Status of Grid Scale Energy Storage and Strategies for Accelerating Cost Effective Deployment

2009 SDM Best Thesis Prize Winner

John Kluza (SDM ‘08)
Advisor: Michael Davies

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Agenda

• Background
• Motivation
• Individual Functions/Markets
• Energy Storage Technologies
• Implementations to Combine Applications
• Challenges, Opportunities and Strategies for Implementation
• Conclusions
• Comments a couple years on
Background: Before and After SDM

• MIT SDM offered an effective transition in function and sector
• Currently:
  • Satcon Technology – Business Development Manager, Emerging Applications (storage, solar/storage hybrids, fuel cells, tidal power)
• Previously:
  • Energy storage and smart grid analyst at Lux Research and GTM Research
  • MIT SDM ’08 (Graduated June 2009)
    • MIT Energy Club Lecture Chair
    • Interned at A123 Systems and Winslow Management
  • The Mathworks (MATLAB) – Consulting Engineer & Application Sales Engineer
  • Penn State MS Mech Engr (Controls/Robotics) & Lehigh BS Mech Engr
Motivation

• Can distributed energy storage be cost effective? How might this work?

• Why is this important?
  – Variable renewables need backup at high penetration
  – More efficient use of generation, transmission and distribution assets
  – More efficient use of fuel resources
  – Improve power quality/reliability requirements
Refresher: Power vs Energy

- Energy storage is to water capacity as
- Power delivery is to water flow

Source: Mohamed Rhamane GE 2009 ASM/TMS Annual Symposium 5/11/09
Methodology

• Identify and quantify unique benefit streams (cash and non-cash applications)
  – Single applications tend to be too small benefit
• Classify actual/proposed installations into practical installation types (implementations)
  – Accrue a few kinds of benefits to owner to become profitable
  – Analyze technical, legal and economic aspects of each implementation using each technology
Grid Value Chain

• Where?

Source: Oncor
Grid Value Chain

• Value can be created on many parts of the grid
Applications

- Generally combine applications to make a profitable deployment
Energy Applications: Arbitrage

• Selling on RT market when conditions are favorable
• Battery deterioration significant
• Cash payments

Data: NE ISO
Energy Applications: T&D Deferral

- Only in operation at critical peaks
  - Few hours of operation required a year

- Avoids carrying cost of new infrastructure

- Only practical to defer for a limited amount of time

- Avoided cost (non-cash)


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MITsdm system design and management
Power Applications: Frequency Regulation

- Maintains fine balance between generation and load
- Tough to do well with existing thermal plants
- Low operating cost storage helps
- Cash payments in some ISO’s

Image source: Kirby

Image source: NYSERDA

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Power Applications: Frequency Regulation

- Map of ISO territories (Independent System Operators which coordinate region’s generation)
- NY ISO, ISO NE, MISO, PJM have open mkts
- CA ISO soon

Source: FERC
Hybrid Application: End-user Rate Reduction

- Especially commercial/industrial customer demand charges and TOU rates
- Payment for T&D infrastructure to serve them
- Avoided cost
Applications: Renewables
Firming/Shifting

- Firming is power/short term (clouds passing by PV)
- Shifting is energy/long term (night time wind)
# Application Value Created

<table>
<thead>
<tr>
<th>#</th>
<th>Power or Energy App?</th>
<th>Application</th>
<th>NY Unit Benefit, $/kW, over 10 Years**</th>
<th>CA Unit Benefit, $/kW, over 10 Years**</th>
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<tbody>
<tr>
<td>1</td>
<td>Energy</td>
<td>Bulk Electricity Time Shifting</td>
<td>394</td>
<td>200 to 300</td>
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<td>2</td>
<td>Energy</td>
<td>Electric Supply Capacity (NY)</td>
<td>753</td>
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<td>3</td>
<td>Energy</td>
<td>Central Generation Capacity (Avoided Cost) (EPRI)</td>
<td>215</td>
<td></td>
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<tr>
<td>4</td>
<td>Energy</td>
<td>Reduce Transmission Capacity Requirements</td>
<td>93</td>
<td>72</td>
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<tr>
<td>5</td>
<td>Energy</td>
<td>Reduce Transmission Congestion</td>
<td>72</td>
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<td>Energy</td>
<td>Transmission and Distribution Upgrade Deferral (NY)</td>
<td>1200</td>
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<td>Energy</td>
<td>Distribution Upgrade Deferral Top 10th. Percentile Benefits (EPRI)</td>
<td>1,067</td>
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<td>8</td>
<td>Energy</td>
<td>Distribution Upgrade Deferral 50th. Percentile Benefits (EPRI)</td>
<td>666</td>
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<tr>
<td>9</td>
<td>Energy</td>
<td>Transmission Upgrade Deferral (EPRI)</td>
<td>650</td>
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</table>

### Utility Oriented Applications - Energy Focus

### Utility Oriented Applications - Power Focus

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<td>6</td>
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<td>Frequency Regulation</td>
<td>789</td>
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<td>Power</td>
<td>Operating Reserve</td>
<td>258</td>
<td>72</td>
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<td>8</td>
<td>Power</td>
<td>Transmission Support</td>
<td>169</td>
<td>82</td>
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</table>

### End-User Applications

<table>
<thead>
<tr>
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<th>Power or Energy App?</th>
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<tbody>
<tr>
<td>9</td>
<td>Energy</td>
<td>Electric Bill Reduction: Demand Charges</td>
<td>1076</td>
<td>465</td>
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<td>10</td>
<td>Energy</td>
<td>Electric Bill Reduction: Time-of-use Pricing</td>
<td>1649</td>
<td>1004</td>
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<td>11</td>
<td>Power</td>
<td>Electric Service Reliability</td>
<td>359</td>
<td>359</td>
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<td>12</td>
<td>Power</td>
<td>Electric Service PQ</td>
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</table>

### Renewables

<table>
<thead>
<tr>
<th>#</th>
<th>Power or Energy App?</th>
<th>Application</th>
<th>NY Unit Benefit, $/kW, over 10 Years**</th>
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<tbody>
<tr>
<td>13</td>
<td>Energy</td>
<td>Renewable Electricity Production Time-shift</td>
<td>832</td>
<td>655</td>
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<td>14</td>
<td>Power</td>
<td>Renewable Electricity Capacity Firming</td>
<td>323</td>
<td>172</td>
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</tbody>
</table>

Note: Grayed out boxes indicate placeholder values from EPRI; the actual benefit was not estimated.

* MW of cumulative market potential over ten years.

** $ present worth, over ten years, 2.5% inflation, 10% discount rate, mid year convention.

Assumption: Transportable storage could provide the same single year benefit at several locations.

Assumption: Existing resources/equipment, especially if it has useful life, will not be replaced with storage.

Available Technologies

- Flow Batteries
- Advanced Lead Acid
- Sodium Sulfur
- Lithium Ion
- High Speed Flywheels

Source: Kluza at GTM Research
Available Technologies: Flow battery

• Vanadium Redox
  – Pro’s: Good cycle life, power and energy decoupled, scalable, low maintenance
  – Con’s: Cost, moderate efficiency, complexity, size

• Zinc-Bromine
  – Pro’s: Excellent cycle life potential, low $/kWh cycled, power and energy decoupled, scalable, low maintenance
  – Con’s: Cost, moderate efficiency, complexity, plating, size

• Others in development
  – Iron-Chromium
  – Cerium-Zinc
  – Zinc-Chloride

Source: Prudent
Available Technologies: Advanced Lead Acid Batteries

- Many types
- General characteristics
  - Pro’s: Good power density, modest cycle life, low maintenance, existing manufacturing base, low cost anticipated
  - Con’s: Low energy density, still in development

Source: Furukawa
Available Technologies: Sodium Sulfur Batteries

- **Pro’s**: Moderate cycle life, good energy density, availability, good efficiency, low maintenance
- **Con’s**: Cost, high temperature required for operation, dangerous active material, monopoly supplier

- One current supplier (NGK in Japan)
- GE and FIAMM in early production of other molten battery chemistries

Source: NGK
Available Technologies: Lithium Ion Batteries

• Many chemistries in this category
  – LCO (traditional, used in consumer devices, not grid)
  – LFP (on grid)
  – NCA (on grid)
  – LTO (on grid)
  – LMS (not on grid now)

• Generally:
  – Pro’s: Good cycle life, good efficiency, excellent power and energy density, improved safety
  – Con’s: Cost (esp. per kWh), cycle life in some applications, concerns about lithium & rare earth supply

Source: HowStuffWorks
Available Technologies: Flywheels

• Focusing on high speed flywheels here
  • High speed has sufficient output duration
  • Low speed units are in use in some UPS’s for bridging power

• Pro’s: High power density, minimal environmental requirements, extremely long cycle life

• Con’s: Cost, low energy density

Source: Beacon Power
Technology Costs for Comparisons

- Capital Cost Very Rough Estimates
  - Often secret or obscured
- $/kW or $/kWh matter more depending on application

<table>
<thead>
<tr>
<th>Technology</th>
<th>NaS</th>
<th>NaS 90%</th>
<th>ZnBr</th>
<th>VRB</th>
<th>Li-ion 90%</th>
<th>Flywhl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.89</td>
<td>0.89</td>
<td>0.8</td>
<td>0.85</td>
<td>0.9</td>
<td>0.85</td>
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<tr>
<td>Cycle life</td>
<td>2,500</td>
<td>4,500</td>
<td>10,000</td>
<td>10,000</td>
<td>5,000</td>
<td>200,000</td>
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<tr>
<td>Cost of storage ($/kW)</td>
<td>2,500</td>
<td>2,778</td>
<td>2,000</td>
<td>4,154</td>
<td>370</td>
<td>2,000</td>
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<tr>
<td>Cost of storage ($/kWh)</td>
<td>347</td>
<td>386</td>
<td>357</td>
<td>692</td>
<td>1,481</td>
<td>8,000</td>
</tr>
</tbody>
</table>

- (20/20 Hindsight after thesis – power electronics are roughly $250/kW alone, so Li-ion system cost here is low)
- Comparisons – Flow; NaS vs NaS 90%; Li-ion vs Flywheel

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Available Technologies

• Relative cost to cycle a kWh in load shifting type applications

• Flywheels can cycle indefinitely, however very expensive upfront for energy applications, better for power applications

Source: Kluza at GTM Research, Credit Suisse, ESA
Implementations

1. Wholesale Load Shifting
2. Renewable Power Management
3. T&D Capacity Deferral Focused
4. Ancillary Services Focused
5. Community Support
6. Industrial Energy Management

- Assuming able to do multiple applications at same time, or non-coincidentally

Source: Prudent Energy

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## Implementation Value

<table>
<thead>
<tr>
<th>Imp #</th>
<th>Implementation</th>
<th>App’s Included</th>
<th>NY 10 yr Max Benefit ($/kW)</th>
<th>CA 10 yr Max Benefit ($/kW)</th>
<th>Output Duration (Min/Max)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Wholesale load shifting arbitrage</td>
<td>Wholesale load shifting arbitrage</td>
<td>394</td>
<td>250</td>
<td>2/8 hrs</td>
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<tr>
<td>2</td>
<td>Renewables Management</td>
<td>Renewables shifting, frequency regulation</td>
<td>1621</td>
<td>655+ NA</td>
<td>4/6 hrs</td>
</tr>
<tr>
<td>3</td>
<td>T&amp;D Capacity Deferral</td>
<td>Load shifting, T&amp;D cap deferral, Reduce trans. congestion, Reliability</td>
<td>2025</td>
<td>1676</td>
<td>2/6 hrs</td>
</tr>
<tr>
<td>4</td>
<td>Ancillary Services</td>
<td>Operating reserve, Frequency regulation</td>
<td>1047</td>
<td>NA</td>
<td>10 min/1 hr</td>
</tr>
<tr>
<td>5</td>
<td>Community Energy Storage</td>
<td>T&amp;D cap deferral, Reliability, Power Quality, Renewables firming</td>
<td>2599</td>
<td>2315</td>
<td>2/6 hrs</td>
</tr>
<tr>
<td>6</td>
<td>Industrial Energy Management</td>
<td>Demand charge reduction, Reliability, Power Quality</td>
<td>2152</td>
<td>1541</td>
<td>4/6 hrs</td>
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</tbody>
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# Implementation Profitability Expectations

Based on thesis research

<table>
<thead>
<tr>
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<th>Zn-Br flow battery</th>
<th>VRB flow battery</th>
<th>Nas battery</th>
<th>Lithium ion battery</th>
<th>High speed flywheel</th>
</tr>
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<tr>
<td>1 Wholesale Load Shifting</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 Renewable Power Management</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3 T&amp;D Capacity Deferral Focused</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4 Ancillary Services Focused</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5 Community Support</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>6 Industrial Energy Management</td>
<td>+</td>
<td>0/+</td>
<td>-</td>
<td>-</td>
<td>-</td>
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Based on public data from industry

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<td>NA</td>
<td>+</td>
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<tr>
<td>3 T&amp;D Capacity Deferral Focused</td>
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<td>NA</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>6 Industrial Energy Management</td>
<td>+</td>
<td>NA</td>
<td>+</td>
<td>NA</td>
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</table>

* Only including revenue from wholesale load shifting activities

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Challenges of implementations

• Technologies are capable, but expensive

• Government regulation complicates
  – Many regulating bodies
  – Who accrues revenue from what (e.g. rate base)

• Benefit streams are not all cash

• May need to move system a few times during lifetime to gain full value

Source: Premium Power

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Brief Conclusions

• Multiple grid-scale markets of different maturity & total size
  – Combining applications is key (esp. wholesale arbitrage alone won’t do it!)

• While not necessarily grid scale, displacing oil-fired generation is often cost effective and can be an entry point.

• Power market is attractive now with existing tech
  – Lithium ion – near term attractive for ancillary services and community ES
  – HS Flywheels – near/mid term attractive for ancillary services

• Energy market is limited now for cost and regulatory reasons, but larger LT
  – NaS – near term attractive for industrial mgmt, foreign high value app’s
  – Zinc-Bromine – mid term attractive for T&D deferral, Industrial mgmt, renewables mgmt; waiting on tech to scale

• Regulatory support is critical
  – Need to build awareness, clarify pitch
Events moving forward

• Supporting bills proposed in Congress
• California orders CA-ISO to set storage portfolio standard to hit 33% RPS
• ARRA & ARPA-E stimulus
• Utility and gov demo’s
• Private company projects – AES, First Wind, Acciona, Tres Amigas, etc
Comments a few years on

• Challenges remain
  – Cost is gradually decreasing but still high
    • Thermal shifting has identified its opportunity here
    • More lead-based options developing
  – Challenging to get paid for multi-applications
  – Complex value proposition
    • Difficult to forecast market

• Situation analysis critical for each opportunity
  – Generation mix
  – Geography and grid architecture
  – Regulatory structure
Comments a few years on

• Encouraging signs
  – Regulatory support building (FERC, incentives, ISO’s, IEEE)
    • Wind integration charges & renewables ramp limits more common
  – ESA and industry events attendance sharply up
  – More analysis and communication has begun to standardize sizes, applications, and components
  – BOP offers opportunities for optimization
    • Solar PV + storage offers cost reduction and system performance improvement (Satcon demo projects)

• Avoid competing with generators on their “turf”
  – Do what traditional assets are bad at/can’t help with

• T&D is very contentious to site in developed areas
Questions?

Source: Xcel Energy

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