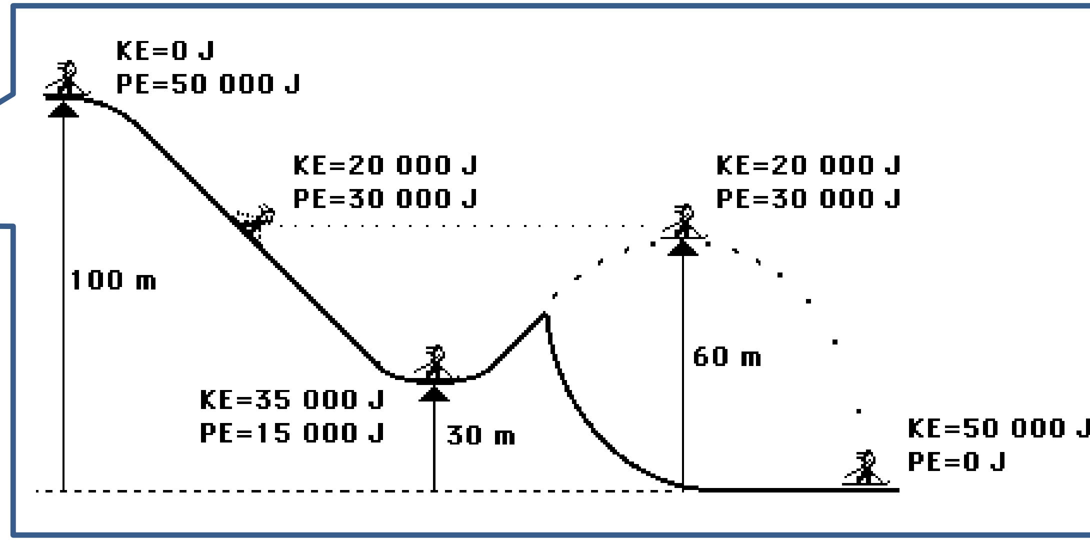
# Advanced Energy System Eng.

# Definition & forms of energy



- **Energy: the capacity or capability to do work**
- **Forms of energy**
  - biofuels (e.g., wood)
  - chemical
  - electrical
  - mechanical-kinetic
  - mechanical-potential
  - gravitational
  - nuclear
  - heat (thermal)
  - radiation
  - magnetic
  - sound




- **Energy conversion:** transformations between different forms of energy
  - conversion efficiency → input > output : < 100%

- **e.g.,** solar cell ~ 10% (radiant to electrical)
  automobile engine ~25% (chemical to thermal, thermal to mechanical)
  fuel cell ~60% (chemical to electrical)
  secondary battery ~75% (chemical to electrical, electrical to chemical)

# Energy flow upon the Earth from natural sources

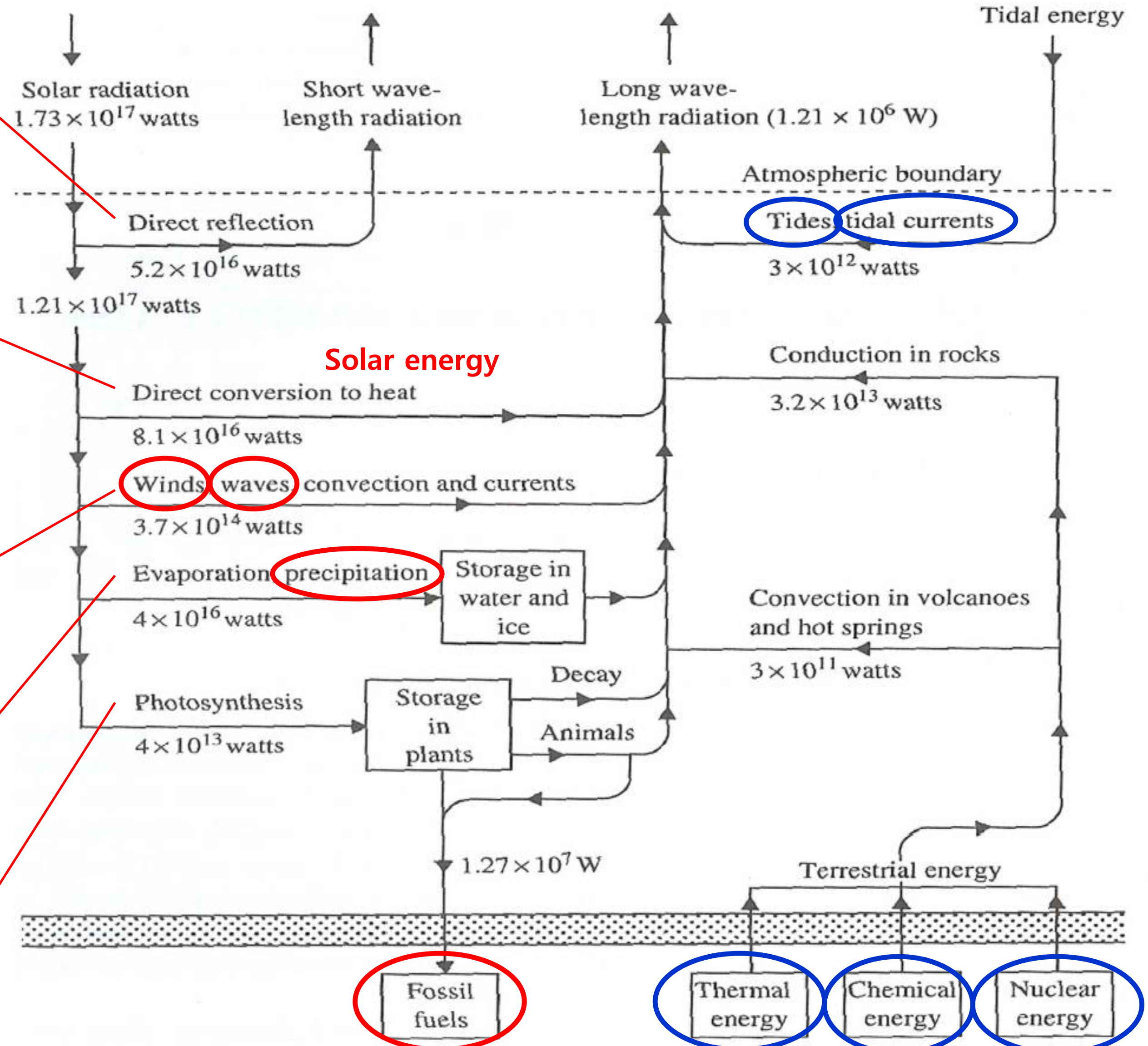
**~30% of the incoming solar radiation**
**($5.2 \times 10^{16}$ W)**
reflected back into space in
the form of short-wave radiation

**~ 47% of incoming solar radiation**
**($8.1 \times 10^{16}$ W)**
absorbed by oceans, land, atmosphere
converted to low-grade heat & then
re-radiated as long wavelength
radiation

**~0.21% of incoming solar radiation**
**($3.7 \times 10^{14}$ W)**
ocean and atmospheric convection and
circulations →
wind, wave, ocean current motion

**~23% of incoming solar radiation**
**($4 \times 10^{16}$ W)**
hydrological cycle (evaporation, rivers…)

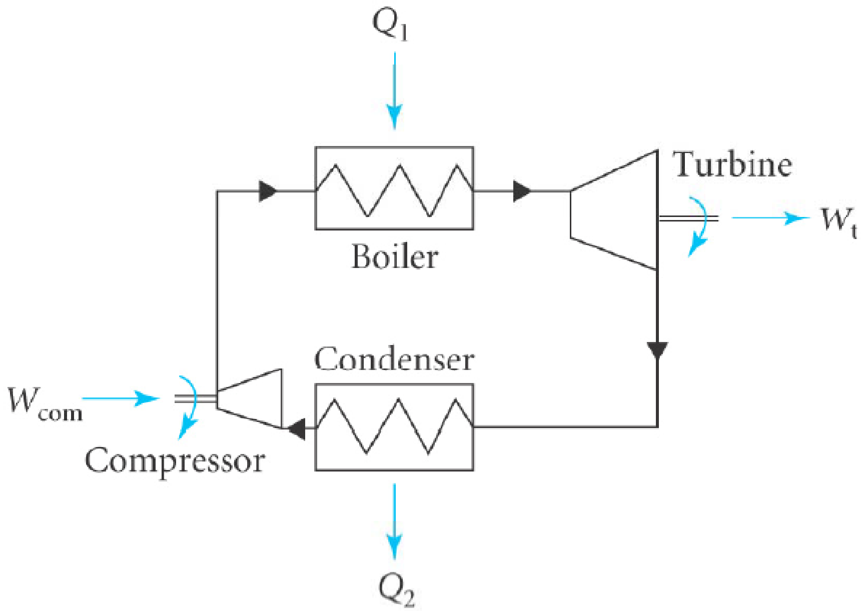
**~0.0023% of incoming solar radiation**
**($4 \times 10^{13}$ W)**
photosynthesis
(cf. annual energy of photosynthesis ~
world commercial energy consumption
(~1020 J)



# Thermal Energy

## 4. Closed cycle for a steam power plant

(1) Compressor (boiler feed pump): work $W_{com}$ done on the system to compress cold **water** from subatmospheric pressure to high pressure
(2) Boiler: heat $Q_1$ added to the system to convert cold water into steam
(3) Turbine: work $W_t$ done by the system (i.e. by steam) on the turbine blades
(4) Condenser: heat $Q_2$ lost from the system to the environment in converting steam back to cold water



# Thermal Energy

After each complete cycle, the working fluid has the same internal energy, U
→ net change in internal energy is zero, $\Delta U = 0$

$$(Q_1 - Q_2) - (W_t - W_{com}) = 0$$

The efficiency of the process, $\eta$ = [net work output]/[heat input]

$$= (W_t - W_{com})/Q_1$$
$$= (Q_1 - Q_2)/Q_1$$
$$= 1 - (Q_2/Q_1)$$

$Q_1$ & $Q_2 > 0 \rightarrow \eta < 1$: system is less than 100% efficient
→ "2nd law of thermodynamics": heat increases the disorder (entropy), no system operating in a closed cycle can convert all the heat absorbed from a heat reservoir into the same amount of work

**Carnot:** maximum possible efficiency of a heat engine operating in a closed cycle between two heat reservoirs depends only on the ratio of the absolute temperatures of the reservoirs *(s-T-s-T constant)*

$$\eta_C = 1 - (T_2/T_1)$$

$T_1$ and $T_2$ are the absolute temperatures (K) of the upper & lower reservoirs

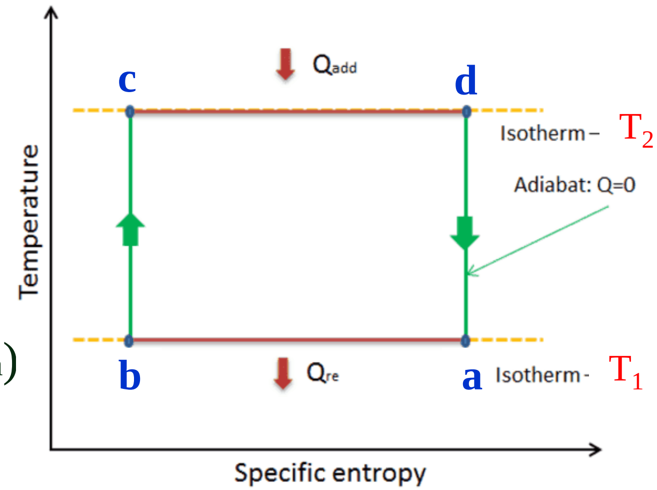
# Thermal Energy

**Efficiency of a Carnot cycle**

Consider ideal gas ($pV = nRT$) operating in the closed cycle *abcda*

*ab* & *cd* are isotherms at $T_1$ & $T_2$;

*bc* & *da* are reversible adiabatics (i.e., no heat transfer with the surroundings)




By the 1st law of thermodynamics,

$$dQ = dU + pdV = C_v dT + pdV$$

($C_v$: specific heat at constant volume)

Along isotherm *ab*, $dT = 0 \rightarrow dQ = pdV$

$$Q_1 = \int pdV = nRT_1 \int (dV/V) = nRT_1 \ln(V_b/V_a)$$

Along *cd*, $Q_2 = nRT_2 \ln(V_c/V_d)$

$$Q_2/Q_1 = [T_2 \ln(V_c/V_d)]/ [T_1 \ln(V_b/V_a)]$$

Along adiabatic *da*, $dQ = 0 \rightarrow C_v dT = -pdV$

$$\rightarrow C_v(dT/T) = -nR(dV/V)$$

$$\rightarrow C_v \ln(T_1/T_2) = -nR\ln(V_a/V_d)$$

Along adiabatic bc, $C_v \ln(T_1/T_2) = -nR\ln(V_b/V_c)$

$\rightarrow (V_a/V_d) = (V_b/V_c)$ or $(V_c/V_d) = (V_b/V_a)$

$\Rightarrow$ $Q_2/Q_1 = T_2/T_1$ $\qquad$ $\eta = 1 - (Q_2/Q_1) = \mathbf{1 - (T_2/T_1)}$

## 6. Disadvantages of a Carnot cycle for a steam power plant

- $T_1$ of the upper reservoir to be constant
  → only achieved along an isobar in region II
  → not possible to operate the boiler in the dry steam region (III) since T rises
  → upper temperature of the cycle, $T_1$, is constrained by the maximum temperature of the two-phase boundary

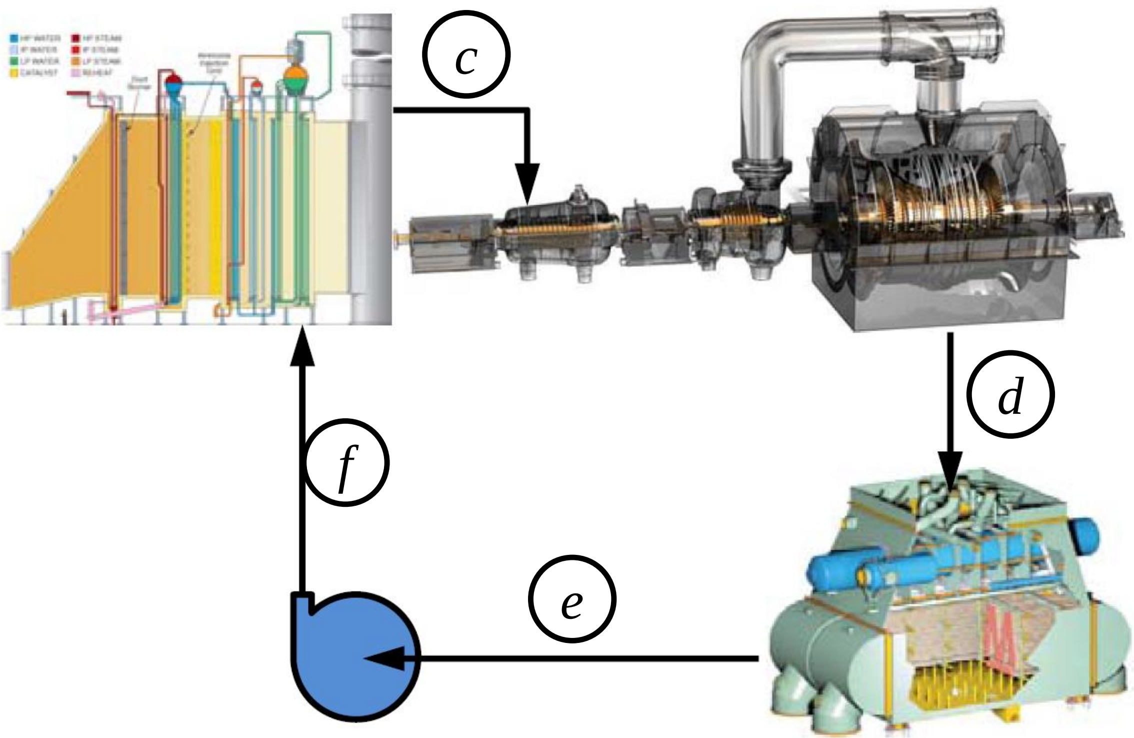
- Another problem arises in the turbine: turbine operates with a two-phase mixture of water and steam (region II) → momentum of fast moving water droplets in the mixture damages the turbine blades and shortens the life of the turbines

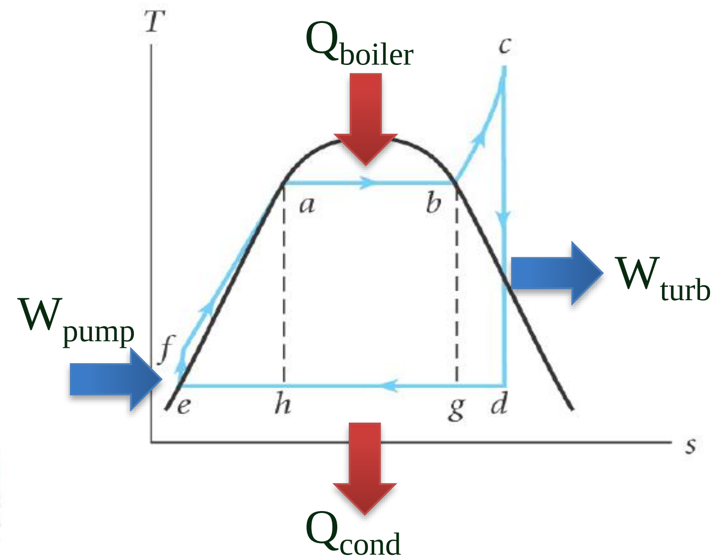
- Same in compressor: damage the blades of the compressor.
  Volume of steam in the mixture is very large → large compressor needed so expensive

- Carnot cycle: impractical for a steam power plant

# Thermal Energy

## 7. Rankine cycle for steam power plants



# Thermal Energy

(2) Rankine cycle with reheat

Reheat is becoming common for the large combined cycle power plants, where inlet pressures and temperatures are rising to those commonly found in traditional fossil power plants.

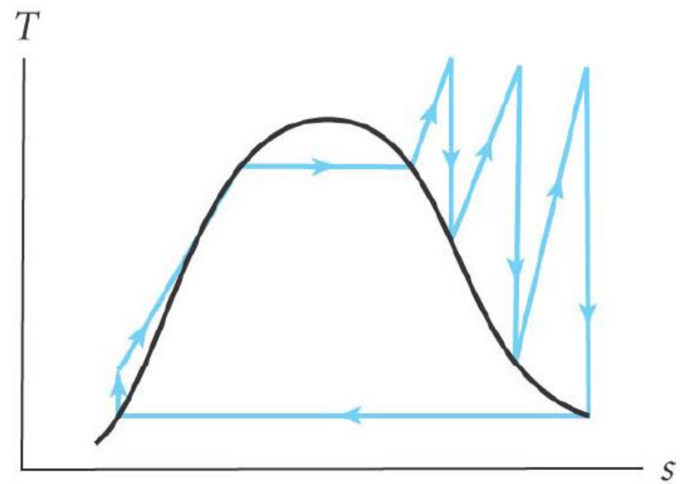
Rankine cycle without reheat: *difficult to completely eliminate water droplets* which have high momentum and wear out the turbine blades

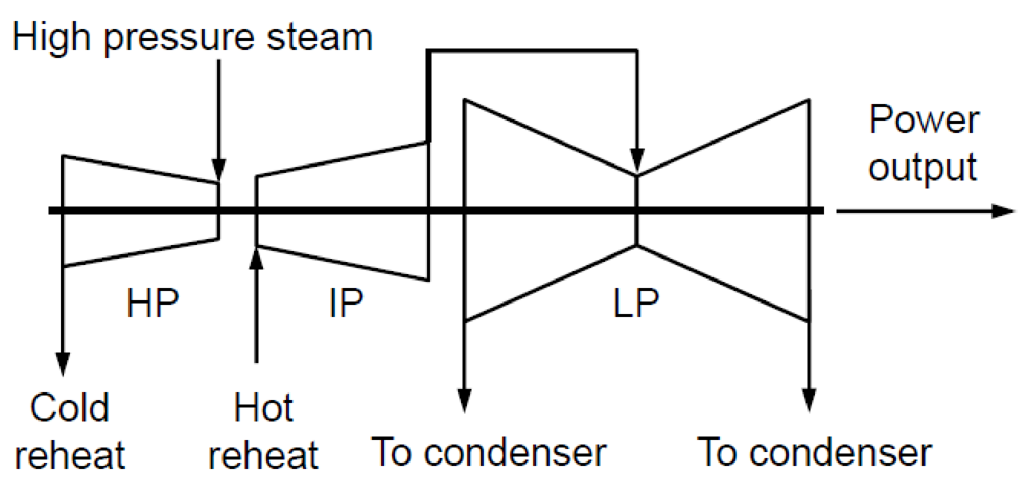
→ "with reheat" is introduced → steam is reheated several times before entering the condenser

→ increase efficiency and eliminate water droplets

Maximum operating temperature in the superheater: 650°C (손상방지를 위해)

Efficiency of the state-of-the-art technology:  40~45%

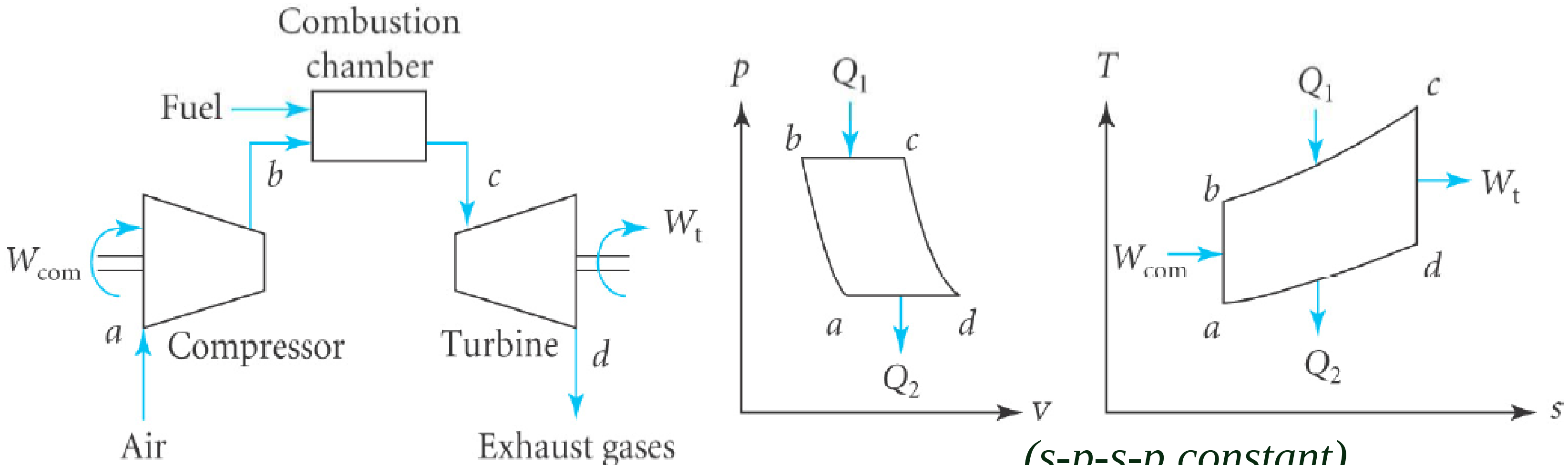


# Thermal Energy

## 8. Gas turbines & the Brayton (or Joule) cycle

- Gas turbine: gaseous products of combustion is 1100 ~ 1600°C (ceramic coating on turbine blades, thermal barrier coating, TBC)
- Gas turbine for power generation is originated from the jet turbine engine
- Jet engine: combustion of gaseous fuel & expansion of exhaust gases
  → same phase, no condenser,
  → smaller and cheaper than steam engine
- Brayton (or Joule) cycle: atmosphere acts as the heat exchanger ➔ ***closed cycle***




*(s-p-s-p constant)*

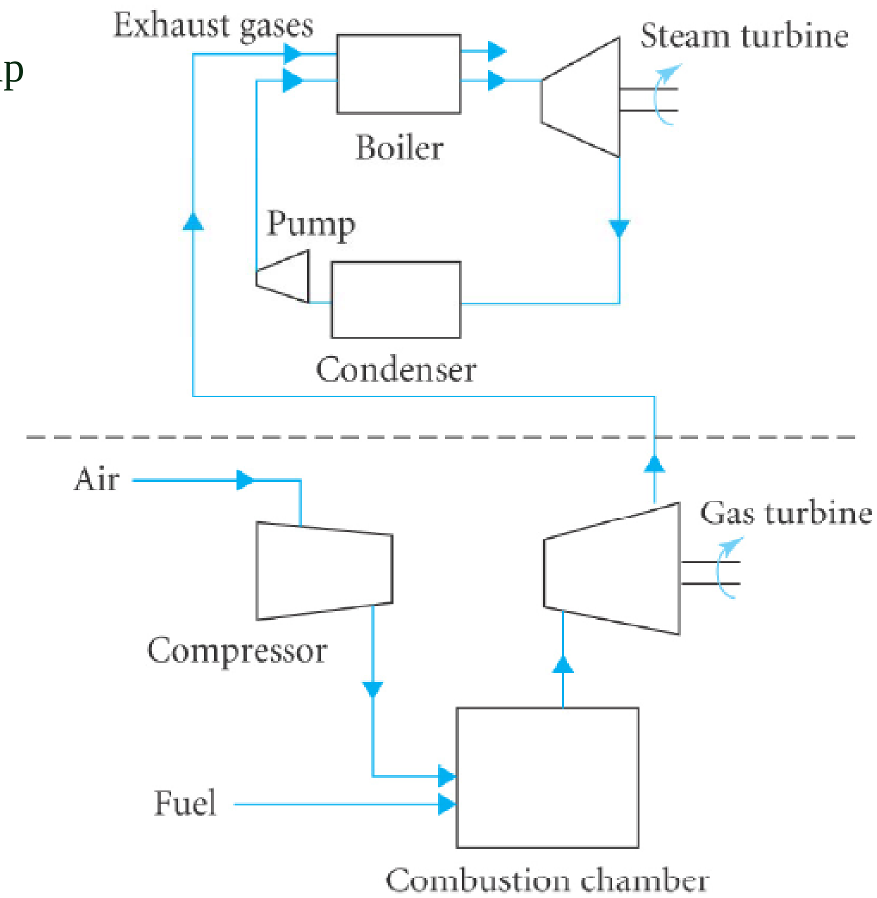
# Thermal Energy

## 9. Combined cycle gas turbine (CCGT)

- Hot exhaust gases from gas turbine used to heat up the water for steam power plant
  (HRSG, heat recovery steam generator)

- Increase the cycle efficiency: CCGT
  → η ~60%

- Combined heat and power cycle (CHP)
  → η ~80%
  - condenser is generally operated at the higher temperature than steam power plant
  - Waste heat is used for the local heating nearby
  - Disadvantage: expensive → can be used for highly populated area or industrial complex



# Thermal Energy

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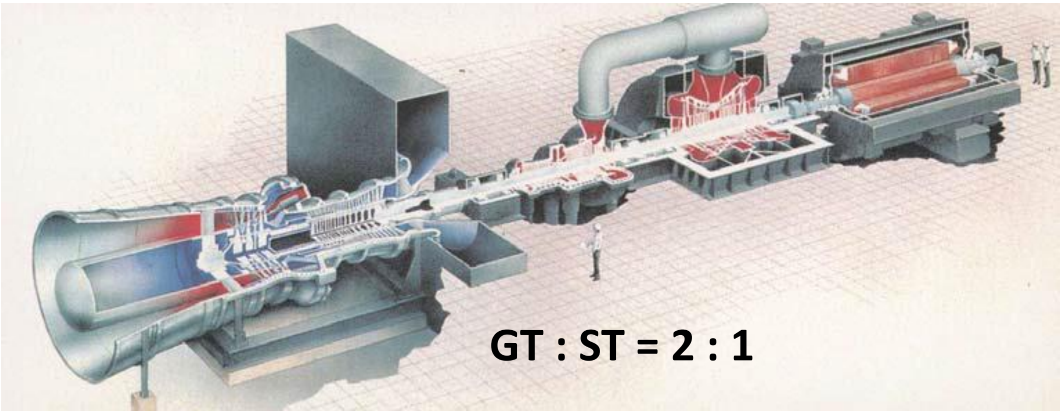


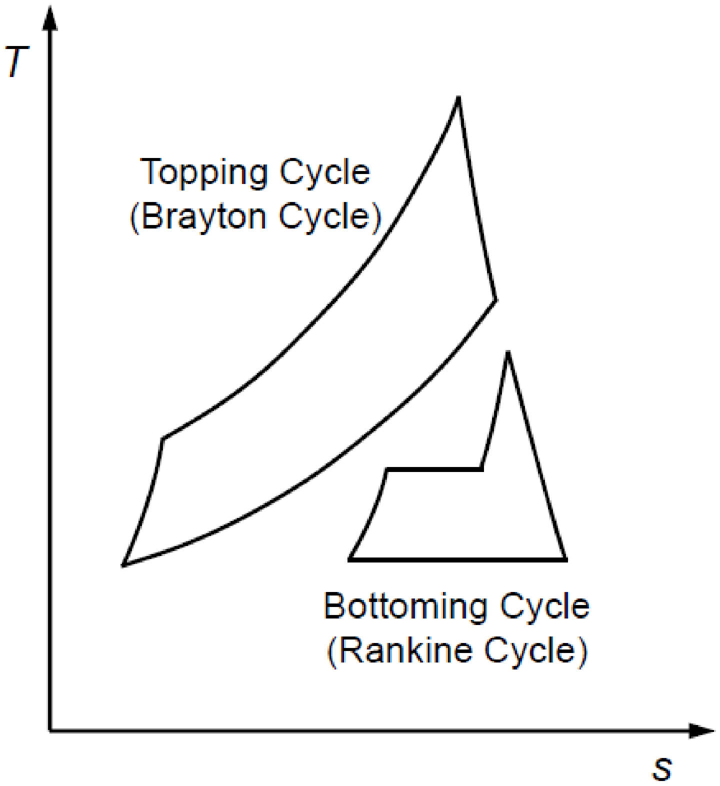

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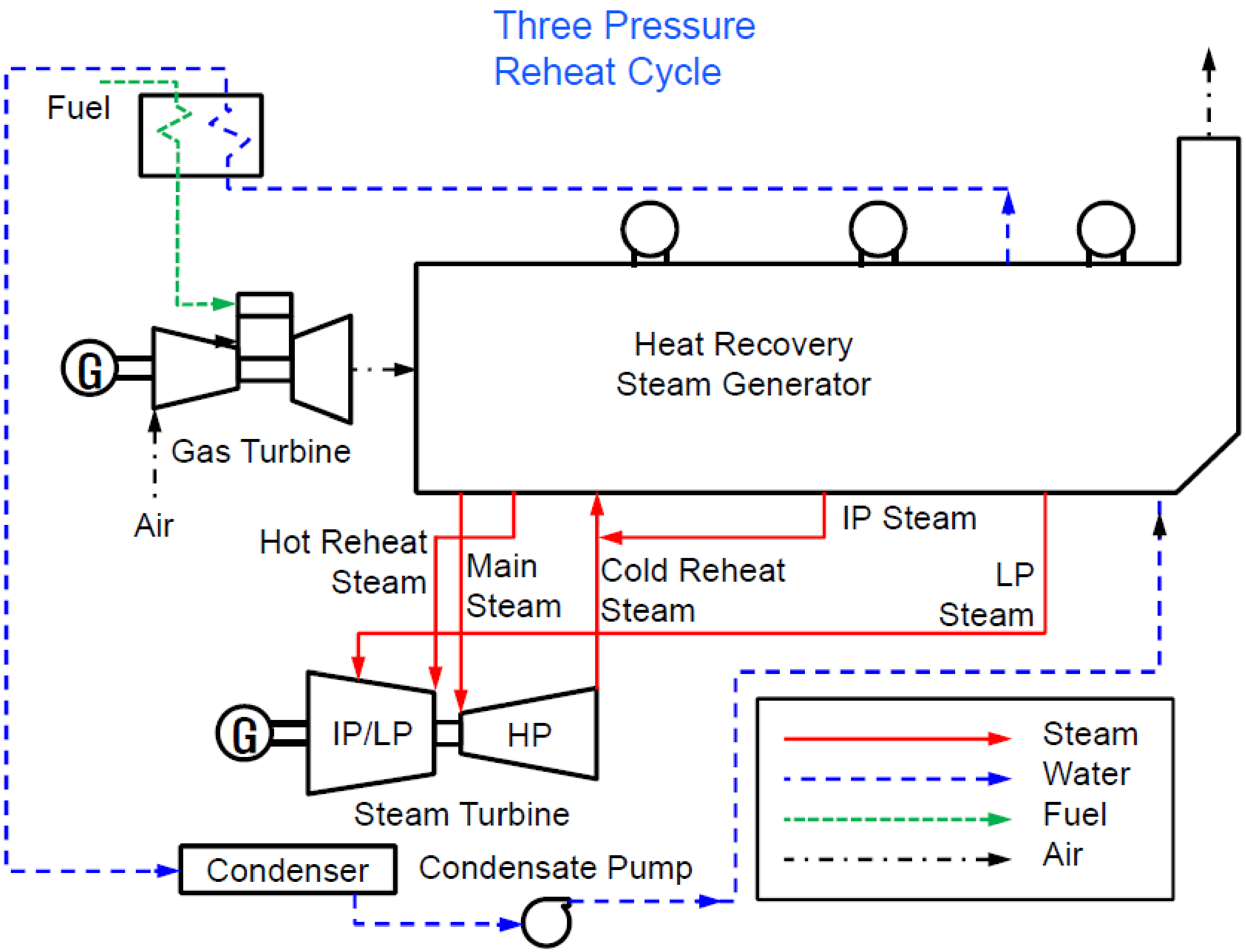
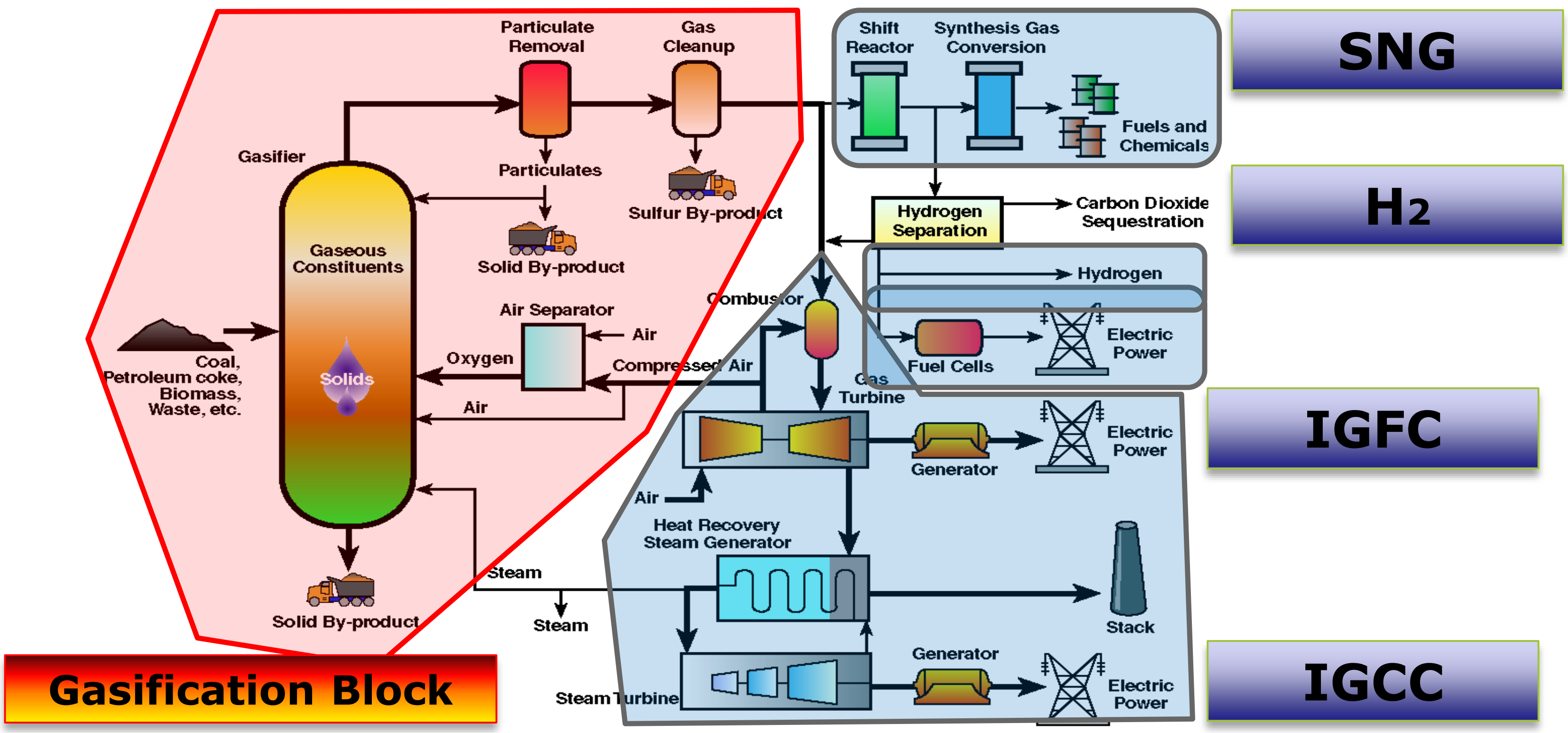


# Thermal Energy

## 12. Gasification

- IGCC (Integrated Gasification Combined Cycle)
- IGFC (Integrated Gasification Fuel Cell)
- SNG (Synthetic Natural Gas or Substitute Natural Gas )



# Thermal Energy

- IGCC can be efficiently combined with carbon capture and storage (CCS)