The Value of Hydro and Battery Storage in Transforming Wholesale Power Markets

PREPARED FOR

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THE Brattle GROUP

Agenda

I. The value of hydro storage

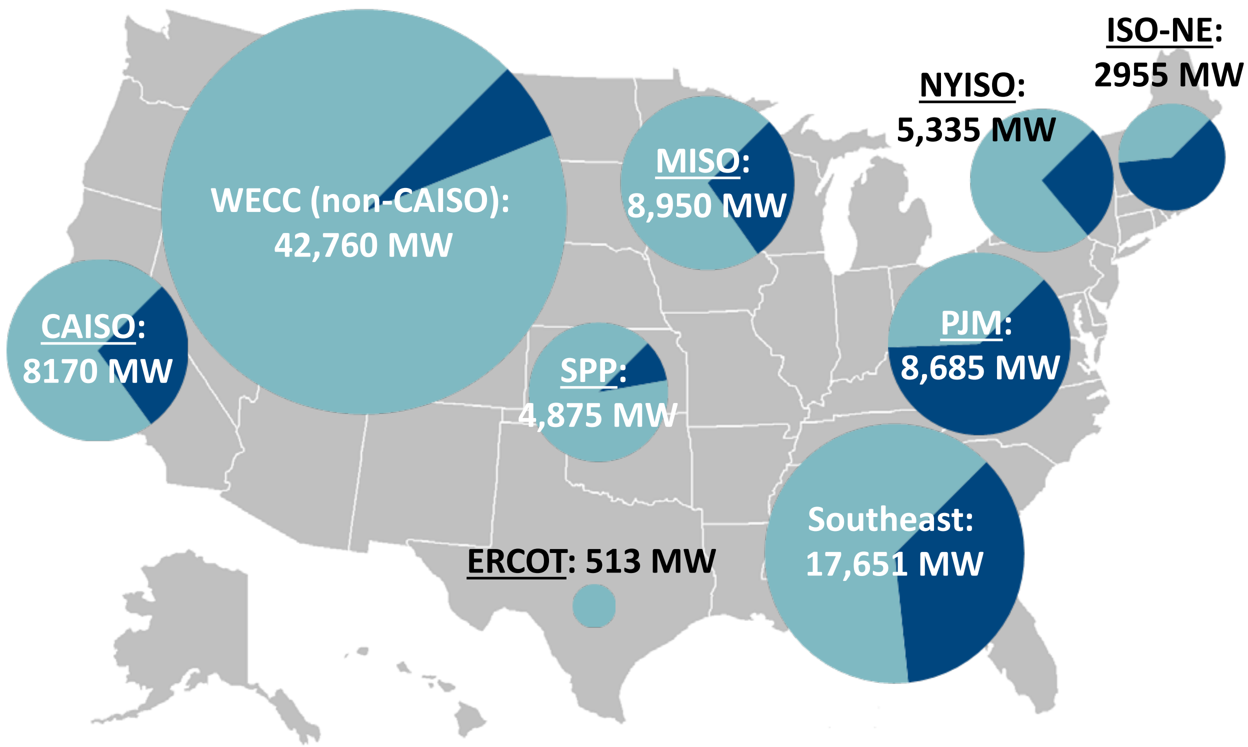
II. Wholesale market value streams

III. T&D-deferral and customer-reliability value of distributed storage

IV. Impacts of electricity industry transformation

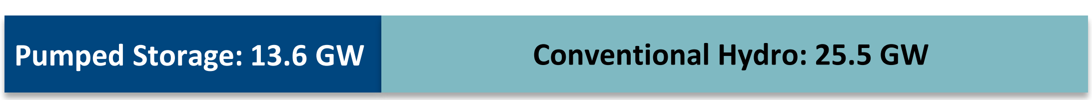
Substantial Base of Existing Large Hydro Resources

Existing Hydro Capacity in U.S. Regional Markets



- The vast majority of conventional hydro resources offer grid flexibility.
- Even pondage hydro plants, sometimes labeled as run-of-river, usually have a dam that enables then to control water flow and generation on hourly, daily, and in occasion weekly timeframes.

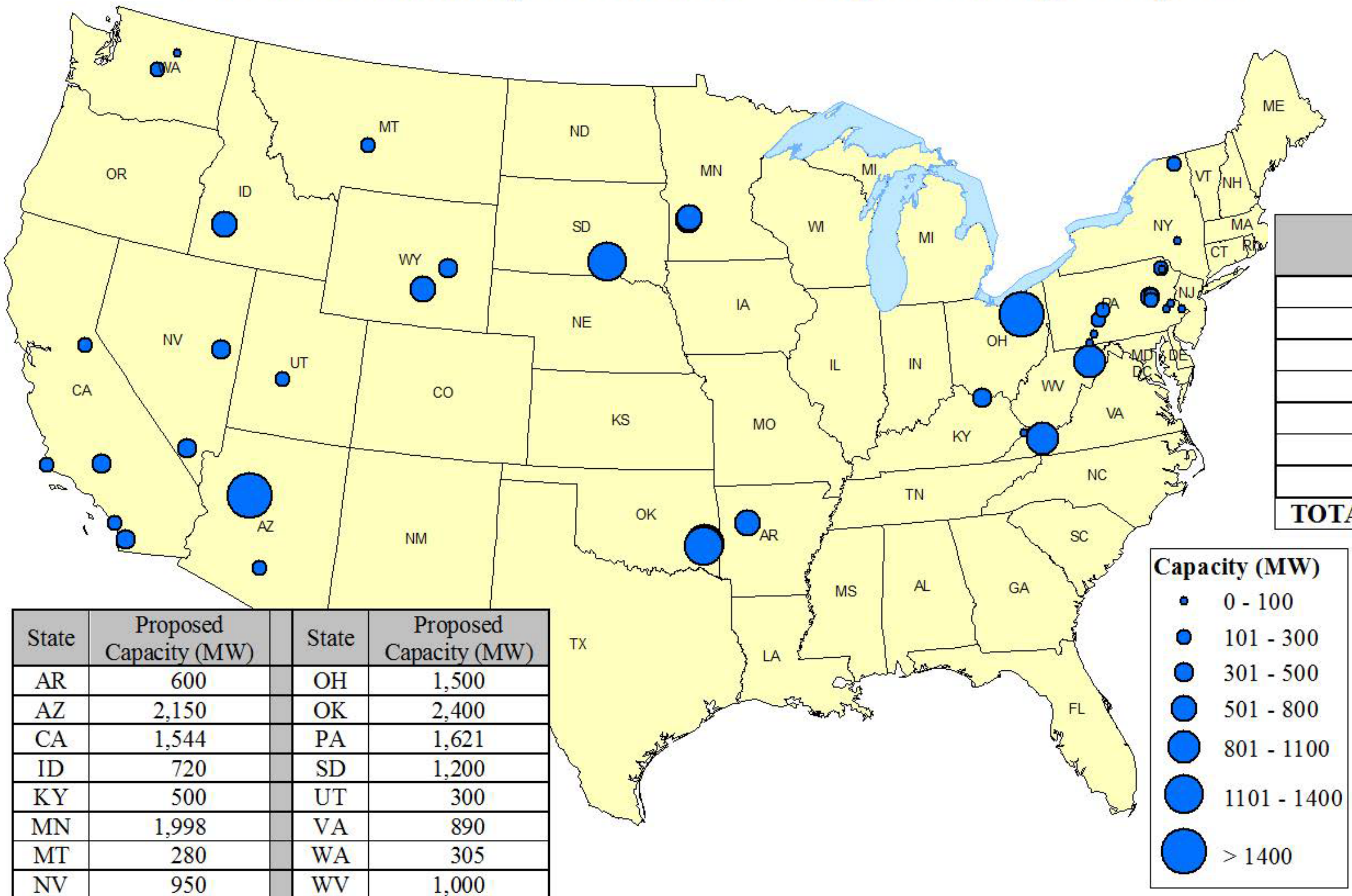
Hydro Storage Capacity in U.S. RTO Areas



Sources and Notes: The Brattle Group analysis based on SNL and other data of existing hydro plants over 25 MW.

Proposed Pumped-Hydro Plants in the US

Issued Preliminary Permits for Pumped Storage Projects



State	Proposed Capacity (MW)	State	Proposed Capacity (MW)
AR	600	OH	1,500
AZ	2,150	OK	2,400
CA	1,544	PA	1,621
ID	720	SD	1,200
KY	500	UT	300
MN	1,998	VA	890
MT	280	WA	305
NV	950	WV	1,000
NY	289	WY	1,100
TOTAL CAPACITY			19,347 MW

Source: FERC Staff, September 1, 2019

https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage/issued-permits.pdf

Pending Permits

State	Proposed Capacity (MW)
AZ	10,850
CA	4,000
GA	80
NV	4,000
OK	1,200
PA	400
UT	4,210
TOTAL CAPACITY	24,740 MW

https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage/pending-permits.pdf

Hydro Storage Underperformance in Today's E&AS Markets

The full value of hydro storage often is not realized by operators in energy and ancillary services markets

- *Resource limitations*:
  - Pumped-storage hydro: min output, min pump, time to switch, and others
  - Pondage and reservoir hydro: minimum flow constraints, cascading hydro operation, environmental, public safety, and public recreation constraints
- *Operational practices*:
  - Heuristic procedures developed to address the resource limitations
- *Market limitations*:
  - Market design, rules, optimization systems
  - The US energy markets developed with a focus on thermal resources
- *Transmission congestion*:
  - Some hydro facilities are located in areas subject to frequent transmission limitations

Hydro storage resource owners will need to re-evaluate these constraints to create additional flexibility that can be offered into the market

RTO Market Rules and Software Challenges

RTO rules and operational tools often limit hydro resources' market participation and ability to capture their full wholesale market value

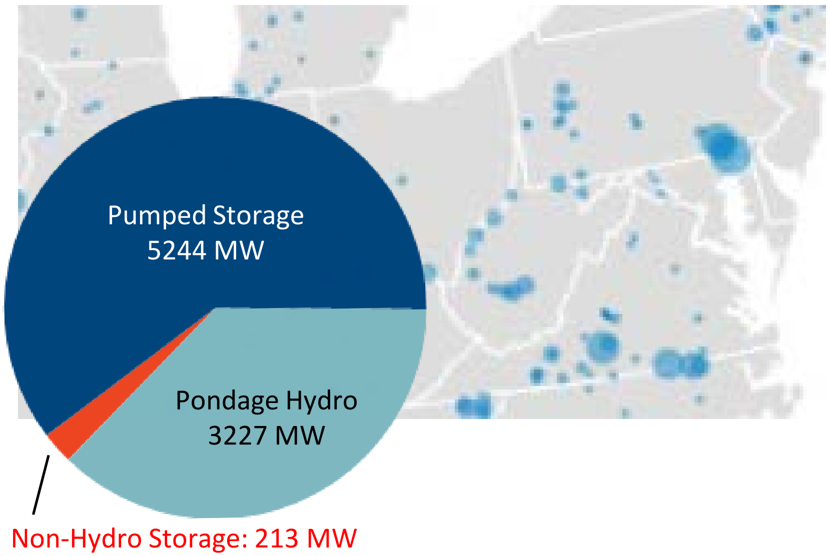
Example: PJM Today

- *Although opportunity costs are generally allowed, they are not well-defined or actively used for hydro units.*
- *Pumped-storage hydro can be scheduled by PJM, outside its market optimization engine.*
- *Hydro plants not scheduled by PJM (including all pondage plants) cannot submit price-based offers (they must self-schedule).*
- *Market enhancements have not yet focused on hydro plants.*

Potential Market Improvements

- ***Allow offering hydro energy at a price.***
- ***Optimize hydro scheduling as part of market clearing (pumped and pondage).***

Hydro Plants in the PJM footprint



Sources:
PJM hydro rules: PJM Operating Agreement, Schedule 1, Section 1.10 Scheduling, http://www.pjm.com/directory/merged-tariffs/oa.pdf
Hydro plants: The Brattle Group analysis based on SNL and other data.

Notes:
** Other resources can submit price-based offers even if they do not have "fuel costs."*

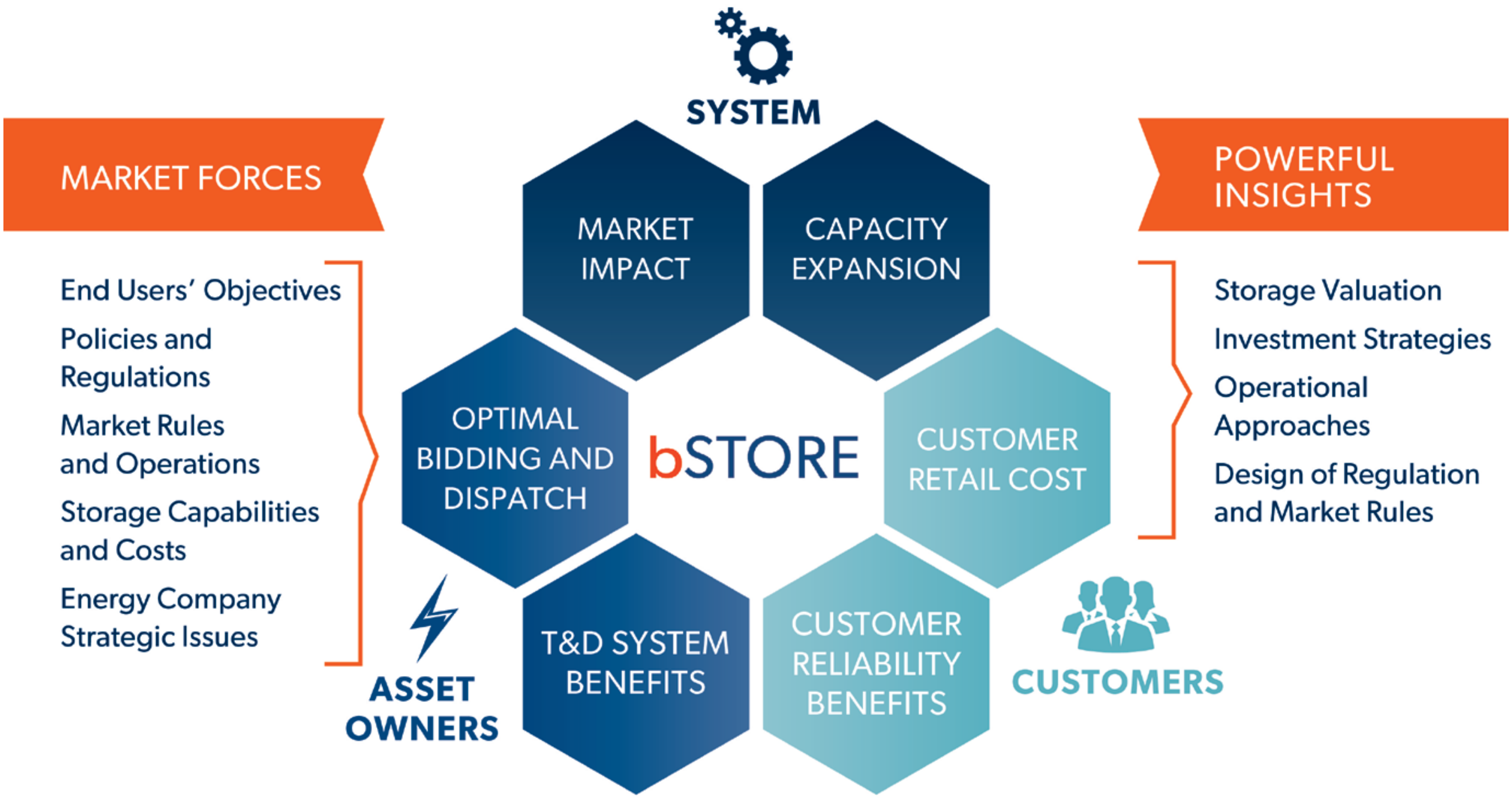
RTO/ISO Wholesale Market Products

RTOs procure **multiple market products**. Fast-responding energy storage is well suited to providing many of the products.

Market Product	Description	Function
Day-ahead Energy	Initial scheduling of resources that occurs 24 hours in advance of the delivery day	- Enables scheduling of resources with long startup times - Provides operational and financial certainty for market participants
Real-time Energy	Updated resource scheduling that occurs 1 hour to 5 minutes in advance of delivery	- Allows operators to account for forecast error in the day-ahead market
Regulation	Resources set aside to ramp up/down in response to minute-to-minute load fluctuations	- Typically provided by generators equipped with automatic governor control (AGC) and telecommunications equipment, capable of responding to a regulation signal within five minutes - Increasingly provided by battery storage in RTO markets - Quantity procured is **SMALL**
Contingency Reserves	Resources set aside to respond in the event of a major system contingency, e.g. an unexpected, large generator or transmission failure	Two categories: - *Spinning/synchronized reserves:* Resources synchronized to the grid and capable of quickly increasing output or decreasing load quickly (typically within 10 minutes) - *Non-spinning / Non-synchronized reserves*: Resources not synchronized, but capable of coming online quickly in response to a contingency, typically within 30 minutes
Flexible Reserves	Resources set aside to account for demand and renewable forecasting errors	- In CAISO, "flexible ramping product" sets aside resources to provide upward and downward flexible ramping capacity to manage forecasting error - Similar product in MISO

Additional services (e.g. voltage support & blackstart) not procured through markets

Brattle's bSTORE Storage Modeling Platform



bSTORE Application for Hydro E&AS Market Optimization

Optimal Bidding and Dispatch

Markets Sequence
Co-optimize Day-Ahead and Real-Time participation

Product Selection
Co-optimize revenues from Energy and Ancillary Services

Market Uncertainty
Imperfect foresight, develop strategies with recourse

Price Impacts
Locational market response to change in plant operations

Market Constraints
Account for RTO Rules and Software limitations

Resource Constraints
Quantify impacts of Plant & Environmental constraints

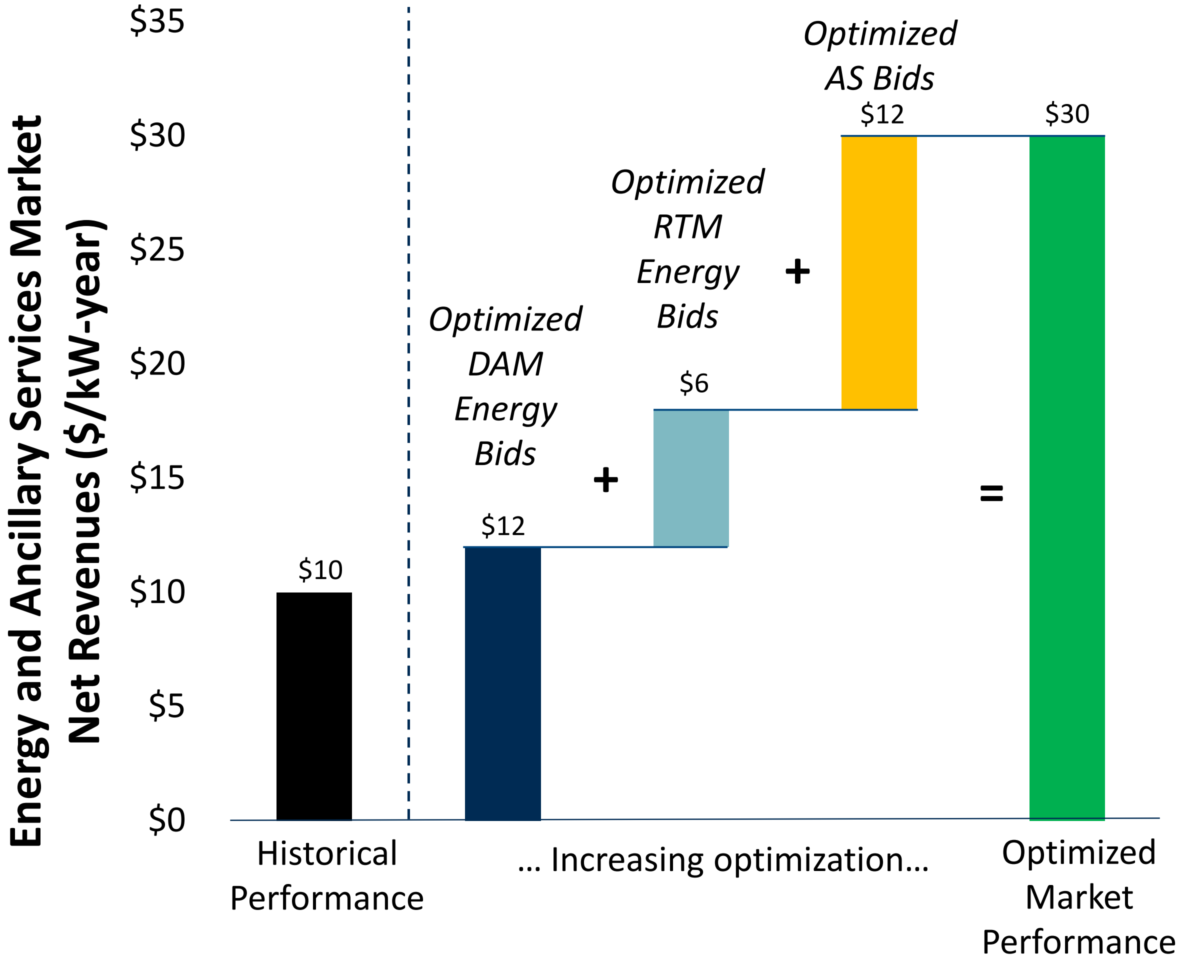
Transmission
Full network model supports nodal simulations

Module Features

- Mixed Integer Programming (MIP) solver as used by RTOs
- Rolling-horizon simulation with look-ahead optimization
- Sequential model of DA, RT and other decision cycles with feedback loops
- Scenario-based & heuristic-based uncertainty modeling
- Hydro modeling
  - Generation constraints
  - Reservoir constraints
  - Cascaded plants w/ delays
  - Value of water: calculate (long-horizon problems) or specify (short-horizon)

Case Study: Flexible-Hydro is Currently Underutilized and Undervalued

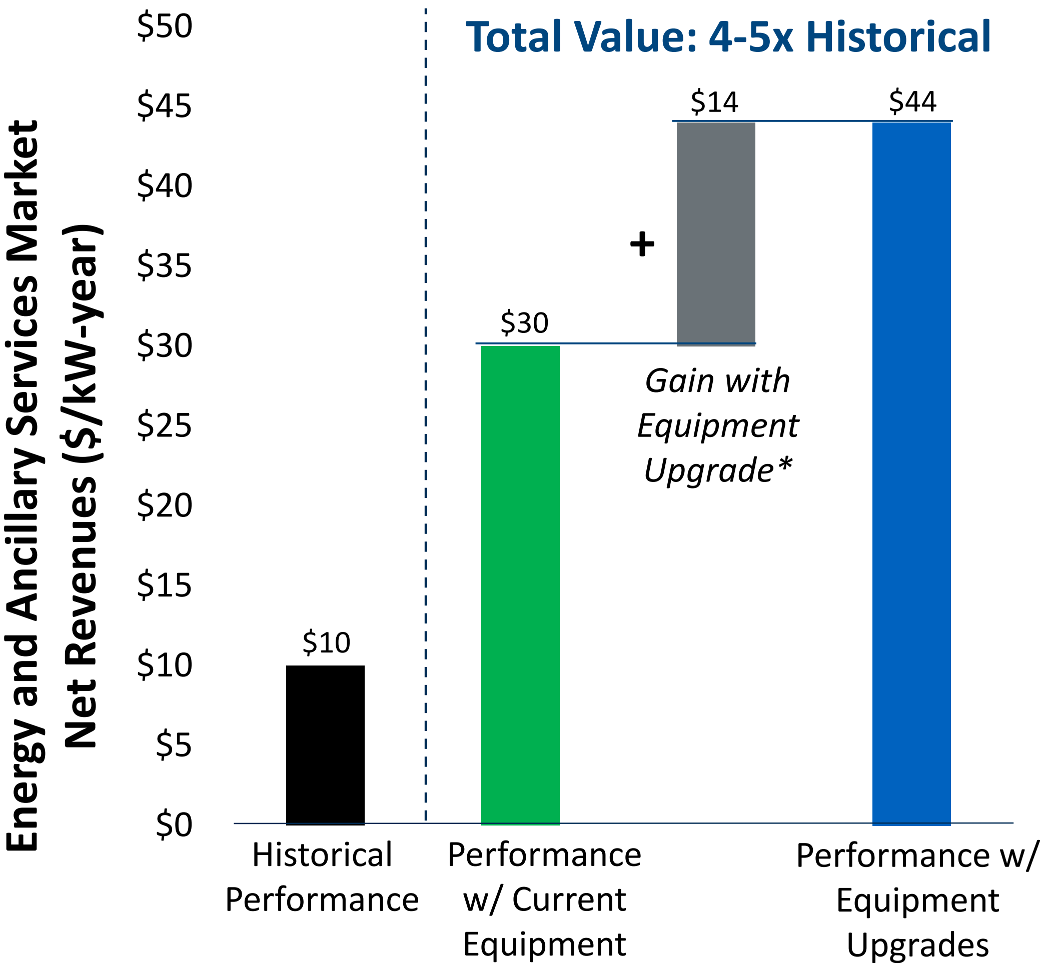
Example: Pumped Storage Hydro plant operating in U.S. RTO market



- Neither hydro nor market operators are currently optimizing the value of flexible hydro resources
- Hydro asset owners often have limited incentives to maximize market value
- **Optimized operating strategies can increase storage revenues 2–3 times!**
  - Accounting for: existing market rules considering DA/RT energy and AS markets, uncertainties, market impacts, and operational constraints

U.S. Case Study: The Value of Increasing the Flexibility of Existing Hydro Plants

Equipment upgrades can further increase the value of hydro plants



- Legacy plants may be subject to costly constraints:
  - Time to switch pump/generate modes can be too long
  - Limits AS and RT energy market opportunities

  * Equipment upgrades to enable fast mode switching enables substantial AS and RT market gains
- **The value of enhancing flexibility of hydro plants will only increase by the ongoing transformation of wholesale power markets**

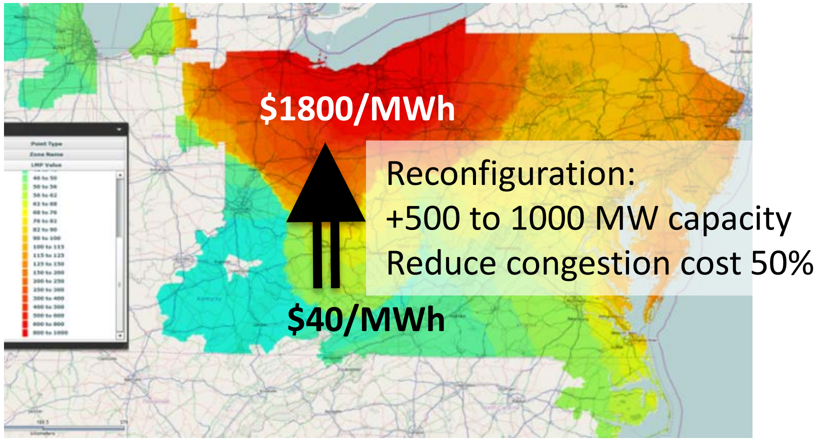
Transmission Congestion Relief Strategies Available to Enhance Asset Values

Congestion affecting hydro-storage projects can usually be relieved cost-effectively by employing advanced transmission technologies

- Congestion is often seen by the plant owner as an erratic price signal
- Advanced transmission technologies provide cost effective and timely means to relieve plant congestion under these conditions
  - *Transmission reconfigurations (topology control/line switching)*
  - *Power flow control devices*
  - *Dynamic line ratings*

Case Study: PJM

- ✓ *Extreme peak conditions with outages*
- ✓ *Reconfiguration can increase transfer capacity by **5-10% (500-1000 MW)***
- ✓ ***50% reduction in congestion cost***
- ✓ *Similar relief of more localized congestion in PJM, SPP, MISO, ERCOT, UK*



PJM Real Time Prices, 18/7/2013, 15:30 (pjm.com)

Opportunities for Existing and New Hydro Generation

Existing hydro resources are well positioned to compete in a markets-based wholesale power industry

- Wholesale power market regulations and designs will need to be evolve with evolving customer preferences, technological changes, and associated system needs
- Hydro resources will need to be better optimized into (DA+RT) energy, ancillary services, flexibility, and capacity markets
- Upgrades to existing resources may be warranted to increase operating flexibility and capture additional market revenues

New hydro generation investments will be challenged

- Substantial lead-times, permitting challenges, scale, high costs, and capital-intensive nature are a significant handicap of new hydro resources
- Rapid technological change (e.g., low-cost wind, solar, and batteries) combined with general uncertainty about future industry direction will favor shorter-lead-time, less capital-intensive technologies
- Who really should or would want to take the substantial investment risk?

Agenda

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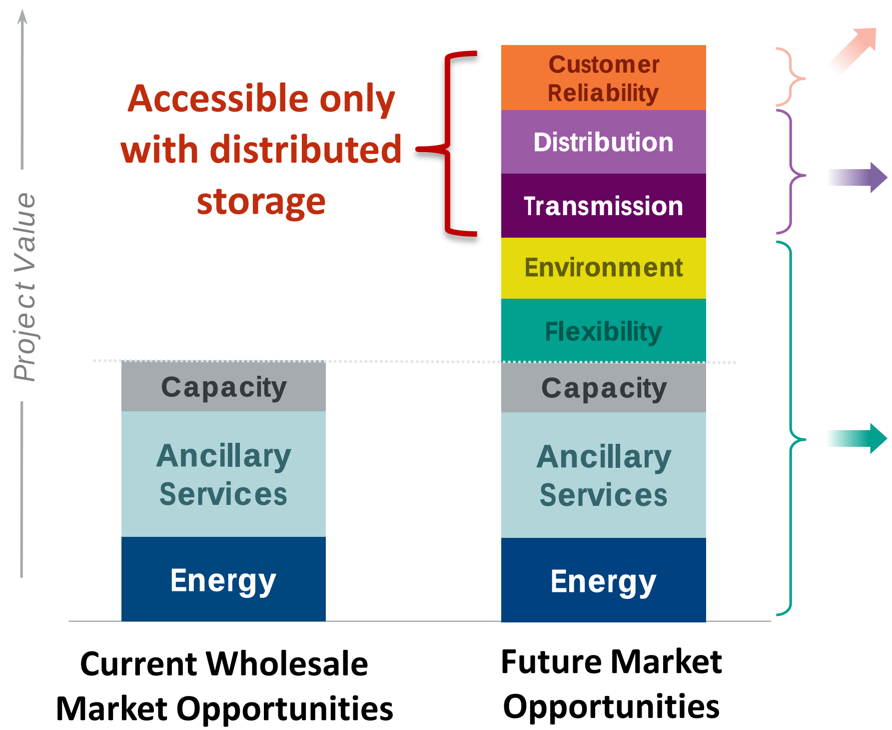
IV. Impacts of electricity industry transformation

The Multiple Value Streams of Storage

Storage can capture multiple value streams, but some of them are not accessible by hydro storage because they require the locational flexibility of distributed storage resources

Storage Value Components



Customer Value

- Increased reliability (reduced outages)
- Increased engagement in power supply

Utility Infrastructure Value

- Deferred or avoided investments in distribution and transmission infrastructure
- Voltage support & improved power quality

Wholesale Market Value

- Traditional value drivers: energy arbitrage, fast-response capabilities, and avoided capacity
- Realizing additional value due to higher quality A/S and load following reserves
- Flexibility and clean-energy products will provide additional revenue opportunities in the future

Focus of next slides

Storage Modeling Approaches

Price-taker Simulation

- Models only the storage resources of interest
- E&AS price profiles are specified
  - Fixed prices
  - Dispatch-sensitive prices
- If price time series are historical, they can capture price volatility well
- Application: assess incremental assets to a given portfolio

Increased model complexity needed to model broader system changes

System Simulation

- Models entire system
- E&AS price profiles are intrinsic to the model, depends on:
  - Resource mix
  - Fuel prices
- To ensure appropriate price volatility, it is critical to model in detail the sources of uncertainty
- Application: determine the impacts of broad portfolio changes

Modeling choices important for both approaches:

- *Optimization time horizon: long-enough to calculate storage value*
- *Simulation period: representative of price fluctuations*
- *Time granularity: hourly? 5-minutes?*

Storage Modeling Parameters

Storage can be **robustly modeled** with a **set of technical and cost parameters**.

Technical Parameters
Storage size (MW)
Storage duration (hours) / **storage capacity** (MWh)
Round trip efficiency (RTE) (%)
Ramp rate (MW/min)
Max/min allowable state of charge (reservoir level)
Degradation characteristics

Cost Parameters
Variable operations and maintenance (O&M) cost
Fixed O&M
Capital cost

Uncertainty and Variability in Storage System Simulations

Price volatilities are intrinsically calculated when running System Simulations

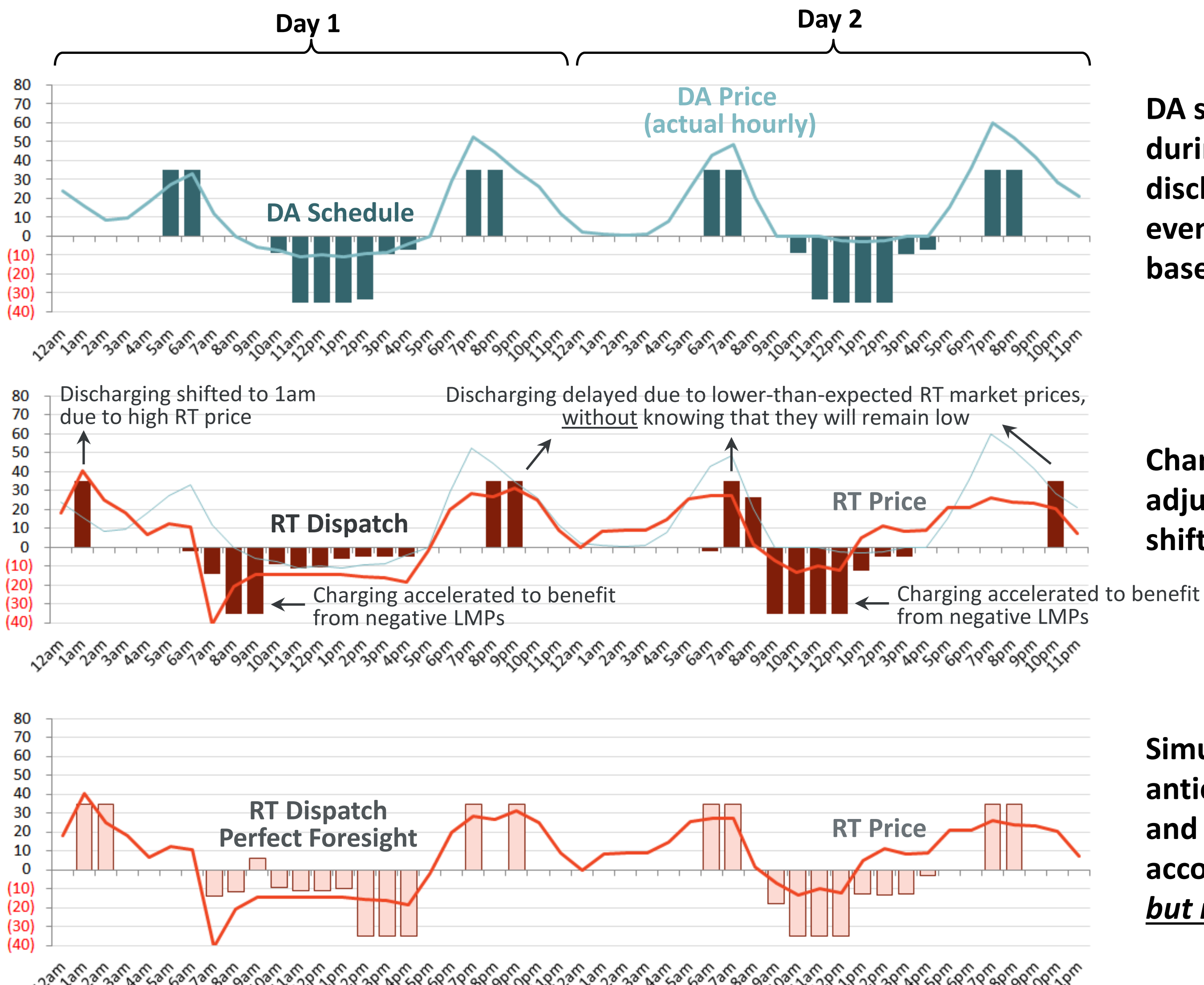
- Modeling of multiple decision timeframes
  - Month/Week ahead (for long duration, e.g., hydro storage)
  - Day-ahead offer preparation and RTO clearance
  - Intra-day updates
  - RT market clearing
- Resource and transmission outages: when do they become known?
- Resource forecast uncertainty modeled in each timeframe
- Benchmarking average prices is not sufficient, need to benchmark price variability as well

Uncertainty and variability modeling are critical inputs!

Dispatch Strategies and Foresight

Dispatch Strategy	Description	Foresight Assumption
Ancillary Services Only	Schedule storage capacity to solely provide ancillary services (frequency regulation or spinning reserves); do not co-optimize with providing energy	No foresight required
Day-Ahead (DA) Energy Only	Schedule over the next day based on a day-ahead forecast of system conditions	Day-ahead forecast or equivalent
DA Energy + Ancillary Services	Schedule to provide energy and/or ancillary services in all hours	Day-ahead forecast or equivalent
DA + Real-Time (RT) Energy Redispatch	Adjust DA scheduling in real-time based on current and near-term expected system conditions	Day-ahead forecast or equivalent, then: • If redispatching with hourly granularity, expectation of conditions over next hour • If redispatching with 5-min granularity, expectation of conditions over next 5 – 60 minutes

Dispatch into DA+RT Energy Market With and Without Perfect Foresight

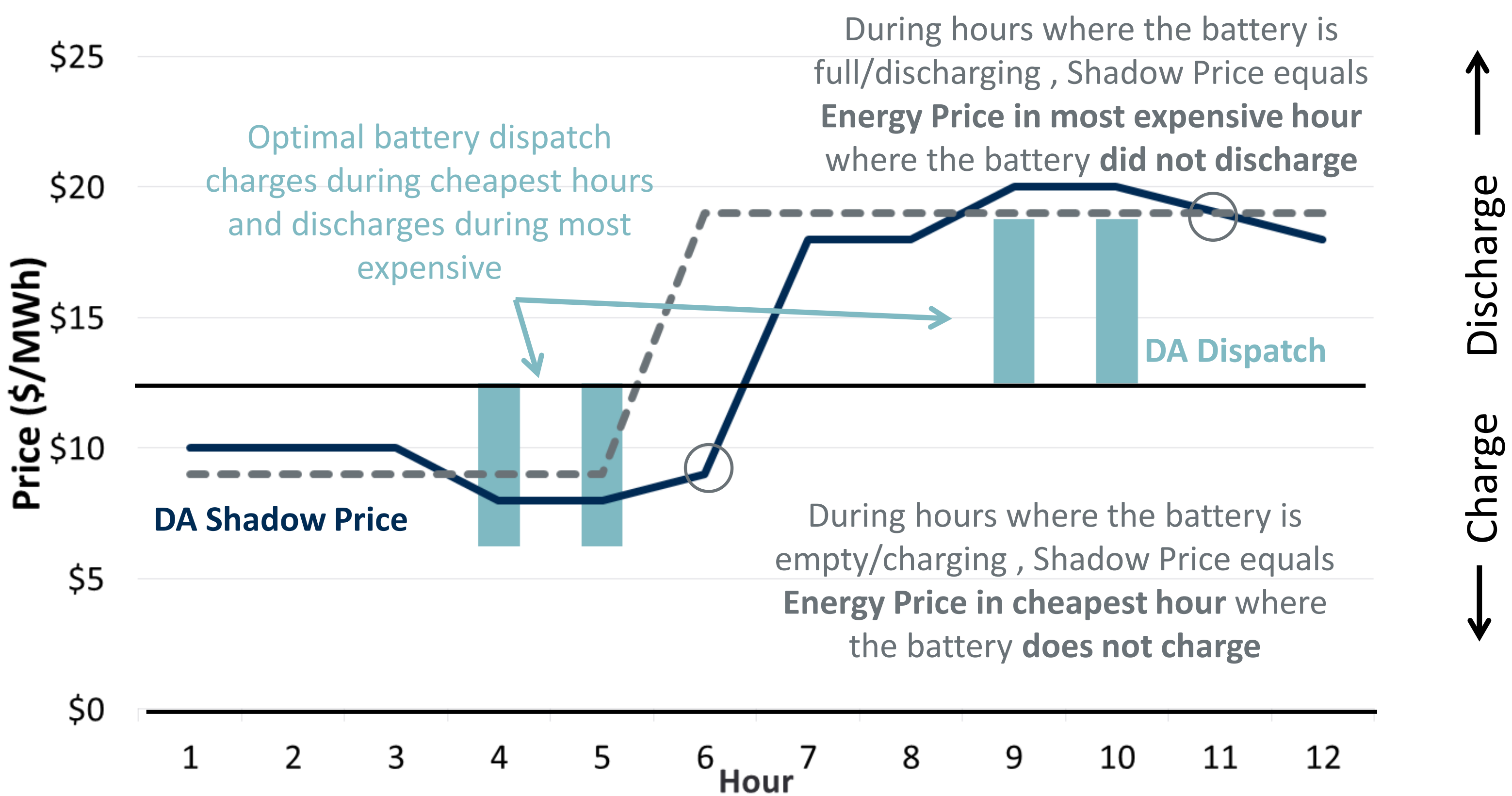


DA schedule set to charging during the day (10am–4pm) and discharging during morning & evening peaks (5–6am, 7–8pm) based on price expectations

Charging/discharging decisions adjusted due to unexpected price shifts in real-time

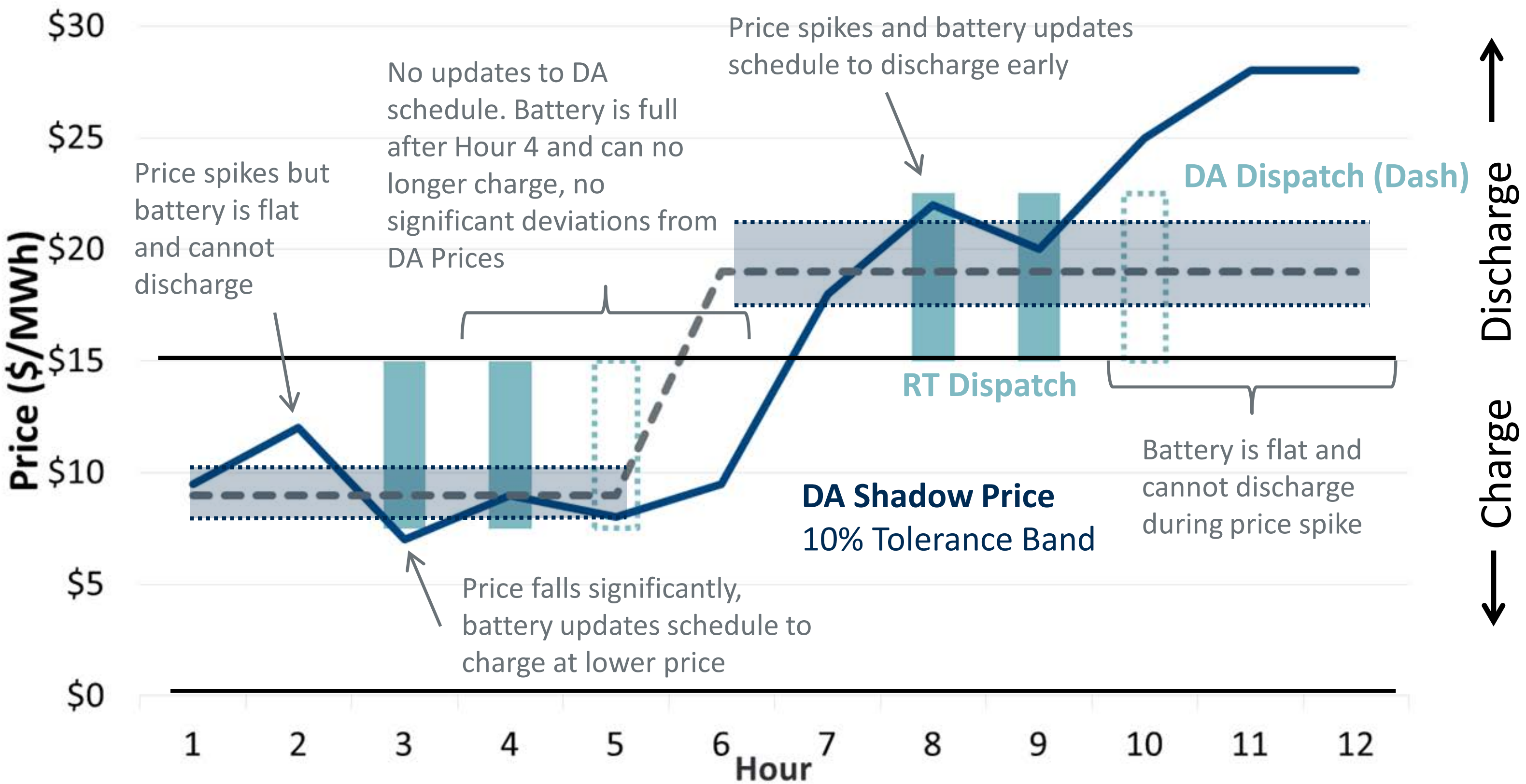
Simulations with perfect foresight anticipates highest-lowest RT prices and determines battery decisions accordingly *(this is more profitable, but not realistic)*

Shadow-price and Dispatch in DA cycle



- Simplified example illustration purposes only.
- Assumed battery w/ 2-hour charging/discharging capacity with no losses + sufficient solar to charge in each hour.
- Within a cycle, if Energy Price < SP, battery will charge, if Energy Price > SP, battery will discharge.

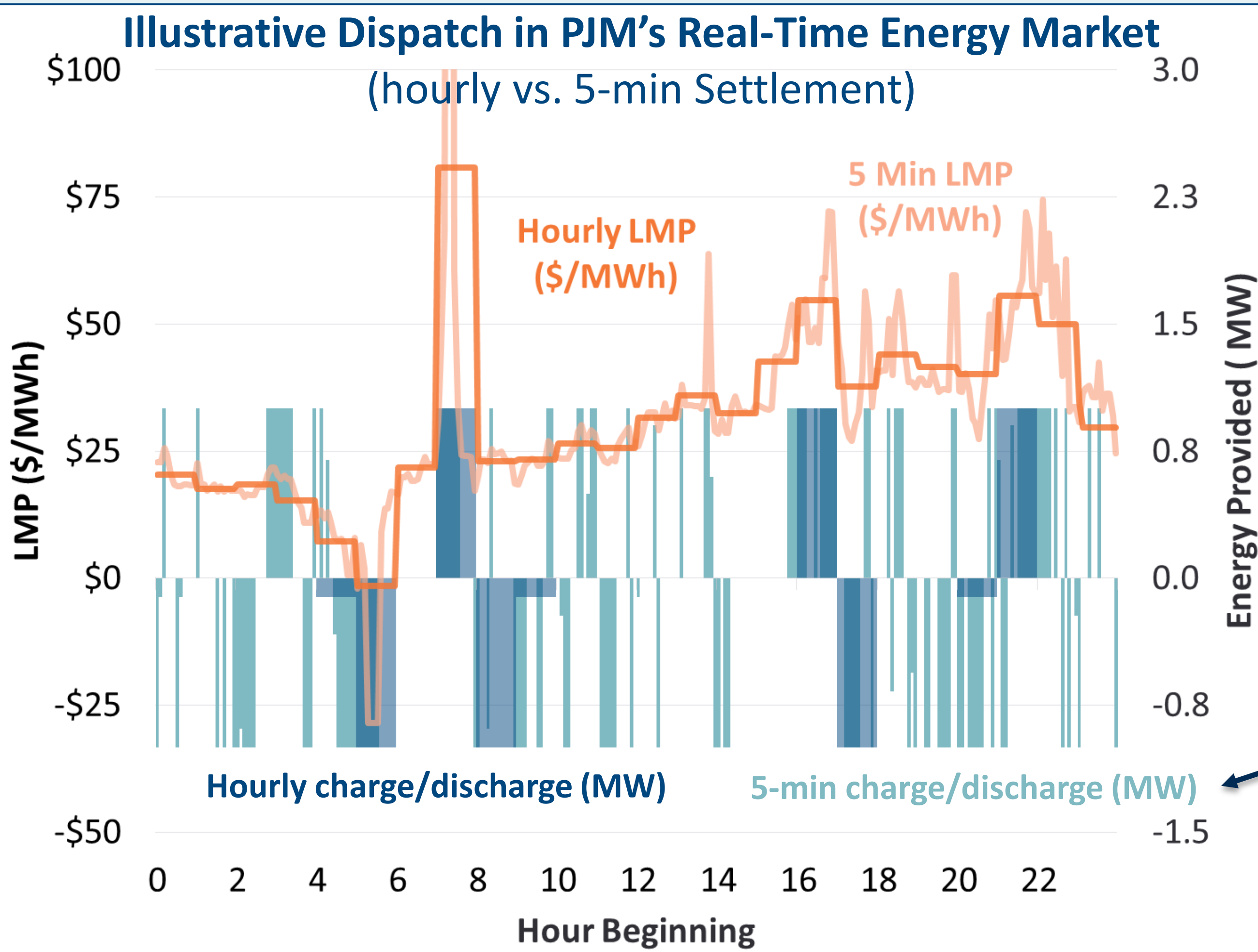
RT Re-dispatch with Imperfect foresignt



- Simplified example for illustration purposes only.
- Assumes battery w/ 2-hour charging/discharging capacity with no losses + ability to charge in each hour.
- Within a cycle, if Energy Price < DA Shadow P, battery will charge, if Energy Price > DA SP, battery will discharge.

Energy Arbitrage in 5-min RT Markets

Arbitrage opportunities are higher in Real-Time due to its volatility, but uncertainty modeling and 5-min granularity become more important.

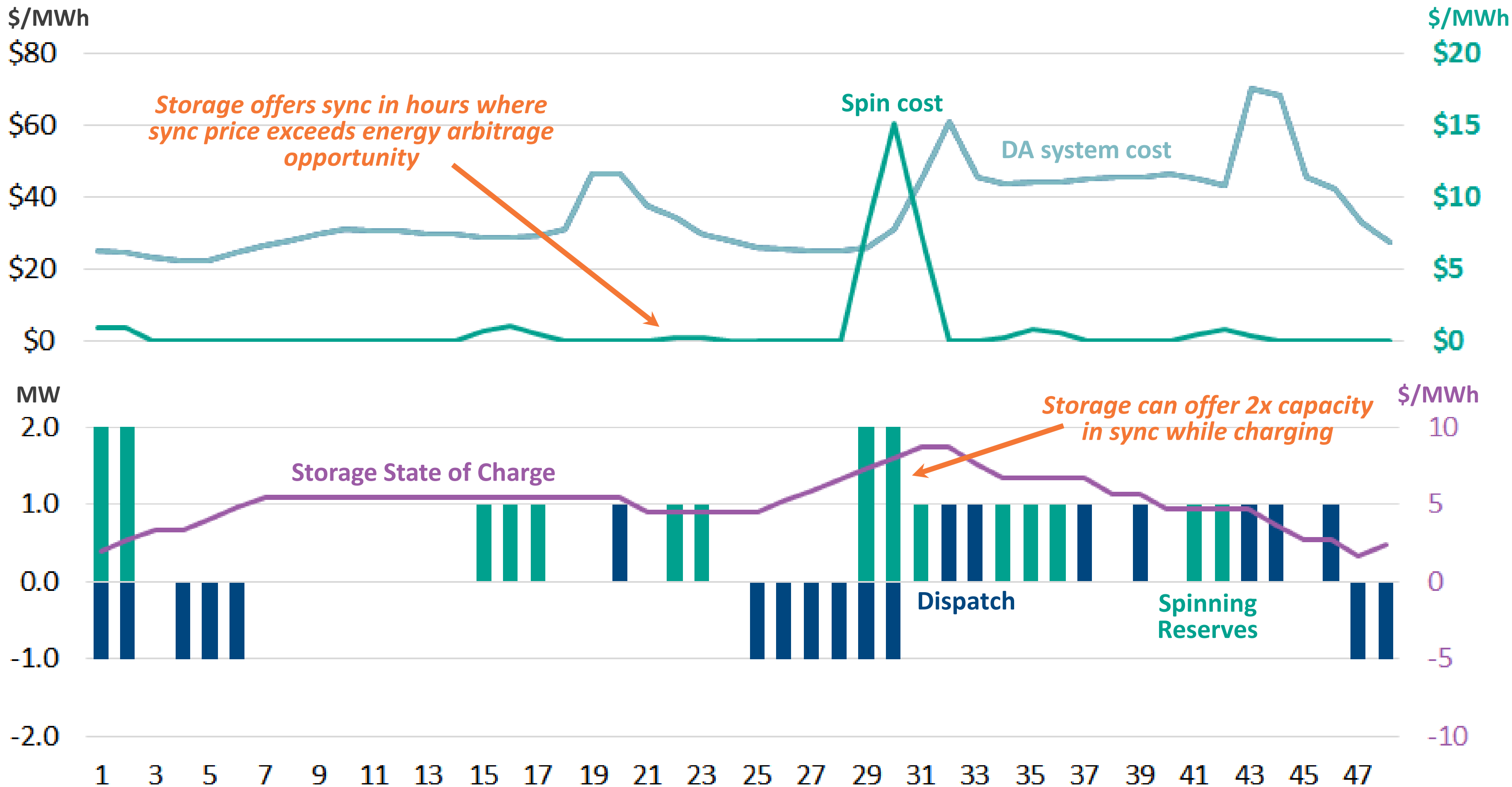


More active charging and discharging against more volatile 5-min prices

Note: Example data from PJM. Price spike in hour 7 occurs for two consecutive 5-minute increments.

Modeling DA Energy+Spin Participation

In this strategy, **storage provides both energy and spinning reserves**. Batteries can effectively **provide spin at low cost** if sufficiently charged.

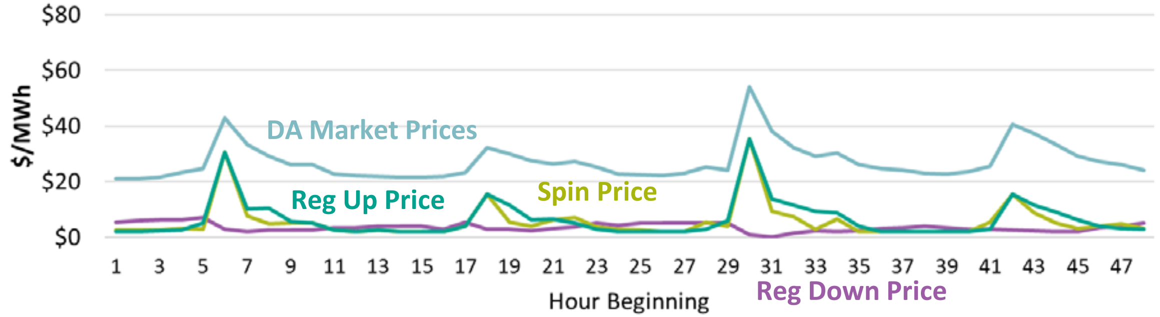


Notes: Intervals shown are for a 10-hour, 1-MW battery.

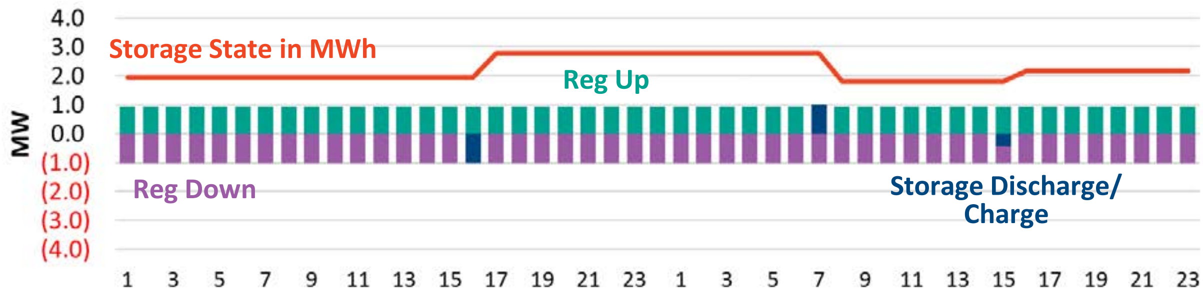
Modeling Energy+Spin+Reg Participation

In this strategy, **storage provides energy, spin, and regulation**. Optimal control may become challenging as battery provides more services.

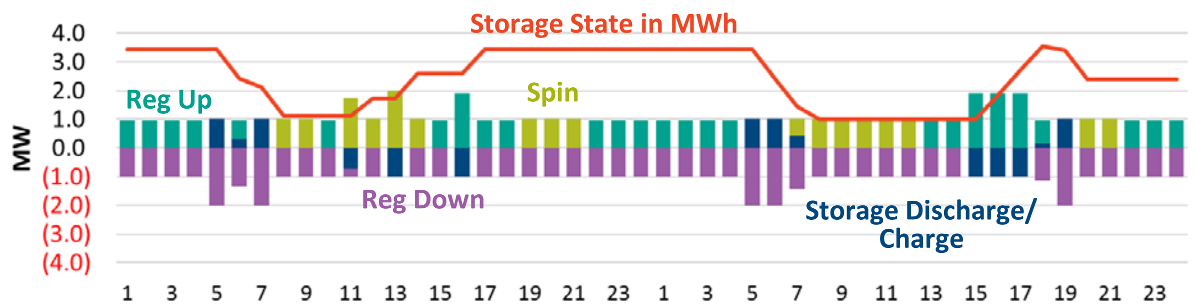
DA Energy and Ancillary Service Prices



DA Energy + Regulation



DA Energy + Regulation + Spin

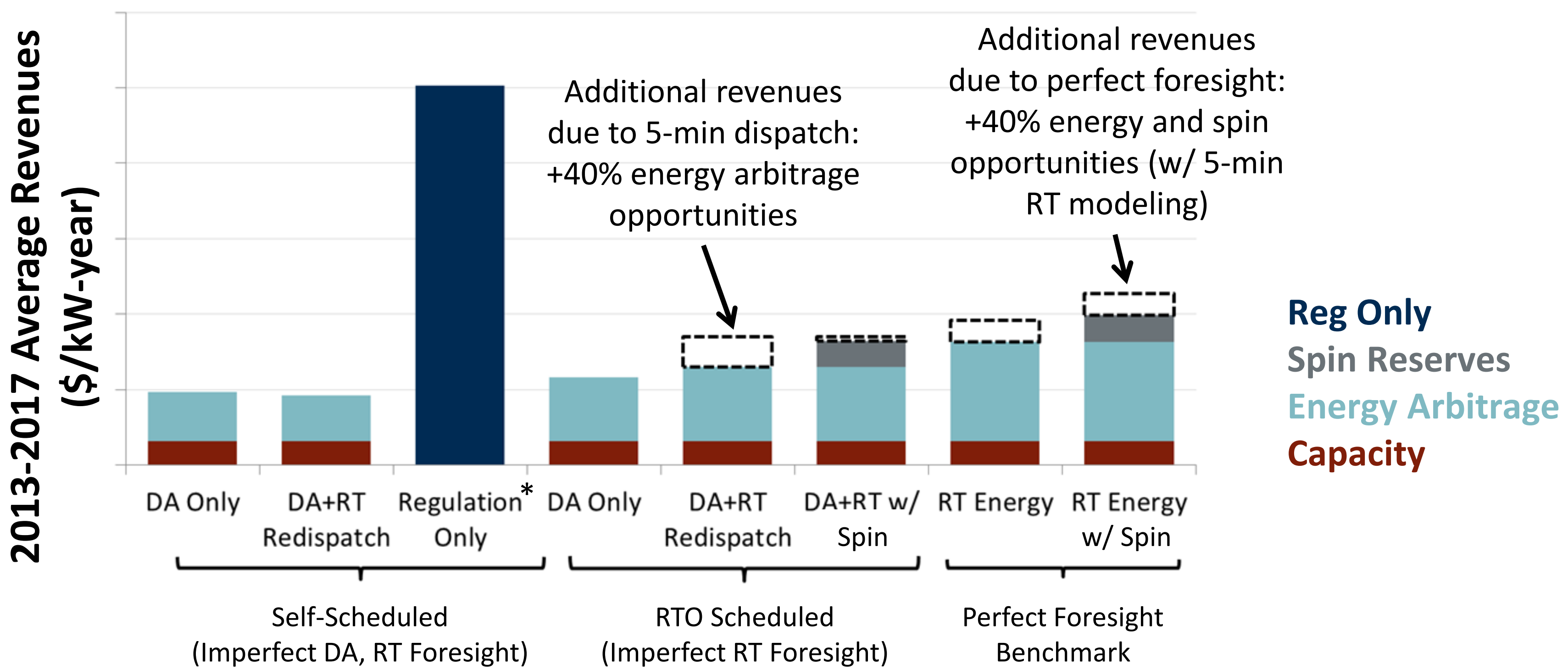


Notes: Intervals shown are for a 4-hour, 1-MW battery.

Impacts of RT Markets and Uncertainties

The impacts of uncertainty modeling and 5-min RT modeling can be very significant, e.g., +/- 25-50% changes in E&AS performance.

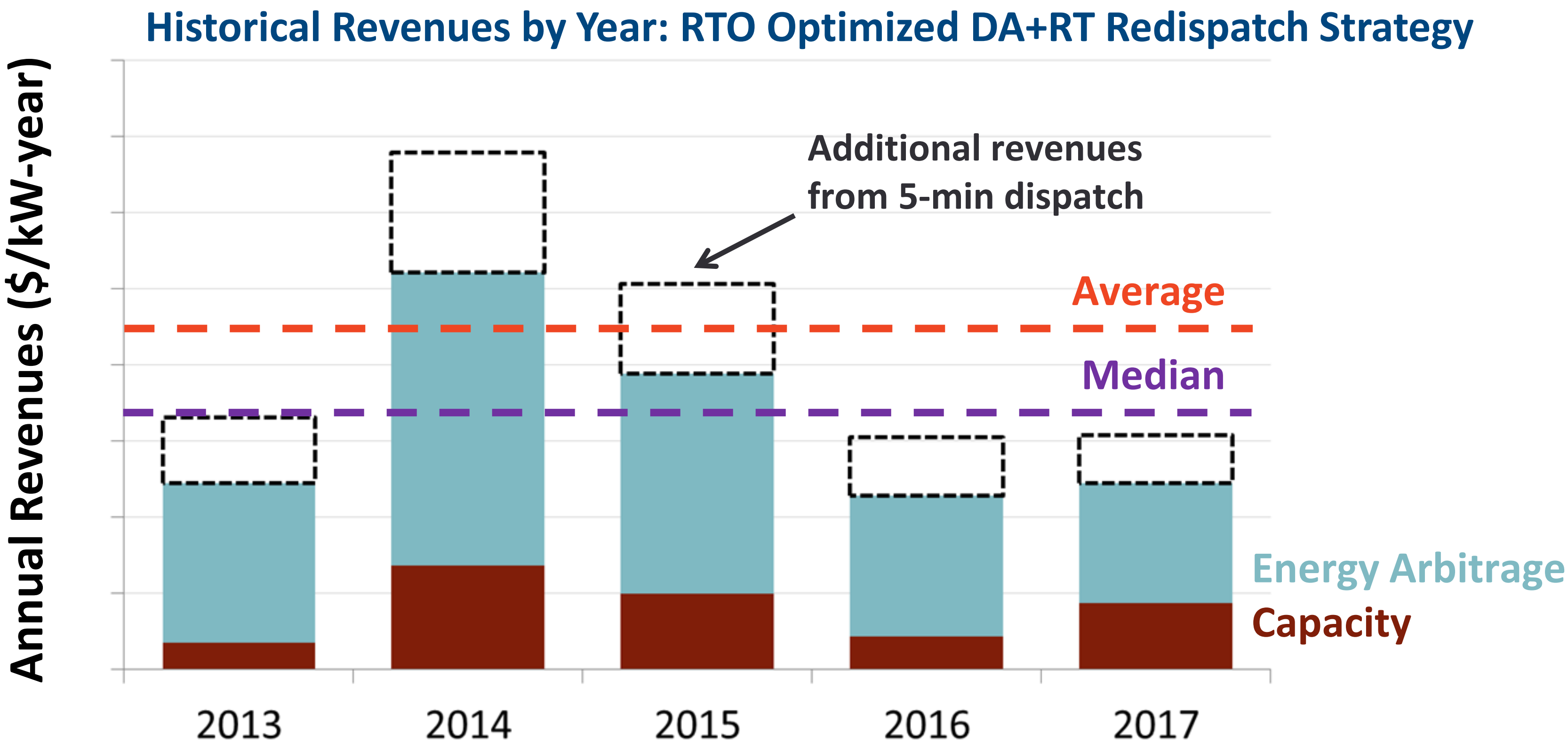
Average Annual Revenues, 2013–2017, for a 1 MW, 4-hour Battery in an RTO Market



Note: Assumes 90% efficient battery with 4-hour duration.
*Regulation is based on PJM's "Reg D" (a thin market that is rapidly dexlining in value)

How Much Does the Annual Energy Market Value Change over Time?

Annual revenues vary by a factor of 2x across 2013 – 2017. Price-taker modeling is especially sensitive to too-short simulation periods.



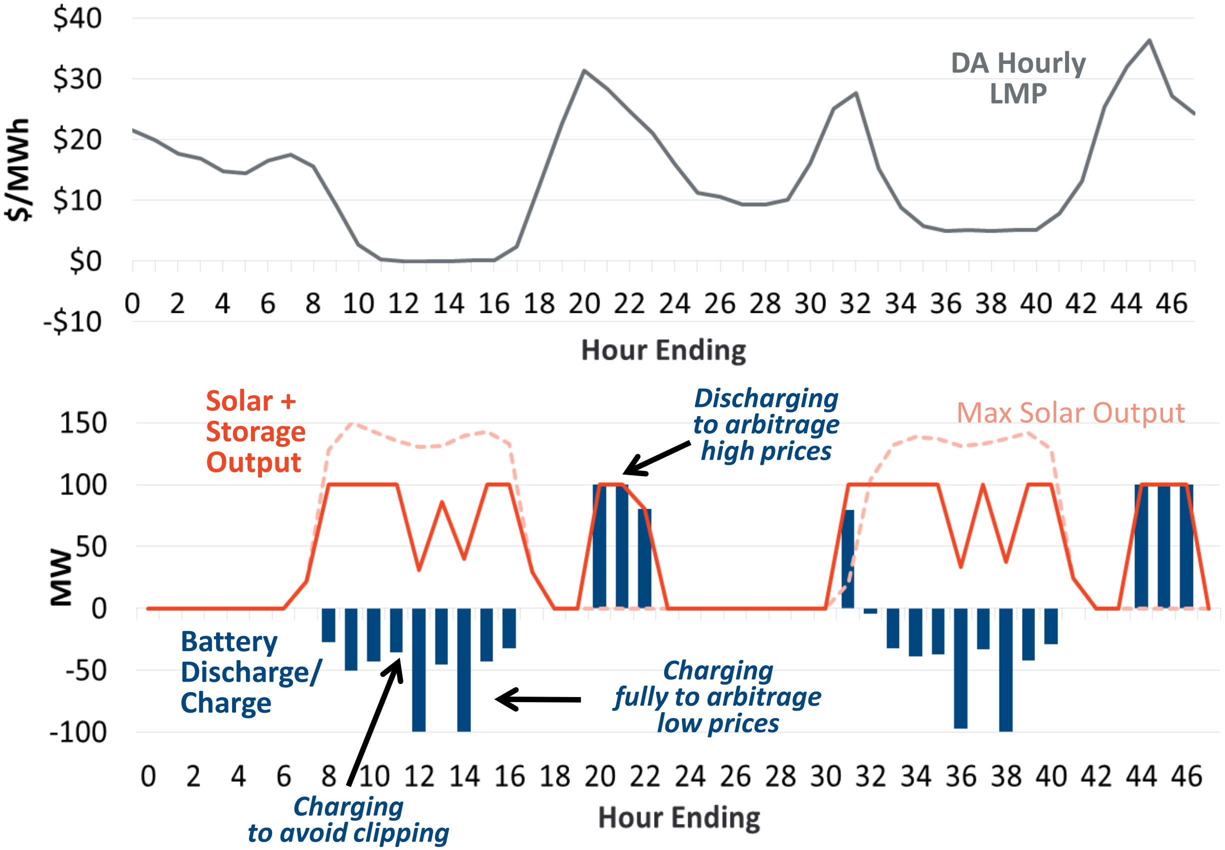
Notes: Assumes 90% efficient battery with 4 hour duration, 24 hr foresight over DA prices, 1 hr foresight over hourly RT prices, and 15 minute foresight over 5-min RT prices .

Solar+Storage: Operations

Co-located storage can increase solar revenues by increasing energy arbitrage opportunities and firming capacity.

Energy-Only Storage Operations (No Grid Charging)

150 MW PV, 100 MW storage, 100 MW Interconnection Limit configuration



- Eliminates PV clipping and economic curtailment
- Opportunistically charges in daytime hours to arbitrage low prices
- Opportunistically discharges to arbitrage high prices

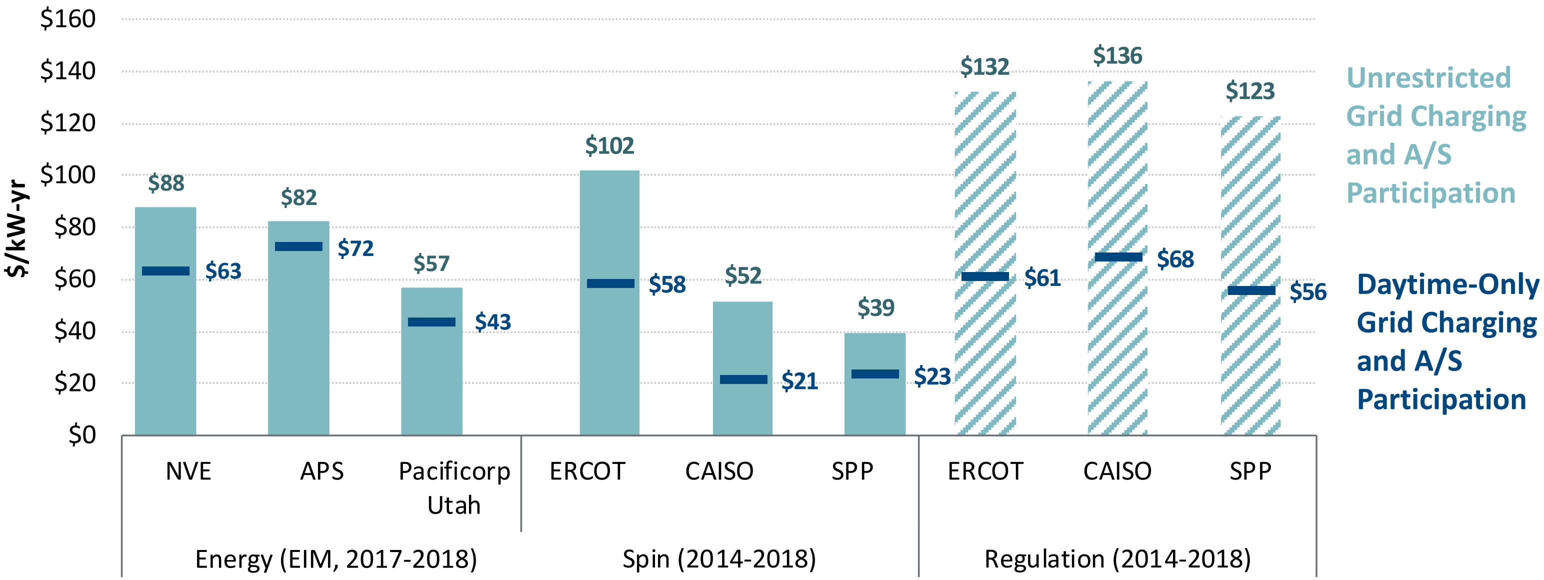
Note: Illustrative CAISO data

Solar+Storage: Effect of Limiting Grid Charging

Restricting grid charging in order to maximize ITC payments can affect energy revenues.

- For PNM, Brattle approximated the effects of pairing storage with solar, we simulate a case in which charging is restricted to daytime hours
- Results in a 12-28% decrease in potential energy revenues across locations analyzed
- A/S revenues decrease by a greater amount (42-59%)

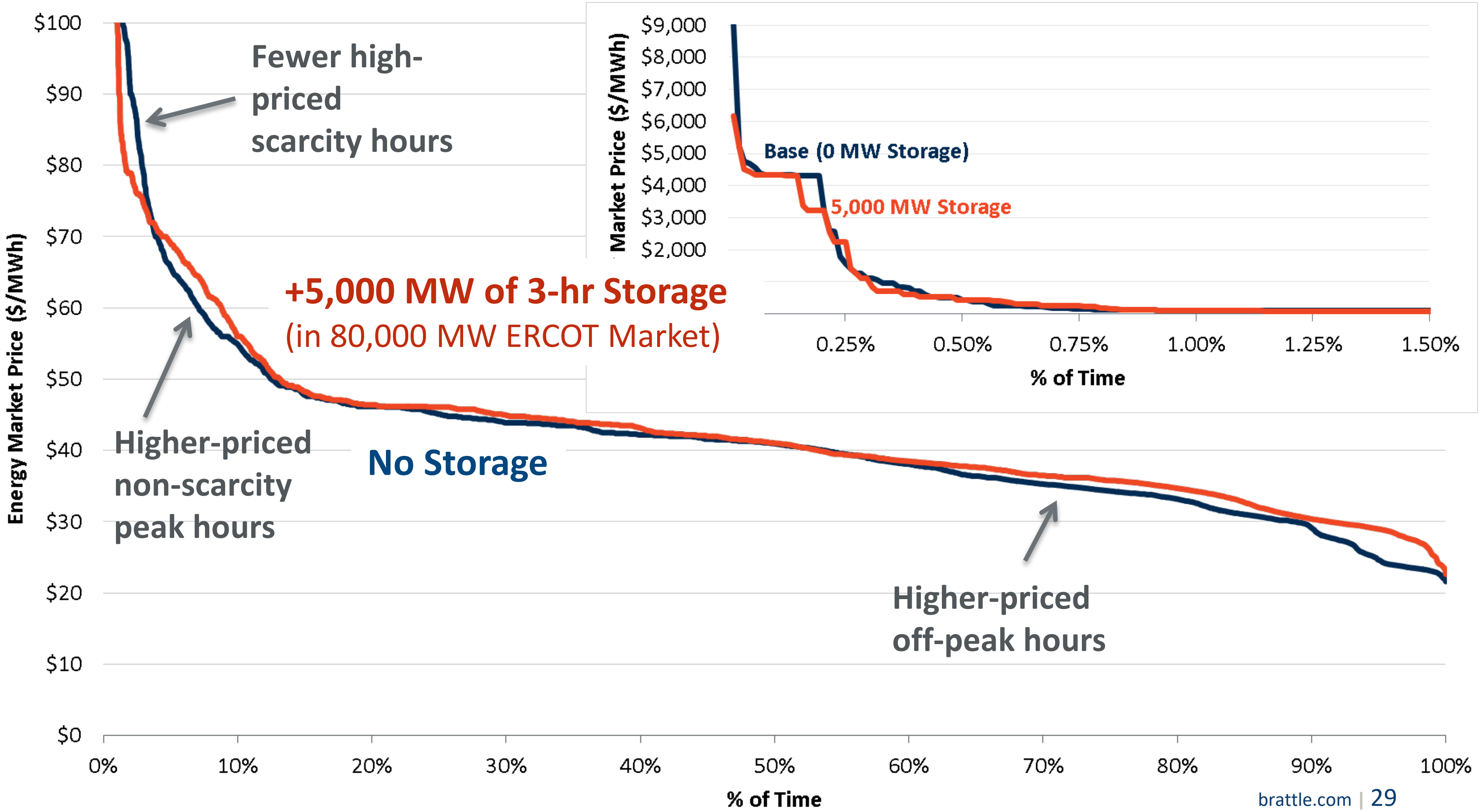
Energy and A/S Revenue With and Without Limits on Grid Charging



Note: Results shown for 4hr, 100 MW battery

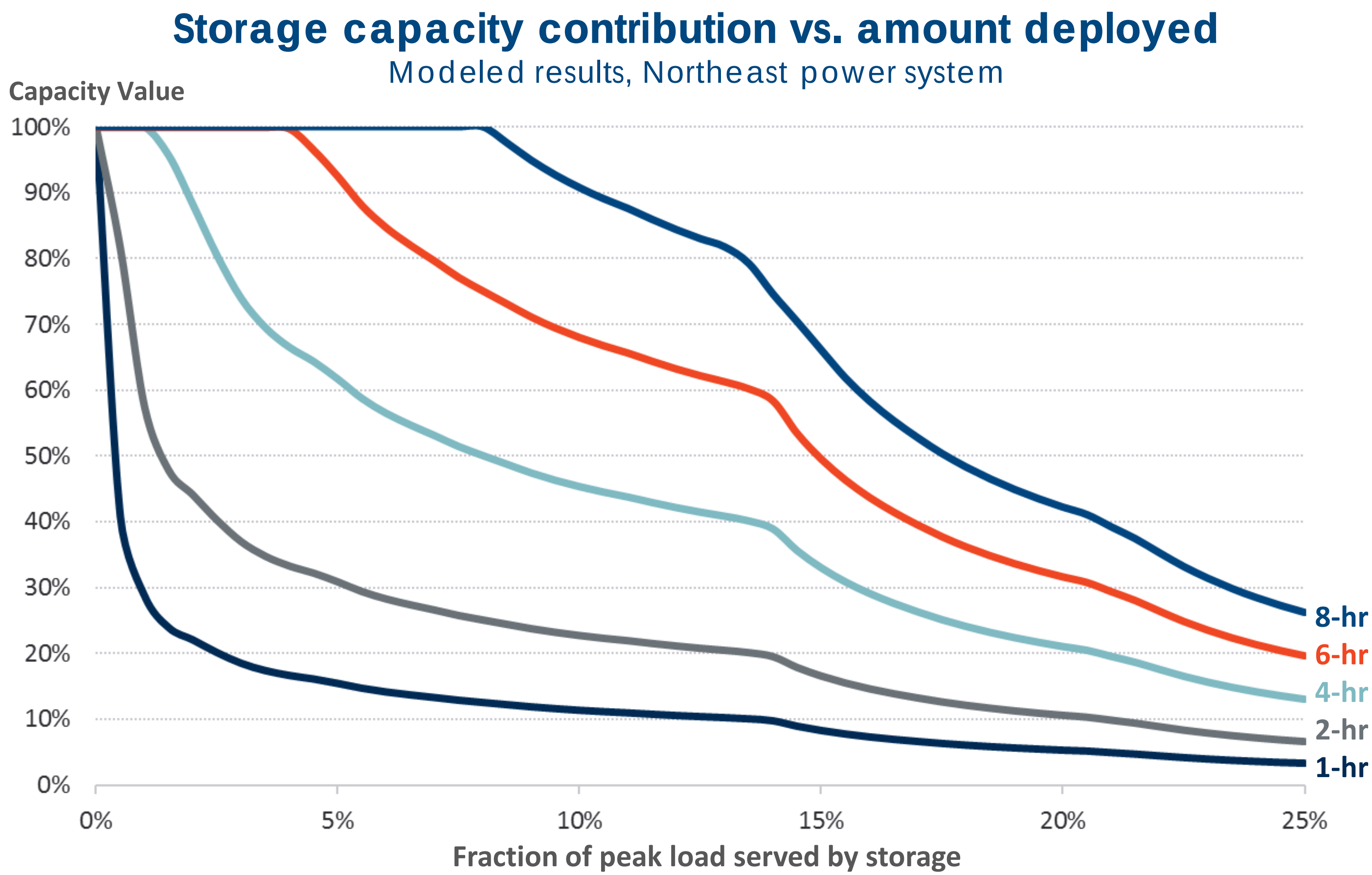
Storage Can Increase the Value of Many Existing Generating Resources

Storage will increasingly become the new marginal resource, reducing super-peak prices while supporting near-peak and off-peak prices



Estimating Storage's Capacity Value

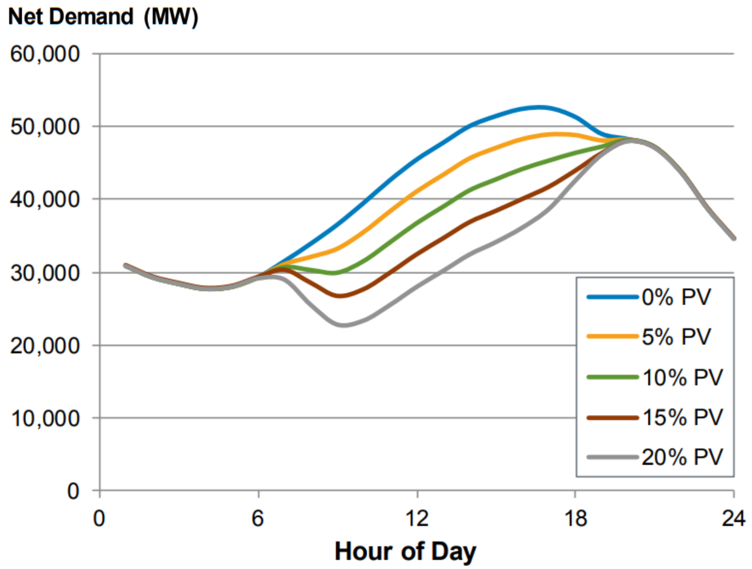
The **capacity contribution** of storage depends on the **type of storage**, the **nature of peak load events**, and the **amount of storage deployed**.



Estimating Storage's Capacity Value

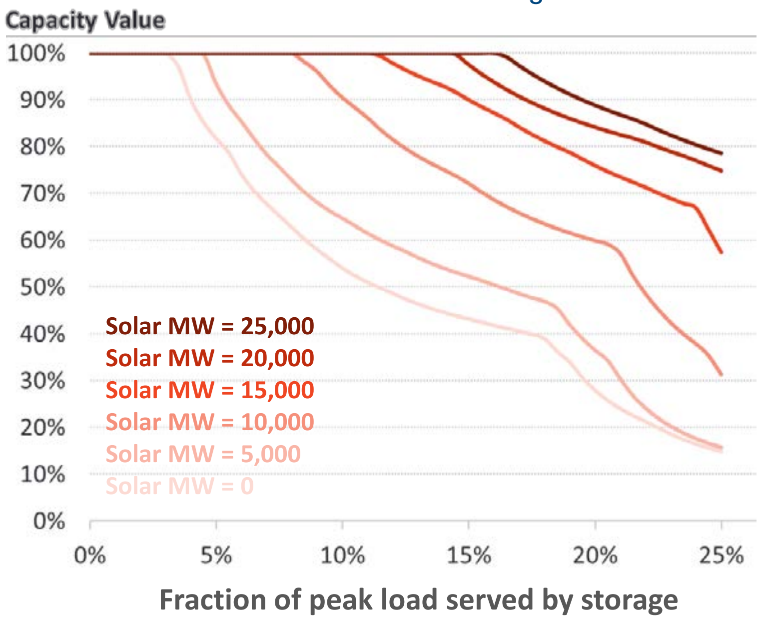
The **capacity contribution of storage** is **higher** in systems with **significant solar deployments**, as solar tends to compress peak load events into fewer hours.

Effect of PV on peak load shape



Effect of PV on storage capacity contribution

4-hour duration storage



Sources:

Brattle analysis.

NREL (2018) The Potential for Energy Storage to Provide Peaking Capacity in California under Increased Penetration of Solar Photovoltaics

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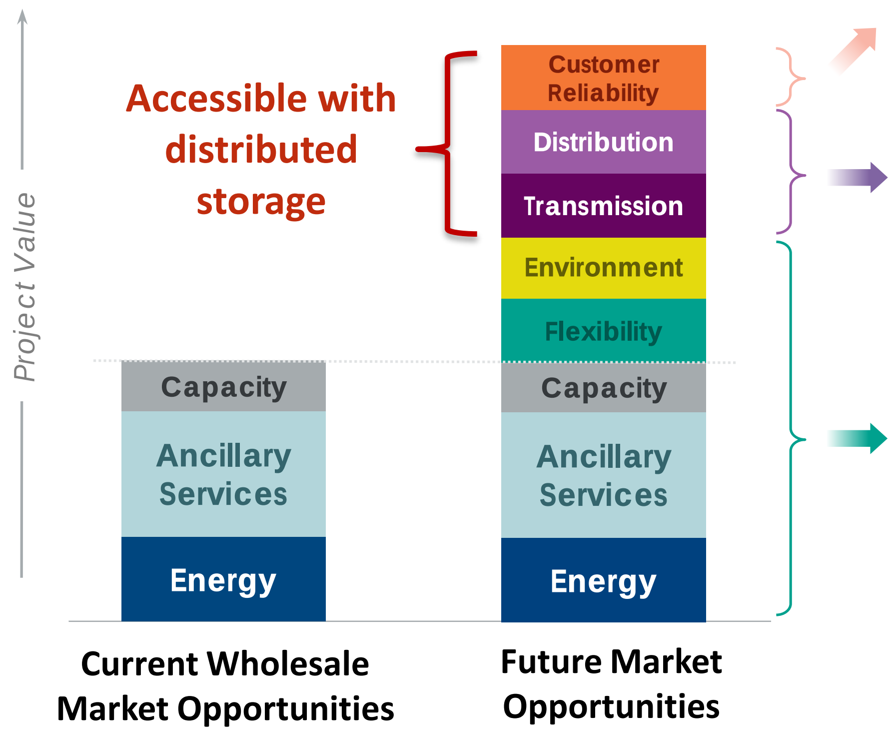
Distributed Storage: Additional T&D and Customer-Reliability Values

Maximizing distributed storage's potential requires capturing wholesale, T&D, and customer value streams. But new regulatory frameworks are needed to capture the full value.

Focus of next slides

Storage Value Components



Customer Value
- Increased reliability (reduced outages)
- Increased engagement in power supply

Utility Infrastructure Value
- Deferred or avoided investments in distribution and transmission infrastructure
- Voltage support & improved power quality

Wholesale Market Value
- Traditional value drivers: energy arbitrage, fast-response capabilities, and avoided capacity
- Realizing additional value due to higher quality A/S and load following reserves
- Flexibility and clean-energy products will provide additional revenue opportunities in the future

Transmission & Distribution Deferral Value

Capital expenditure data can be used to identify **high-value T&D deferral opportunities** and evaluate how storage could defer investments.

- For example, NV Energy provided Brattle cost data and descriptions for 260 capital projects from 2014-2027
- We estimated the subset that could be deferred by storage
  - We identified 35 projects (14% of total) are potentially deferrable by storage
  - Primarily transformer upgrades needed to support local load growth
  - We estimated the value of deferring each investment by 15 years
- We made several assumptions to approximate how much storage may be require to defer an investment
  - **Initial Peak Load:** based on NV Energy's project descriptions
  - **Rate of Load Growth:** Assumed 2%
  - **Hourly Load Shape:** Based on average residential or C&I load shapes
- We sized the storage to 15 year load growth

Transmission & Distribution Deferral Value

Deferral benefits largest when (1) load growth is relatively small and predictable, and (2) expensive T&D infrastructure can be deferred by small amount of storage

Examples of T&D Cost Deferral by Customer Class

			Customer Class	
			Residential	C&I
Starting Peak Load	[1]	(MW)	10	10
Peak Load Growth Rate	[2]	(%)	2%	2%
Total Peak Load in 15 years	[3]	(MW)	13.5	13.5
Required Battery Size / Growth	[4]	(%)	166%	253%
Battery Size to Defer 15 years	[5]	(MW)	5.7	8.7
Substation Upgrade Cost	[6]	($ million)	$3	$3
Cost Avoided by 15-yr Deferral	[7]	(%)	67%	67%
Deferral Savings	[8]	($/kW)	$349	$229
Annual Charge Rate Assumption	[9]	(%)	10%	10%
Estimated Value of Deferral	**[10]**	**($/kW-yr)**	**$36**	**$23**

Sources and Notes:
Table reflects data and calculations for Nevada Power Company customer classes.
[1] and [6]: Example assumptions roughly consistent with substation in NPC.
[2]: Peak load growth assumption uniform for all NV Energy feeders.
[3]: $[1] \times (1 + [2])^{15}$
[4]: Calculated using load shapes derived from NV Energy load data. Equal to 123% for SPPC Residential and 175% for SPPC C&I.
[5]: [4] × ([3] − [1])
[7]: NPV of 15-year investment deferral, consistent with NVE financing cost rates.
[8]: ([6] × [7])/(1,000 × [5]). Savings in $/kW of storage installed.
[9]: Payment on a level-real annualization of [8], levelized over a 30-year investment life.
[10]: [8] × [9] Savings in $/kW-year of storage installed.

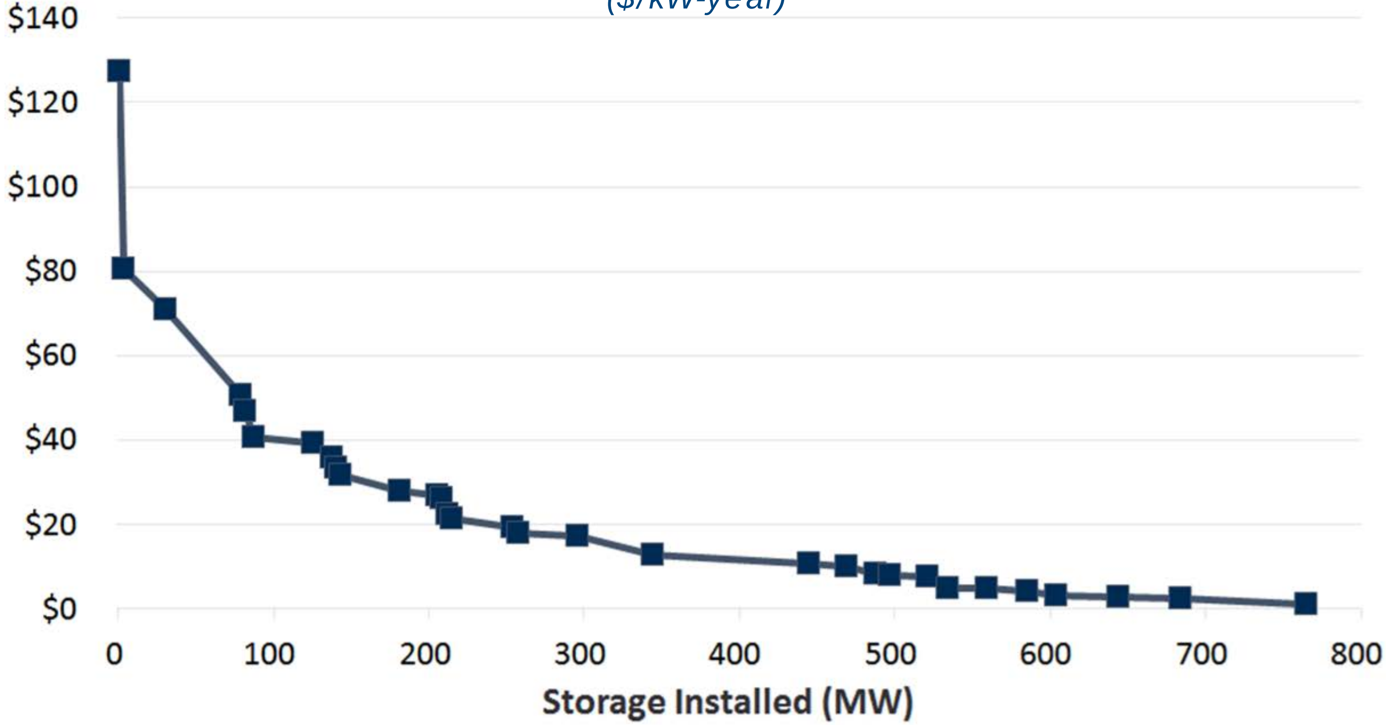
Sources and Notes:
Hledik et al. (2018). The Economic Potential for Energy Storage in Nevada

Transmission & Distribution Deferral Value

We identified a small number of **high-value opportunities** to **defer specific T&D investments**.

Marginal T&D Deferral Benefit of Storage for Individual T&D Projects

($/kW-year)



Sources and Notes:

Hledik et al. (2018). The Economic Potential for Energy Storage in Nevada. Points reflect individual projects from NV Energy's 2018 transmission and distribution capital expenditure outlook identified as deferrable by storage. Although NV Energy's outlook is over a 10-year span, we annualize the size and value of opportunities. We order projects by $/kW-year value, and plot to estimate the marginal benefit for storage from T&D investment deferral. Values in nominal dollars.

Customer Reliability Value

We evaluated the **reliability value to customers** of **deploying storage** on **specific feeders** that **historically experienced frequent outages**.

- NV Energy provided data on 43,000 distribution-level outages for 2014-2018
- We evaluated customer outage reduction benefits of siting storage at least-reliable feeders
  - Simulated storage deployed at each identified feeder, sized at average feeder peak load
  - Accounted for both the duration (hours) and magnitude (MWh) of each outage
  - Accounted for unpredictability of outages
  - Assumed customers value improved reliability at $12,500/MWh value of lost load (VOLL)
- Analysis assumed feeders could be “islanded” in event of an outage
  - Requires grid modernization investments, e.g. microgrids, automated distribution switching
  - We separately reported cost-effective storage levels if grid modernization efforts not made and customer outage value cannot be captured

Customer Reliability Value

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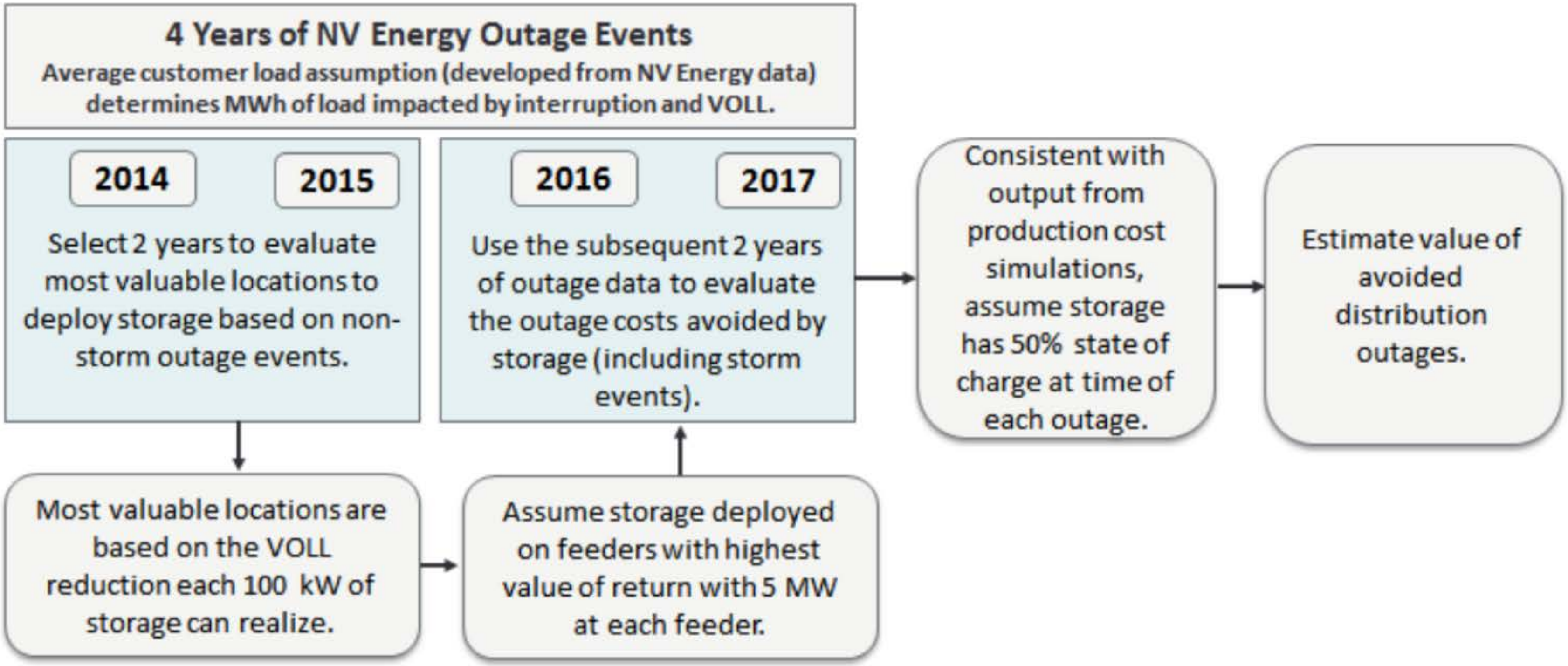
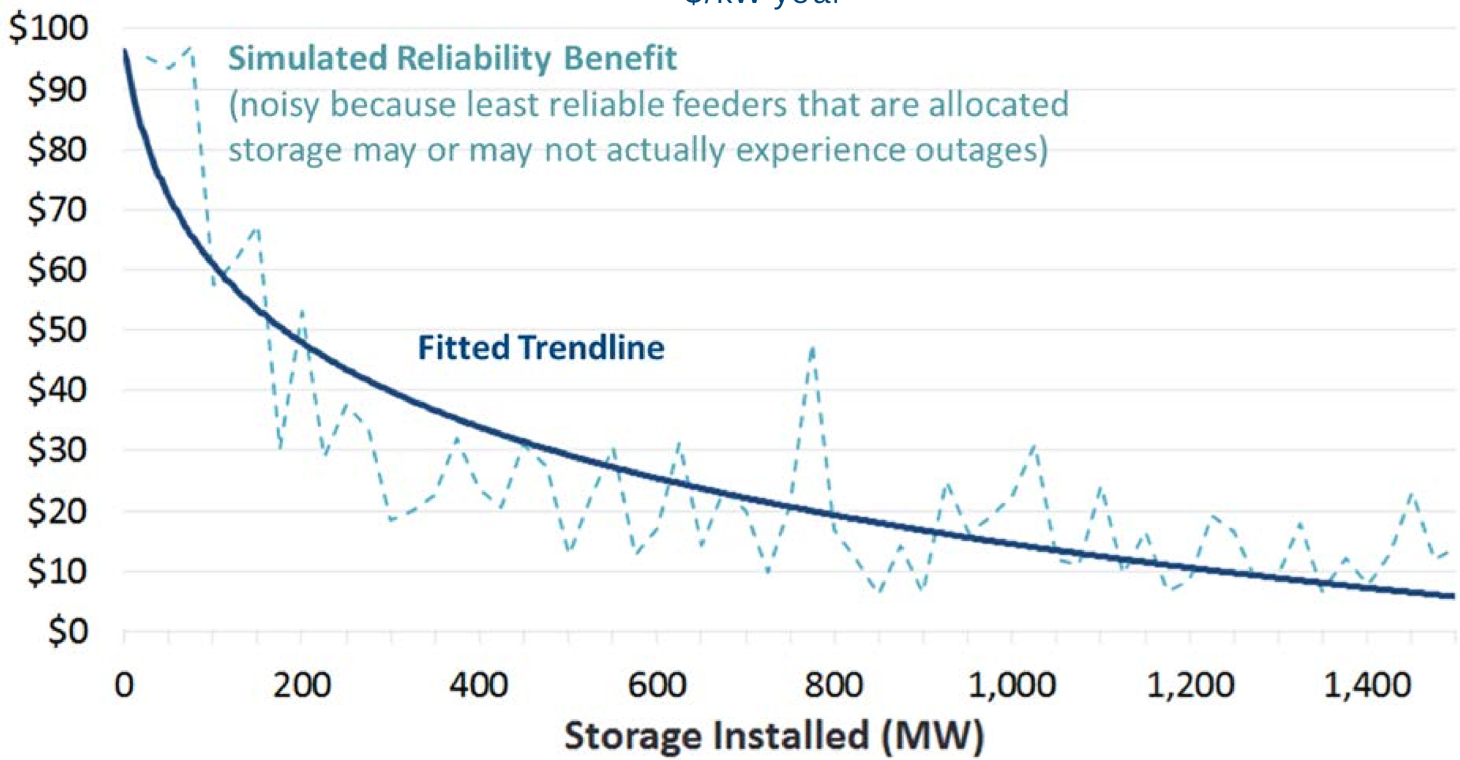


Sources and Notes:
Hledik et al. (2018). The Economic Potential for Energy Storage in Nevada

Customer Reliability Value

We found the **marginal reliability benefit of distributed** is **initially high**, but **falls off relatively rapidly** as **storage is deployed** to least reliable feeders.

Incremental Reliability Benefit of Storage
$/kW-year



Sources and Notes:
Hledik et al. (2018). The Economic Potential for Energy Storage in Nevada
All values in nominal dollars.

Limitations on "Value Stacking"

The ability of to simultaneously provide multiple value streams is constrained by locational and operational limitations.

Locational limitations: Benefits derived from avoided outages and deferred T&D investment tend to be site-specific

Operational limitations: Arise because amount of energy stored is limited

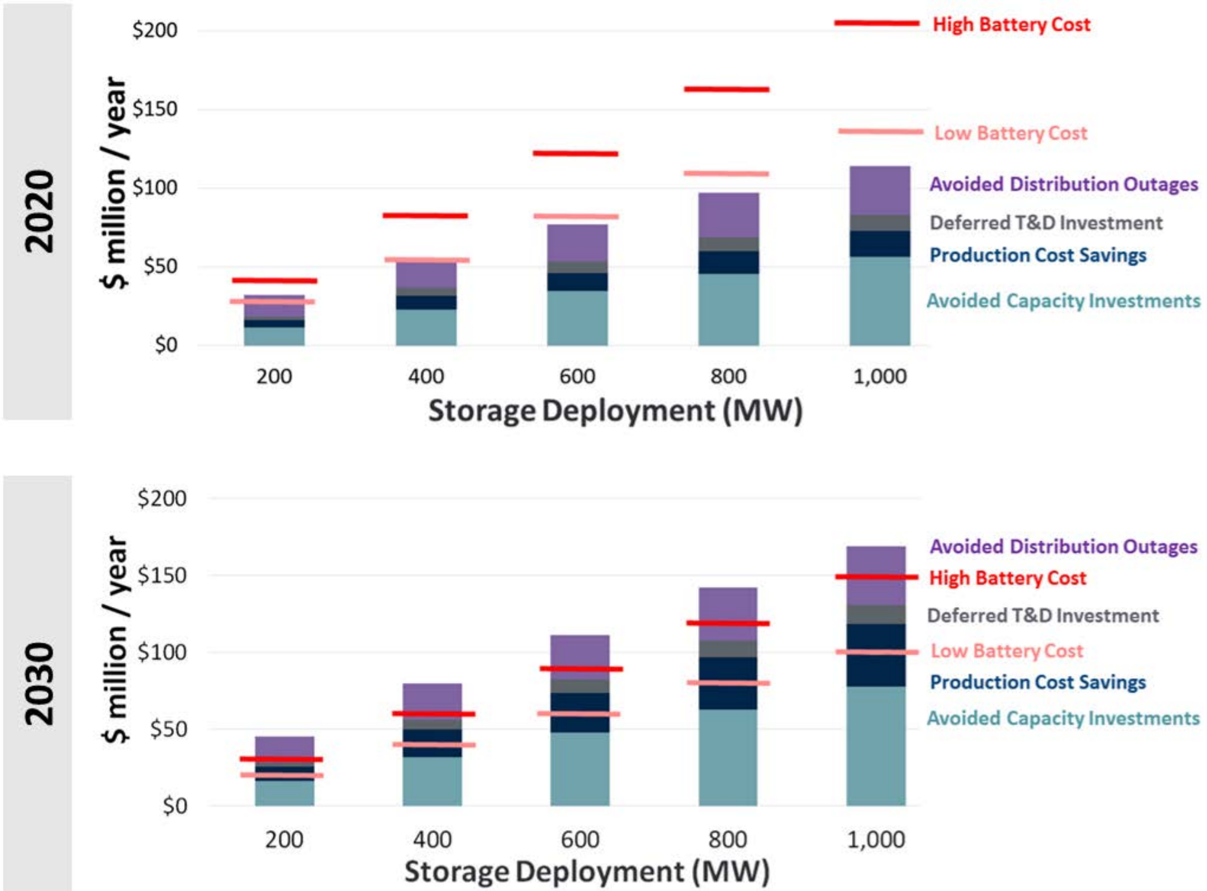
Example modeling assumptions to account for constraints in "value stacking":

- **T&D deferral:** Assume storage deployed for T&D deferral prioritizes reducing <u>local peak</u> load over all other services
- **Capacity:** Assume storage must fully charge in advance of <u>system peak</u> load hours
- **Energy:** Dispatch is affected by T&D deferral and capacity requirements; cannot simultaneously provide energy and certain ancillary services
- **Customer outage reduction value:** Assume outages cannot be anticipated and have 50% SOC at time of event; but in reality storage operators can chose to be at full charge in anticipation of outage events (e.g., forecast storms)

Our simulations show that these limits do not substantially reduce the joint value relative to sum of individual value streams

Total System Benefits and Costs of Storage at Various Deployment Levels

Nevada Case Study: modeled benefits and market impact for very different system conditions and significant changes in the resource mix over time

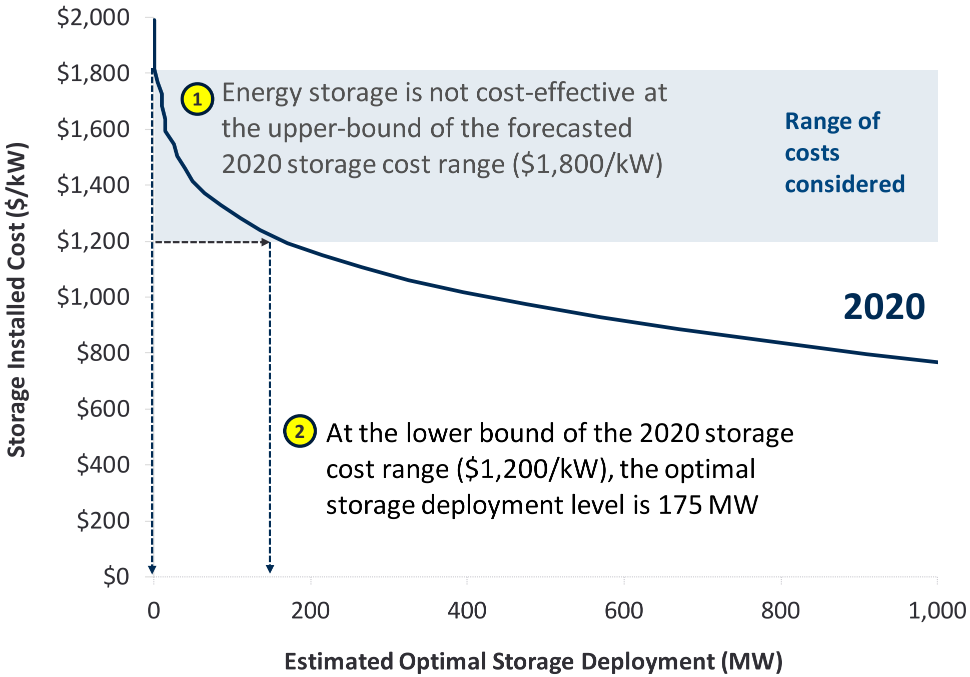


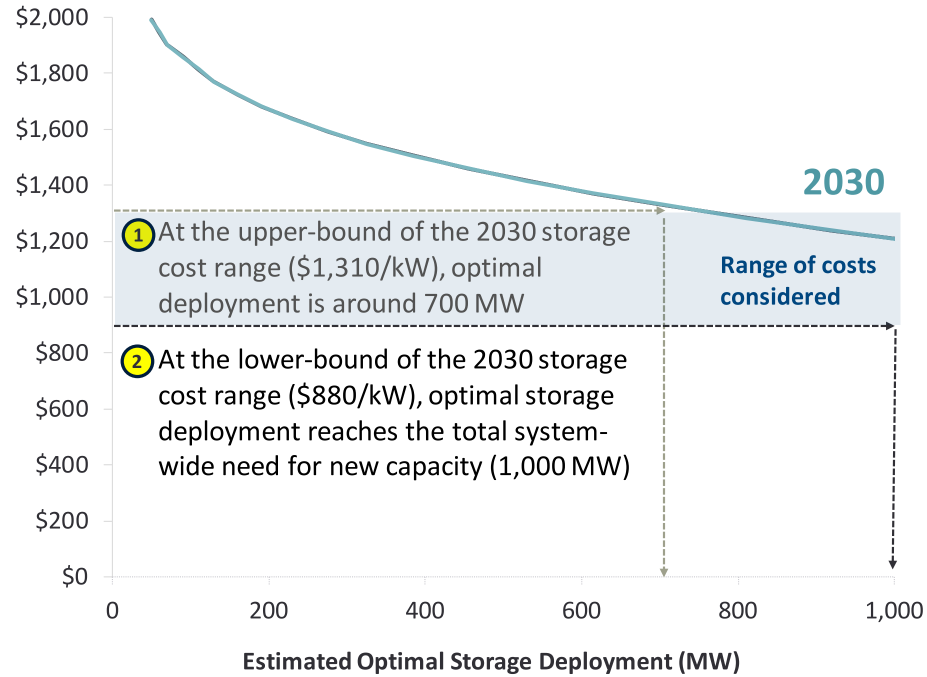
Note: All values are in nominal dollars;
Source: The Economic Potential for Energy Storage in Nevada, October 2018,
https://brattlefiles.blob.core.windows.net/files/14725_nevada_energy_storage_study_presentation.pdf

Optimal Storage Deployment Curves

Nevada Case Study: Developed an "optimal deployment curve" to account for cost uncertainty and changing system conditions.

Cost-effective storage potential increases with declining storage costs and increased system needs





Notes:
Costs are shown in nominal dollars. Values are based on an assumed energy storage configuration of 10 MW / 40 MWh.

Agenda

I. The value of hydro storage

II. Wholesale market value streams

III. T&D-deferral and customer-reliability value of distributed storage

IV. Impacts of electricity industry transformation

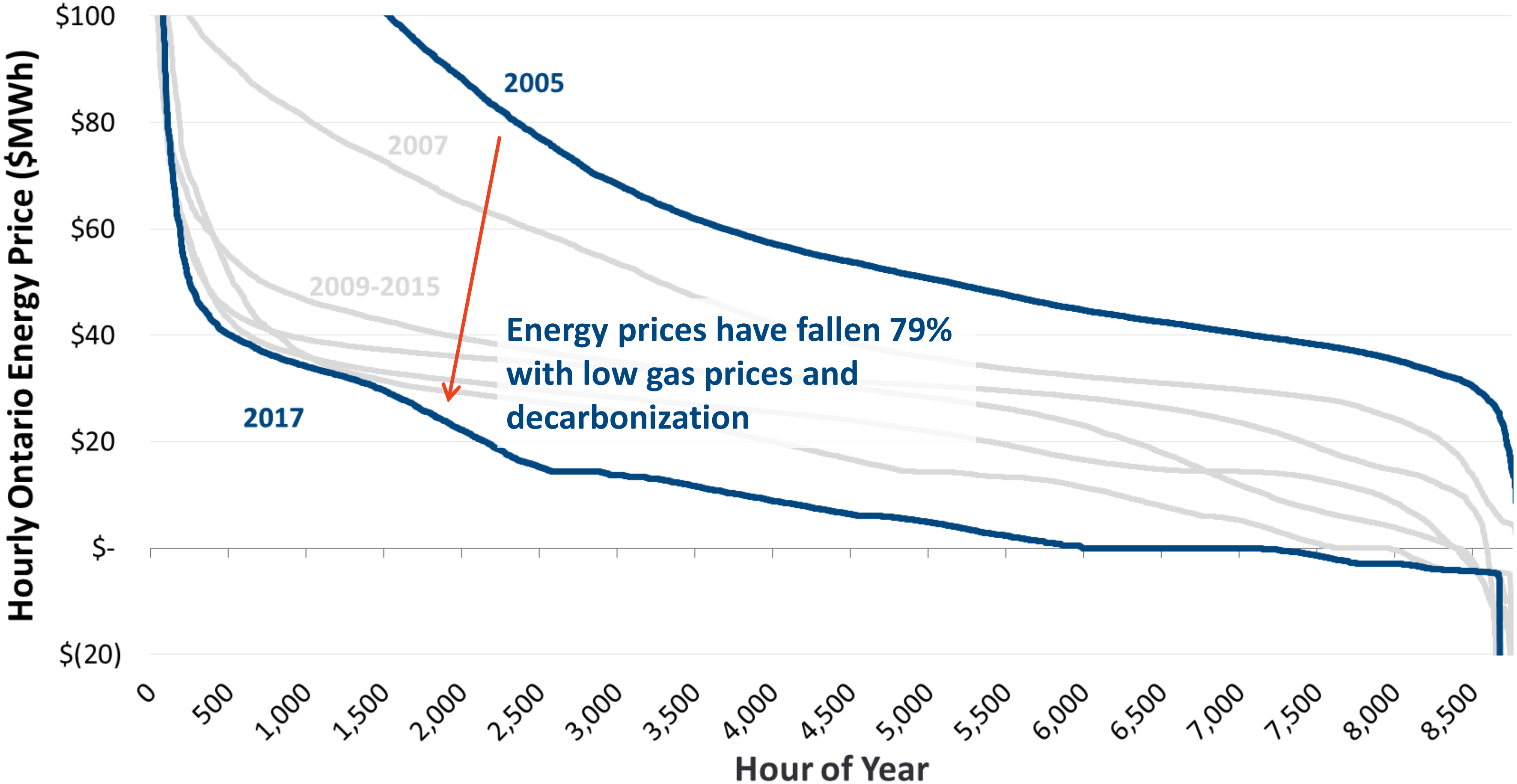
Transformative Changes of the Electricity Industry

- **Declining costs of solar and wind resources** will increasingly dominate the power grid with **low-marginal-cost** generation
- **Low natural gas prices** place significant downward pressure on coal and nuclear plants
- **Reduced growth in traditional electricity consumption**, even in the age of "internet of things"
- **Increased customer preferences for conservation and clean energy**
- **Increased desire for other environmental preferences** related to air emissions, water usage, waste disposal, and land use for all power plants
- **Technological advances** that allow customers and electric utilities to better monitor and control electricity usage
- **Increasing electrification** of transportation and heating

These are significant changes that utilities, grid operators, generators, and regulators have to manage

Energy Markets “Bottom Out” with Clean, Low-Marginal-Cost Generation

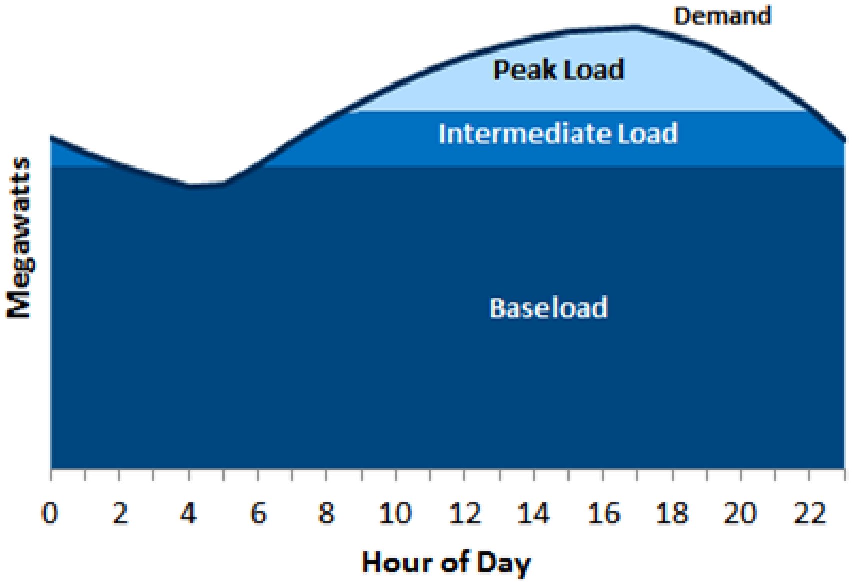
Ontario experience: very low or negative prices with a 90% clean and low-marginal-cost fleet; only 1/3 of all hours priced above $15/MWh!



Global Phenomenon: Changing Supply Mix = Need for More Flexibility

The resulting cleaner, more diverse supply mix requires significantly more flexibility, an attribute hydro resources are especially able to supply

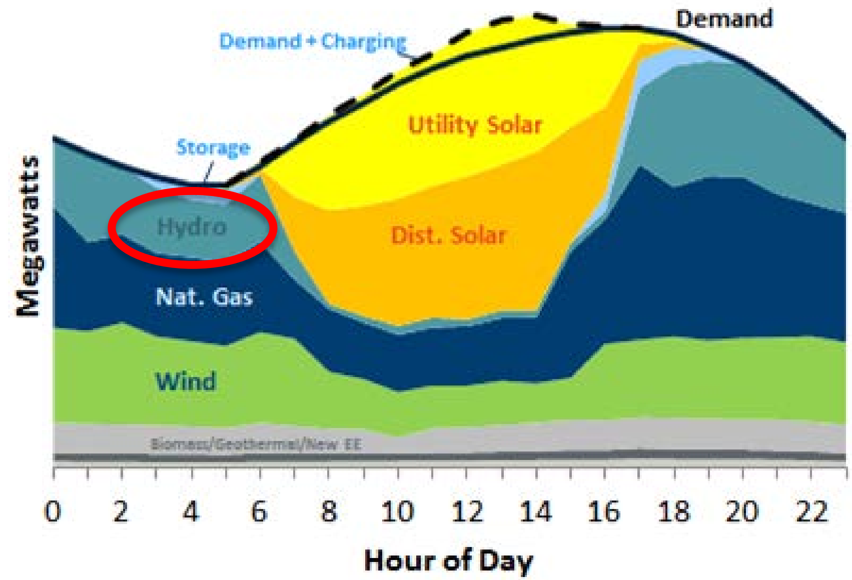
Electricity Demand and Traditional Supply Mix



Source: The Brattle Group.

Electricity Demand and Supply Mix with High Renewable Generation

(High-Solar Example)



Source: The Brattle Group.

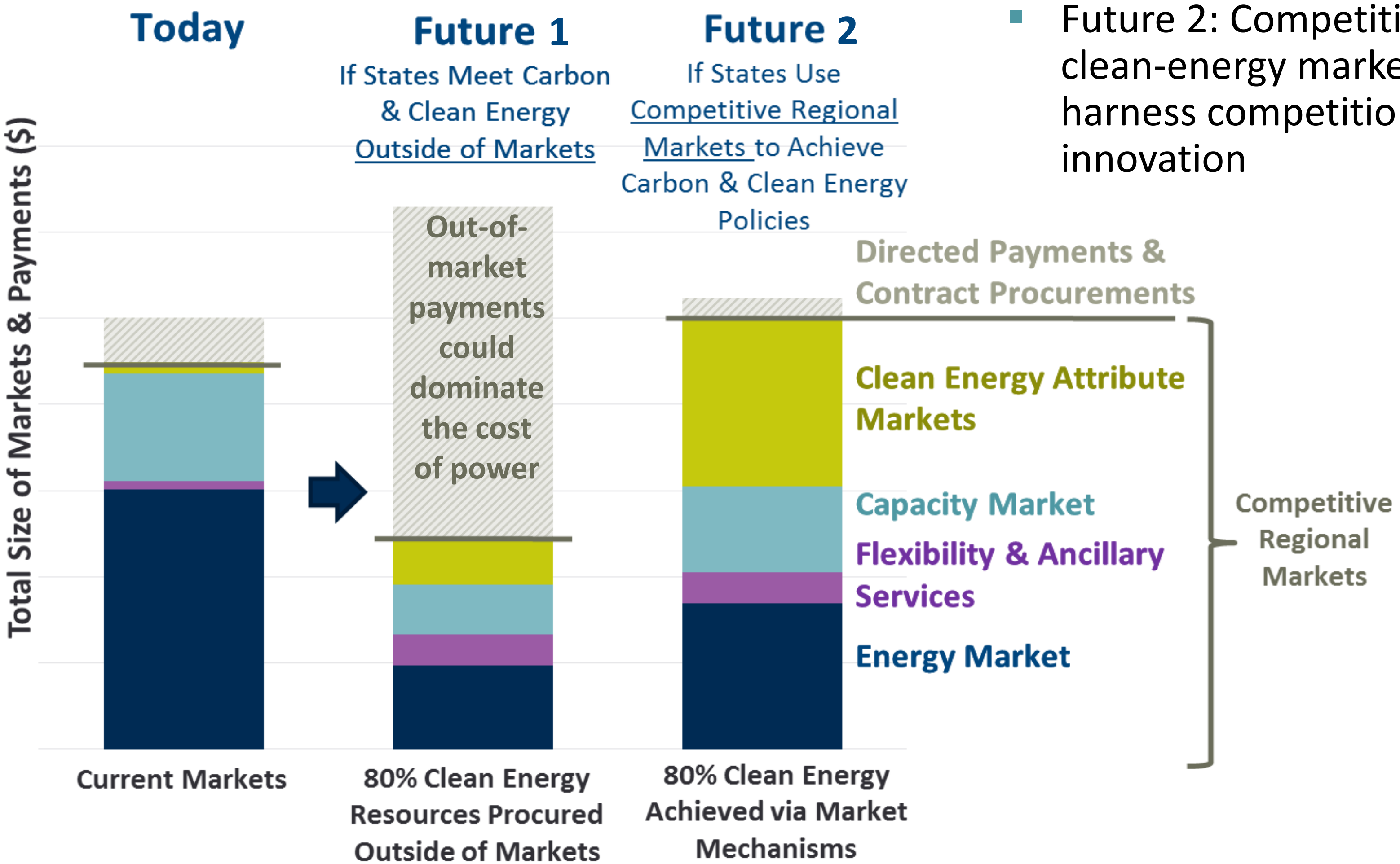
Revenue Sources will Shift from Energy to Other "Products"

Markets designed for a clean, low-marginal-cost resource mix will need to focus more on flexibility and clean-energy products

Products	Value	Market Implications
Average Energy	↓	▪ Lower energy prices during low-load and on average in most hours will most strongly affect baseload and dominant variable resources
Scarcity Pricing	↑	▪ But higher peak prices, driven by volatility, scarcity pricing, and demand response/storage; rewards fast-response resources
Flexibility & Reserves	↑	▪ Need for greater quantities and new types of flexibility products ▪ Higher ramping needs reward flexibility
Capacity	↓↑	▪ Value may go up or down ▪ Down if additional clean energy contributes to excess supply for a period, or if new capacity sellers are attracted by other value streams ▪ Up if new fossil plants are needed for capacity, but only a small portion of their capital costs can be recovered from other markets
Clean Attributes	↑	▪ Some form of CO_2 pricing and/or clean energy payments introduced to meet policy and/or customer demand ▪ Value must be large enough to attract new clean resources
Adjacent Customer & Distribution Markets	↑	▪ Technology and consumer-driver demand for adjacent products and services (smart home, electric vehicles) ▪ Participation may overlap with wholesale, clean, and retail/distribution markets
Interties & Geographic Diversification	↑	▪ Increasing value of larger, more diverse regional markets ▪ Greater value of trade/diversification across market seams through inter-regional grids

How Will Clean-Energy Products be Integrated into Wholesale Markets?

For wholesale markets to stay relevant, clean energy product markets are the "missing link" to align with customers and policy makers' preferences.



- Future 2: Competitive clean-energy markets to harness competition and innovation

“Product Markets” Mobilize Competition from a Wider Range of Resources

Storage resources are well positioned to compete in the emerging products-based wholesale power markets

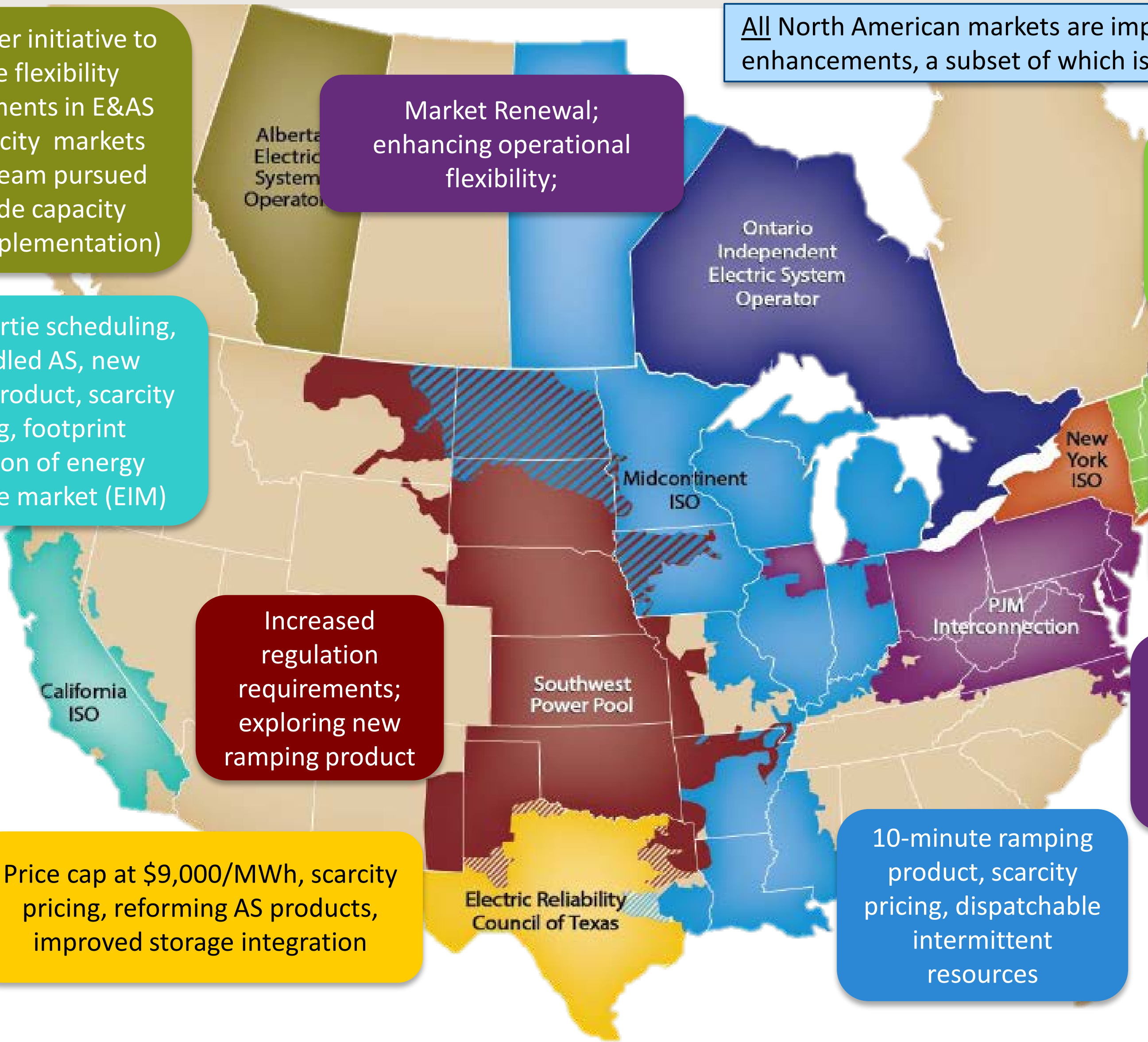
Resources/Technologies (Existing and New)

Products	Nuclear	RoR Hydro	Hydro w/ Storage	Coal	CC	CT	Wind	Solar	Battery Storage	DR	EE	Imports	Number of Competing Technologies
DA Energy	✓	✓	✓	✓	✓	O	✓	✓	O	O	O	✓	10
RT Energy (5 min)	O	✓	✓	✓	✓	O	✓	✓	O	O	O	O	9
Regulation	X	✓	✓	✓	✓	O	O	O	✓	O	X	O	7.5
Spinning Reserves	X	O	✓	✓	✓	✓	X	X	✓	O	X	O	6.5
Non-Spinning Reserves	X	X	✓	X	✓	✓	X	X	✓	O	X	O	5
Load following / Flexibility	O	O	✓	O	✓	✓	O	O	✓	O	X	O	7.5
Capacity / Res. Adequacy	✓	O	✓	✓	✓	✓	O	O	O	✓	✓	✓	10
Clean Energy	✓	✓	✓	X	O	O	✓	✓	O	O	✓	✓	9
Reactive / Voltage Support	✓	✓	✓	✓	✓	✓	O	O	✓	X	X	O	8.5
Black Start	X	✓	✓	O	✓	✓	X	X	O	X	X	O	6

Legend — **Technical Capability to Provide Service**
- ✓ Well Suited (1.0)
- O Neutral (0.5)
- X Not / Poorly Suited (0)

Example: Efforts to Enhance Flexibility

All North American markets are implementing broad flexibility enhancements, a subset of which is reported here.



Stakeholder initiative to explore flexibility enhancements in E&AS and capacity markets (work stream pursued alongside capacity market implementation)

Market Renewal; enhancing operational flexibility;

Capacity performance incentives, scarcity pricing, additional "replacement reserve" AS product, DR integration

5-min intertie scheduling, unbundled AS, new ramping product, scarcity pricing, footprint expansion of energy imbalance market (EIM)

Updated scarcity pricing to align with neighboring systems, coordinated intertie scheduling with ISO-NE and PJM

Increased regulation requirements; exploring new ramping product

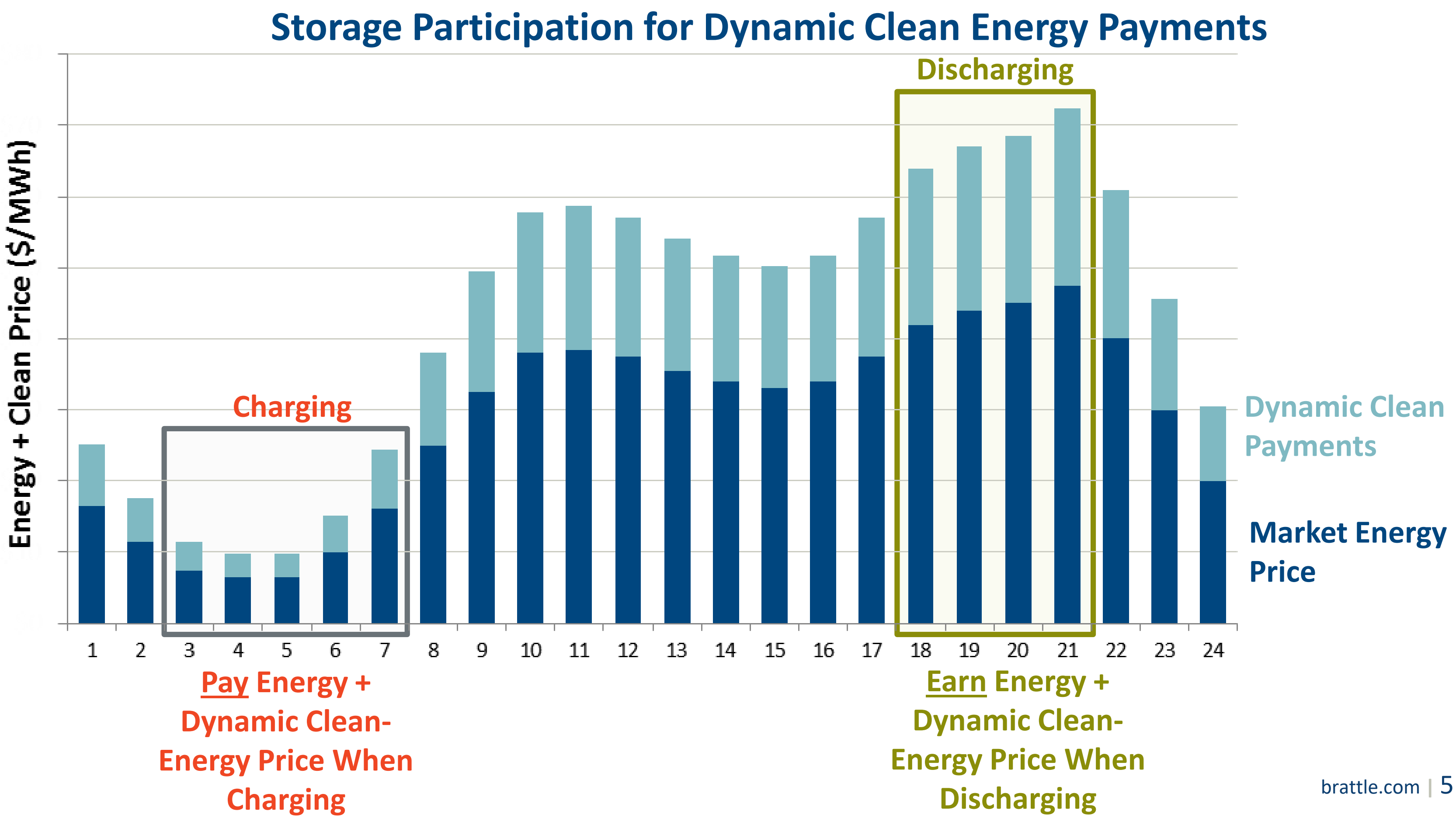
Capacity performance incentives, AS co-optimization, scarcity pricing, DR integration

Price cap at $9,000/MWh, scarcity pricing, reforming AS products, improved storage integration

10-minute ramping product, scarcity pricing, dispatchable intermittent resources

Dynamic Pricing of Clean Energy Will Further Enhance Storage Value

Dynamic payments for clean energy at the right times to displace emissions provide improved price signals and will further enable storage



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Mr. Johannes (Hannes) Pfeifenberger is an economist with a background in power engineering and over 25 years of experience in the areas of public utility economics and finance. He has published widely, assisted clients and stakeholder groups in the formulation of business and regulatory strategy, and submitted expert testimony to the U.S. Congress, courts, state and federal regulatory agencies, and in arbitration proceedings.

Hannes has extensive experience in the economic analyses of wholesale power markets and transmission systems. His recent experience includes the analysis of hydro and battery storage economics, transmission benefits, reviews of wholesale power market designs, testimony in contract disputes, cost allocation, and rate design. He has performed market assessments, market design reviews, asset valuations, and cost-benefit studies for investor-owned utilities, independent system operators, transmission companies, regulatory agencies, public power companies, and generators across North America.

Hannes received an M.A. in Economics and Finance from Brandeis University and an M.S. (Dipl. Ing.) in Power Engineering and Energy Economics from the University of Technology in Vienna, Austria.

About The Brattle Group

The Brattle Group provides consulting and expert testimony in economics, finance, and regulation to corporations, law firms, and governmental agencies worldwide.

We combine in-depth industry experience and rigorous analyses to help clients answer complex economic and financial questions in litigation and regulation, develop strategies for changing markets, and make critical business decisions.

Our services to the electric power industry include:

- Climate Change Policy and Planning
- Cost of Capital
- Demand Forecasting Methodology
- Demand Response and Energy Efficiency
- Electricity Market Modeling
- Energy Asset Valuation
- Energy Contract Litigation
- Environmental Compliance
- Fuel and Power Procurement
- Incentive Regulation
- Rate Design and Cost Allocation
- Regulatory Strategy and Litigation Support
- Renewables
- Resource Planning
- Retail Access and Restructuring
- Risk Management
- Market-Based Rates
- Market Design and Competitive Analysis
- Mergers and Acquisitions
- Transmission

Brattle's Storage Experience

Asset Valuation	• Valuing and sizing renewables + storage facilities • Valuing storage across multiple value streams • Developing bid/offer strategies to maximize value • Accommodating storage into IRPs • Supporting due diligence efforts of investors
Market Intelligence	• The state and federal policy landscape • Electricity market fundamentals and opportunities • Storage cost and technology trends • Current and emerging business models
Policy, Regulatory, and Market Design	• Wholesale market design • Market and regulatory barriers • Utility ownership and operation models • Retail rate implications of distributed storage • Implications of storage on wholesale markets

www.brattle.com/storage

Additional Reading

"The Economic Potential for Energy Storage in Nevada," Ryan Hledik et al., Prepared for the Public Utilities Commission of Nevada and Governor's Office of Energy. October 3, 2018.

"Getting to 50 GW? The Role of FERC Order 841, RTOs, States, and Utilities in Unlocking Storage's Potential," Roger Lueken, Judy Chang, Johannes P. Pfeifenberger, Pablo Ruiz, and Heidi Bishop, February 22, 2018

"Battery Storage Development: Regulatory and Market Environments," Michael Hagerty and Judy Chang, Presented to the Philadelphia Area Municipal Analyst Society, January 18, 2018

"U.S. Federal and State Regulations: Opportunities and Challenges for Electricity Storage," Romkaew P. Broehm, Presented at BIT Congress, Inc.'s 7th World Congress of Smart Energy, November 2, 2017

"Stacked Benefits: Comprehensively Valuing Battery Storage in California," Ryan Hledik, Roger Lueken, Colin McIntyre, and Heidi Bishop, Prepared for Eos Energy Storage, September 12, 2017

"The Hidden Battery: Opportunities in Electric Water Heating," Ryan Hledik, Judy Chang, and Roger Lueken, Prepared for the National Rural Electric Cooperative Association (NRECA), the Natural Resources Defense Council (NRDC), and the Peak Load Management Alliance (PLMA), February 10, 2016

"Impacts of Distributed Storage on Electricity Markets, Utility Operations, and Customers," Johannes P. Pfeifenberger, Judy Chang, Kathleen Spees, and Matthew Davis, Presented at the 2015 MIT Energy Initiative Associate Member Symposium, May 1, 2015

"The Value of Distributed Electricity Storage in Texas - Proposed Policy for Enabling Grid-Integrated Storage Investments," Ioanna Karkatsouli, James Mashal, Lauren Regan, Judy Chang, Matthew Davis, Johannes P. Pfeifenberger, and Kathleen Spees, Prepared for Oncor, March 2015

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