

**Tutorial Handout  
Overview of Grid-Scale Energy Storage Systems and Technologies**

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**OBJECTIVE**

This tutorial provides an overview of various machinery-based grid-scale energy storage systems and technologies including thermal, mechanical, and chemical systems. The tutorial covers fundamental working principles, example hardware, role of turbomachinery, and R&D activities for each of these technologies.

**TUTORIAL OUTLINE**

Background and Motivation

- Need for Energy Storage
  - Renewable Variability
  - Fossil Ramp Rate and Off-Design
- Value of Energy Storage
  - Power Quality
  - Spinning Reserve
  - Energy Arbitrage
  - Transmission & Upgrade Deferral
  - Behind-the-Meter Peak Shaving
- Energy Storage Market Growth

## Energy Storage Technologies

- Battery Storage
  - Solid-State Batteries
  - Flow Batteries
- Mechanical Storage
  - Pumped Hydro
  - Flywheel
  - Gravitational
  - Gas-Electric Systems
- Heat Engine-Based Storage
  - CAES
  - Liquid Air
  - CO<sub>2</sub> Phase Change
  - Pumped Thermal
  - Synthetic Fuels
  - Hydrogen
- Thermal Storage
  - Molten Salt/Refrigerant
  - Solids, Liquids
  - Cold Energy Storage

## Applications for Energy Storage

- Existing global energy storage projects
  - Timeline, technology and geopolitical breakdowns
- Example applications at commercial/pilot scale
  - Pumped Hydro Storage
  - Concentrating Solar Power + Thermal
  - Compressed Air
  - PV + Battery
  - Wind + Battery
  - Gas Turbine + Battery
  - Hydrogen Storage
  - Liquid Air
- Storage concepts under development
  - Liquid Air
  - Pumped Thermal
  - Integrated Fossil + Storage
- The Future of Energy Storage
  - Performance Metrics
  - R&D Roadmaps

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