SECTION 2: ENERGY STORAGE FUNDAMENTALS
Performance Characteristics
Energy Storage Performance Characteristics

- Defining performance characteristics of energy storage mechanisms
  - Capacity
  - Power
  - Efficiency
Capacity

- **Capacity**
  - The amount of *energy* that a device can store

- **Total energy capacity,** $E_t$
  - Total energy stored in a device when fully charged

- **Usable energy capacity,** $E_u$
  - The total energy that can be extracted from a device for use
  - Difference between stored energy at maximum state of charge (SoC) and minimum SoC
  - In general, storage devices are not fully discharged, so typically
    \[ E_u < E_t \]
Capacity

- **Units of capacity:**
  - Watt-hours (Wh)
  - (Ampere-hours, Ah, for batteries)

- **State of charge (SoC)**
  - The amount of energy stored in a device as a percentage of its total energy capacity
    - Fully discharged: SoC = 0%
    - Fully charged: SoC = 100%

- **Depth of discharge (DoD)**
  - The amount of energy that has been removed from a device as a percentage of the total energy capacity
Capacity

- We can also characterize storage devices in terms of size or mass required for a given capacity

  - **Specific energy**
    - Usable energy capacity per unit **mass**
    - Units: Wh/kg
    
    \[ e_m = \frac{E_u}{m} \]

  - **Energy density**
    - Usable energy capacity per unit **volume**
    - Units: Wh/m^3 or Wh/L
    
    \[ e_v = \frac{E_u}{V} \]

- These are very often used (incorrectly) interchangeably
**Power**

- **Power** is an important metric for a storage system
  - Rate at which energy can be stored or extracted for use
    - Charge/discharge rate
  - Limited by loss mechanisms

- **Specific power**
  - Power available from a storage device per unit mass
  - Units: W/kg
    \[ p_m = \frac{P}{m} \]

- **Power density**
  - Power available from a storage device per unit volume
  - Units: W/m³ or W/L
    \[ p_v = \frac{P}{V} \]
Power vs. Energy

- Capacity and the rate at which energy can be stored or extracted are different characteristics
  - Applications determine which is most important

- High specific power
- Low specific energy
- Low specific power
- High specific energy
Another important performance characteristic is efficiency

- The percentage of energy put into storage that can later be extracted for use

All storage systems suffer from losses

- Losses as energy flows into storage
- Losses as energy is extracted from storage
Round-Trip Efficiency

- **Round-trip efficiency**
  - Energy extracted from a storage system as a percentage of the energy put into the system

\[
\eta_{rt} = \frac{E_{out}}{E_{in}}
\]

\[
\eta_{rt} = \frac{E_{in} - E_{loss,in} - E_{loss,out}}{E_{in}}
\]
Round-Trip Efficiency

- We can define a **charging efficiency**
  - Amount of energy stored as a percentage of the energy input
    \[ \eta_{in} = \frac{E_S}{E_{in}} = \frac{E_{in} - E_{loss, in}}{E_{in}} \]

- And a **discharging efficiency**
  - Amount of energy output as a percentage of the energy stored
    \[ \eta_{out} = \frac{E_{out}}{E_S} = \frac{E_S - E_{loss, out}}{E_S} \]
    \[ \eta_{out} = \frac{E_{in} - E_{loss, in} - E_{loss, out}}{E_{in} - E_{loss, in}} \]
Round-Trip Efficiency

- The round trip for energy in a storage system is a cascade of the *charge* and *discharge* processes
  - Round trip efficiency given by:
    \[ \eta_{rt} = \eta_{in} \cdot \eta_{out} \]

- In general, efficiency is a function of:
  - Charging/discharging power, \( P_{in} \) and \( P_{out} \)
  - State of charge
Charging Time

- Typically, what is needed is a certain power for a certain time

- **Charging time**
  - The time it takes to go from minimum SoC to maximum SoC at a given power input
  - The time it takes to store the usable energy, $E_u$

$$t_c = \frac{E_u}{P_c}$$

where $P_c$ is the rate of energy storage

- Note that, due to losses, the rate of energy storage, $P_c$, is *less* than the input power, $P_{in}$
The power we have direct control over is the input power, $P_{in}$.

The charging time in terms of input power is

$$t_c = \frac{E_u}{P_{in} - P_{loss,in}} = \frac{E_u}{P_{in} \cdot \eta_{in}}$$
Discharge Time

- **Discharge Time**
  - The time required to go from maximum SoC to minimum SoC at a given output power.
  - Due to losses, the rate of discharge, $P_d$, is greater than the output power, $P_{out}$.

\[
t_d = \frac{E_u}{P_d}
\]

- Again, the power of interest is the power we have direct control over, the output power, $P_{out}$, so

\[
t_d = \frac{E_u}{P_{out} + P_{loss, out}} = \frac{E_u}{P_{out}/\eta_{out}} = \frac{E_u}{P_{out}} \cdot \eta_{out}
\]
Ragone Plots
Ragone Plots

- Two primary figures of merit for energy storage systems:
  - Specific energy
  - Specific power

- Often a tradeoff between the two
  - Different storage technologies best suited to different applications depending on power/energy requirements

- Storage technologies can be compared graphically on a Ragone plot
  - Specific energy vs. specific power
  - Specific storage devices plotted as points on the plot, or
  - Categories of devices plotted as regions in the Ragone plane
Ragone Plots

Energy-Storage Technologies Ragone Plot

Specific Energy [Wh/kg]

10^3
10^2
10^1
10^0
10^-1
10^-2

Specific Power [W/kg]

10^1
10^2
10^3
10^4

Energy Storage A
Energy Storage B
Energy Storage C
Energy Storage D
Energy Storage E
Energy Storage F
Energy Storage G

ESD2
ESD1
ESD6
ESD5
ESD4
ESD3
Any given storage system will have a specific energy capacity and a specific power rating.

- A point in the Ragone plane, \((p_m, e_m)\)

Discharge time at rated power for that point (neglecting losses):

\[ t_d = \frac{e_m}{p_m} \]

- Constant discharge time maps to lines with unity slope on a Ragone plot.
- Storage systems that lie on the same line have equal discharge times at rated power.
Ragone Curves

- Ragone plots we’ve seen so far plot a storage device at one operating point
  - Maximum or rated power

- Can also depict a device’s energy capacity over a range of power
  - A Ragone curve

- Most curves share a similar characteristic shape
  - Available energy decreases at higher power
  - Fraction of energy lost as heat increases
Thévenin Equivalent Model

- What is the reason for the characteristic shape of Ragone curves?

- Consider that we could model a storage device with an electrical **Thévenin equivalent**
  - Need not be an electrical storage device

- Open-circuit voltage is some function of SoC
  - Possibly linear
  - May be highly nonlinear
  - Or, could be constant
Three power components associated with discharge

- $P_d$: discharge power
  - The rate at which energy leaves storage: $P_d = V_{oc} i_o$

- $P_{loss}$: power lost during discharge
  - Modeled as heat dissipation in the Thévenin resistance: $P_{loss} = i_o^2 R_s$

- $P_{out}$: output power flowing to the external system
  $$P_{out} = v_o i_o = (V_{oc} - i_o R_s) i_o$$
  $$P_{out} = V_{oc} i_o - i_o^2 R_s = P_d - P_{loss}$$
Thevenin Equivalent Model

- Discharge time:
  \[ t_d = \frac{E_u}{P_d} \]

- Amount of energy extracted from the storage system:
  \[ E_{out} = P_{out} \cdot t_d = E_u \frac{P_{out}}{P_d} \]

- Substituting in expressions for \( P_{out} \) and \( P_d \), we have
  \[ E_{out} = E_u \left[ \frac{V_{oc} i_o - i_o^2 R_s}{V_{oc} i_o} \right] \]
  \[ E_{out} = E_u \left[ 1 - i_o \frac{R_s}{V_{oc}} \right] \]
Available Energy vs. Output Power

\[ E_{\text{out}} = E_u \left[ 1 - i_o \frac{R_s}{V_{oc}} \right] \]

- We can see that the available energy decreases as \( i_o \) increases.

- **Available energy decreases as output power increases**

- Illustrated by the characteristic shape of Ragone plots
Storage System Configurations
Storage System Configurations

- Our focus is grid-connected energy storage
  - Energy stored in many different domains
  - Input and output energy is electrical
    - Three-phase AC power

- Conversion is required between the storage domain and the electrical domain
  - Transformer
  - Power conversion system (PCS)

![Diagram showing the connection between the grid, transformer, power conversion system, and storage system. The electrical domain includes 3-phase AC power, and the storage domain includes mechanical, chemical, electrical DC, and thermal energy forms.]
- **Mechanical storage**
  - Pumped hydro, flywheels, compressed air
  - PCS includes a *motor/generator*
    - Possibly driven by a turbine
  - Motor/generator may be connected directly to the grid
    - *Synchronous* with the grid
    - Runs at *fixed speed*
System Configurations – Mechanical

- Alternatively, motor/generator can be run at variable speed
  - Maximize efficiency
  - Interface to grid through power electronic converter
- Two options for variable-speed operation:
  - Singly-fed motor/generator
  - Doubly-fed motor/generator
System Configurations – Mechanical

- **Singly-fed motor/generator**
  - Synchronous machine
  - Stator driven with variable-frequency AC from power electronic converter
  - Field windings on rotor supplied with DC excitation voltage
    - Same as for fixed-speed synchronous machine
  - Converter must be rated for full motor/generator power
    - Large, expensive
System Configurations – Mechanical

- **Doubly-fed motor/generator**
  - Doubly-fed asynchronous machine (DFAM)
  - Stator connected to grid-frequency AC
  - Field windings on rotor supplied with variable-frequency excitation voltage

- Converters need not be sized for rated motor/generator power
  - Only supply lower-power excitation to the rotor
Variable-speed motors/generators require a static frequency converter (SFC)
- Both for singly- and doubly-fed configurations
- Power electronic switching converter
- Convert between grid-frequency to other frequencies

Common SFC topologies
- Cycloconverter (CCV)
  - AC-AC converter
- Voltage-source converter (VSC)
  - AC-DC-AC converter
Cycloconverter

- Cycloconverter
  - AC-to-AC frequency converter

- Direct conversion between grid and variable frequency AC
  - No intermediate DC link

- Switching thyristor bridge circuits
  - Controllable connections between all input and output phases
Voltage Source Converter

- Voltage source converter (VSC)
  - Back-to-back AC/DC converters
  - DC link between converters
  - Variable frequency AC on motor/generator side

- VSC topologies include:
  - Two-level PWM
  - Multi-level PWM
  - Multi-level modular converter (MMC)
**System Configurations – Electrical/Electrochemical**

- **Electrical and electrochemical storage**
  - Ultracapacitors, batteries
  - Output from storage device is already in the *electrical* domain, but it is **DC**
  - Need AC/DC conversion to interface with the grid

- **AC/DC conversion**
  - Charging: AC-to-DC – *rectification*
  - Discharging: DC-to-AC – *inversion*

- **Voltage source converter is a common choice here**
  - Independent control of real and reactive power control
  - Allows storage to provide black start capability