SECTION 1: GRID-CONNECTED ENERGY STORAGE

ESE 471 – Energy Storage Systems

Introduction

Energy Storage

- Our desire to ***store energy*** is largely a desire to store ***electrical energy***
  - Energy that was or will be consumed/transferred as electrical energy
  - But, most energy is stored in forms ***other than electrical***
- ***Energy storage domains***:
  - Potential
  - Kinetic
  - Electrical
  - Electrochemical
  - Thermal
  - Magnetic

Energy Storage Challenges

- Storage of energy is not as simple as storage of other commodities
- Technical challenges/considerations
  - Cost
  - Size
  - Capacity (energy)
  - Power
  - Efficiency
  - Safety
  - Lifetime

Categories of Energy Storage

- ***Mobile*** energy storage
  - EVs/HEVs
  - Phones/computers
  - Power tools
  - Portable lighting
- ***Fixed*** energy storage
  - ***Grid-connected***
    - Utility-scale
    - Small-scale, e.g. Powerwall
  - ***Off-grid***
    - Remote locations
    - UPS, e.g. data centers
- Our focus in this course will be ***fixed, grid-connected energy storage***

Types of Energy Storage

- ***Potential energy storage***
  - Pumped hydro (PHES)
  - Compressed air (CAES)
  - Rail energy storage
- ***Kinetic energy storage***
  - Flywheels
- ***Electrical energy storage***
  - Ultracapacitors
- ***Magnetic energy storage***
  - Superconducting magnetic energy storage (SMES)
- ***Electrochemical energy storage***
  - Batteries
  - Flow batteries
  - Hydrogen
- ***Thermal energy storage (TES)***
  - Molten salts
  - Phase-change materials (PCMs)
  - Water heaters

Course Overview

- Section 1: Grid-Connected Energy Storage
- Section 2: Energy Storage Fundamentals
- Section 3: Pumped Hydro
- Section 4: Ultracapacitors
- Section 5: Flow Batteries
- Section 6: Battery Storage for Off-Grid Applications

Dr. Webb

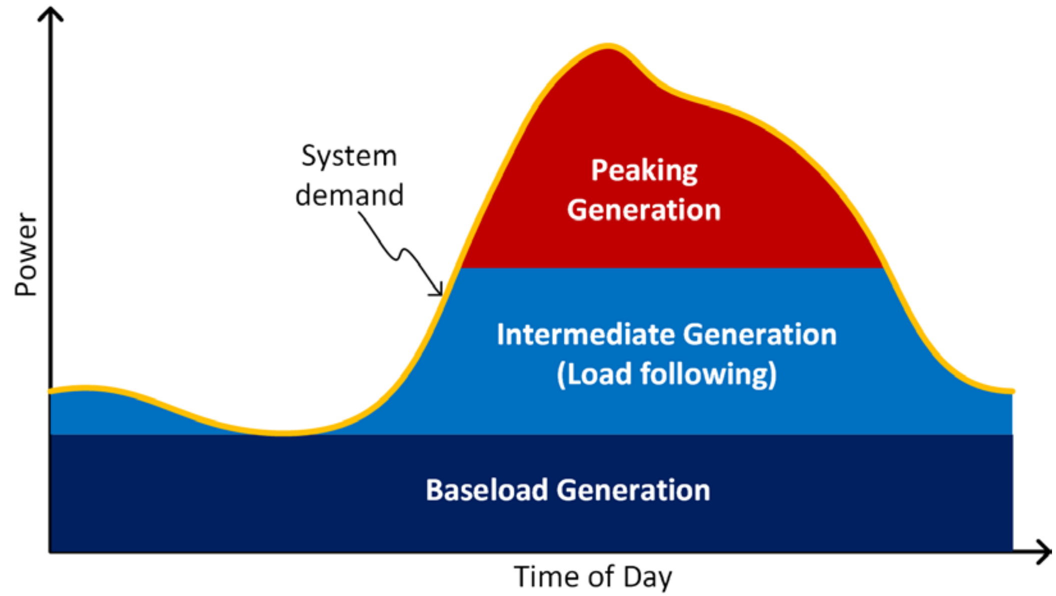
- Section 7: Batteries
- Section 8: Thermal Energy Storage
- Section 9: Compressed Air Energy Storage
- Section 10: Fuel Cells
- Section 11: Flywheel Energy Storage

Dr. Kastantin

Grid-Connected Energy Storage

Load Curves and Generation

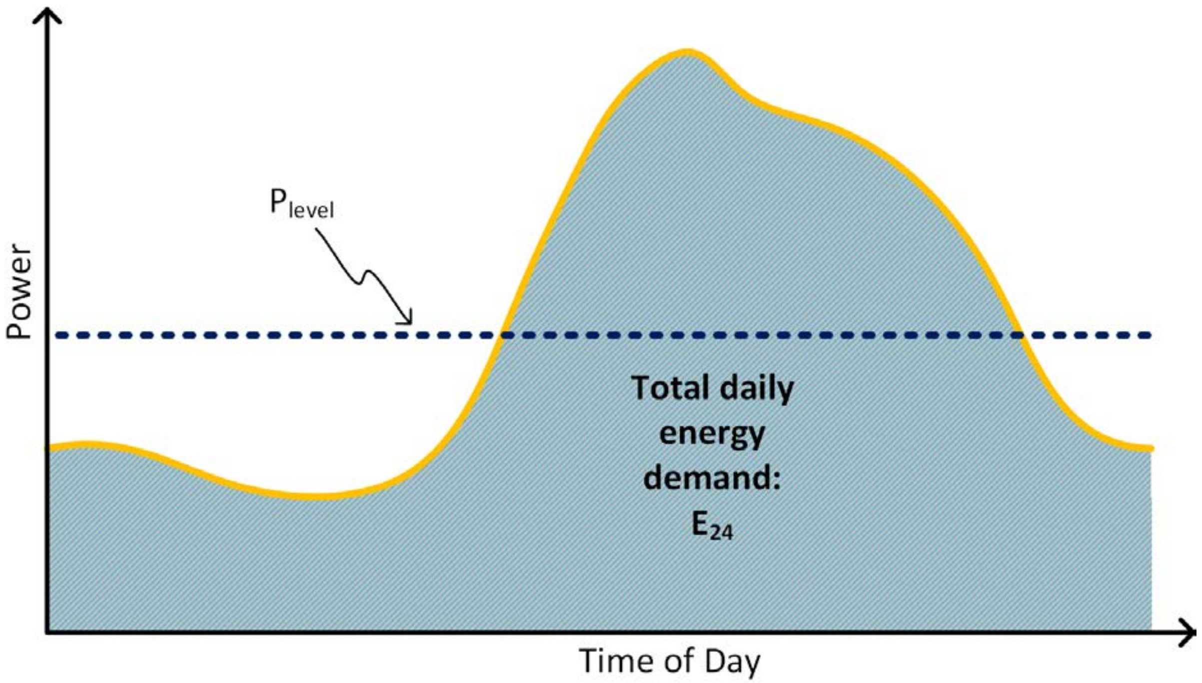
- Electrical power demand varies daily, weekly, seasonally
- At any instant in time, generation must exactly match demand
- Categories of generation
  - ***Baseload***:
    - Large coal and nuclear plants (or hydro)
    - Power output not easily/efficiently varied
  - ***Intermediate***:
    - Combined-cycle gas-fired plants (or hydro)
    - Follow load as it increases beyond baseload
  - ***Peaking***:
    - Simple-cycle gas turbines (or hydro)
    - Supply power during times of peak demand



Load Leveling with Storage

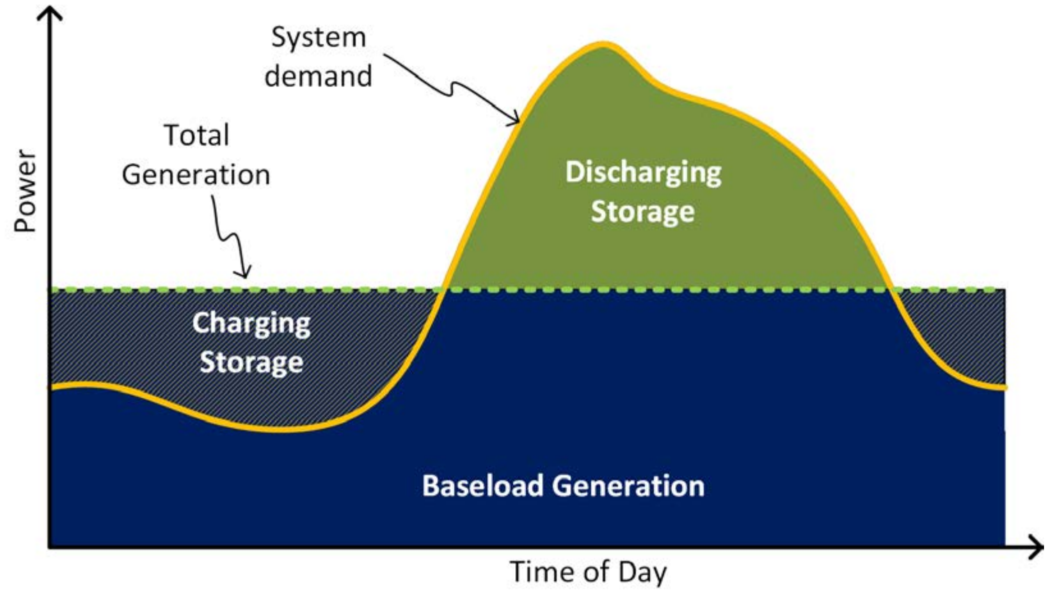
- Integral of the load is the total daily energy demand, E_{24}
  - This amount of energy could be generated at a constant rate:

$$P_{level} = \frac{E_{24}}{24\ hr}$$



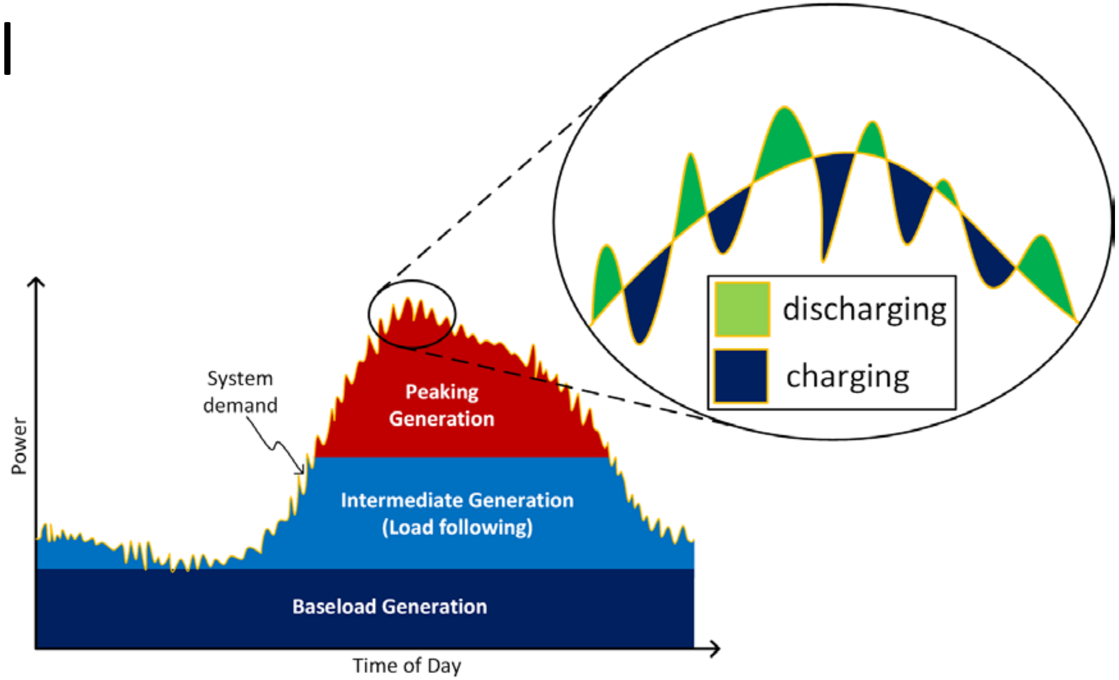
Load Leveling with Storage

- Since demand is not constant, constant generation would require storage
  - Generation exceeds demand:
    - Charge storage
  - Demand exceeds generation:
    - Discharge storage
- In theory, generation could be constant



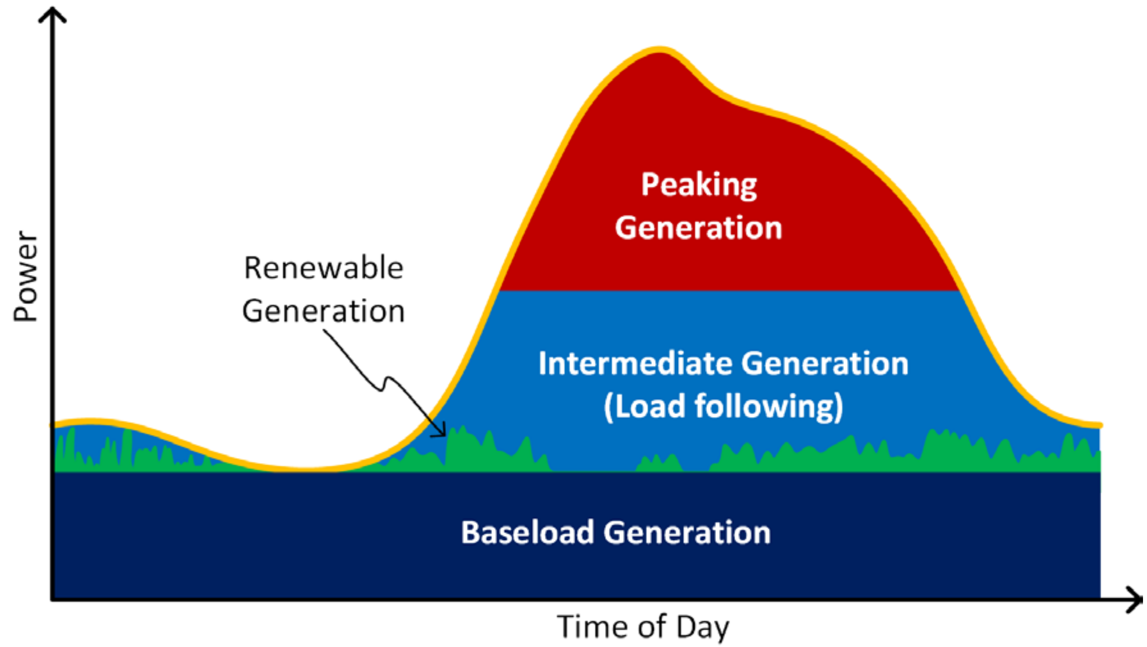
Short-Term Variation

- Load following and peaking generation
  - Meet demand variation over the course of hours
- Demand also varies minute-to-minute
  - Utilities must track this rapid variation as well
- Another potential storage application
  - High power
  - Low energy
  - Rapid variation



Integration of Renewables

- Proliferation of renewable generation poses challenges for the grid
  - Variable generation – sun/wind
    - Largely unpredictable
    - Peak generation and peak demand are uncorrelated
  - Difficult to absorb variability
  - Renewable generation often curtailed
- Storage can smooth the flow of power from renewable sources



Grid-Connected Energy Storage

- In this course, we will cover many different energy-storage technologies
  - Mechanical
  - Thermal
  - Electrochemical
  - Electrical
- First, we'll take a closer look at how and why energy storage can be ***integrated into the electrical grid***
  - ***Benefits and uses*** of grid-connected storage
  - ***Location*** of storage within the electrical grid

Uses of Grid-Connected Storage

- Services provided by grid-connected energy storage can be grouped into five categories:
  - Bulk energy services
  - Ancillary services
  - Transmission and distribution services
  - Integration of renewable generation
  - Customer energy management services

Location of Storage within the Grid

- Grid-connected storage can be placed at different locations throughout the grid:
  - Large baseload power plants
  - Renewable generation sites – wind/solar farms
  - Transmission substations
  - Distribution substations
  - Customer sites
- The best location depends on the application
  - What portion of the grid will benefit from the storage?
  - When power flows to the grid from storage, power flow from somewhere else is reduced
- Next, we'll go through each of the potential services, noting typical locations for storage in each case

Bulk Energy Services

- **<u>Bulk energy services</u>**
  - Supplying large amounts of power to the grid for potentially long durations
- Three categories of bulk energy services:
  - ***Arbitrage***
  - ***Load leveling***
  - ***Generation capacity upgrade deferral***

- ***Arbitrage*** involves electrical energy time shifting
  - Utilities purchase electrical power at times of low demand/low cost, store it, and sell it at a profit at times of high cost/high demand

Bulk Energy Services – Load Leveling

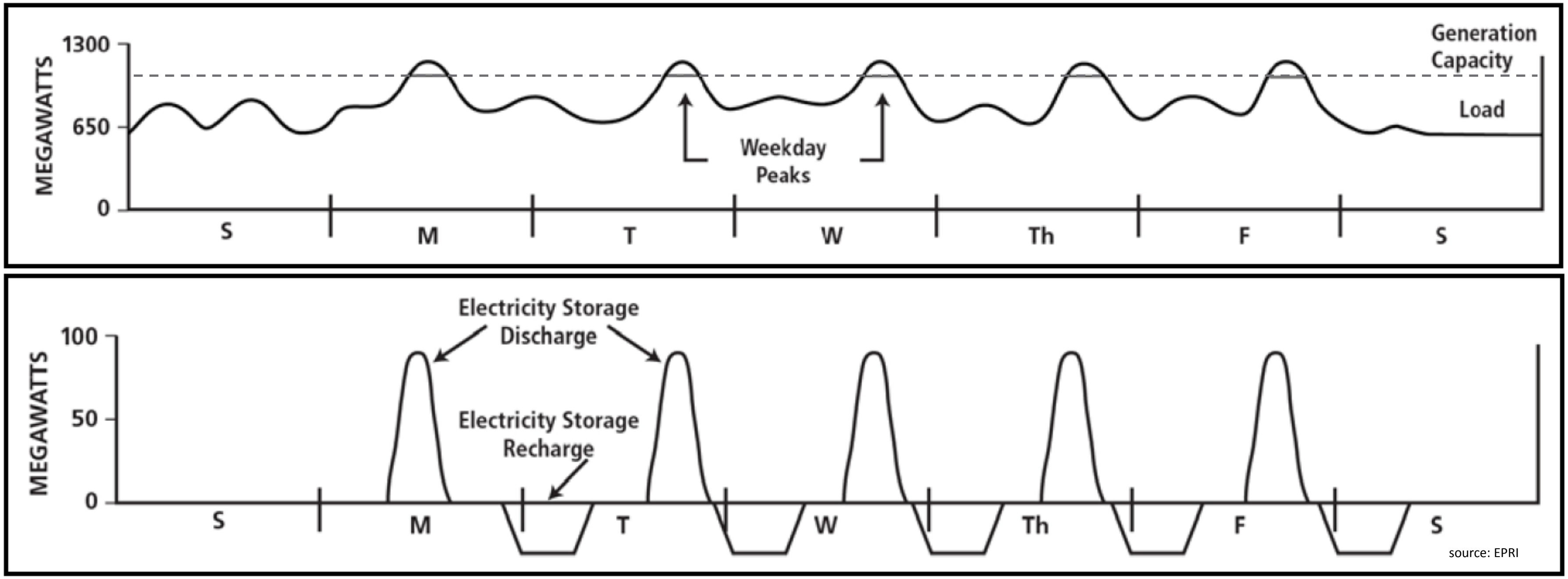
- ***Load leveling*** involves the use of storage at a generation facility to smooth a daily demand curve
- Storage can fill the role of gas turbine peak generators
- Allows baseload plants to operate at relatively constant power
  - Power dumped into storage during off-peak hours
  - Stored energy discharged to the grid to satisfy peak loads

Bulk Energy Services – Capacity Upgrade Deferral

- Power plants must be sized to meet peak demand
  - As demand grows to exceed generation capacity, more capacity must be added
- ***Generation capacity upgrade deferral***
  - The use of storage for ***peak shaving*** to ***delay the need to add additional generation capacity***
- Functionally similar to load leveling, but with a different goal
  - Investment deferral instead of efficiency/economy
- ***Shifts the generation capacity requirement from power to energy***

Bulk Energy Services

- Storage used for load leveling or upgrade deferral:



Bulk Energy Services – Storage Requirements

- **Bulk energy services storage requirements**
  - Power: 100 – 1000 MW
  - Discharge time: 1 – 12 hours
  - Cycles: ~1/day
  - Typical location: power plant
  - Suitable technologies: PHES, CAES

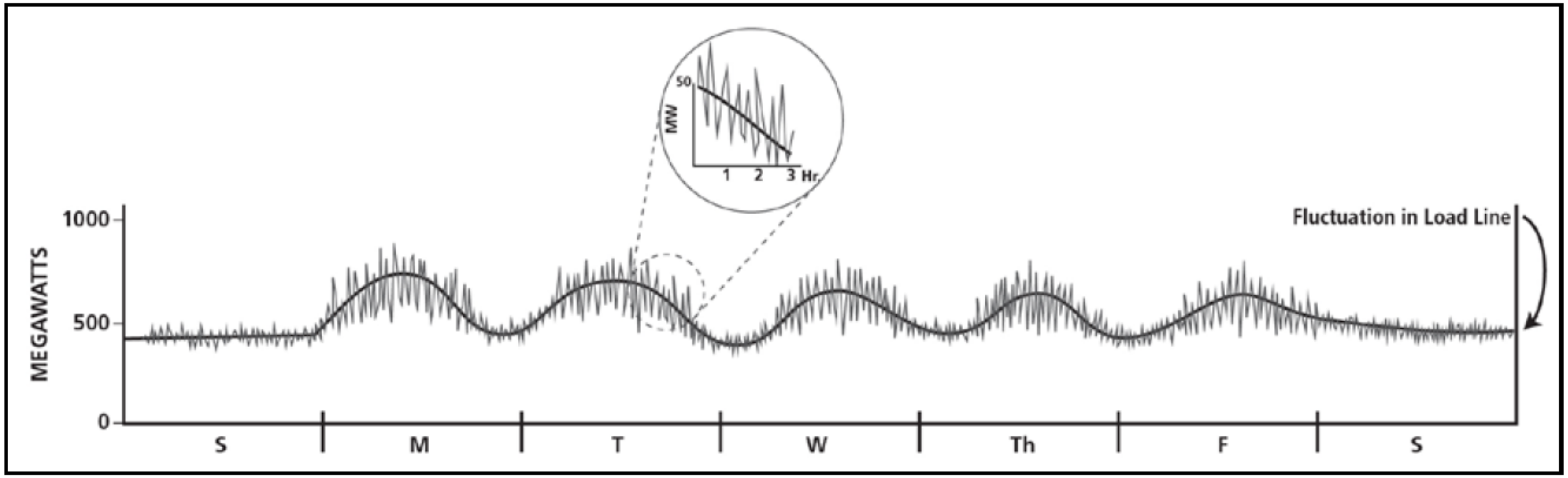
Ancillary Services

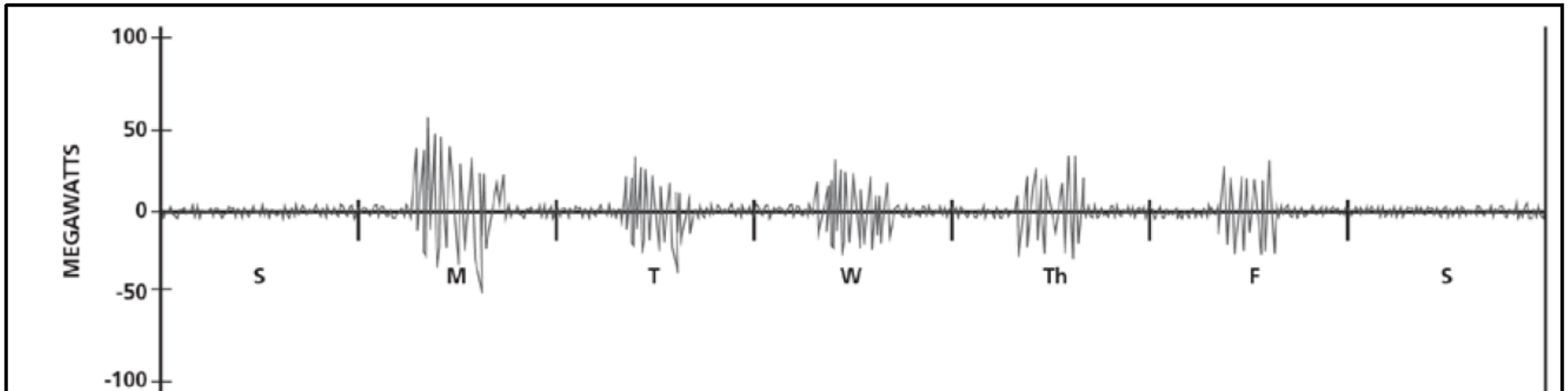
- **<u>Ancillary services</u>**
  - All of the secondary functions of the electrical utilities (other than providing bulk power) necessary to ensure power quality and reliability
  - Mandated by FERC
- Ancillary services include:
  - ***Frequency regulation***
  - ***Load following***
  - ***Voltage support***
  - ***Black start capability***
  - ***Spinning***, ***non-spinning***, and ***supplemental reserve***
- All involve injecting additional power (real or reactive) onto the grid as needed
  - Differ in terms of ***time scale*** and objective

Ancillary Services – Frequency Regulation

- As demand on the grid varies from moment to moment, generation must vary to match it
  - This precise balance is necessary for maintaining the frequency on the grid at 60 Hz (or 50 Hz)
- Baseload plants operating in ***frequency regulation*** mode must rapidly vary output to meet demand
  - Requires operation below capacity
  - Inefficient
  - Wear and tear on generation equipment
- ***Regulation*** involves satisfying demand fluctuations around (above and below) some base load
  - A ***zero-energy service***
  - An ideal application for storage

Ancillary Services – Frequency Regulation





source: EPRI

Ancillary Services – Frequency Regulation

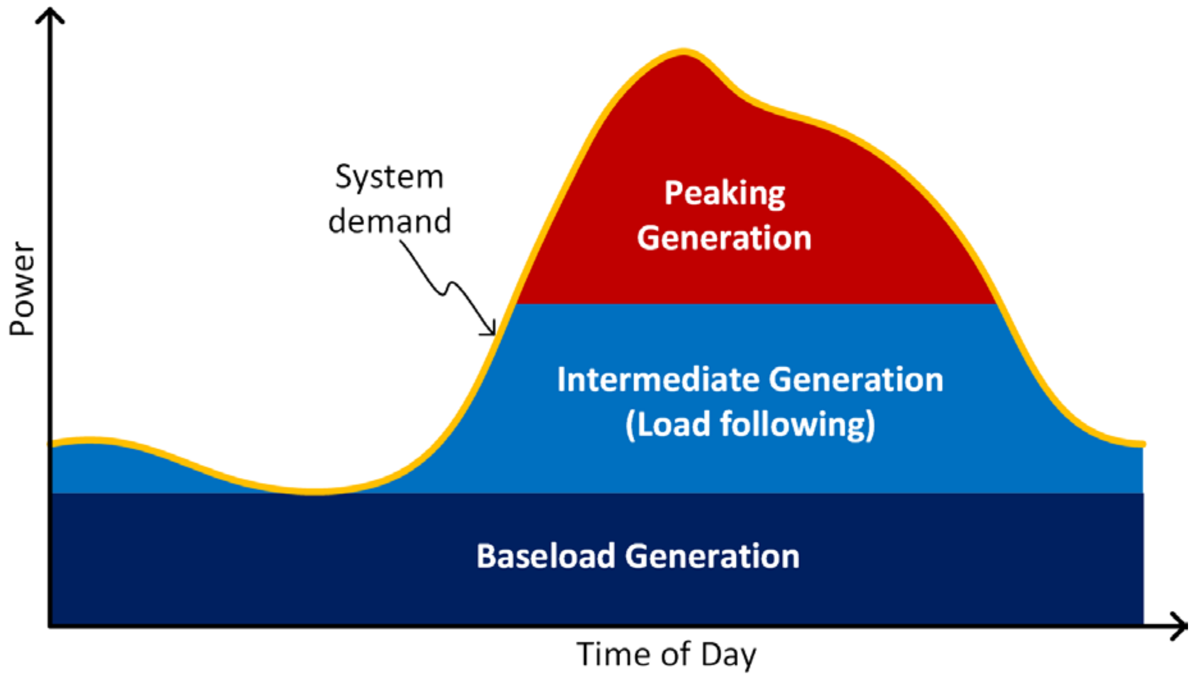
- **Frequency regulation storage requirements**
  - Power: 1 – 200 MW
  - Discharge time: 1 – 60 minutes
  - Cycles: 20-40/day
  - Typical location: power plant, T&D substations

Stephentown, NY flywheel storage plant:
$\pm$20 MW for frequency regulation

  - Suitable technologies: flywheels, batteries, flow batteries, ultracapacitors

Ancillary Services – Load Following

- Similar to regulation, ***load following*** involves providing variable supply to meet varying demand
  - Longer time scale
  - Following the daily variation of the load

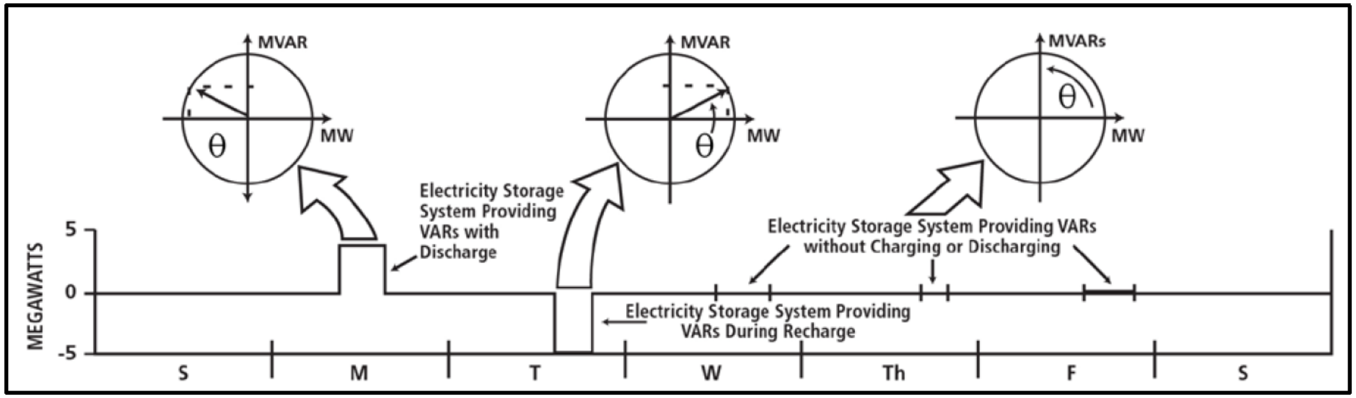


Ancillary Services – Load Following

- **Load following storage requirements**
  - Power: 1 – 2000 MW
  - Discharge time: 15 min – 1 day
  - Cycles: 1-29/day
  - Typical location: power plant
  - Suitable technologies: PHES, CAES

Ancillary Services – Voltage Support

- Grid operators are required to maintain voltage levels on the grid within a specified range
  - Varying reactive loads can cause deviations from nominal voltage levels
- ***Voltage regulation*** involves injecting (or absorbing) reactive power onto (or from) the grid
  - Storage, along with power electronics, makes this possible



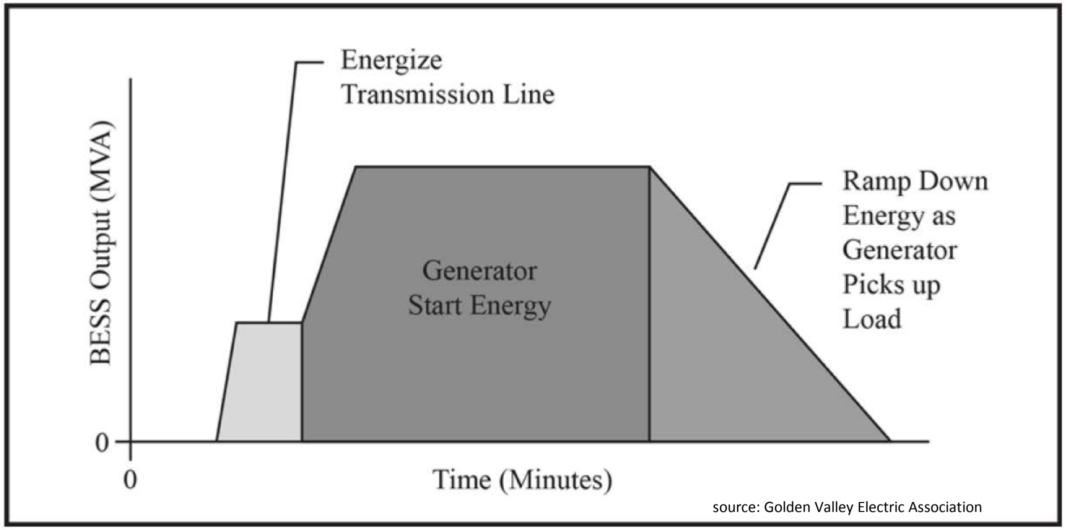
source: EPRI

Ancillary Services – Voltage Support

- **Voltage regulation storage requirements**
  - Power: 1 – 40 MW
  - Discharge time: 1 – 60 sec
  - Cycles: 10-100/day
  - Typical location: power plant, T&D substations
  - Suitable technologies: batteries, flow batteries, flywheels, ultracapacitors

Ancillary Services – Black Start

- In the event of a wide-area catastrophic failure of the grid, power is required to
  - Reenergize the affected portions of the grid
  - Bring power generation plants back online
- Storage can provide the required power
- Need not be the only job of this storage
  - May also regularly provide many of the other services described here



Ancillary Services – Black Start

- **Black start storage requirements**
  - Power: 100 kW – 400 MW
  - Discharge time: 1 – 4 hours
  - Cycles: < 1/year
  - Typical location: at or well-connected to power plant
  - Suitable technologies: PHES, CAES, batteries, flow batteries

Ancillary Services – Reserve Capacity

- FERC requires that utilities have ***backup generation capacity*** that can be brought online in varying amounts of time in the event of a loss of generation
- **Spinning reserve**
  - Online, but unloaded, generation capacity
  - Response time: < 15 min
  - May also serve double duty providing frequency regulation
    - Frequency responsive spinning reserve
- **Non-spinning reserve**
  - Same function as spinning reserve, but need not be online and synchronized to the grid
  - Response time: < 30 min

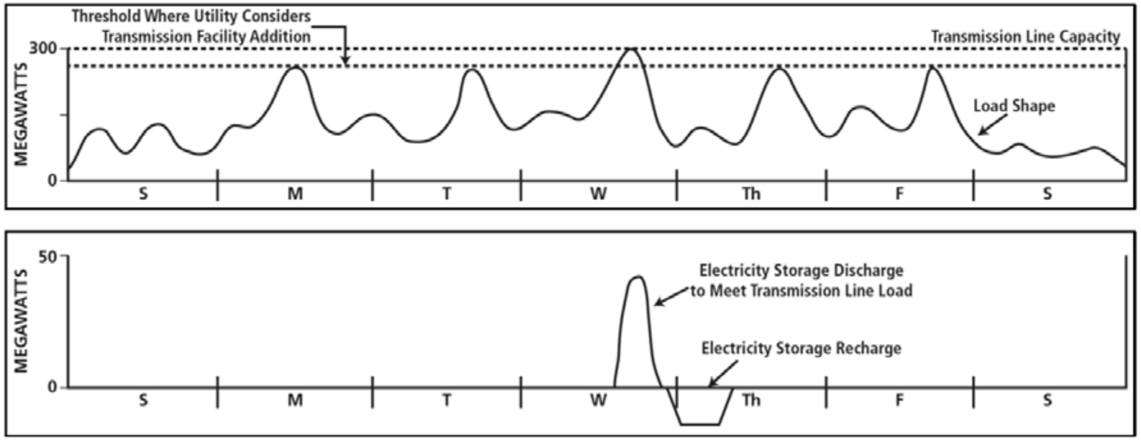
Ancillary Services – Reserve Capacity

- **Supplemental reserve**
  - Backup for spinning and non-spinning reserve
  - Response time: < 1 hour

- **Spinning, non-spinning, and supplemental reserve storage requirements**
  - Power: 10 – 2000 MW
  - Discharge time: 15 min – 2 hours
  - Cycles: < 1/day
  - Typical location: power plant, T&D substations
  - Suitable technologies: PHES, CAES, batteries, flow batteries

T&D Infrastructure Services

- Transmission and distribution (T&D) networks must be sized to handle peak loads
- When demand exceeds T&D network capacity, network infrastructure must be upgraded
  - Potentially a huge investment
- Instead, install storage ***downstream*** from the bottleneck
  - Charge storage during off-peak times
  - Discharge at peak load to reduce upstream peak load



source: EPRI

- Infrastructure investment can be delayed or perhaps avoided entirely

T&D Infrastructure Services

- **T&D services storage requirements**
  - Power: 1 – 500 MW
  - Discharge time: 2 – 5 hours
  - Cycles: ~1/day
  - Typical location: T&D substations
  - Suitable technologies: batteries, flow batteries

Integration of Renewables

- Renewable energy sources, such as wind and solar are inherently variable
  - Somewhat predictable (daily variation)
  - Largely unpredictable (minute-to-minute variation)
- Increased renewable generation could threaten grid stability
- Storage can smooth out fluctuating generation

Integration of Renewables

- **Integration of renewables storage requirements**
  - Power: 1 – 400 MW
  - Discharge time: 1 min – 1 day
  - Cycles: 0.5 - several/day
  - Typical location: renewable generation sites, T&D substations
  - Suitable technologies: batteries, flow batteries, PHES, CAES

Customer Energy Management Services

- Smaller-scale energy storage systems may also be implemented at individual customer sites
  - Power quality/ reliability
  - Retail energy time shifting

source: Cisco

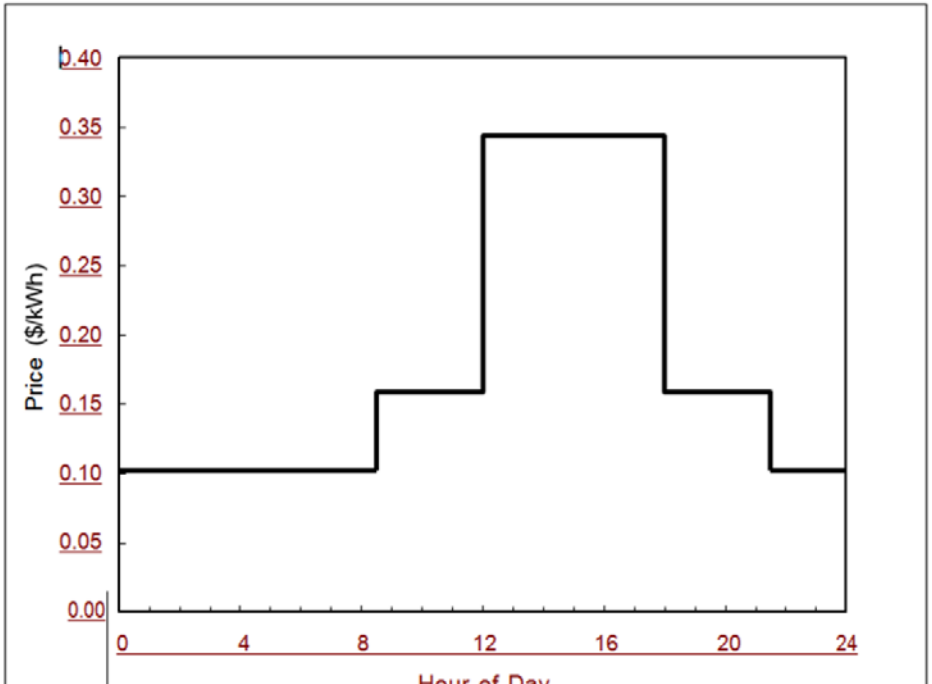
Customer Energy Management Services

- ***Power quality/reliability***
  - Customers that cannot afford power outages or drops may utilize on-site storage
  - Uninterruptible power supply (UPS)
  - Hospitals, data centers, wafer fabs, etc.
  - Short-term power bridging the gap to diesel generator startup

- **Storage requirements**
  - Power: 1 kW – 10s MW
  - Discharge time: seconds – minutes
  - Cycles: < 1/day
  - Typical location: customer site
  - Suitable technologies: batteries, flywheels, ultracapacitors

Customer Energy Management Services

- ***Retail energy time shifting***
  - Commercial/industrial customers pay time-of-use (TOU) tariffs
  - Retail cost per kWh is higher during times of peak demand
  - Storage can be employed to shift load from peak pricing to off-peak pricing



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Customer Energy Management Services

- **Storage requirements**
  - Power: 1 kW – 10s MW
  - Discharge time: 1 – 6 hours (depends on TOU schedule)
  - Cycles: ~1/day
  - Typical location: customer site
  - Suitable technologies: batteries, flow batteries

Uses of Grid-Connected Storage