18-Renewable Energy Integration

ECEGR 452

Renewable Energy Systems

Overview

- Introduction
- Generation
- Thermodynamic Cycles
- Generator Characteristics
- Load
- Generator Commitment

Introduction

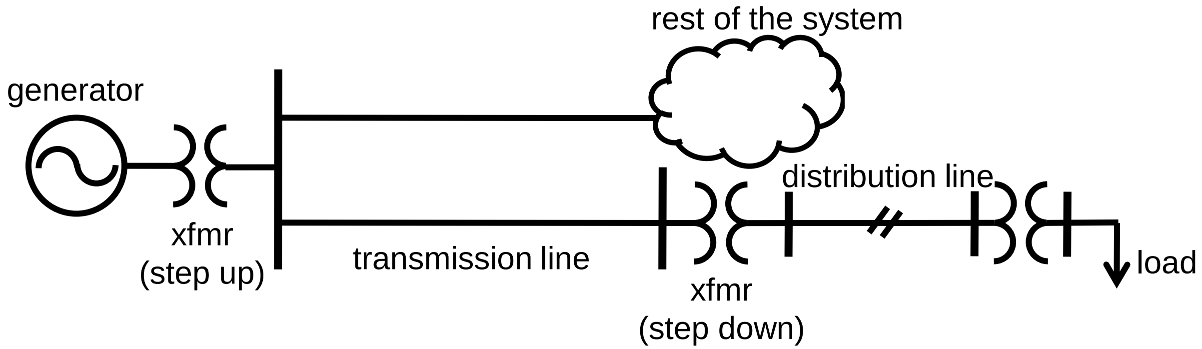
- The power system is NOT “plug-and-play”
- Renewable resources are not always good citizens
  - intermittent availability
  - variable power output
  - difficult to predict (in many cases)
  - reactive power consumers (if induction generators are used)

Introduction

- A level of accommodation is necessary to integrate renewable resources
- What determines how ease/difficult it is to integrate?
  - characteristic of renewable resource
  - characteristics of the power system
- This lecture is devoted to understanding the basics of power systems

Introduction

- Recall that power systems are comprised of three classifications of components
  - generation
  - transmission
  - load



Generation

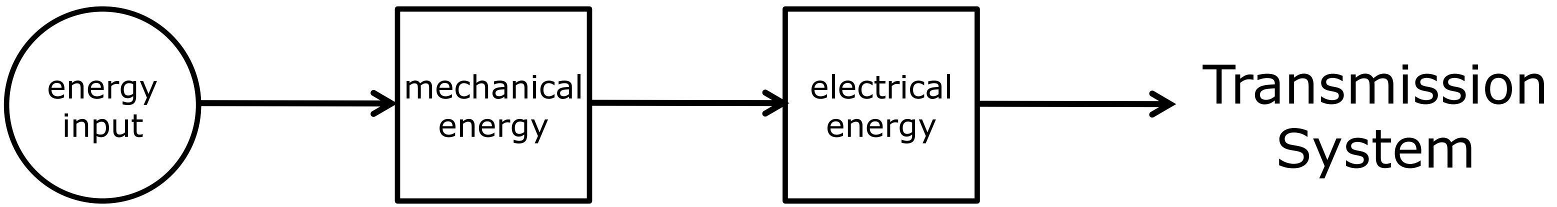
- Total number of generators in U.S.: 16,924
  - Natural Gas: 5,470
  - Hydro: 3,988
  - Petroleum: 3,744
  - Coal: 1,493
  - Renewables: 1,823
  - Nuclear: 104
- Total nameplate capacity: 1,075,000 MW

Generation

- Technical specifications rely largely on:
  - fuel source
  - thermodynamic cycle
  - generator (electrical)

Thermodynamic Cycles

- Common thermodynamic cycles:
  - Rankine
  - Brayton
- A working knowledge of each will suffice



Thermodynamic Cycles

- Efficiency of the energy conversion process is never 100%

$$\eta = 100 \times \frac{P_o}{P_{in}}$$

- Where
  - P_o: output power (W)
  - P_{in}: input power (W)

Thermodynamic Cycles

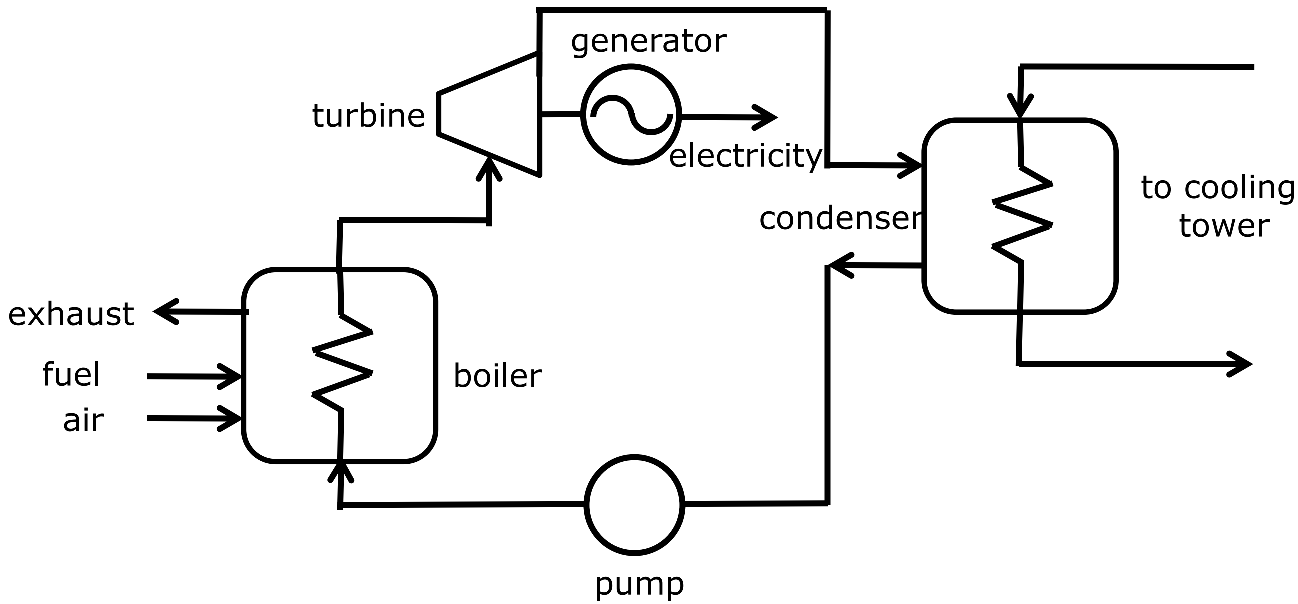
- Carnot Efficiency: upper limit of the efficiency of a thermodynamic process

$$\eta_c = 1 - \frac{T_C}{T_H}$$

- Where
  - T_c: temperature of cold reservoir (K)
  - T_h: temperature of hot reservoir (K)

Rankine Cycle

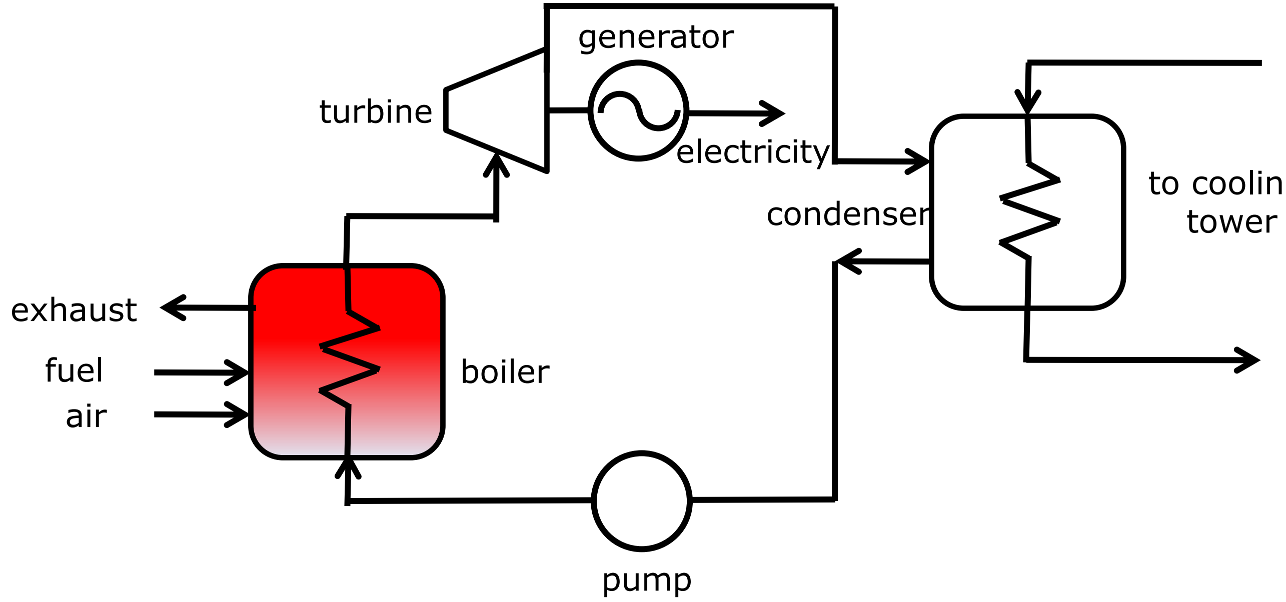
- Used in coal/nuclear power plants
- Steam is the working fluid
- Temperatures around 540° C



Rankine Cycle

Fuel is combusted in the boiler

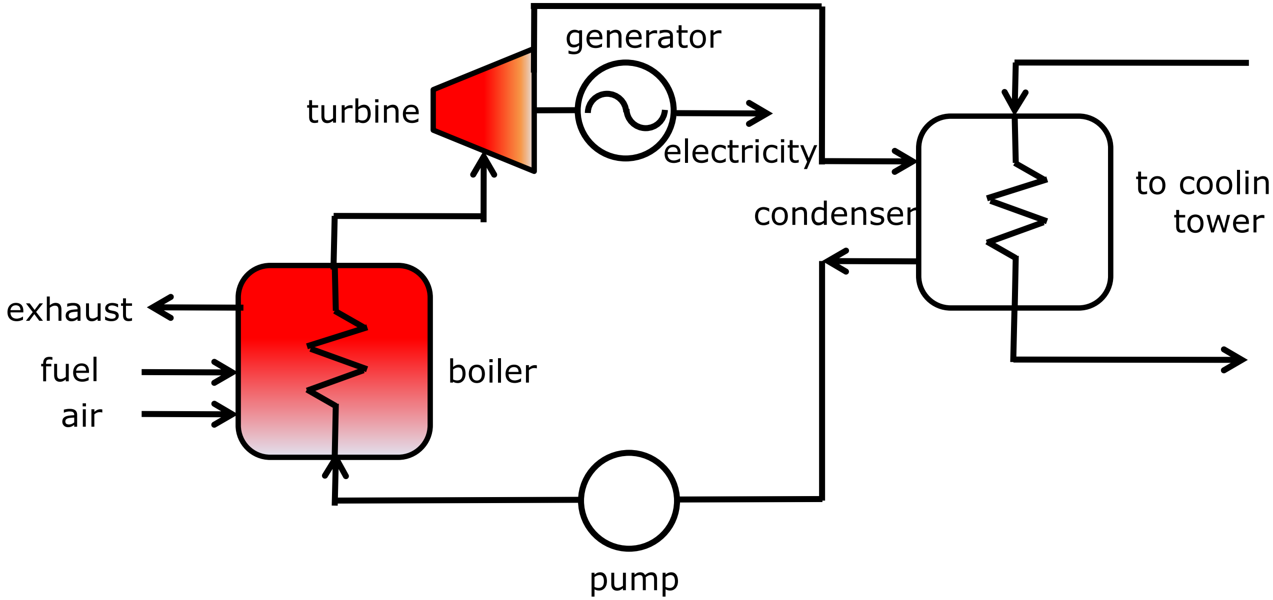
- Energy is transferred to the water, which vaporizes into steam



Rankine Cycle

Steam expands through the turbine

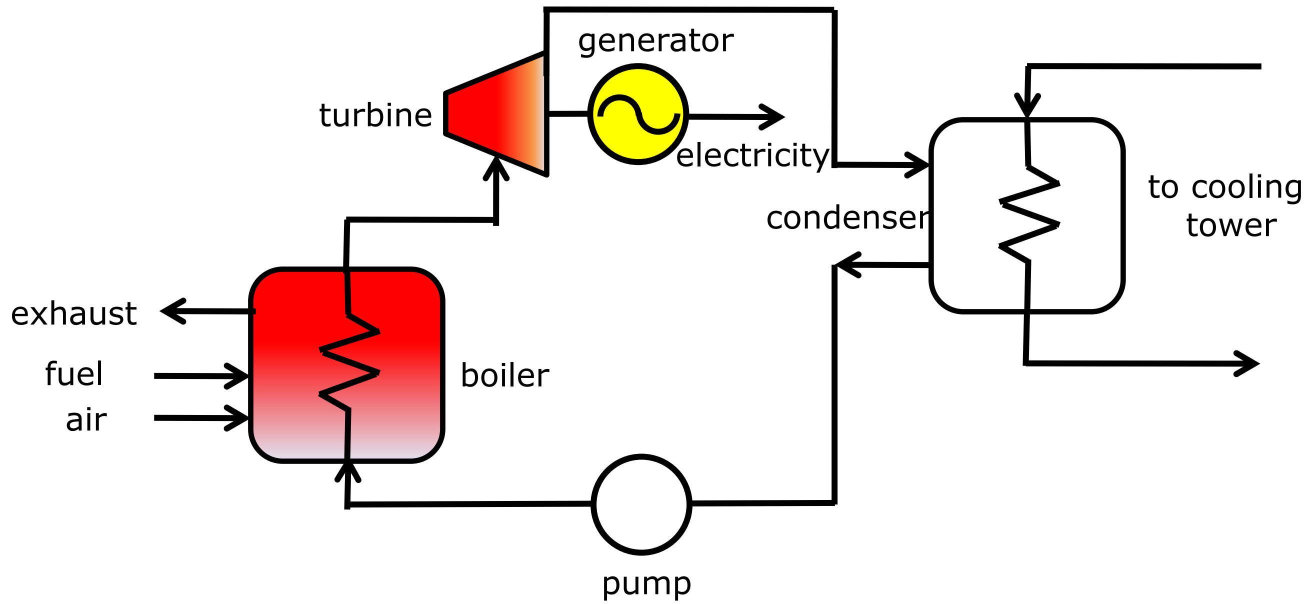
- Pressure is reduced
- Turbine shaft spins



Rankine Cycle

Synchronous generator produces electricity

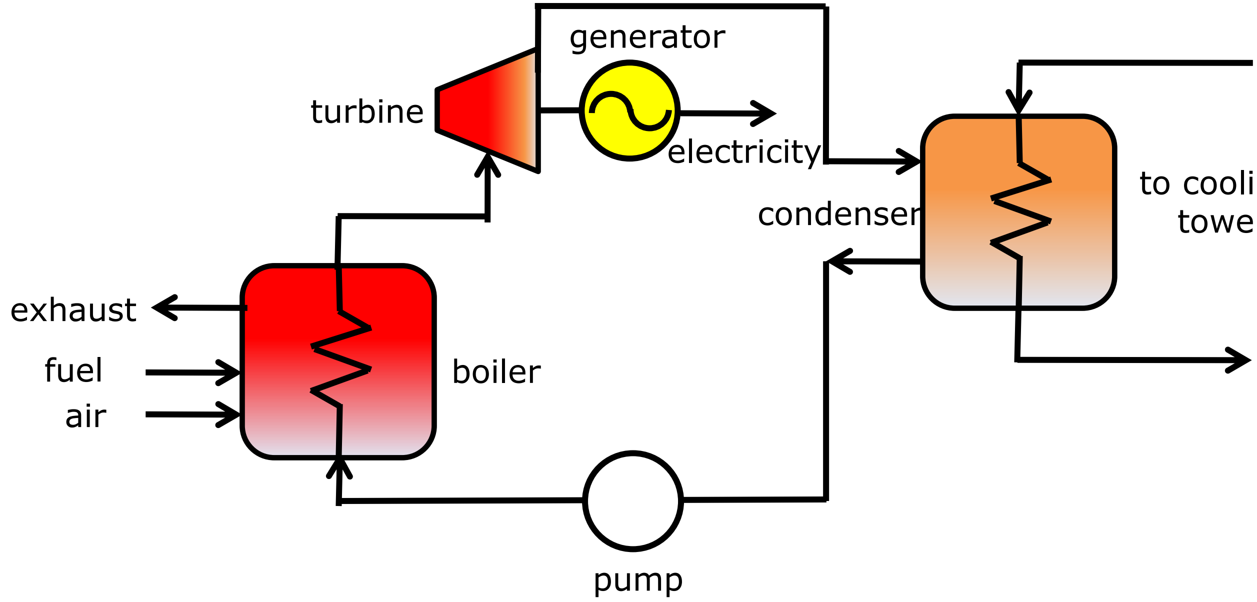
- Provides a counter torque to the shaft



Rankine Cycle

Steam is cooled in the condenser

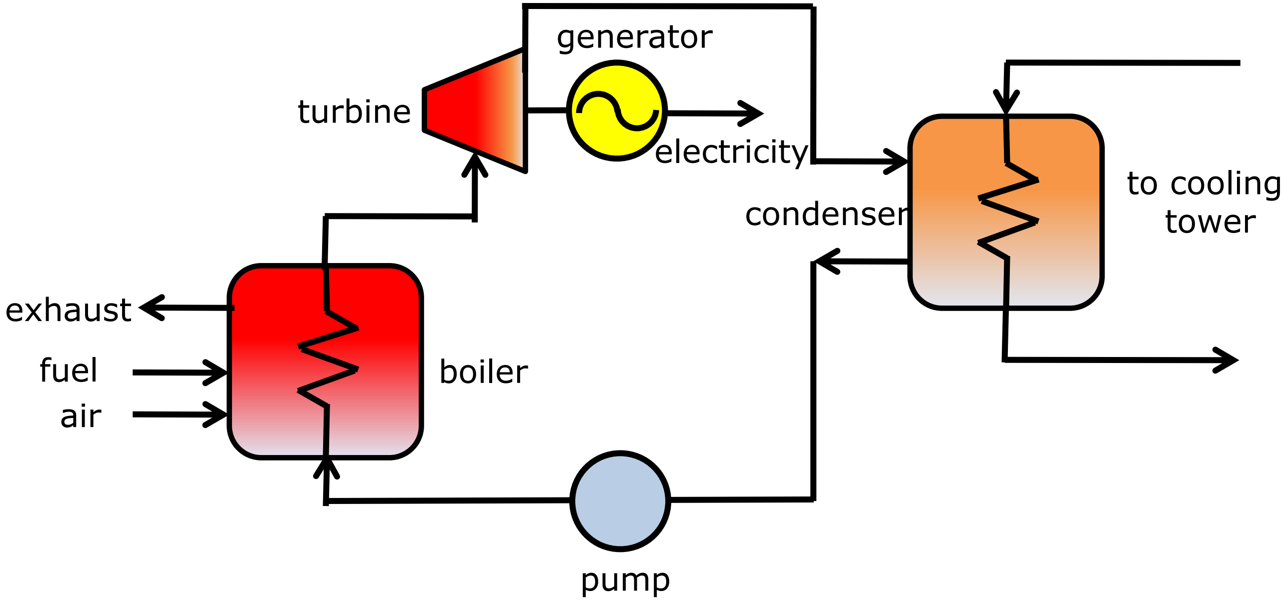
- Steam condenses into water
- Cooling of the working fluid helps suck the steam through the steam turbine



Rankine Cycle

Condensed water is pumped back into the boiler

- Work is required to operate the pump



Rankine Cycle

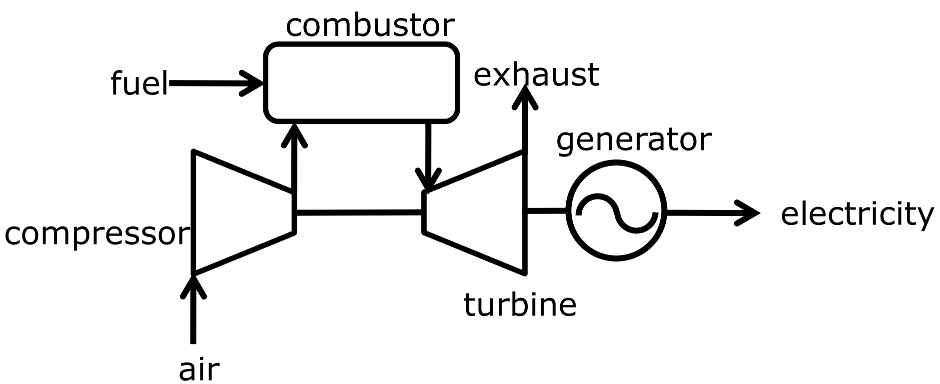
- Heat is input into the boiler
- Work is input into the pump (small amount)
- Work is output by the turbine
- Heat is output by the condenser

Rankine Cycle

- Steam temperature is around 540 ^{o}C
  - Thermal stress limitations
- Condensed water is around 30 ^{o}C
- What is the upper (Carnot) efficiency of this operation?

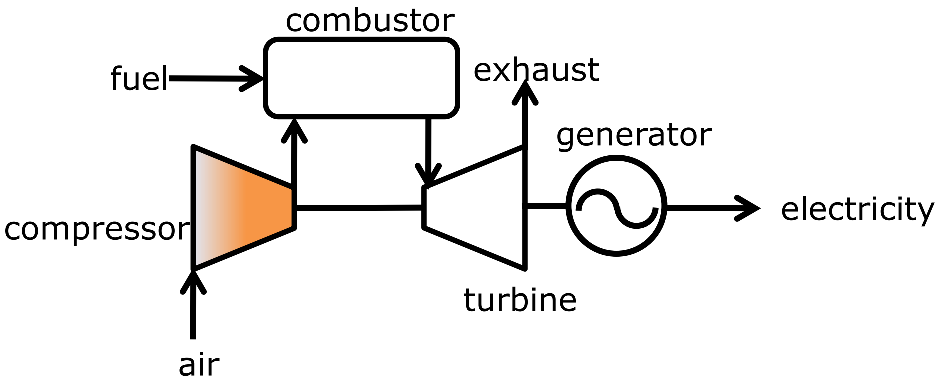
Brayton Cycle

- Used in natural gas power plants (Combustion Turbine (CT))
- Same cycle as jet engines
- Temperatures around 1400° C



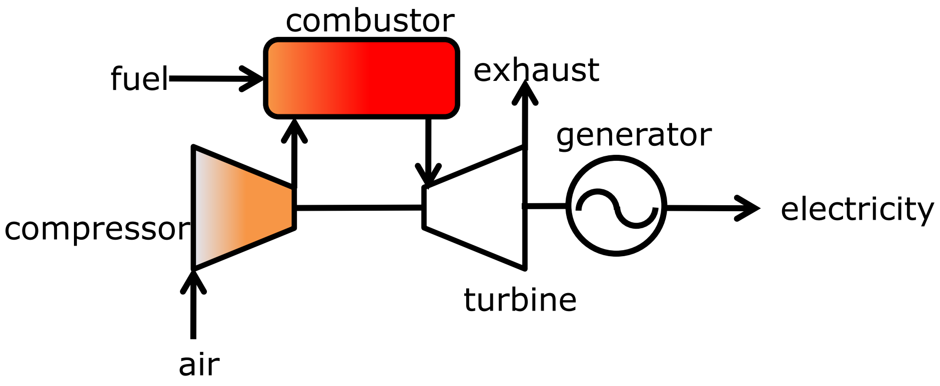
Brayton Cycle

- Air is compressed
  - Compression ratios up to 30:1
  - Compressor is mechanically driven by the turbine shaft



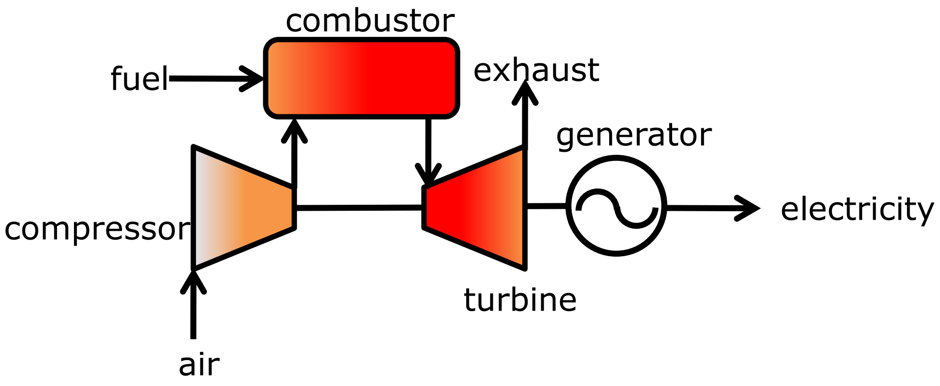
Brayton Cycle

- Compressed air is mixed with fuel (natural gas) and combusted
  - Very high temperature, up to 1400 ^oC



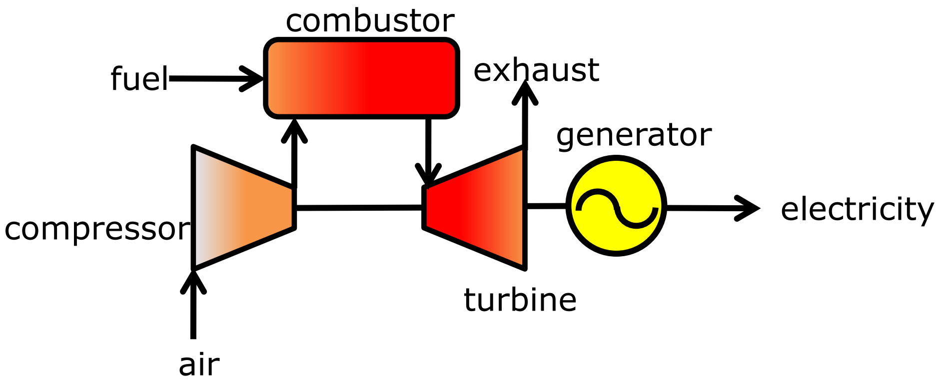
Brayton Cycle

- Gases expand in the turbine
  - Coupled with generator and compressor



Brayton Cycle

- Synchronous generator produces electricity
  - Provides a counter torque to the shaft



Brayton Cycle

- High operating temperatures increase efficiency, but work required to compress decreases the efficiency
- Typically in the range of 25-35%

Generators

- There are many variations on the cycles described to increase efficiency
  - Combined cycle use the exhaust heat from a CT to generate steam
    - Efficiencies up to 60%
- If steam is used directly for another process, then efficiencies up to 85% can be realized

Generator Characteristics

- Approximately 90% of electrical energy generated use Rankine or Brayton cycles
- Large variation within these generator types

Generator Characteristics

- Capacity: maximum amount of real power that can be produced by an energy source, also known as nameplate capacity

- Capacity Factor: expressed as the percentage (energy produced)/(capacity x time under consideration), includes expected and unexpected outages

Generator Characteristics

- Real Power Limitations (max and min): minimum is usually dictated by stable combustion limitations, maximum is determined from equipment ratings

- Reactive Power Limitations (max and min): usually dictated by the generator exciter (limited by the field winding rating)

Generator Characteristics

- Regulation: the ability of a generator to vary its real power output up and down on time scales less than five minutes in accordance with a control signal.

- Start-up time: the amount of time it takes for a generator to safely be brought from an off state to its minimum generation amount.

- Shut-down time: time it takes for a generator to transfer from its minimum output to grid disconnection.

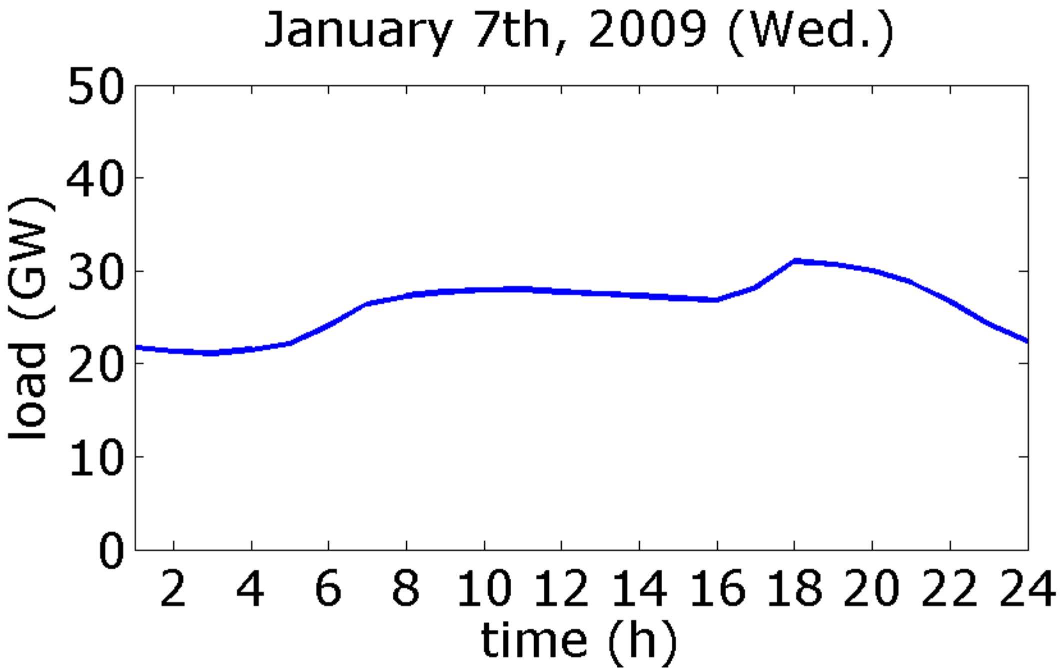
Comparison

Characteristic	Coal	Nuclear	Natural Gas
Thermodynamic Cycle	Rankine	Rankine	Brayton
Efficiency	35-45%	35-45?%	25-35%
P_{max} (includes plants with multiple generators)	0.5-3.2 GW	1-3.8 GW	<1GW
P_{min}	15-25% of P_{max}	???	Near 0
Capacity Factor	high	high	low
Start-up/Shut-down time	hours	hours to days+	Minutes
Ramp Rate	Slow (1%/min)	Very slow (hours)	Very fast (5%/min)
Regulation Range	±3-4%	None	±10%

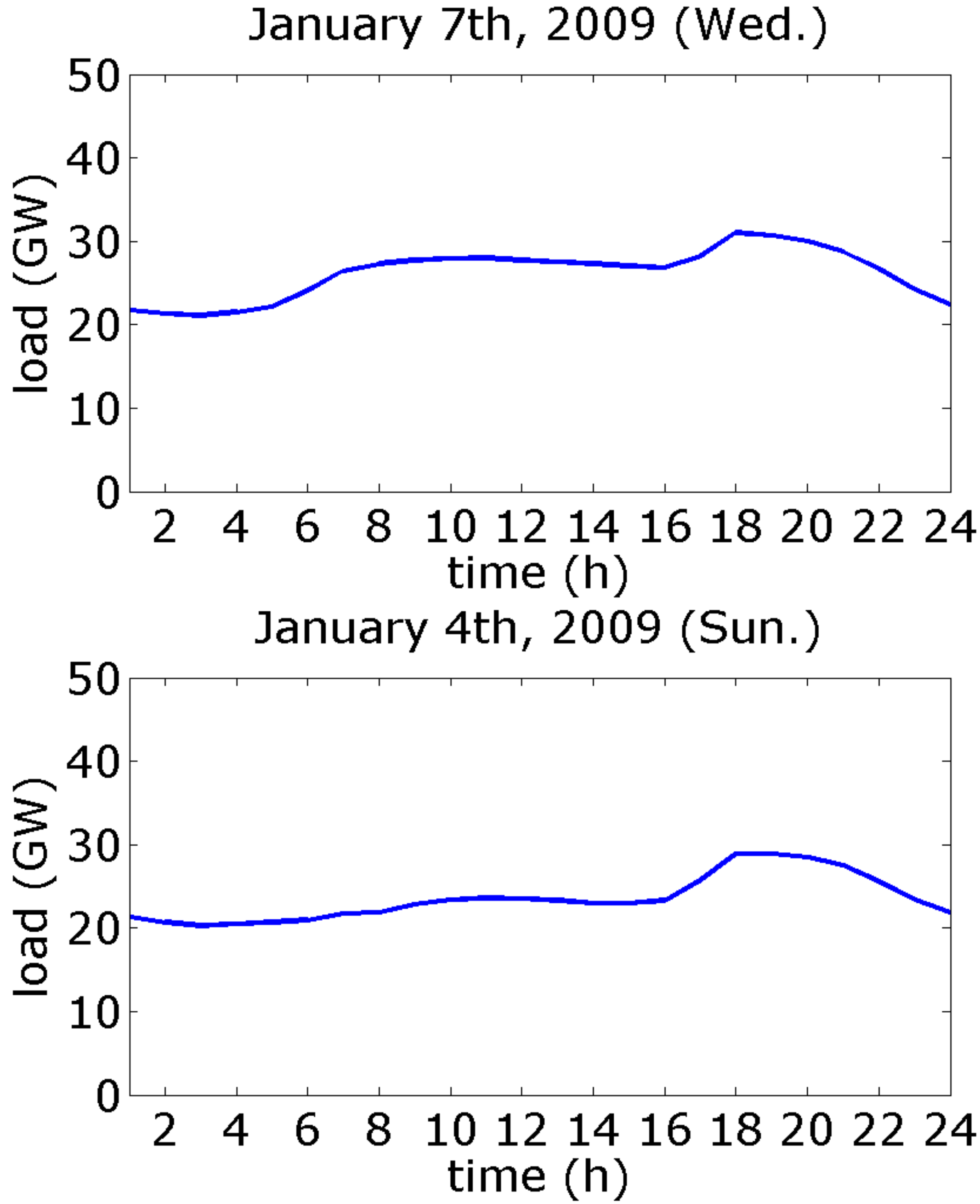
Load

- contiguous US: 760,108 MW
- load follows patterns (Load Profile)

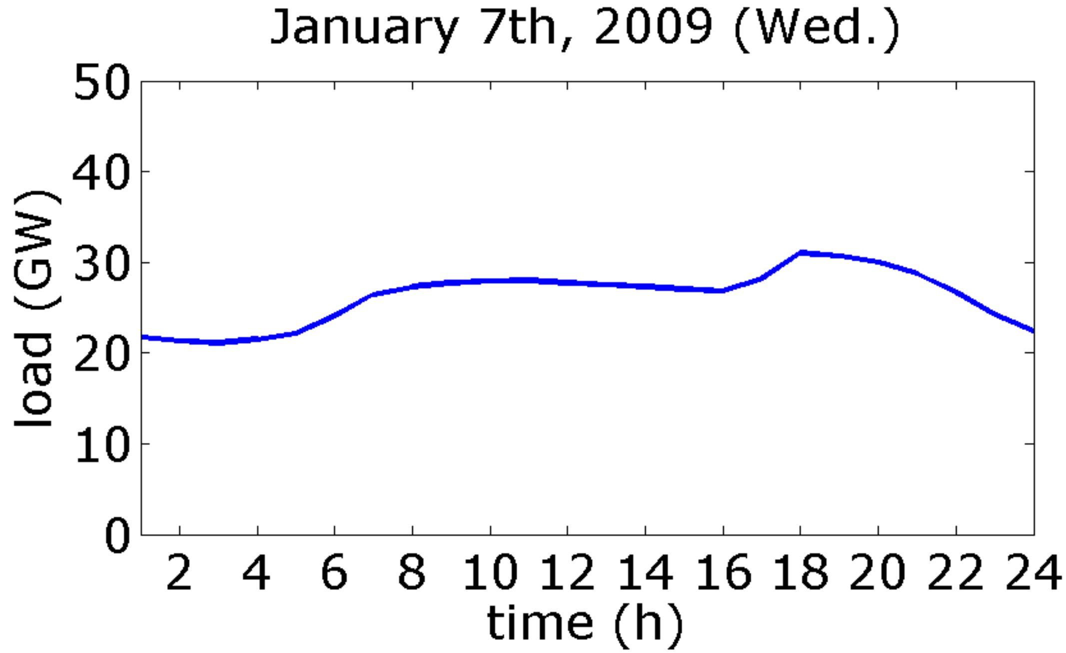
Date: January 7th, 2009 (Wednesday)

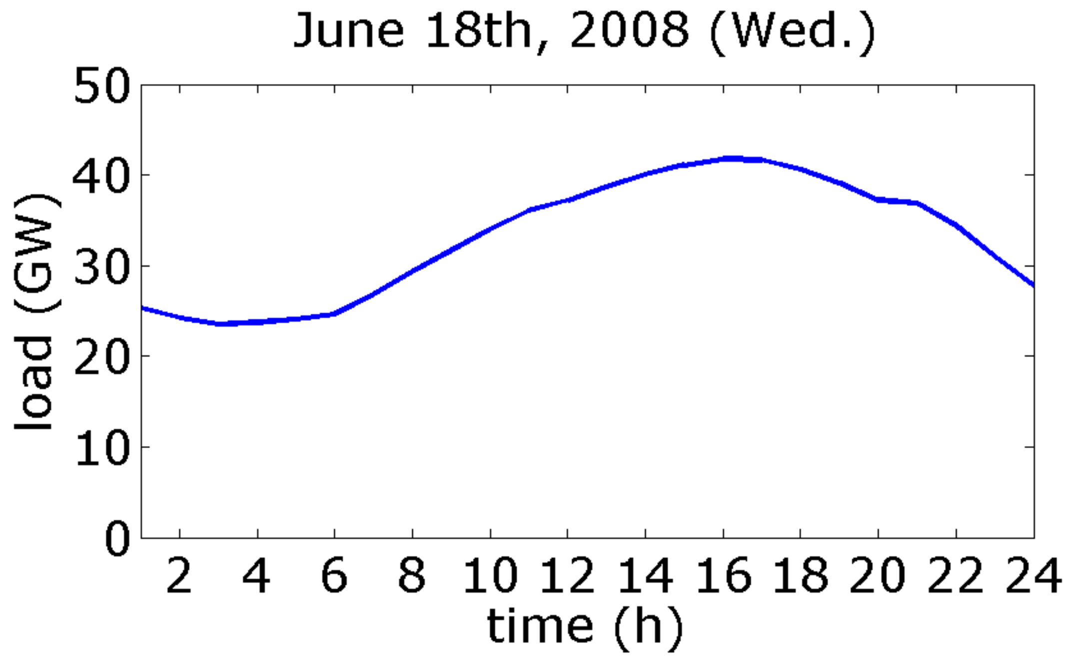


- Impact of day of the week



- Impact of season





Generator Commitment

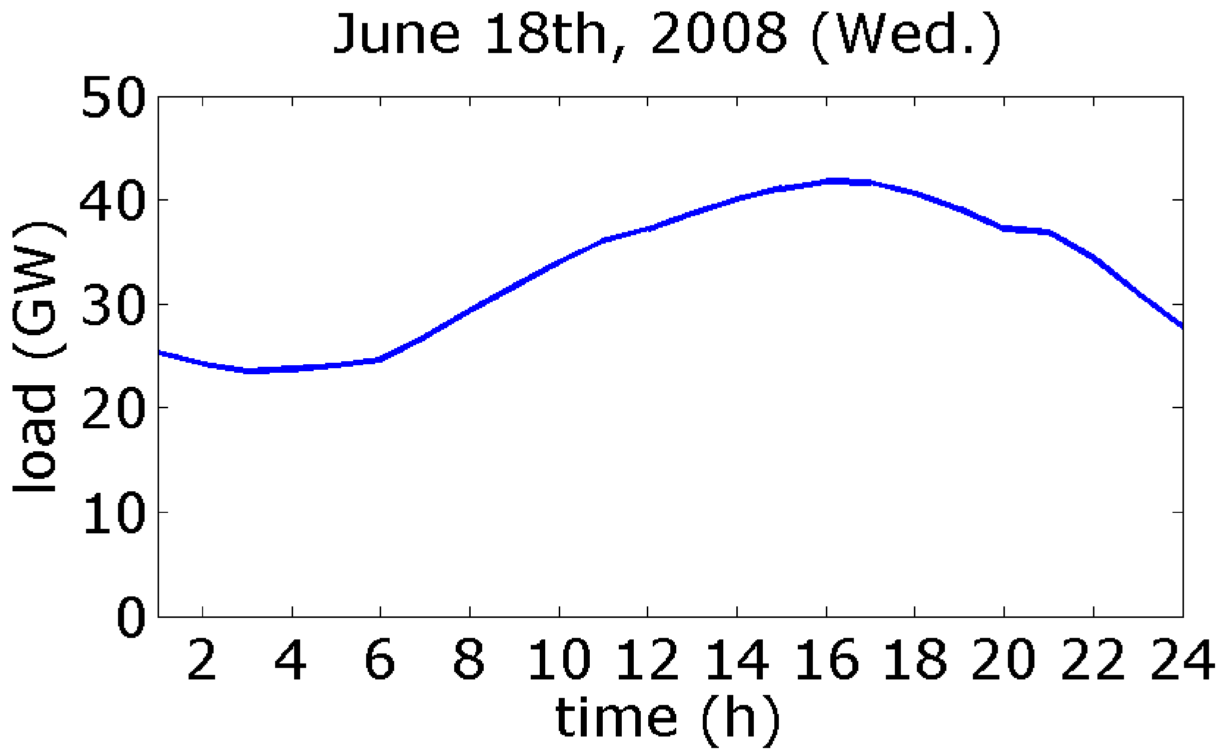
- System operators attempt to dispatch and commit generators to match supply and demand, plus a safety margin in case of a contingency
- Mismatch in load and supply results in frequency deviation from the nominal (60 Hz)
- Prolonged or severe deviations damage equipment and can cause blackouts

Generator Commitment

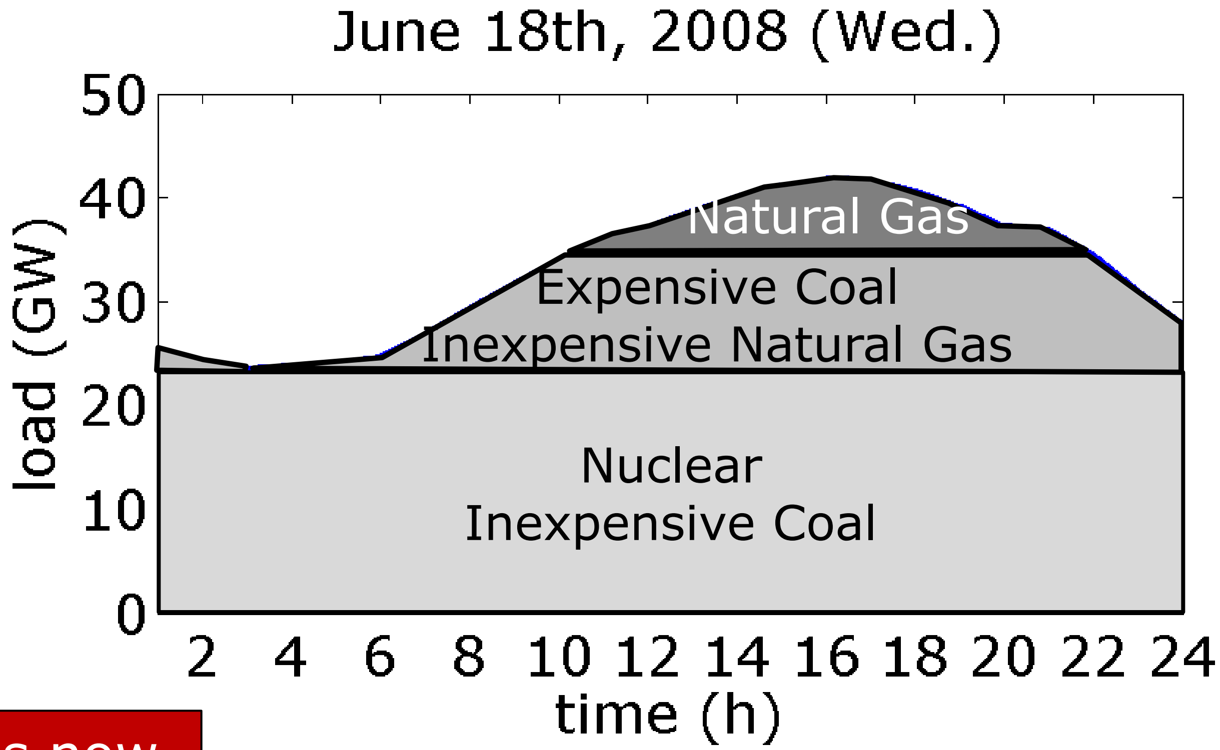
- Nuclear and Coal-fired power plants
  - Long start-up times from several hours to days
  - Slow ramp rates
  - Inexpensive
- Natural Gas power plants
  - Short start-up times
  - Fast ramp rates
  - Expensive

Generator Commitment

- How should power plants be dispatched to satisfy the load?



Generator Commitment

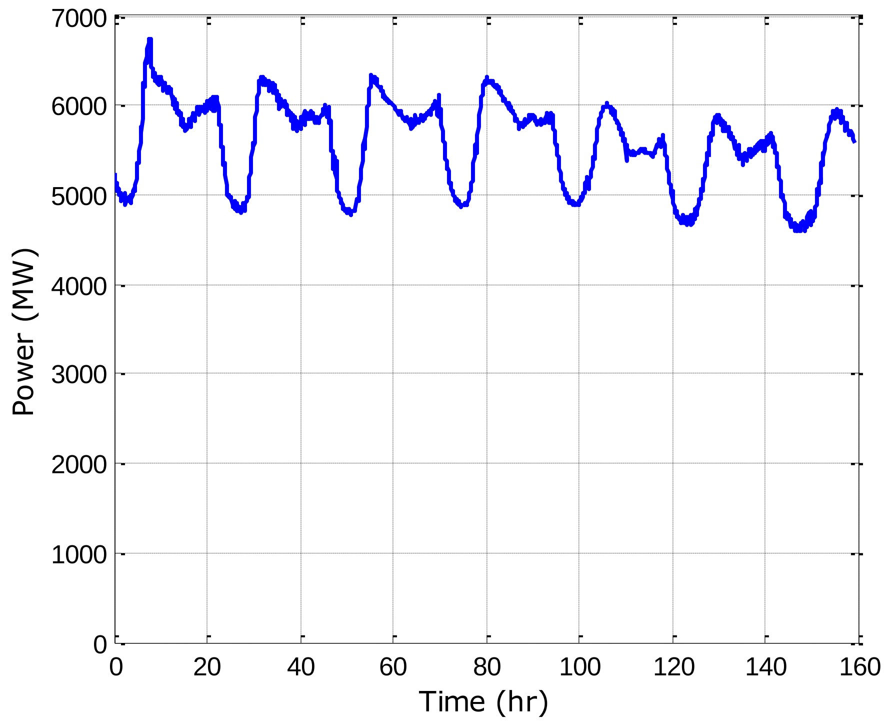


Natural gas is now displacing coal

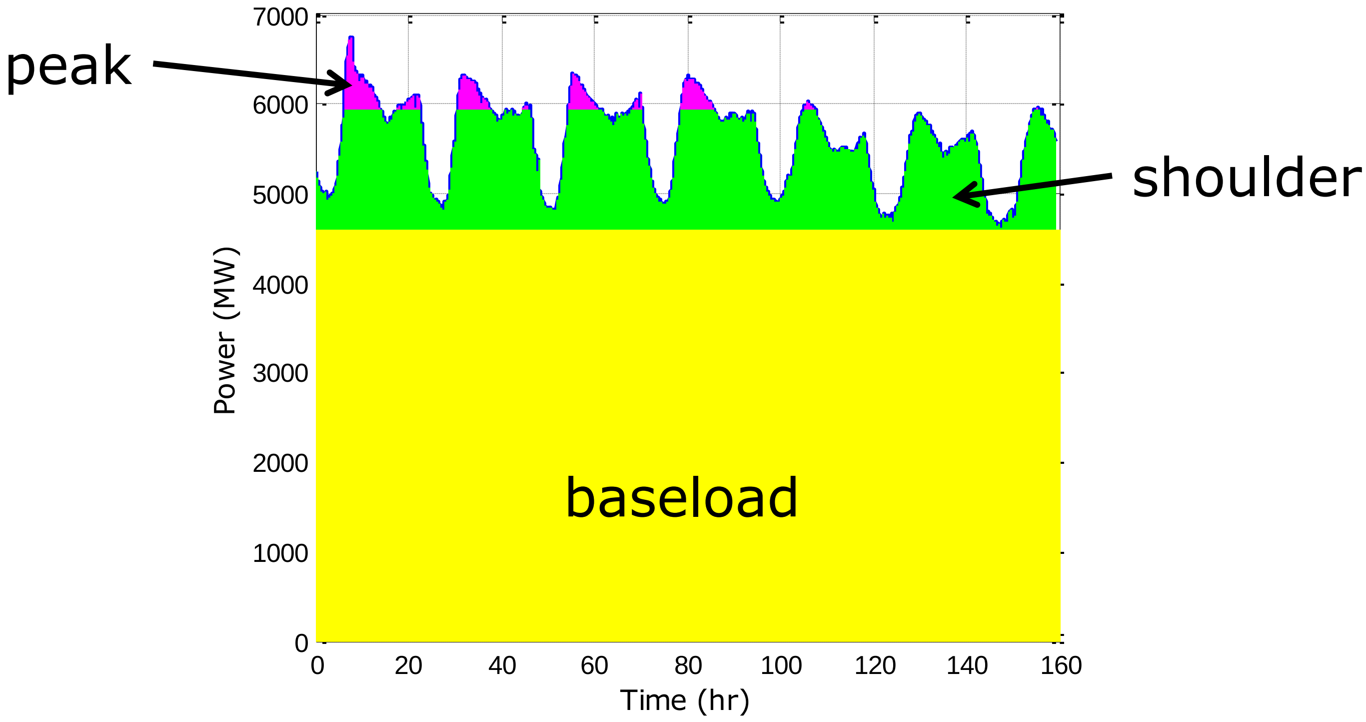
Integration of Renewable Resources

- How does the inclusion of uncontrollable renewable resources affect generator commitment?
  - We can control the resource to produce less power, but not more

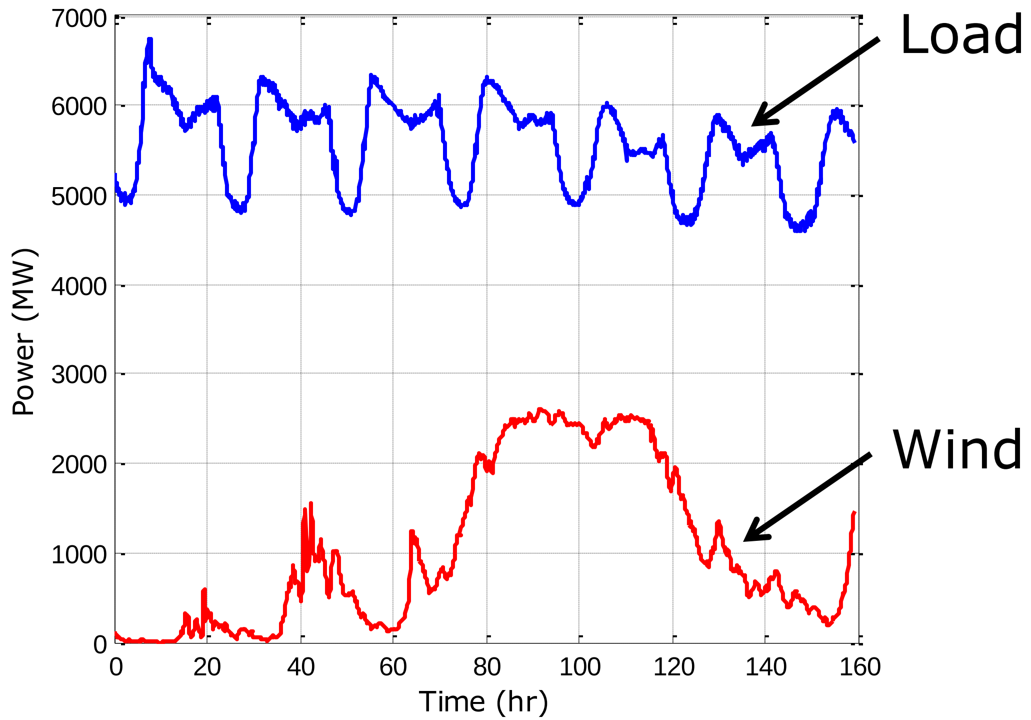
Integration of Renewable Resources



Integration of Renewable Resources

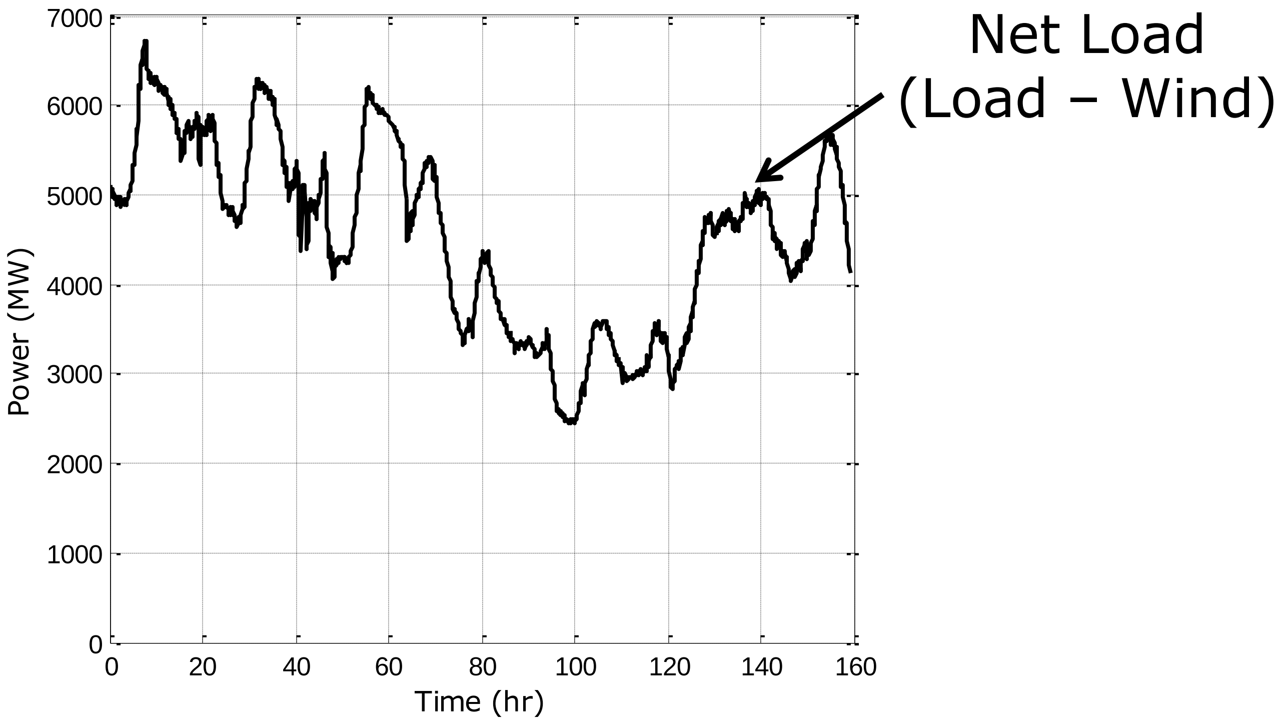


Integration of Renewable Resources

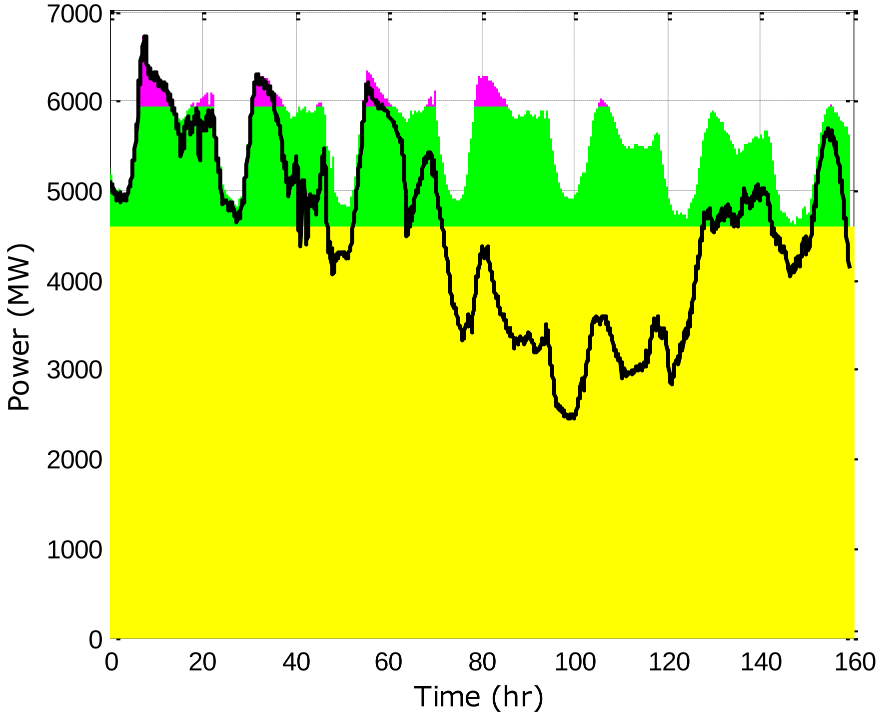


Note: Total Wind Plant Capacity is 2780 MW

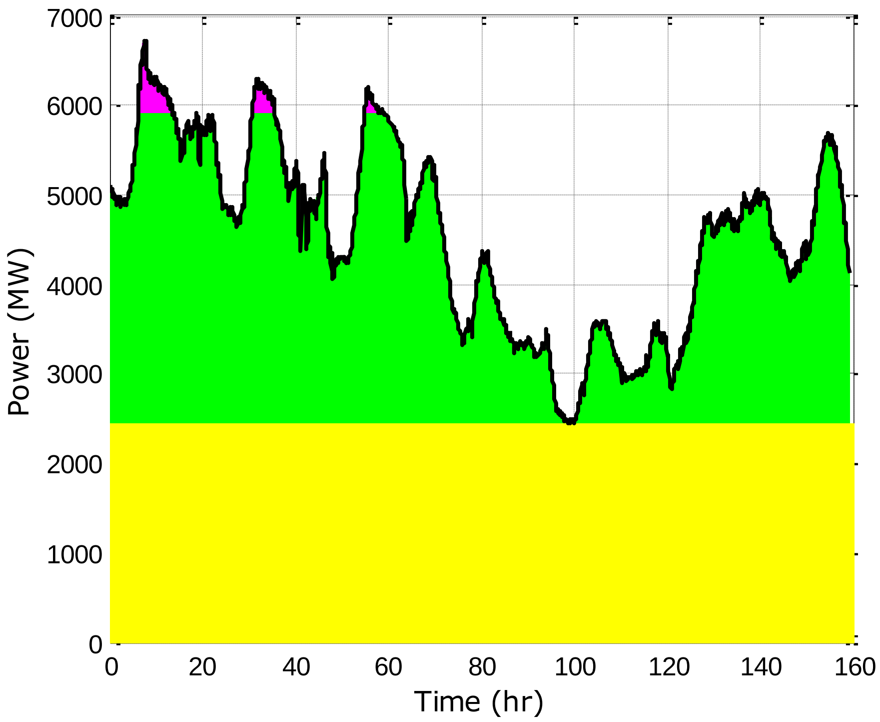
Integration of Renewable Resources



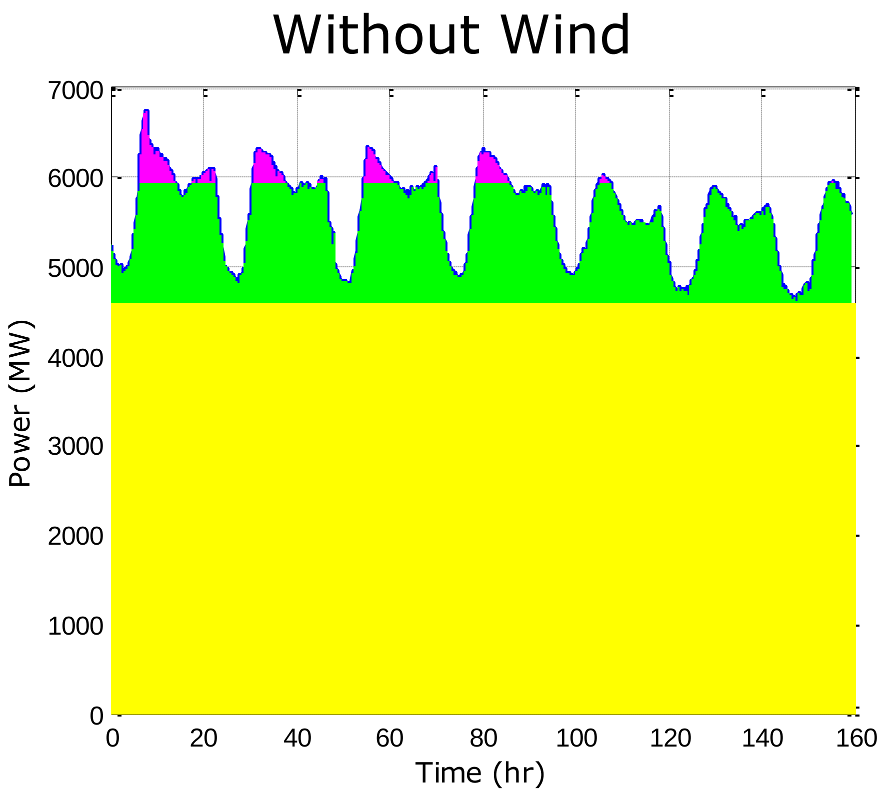
Integration of Renewable Resources

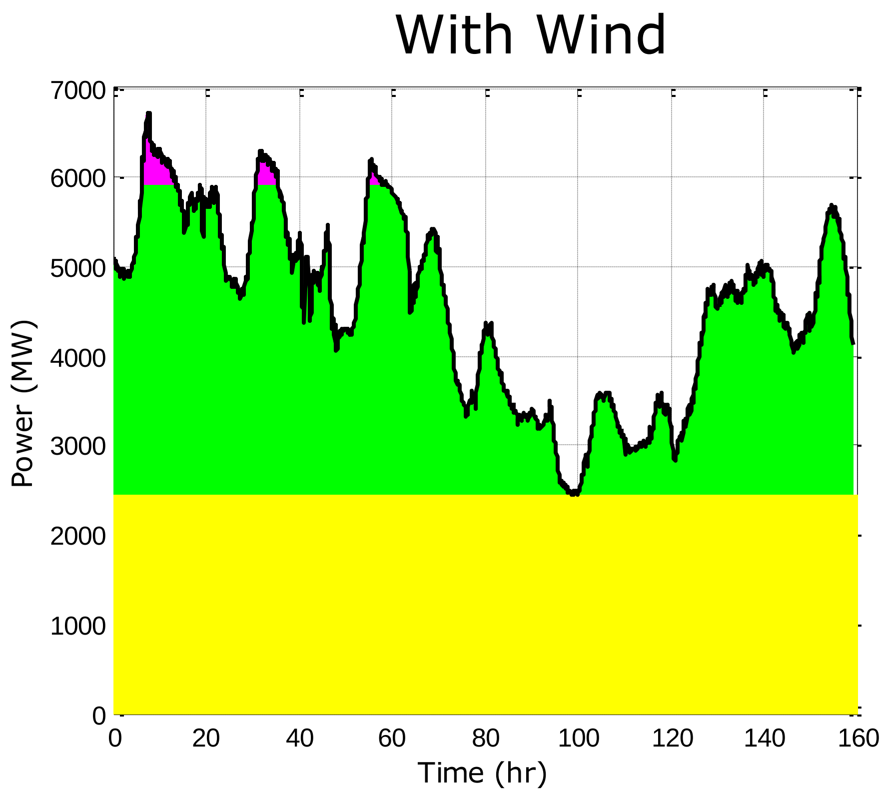


Integration of Renewable Resources



Integration of Renewable Resources





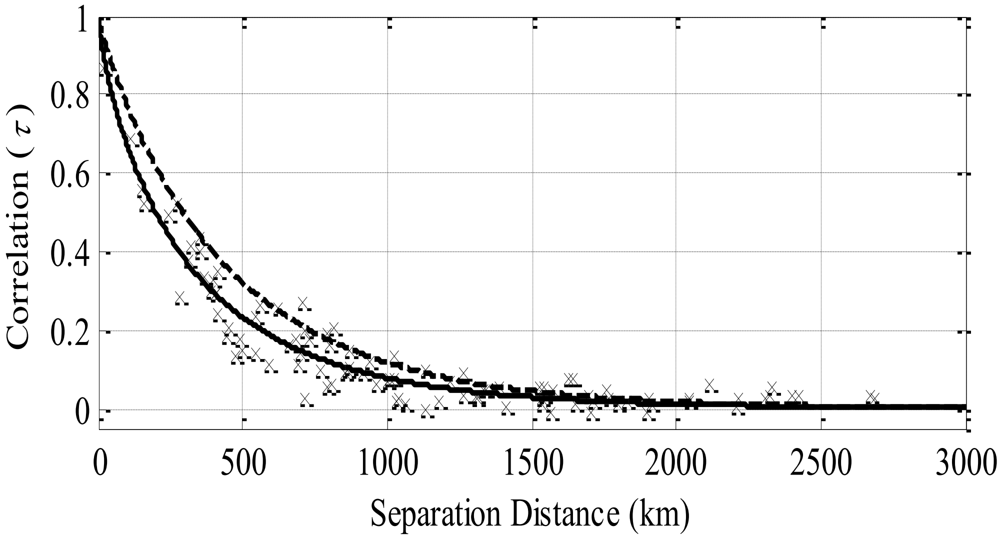
Integration of Renewable Resources

- Presence of wind plants disrupts the “natural” commitment of generators
- Assuming integration is done into an existing system (i.e. non-renewable generators are already built)
  - Baseload units may not run continuously
  - Shoulder units may start-up, shut down and ramp more frequently
  - Peaking units may or may not be used more often
- All of the above threaten reliability and economy of the power system

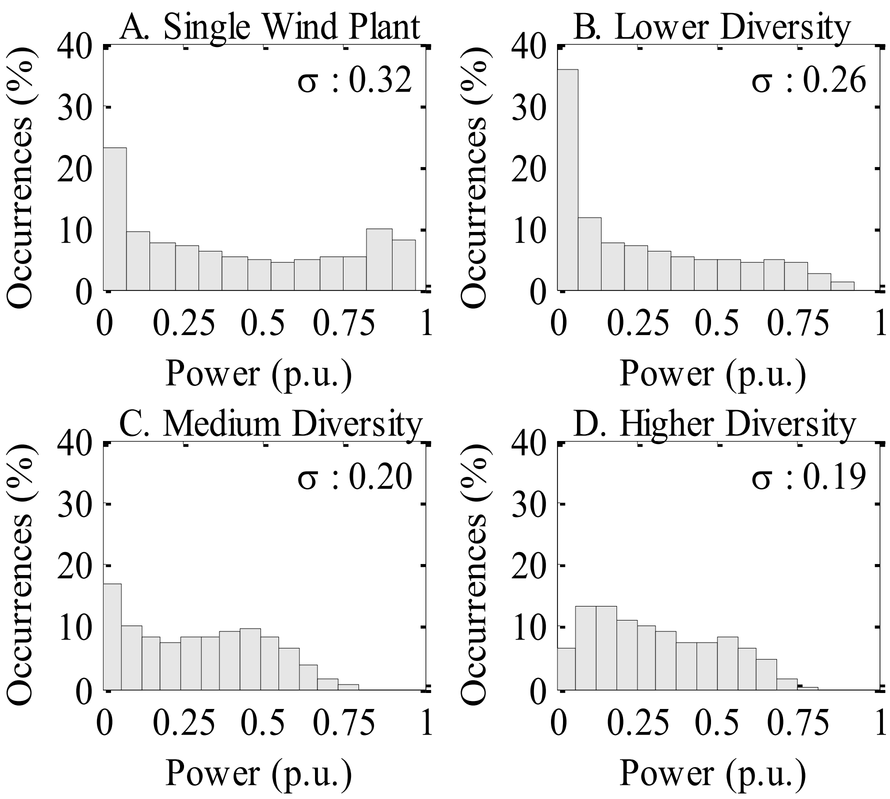
Integration of Renewable Resources

- Factors affecting integration of renewable resources:
  - Capacity
  - Resource characteristic
    - Correlation with load
    - Variability
    - Uncertainty
  - Transmission
  - Generation Resource Mix (flexibility of the system)

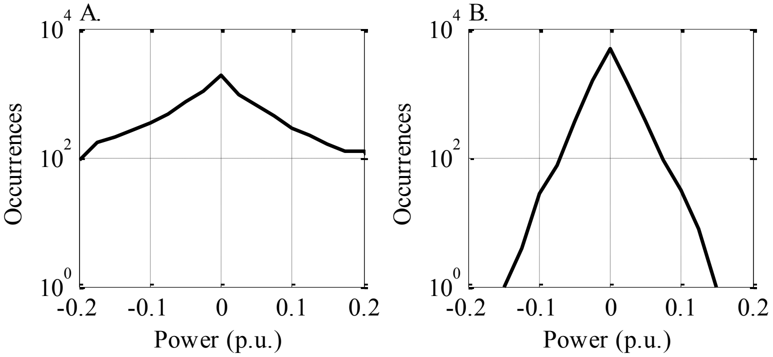
Geographic Diversity



Geographic Diversity



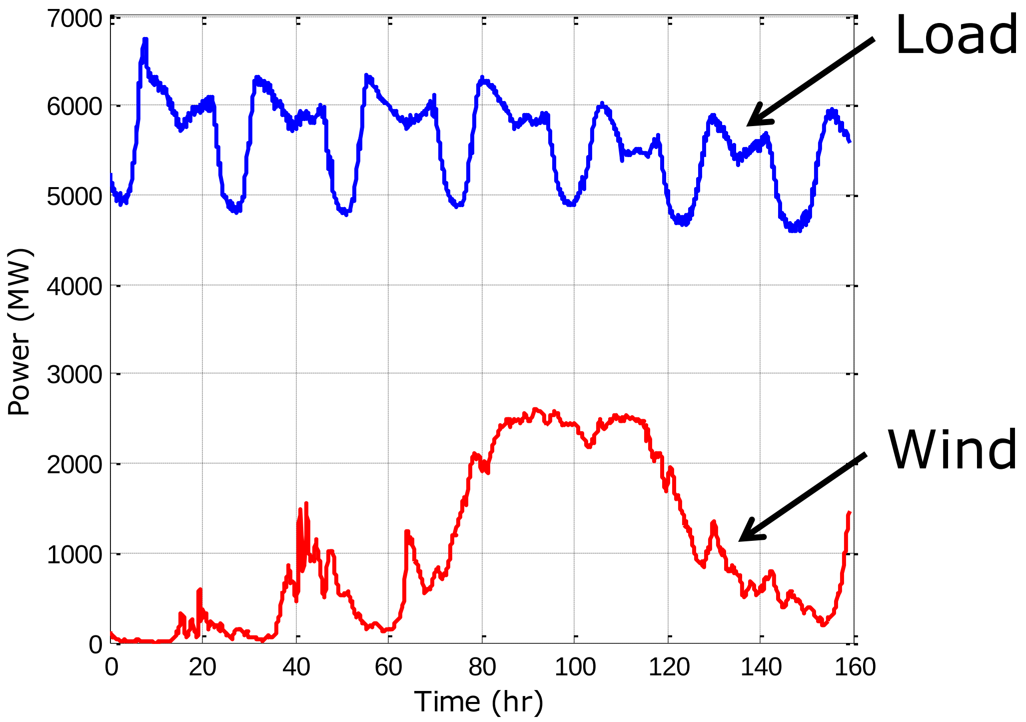
Smoothing Effect



Renewable Resource Penetration

- Penetration by Energy: ratio of energy from renewable resource to energy consumed by load over a given period
- Penetration by Capacity: ratio of total wind plant capacity to peak load (annual or given period)

Renewable Resource Penetration

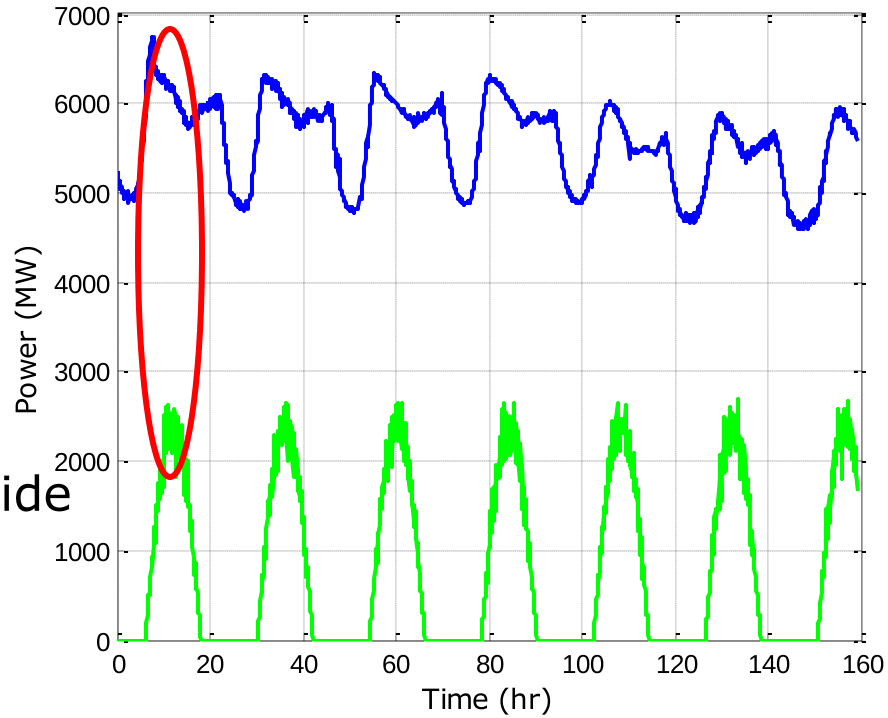


Renewable Resource Penetration

- Penetration by Energy: 18%
- Penetration by Capacity: 42%

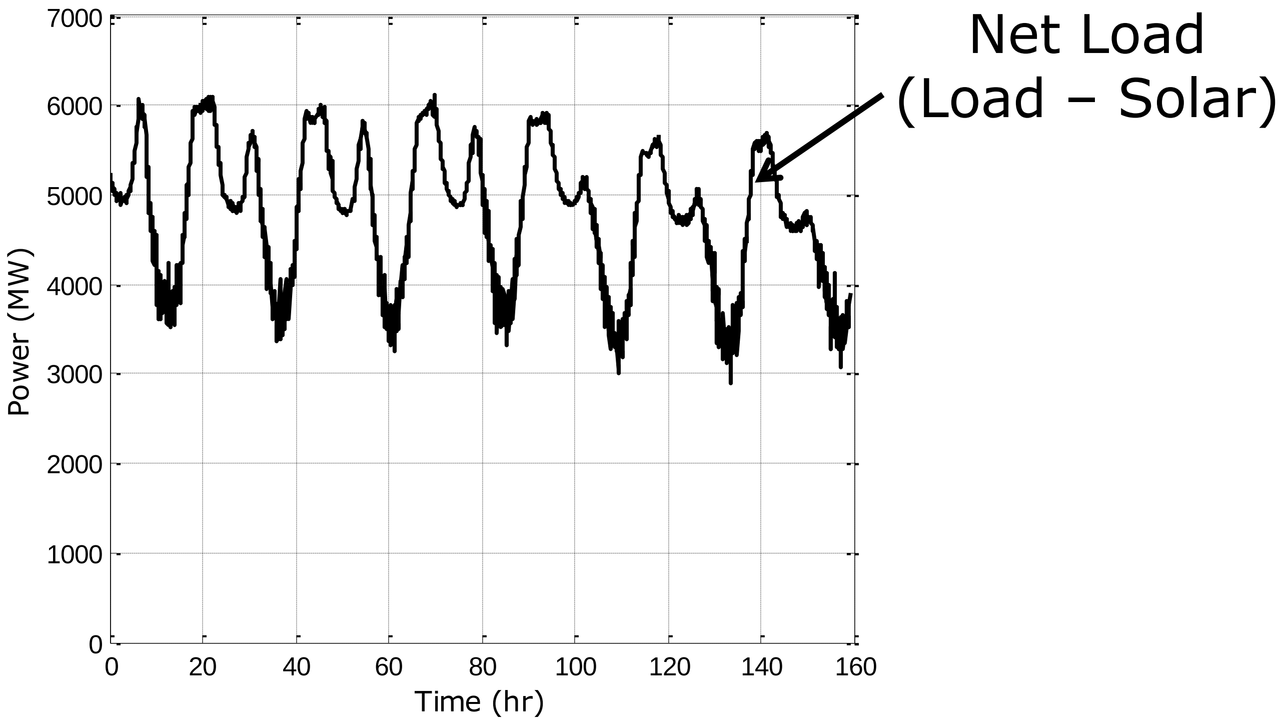
Integration of Renewable Resources

- Assume that instead of wind plants, the renewable resources is PV plants (2,780 MW)



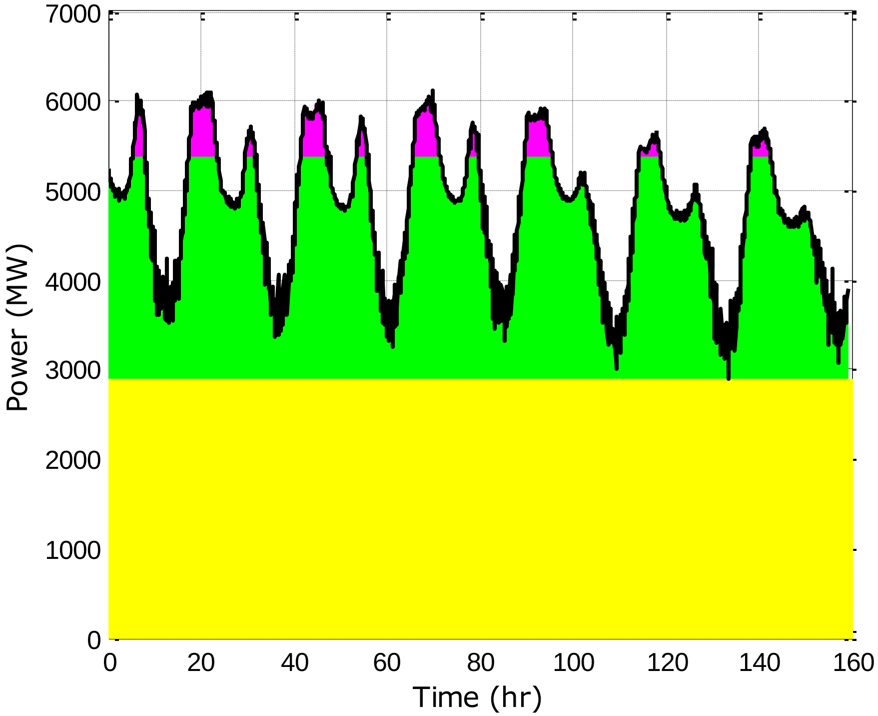
Solar tends to coincide with peak load

Integration of Renewable Resources

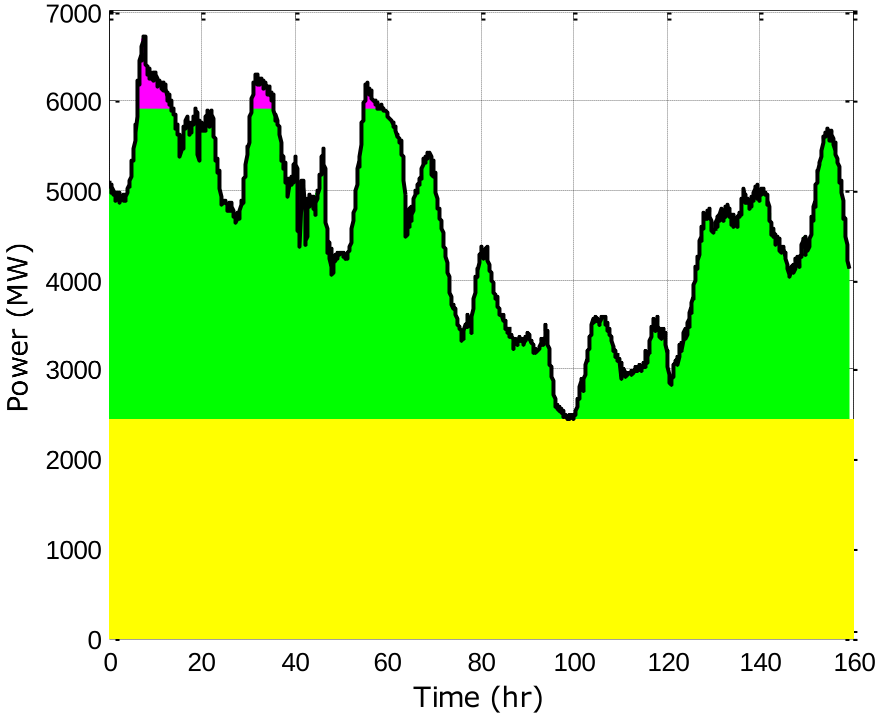


Integration of Renewable Resources

With Solar



With Wind



Integration of Renewable Resources

- Integration of solar power tends to be easier than with wind power
  - Easier to forecast
  - Coincides with peak load
    - Beneficial to offset air conditioning load in hot climates

Integration of Renewable Resources

- Solutions:
  - Curtail renewable resources
  - Add energy storage
  - Include forecasting
  - Demand Response