Understanding the Economic Value of Electricity Storage: Some Key Drivers*

Prepared for:

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Energy Analysis Office, Washington, D.C.

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* This presentation is based on recent work with Jurgen Weiss (LECG) and also in part on earlier work with Frank Graves (TBG) and Dean Murphy (TBG).
** Thomas Jenkin was not affiliated with NREL at the time of the original presentation

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Overview

- Presentation provides an understanding of some of the key drivers for economic value of storage

Topics

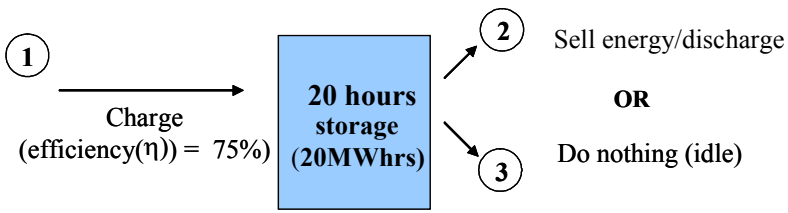
- Introduction to the value of storage
- Estimating the arbitrage value of storage
- How do real storage devices operate? Example of the operation of a pumped storage facility
- The value of electricity storage in a functioning wholesale power market. Example of PJM
- Impact of natural gas prices on the attractiveness of storage by region
- Device size and its impact on the value of storage, including sources beyond arbitrage
- Some renewable energy considerations
- Compressed air – A hybrid form of storage
- Summary

Introduction - Sources of value for storage

One of the most obvious potential sources of economic value of storage comes from energy arbitrage:

- Arbitrage refers to the ability to - at a single location - "store" energy using low price off-peak power and then later discharge the stored energy at times of higher price on-peak power

The Basic Device (1 MW)



[Initially assume operation does not affect prices – reasonable for small devices]

- The charge-discharge process has an energy efficiency loss of typically 20% to 30%, depending on the technology and alternative form of energy In contrast, the difference between off-peak and peak prices can often be 200% to 400%+, or more
- Typically, once built, it often makes economic sense for the storage device to run
- The decision whether to build such a device in the first place depends on the capital costs for investment [$/kW]:
  - Market structure and rules also play a role
- There are number of less obvious – but related - sources of value for storage devices, including the provision of ancillary services, better system utilization and deferred generation and transmission investments.
- There are also some "fast" applications, such as voltage support and power quality that may also potentially offer significant economic value. [Some of these applications are technology [and size] specific]. These are not covered in this presentation.

Sources of value for storage - Types of electricity/energy storage

Electrical Energy → Alternate Form of Energy → Electrical Energy

- Common to pure electricity storage systems is their ability to convert low cost power to an alternate form of energy, and then convert this energy back to electrical energy at a later point in time

Types of Electricity Storage Device [*Alternative Form of Energy*]

- ***Pumped Storage*** [*Water [elevated]*]
  - Pumped storage device comprises of an artificial lake on top of a mountain, connected – via a tunnel - to a river or reservoir hundreds or thousands of meters below
  - At night when the price of power is low turbines are used to pump water upward – so that the level of the lake rises
  - During the day, the water in the lake is allowed to drive the turbines to generate power
  - These devices can be large. 1,000 MW+ is not uncommon
- ***Batteries [conventional and flow]*** [*Electrochemical*]
  - Some interest in flow-batteries; typically 10 to 20MW
- ***Others e.g. Flywheels*** *[Rotational energy]*, ***Capacitors*** *[Electrostatic]*

Hybrid Electricity Storage

- ***Compressed Air Energy Storage ('CAES')*** *[Compressed Air]*

Estimating the arbitrage value of storage for a small device

Linear programming was used to **optimize** the arbitrage operation of a hypothetical device facing hourly prices with certainty (hindsight)

- The storage device was assumed to have the following characteristics:
  - Capacity 1MW, Storage Inventory: 20 Hours Efficiency(η): 75%
  - Device does not affect market prices
- Operation of device was optimized over successive two-week periods
  - Operator assumed to know regional market spot prices in advance (with certainty)
  - Device assumed to start and finish two-week periods in the same inventory state (half-full)
- Potential annual economic value ($/kW-year) is obtained by aggregating profits from over the 26 two-week periods

$$\textbf{Max } \Pi = \textbf{Max } \Sigma_{t=1-168} (\pi_t) = \Sigma_{t=1-168} p_i D_i - p_i C_i$$ *The Optimization Problem*

Constraints	*Physical Meaning*
(i) $0 <= D_i, C_i <= 1MW$	Device can charge or discharge up to 1 MW
(ii) $D_i + C_i < 1MW$	Absolute sum of charging and discharging up to 1 MW
(iii) $\Sigma_{t=1-168}[D_i - C_i\eta] = 0$	Conservation of Energy
(iv) $S_{Max} = 20$ MWhrs	Device size
(v) $S_{i=1} = S_{i=168} = 10$MWhs	Start and end in same state: Half-full
(vi) 0MWhs $<= S_i <= 20$MWh	Device size

Note: the device is assumed to be small; that is a **price taker** rather than a price maker

Estimating the arbitrage value of storage for a small device and the impact of constraint

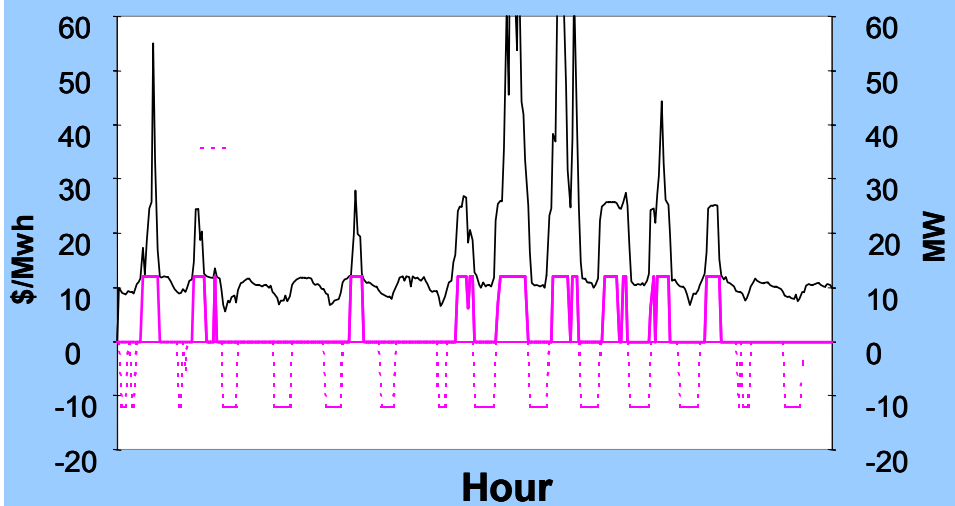
Charge/discharge strategy follows pricing:

- The fact that the device does not always fully discharge in peaks reflects the operational limitations of the device
- 20 hours of storage captures most of the value for a device optimized over one to two week periods

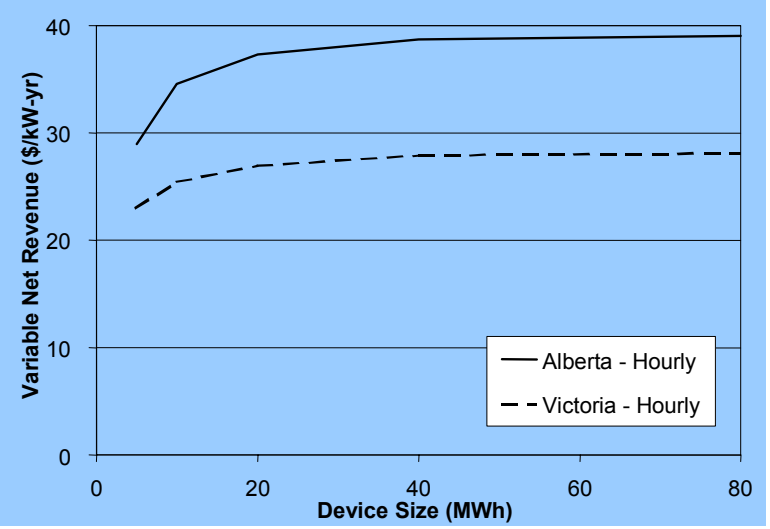
Optimized Charge and Discharge Characteristics of Hypothetical Storage Device

20-Hour Storage

Captures over 80% potential value



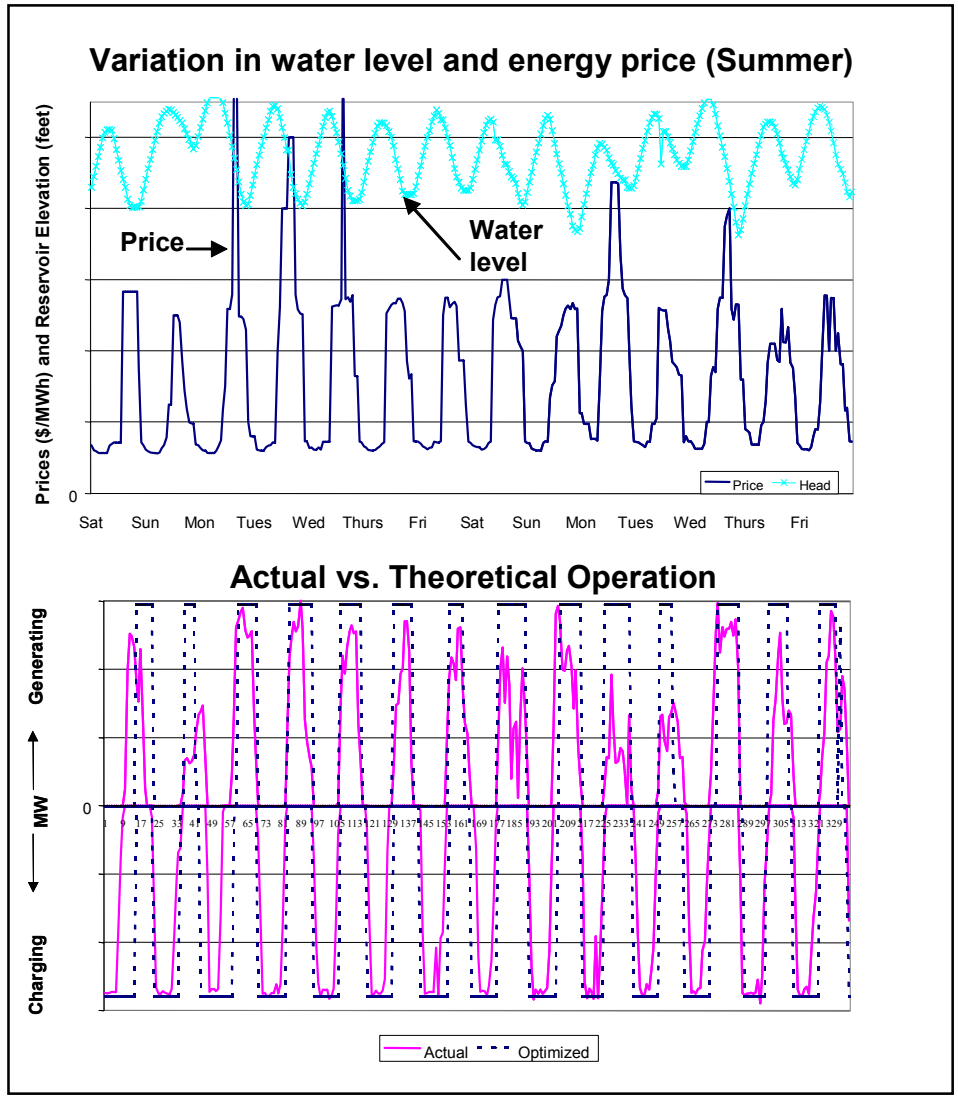
Effect of Energy Inventory Constraint on Storage Value



Do storage devices maximize arbitrage value? – A real example of the actual operation of a pumped storage device

- Figures show actual operation of a pumped storage device facing system prices
- Top figure shows:
  - Hourly variation in water level over a two week period
  - Hourly price variation over the same period
- Lower figure shows actual vs. "optimal" charge/discharge behavior for arbitrage
- Figures show partial pursuit of arbitrage:
  - Device uses similar charge/discharge strategy over each 7 day period
  - Does not fully chase larger price spikes
  - Captures approximately 72% of arbitrage value in this case
  - Device also being used for reserves and other ancillary services
- More optimal strategy – from an energy arbitrage perspective – may be to charge more over the weekend than during the weekdays

Note: Device size 1000MW+. Impact of size on optimal behavior is considered later.



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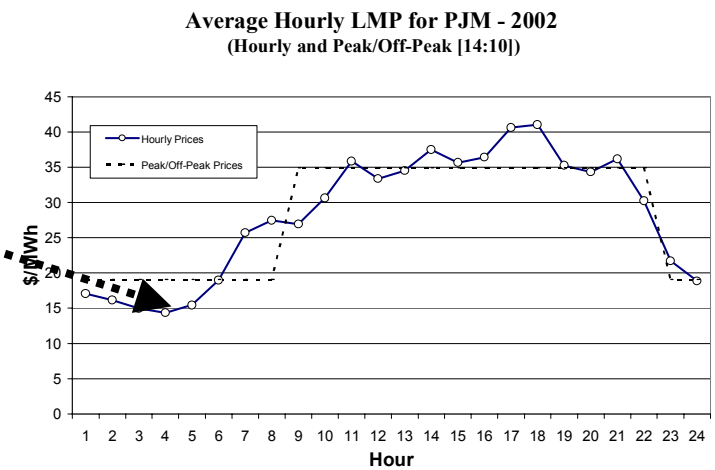
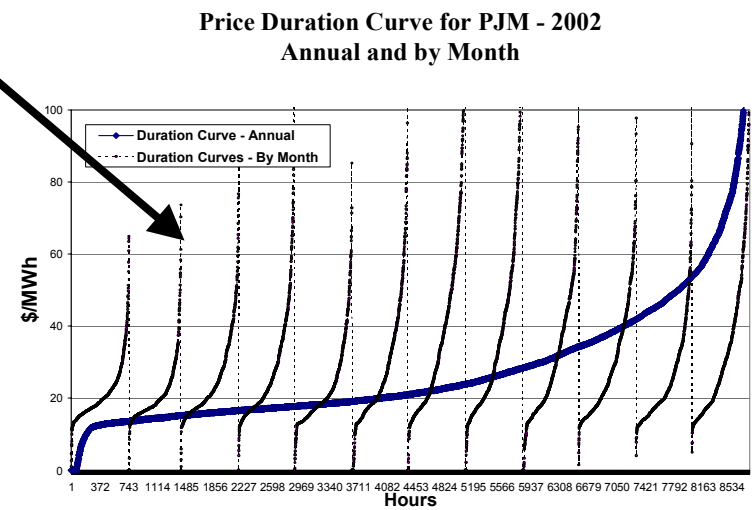
Alternative methods can be used to bound the arbitrage value of storage

- Optimization approach described earlier assumes perfect foresight.
- Two alternate methods can be employed to bound the value of a storage device
  - **Simple charge-discharge rule** [e.g., daily charge into lowest price 10 hours [on average], discharge into highest price 8 hours [on average] - Lower bound
  - **Price duration curve approach** [for month] [Ignore device constraints – sequentially map highest value hours to lowest price (1.25) hours] - Upper bound
- Simple charge discharge rule, perhaps modified to always charge into large price spikes will capture much of the device value
- Slightly better modified rule would be to have different optimal charge/discharge hours for each quarter [based on historical information]
- Optimization approach will fall between these two methods [recall impact of constraints on optimized value]



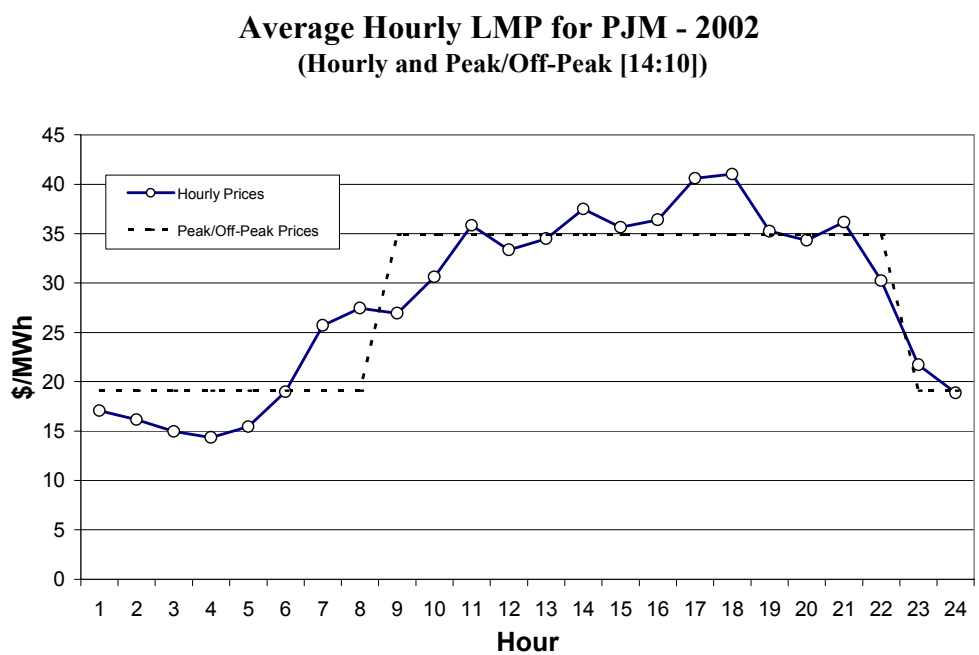


Use of a (too) simple operation rule leads to an estimate approximately $40/kW-yr in PJM

- Assume device has a 20% efficiency loss
  - One hour charge results in 0.8 hours discharge (equivalent to a 25% price premium (0.25 = [(1/0.8)-1])
  - 10 hours charging enables 8 hours discharging
- Value = [(Average discharge price difference) x Hours discharged daily x Days]/1000

  = [((Average price of top 8 hours) – (Average price of lowest 10 hours/0.8)) x 8 x 365]/1000

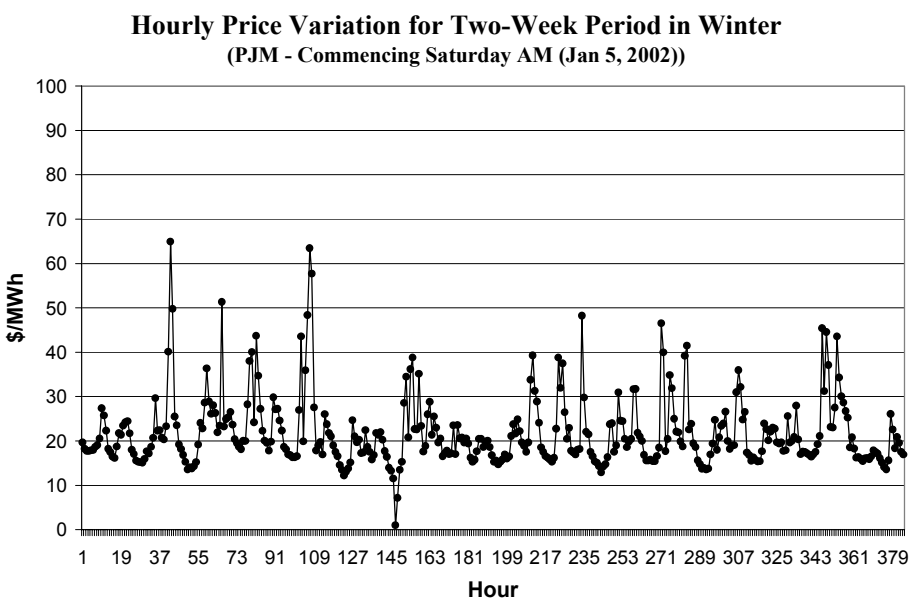
  = **$39/kW-yr** = [(($37.3/MWh) – ($19.1/MWh/0.8)) x 8 x 365]/1000
- This is also the amount that could be captured by following the same daily charge/discharge operational rule throughout the year

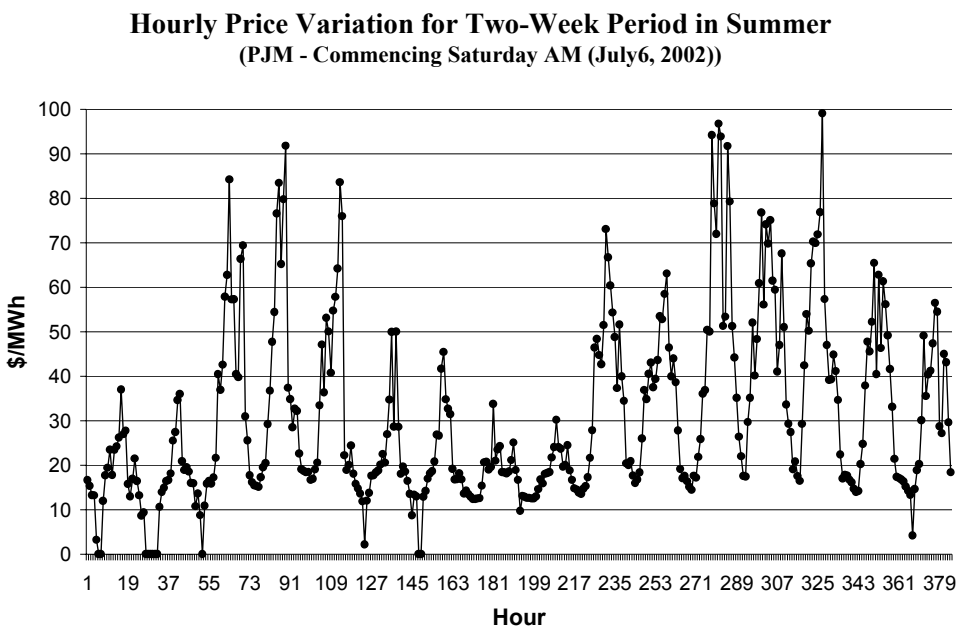


Changing to season specific hours increases the value to about $50/kW-yr

Price volatility varies significantly by week and season – This adds value that is not captured using simply the average hourly prices for the year

- Figures show hourly price variation for PJM for two-week periods in January and July
- Hourly peak prices vary significantly by day, week and by season
- By contrast off-peak prices show much less variation





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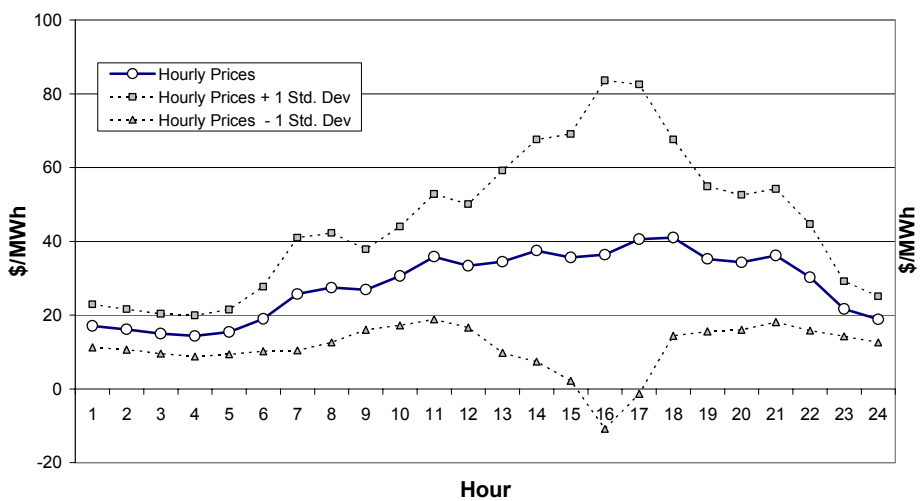
Simply using the average hourly prices for the year misses the extra value that arises from such volatility

Prior analysis underestimates the value of storage for at least two reasons:

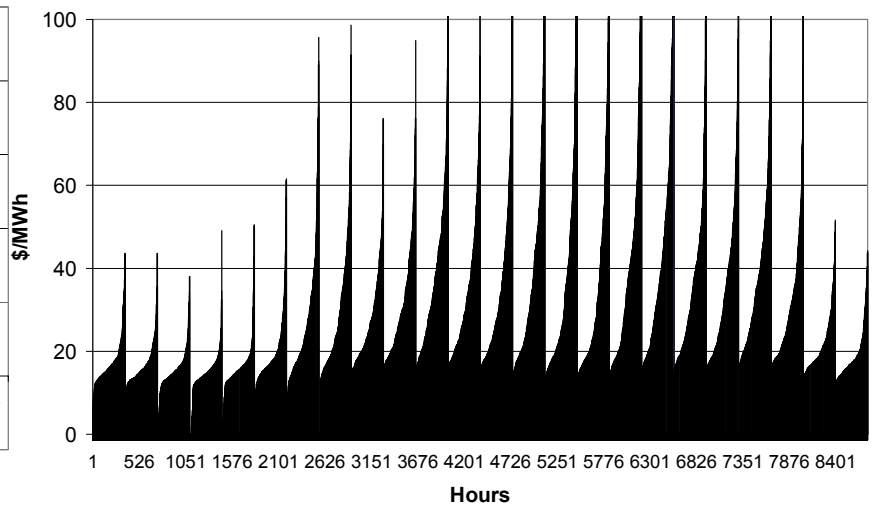
- Implicitly, but wrongly, assumes that some uneconomic hours are discharged into [see both figures]
- Implicitly, but wrongly, assumes that best hours to discharge remain the same throughout the year [see figure on rhs, next page and also discussion of duration curve analysis]

Note: Care needs to be taken when interpreting the standard deviation because the distribution is asymmetric.

Average Hourly LMP for PJM +/- One Std Dev - 2002

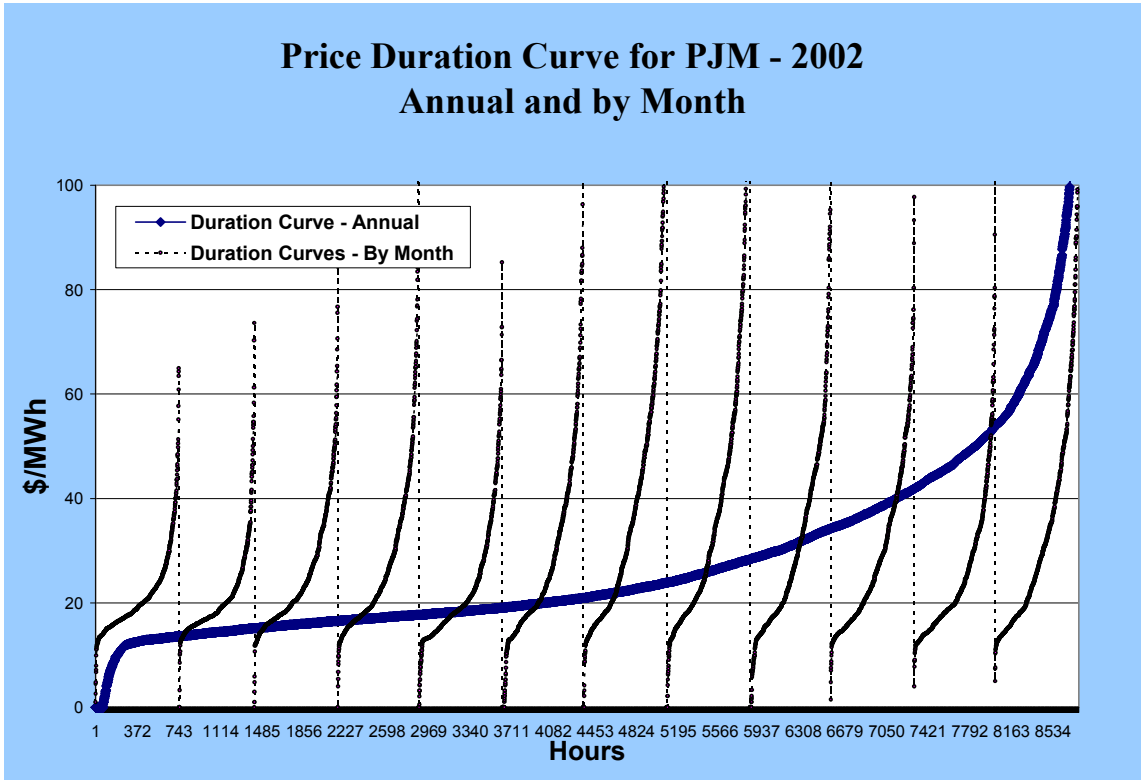


Price Duration Curve for PJM for Each Hour - 2002



Monthly price duration curve provides upper bound for the value of storage at approximately $80/kW-yr

- Monthly - rather than annual – price duration curves better reflect likely constraints on typical storage device
  - Upper limit of arbitrage value of storage rises to $82/kW-yr
  - Approach too optimistic; does not reflect likely operational constraints of most storage devices



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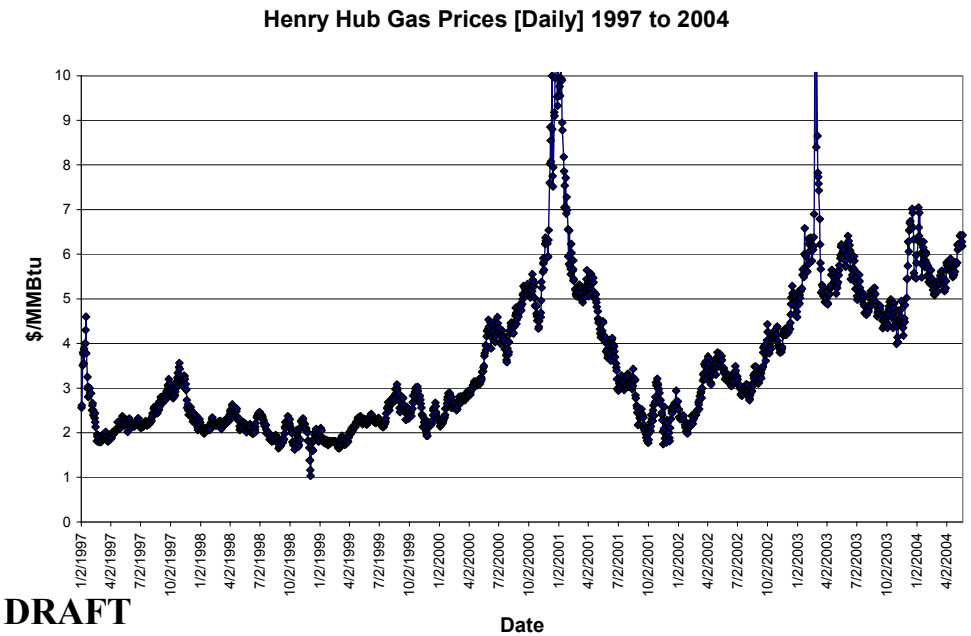
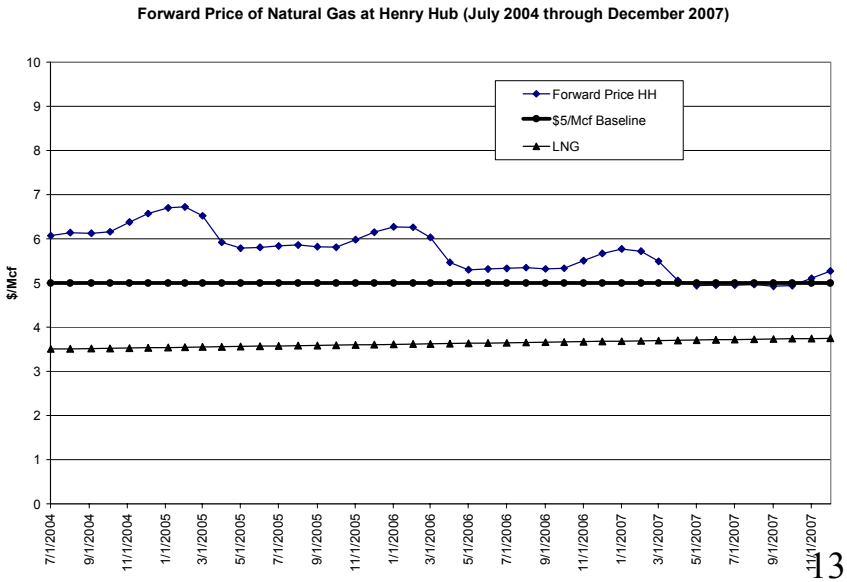
High natural gas prices increase in the relative value of electricity storage (and renewables)

- Large investments in gas-fired generation has led to a capacity bubble in many regions - These investments were made at a time when "average" gas prices had been and were expected to remain in the $2 to $3/MMBtu range
- More recently, the United States has been exposed to $6+/MMBtu natural gas prices for a sustained period
  - Today, many analysts/observers expect natural gas prices to remain elevated
  - This view is supported by current NYMEX futures prices for natural gas at Henry Hub [Futures prices fall to $4.80/MMBtu in the Summer of 2010]
- A $2/MMBtu increase in the price of natural gas substantially increases the cost of running conventional gas-fired generation
  - 10,000 Btu/kWh heat rate corresponds to an increase of $20/MWh (or 2c/kWh)
  - 7,000 Btu/kWh heat rate corresponds to an increase of $14/MWh (or 1.4c/kWh)
  - Substantial when one considers the magnitude of the wind tax credit [1.5c/kWh] [though comparison only applies for hours when gas on margin]





Higher natural gas prices make the value of storage more attractive relative to conventional generation

- Higher gas prices push power prices up at peak times when – as is common - gas in on the margin
- However, conventional gas-fired generation on the margin does not profit more under such scenarios because it is still on the margin, i.e., the cost of fuel has increased
- By contrast a storage device's fuel is "off-peak" power. This will be much less affected by the price of gas – though it depends on the fuel mix
  - If the off-peak charging hours are driven by nuclear or hydro – storage will receive the complete benefit from the rise in gas price
  - Even if gas is on the margin for some of the off-peak hours – rising gas prices – will increase the value of storage. This is because a $1/Mcf rise in gas prices will lift the peak price more than the off-peak price due to the better heat rate/efficiency of the off-peak units

Fuel mix by region will affect the value of storage. Gas determines electricity price [as determined by Henwood]

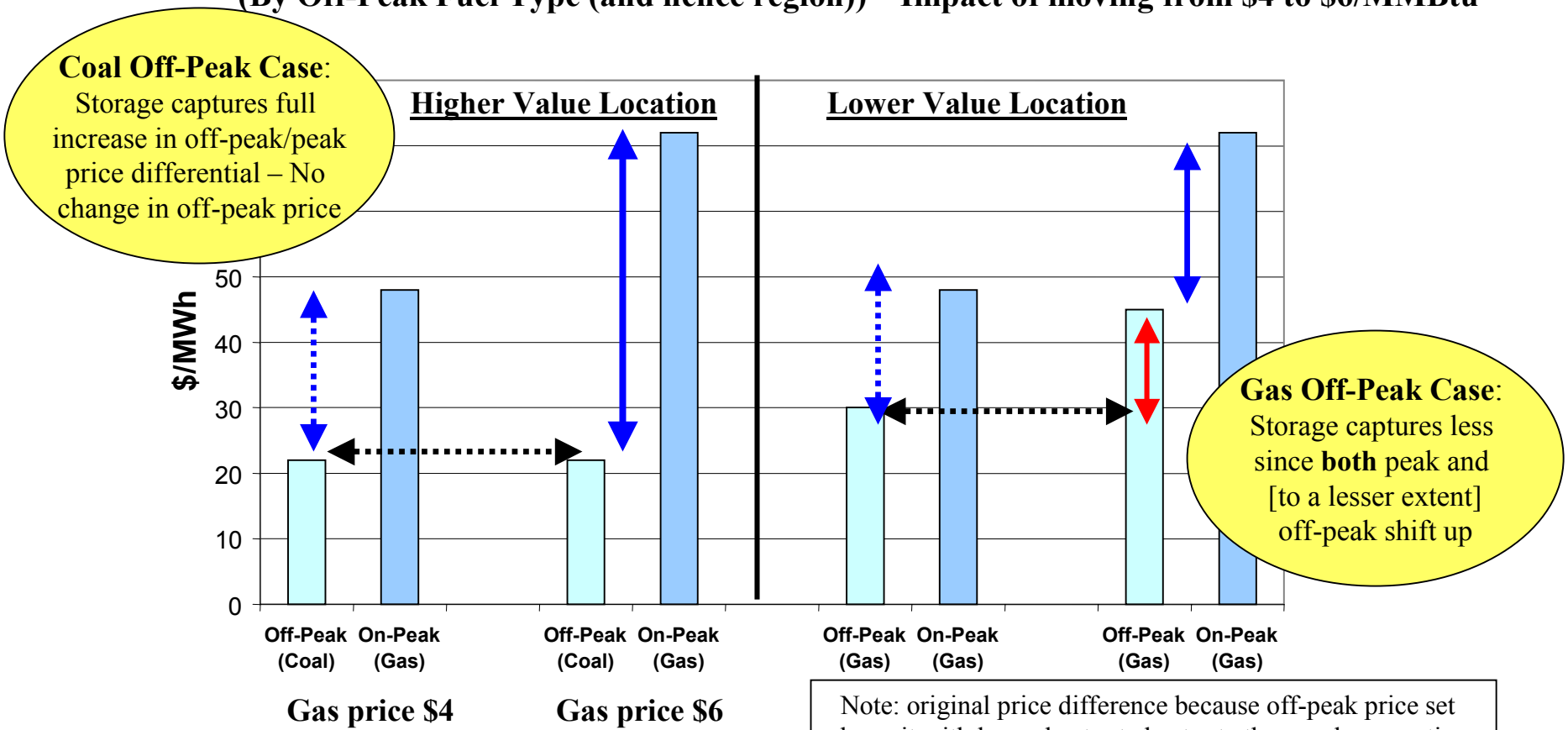
- Less than 40% (Midwest, Southeast)
- 40-60% (West)
- 60-100% (Texas/ERCOT, Alberta, NY Load pocket – comment on basis issue)

- Moreover, storage has societal value since it provides a natural hedge against gas-driven price peaks

Comment on Renewable Energy & Gas Prices:
Since renewable energy has zero variable cost (excl. O&M), increases in natural gas prices flow directly through to the bottom line, e.g., For a 10,000 HR gas-fired unit on the margin, a $2/MMBtu increase in gas prices increases the relative attractiveness of wind, say, by $20/MWh [provided the gas unit is still on the margin]- obviously natural gas will only be the margin for some fraction of hours during the day (also depending on fuel)

Higher natural gas prices make the value of storage more attractive – though this varies by region based on off-peak fuel mix

Impact on Relative Change in Value of Storage with Increase in Gas Price
(By Off-Peak Fuel Type (and hence region)) – Impact of moving from $4 to $6/MMBtu



Note: original price difference because off-peak price set by unit with lower heat rate heat rate than peak generation

Impact of device size on benefits/costs of storage

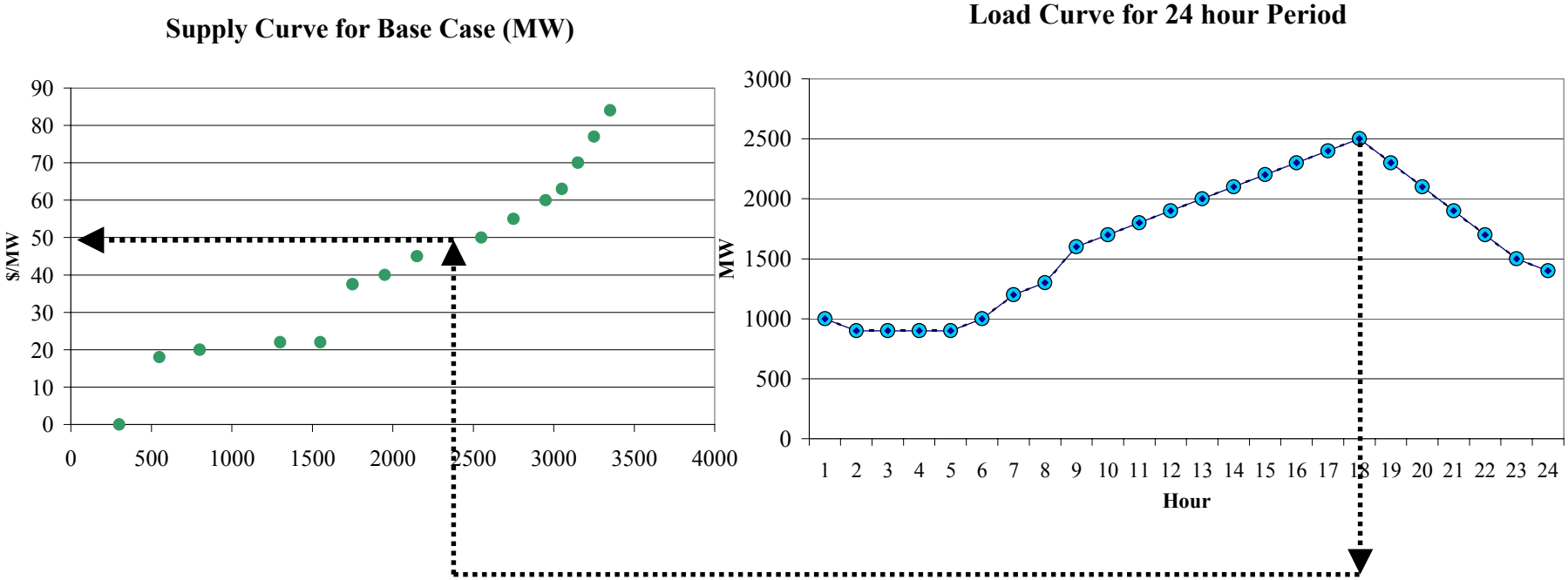
- Up to this point the storage device has been considered small enough not to affect prices
  - The device is a price taker
  - The device captures peak/off-peak price differentials without collapsing them

  This is a reasonable approximation if device is too small to change the marginal unit
- The presence and operation of a storage device can be expected to affect peak and off-peak prices.
- The larger the device, the more price differences can be expected to be reduced as load is effectively shifted from peak to off-peak
  - Such a device is no longer a price taker
- However, reduced arbitrage opportunities will be off-set by reduced production costs [and system sales] and a more energy efficient system. Intuitively, this is because:
  - Plants with better heat rates will be running longer [to charge the storage device]
  - Plants with worse heat rates will be running less [due to part of the peak demand being now met by the storage device]

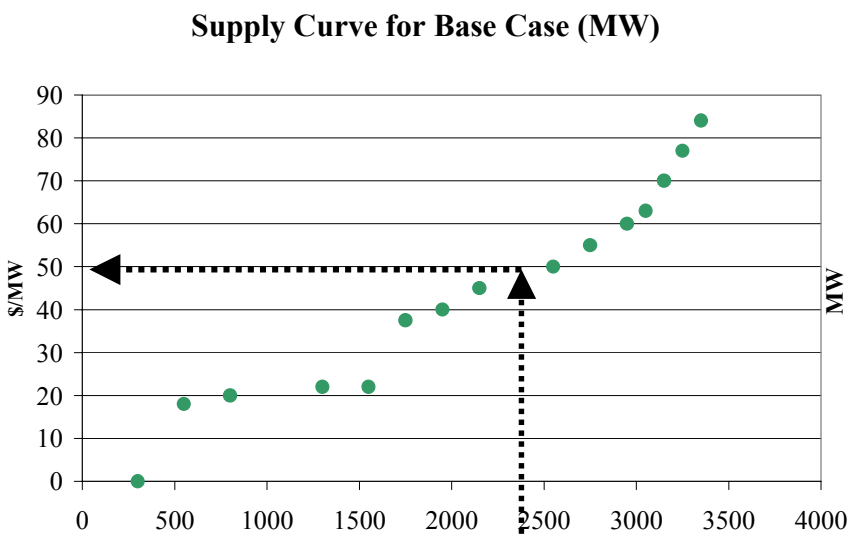
  This topic is introduced here and further work is currently being undertaken re: the relative size of the device, the shape of the supply curves and the shape of the demand curve

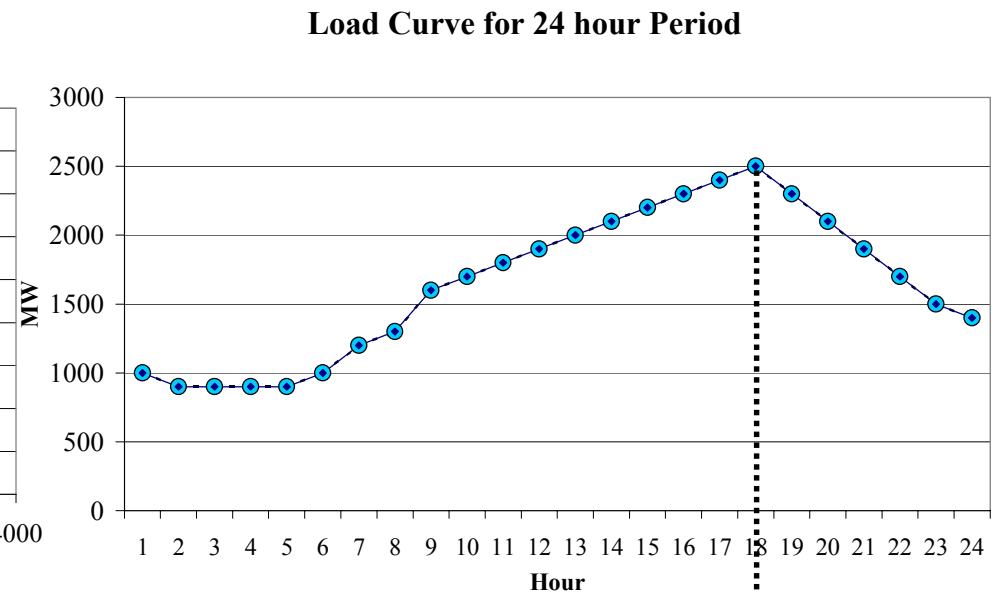
Impact of device size on benefits and costs - illustrative

- Build a simple supply curve:
  - Base Case System has 15 plants (1 hydro, 4 coal, 6 gas and 4 oil)
- Assume hourly demand for typical day is inelastic:
  - This allows the price to be estimated for a given demand. P = P(D)
  - In this way 24 hour demand and supply curve can be used to generate generate 24 hour price curve

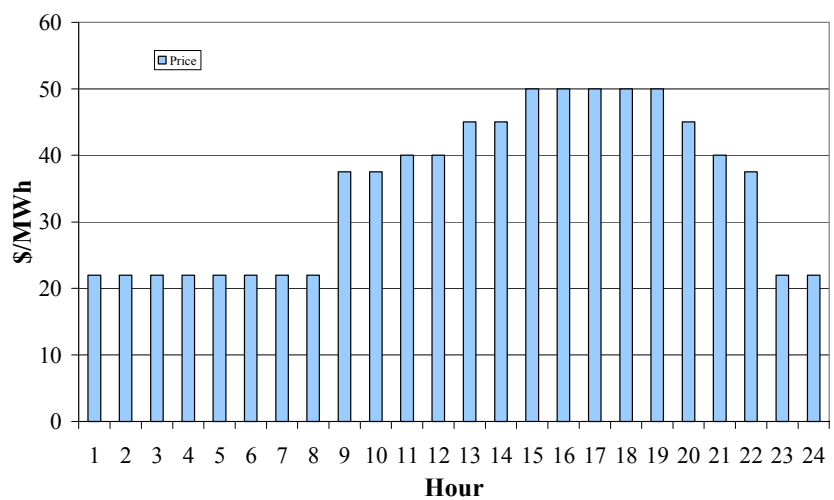


Impact of device size on benefits and costs - illustrative





Price Profile generated from Demand Profile Via Supply Curve



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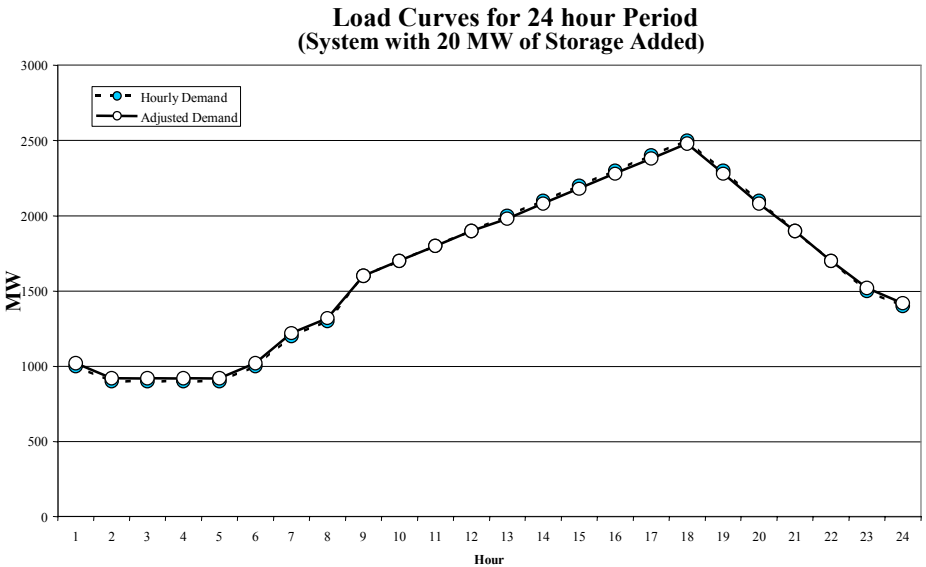
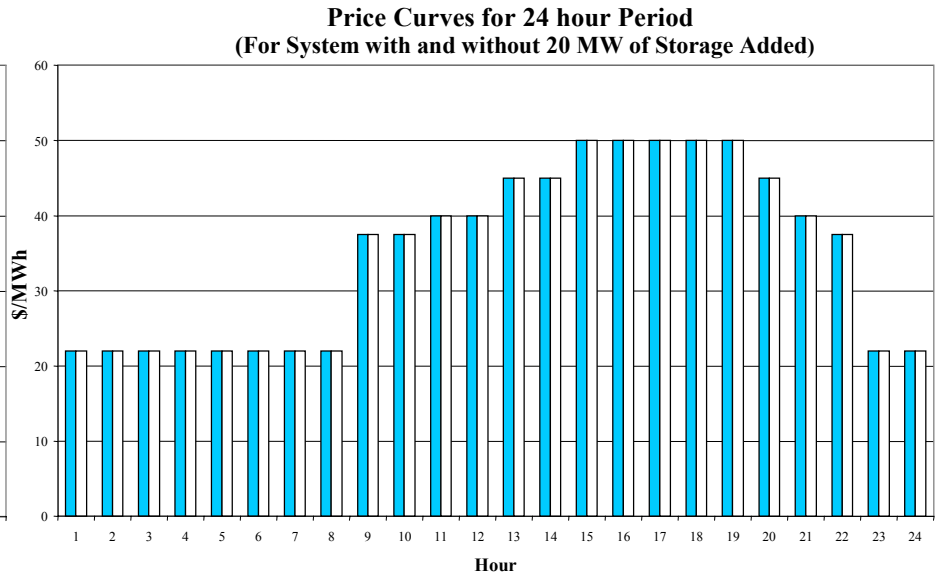
A small storage device does not flatten price peak and so does not affect arbitrage value - illustrative

- A 1MW device does not affect prices and arbitrage value is $165 per day
- Similarly, a 20MW device also <u>for this supply/demand curve combination</u> does not affect prices and arbitrage value is $3,300 per day or $165/MW per day
- In both cases the arbitrage value is <u>equal</u> to the reduction in Sales Revenue from the System ($165 and $3,300, respectively)





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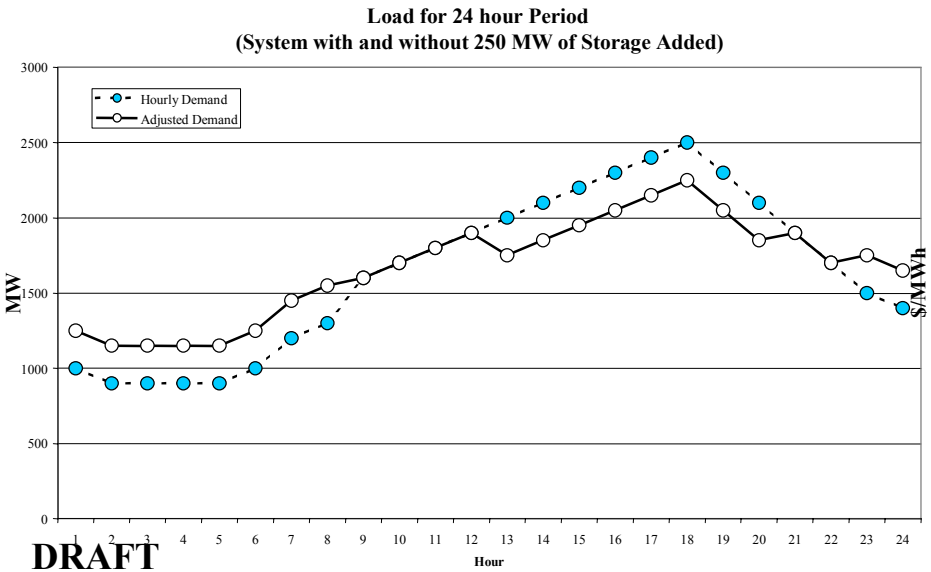
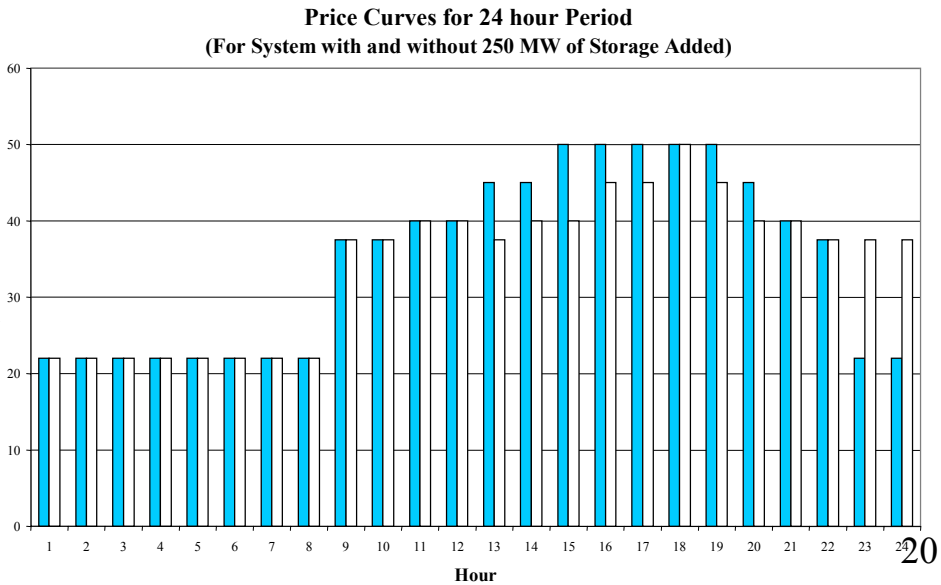
Larger storage device will reduce peak/off-peak price difference
- illustrative

- For a 250 MW device, the peak/off-peak price difference is lowered - In this example the price of charging electricity remains largely flat and the price for discharged energy is lowered
- Although the arbitrage savings for a 250MW device is much larger than for a 20MW device ($22,875 vs. $3,300), it is reduced on a $/MW-day basis [$95 vs $165] due to the narrower price difference
- However, in this case, the overall reduction in cost of system sales provides more societal/economic value on a per MW basis than the 20MW device [Over $70k per day for the 250MW device or over $280/MW-day of storage cf. $165/MW-day for the 20MW device].
  - The higher marginal prices at charging and lower marginal prices at discharging are applied to the entire system [1,000 to 2,500MW]
  - A double effect: increase in charging prices was (usually) less than the decrease in discharge prices [for the marginal unit] and the off-peak load is much lower than the peak load





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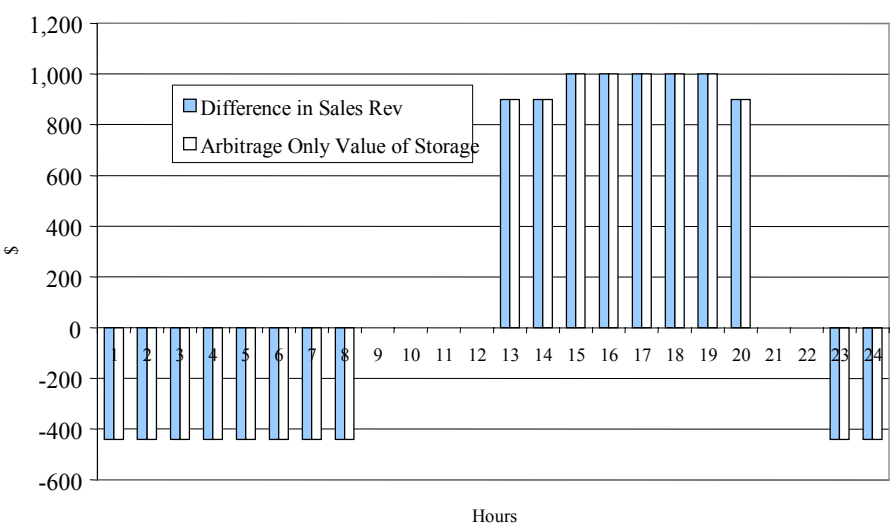
Large storage devices can be more valuable than smaller storage devices on a $/MW basis - illustrative

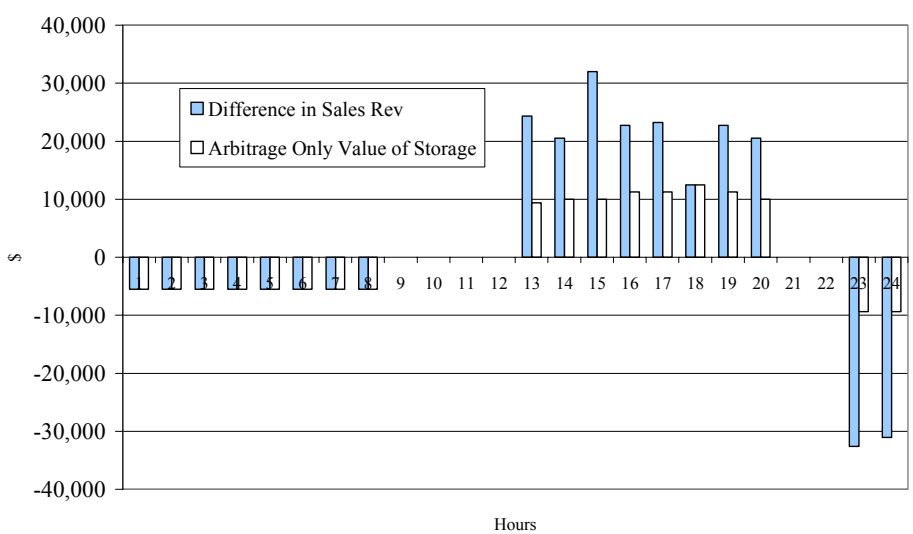
- The overall reduction in cost of system sales provides more societal/economic value on a per MW basis than the 20MW device [Over $70k per day for the 250MW device or over $280/MW-day cf. $165/MW-day for the 20MW device].
  - The higher marginal prices at charging and lower prices at discharging are applied to the entire system load

  Note: similar but smaller reductions in production costs – since only applies to displaced units
- Other economic benefits arise from increased efficiency since flattening peak/off-peak prices leads to:
  - more efficient utilization of better/lower heat rate units;
  - improved capacity margin [reducing the need for new generation];
  - less on/off issues for generation and better utilization of the transmission system [avoiding the need for new transmission build].

Comparison of Difference in Sales Revenue Vs. Arbitrage Value (20MW device)



Comparison of Difference in Sales Revenue Vs. Arbitrage Value (250MW device)



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Energy Storage and Renewable Energy

- Wind, solar and some hydro are intermittent
- Wind in systems will add supply variations
- To the extent that it is preferable and/or desirable to firm up this supply storage is a natural choice – the benefits will be set by value of firmness and/or penalties for non compliance
- The economic benefit of integrating storage and wind needs to be considered carefully in incremental terms relative to the value of the storage device and wind farm operating independently
- Practically, there are some obvious benefits in terms of system efficiency
  - Consider a location in Texas where the wind output is sometimes transmission constrained. When it is very windy, some of the peak output is wasted.
  - One alternative is to increase the transmission, but is this economic if this capacity will rarely be used?
  - Using storage would enable the wind output to be captured, improve the utilization of the transmission line [this must increase the value of the transmission asset], and possibly allow additional wind farms to be added without the need to build more transmission
- Value capture will significantly depend on both intrinsic value and market structure

Hybrid-Technologies – The "case" for CAES

- The overall efficiency of a Combustion Turbine ("CT") or Combined Cycle Gas Turbine ("CCGT") is given by the heat rate, which specifies how much gas is needed to generate 1MWh of power [low heat rates are better]
- Conventional forms of gas-fired generation (CTs or CCGTs) can use over 50% of the energy from gas simply to compress the gas/air mixture
- Compressed Air Energy Storage (or CAES) technology is effectively a hybrid of a storage device and conventional gas generation
- CAES devices use cheap off-peak power to "charge" or compress air in advance of when it will be used.
- When the CAES device generates power during peak hours, the existing compressed air reduces the amount of energy used from the gas to compress air.
- As a result, less gas is needed to generate 1MW for a CAES facility. This is reflected by the lower heat rate of the device:

Generator	Heat Rate (Btu/kWh)
– CT	8,500-12,000
– CCGT	6,300-8,000
– CAES	4,500

- True economic analysis of a CAES device should compare the incremental cost of the compression equipment to the incremental economic benefit of the compression – relative to a CT or CCGT

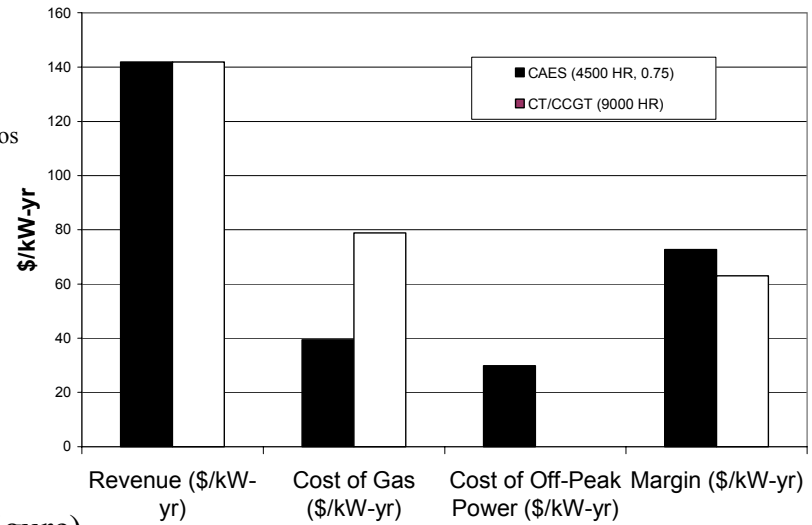
  Note: The notion that it is hybrid storage device is supported by the fact that – compared to other forms of storage – it provides a more partial hedge against rises in natural gas prices still it still uses natural gas [though less of it on a Btu/kWh basis] to generate power.

The bounded arbitrage approach used to value of a pure storage device can also be applied to bound the value of CAES

- A simple example of this analysis is shown below using the 2002 price duration curve approach. The example assumes:
  - 4,500 Btu/kWh HR for CAES and 9000Btu/KWh HR for CT/CCGT
  - Gas price $3/MMBtu
  - CAES analysis done for 0.6 and 0.75 compression ratios
  - 10 hours discharge per day for 365 days for both devices
    - Highest prices used for discharge
    - Lowest prices used for CAES for charging
    - 6 and 7.5 hours charging required for 0.6 and 0.75 compression ratios

  Note: No price violation (for charging or spark-spread)

Comparison of CAES with CT/CCGT - Duration Curve Approach - PJM - 2002



Results (*Draft*)

- In general results make sense (given same operational hours assumed)
  - Revenue for both devices identical
  - Cost of gas for CAES 50% of cost for CT/CCGT
  - Charging cost for CAES but none for CT/CCGT
- Devices worth $60 to $70/kW-yr+ for 0.75 ratio (see figure)
  - **This is the number to tie/compare with $80/kW-yr+ prior analysis**
  - CAES worth **$10/kW-yr more** than CT/CCGT at 0.75 ratio
  - These number will change significantly for different gas price, HR and operational assumptions
- Moreover the incremental value of CAES increases to **$17/kW-yr** for 0.60 ratio

Summary

A wide range of issues affect the economic value of electricity storage[(i), (ii)]

- Peak/Off-peak power price differences in the United States creates economic value for storage devices from arbitrage – Buy low/Sell high
- Three approaches used to estimate arbitrage value for "small" storage devices:
  - Formal optimization approach (perfect hindsight)
  - Average daily hourly price (on an annual and seasonal/quarterly basis)
  - Duration curve approach (on an annual and monthly basis) – for upper limit estimate
- On an hourly basis, the value of storage in PJM increased in 2002 to **$50-$60/kW-yr**, or more*
- A $50-$60/kW-yr arbitrage opportunity could support capital investments in the range of $350-$500/kW
- Higher natural gas prices add to the economic attractiveness of storage though it depends on the fuel mix used for off-peak power
- Large scale storage systems can add more value than small systems (on a $/MW), even if the energy arbitrage opportunity is reduced. Additional benefits of large systems include:
  - Lower system sale costs [and to a lesser extent production costs]
  - More efficient use of system [better utilization of transmission and lower cost generation] and increased capacity factor
  - Avoidance/delay in need to build new transmission and generation
  - Improved economics of renewable systems under certain circumstances
- Compressed air energy storage ("CAES") is a hybrid storage-conventional generation that is increasingly attractive
- Storage integrated with renewable energy can add significant incremental value under certain circumstances

(i) There are many other potential sources of value for electricity storage, including "fast" applications such as voltage stability and power quality; these were not covered in this presentation.

(ii) When considering multiple (two or more) applications and/or sources of value from a single device care must to taken to ensure that anticipated multi-application use is physically feasible and to identify the real overall economic benefits (and avoid double counting).