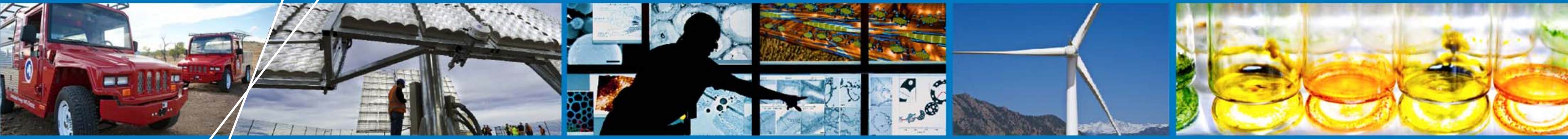
The Value of Energy Storage for Grid Applications (Report Summary)



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Project Overview

- **This report is one of a series stemming from the U.S. Department of Energy (DOE) Demand Response and Energy Storage Integration Study.**
- **This study is a multi-national-laboratory effort to assess the potential value of demand response and energy storage to electricity systems with different penetration levels of variable renewable resources and to improve our understanding of associated markets and institutions.**
- **This study was originated, sponsored, and managed jointly by the Office of Energy Efficiency and Renewable Energy and the Office of Electricity Delivery and Energy Reliability.**

Analysis Goals

- **Understand the value of energy storage providing multiple grid services**
- **Evaluate differences in system value in a vertically integrated utility versus in a market environment**

Approaches to Valuing Energy Storage

- **Market-price-based simulation**
  - Dispatch against historic market prices
  - Relatively easy
  - Cannot evaluate change in generation mix
- **Grid simulation**
  - Uses production cost simulations to evaluate cases with and without storage
  - Can evaluate any desired generation mix, fuel price, etc.
  - Can be expensive and time consuming

Examples of Market-Price Simulations

Market Evaluated	Location	Years Evaluated	Annual Value ($/kW)	Assumptions
Energy Arbitrage	PJM[a]	2002–2007	$60–$115	12 hour, 80% efficient device. Range of efficiencies and sizes evaluated. Also considers price difference suppression effect in a market setting using price/load relationships.
	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. Evaluates ISO-NE, CAISO, PJM
	CA[d]	2003	$49	10 hour, 90% efficient device.
	CA[f]	2010–2011	$25–$41	4 hour, 90% efficient device.
	CA[h]	2011	$46	16 hour, 75% efficient pumped storage device.
Regulation Reserves	NYISO[b]	2001–2005	$163–$248	
	USA[e]	2003–2006	$236–$429	PJM, NYISO, ERCOT, ISO-NE.
	CA[f]	2010–2011	$117–$161	Co-optimized arbitrage and regulation, most value is derived from regulation.
Contingency Reserves	USA[e]	2004–2005	$66–$149	PJM, NYISO, ERCOT, ISO-NE.
Combined Services	CA[f]	2010–2011	$117–$161	Arbitrage and regulation, most value is derived from regulation.
	CA[h]	2011	$62–$75	Arbitrage, regulation, and contingency. Included operational constraints of pumped storage.
	USA[g]	2002–2010	$38–$180	Arbitrage and contingency. CAISO, PJM, NYISO, MISO.

[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
[f] Byrne and Silva-Monroy 2012
[g] Drury et al. 2011
[h] Kirby 2012

Examples of Grid Simulation Analysis

Location	Model	Notes
Western Interconnection[a]	PROMOD	Evaluates arbitrage and renewable energy balancing services for a variety of devices in various locations throughout the Western Interconnection.
Maui[b]	PLEXOS	Evaluates several storage technologies providing operating reserves and arbitrage/time-shifting. Considers changes in fuel use and renewable curtailment.
MISO[c]	PLEXOS	Preliminary analysis of storage, identified challenges in simulating both day-ahead and real-time markets in a large system.
MISO[d]	PROSYM	Evaluated a proposed compressed air energy storage project in Iowa.

[a] Kintner-Meyer et al. 2012
[b] Ellison et al. 2012
[c] Rastler 2011
[d] Black and Veatch 2005

Our Approach

- Use a commercial production cost model (PLEXOS)
- Evaluate differences in production cost with storage to obtain system value
- Evaluate "market revenue" using marginal prices produced by the model

Test System

- Two balancing areas in Colorado/Wyoming (wanted a relatively compact and isolated system to examine small differences)
- Used publicly available data from Transmission Expansion Policy Planning Committee (TEPPC) 2020 model
- Data includes plant capacities, heat rates, outage rates (planned and forced), and several operational parameters, such as ramp rates
- Generator database was modified to include part-load heat rates based on Western Wind and Solar Integration Study Phase II (WWSIS II) study
- Total of 201 thermal and hydro generators
- Start-up costs were added using the start-up fuel requirements in the generator database plus the operations and maintenance (O&M) related costs based on estimates prepared for the WWSIS II study
- Adjusted the generator mix to achieve a generator planning reserve margin of 15% by adding a total of 1,450 MW (690 MW of combustion turbines and 760 MW of combined cycle units)

General Characteristics

System Capacity (MW)	
Coal	6,157
Combined Cycle (CC)	3,988
Gas Turbine (CT)/Gas Steam	4,259
Hydro	777
Pumped Storage	560
Wind	3,347 (10.7 TWH)
Solar PV (AC Rating)	878 (1.8 TWH)
Other[a]	513
Total	**15,793**

- Wind/solar provide ~16% energy
- Gas averages ~$4.1/MMBTU

Reserves

- **Contingency based on Comanche III (Rocky Mountain Reserve Sharing Group Rules)**
- **Regulation reserves based on variability of net load**
  - Only regulation up in these simulations
  - 5 minute ramp product
  - Range 77-166 MW, average of 120 MW – 1.3% avg load
- **Flexibility reserves based on variability of net load on longer time frame**
  - Only flex up in these simulations
  - 20 minute ramp product
  - Didn't do 5-minute dispatch to capture actual deployments
  - Range 15-85 MW, average of 57 MW – 0.6% avg load
- **Total spinning requirement averages 582 MW or about 6.4% of average load**

Additional Reserve-Related Modifications

- **TEPPC database has no restrictions on what units can provide reserves**
  - Pumped Hydro Storage (PHS) plants could cycle down to <1% of output
  - No costs for providing regulation reserves
- **Modifications**
  - CTs cannot provide regulation reserves
  - PHS added 40% minimum generation point
  - PHS added 70% regulation point (we are currently not tracking separate up and down so need to provide symmetric operation
  - Only 60% of remaining units (as measured by ramp rates) provide regulation (based on PLEXOS database from the California Independent System Operator)

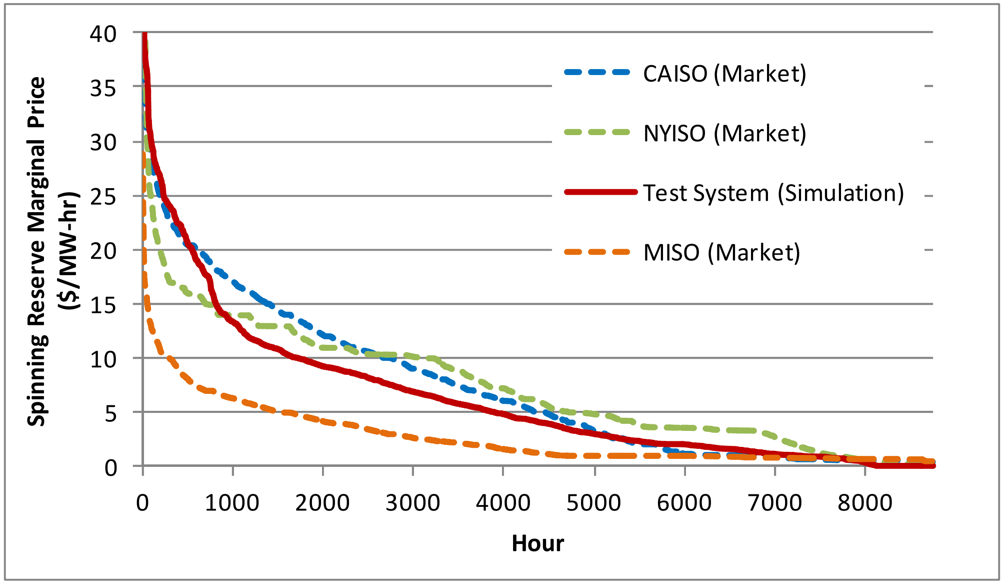
Assumed Cost of Regulation Reserve

Generator Type	Cost ($/MW-h)
Supercritical Coal	15
Subcritical Coal	10
Combined Cycle (CC)	6
Gas/Oil Steam	4
Hydro	2
Pumped Storage	2

Cost of non steady-state operation

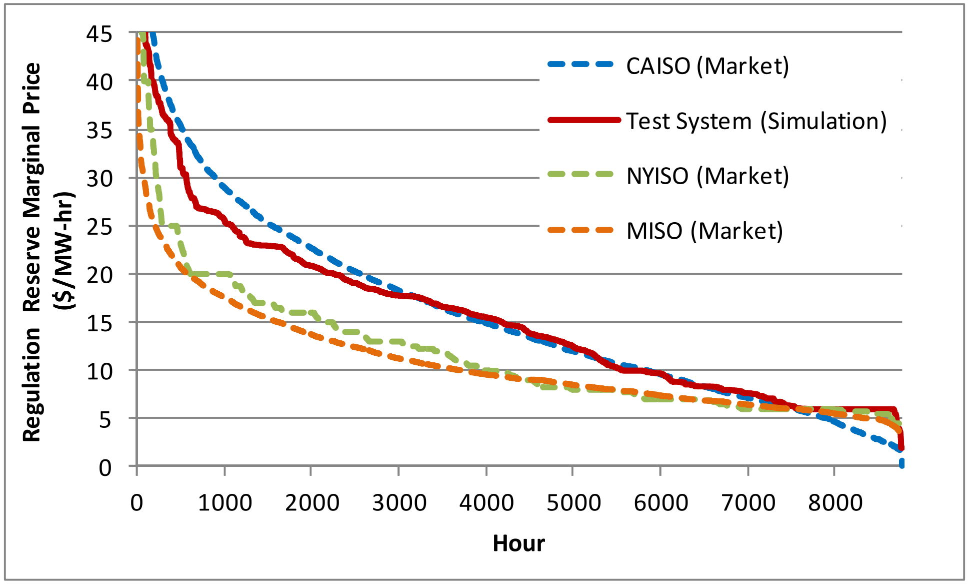
Equivalent to a regulation bid price in a restructured market

Results – Contingency Spin Prices



- Avg =$6.3/MW-hr
- For comparison, 2011 average market clearing prices of $7.4/MW-hr in NYISO, $2.8/MW-hr in MISO, and $7.2/MW-hr in CAISO

Results – Regulation Reserve Prices

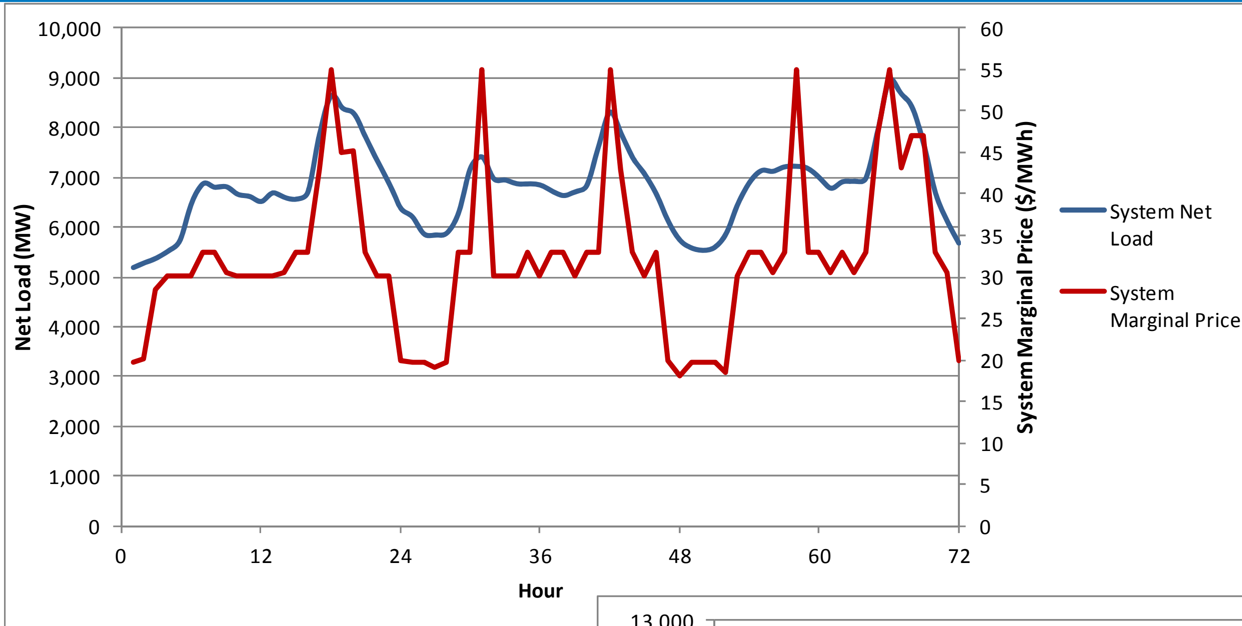


- Avg = $16.1/MW-hr
- For comparison 2011 average market clearing prices of $11.8/MW-hr in NYISO, $10.8/MW-hr in MISO, and $16.1/MW-hr in CAISO

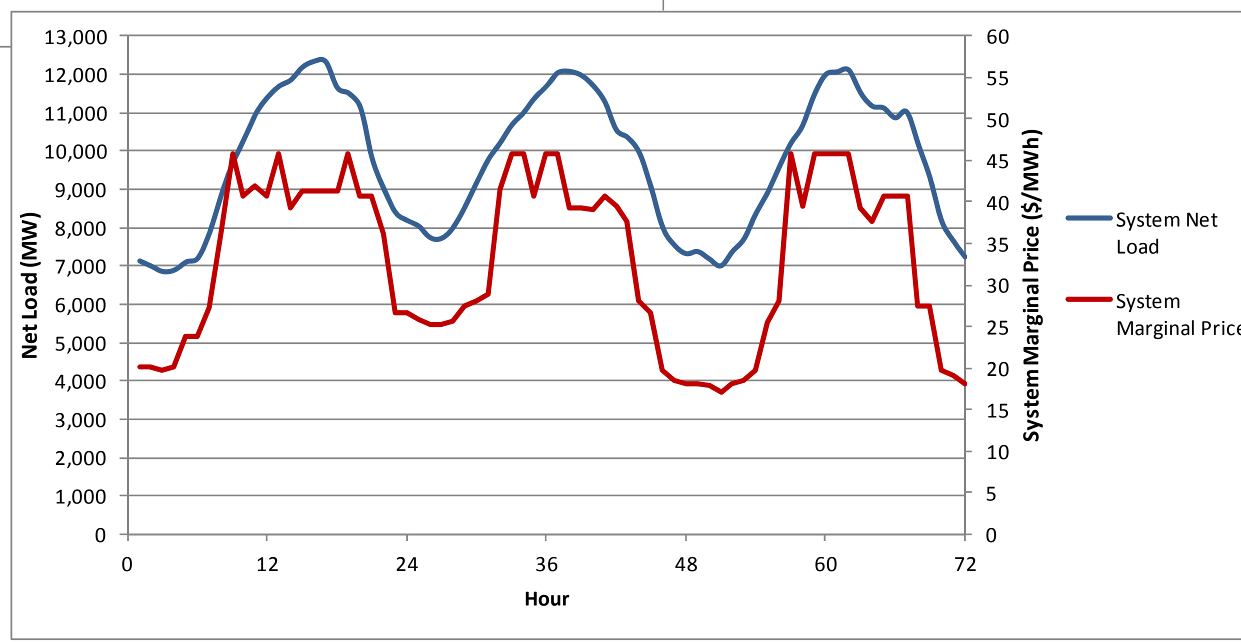
Storage Devices

- **Energy Only**
  - 75% AC-AC efficiency
  - No minimum generation, ramp constraints
  - 8 hours
  - Base device is 300 MW
- **Reserves Only**
  - Can provide 100% of rated capacity as any reserve service
  - Make-up energy assumes 25% energy throughput, 80% efficiency
  - Base device is 100 MW
- **Energy + Reserves**
  - PLEXOS co-optimizes provision of energy or reserves depending on whatever service minimizes system production cost

Results – Price/Load Relationships

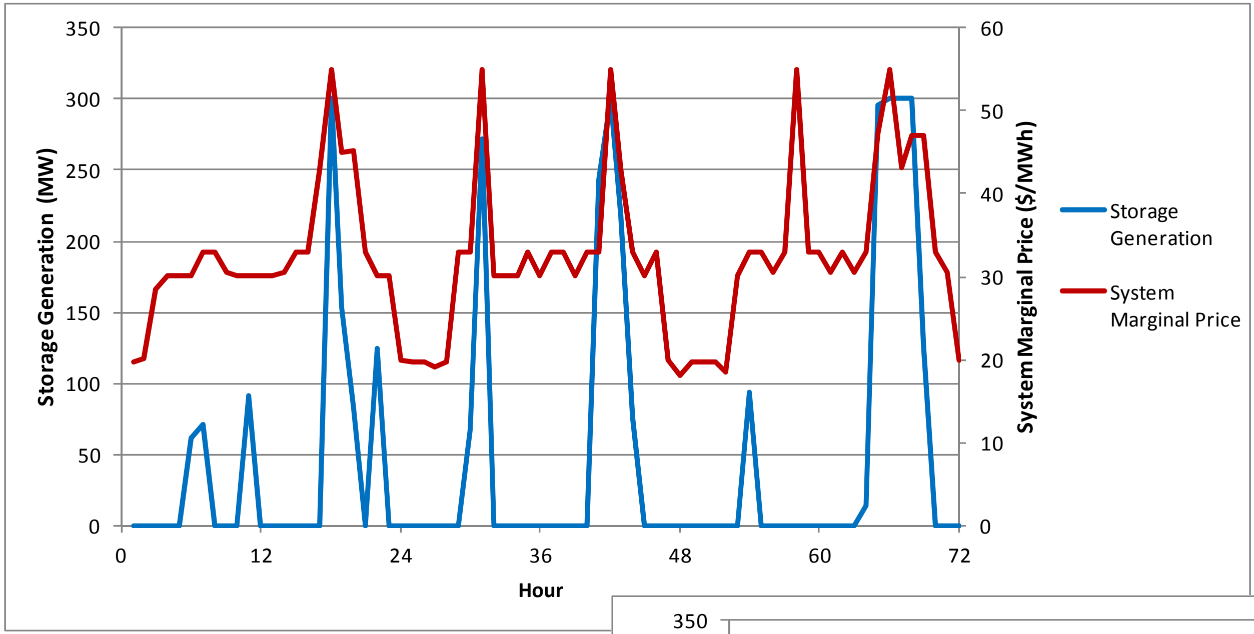


February 3-5



July 19-21

Results – Storage Dispatch (Energy)



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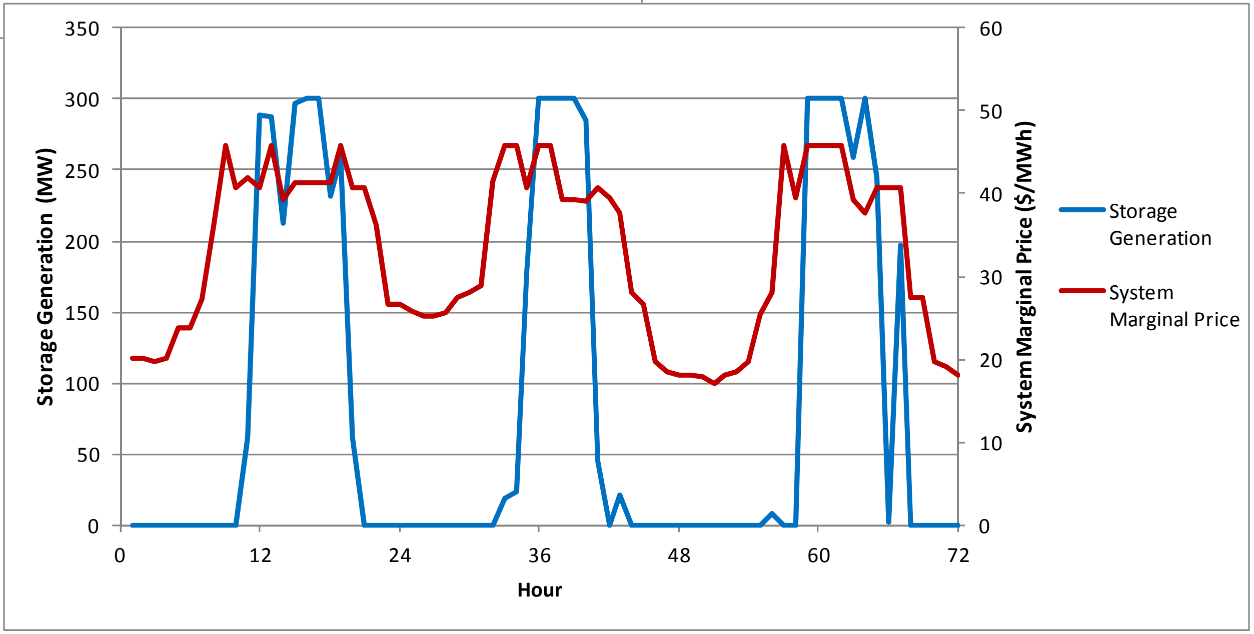
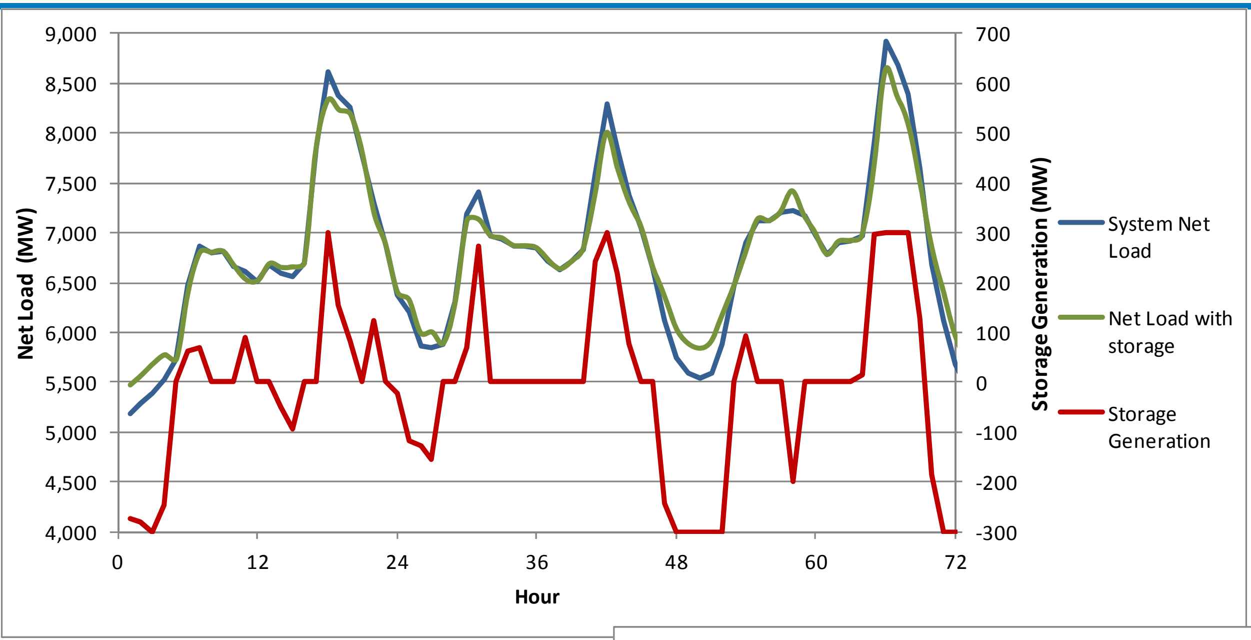


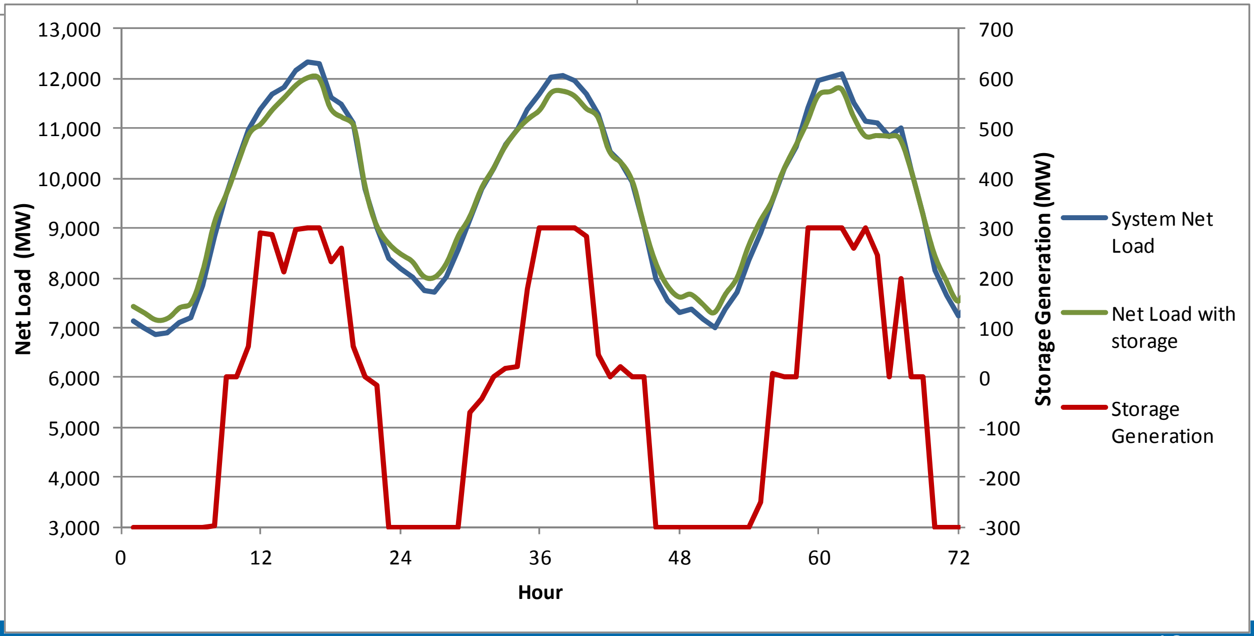
July 19-21

Results – Net Load (Energy)



February 3-5

July 19-21



Results – Fuel/Generation

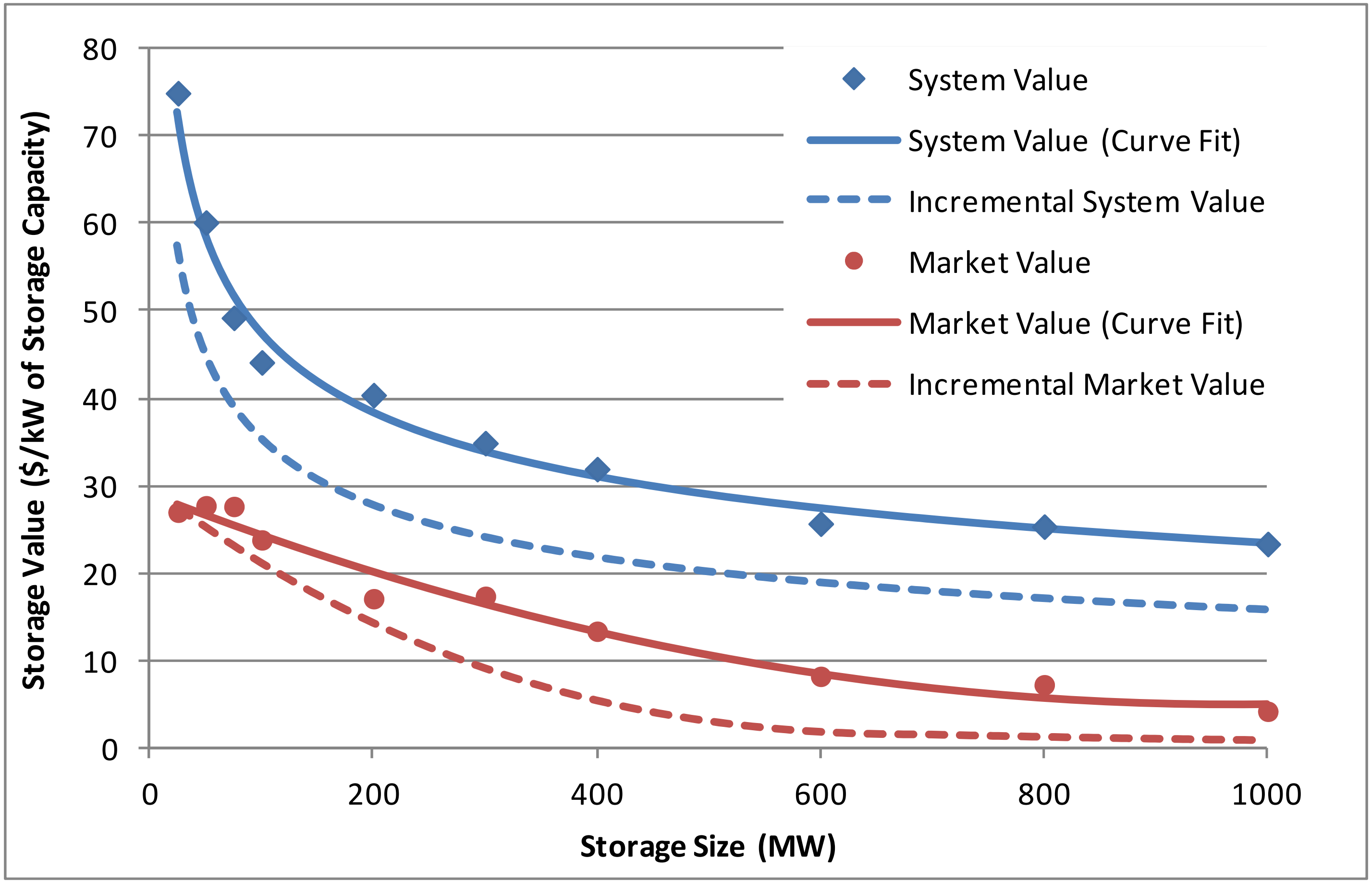
	Base Case	With Storage (300 MW)	Increase with Storage
Generation (GWh)			
Coal	46,134	46,375	241
Hydro	3,792	3,792	-
Gas CC	14,761	14,947	186
Gas CT	1,024	763	-260
Other	103	89	-14
Existing Pumped Storage	1,054	1,050	-4
New Storage	-	465	465
PV	1,834	1,834	0
Wind	10,705	10,705	0
Total Generation (GWh)	79,407	80,020	613
Fuel Use (1,000 MMBtu)			
Coal	488,140	490,930	2,790
Gas	126,651	124,728	-1,923
Total Fuel	614,719	615,658	867

Results – Change in Production Costs (300 MW Device)

	Base Case	With Storage (300 MW)	Increase with Storage
Total Fuel Cost (M$)	1,210.5	1,204.7	-5.8
Total Variable Operations and Maintenance Cost (M$)	152.1	152.8	0.7
Total Start Cost (M$)	58.2	52.8	-5.5
Total Regulation “Adder” Cost (M$)	4.7	4.8	0.1
Total Production Cost (M$)	1,425.6	1,415.1	-10.5

~50% of value from avoided starts
Price taker value - $8.5 million
Market value - $5.2 million

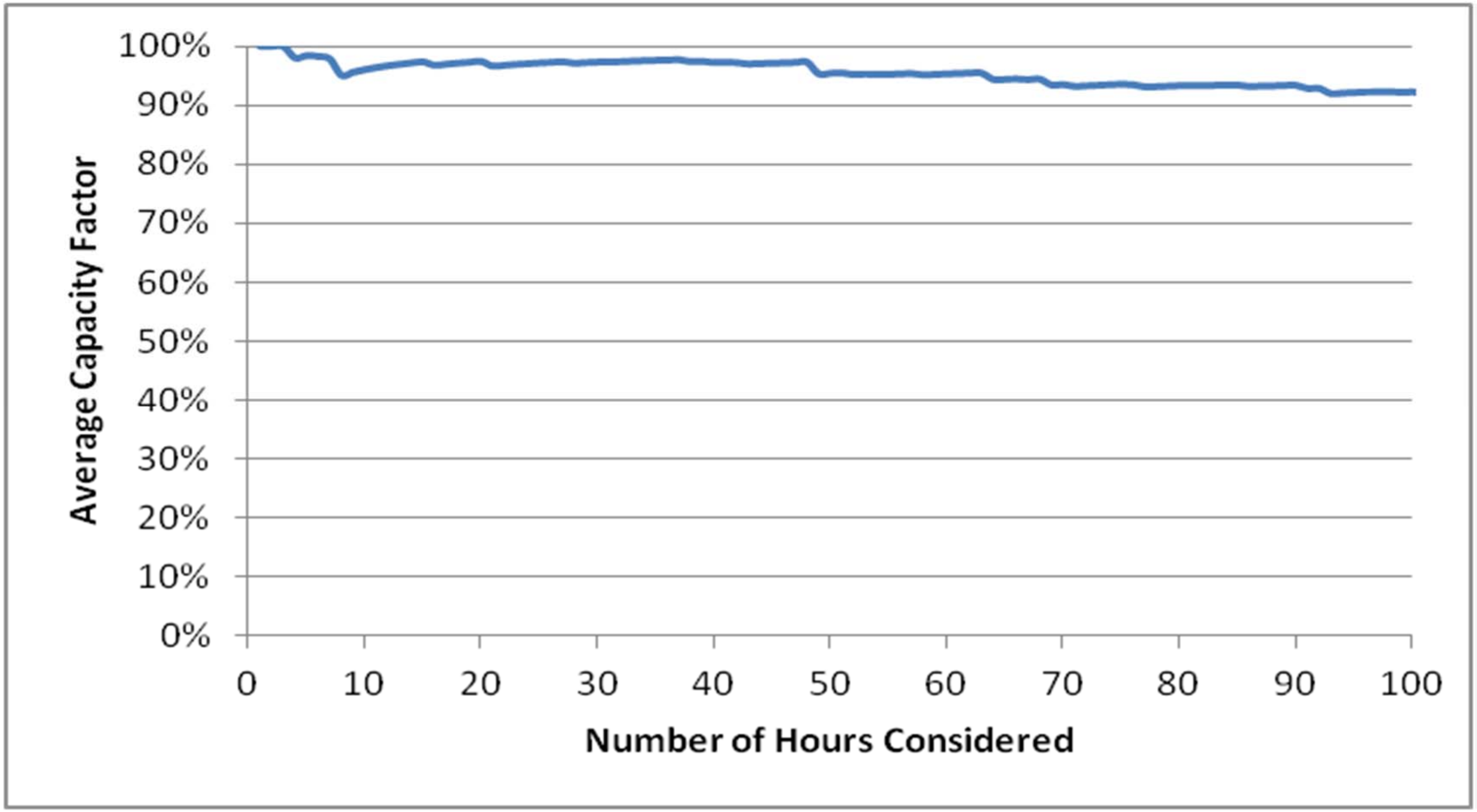
Results – Value as a Function of Size



Results – Sensitivities

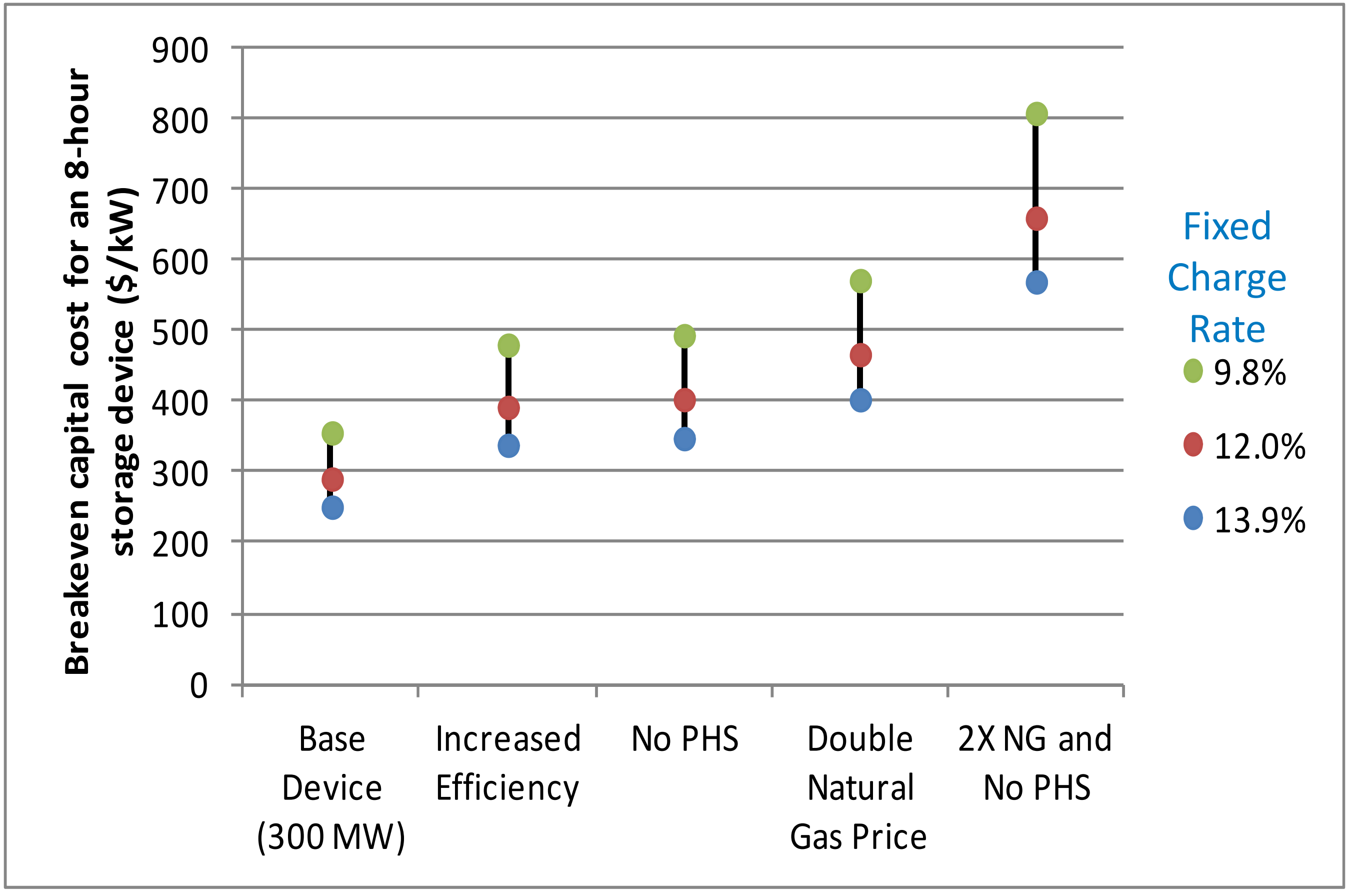
Scenario	Annual Value ($/kW)	Increase in Value for a 300-MW Device
Base 300-MW Device	34.9	-
Remove Existing Pumped Storage	48.4	39%
Increase Efficiency from 75% to 90%	47.1	35%
Double Natural Gas Prices	56.1	61%
Remove Existing Pumped Storage and Double Natural Gas Prices	79.3	127%

Results – Capacity Value



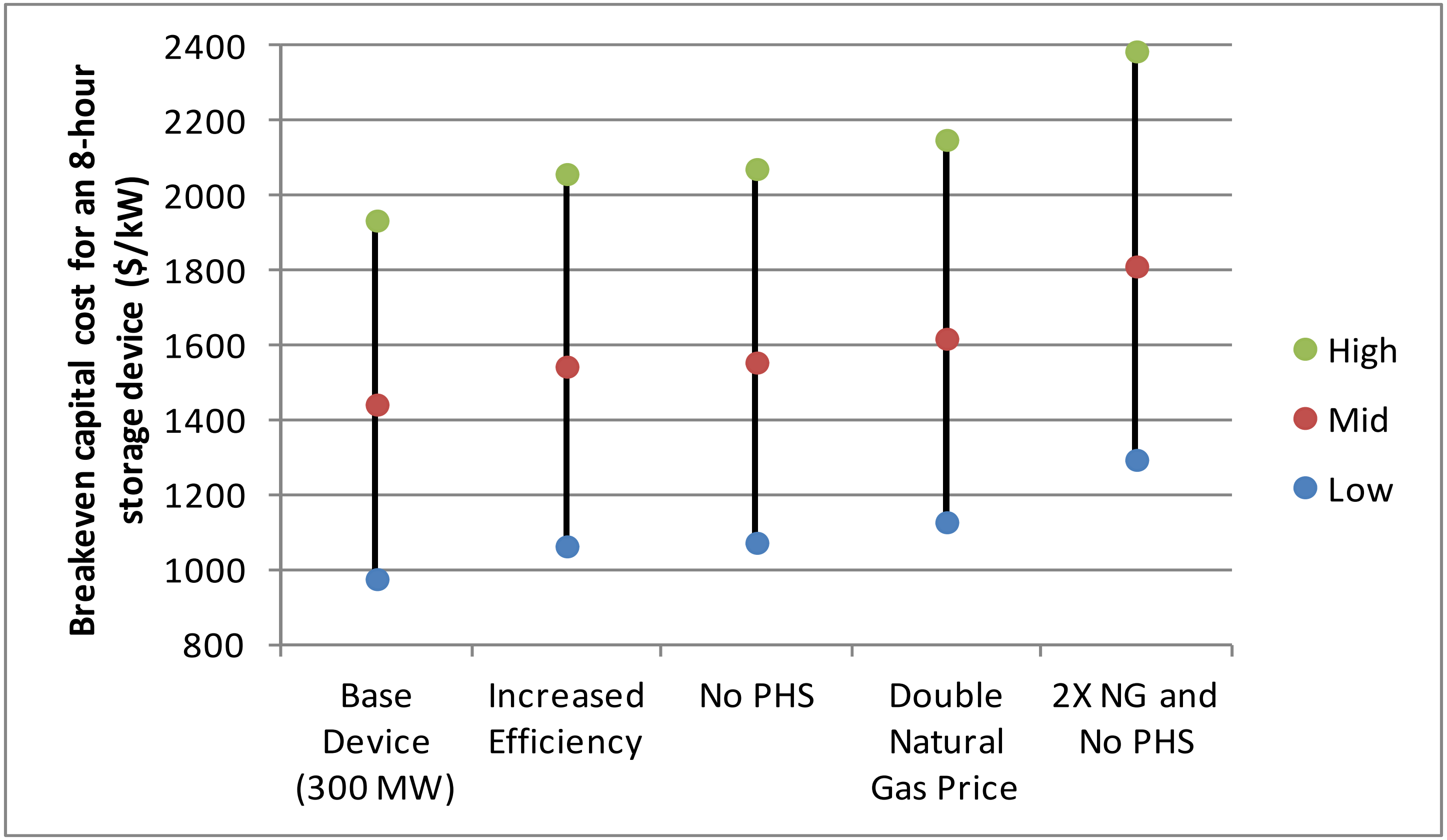
Assume a storage plant with 8 hours of capacity is functionally equivalent to a CT for capacity planning purposes

Results – Breakeven Cost (Operational Value)



Simplified breakeven cost determined by dividing annual value by a fixed charge rate

Results – Breakeven Cost (Operational + Capacity Value)



Uses same operational value as previous slide + capacity cost of a new CT

Low = $724 Mid = 1151 High =$1,578/kW

Results –100 MW Reserves Only Device

	Energy Only	Spinning Contingency Only	Regulation Only
Generation (GWh)			
Coal	111	114	180
Hydro	0	0	0
Gas CC	24	-79	-230
Gas CT	-65	-59	14
Other	-10	-3	-7
Existing Pumped Storage	3	-59	-95
Battery	175	0	0
Regulation Make-Up*			42
PV	0	0	0
Wind	0	0	0
Total Generation	237	-85	-139
Fuel Use (1,000 MMBtu)			
Coal	1,240	1,151	1,942
Gas	-736	-1,571	-2,214
Regulation Make-Up*	0	0	378
Total Fuel	505	-420	106

A positive number indicates an increase, while a negative number indicates a decrease relative to the base case.

* Make-up energy is real energy that would actually be derived from a mix of coal- and natural-gas-fired generators but was not explicitly tracked in the simulation. The make-up fuel is estimated based on multiplying the total generation by an average heat rate of 9,000 BTU/kWh.

Results – Reserves Device (Production Cost)

Cost Component	Change In Operational Cost (Million $) Compared to Case Without Additional Storage		
	Energy Only	Spinning Contingency Only	Regulation Only
Total Fuel Cost	-3.3	-6.8	-8.5
Total O&M Cost	0.3	0.2	0.3
Total Start Cost	-1.5	0.1	0.1
Total Regulation "Adder" Cost	0.0	-0.1	-4.3
Regulation Make-Up Energy Cost*	0.0	0.0	1.4
Total Production Cost	-4.4	-6.5	-11.0

A positive number indicates an increase, while a negative number indicates a decrease relative to the base case.

* Valued derived outside the production simulation.

Results – Reserves Device (Value)

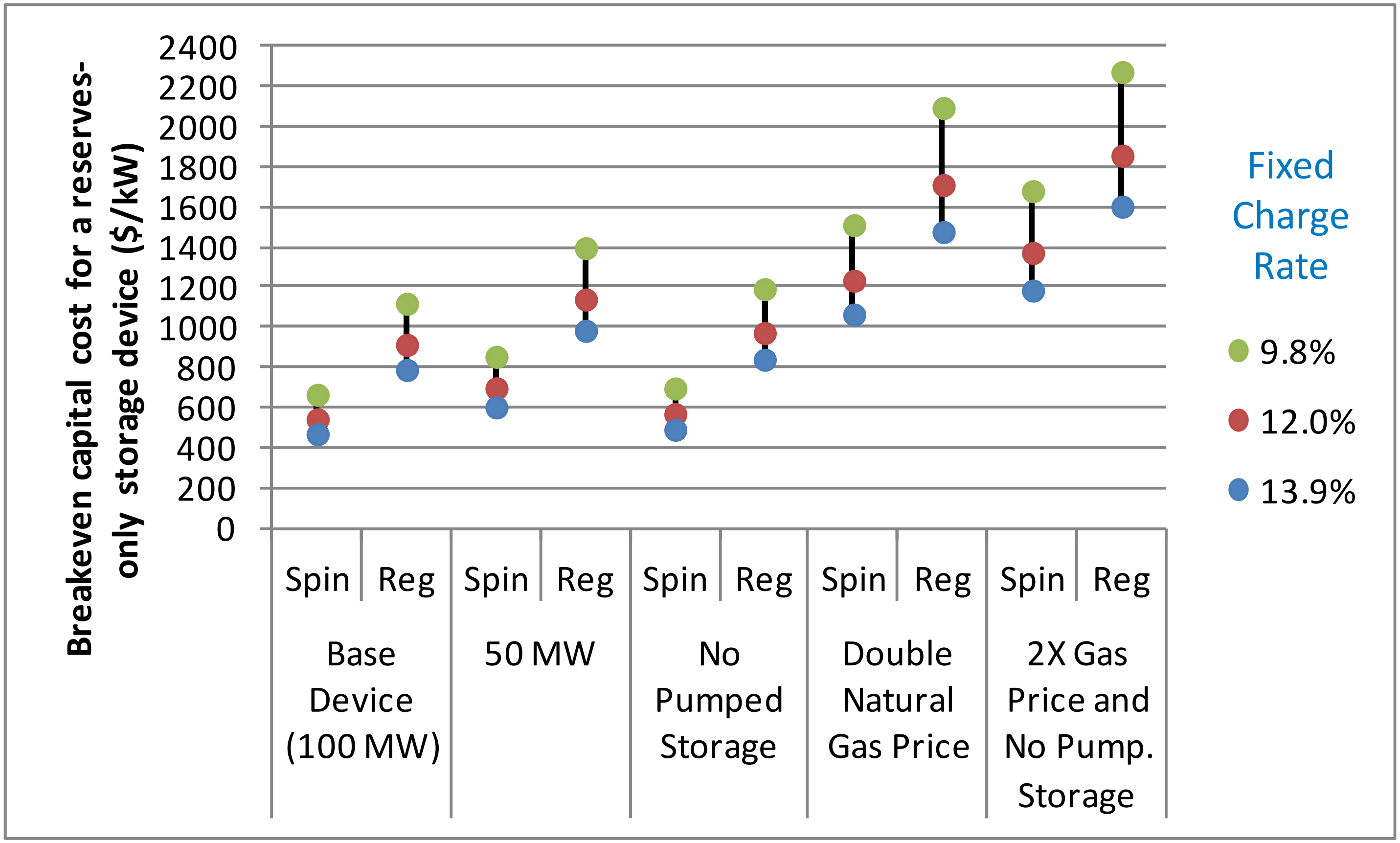
	Annual Value ($/kW)	
Scenario	**Spinning Reserves**	**Regulation Reserves**
Base 100-MW Device	65.2	109.8
Reduced Size (50 MW)	83.8	136.9
Remove Existing Pumped Storage	68.3	116.9
Double Natural Gas Prices	148.1	205.4
Remove Existing Pumped Storage and Double Natural Gas Prices	164.8	222.9

Difference Between System and Market Value

	Spinning Reserves Annual Value ($/kW)	
Scenario	System	Market
50-MW Device	83.8	51.5

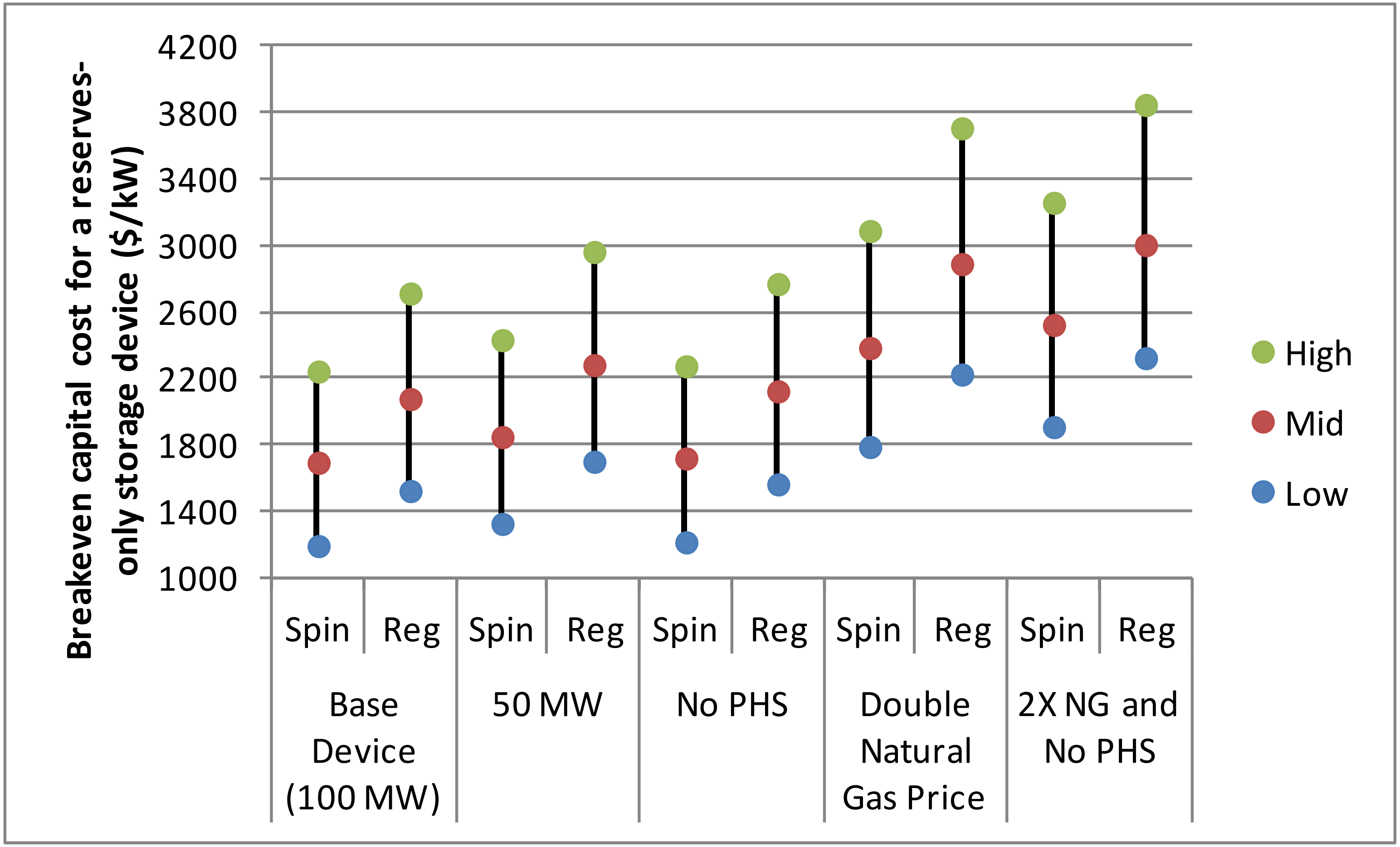
Scenario	**Regulation Reserves Annual Value ($/kW)**	
	System	Market
First 50 MW	136.9	113.4
Next 50 MW	82.6	6.3

Results – Breakeven Cost (Operational)



Simplified breakeven cost determined by dividing annual value by a fixed charge rate

Results – Breakeven Cost (Operational + Capacity Value)



Uses same operational value as previous slide + capacity cost of a new CT

Low = $724 Mid = $1,151 High =$1,578/kW

Co-Optimization

- **Considered two devices**
  - Same device as previous without restrictions on flexibility
  - Constrained device with a 40% minimum generation level (used to approximate the performance of a pumped storage device)
- **Considered two operating modes**
  - No reserves while charging
  - Both spin and regulation reserves while both charging and discharging

Co-Optimization Results

	Annual Value ($/kW-yr)	
Scenario	**No Reserves While Charging**	**Reserves While Charging**
Base Case	114.5	127.7
Restricted Flexibility Case (Similar to Pumped Storage)	54.0	63.4

40% minimum generation point restricts reserves sales

- Limited arbitrage value prevents device from providing energy services
- Adding the ability to provide reserves while charging increases system benefits

Next Steps

- **Impacts of increased renewables**
- **Sub-hourly dispatch**
  - Can storage aid in addressing forecast errors?
  - Can new rules enhance storage value? (mileage payments)
- **Distributed storage**

Learn More

Download the full report at:

http://www.nrel.gov/docs/fy13osti/58465.pdf

Denholm, P.; Jorgenson, J.; Hummon, M.; Jenkin, T.; Palchak, D.; Kirby, B.; Ma, O.; O'Malley, M. (2013). ***Value of Energy Storage for Grid Applications*****. TP-6A20-58465. Golden, CO: National Renewable Energy Laboratory.**

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