Fundamentals of Energy Storage

Prateek Joshi and Carishma Gokhale-Welch

*National Renewable Energy Laboratory*

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Background

This slide deck was developed for and presented at an Energy Fundamentals Course hosted by the Bangladesh University of Engineering and Technology (BUET) in October 2022. The National Renewable Energy Laboratory (NREL) helped organize this course in partnership with the United States Agency for International Development (USAID). The students in this four-day course were postgraduates and working professionals in the energy sector or related industries in Bangladesh. While some of the content in the slide deck is tailored to Bangladesh specifically, this presentation is intended to be a general primer on energy storage that can be utilized for similar purposes by other universities or organizations throughout the world. The content of this slide deck is not intended to be fully comprehensive of all energy storage concepts.
1. Storage Trends
   a. Global trends
   b. Regional trends

2. Storage Technology
   a. Electrochemical
   b. Mechanical
   c. Thermal

3. Battery Storage
   a. Attributes
   b. Utility-scale & Distributed
   c. Resilience

4. Grid Services
   a. Energy & capacity
   b. Ancillary services
   c. Transmission
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Image: Werner Slocum (NREL)
Global Trends

Figure. Global energy storage build by market, 2015-2020

Source: Bloomberg New Energy Finance (2022)
Global Trends

Figure. Global energy storage projection by market, 2015-2020

Source: Bloomberg New Energy Finance (2022)
Global Trends

Figure. Stationary storage system (4-hour AC battery energy storage system) cost trend and projection, 2019-2030

Source: Bloomberg New Energy Finance (2022)
Regional Trends

Scenarios for modeled energy storage deployment varied based on:

- Regulations
- Fossil fuel policies
- Battery costs
- Solar PV costs
- Pumped storage hydropower costs
- Storage capacity in Nepal, Bangladesh, and Bhutan

Figure. Energy storage power (A) and energy (B) modeled capacity deployment in India, 2020-2050

Note: Each line represents one modeled scenario. The Reference Case is highlighted in red.

Source: Chernyakhovskiy et al. (2021)
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Image: Werner Slocum (NREL)
Storage Technology Overview

Figure. Ecosystem of energy storage technologies and services

Source: Bowen et al. (2021)

Figure. Global total operational energy storage project capacity, 2020

Data: China Energy Storage Alliance (2020)
# Pumped Storage Hydropower (PSH)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Duration</th>
<th>Reaction Time</th>
<th>Round-Trip Efficiency</th>
<th>Unique Geographic Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSH</td>
<td>Several hours to days</td>
<td>Several seconds to minutes (depends on technology choice)</td>
<td>80%</td>
<td>Separate reservoirs with adequate differences in elevation</td>
</tr>
</tbody>
</table>

**Open-Loop PSH**
Projects are continuously connected to a naturally flowing water feature.

**Closed-Loop PSH**
Projects are not continuously connected to a naturally flowing water feature.

## Advantages
- Most developed and widely commercialized energy storage technology in power sector
- Large capacities and long durations make it well suited to provide a variety of grid services

## Challenges
- Limited by geographic requirements
- High capital costs

Source: Bowen et al. (2021)
Power-To-Gas: Hydrogen

**Advantages**

- Potential to provide seasonal long-duration storage
- Applications for hydrogen in transportation and industry

**Challenges**

- Costs of electrolysis and subsequent power generation are currently high
- Significant support infrastructure required

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**Select methods for producing hydrogen**

<table>
<thead>
<tr>
<th>Method</th>
<th>Status</th>
<th>Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification</td>
<td>Mature</td>
<td>Coal or biomass</td>
</tr>
<tr>
<td>Steam (Methane)</td>
<td>Mature</td>
<td>Natural gas or biogas</td>
</tr>
<tr>
<td>Reforming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton-Exchange</td>
<td>Pilot for</td>
<td></td>
</tr>
<tr>
<td>Membrane</td>
<td>at-scale</td>
<td></td>
</tr>
<tr>
<td>Alkaline</td>
<td>Mature at</td>
<td>Electricity plus water</td>
</tr>
<tr>
<td>Solid Oxide</td>
<td>R&amp;D</td>
<td></td>
</tr>
</tbody>
</table>

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*Source and Image: Bowen et al. (2021); Denholm et al. (2021)*
Thermal Energy Storage (TES)

**Sensible heat storage**
- Uses temperature changes within a solid or liquid medium to store thermal energy.

**Latent heat storage**
- Phase change materials that absorb and release thermal energy through melting and freezing.

**Thermochemical storage**
- Releases or stores thermal energy as a byproduct of chemical reactions.

Applications of TES

- TES decouples electricity supply from heat supply in district heating systems, enabling flexibility.
- TES allows electricity production from concentrated solar power plants even when sunlight is not available.

Source: Bowen et al. (2021)

Images: Engie; Dennis Schroeder (NREL)
# Electrochemical Battery Storage

## Advantages

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-Ion</td>
<td>- Relatively high energy and power density</td>
<td>- High upfront cost ($/kWh) relative to lead-acid (potentially offset by longer lifetimes)</td>
</tr>
<tr>
<td></td>
<td>- Lower maintenance costs</td>
<td>- Poor high-temperature performance</td>
</tr>
<tr>
<td></td>
<td>- Rapid charge capability</td>
<td>- Safety considerations, which can increase costs to mitigate</td>
</tr>
<tr>
<td></td>
<td>- Many chemistries offer design flexibility</td>
<td>- Currently complex to recycle</td>
</tr>
<tr>
<td></td>
<td>- Established technology with strong potential for project bankability.</td>
<td>- Reliance on scarce materials.</td>
</tr>
<tr>
<td>Flow (Vanadium-Redox)</td>
<td>- Long cycle life</td>
<td>- Relatively low energy and power density.</td>
</tr>
<tr>
<td></td>
<td>- High intrinsic safety</td>
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</tr>
<tr>
<td></td>
<td>- Capable of deep discharges</td>
<td></td>
</tr>
<tr>
<td>Lead-Acid</td>
<td>- Low cost</td>
<td>- Limited energy density</td>
</tr>
<tr>
<td></td>
<td>- Many different available sizes and designs</td>
<td>- Relatively short cycle life</td>
</tr>
<tr>
<td></td>
<td>- High recyclability</td>
<td>- Cannot be kept in a discharged state for long without permanent impact on performance</td>
</tr>
<tr>
<td>Sodium-Sulfur</td>
<td>- Relatively high energy density</td>
<td>- Deep cycling can impact cycle life</td>
</tr>
<tr>
<td></td>
<td>- Relatively long cycle life</td>
<td>- Poor performance in high temperature environments.</td>
</tr>
<tr>
<td></td>
<td>- Low self-discharge</td>
<td>- Toxicity of components</td>
</tr>
</tbody>
</table>

*Source: Bowen et al. (2021)*

![USAID](https://example.com/usaid.png)  
![NREL](https://example.com/nrel.png)

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Image: Werner Slocum (NREL)
Attributes

Energy storage projects are rated based on **power** (MW/kW) and **energy** (MWh/kWh).

**State of Charge**
The percentage of battery energy capacity still available in the battery.

**Depth of Discharge**
The percentage of the battery that has been discharged relative to the total battery energy capacity.

**Round-Trip Efficiency**
The ratio of the energy recovered from the battery to the energy input into the battery. Losses include heat loss.

*Images: Future Green Technology (2018)*
Utility-Scale and Distributed Storage

Figure. Global energy storage build by sector, 2015-2020

Source: Bloomberg New Energy Finance (2022)
Distributed Battery Storage for Resilience

When coupled with a renewable distributed energy generation source (e.g., solar PV), battery storage can provide backup generation for extended periods of time (days to weeks):

- Decreases the size of other backup generation (e.g., diesel generators) and extends limited fuel supply
- Is a fully renewable backup power source (when coupled with renewables) that does not need refueling
- Can provide revenue streams while grid connected (e.g., demand charge reduction, demand response programs, energy arbitrage, etc.)

Source: Elgqvist (2020)
Considerations for Distributed Storage as Backup Power

- There are considerations for using renewable energy and storage to provide backup power in the event of a grid outage (in addition to the ones for grid-connected-only systems).
- Different technology solutions have different costs and can provide different levels of resilience.

Source: Elgqvist (2020)
Image: David Shankbone (Wikimedia Commons)
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Image: Werner Slocum (NREL)
Storage Can Provide Flexibility and Help Integrate Renewables

Source: Chernyakhovskiy et al. (2021)
Storage Can Provide Services Throughout the Grid

**Generation**
- Storage Applications
  - Address supply disruptions
  - Address variability of renewable resources
  - Provide peaking capacity

**Transmission**
- Storage Applications
  - Defer transmission upgrades
  - Relieve transmission congestion
  - Provide grid (ancillary) services

**Distribution**
- Storage Applications
  - Defer distribution upgrades
  - Provide backup power during outages
  - Support microgrids
  - Reduce demand charges

*Image: Clear Path (2018)*
“Effectively increase available load during periods with excess generation for peak demand management and reduction of renewable energy curtailment.”

“Stabilize net electricity demand to minimize thermal unit ramping and cycling and minimize errors in renewable energy and demand forecasts.”

“Provide capacity to meet generation requirements during peak loading periods and contingency events.”

Source: Rose and Joshi (2021)
Ancillary Services

<table>
<thead>
<tr>
<th>Timescales</th>
<th>Frequency Regulation</th>
<th>Voltage Regulation</th>
<th>Spinning Reserve</th>
<th>Nonspinning Reserve</th>
<th>Black Start</th>
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<tbody>
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<td>mSec</td>
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<td>Day</td>
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</tbody>
</table>

"Provide power to maintain generation-load balance and prevent frequency fluctuations."

"Inject or absorb incremental voltage to maintain voltage stability on the transmission system."

"Provide immediate response to maintain electricity output during a contingency event."

"Maintain electricity output during contingency events within a short time period."

"Start main turbine of grid-connected generator, or feed power into the grid so other plants can start up and restore power."

Source: Rose and Joshi (2021)
Transmission Services

“Provide extra capacity to meet anticipated load growth for the purpose of delaying, reducing, or avoiding transmission system investments.”

“Absorb power to reduce network congestion.”

Source: Rose and Joshi (2021)
Thank you!

Prateek.Joshi@nrel.gov
References


