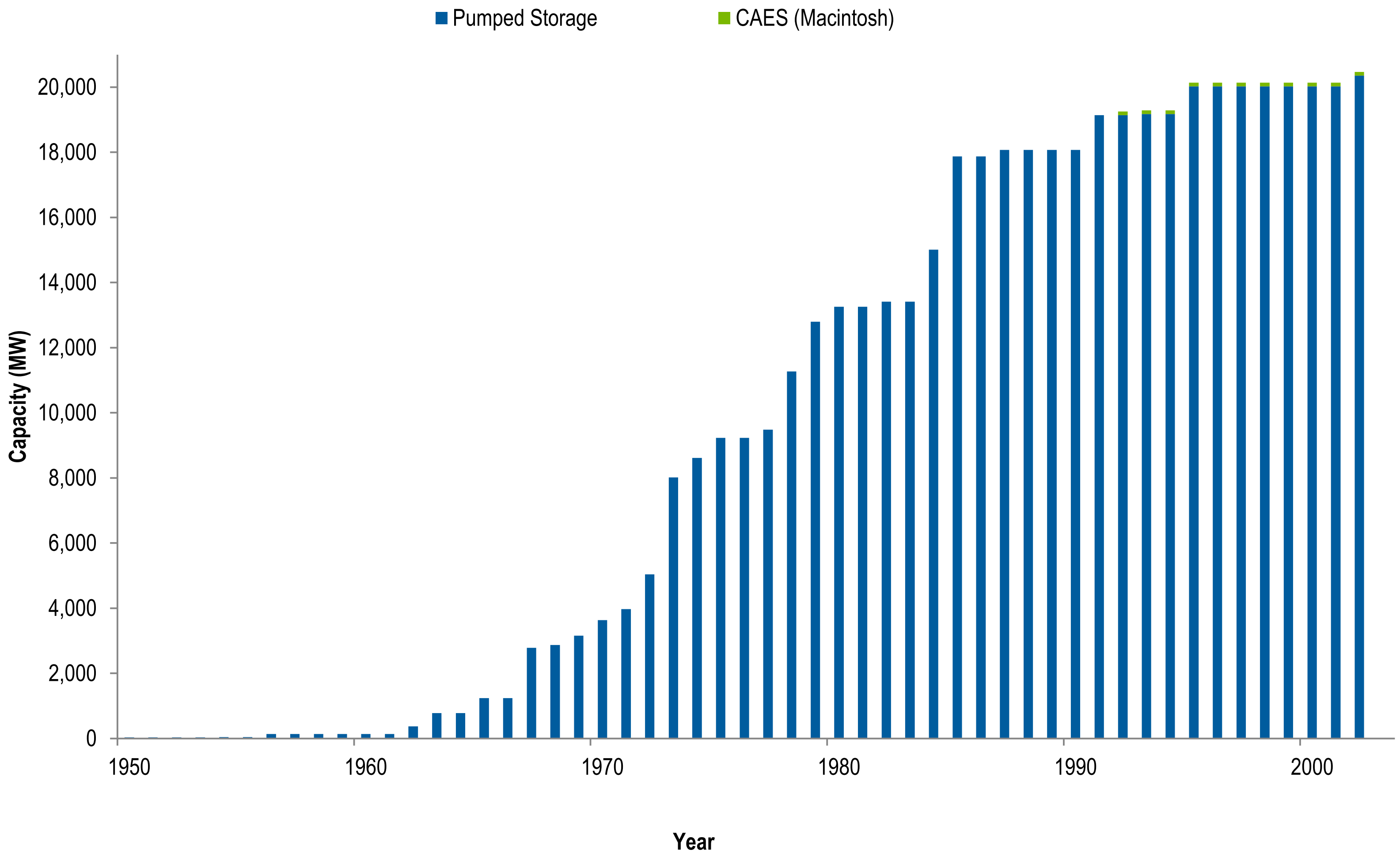
Was an attractive alternative to other load-following generators



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

Growth in Pumped Storage



Limited Storage Built after 1980

- Collapse of oil and gas prices
- Repeal of fuel use act
- High-efficiency low cost gas turbines become available
- PHS gets more expensive
- Incomplete valuation of benefits
- 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
- Volatility in fossil fuel prices
- T&D siting challenges
- Perceived need for storage with renewables
- **Emergence of electricity markets**

  - Puts value on operating reserves

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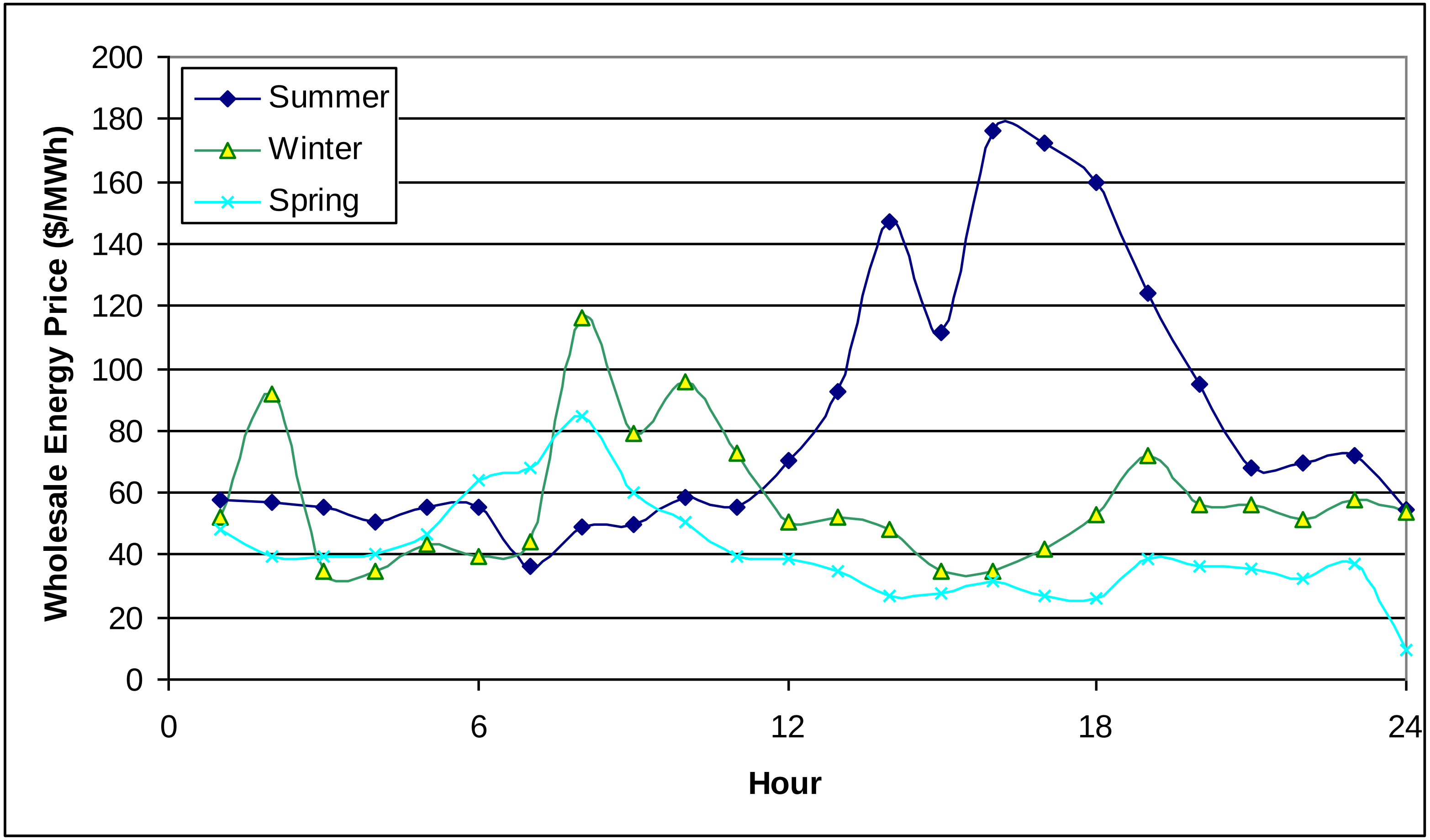
Value in Restructured Markets

- Use historical market data to estimate what a storage plant would have received if optimally dispatched (big caveat)

- Typically Single Unit Optimal Dispatch Simulations (Price Taker)
  - Based on historical price and load patterns
  - Typically assumes perfect foresight
  - Multi Unit Dispatch
  - Can evaluate some price-suppression impacts (using price load relationships)

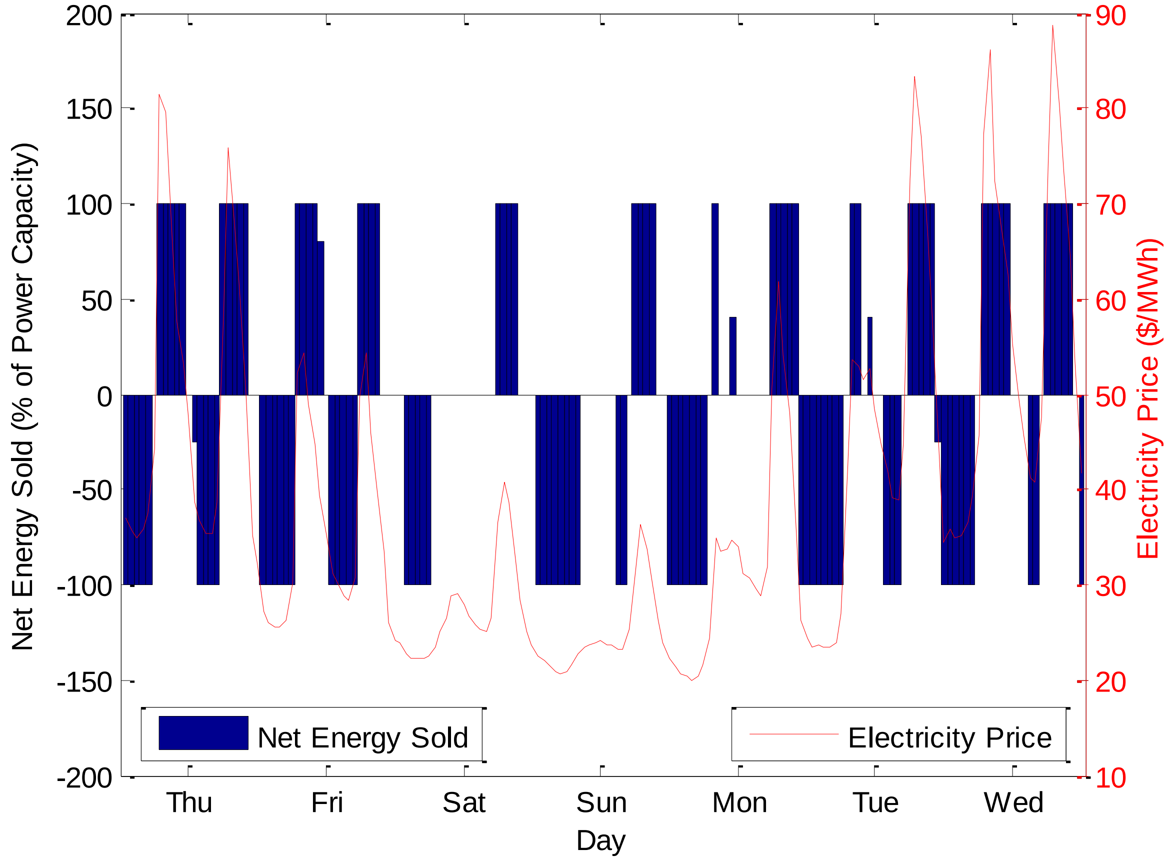
Example - Load Leveling & Arbitrage



Example: Storage in PJM

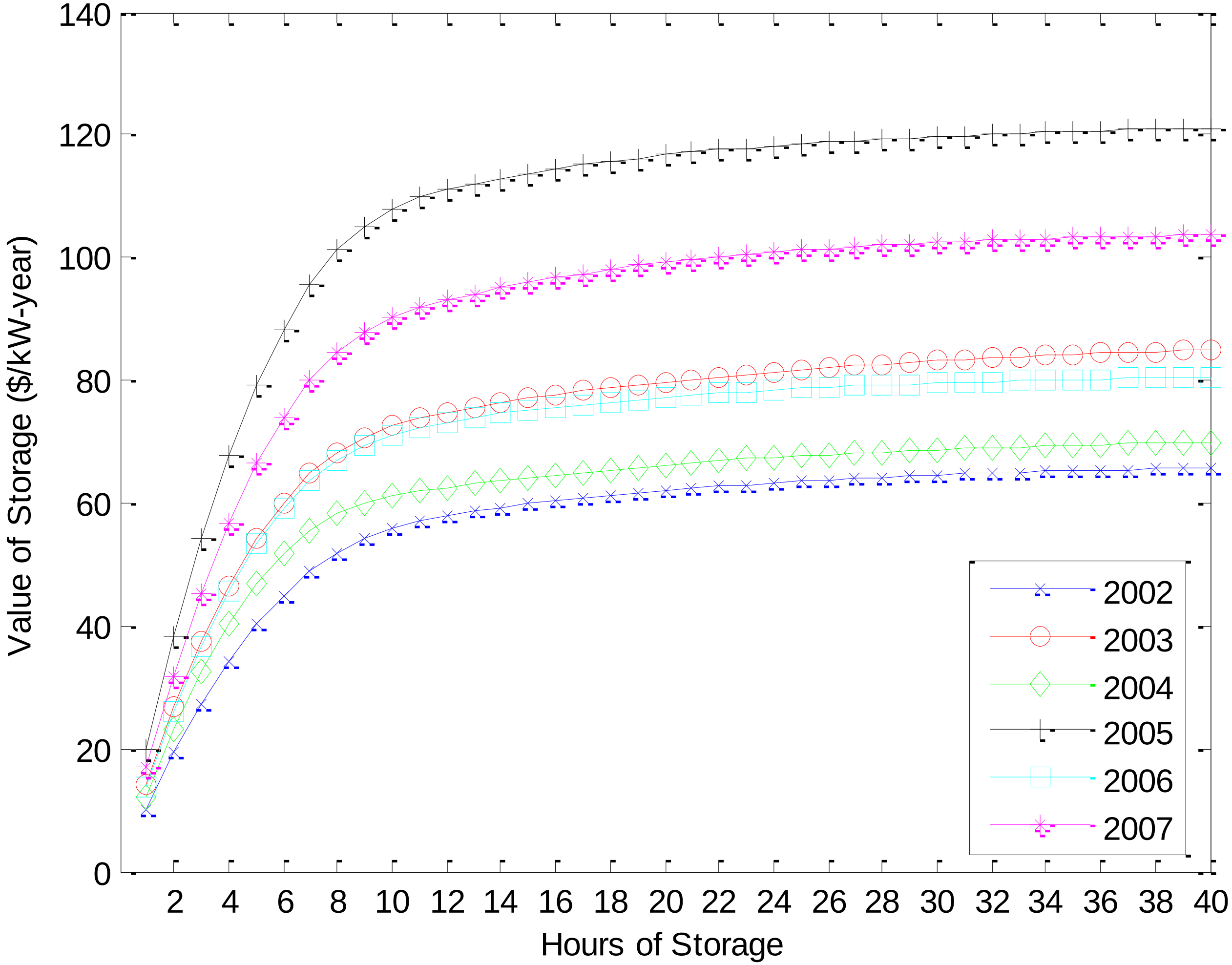
- 75% AC-AC Efficiency
- Perfect foresight of prices for 1 week

Optimal Dispatch



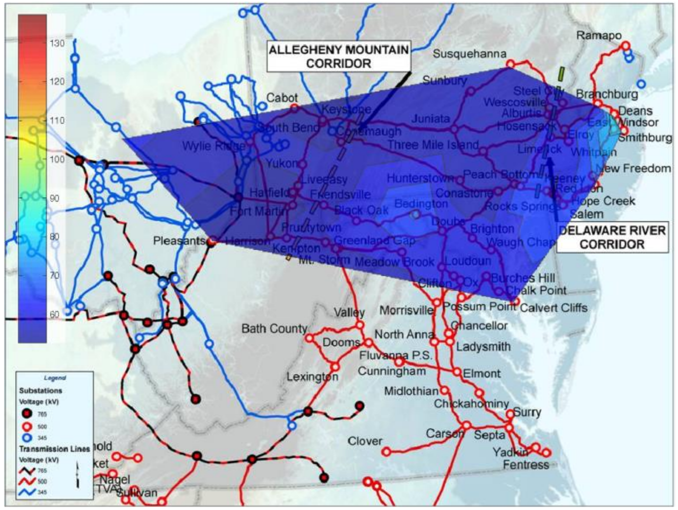
Energy Arbitrage in PJM

Value

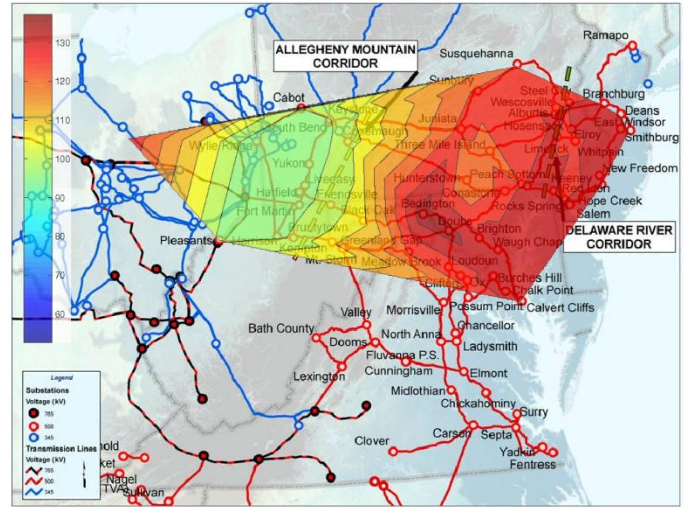


Energy Arbitrage in PJM

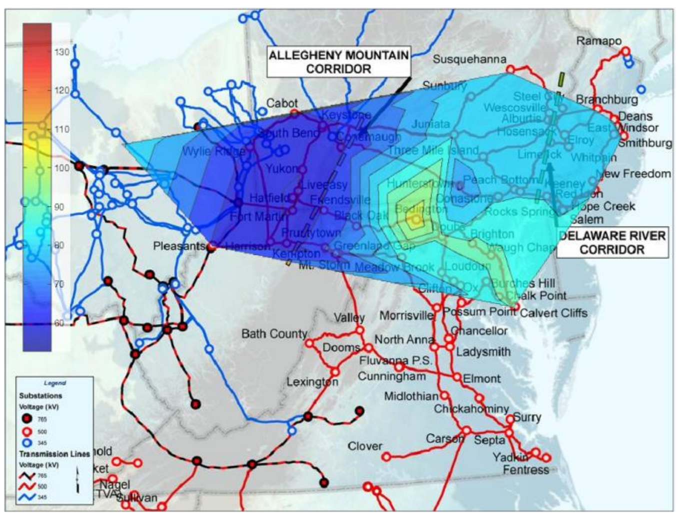
Locational Variation – Arbitrage Value



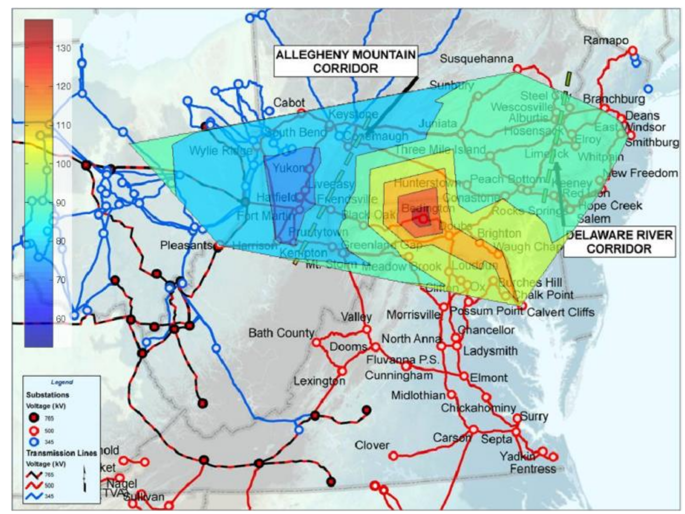
2004



2005



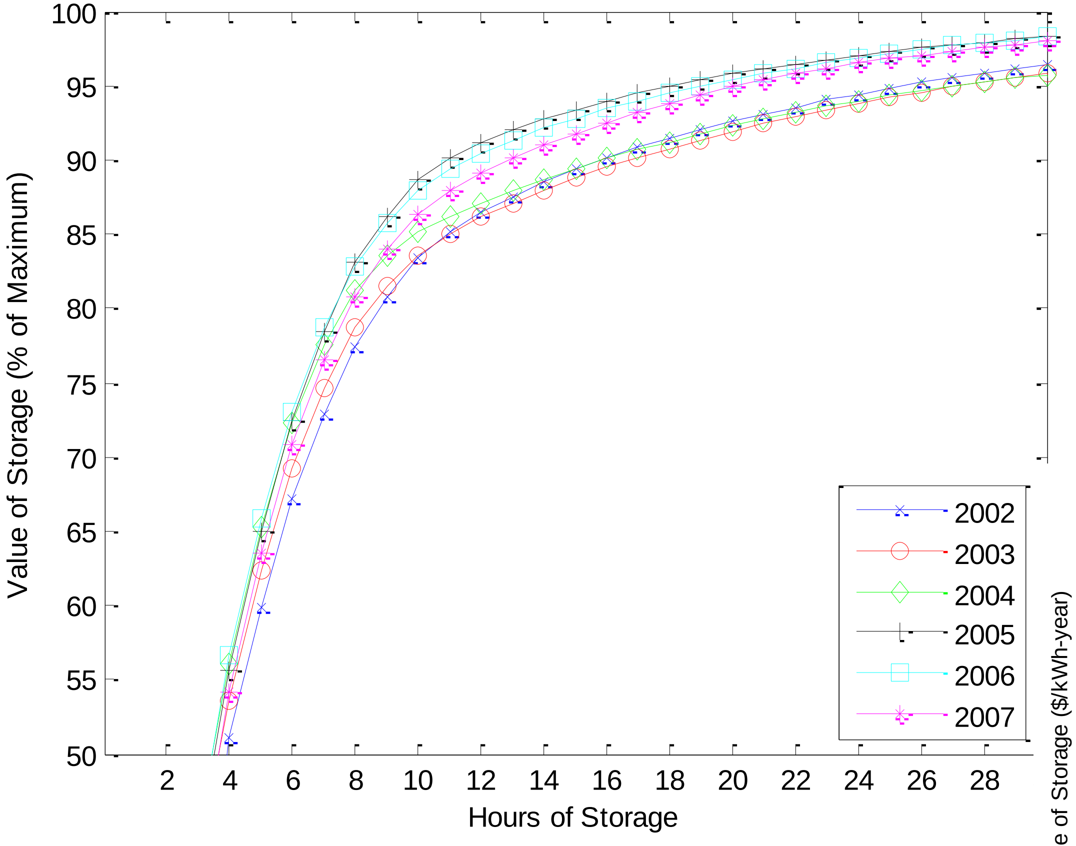
2006



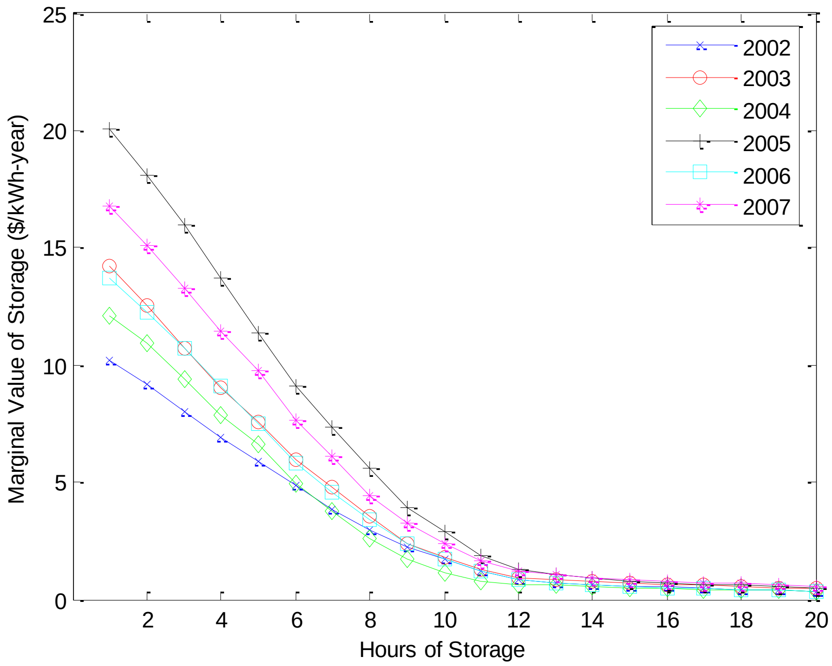
2007

Sioshansi, Denholm & Jenkin (2009) The Value of Electricity Storage in PJM: Arbitrage and Some Welfare Effects.

Sizing Optimization

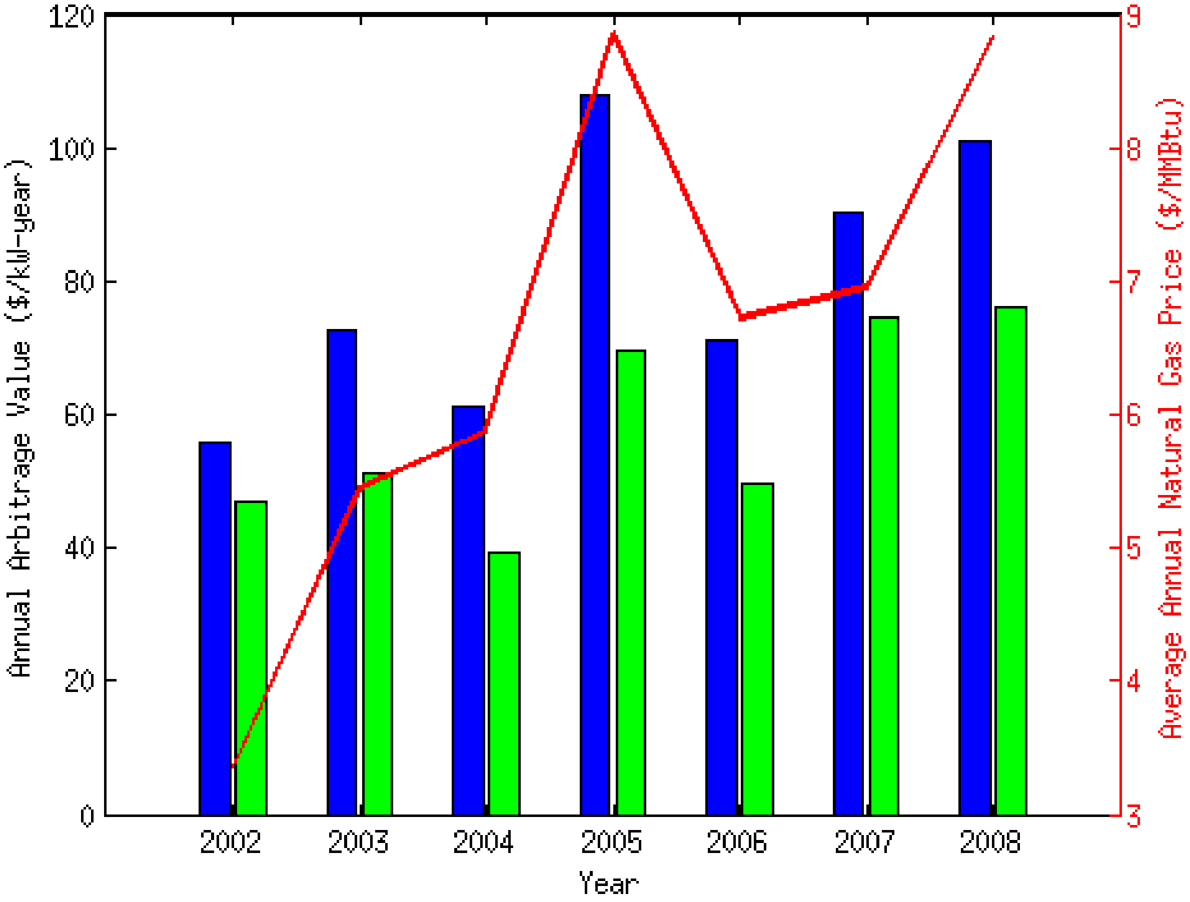


Total Value



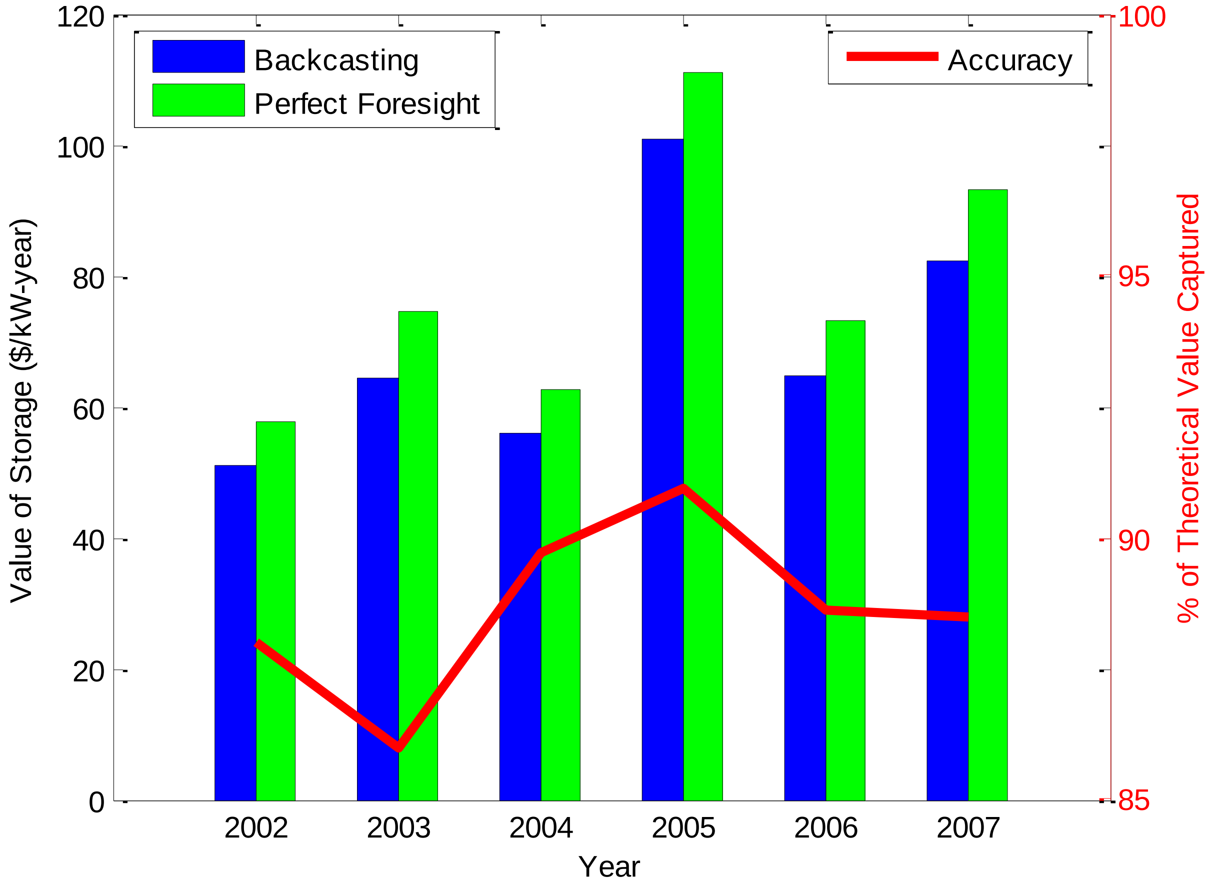
Marginal Value

Comparison of CAES to Pure Storage



Blue=PHS Green = CAES

Forecasting & Uncertainty Analysis



What we have learned

- Arbitrage value is volatile
- Depends highly on location
- Price patterns are reasonably predictable
- First few hours get most of the value

- AND

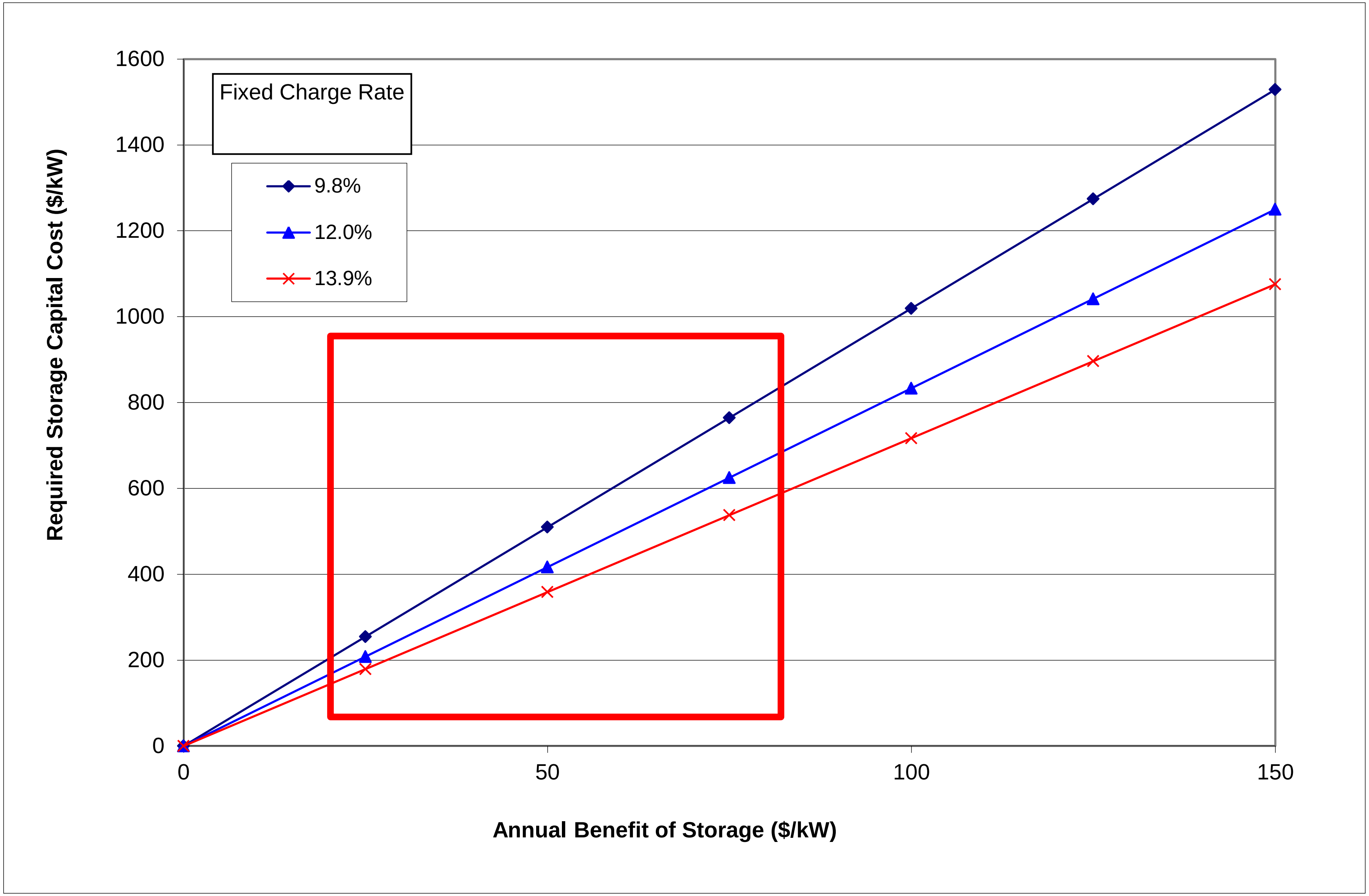
- None of this makes very much money

Arbitrage Estimates

Location	Years Evaluated	Annual Value ($/kW)	Assumptions
PJM[a]	2002-2007	$60-$115	12 hour, 80% efficient device. Range of efficiencies and sizes evaluated
NYISO[b]	2001-2005	$87-$240 (NYC) $29-$84 (rest)	10 hour, 83% efficient device. Range of efficiencies and sizes evaluated.
USA[c]	1997-2001	$37-$45	80% efficient device, Covers NE, No Cal, PJM
CA[d]	2003	$49	10 hour, 90% efficient device.
CA[f]	2010-2011	$25-41	4 hour, 90% efficient device

[a] Sioshansi et al. 2009
[b] Walawalkar et al. 2007
[c] Figueiredo et al. 2006
[d] Eyer et al. 2004
[f] Byrne and Silva-Monroy 2012

Supported Capital Cost



Why So Low?

1. Relatively few hours of really high prices
2. Periods of high on-peak prices may have high off-peak prices
3. Periods of low off-peak prices have low on-peak prices
4. Relies on scarcity pricing which may not support adequate capacity payments
    - "Missing Money" Problem
5. Misses other sources of benefits from load-leveling

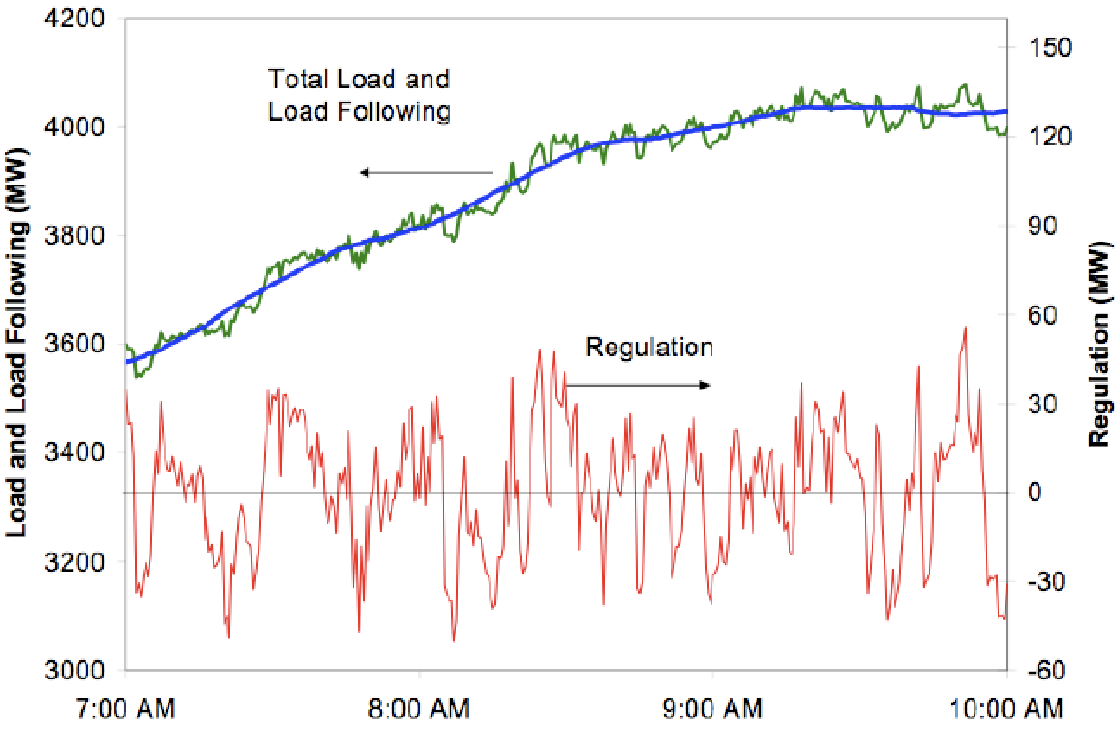
Reserves to the Rescue?

- Ancillary Services and Operating Reserves
- Provide stable and reliable operation
  - Voltage and reactive power support
  - Frequency Regulation
  - Spinning Reserve
  - Operating Reserve
  - Black Start

Regulation and Spinning Reserves

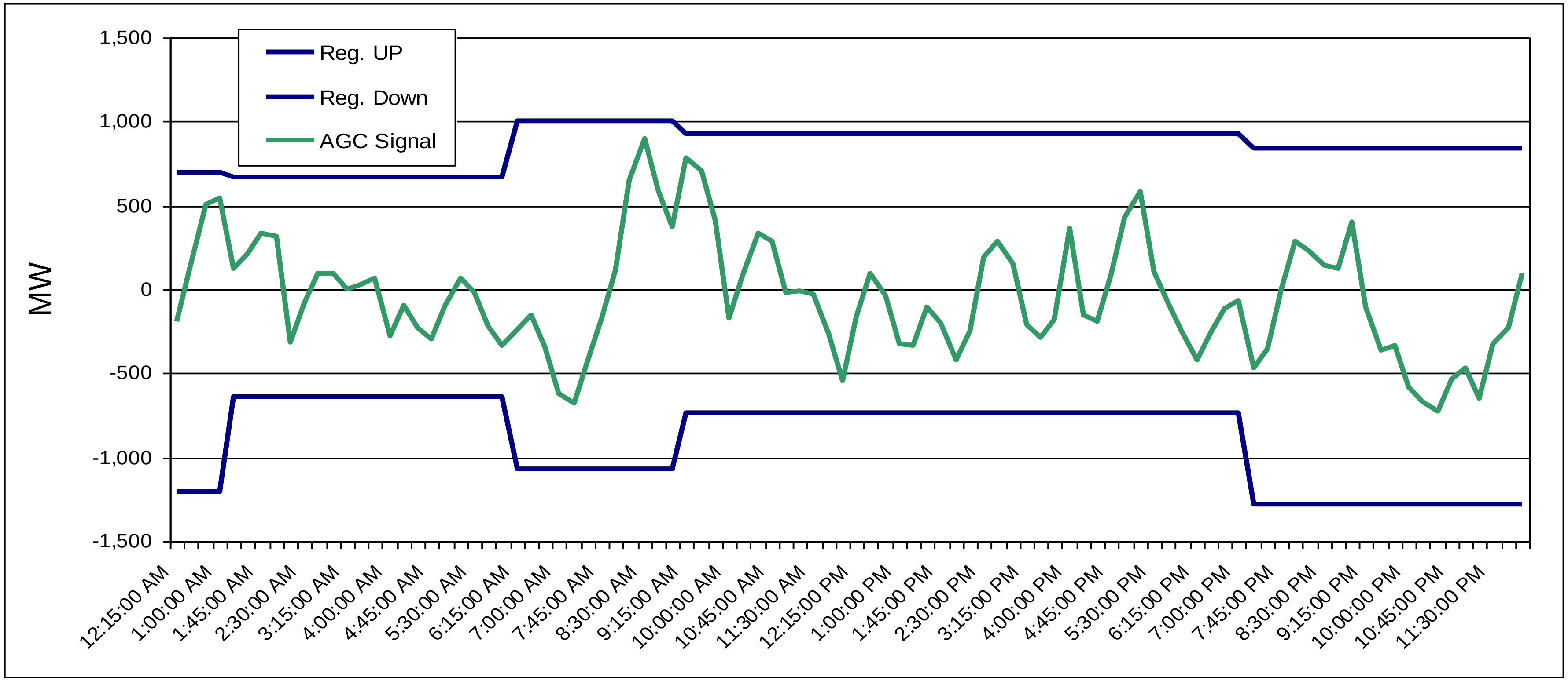
- Not uniformly defined
- Frequency Regulation
  - Serves the random, rapid variation around the normal load
  - Highest value
- Contingency Reserve (often referred to as spinning reserves)
  - Quickly replaces a lost generator or transmission line
  - Infrequently called ~ 1x/week for about 10 minutes

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

Actual Deployment



ERCOT Regulation: Requirement vs. Deployed

Spinning Reserves

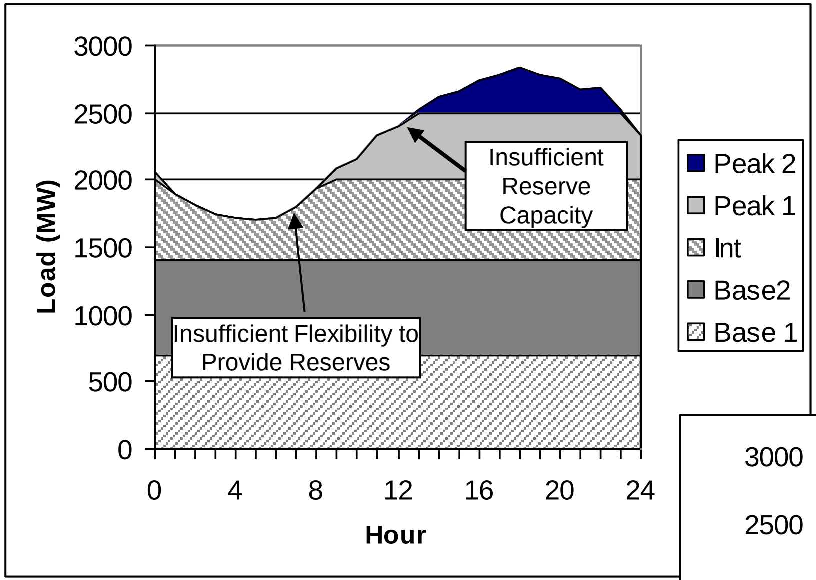
Spinning reserve

- Generators that are running and ready to provide energy OR responsive load that can be dropped within a few minutes
- Infrequently called upon, and are the first to be restored when a contingency occurs

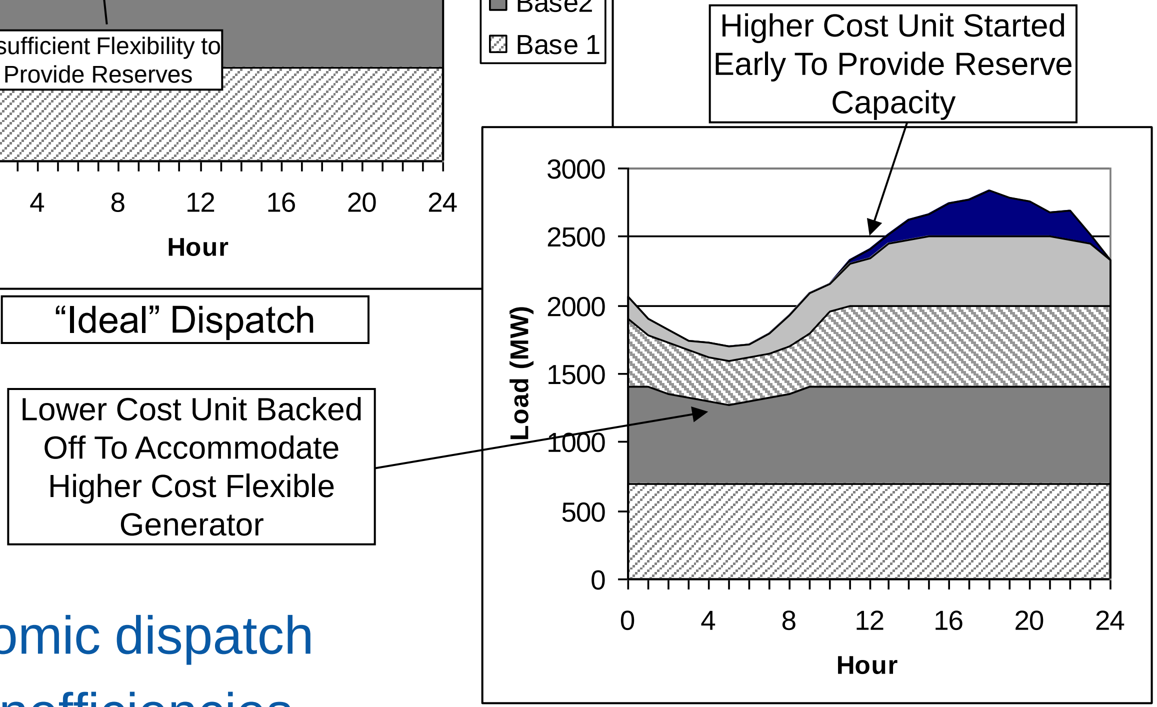
PJM Example:

Year	Number of Events	Total Duration	Average Duration
2006	39	6 hours	9 minutes
2005	93	19 hours	12 minutes

Reserve Requirements Add Costs



"Ideal" Dispatch



Reserve Constrained Dispatch

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

Reserve Prices in Restructured Markets

SUM of:

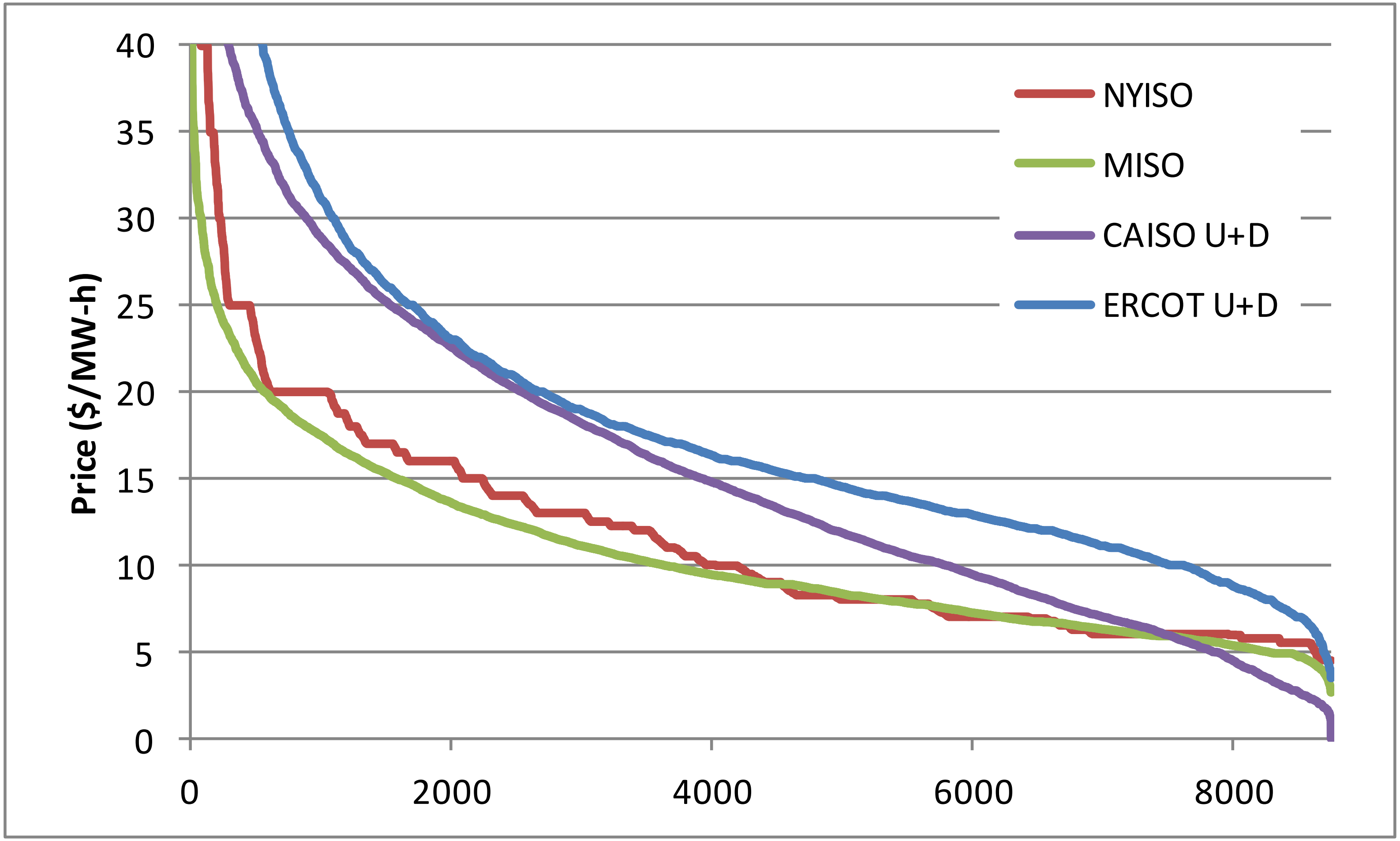
1. Bid Price
   - Real cost of providing reserve service including O&M, heat rate impacts
   - May only apply to regulation depending on market
2. Opportunity Cost (calculated by SO)
   - Should include part-load operation
   - Will include scarcity prices

Plus actual energy payments

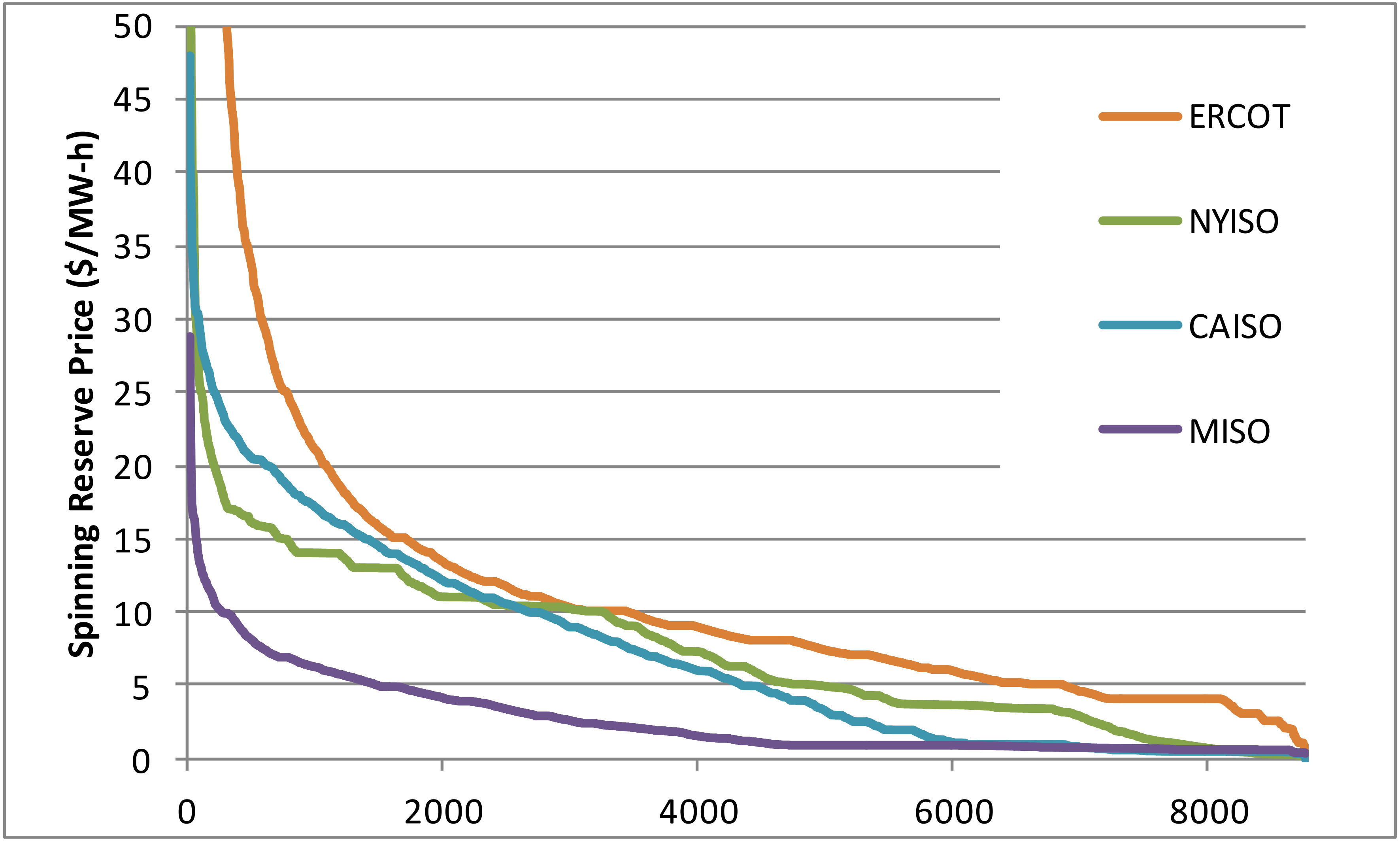
Reserve Prices

	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Annual Average and Maximum $/MW-hr								
	California								
Regulation up+down	35.5 164	28.7 166	35.2 188	38.5 399	26.1 421	33.4 618	12.6 500	10.6 124	16.1 120
Spin	6.4 92	7.9 125	9.9 110	8.4 225	4.5 400	6.0 400	3.9 416	4.1 66	7.2 48
	ERCOT								
Regulation up+down	16.9 177	22.6 156	38.6 1451	25.2 351	21.4 322	43.1 534	17.0 528	18.1 517	31.3 2744
Responsive	7.3 150	8.3 51	16.6 731	14.6 351	12.6 100	27.2 2000	10.0 185	9.1 125	22.9 2606
	New York East								
Regulation	28.3 195	22.6 99	39.6 250	55.7 250	56.3 300	59.5 300	37.2 500	28.8 250	11.8 95
Spin	4.3 55	2.4 44	7.6 64	8.4 171	6.8 53	10.1 68	5.1 39	6.2 63	7.4 81
	MISO (Day Ahead)								
Regulation							12.3 52	12.2 102	10.8 102
Spin							4.0 39	4.0 34	2.8 29
	New England								
Regulation (+"mileage")		54.6 344	30.2 561	22.3 100	12.7 100	13.8 100	9.3 100	7.1 82	7.2 95
Spin				0.3 72	0.4 179	1.7 716	0.7 121	1.8 638	1.0 418

2011 Prices for Regulation



2011 Prices for Spin



Requirements for Storage Providing Reserves

1. Synchronized
2. Response Rate
3. Sufficient Energy
   - Time?
   - Net zero energy for regulation?
   - 1 Hour or less should be sufficient
4. Mileage Payments
   - FERC 755 compliance underway

Common Assumptions for Estimating Value

- Spin = zero energy
- Regulation = zero NET energy
  - Makeup energy = Capacity Bid * hours called * regulation dispatch fraction * losses
  - Regulation dispatch fraction ~10%- 25%
  - Losses = 1-effficiency

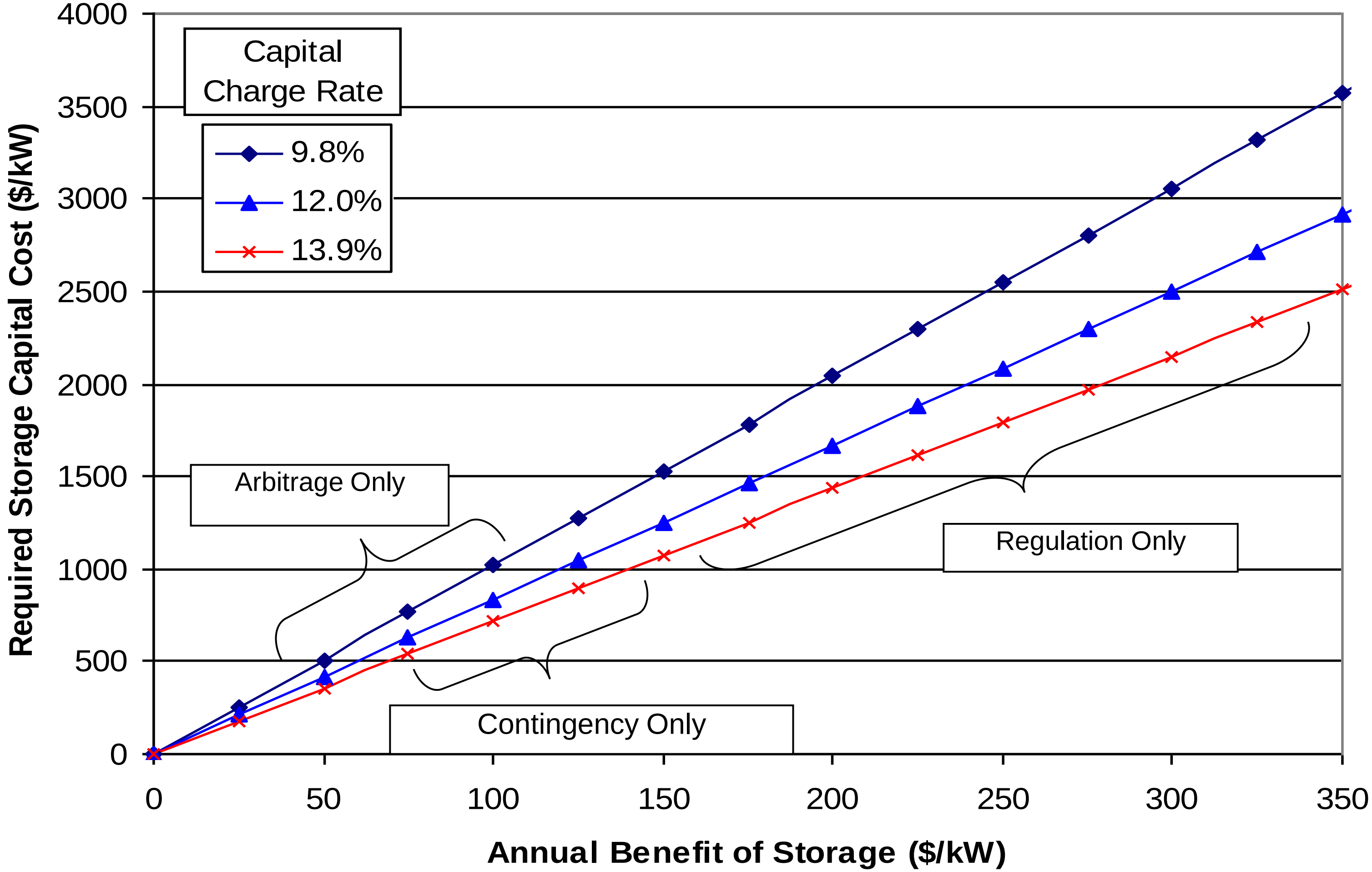
Value of Reserves in Restructured Markets

Historical Values of Energy Storage in Restructured Electricity Markets

Market Evaluated	Location	Years Evaluated	Annual Value ($/kW)	Assumptions
Regulation	NYISO[b]	2001-2005	$163-248	
	USA[e]	2003-2006	$236-$429	PJM, NYISO, ERCOT, ISONE
Contingency Reserves	USA[e]	2004-2005	$66-$149	PJM, NYISO, ERCOT, ISONE

[a] Sioshansi et al. 2009
[b] Walawalkar et al. 2007
[c] Figueiredo et al. 2006
[d] Eyer et al. 2004
[e] Denholm and Letendre 2007

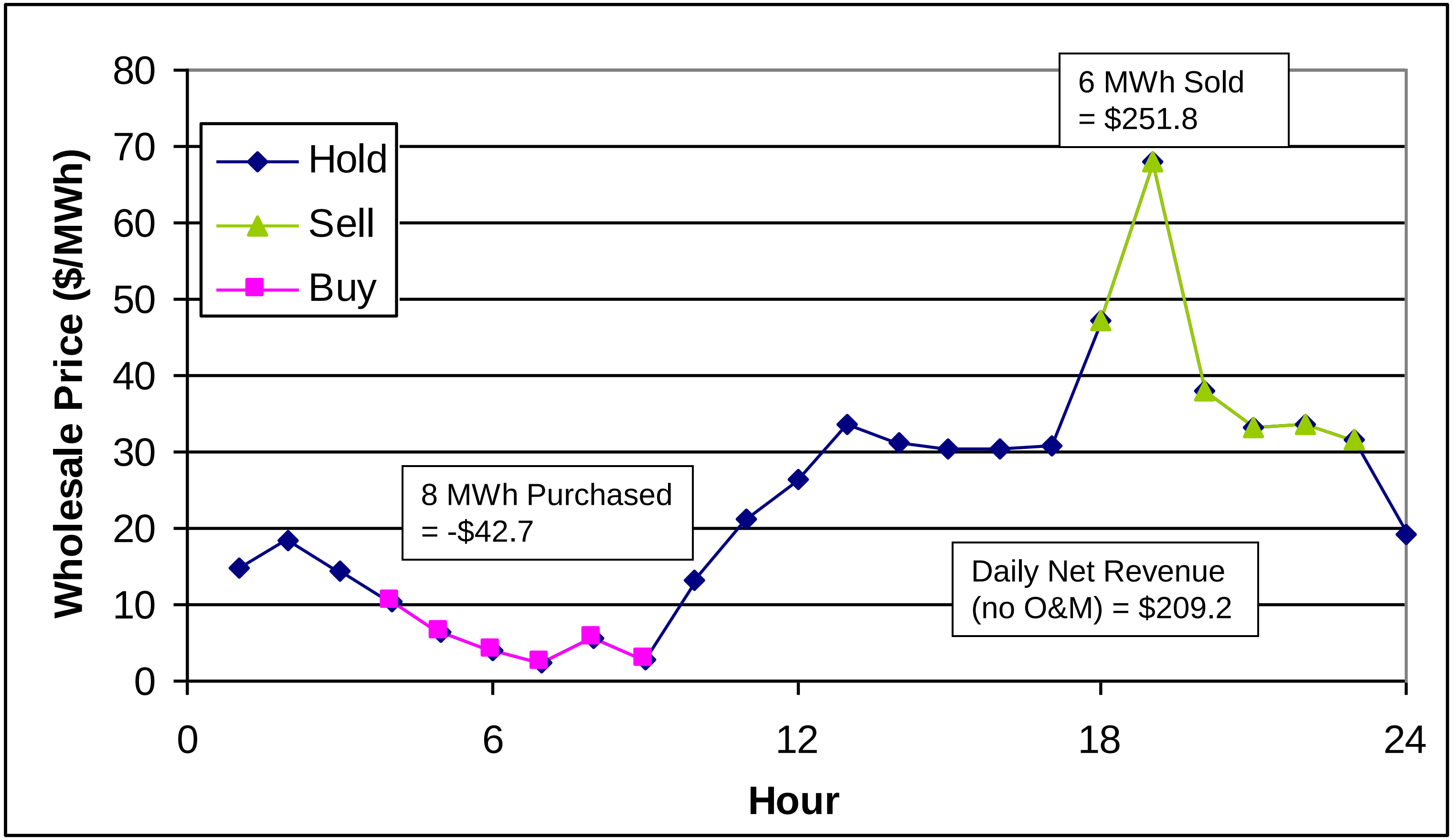
Historical Value of Energy Storage in U.S. Markets



Co-Optimization

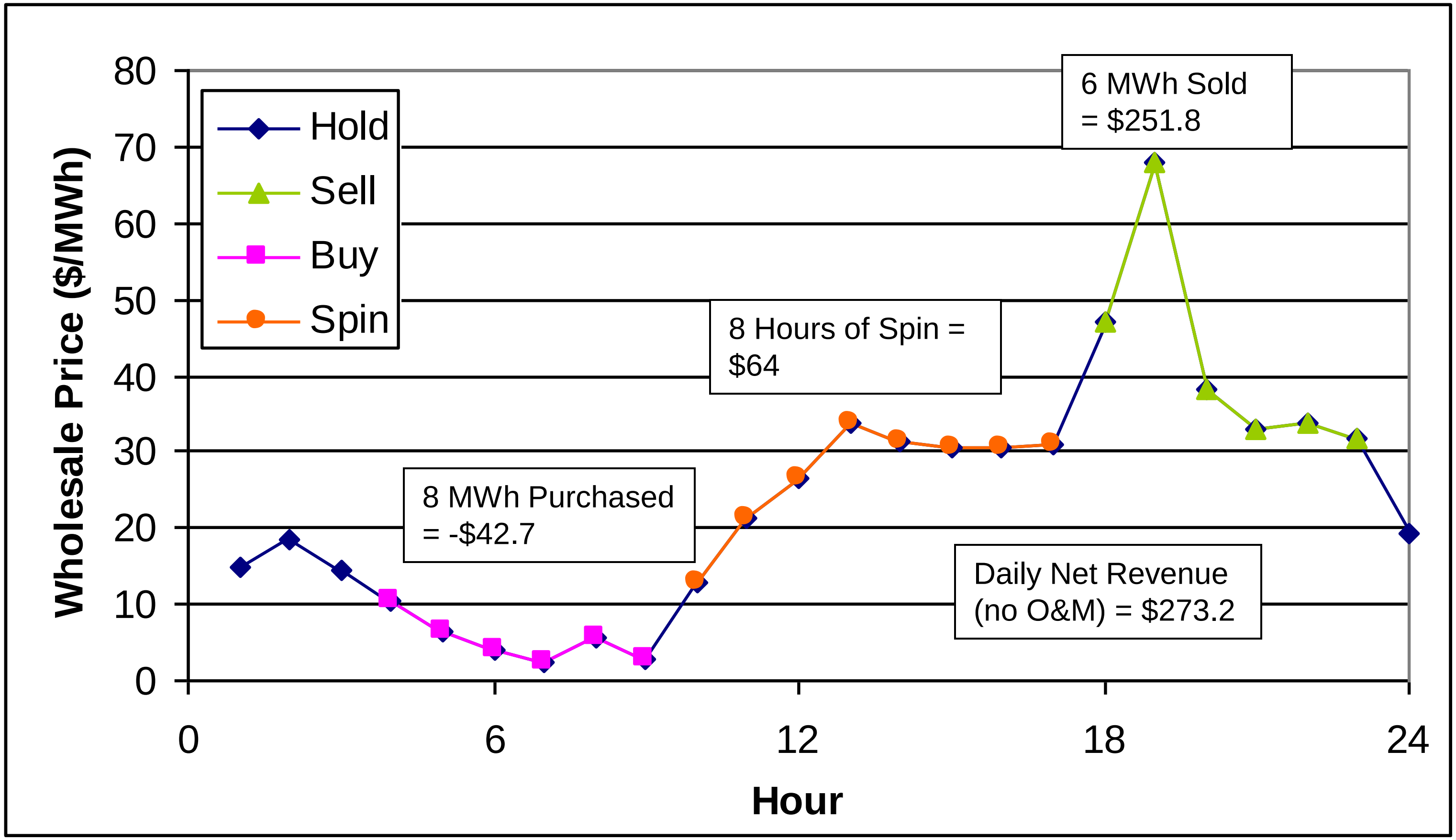
- Storage can provide multiple services simultaneously or sequentially
- Must consider double counting
- Must consider additional energy requirements (worth adding multiple hours of storage?)
- Most suited for devices designed primarily for energy/peak capacity services such as PHS and CAES
  - But may require operation at part load

Example: Arbitrage Only



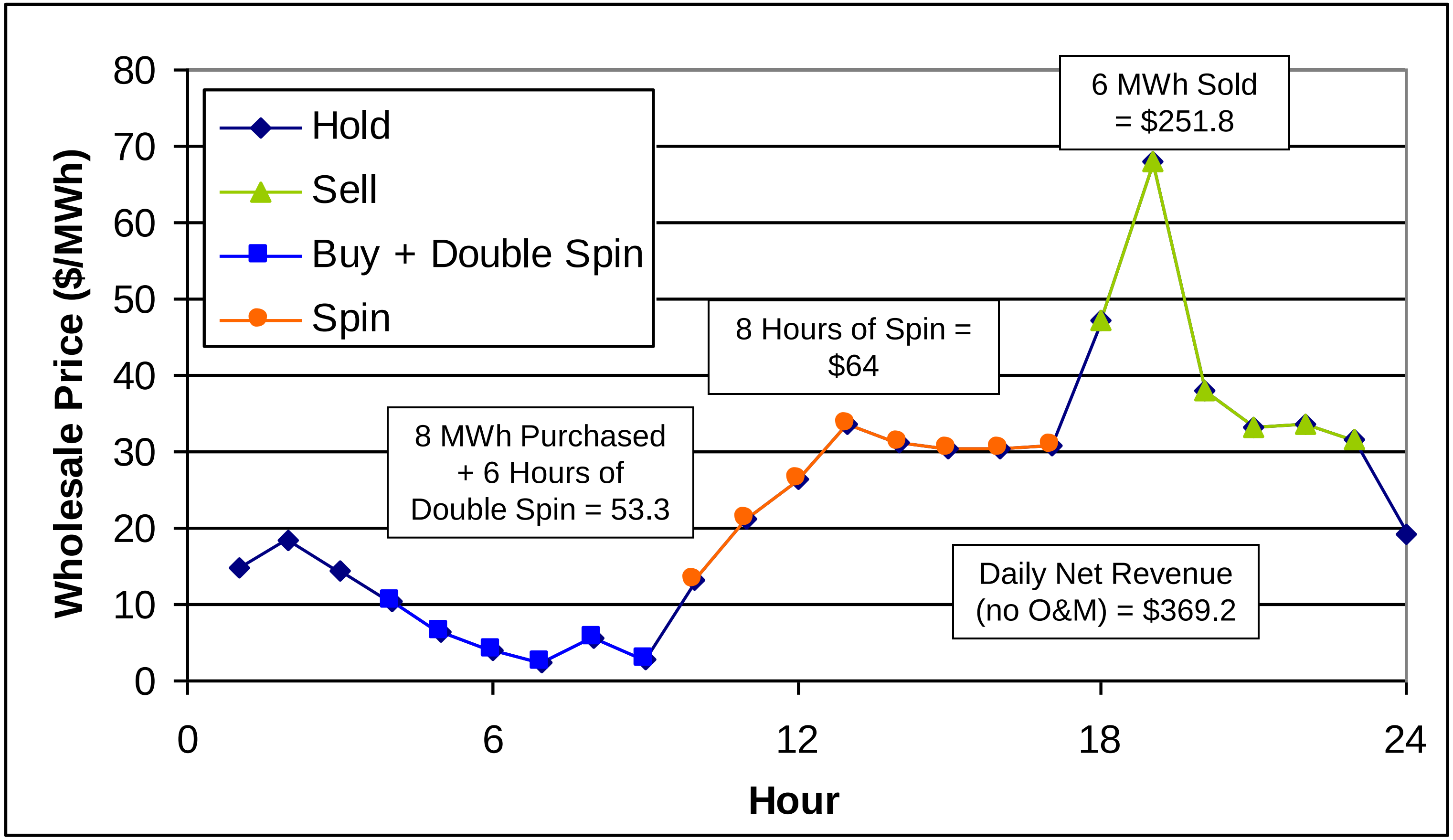
1 MW, 6 MWh Device, 75% efficiency

Add Spinning Reserves..



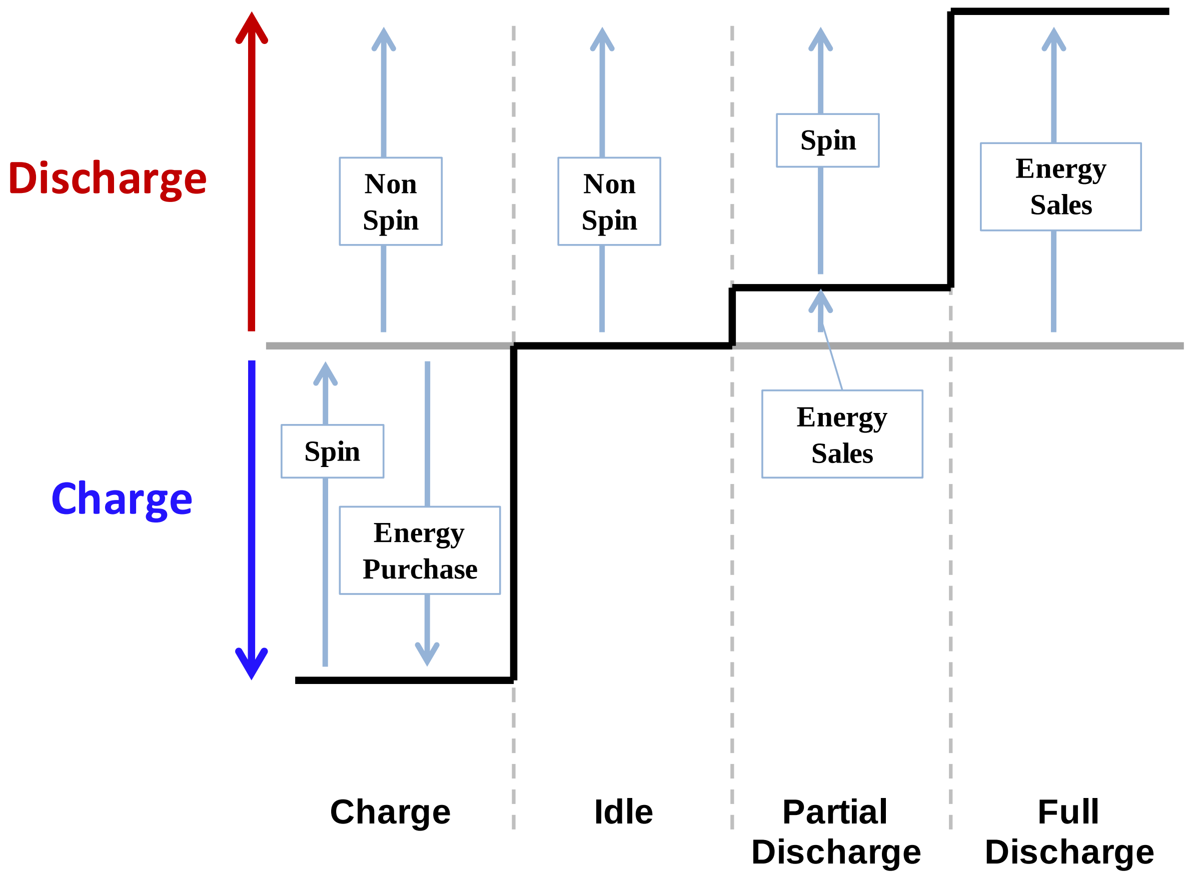
1 MW, 6 MWh Device, 75% efficiency

"Double Spin"



Revenues have increased 76% by combining services

Co-Optimization of Energy and Ancillary Services



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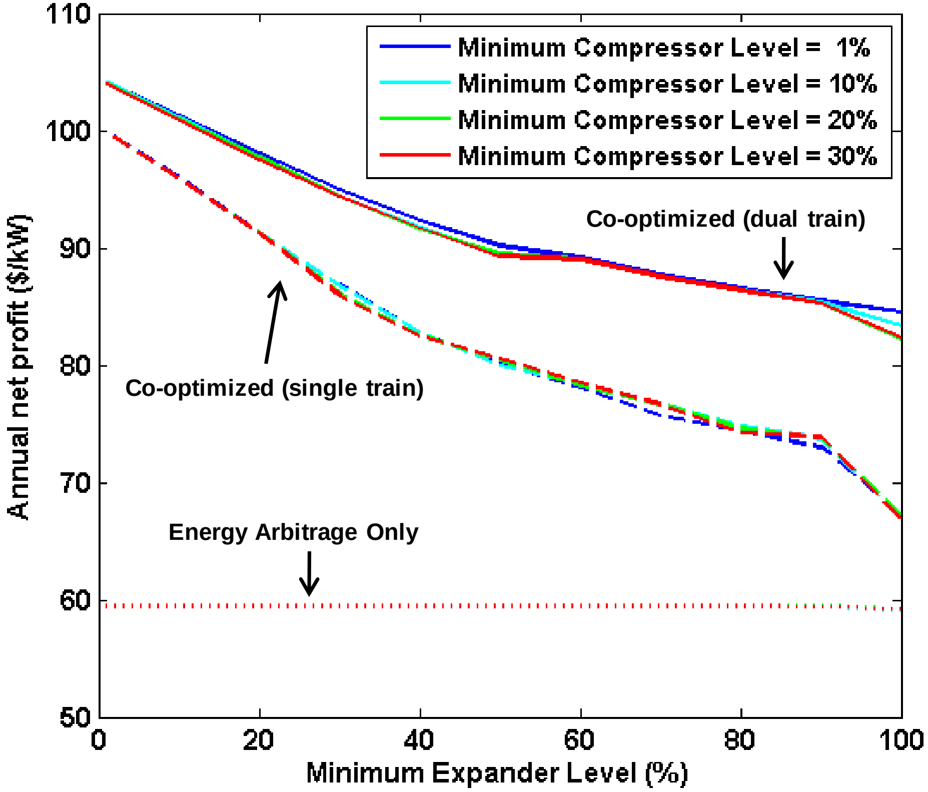

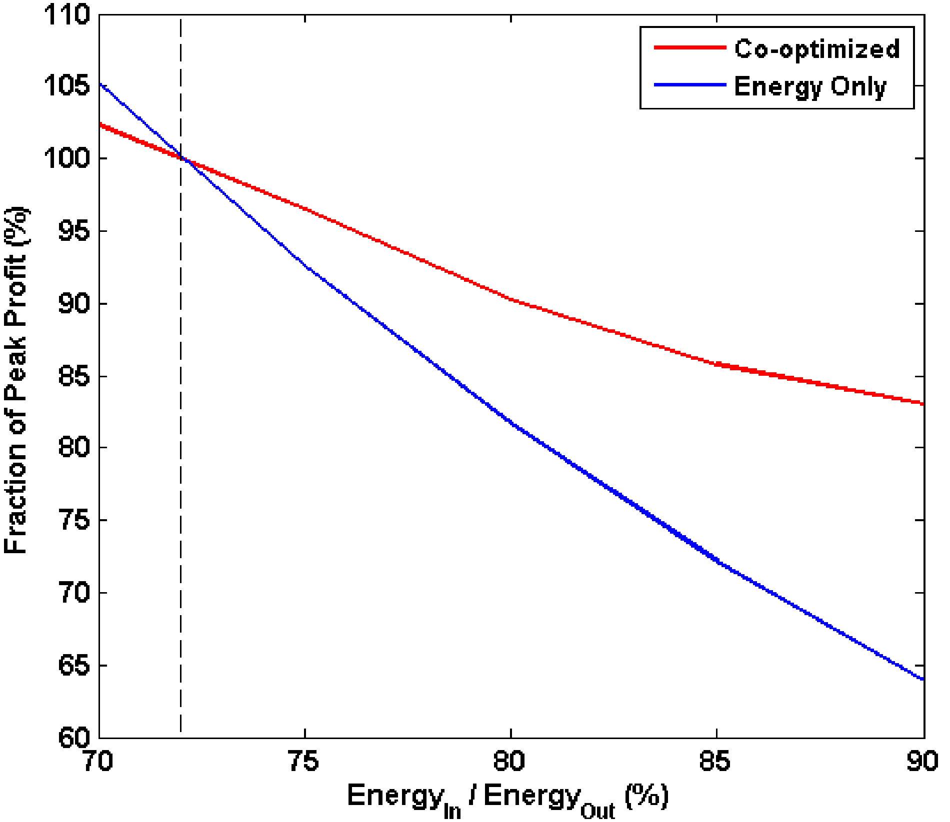

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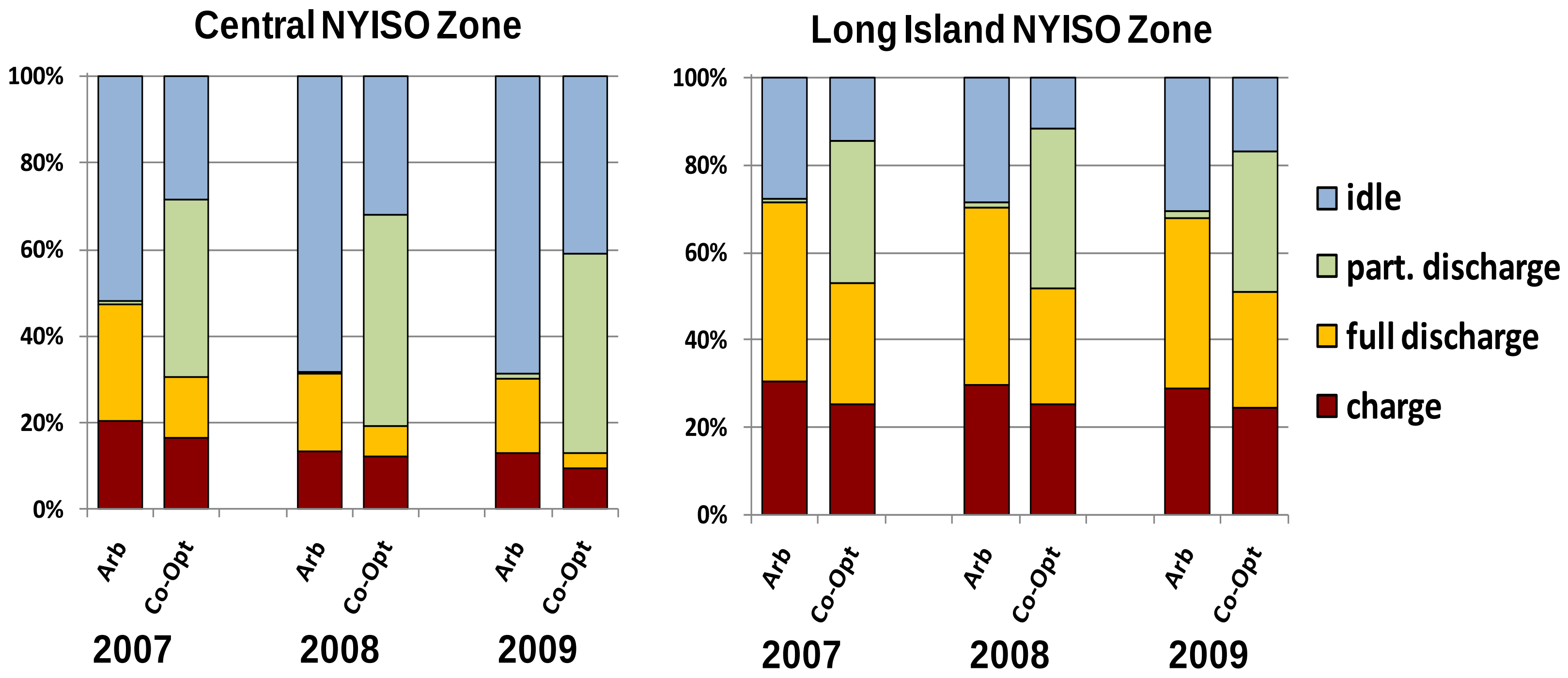

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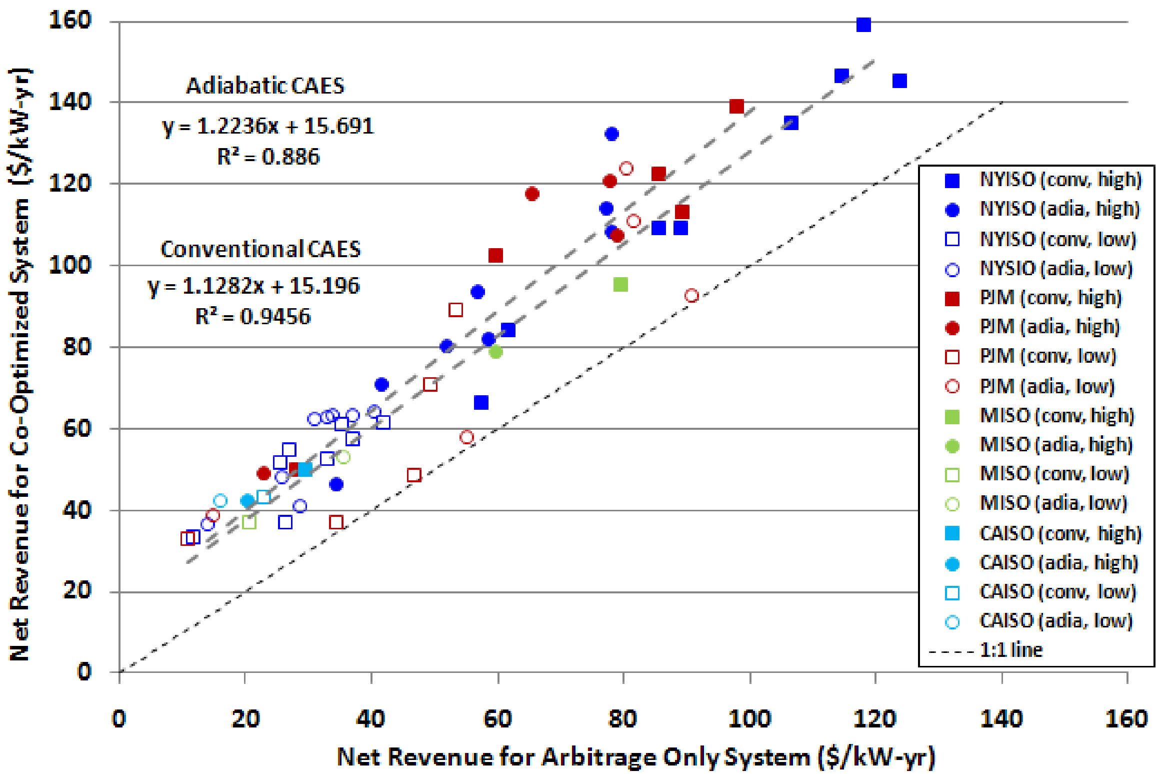
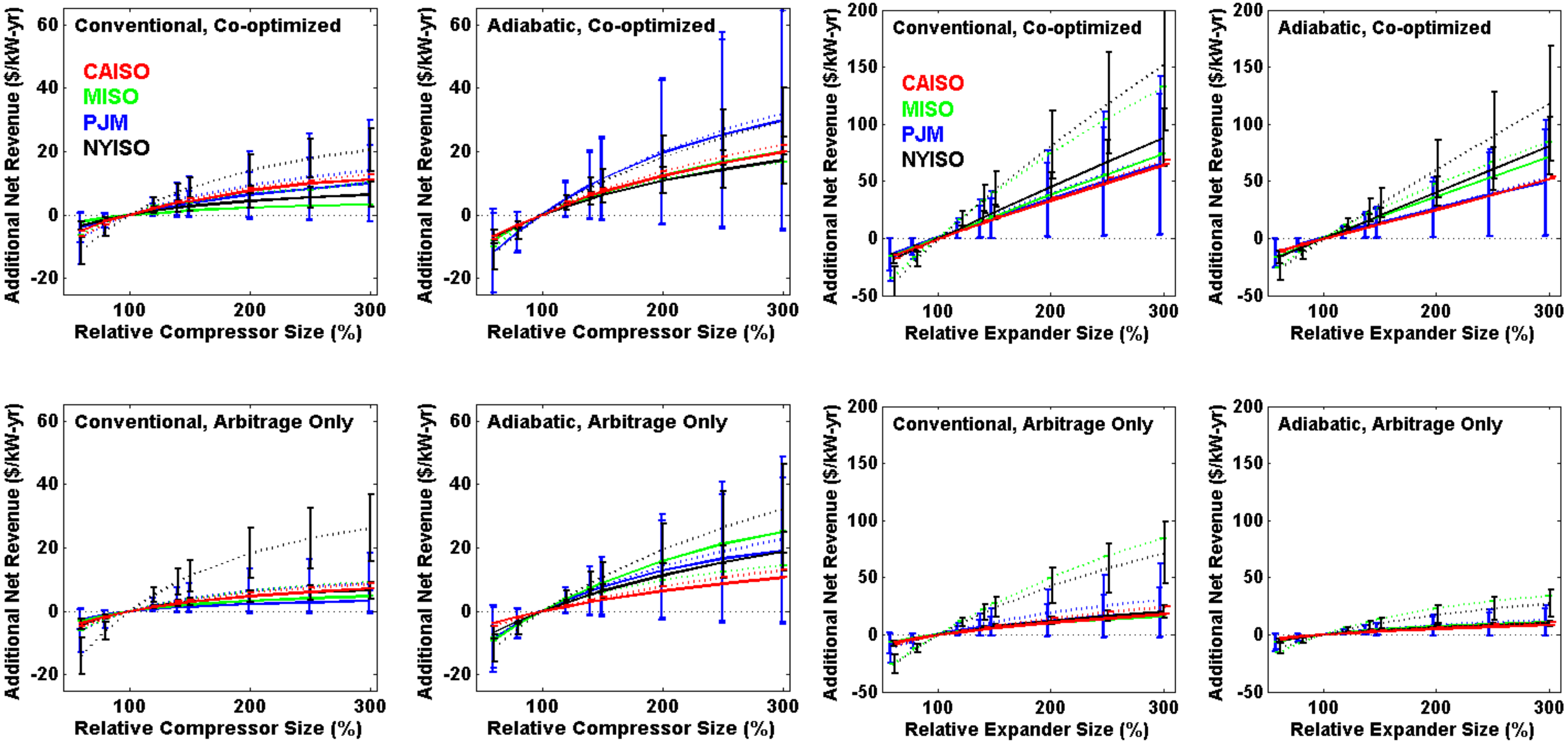


Operating reserves add ~$25/kw-year for a CAES device

Optimized CAES Configuration



General Conclusions about Market Value

- Arbitrage revenues are too small
- Regulation revenues may be sufficient but market is very small
- Overall additional revenue streams are needed
  - Capacity
  - Other benefits not currently captured

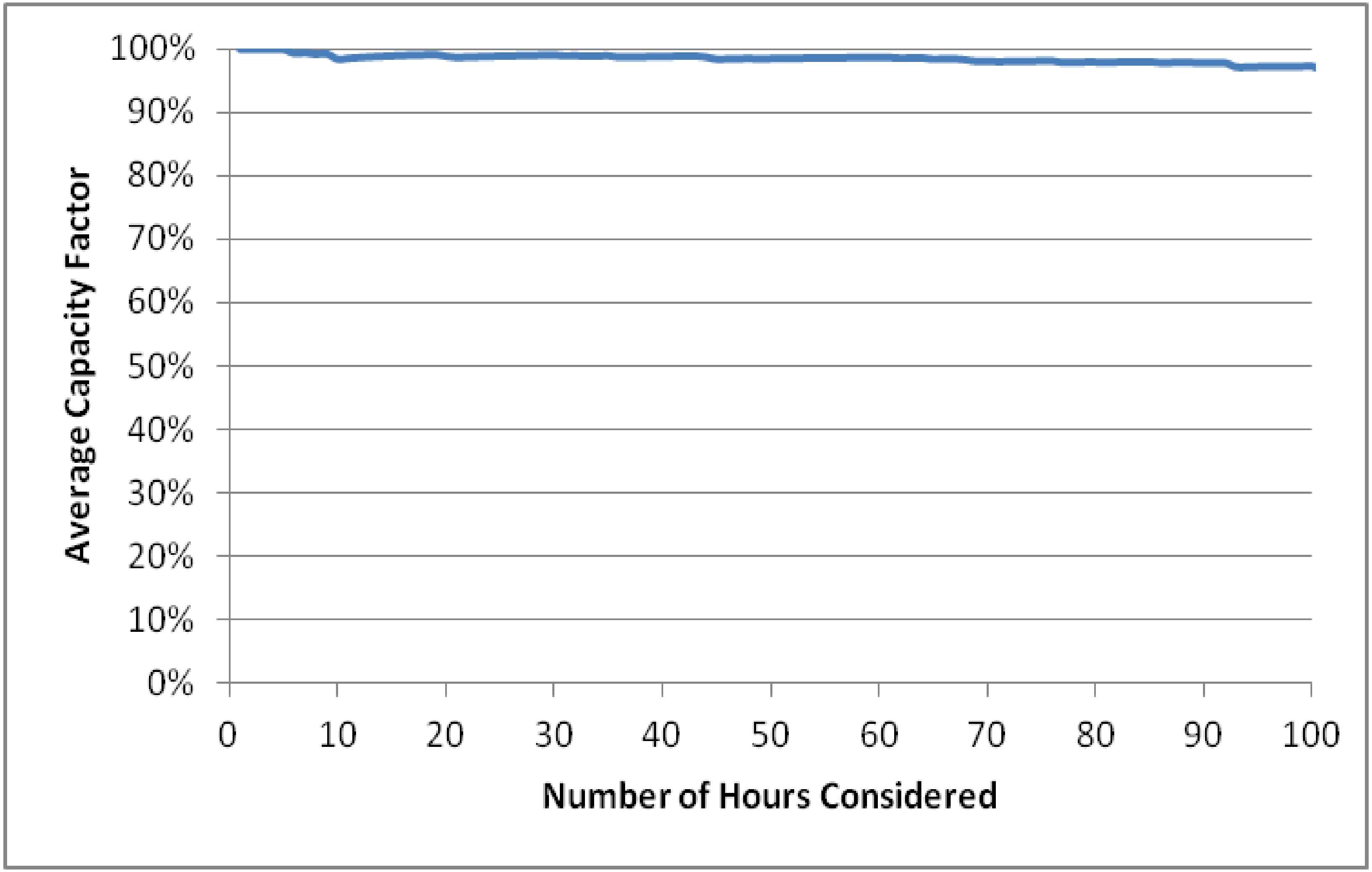
System Value Analysis

- Use additional tools to evaluate overall benefits of energy storage
- Capturing some of these would require changes in regulation
- Examples:
  - System planning capacity or reserves capacity (ensure adequate capacity value)
  - Start-up costs
  - Impact of price suppression
  - T&D deferral and loss avoidance
  - Other benefits on the distribution system
  - RE integration

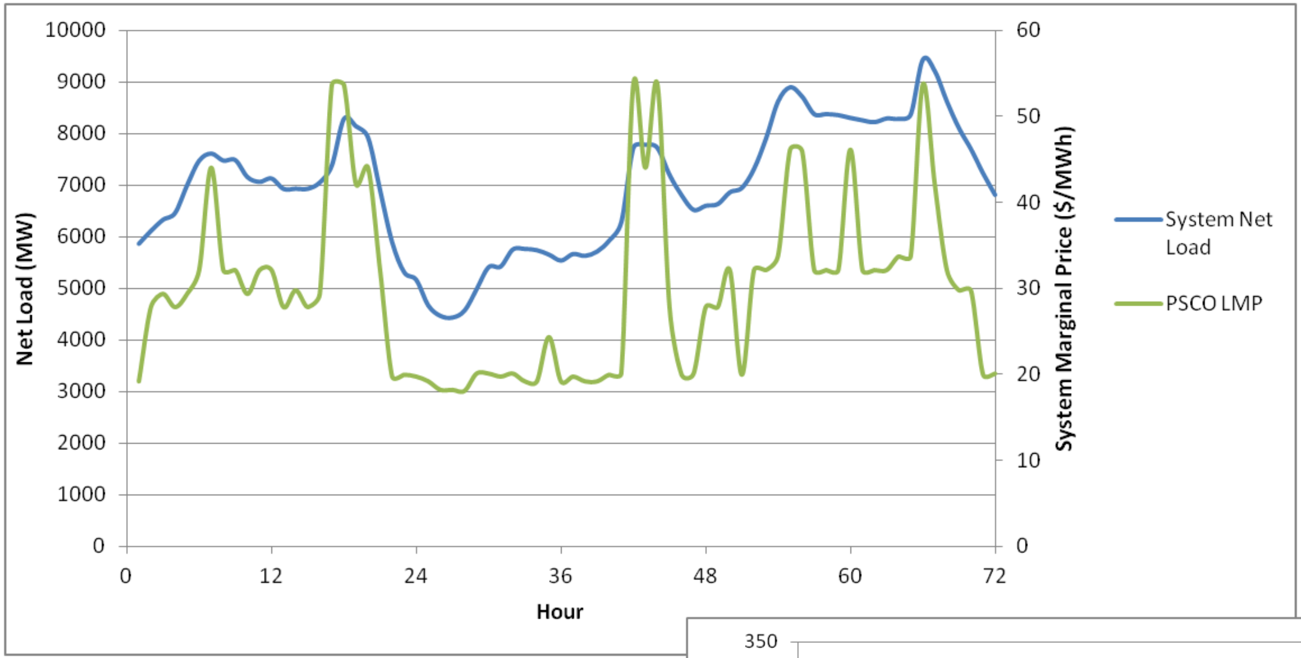
Example

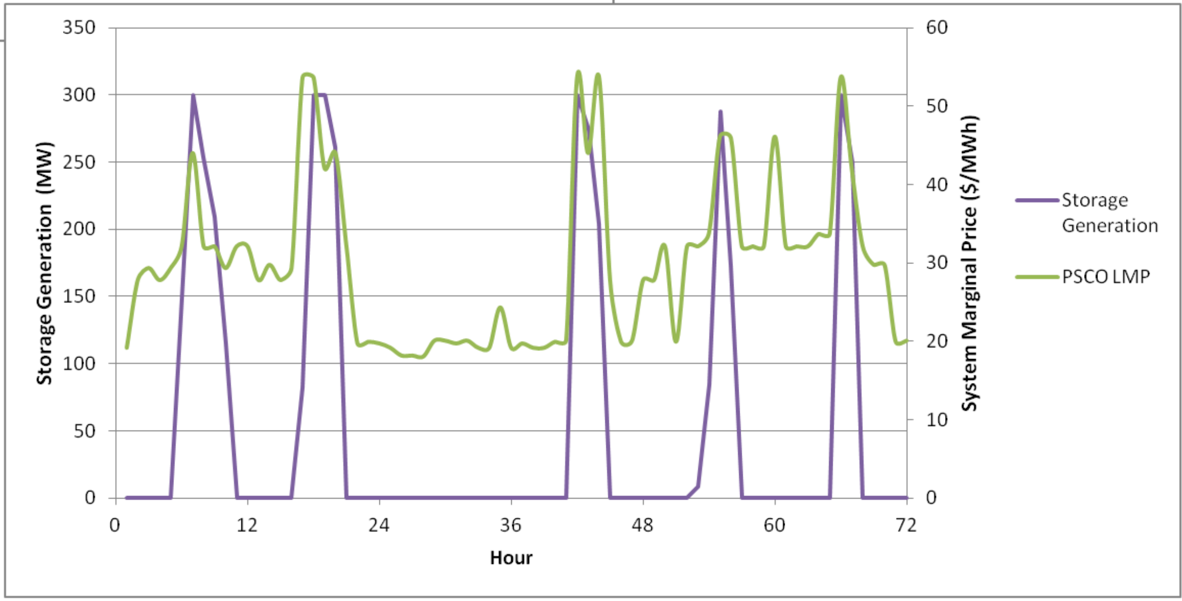
- System value of storage in a system
  - Example of storage value in Colorado
  - Security Constrained Unit Commitment and Dispatch
  - Examine “whole grid” impacts of RE and storage

Capacity Value



Value of Avoided Starts





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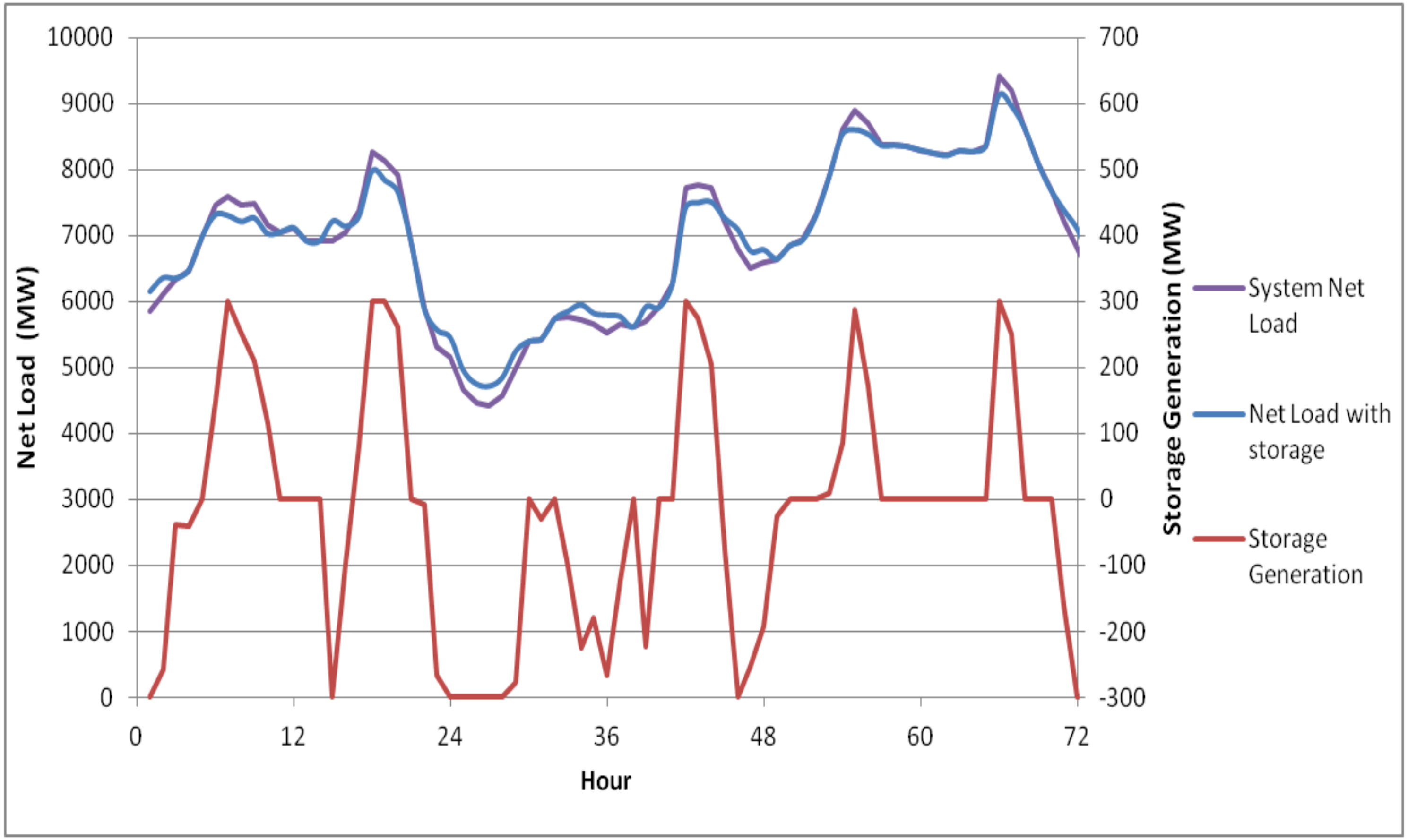


Total Value

	Base Case	With Storage (300 MW)	Increase with Storage
Generation (GWh)			
Coal	45,861	46,159	298
Hydro	3,792	3,792	-
Gas CC	14,972	15,164	192
Gas CT	1,098	784	-314
Other	103	90	-13
Existing Pumped Storage	1,083	1,081	-2
New Storage	-	483	483
PV	1,834	1,834	0
Wind	10,705	10,705	0
Total Generation (GWH)	79,448	80,091	643
Fuel Use (1,000 MMBTU)			
Coal	485,134	488,604	3,470
Gas	129,501	126,936	-2,564

Total Value

	Base Case	With Storage (300 MW)	Increase with Storage
Total Fuel Cost (M$)	1,217.4	1,211.6	-5.7
Total VOM Cost (M$)	151.6	152.4	0.8
Total Start Cost (M$)	57.8	51.3	-6.5
Total Regulation “Adder” Cost (M$)	6.4	6.5	0.1
Total Production Cost (M$)	1,433.1	1,421.8	-11.3

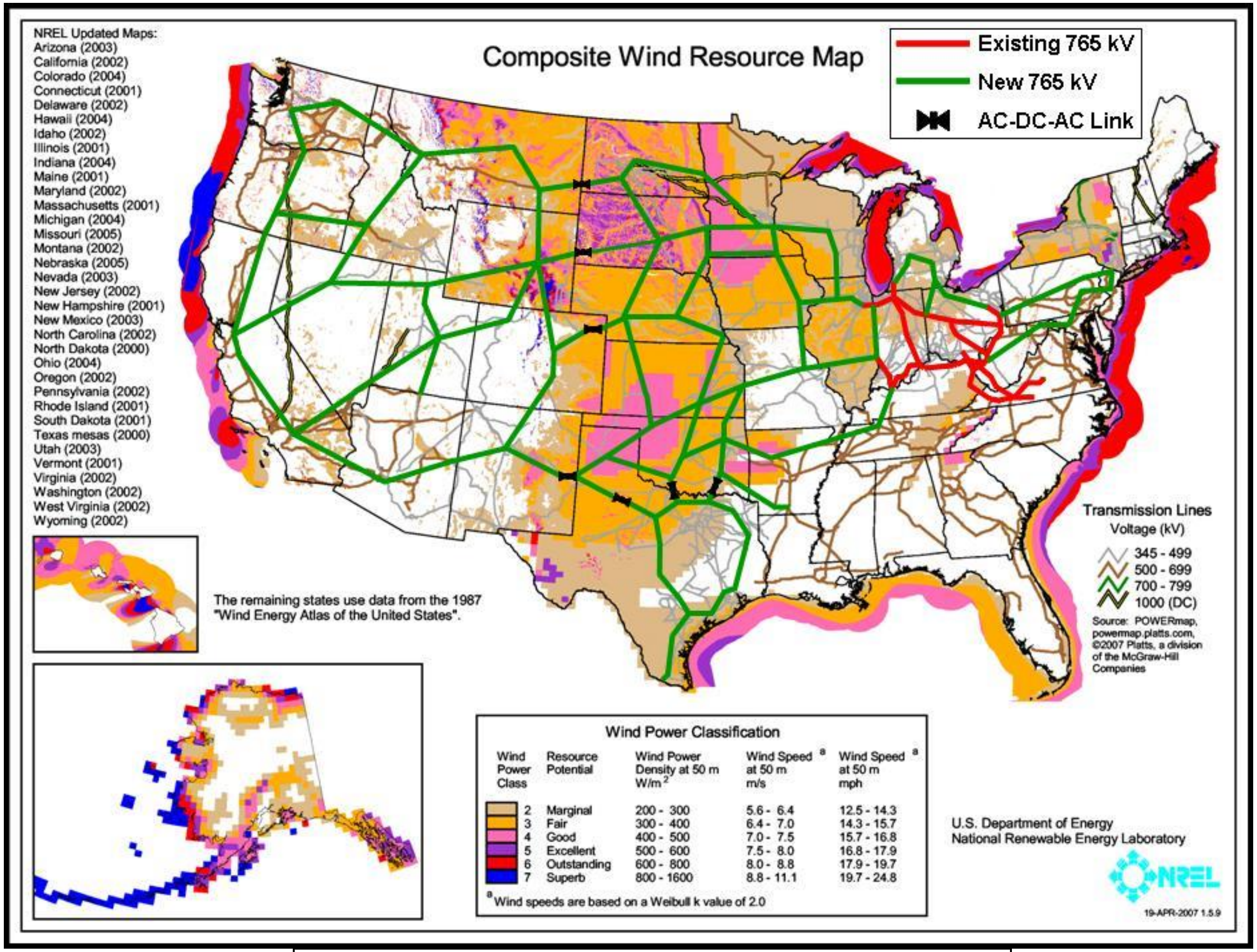
System Value = $11.3 Million
Price Taker Value = $8.5 Million
Optimized Market Value = $4.3 Million
Real Market Value = ???

THIS IS A PROBLEM!

Other sources of benefits

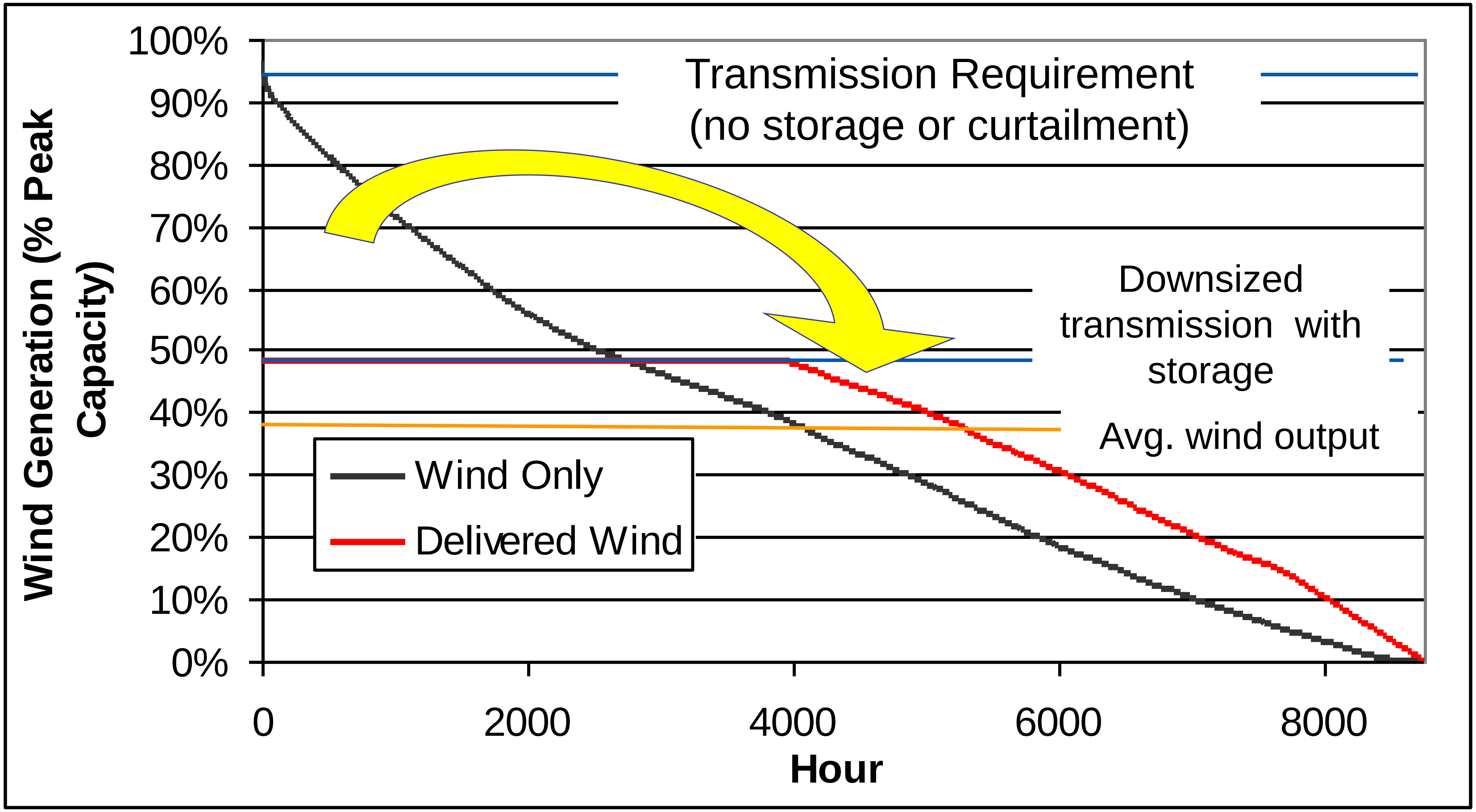
- Distribution system benefits
- Transmission deferral
- Renewable Integration

Storage as a Transmission Deferral/Alternative

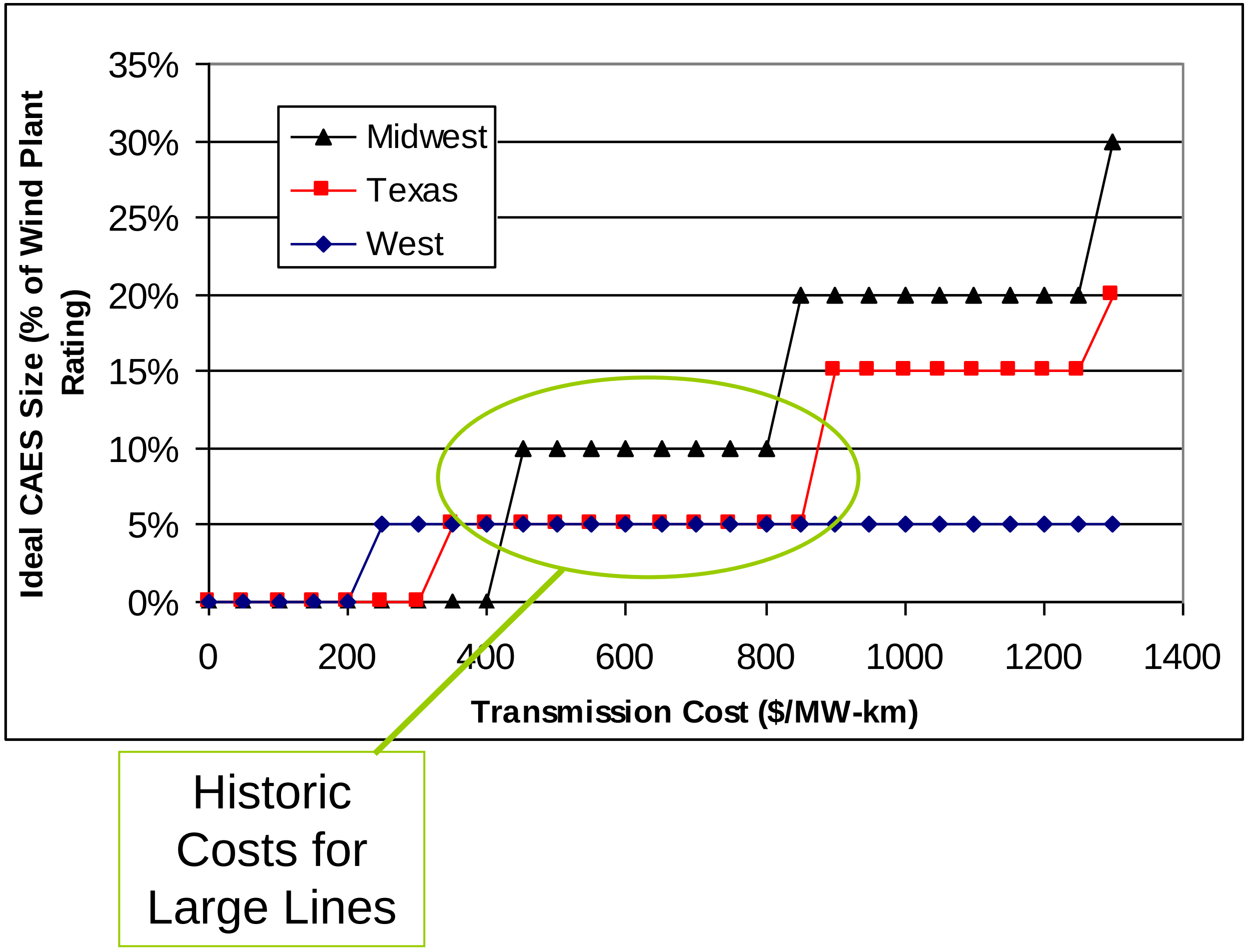


Source: AEP's Interstate Transmission Visions for Wind Integration

Storage As Transmission Alternative

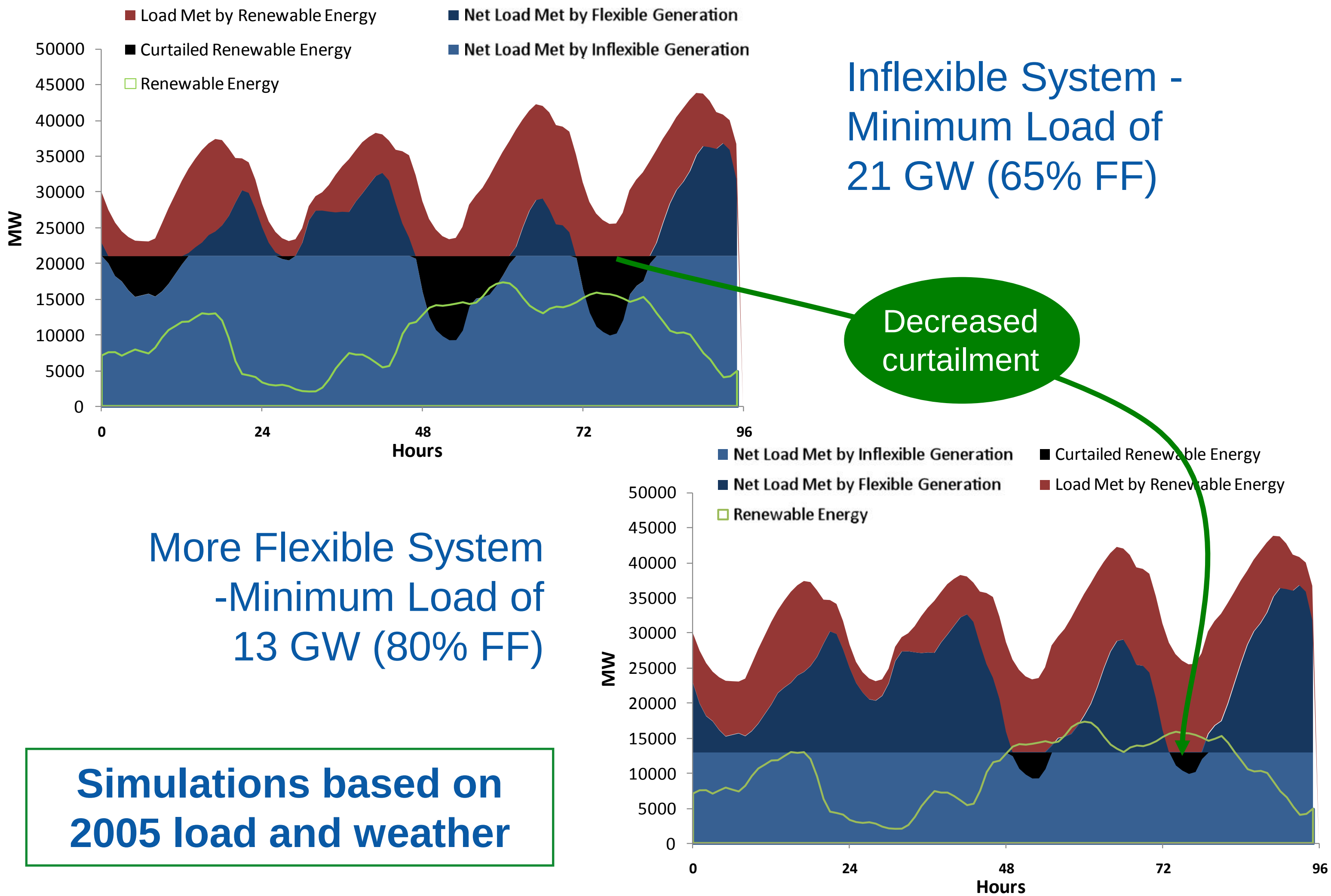


Optimum Mix of CAES and Wind



Increased Use of RE

Needed to accommodate greater amounts of VG without significant curtailment

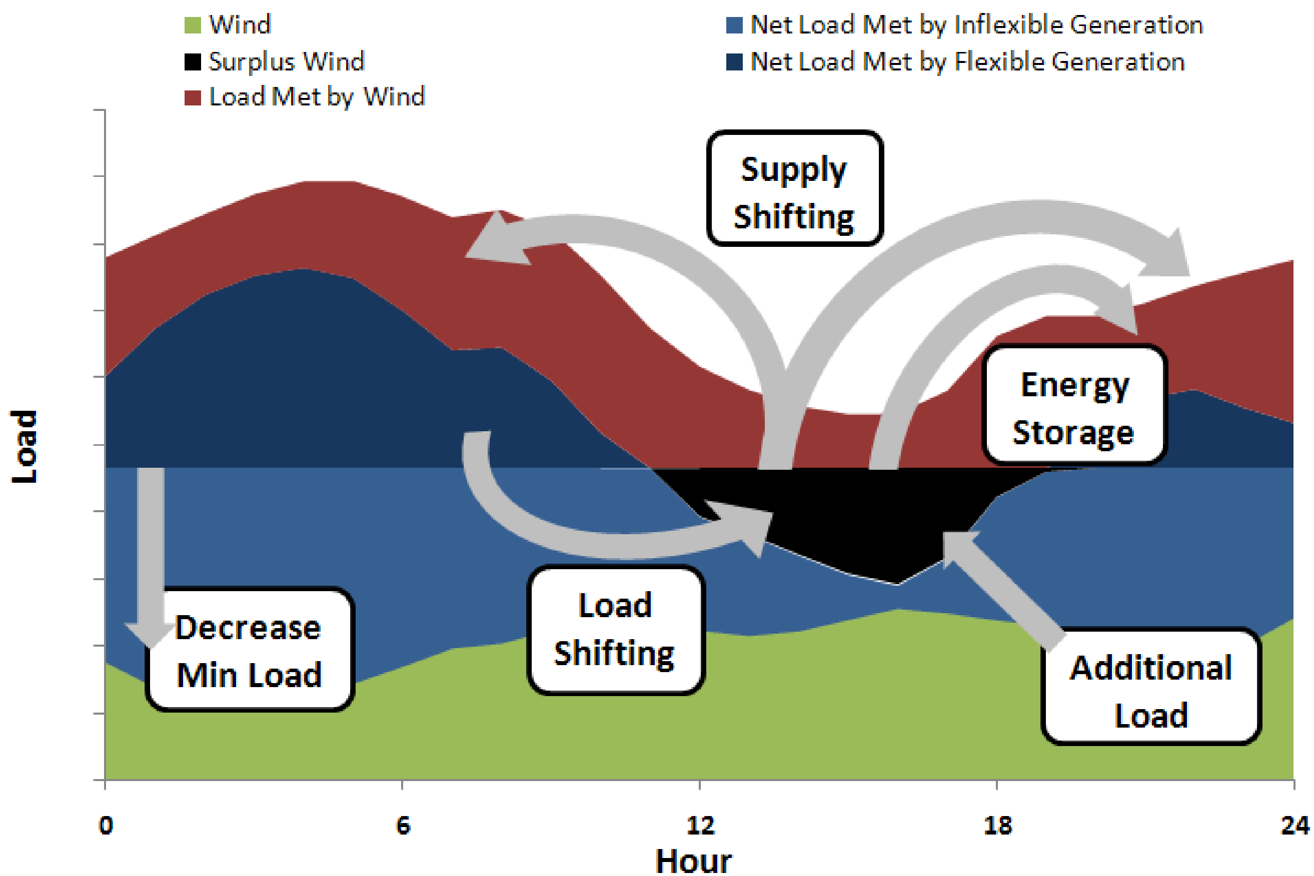


Inflexible System - Minimum Load of 21 GW (65% FF)

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

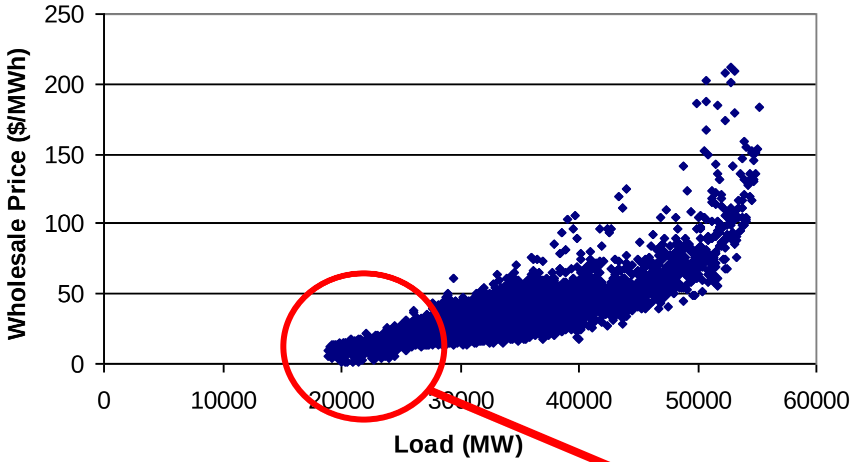
Simulations based on 2005 load and weather

Renewables-Driven Grid Applications



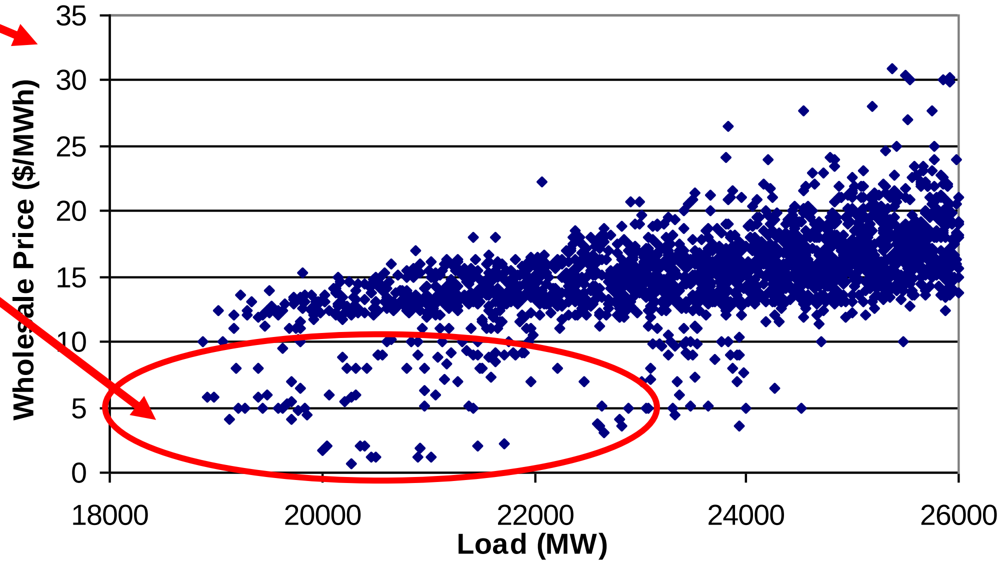
Current System Flexibility

Limited by Baseload Capacity



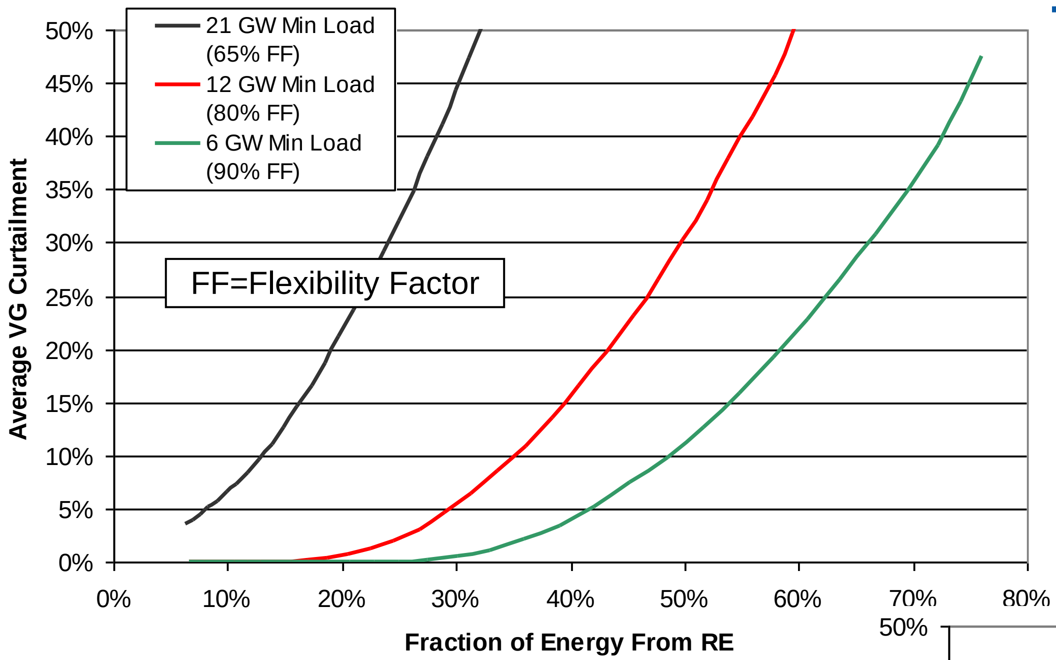
Price/Load Relationship in PJM

Below Cost Bids

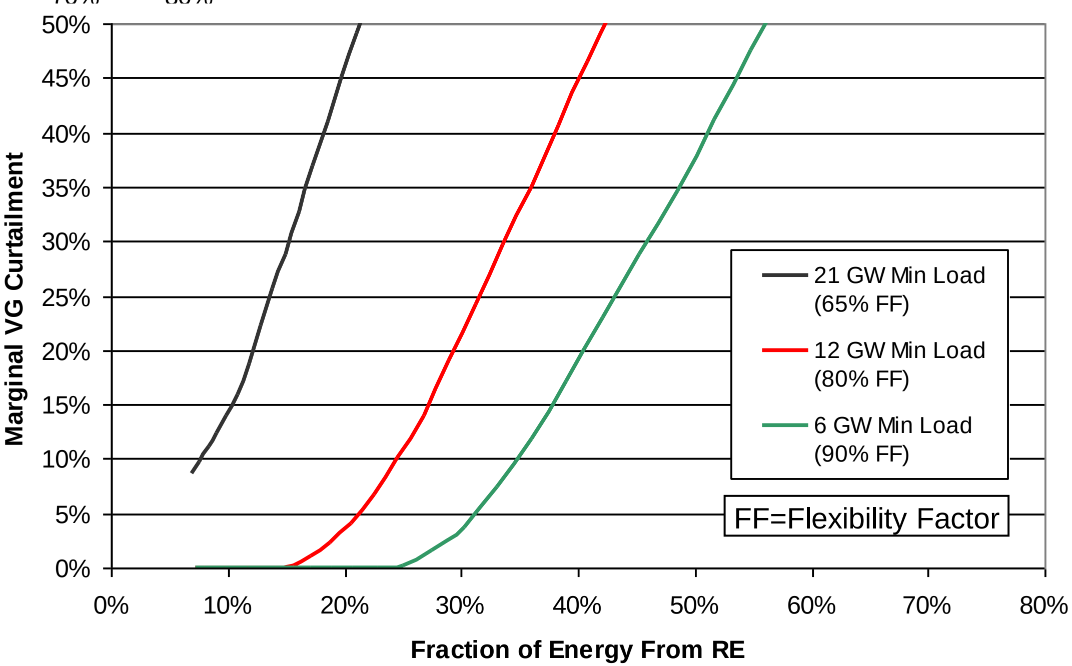


Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind may be curtailed under these conditions

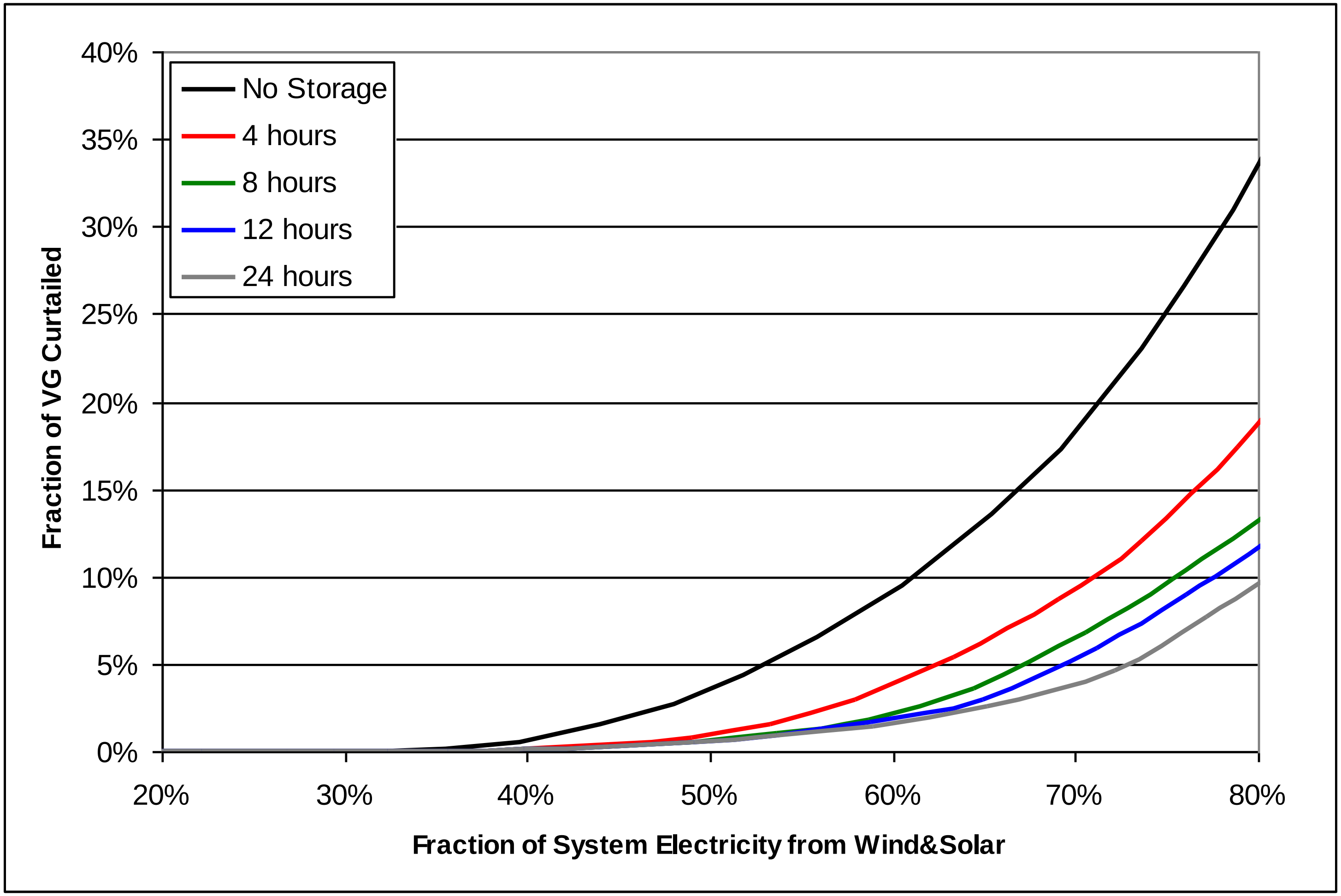
VG Curtailment/Zero to Negative LMPS



Fraction of wind generation occuring at zero LMP – average (top chart) and marginal (bottom chart) – as a function of VG penetration for different system flexibilities in ERCOT



Curtailment Reduction



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 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)

Conclusions (or just my opinions)

- Many studies start and stop with a basic arbitrage value using load lambdas or system-wide production cost
  - This will virtually guarantee that no storage technology in existence will be cost effective
- Multiple value streams appear to be critical
- Significant competition for regulation
- 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 may 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