TECHNOLOGY DEVELOPMENT NEEDS FOR INTEGRATED GRID-CONNECTED PV SYSTEMS AND ELECTRIC ENERGY STORAGE

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Photovoltaic systems are intermittent generators

- Lack inertia to ride through fluctuations caused by cloud movements, etc.
- Energy production can go from full power to nearly zero and back in seconds
- Utility operations and load-side equipment not designed to handle resultant and power value fluctuations
- Storage can help to improve grid reliability, improve power quality, and reduce overall energy costs

This paper discusses the application of electrical energy storage with grid-connected PV systems.

Figure 1: Measured and modeled PV system output on a day with frequent passing clouds.
More PV Means Utility Needs More Backup Generation

As the level of PV penetration on the grid increases...

- PV can become an economic burden to the utility
- So does the need for additional spinning reserve capacity

\[ \text{% Generation} \]

\[ \text{% Penetration} \]
Optimal Integration of Storage with PV Systems Requires Several Considerations

- The specific application and expected benefits
- Suitability of available storage technologies to the application
- Requirements and constraints of integrating distributed generation and electrical energy storage with both the load (residential, commercial, or microgrid) and the utility grid
- Power electronics and control strategies necessary to ensure optimal functioning
- Specific requirements to provide service to the load and to maintain or improve grid reliability and power quality
Applications of Storage with PV

- Two primary application types: peak shaving and reliability
- Peak Shaving, Load Shifting, Demand Response – supplying energy generated at one time to loads at another time
  - Minimize demand charges through reduced peaks
  - Match generation more closely to consumption
- Outtage protection, grid power quality control, microgrids – improving and maintaining quality service to customers under varying conditions
  - Ride-through of utility interruptions
  - Maintain voltage, frequency, power factor
Potential Economic Benefits

**Consumers:**
- Reduced peak demand and time-of-use charges
- Selling power back to utilities

**Utilities:**
- Avoided costs of peak and intermediate power generating capability plus spinning reserve
- Selling carbon credits from PV generation
Current Electrical Energy Storage Technologies

- Economic, technical tradeoffs in power vs. energy capacity
- Lead-acid is still dominant technology
- Li-ion offers promise, but still too expensive and difficult to control
- Carbon-lead-acid offers increased cycle-life, efficiency, and reliability
- Non-battery technologies could be part of future grid solution: flywheels, electrochemical capacitors, others

Specific power vs. specific energy of several energy storage technologies.
Electrical Energy Storage Costs

<table>
<thead>
<tr>
<th>Technology</th>
<th>Current Cost ($/kWh)</th>
<th>10-yr Projected Cost ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooded Lead-acid Batteries</td>
<td>$150</td>
<td>$150</td>
</tr>
<tr>
<td>VRLA Batteries</td>
<td>$200</td>
<td>$200</td>
</tr>
<tr>
<td>NiCd Batteries</td>
<td>$600</td>
<td>$600</td>
</tr>
<tr>
<td>Ni-MH Batteries</td>
<td>$800</td>
<td>$350</td>
</tr>
<tr>
<td>Li-ion Batteries</td>
<td>$1,300</td>
<td>$150</td>
</tr>
<tr>
<td>Na/S Batteries*</td>
<td>$450</td>
<td>$350</td>
</tr>
<tr>
<td>Zebra Na/NiCl Batteries</td>
<td>$800</td>
<td>$150</td>
</tr>
<tr>
<td>Vanadium Redox Batteries*</td>
<td>20 kWh=$1,800/kWh; 100 kWh =$600/kWh</td>
<td>25 kWh=$1,200/kWh 100 kWh =$500/kWh</td>
</tr>
<tr>
<td>Zn/Br Batteries*</td>
<td>30 kW/45 kWh=$500/kWh 2 MWh=$300/kWh</td>
<td>$250/kWh</td>
</tr>
<tr>
<td>Lead-carbon Asymmetric Capacitors (hybrid)</td>
<td>$500</td>
<td>&lt;$250</td>
</tr>
<tr>
<td>Low-speed Flywheels (steel)</td>
<td>$380</td>
<td>$300</td>
</tr>
<tr>
<td>High-speed Flywheels (composite)*</td>
<td>$2500/kW</td>
<td>$800</td>
</tr>
<tr>
<td>Electrochemical Capacitors</td>
<td>$356/kW</td>
<td>$250/kW</td>
</tr>
</tbody>
</table>

Energy Storage Device Capacity Costs (*includes power conditioning system).

- Reflects first costs based on capacity – need to consider various lifetime factors to determine life-cycle costs
- Much work to be done to make the potential benefits of added storage exceed the costs
Electrical Energy Storage Models

• New techniques under development for lead-acid and other new battery technologies
  – Equivalent Circuit
  – Artificial Neural Network
  – Fuzzy Logic

• Few hybrid models to address physical interactions of battery-integrated PV systems

• Some models have large data requirements to address a spectrum of operational environments

• Need for more field performance data to drive model development
R&D Needs: Storage Technologies

Storage technologies need science and engineering improvements to address:

• Increasing power and energy densities
• Extending lifetimes and cycle-life, including partial state-of-charge (PSOC) operations
• Decreasing charge-discharge cycle times
• Ensuring safe operation
• Reducing costs
R&D Needs: Controls

• Optimal efficiency and battery lifetime will be based on charge/discharge cycle control
  – Often specific to manufacturers and products
  – Finish charging potentially very difficult in off-grid (i.e., microgrid) settings

• Integral power conditioning required for 60Hz AC
  – Developments coming from DOE’s Solar Energy Grid Integration Systems (SEGIS) program
    • Linking generation, storage, load control through communications

• Safety control for new technologies (i.e., Li-Ion) will require much development
R&D Needs: Analysis and Models

• Determine life-cycle costs using conventional industry metrics
• Evaluate benefits of integrating solar production, building loads, and storage relative to capital cost, maintenance, and the real-time cost of alternate energy sources (utility power)
• Accurately simulate residential, commercial, and utility systems and provide recommendations for best operation, dispatch, and control
• Develop detailed models of the interrelationships between such parameters as physical conditions, operating rules, regulations, and business decision-making
Conclusions: Recommendations for a Path Forward

A three-pronged approach is recommended:

• Comprehensive systems analysis and modeling
  – Include new modeling tools to address system technical performance optimization; grid operational performance, stability, and reliability; cost/benefits; life-cycle costs; and overall energy systems management

• An industry-led R&D effort focused on new integrated systems
  – Partnership between stakeholders in the storage and PV industries to develop new products
  – Include test and verification of integrated systems

• Development of appropriate codes and standards that facilitate broader market penetration of PV-Storage systems and address all related safety concerns