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

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The Case for Grid-Connected PV/Storage

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**

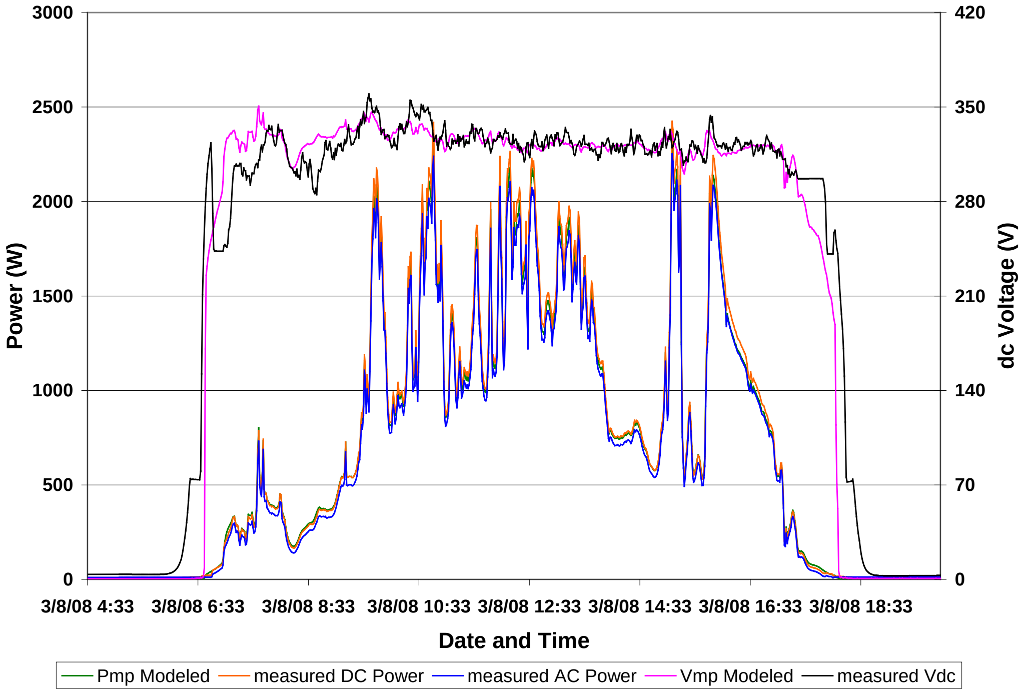

Figure 1: Measured and modeled PV system output on a day with frequent passing clouds.

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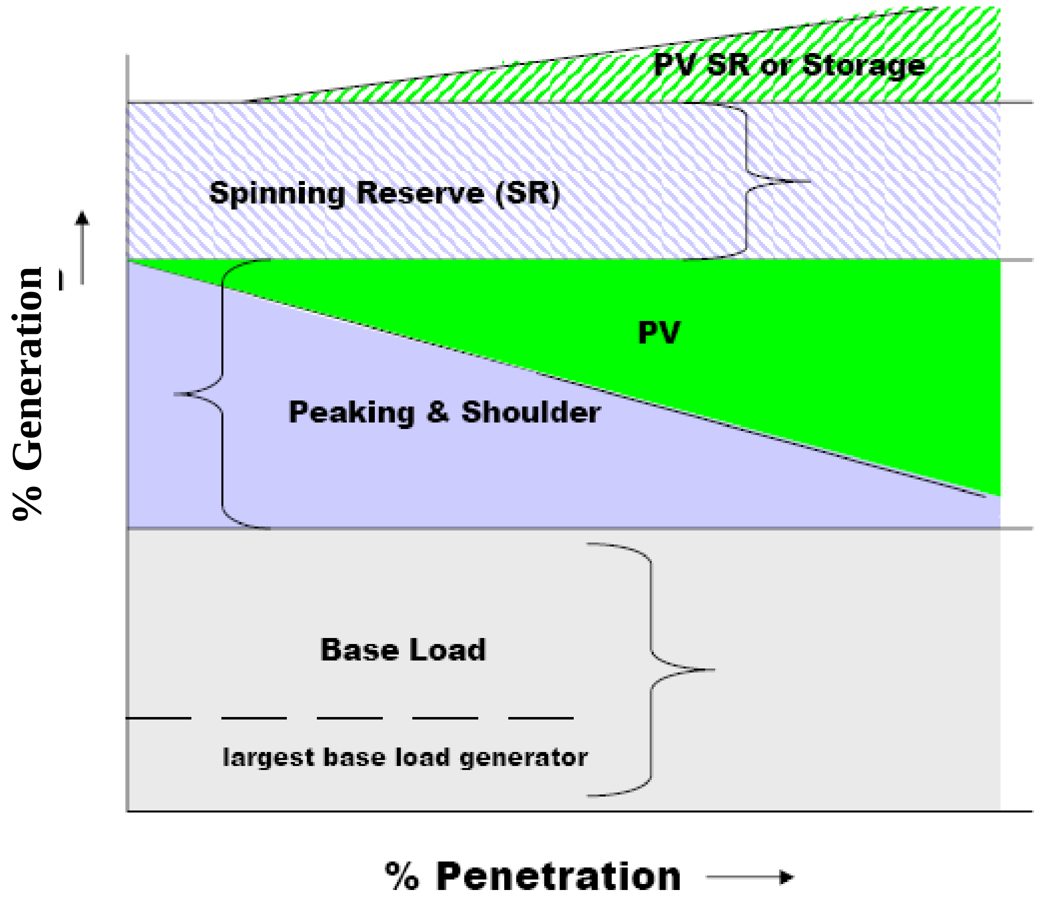
More PV Means Utility Needs More Backup Generation



So does the need for additional spinning reserve capacity

As the level of PV penetration on the grid increases…

PV can become an economic burden to the utility

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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

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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:

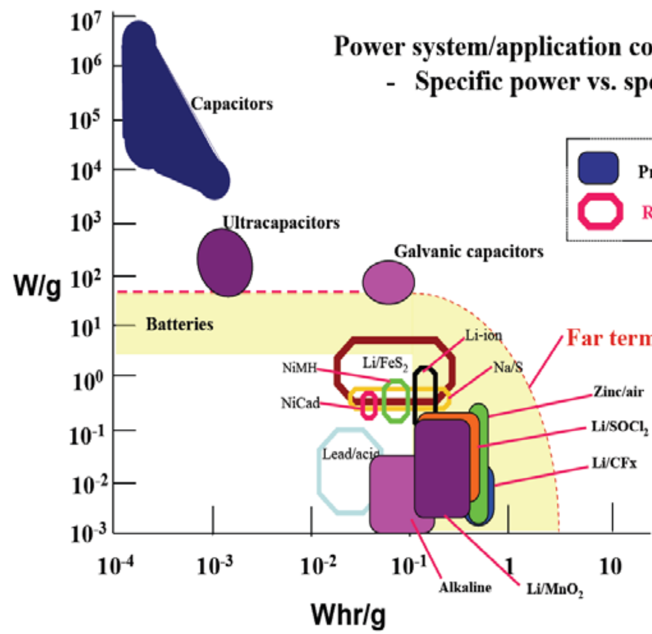
- **Reduced peak demand and time-of-use charges**
- **Selling power back to utilities**

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**



Li-ion Chemistries show some of the greatest power and energy densities

Specific power vs. specific energy of several energy storage technologies.

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Electrical Energy Storage Costs

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

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**

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Electrical Energy Storage Models

- **New techniques under development for lead-acid and other new battery technologies**
  - Eaquivalent 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**

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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**