Energy storage in Electric Power Systems

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Overview

- Impact of variable generation on load curve
- Energy storage technologies
- Battery Energy Storage Systems
  - Residential application
  - Commercial application
- Mobile applications
Solar and wind are excellent sources of clean, renewable energy, but as they contribute a larger share to the generation fleet, their integration will become increasingly challenging.

The reason: solar and wind cannot be dispatched in the same way as other sources of energy, such as nuclear, hydro, and fossil fuels.

Because the grid must operate “just in time,” with generation continually matching demand, special accommodation is required to integrate a significant contribution from the sun or the wind.
Classification of Energy Storage Systems

**Electrical energy storage systems**

**Mechanical**
- Pumped hydro - PHS
- Compressed air - CAES
- Flywheel - FES

**Electrochemical**
- Secondary batteries
  - Lead acid / NiCd / NiMh / Li / NaS
- Flow batteries
  - Redox flow / Hybrid flow

**Electrical**
- Double-layer Capacitor - DLC
- Superconducting magnetic coil - SMES

**Chemical**
- Hydrogen
  - Electrolyser / Fuel cell / SNG

**Thermal**
- Sensible heat storage
  - Molten salt / A-CAES

https://www.energystorageexchange.org/projects
Traditional energy storage: pumped hydro
The choice of an energy storage device depends on its application in either the current grid or in the renewables/VG-driven grid; these applications are largely determined by the length of discharge.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Example Applications</th>
<th>Discharge Time Required</th>
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</thead>
<tbody>
<tr>
<td>Power Quality</td>
<td>Transient Stability, Frequency Regulation</td>
<td>Seconds to Minutes</td>
</tr>
<tr>
<td>Bridging Power</td>
<td>Contingency Reserves, Ramping</td>
<td>Minutes to ~1 hour</td>
</tr>
<tr>
<td>Energy Management</td>
<td>Load Leveling, Firm Capacity, T&amp;D Deferral</td>
<td>Hours</td>
</tr>
</tbody>
</table>
Advantages of expanded use of energy storage

- Energy storage can be employed by utilities to facilitate the integration of photovoltaic (PV) generation and mitigate possible negative impacts on the distribution system by:
  - avoiding system upgrades required for PV integration
  - mitigating voltage fluctuations at the primary distribution side resulting from intermittent distributed PV generation
  - reducing distribution system losses through improved utilization of distributed generation
  - deferring upgrade of substation equipment by time-shifting peak PV generation to coincide with system load peak
# Energy Storage Applications

## Category 1 — Electric Supply
1. Electric Energy Time-shift
2. Electric Supply Capacity

## Category 2 — Ancillary Services
3. Load Following
4. Area Regulation
5. Electric Supply Reserve Capacity
6. Voltage Support

## Category 3 — Grid System
7. Transmission Support
8. Transmission Congestion Relief
9. Transmission & Distribution (T&D) Upgrade Deferral
10. Substation On-site Power

## Category 4 — End User/Utility Customer
12. Demand Charge Management
13. Electric Service Reliability
14. Electric Service Power Quality

## Category 5 — Renewables Integration
15. Renewables Energy Time-shift
16. Renewables Capacity Firming
17. Wind Generation Grid Integration

### Incidental Benefits

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
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<tbody>
<tr>
<td>18</td>
<td>Increased Asset Utilization</td>
</tr>
<tr>
<td>19</td>
<td>Avoided Transmission and Distribution Energy Losses</td>
</tr>
<tr>
<td>20</td>
<td>Avoided Transmission Access Charges</td>
</tr>
<tr>
<td>21</td>
<td>Reduced Transmission and Distribution Investment Risk</td>
</tr>
<tr>
<td>22</td>
<td>Dynamic Operating Benefits</td>
</tr>
<tr>
<td>23</td>
<td>Power Factor Correction</td>
</tr>
<tr>
<td>24</td>
<td>Reduced Generation Fossil Fuel Use</td>
</tr>
<tr>
<td>25</td>
<td>Reduced Air Emissions from Generation</td>
</tr>
<tr>
<td>26</td>
<td>Flexibility</td>
</tr>
</tbody>
</table>
Deferral of Distribution Feeder investment
Expected Growth in U.S. Annual Energy Storage Deployments

Source: GTM Research
Several states have recently introduced policies related to the support and development of energy storage technology markets.
A 34-MW, 245-MWh Na-S battery installation in Japan
Tehachapi wind farm (Capacity: 4,500 MW)
Large-Scale BESS Installations

- 32 MWH BESS features lithium-ion batteries housed inside a substation in Tehachapi, CA.
Distributed Energy BESS
Community Energy Storage (multiple customers)

- Typical CES Power and Energy Ratings
  - 25 kW
  - 50 kWh
Residential Applications (single customer)

- Typical Power and Energy Ratings:
  - 2-5 kW
  - 5-15 kWh
PV-BESS expected to expand as power exported to the grid is becoming less and less costly.
Testing of a BES for Residential Applications

- Part of DOE Smart Grid Demo Projects
- Collaborators: NV Energy and Pulte Homes
Adding a Battery Energy Storage System to the Mix

- Biggest challenge with solar energy: intermittency
- Solution: combine energy storage and load management capability.
- BESS Applications include:
  - Peak shaving
  - Load shifting
  - PV power generation smoothing
  - Align PV generation with load consumption
  - Etc...

4.5 kW/10 kWh Residential BESS
Charge/Discharge Test

NVE ODEA System Test
Daily System Discharge - Charge Energy

Day 1-2: Discharge on Day 1 Afternoon is Recharged on Day 2 Morning. Data Period is 24 HR, Day 1, 12PM to Day 2, 12PM

Feb. 2015

Daily ODEA Electric Discharge Energy

Next Day ODEA Electric Charge Energy
Round trip efficiency

NVE ODEA Systems
Daily Efficiency Values

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-  Overall System Efficiency
-  Inverter Efficiency
-  Charger Efficiency
Application 1: Customer enrolled in TOU pricing

- Battery saves money by reducing consumption during periods when total demand for electricity is highest (1:00pm-7:00pm, June-September)
Application 2: Keep Maximum Demand Below 3 kW

- Use battery to provide power demand above 3 kW limit.
- Use excess PV power to charge battery
Charging/discharging optimization

- Different electricity rate plans
- Payback period exceeds over 10 years (without incentives)

<table>
<thead>
<tr>
<th>Plan A (Peak: 1-8 p.m.)</th>
<th>On-peak S/kWh</th>
<th>Off-peak S/kWh</th>
<th>On-peak demand charge ($/kW)</th>
<th>Service Charge /Mon</th>
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<tbody>
<tr>
<td>Summer</td>
<td>$0.0486</td>
<td>$0.0371</td>
<td>$8.03 $14.63 $27.77</td>
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<td>Summer Peak</td>
<td>$0.0633</td>
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<td>Winter</td>
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<td>$3.55 $5.68 $9.74</td>
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<table>
<thead>
<tr>
<th>Plan B</th>
<th></th>
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<tbody>
<tr>
<td>Winter (Nov-Apr)</td>
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<tr>
<td>On-peak (12-7 p.m.)</td>
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<tr>
<td>Off-peak</td>
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<tr>
<td>Summer (May-Oct)</td>
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<tr>
<td>On-peak (12-7 p.m.)</td>
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<tr>
<td>Off-peak</td>
<td>$0.06118</td>
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<td>$0.02897</td>
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</tbody>
</table>

Figure 2. Daily PV energy distribution

Energy storage system integration with PV can be designed to operate in many ways such as:

- **PV Power Firming**: Level PV output power during cloud transients throughout the day, then gets recharged at night and be ready for the next day.

- **PV Power Smoothing**: the storage system will generate and absorb energy to smooth out PV array power fluctuations.

The next slides evaluate the placement of an BES at the PCC of a commercial-size Concentrating PV system for the purpose of reducing the ramp rate, or “power smoothing”.
PV Plant Description

- Power rating: 55 kW.
- Surface: 300 m²
- No. of cells: 5,600
- Type of cell: III-V multi-junction
- Concentration factor: 500
- Cell efficiency: 25%
Power production during 20-minute period of passing clouds
POWER RAMP RATE (KW/SEC)
Reducing power fluctuations depends on several factors such as desired power quality, PV system location in the feeder and specific controls of voltage regulation equipment.

Ramp rate control (or smoothing) by means of a BES is achieved by continuously monitoring the PV power output and commanding the BES to charge or discharge in a way that limits the combined PV-BES power.
For ramp rate control, the method based on **moving average** (MA) provides satisfactory results as it defines the current direction with a lag because it is based on past power values.

The BES is to supply a power $P_{e,n+1}$ that is equal to the difference between the updated moving average and the new PV power generated, i.e.,

$$
\overline{P}_{e,n+1} = \overline{P}_{s,n+1} - P_{s,n+1} = \overline{P}_{sn} + \frac{(1-n)P_{s,n+1} - P_{s1}}{n}
$$
Power Variability of CPV-BES Combination
POWER RAMP RATE OF CPV-BES COMBINATION

Graph showing the CPV + ESS ramp rate over time (seconds) with different moving averages and a base case.
BES SIZING

300 Wh/1.25 kW (for 1 min moving average)
160 Wh/1.5 kW (for ½ min moving average)
Typical battery charging curve

- What if recommended charge curve is not followed?
- What is the impact of shallow discharges?
Battery discharge curves

- Battery capacity under variable discharge rate?

![Discharge Time VS. Discharge Current (25°C)](image-url)
Lastly ....testing a lemon battery!

4 lemons can power one a bright LED for over 24 hrs!