# 03-Power Plants

Text: Chapter 4

ECEGR 3500

Electrical Energy Systems

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# Overview

- Generation
- Thermodynamic Cycles
- Generator Characteristics
- Hydroelectric Generation

# Generation (2015 Data)

- Total number and capacity of generators in U.S.: 20,068
  - Natural Gas: 5,774;  503,936 MW
  - Hydro: 4,020; 78,956 MW
  - Petroleum: 3,550; 42,321 MW
  - Coal: 968; 304,789 MW
  - Wind: 1098; 73,393 MW
  - Solar PV: 1633; 11,983 MW
  - Solar Thermal: 19, 1,774 MW
  - Geothermal: 197; 3,811 MW
  - Nuclear: 99; 103,860 MW
- Total nameplate capacity: 1,167,365 MW

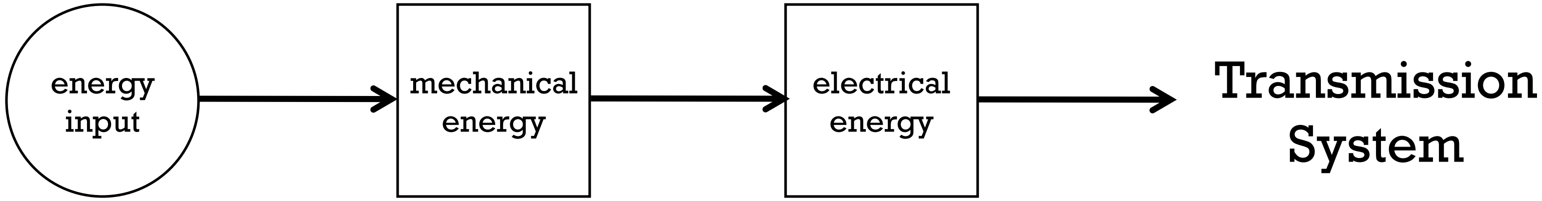
A single power plant may have more than one generator.

# 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

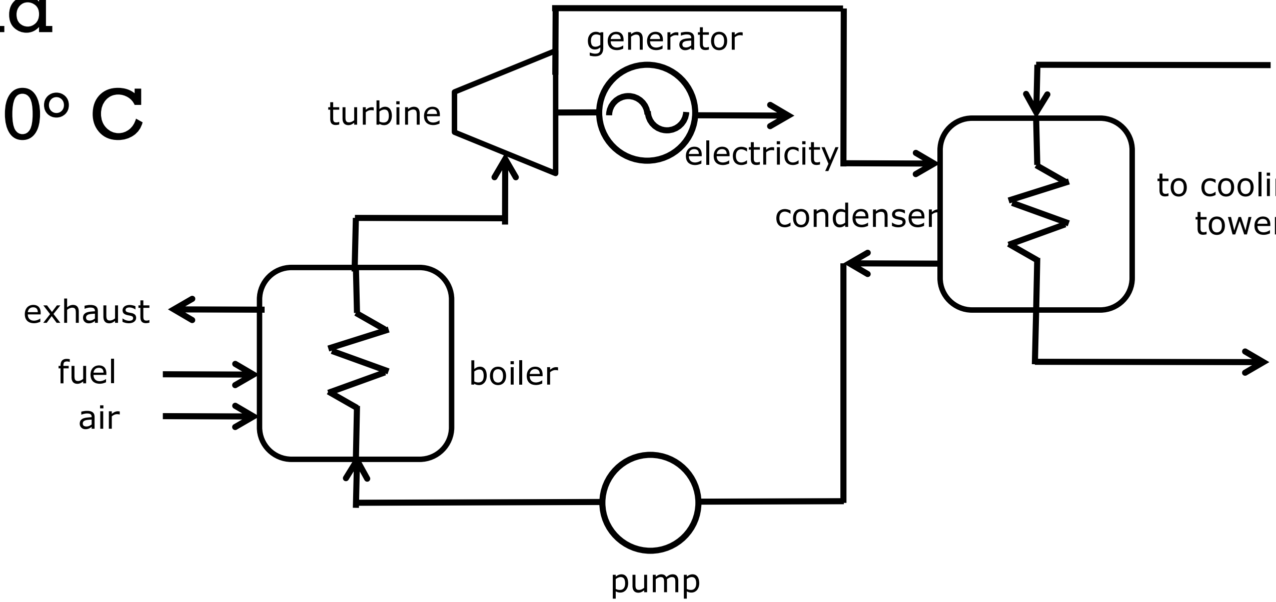
- Carnot Efficiency: upper limit of the efficiency of a thermodynamic process

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

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

# Rankine Cycle

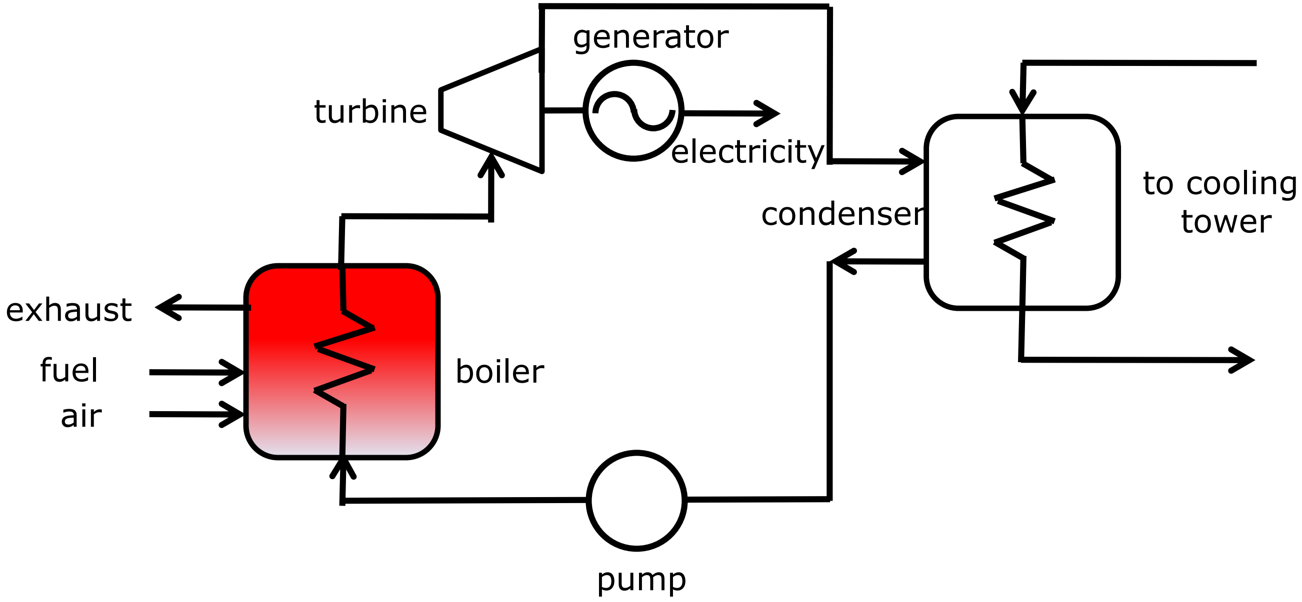
- Used in coal/nuclear power plants
- Steam is the working fluid
- Temperatures around 540° C



# Rankine Cycle

Fuel is combusted in the boiler

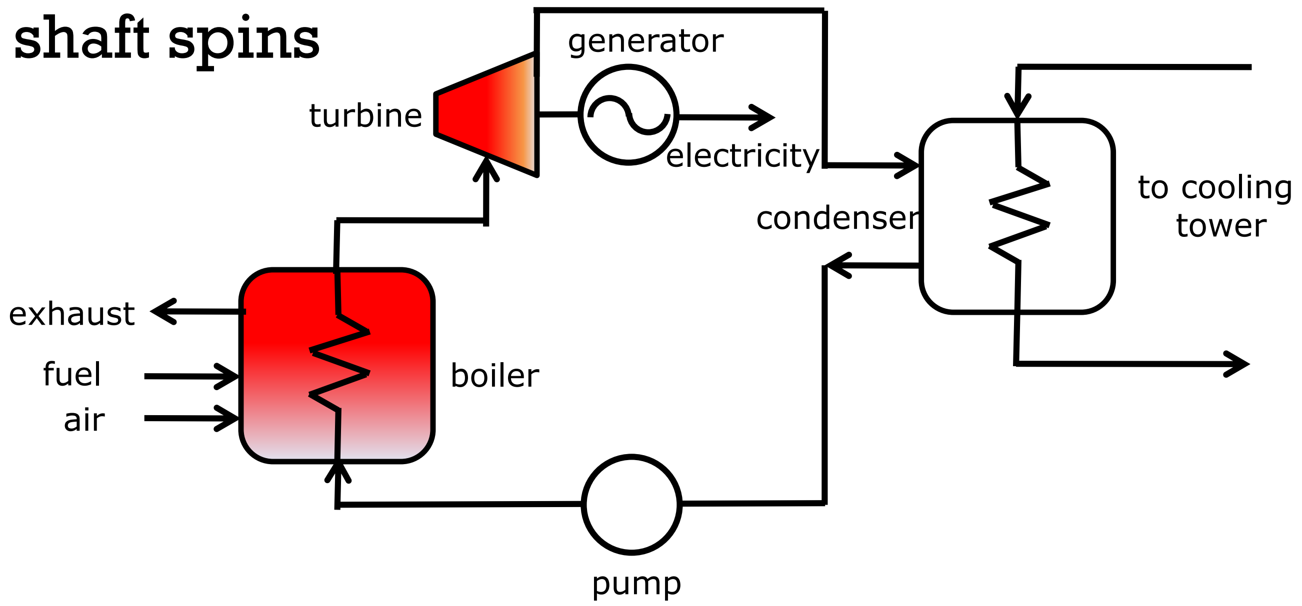
- Energy is transferred to the water, which vaporizes into steam



# Rankine Cycle

Steam expands through the turbine

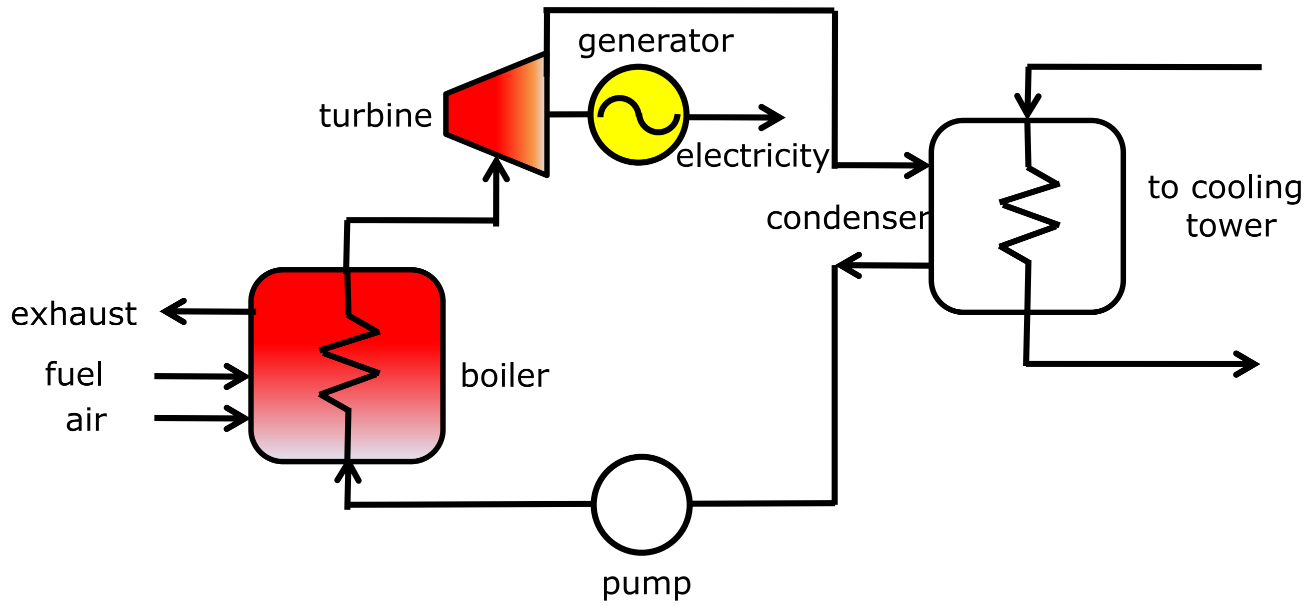
- Pressure is reduced
- Turbine shaft spins



# Rankine Cycle

Synchronous generator produces electricity

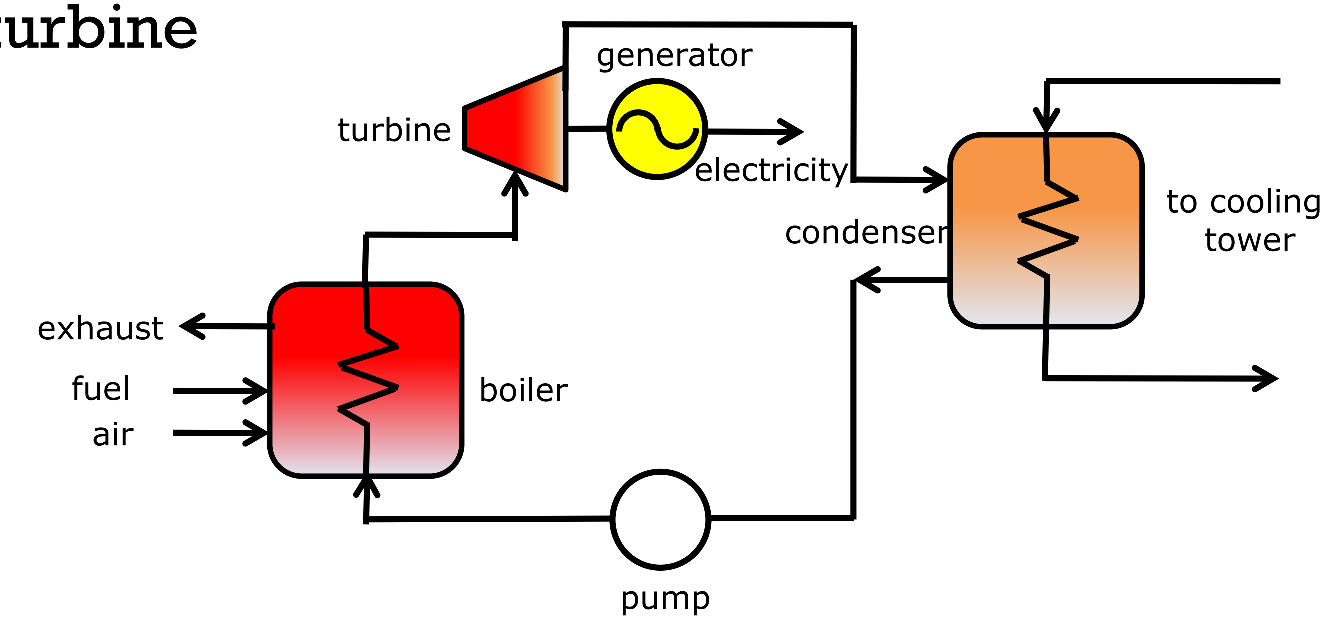
- Provides a counter torque to the shaft



# Rankine Cycle

Steam is cooled in the condenser

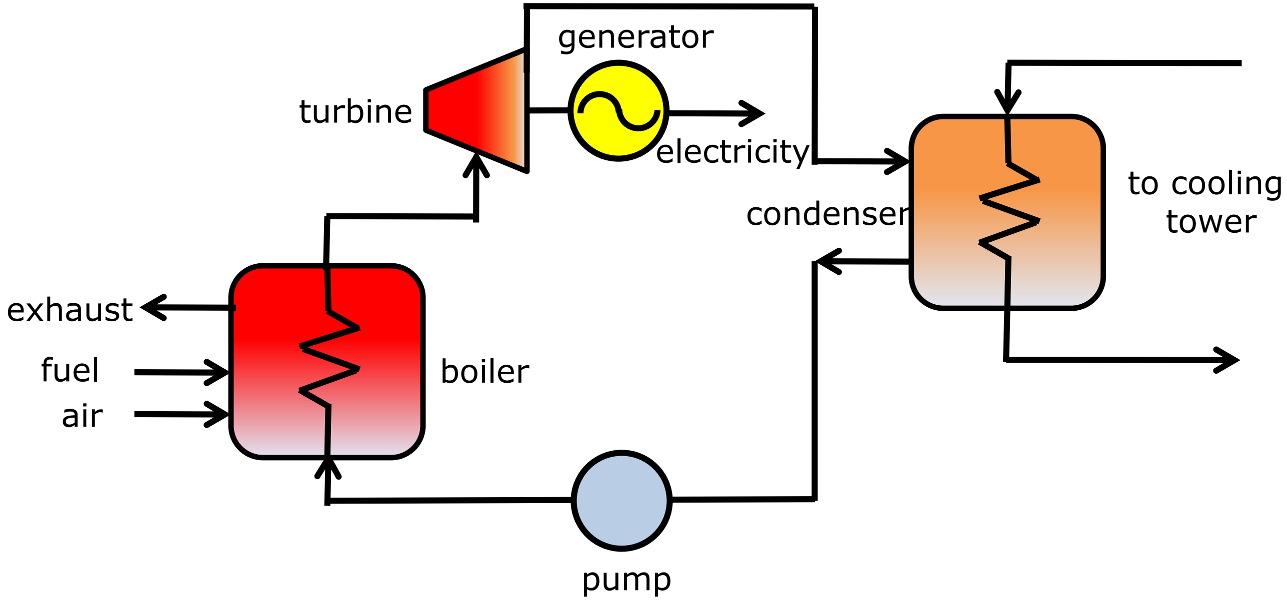
- Steam condenses into water
- Cooling of the working fluid helps suck the steam through the steam turbine



# 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

# Exercise

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

# Exercise

- Carnot efficiency is:

$$\eta_c = 1 - \frac{T_C}{T_H} = 1 - \frac{30 + 273.15}{540 + 273.15} = 62.7\%$$

- In reality, this is much closer to 40%
- Many modifications exist
  - Reheating
  - Use of turbine stages

# Exercise

Thermal power plants typically have two power ratings, a summer rating and a winter rating. Which one do you expect to be higher?

# Exercise

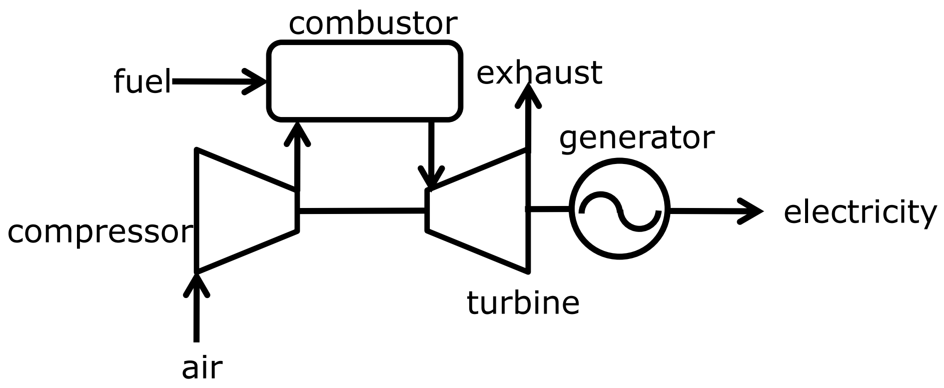
Thermal power plants typically have two power ratings, a summer rating and a winter rating. Which one do you expect to be higher?

Answer: the winter rating is higher because the cold reservoir temperature will be lower. For example the total summer capacity of coal fired plants in the U.S. is 309,680 whereas the winter capacity is 312,293.

Big Bend coal-fired power plant (1730 MW capacity)

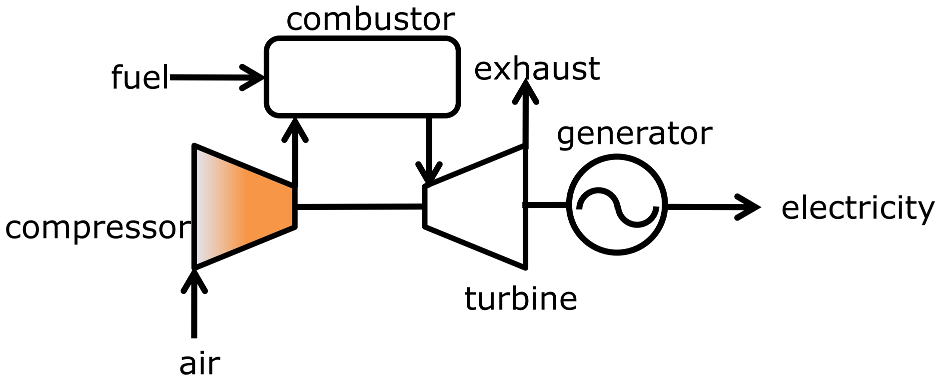
# Brayton Cycle

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



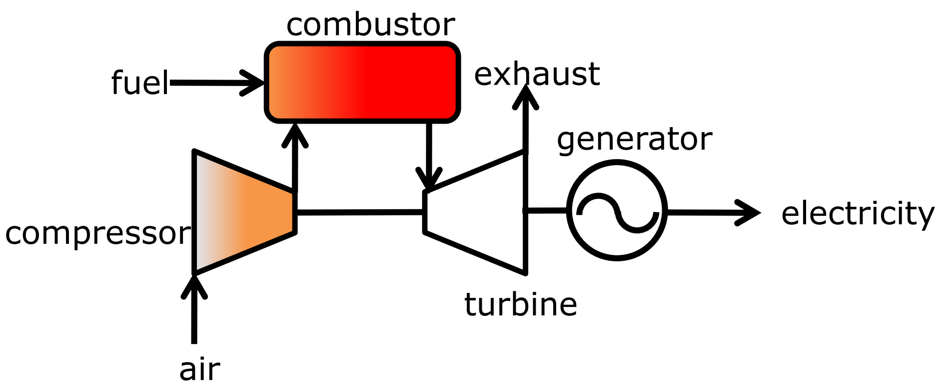
# Brayton Cycle

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



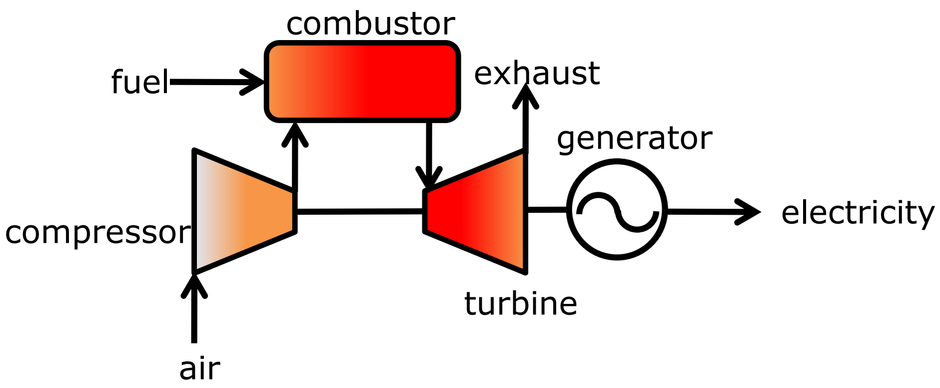
# Brayton Cycle

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



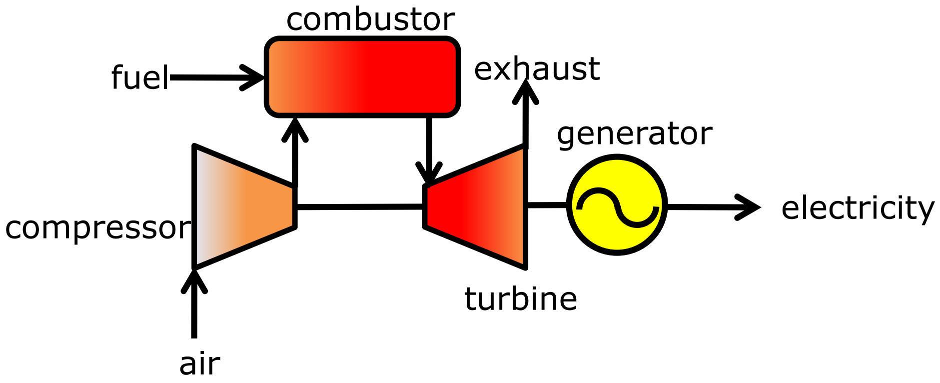
# Brayton Cycle

- 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%

Currant Creek
Natural gas-fired power plant
(525 MW)

# 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

# Exercise

Consider a 1400MW coal-fired power plant whose efficiency is 35 percent. How many kilograms of coal are consumed by the power plant in a single day of continuous rated power production? Assume the specific energy density of the coal used is 20 MJ/kg.

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Consider a 1400MW coal-fired power plant whose efficiency is 35 percent. How many kilograms of coal are consumed by the power plant in a single day of continuous rated power production? Assume the specific energy density of the coal used is 20 MJ/kg.

Answer. A lot. 1 kwh of energy output requires 1/0.35 = 2.857 kwh of input energy. Since 3.6 MJ = 1kWh, one kg of coal provides 20/3.6 = 5.55 kWh of input energy, or 1.94 kWh of output energy. The plant produces 1400 x 24 = 33,600 MWh per day, so about 17,320,000 kg of coal is needed per day.

# 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)

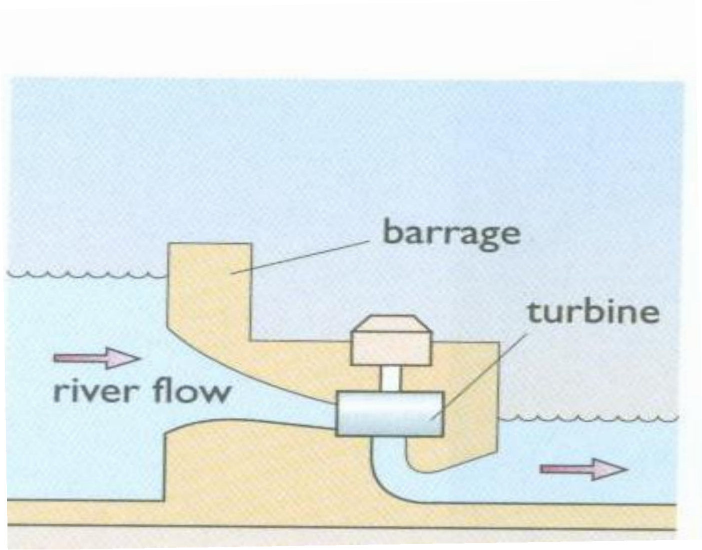
# Generator Characteristics

- 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.

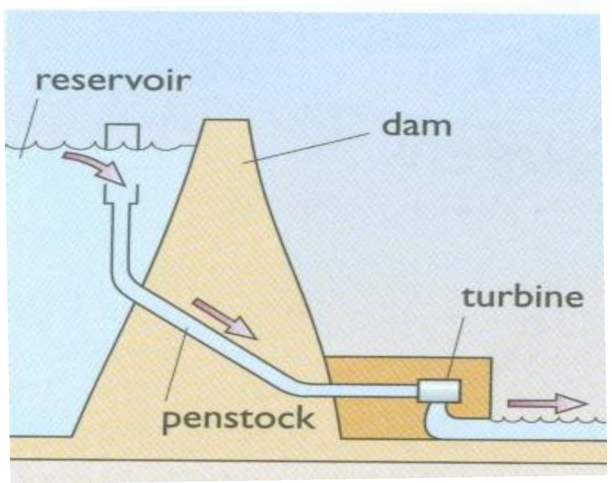
# Comparison

| 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% |

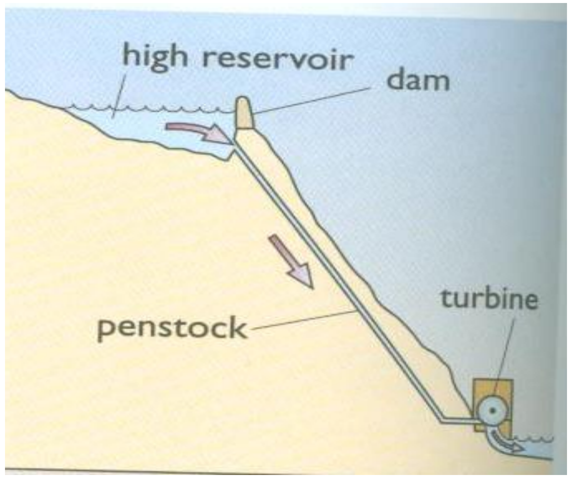
# Hydroelectric Generation




low head




medium head




high head

# Hydroelectric Generation

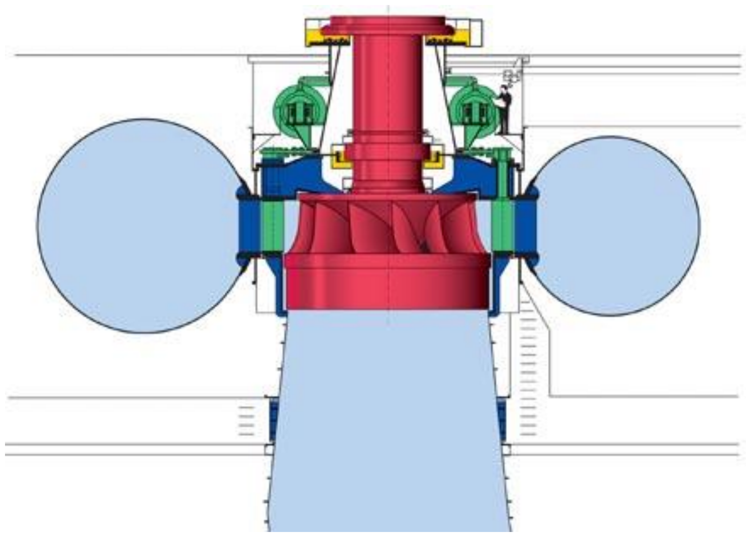
- Turbine types
  - Francis
  - propellers
  - impulse

# Francis Turbine

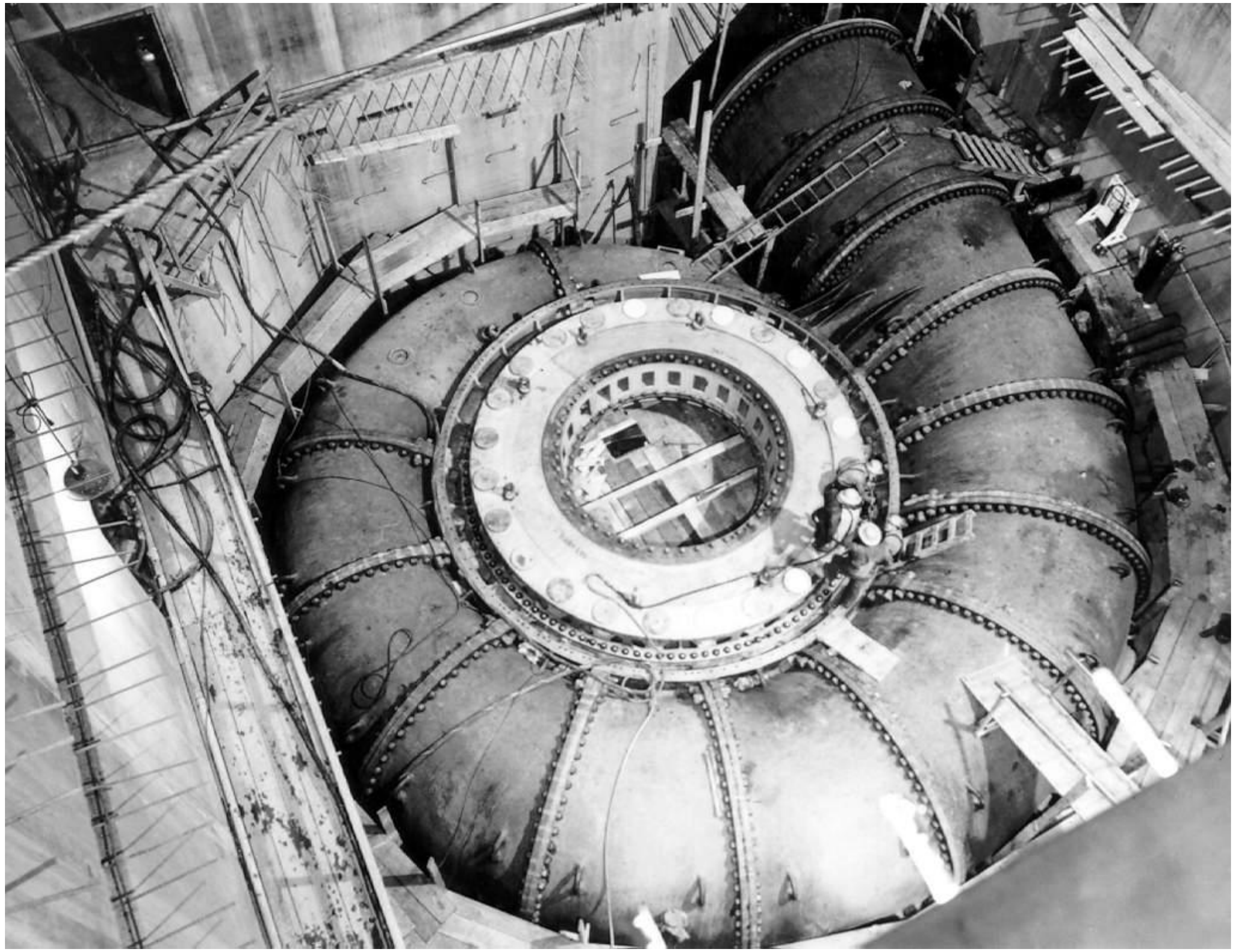

Three Gorges Dam

# Francis Turbines

- horizontal or vertical axis of rotation
- completely submerged turbine blades
- common in medium and large capacity plants
- used in all types of head dams
- large drop in pressure



# Francis Turbines

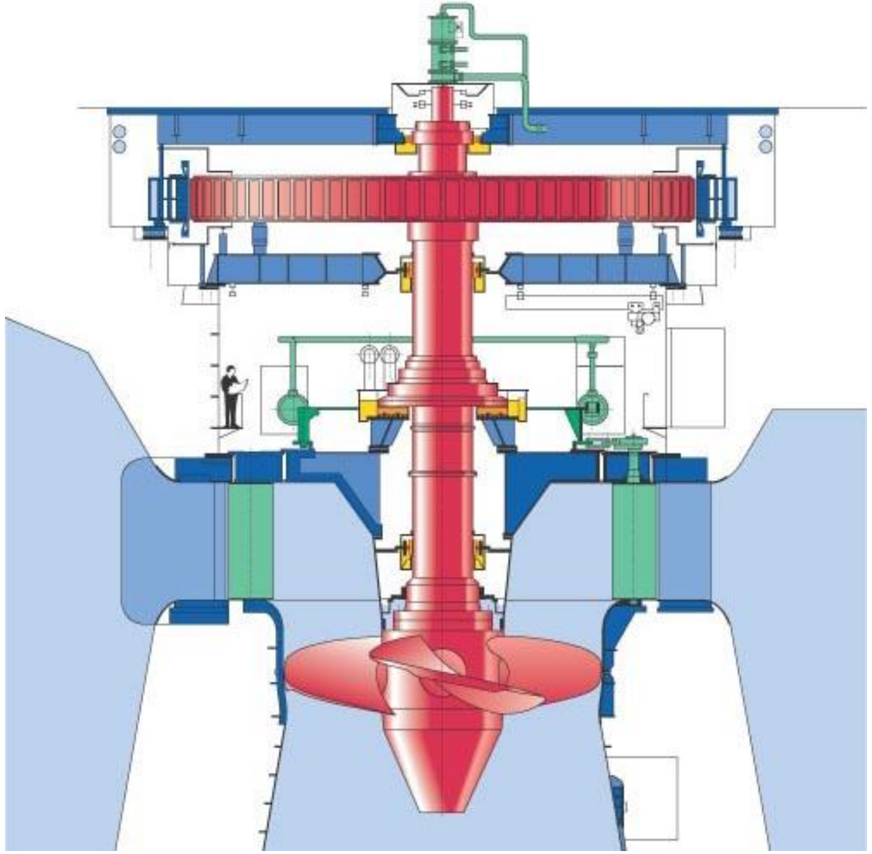


Grand Coulee Dam

# Hydroelectric Generators

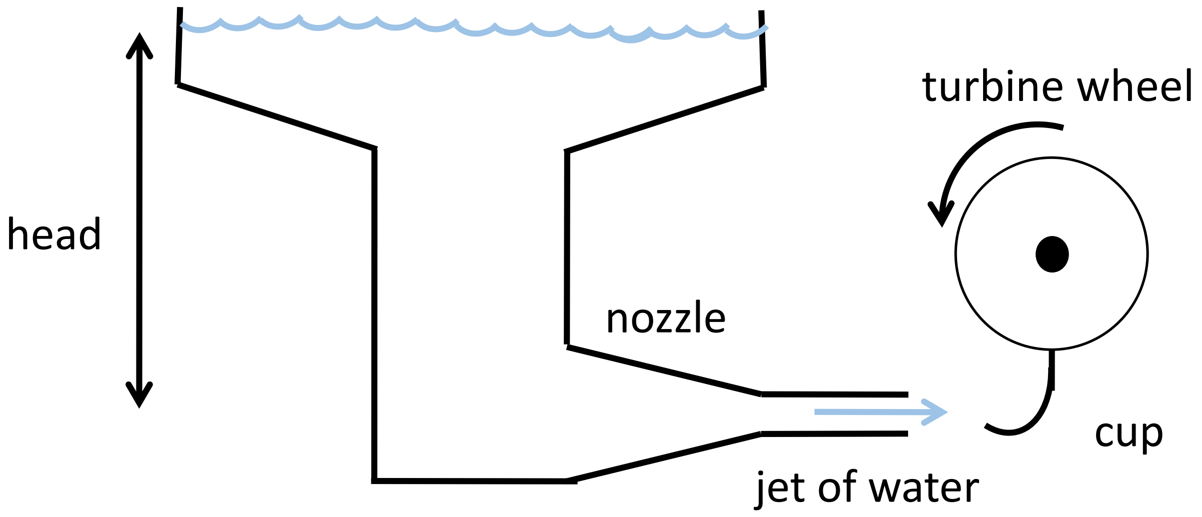
# Propeller: Kaplan Turbine

- used in low-head, high flow applications
- completely submerged blades
- axial flow
- adjustable pitch blades



# Impulse Turbine

- basic idea: use a jet of water to rotate the turbine wheel

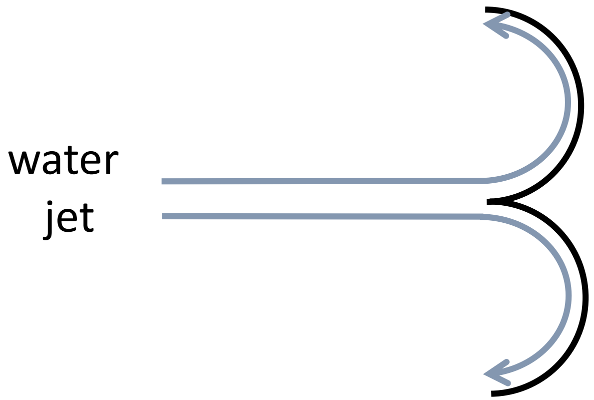


# Pelton Turbine

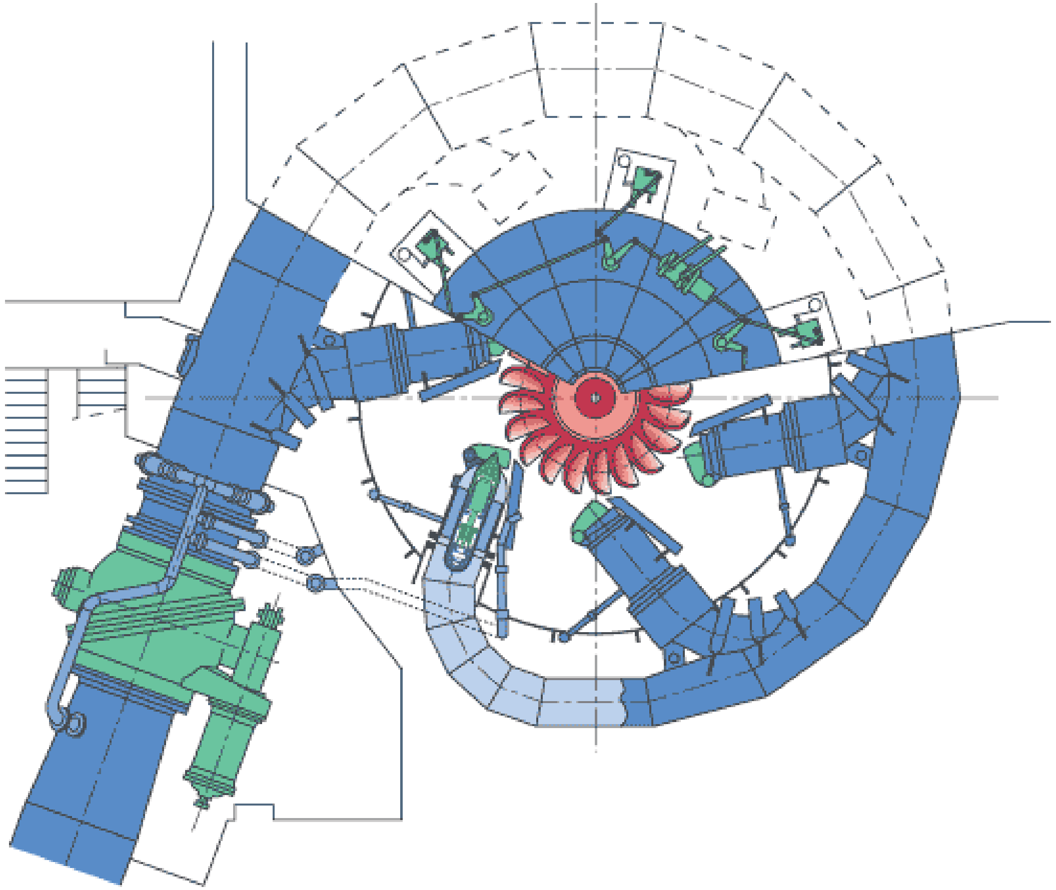
- 100% of kinetic energy can be harnessed
  - ideal conditions
  - unlike wind turbines (Betz Limit)
- cup is polished and smooth, with negligible friction

# Pelton Turbine

Maximum efficiency is obtained when the velocity of the cup is equal to half the velocity of the water jet



# Impulse Turbine: Pelton



# Turbine Applications

- Propeller turbines:
  - high flow rates (10 $m^3/s$ to 50 $m^3/s$)
  - low head (3 m to 50 m)
- Francis turbines:
  - medium flow rates
  - medium head
- Pelton turbines:
  - low flow rate (0.1 $m^3/s$ to 10 $m^3/s$)
  - high head (10 m to 1000 m)