Energy and the Built Environment
CRP 470.004 /570.004

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Lecture 4

Thermodynamics, Thermal Power plants, and combustion

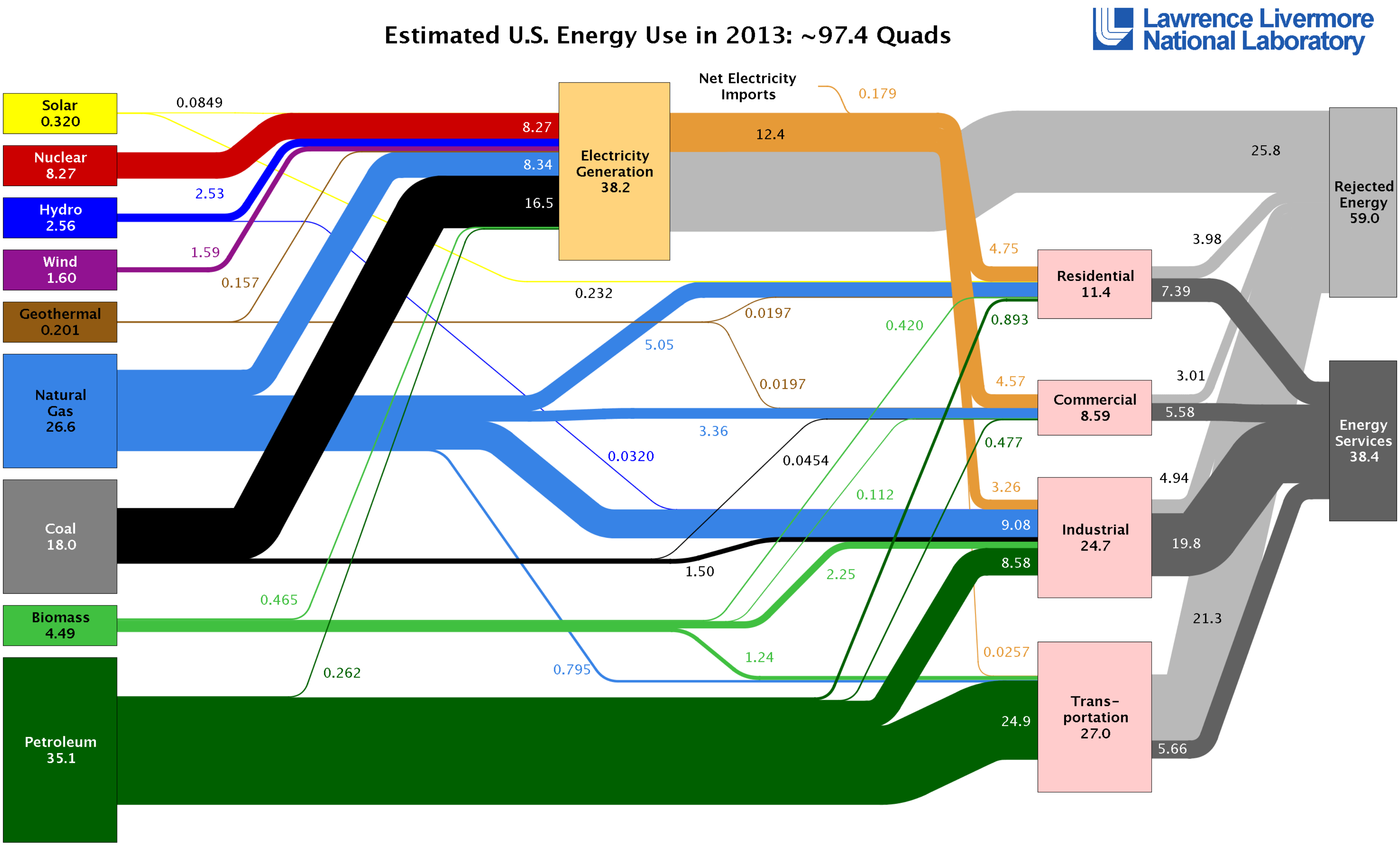
Outline

- Review
- Power plants
- Thermodynamics
- 1st Law of Thermodynamics
- 2nd Law of Thermodynamics
- Carnot System
- Efficiency
- Combustion stoichiometry

Review – a few questions

1. What are the primary global energy challenges (3)
2. What percent of our power comes from coal?
3. Where does most of our oil come from?
4. What are energy services?
5. How many people in the world lack access to electricity?

Sankey Diagram of US energy use

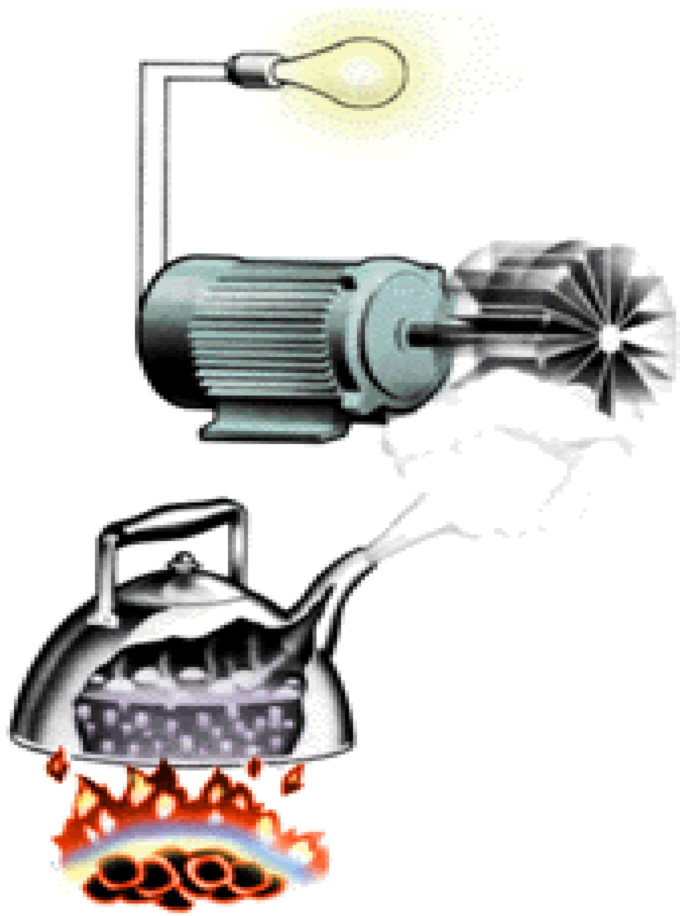


Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

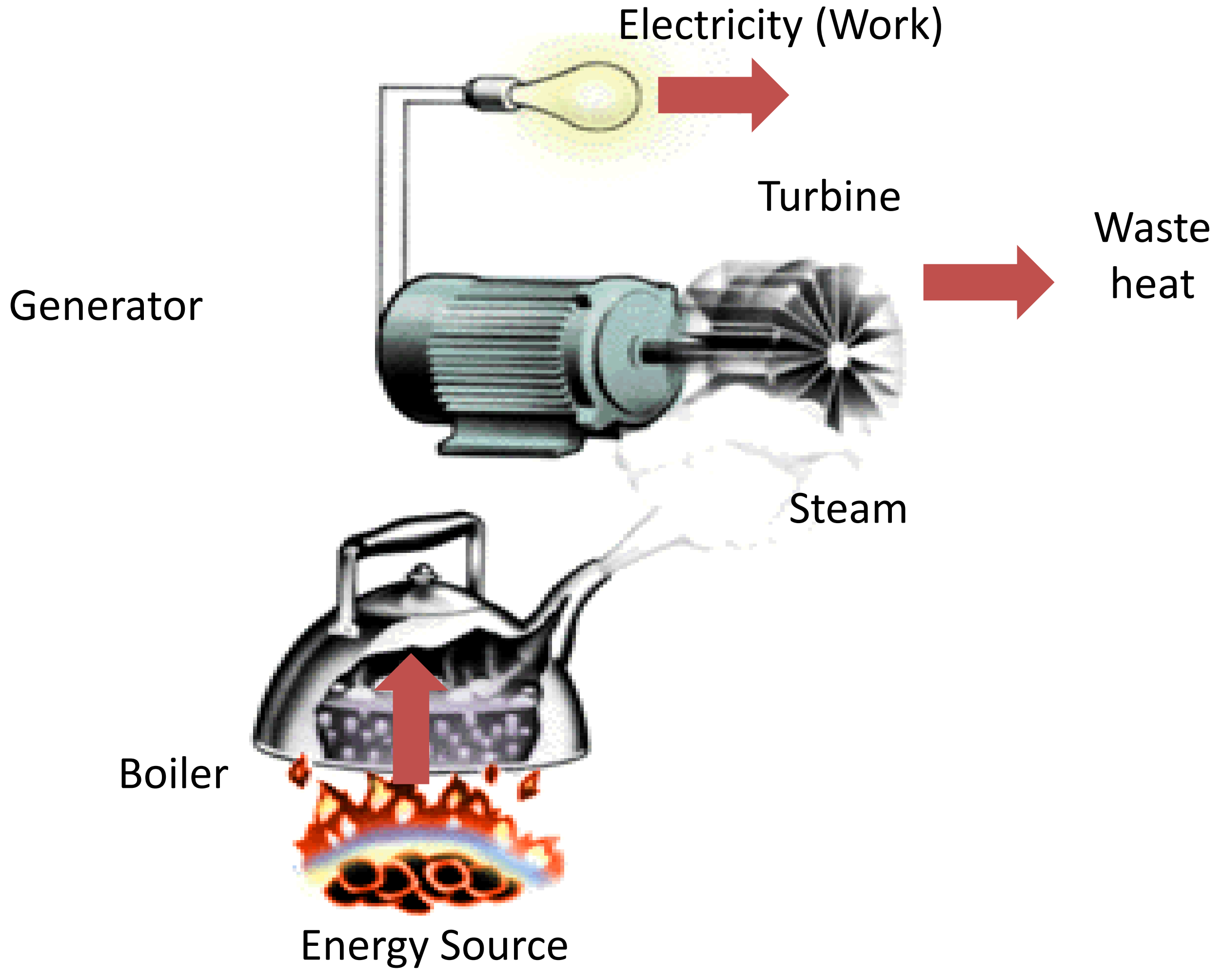
Why does thermo matter?

- Efficiency matters…. A LOT!
- 60 % of our primary energy ends up as rejected heat. Why?
- Half of our energy consumption in homes and buildings are energy services that use electricity
- 87% of our electricity comes from thermal power plants

Thermal power plants

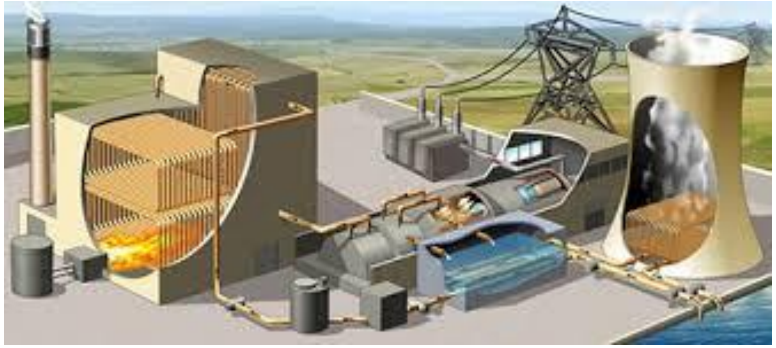


Thermal power plants

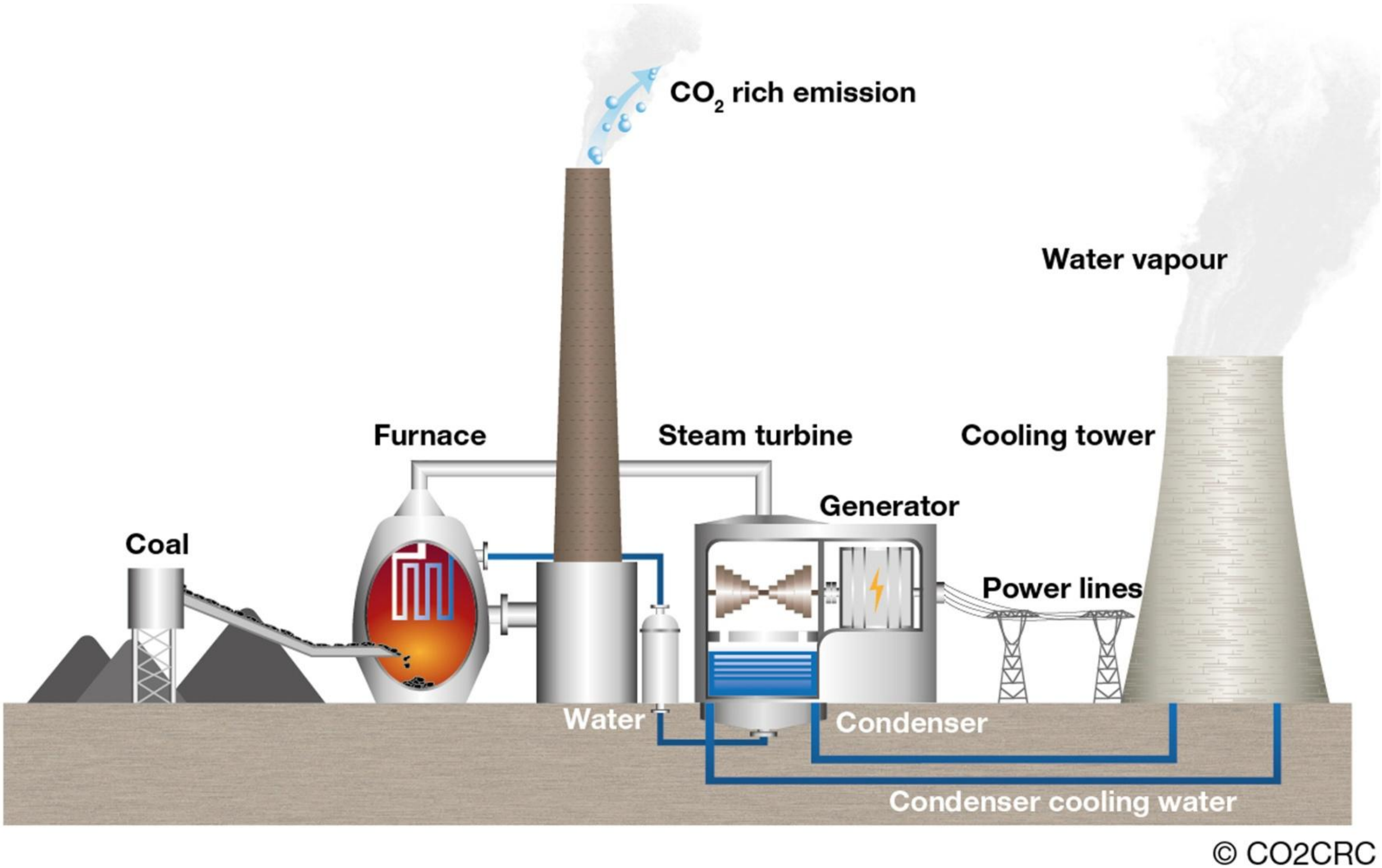


Types of thermal power plants

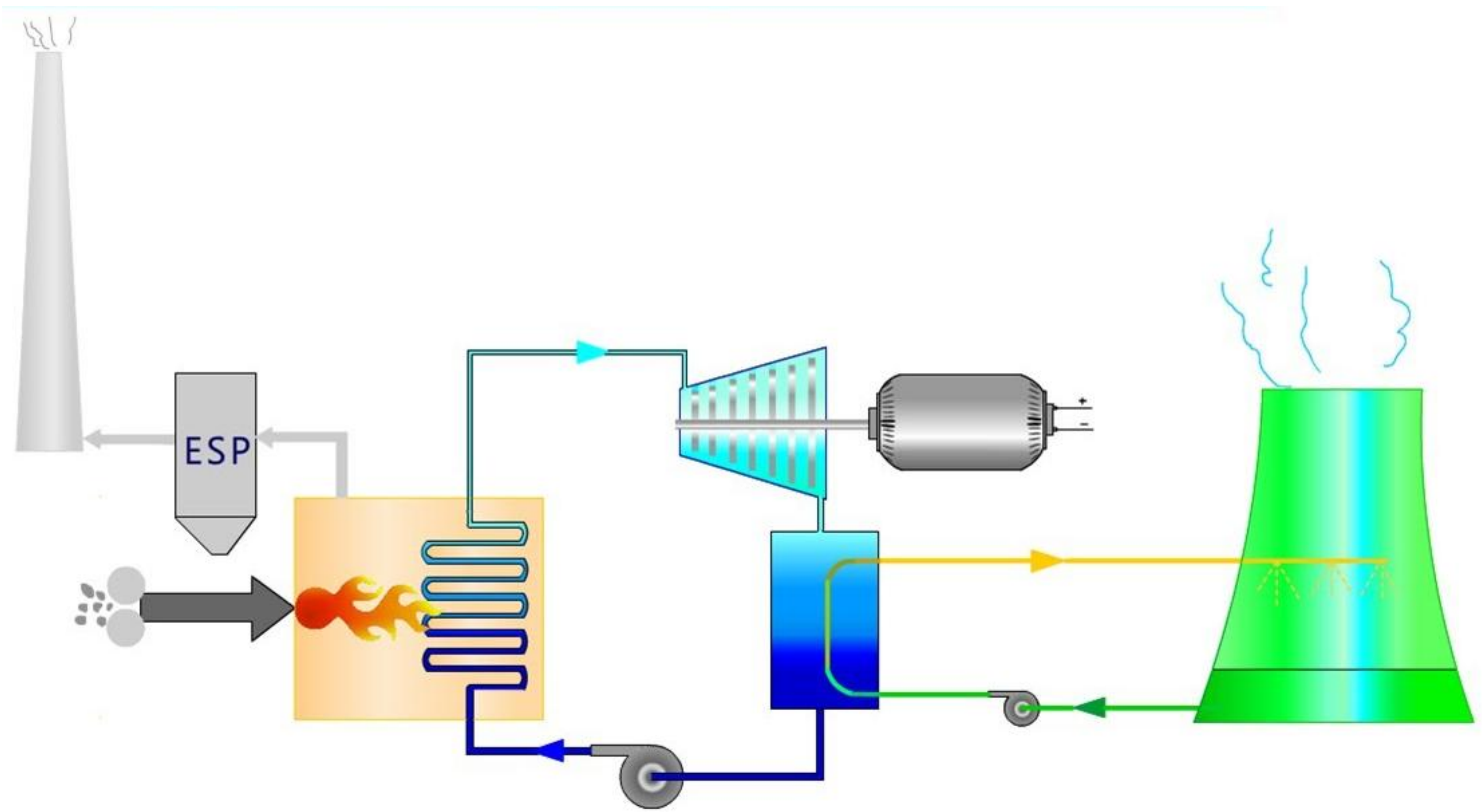
- Coal plants
- Natural gas plants
- Nuclear plants
- Solar thermal plants
- Geothermal plants
- Biomass-based plants
- Diesel plants (internal combustion engines - ICE)



Thermal power plants

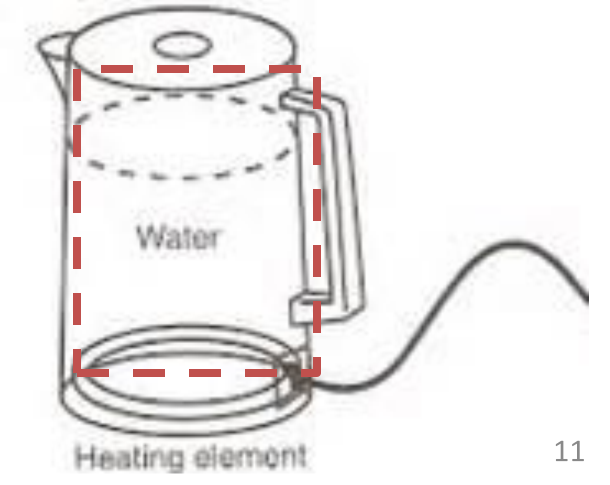


Thermal power plant



Thermodynamic system

- **Thermodynamics** describes the changes in energy of a **thermodynamic system.**
- These changes occur across a **defined boundary**, between the system and its surroundings.
- Energy is transferred to/from a system in the form of heat (Q), work (W), or mass flow

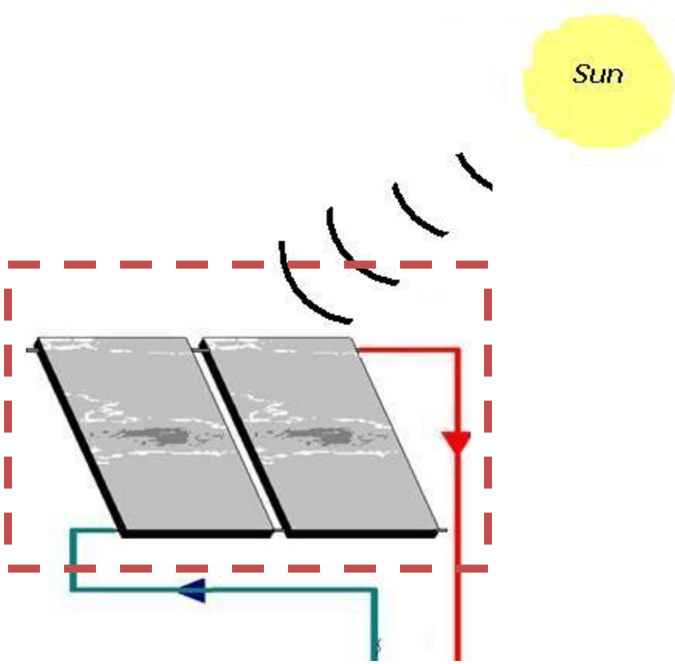


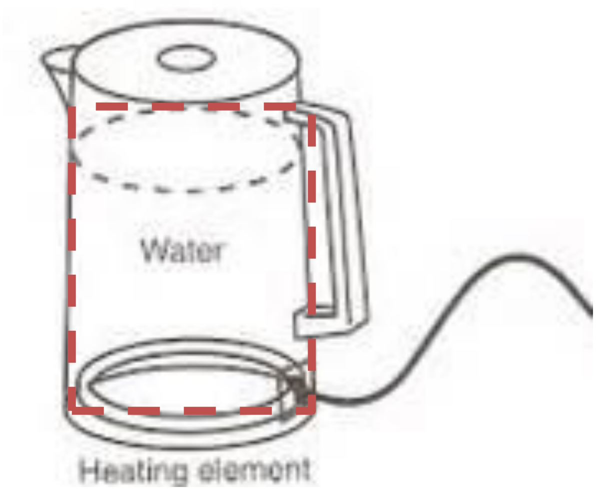
Total energy - E

- The sum of all macroscopic and microscopic forms of energy
- $E = U + KE + PE$
  - where U is the internal energy (microscopic) energy due to the motion and forces of the molecules/atoms.

Closed/Open systems

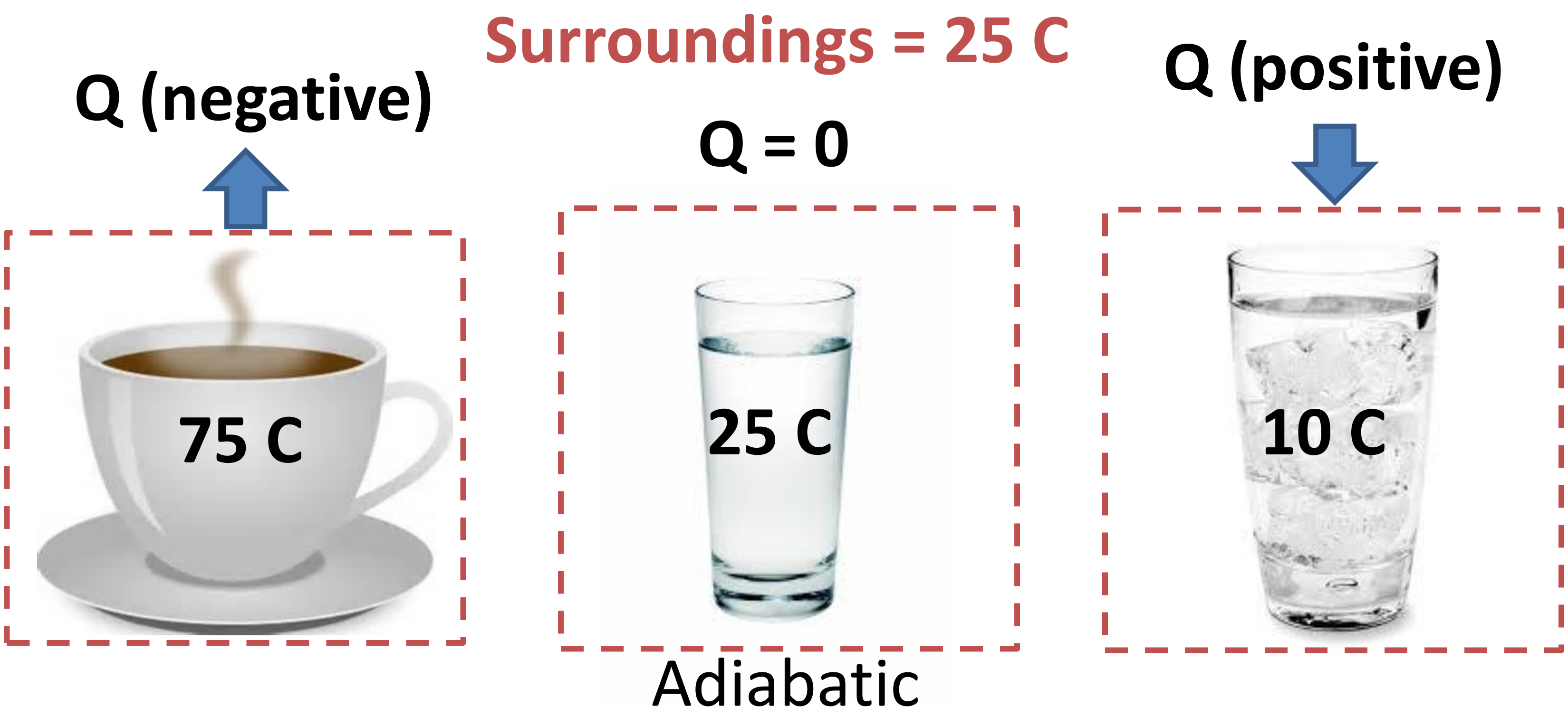
- Energy can only be transferred via heat or work in a **closed system.**
- The walls of an **open system** allow transfer both of matter and of energy.





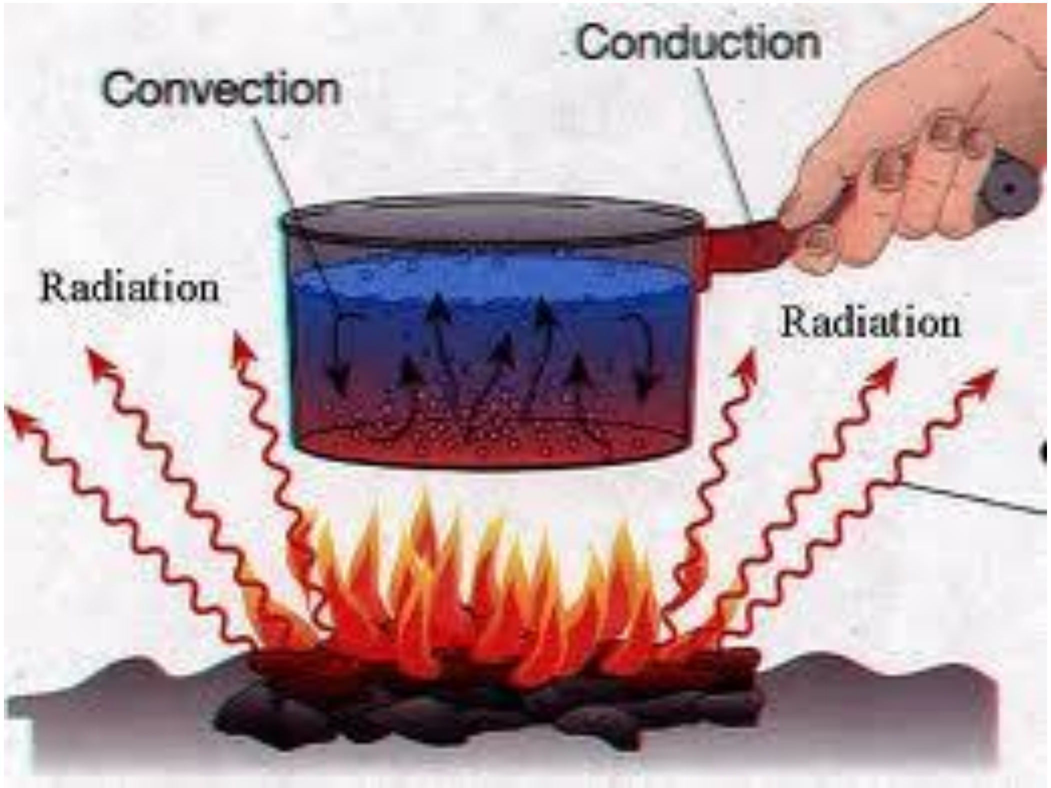
Heat Transfer

- Heat is the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.
- Like work, it is measured at the system boundary, in units of Joules.



3 mechanisms of heat transfer

- Conduction
- Convection
- Radiation

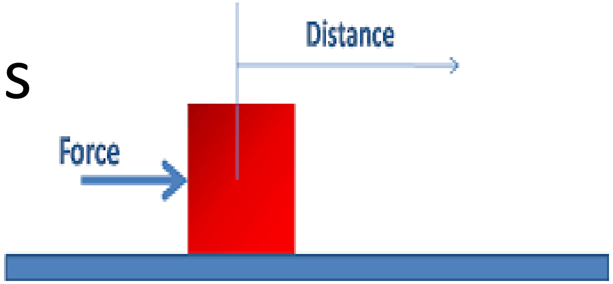


Work

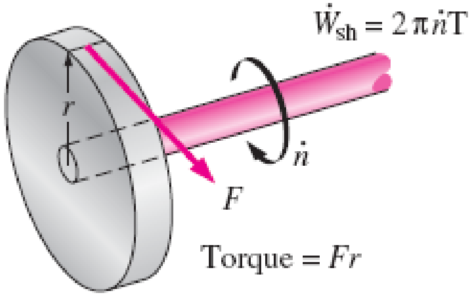
- Work is defined as a force acting over a distance, or W = Fs.
- Work is a measure of energy (Nm = J).
- Power: $\frac{dW}{dt} = \dot{W}$ (J/s = W)

3 common types of work

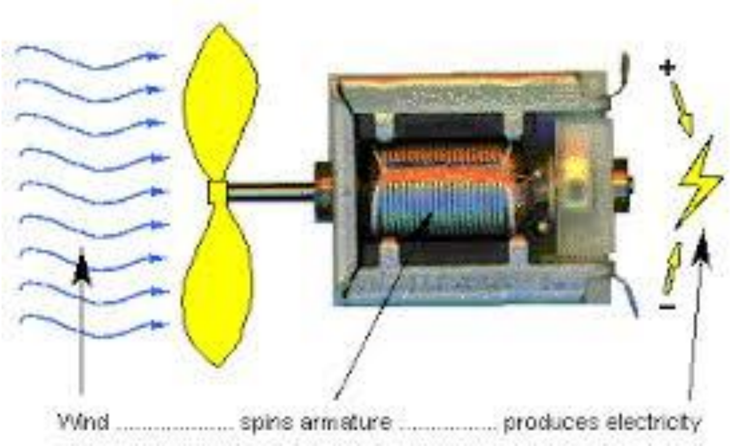
1. Accelerating or raising a mass



2. Shaft work

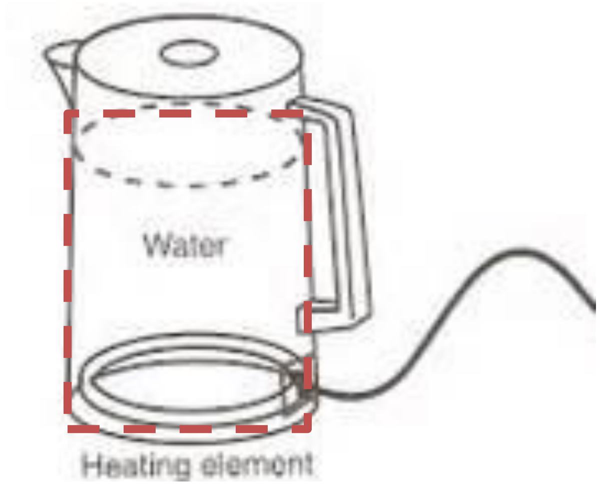


3. Electrical work

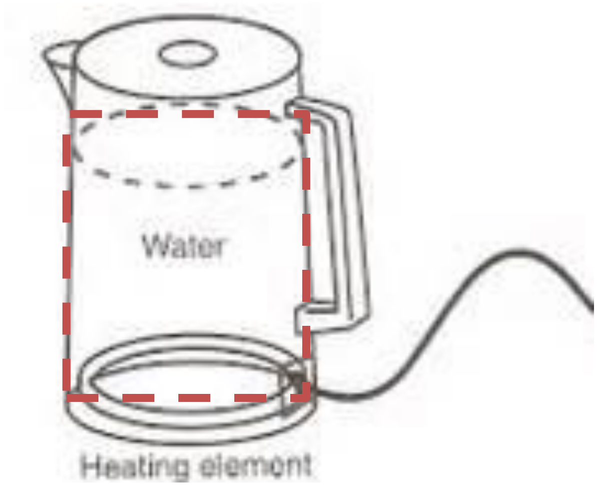


Through what process is the internal energy of the system changed?

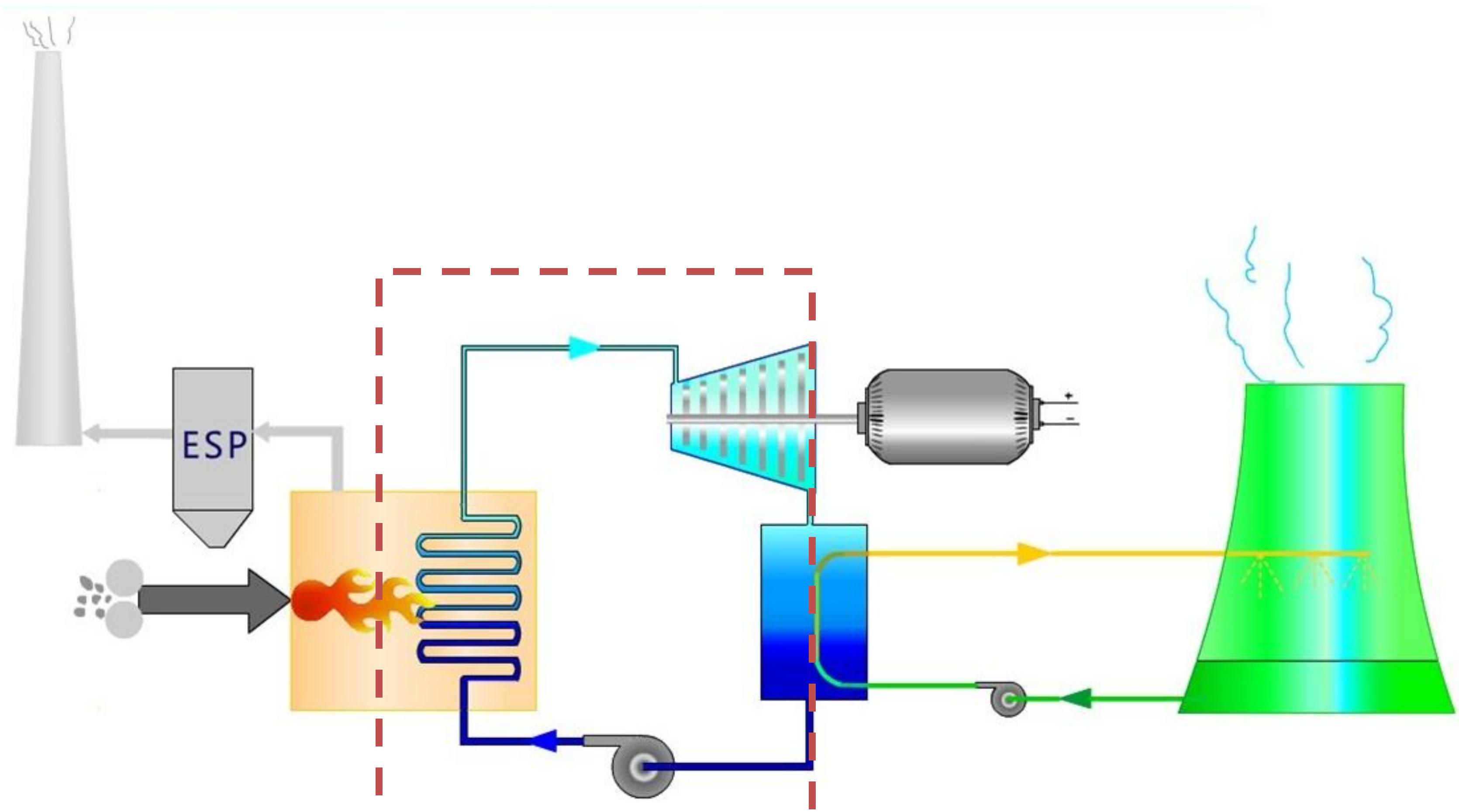
A



B



How is energy entering/leaving this system?



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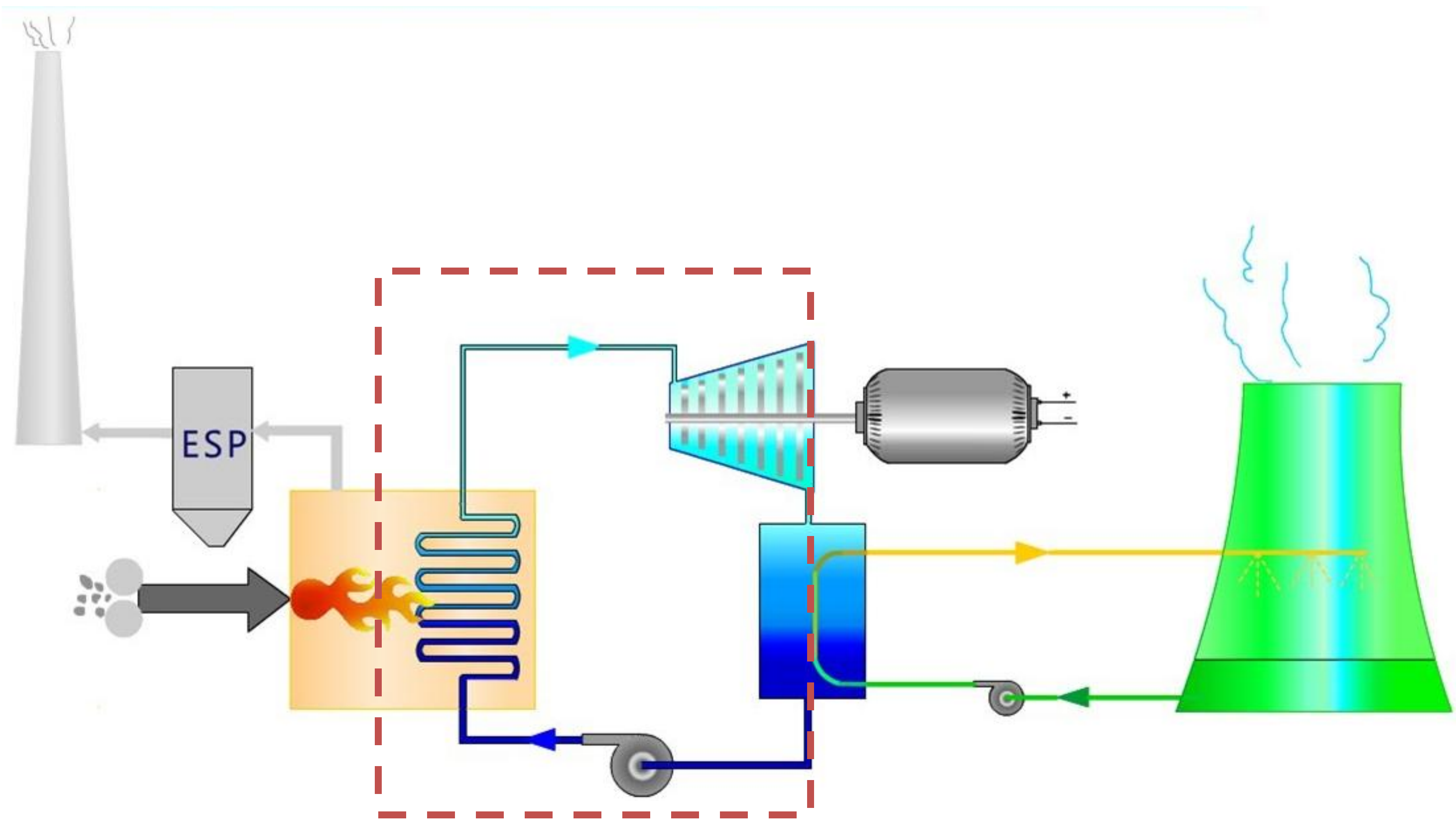


1st Law of Thermodynamics

- Energy cannot be created or destroyed
- Energy must be conserved in an isolated system
- It is about accounting for energy flows…

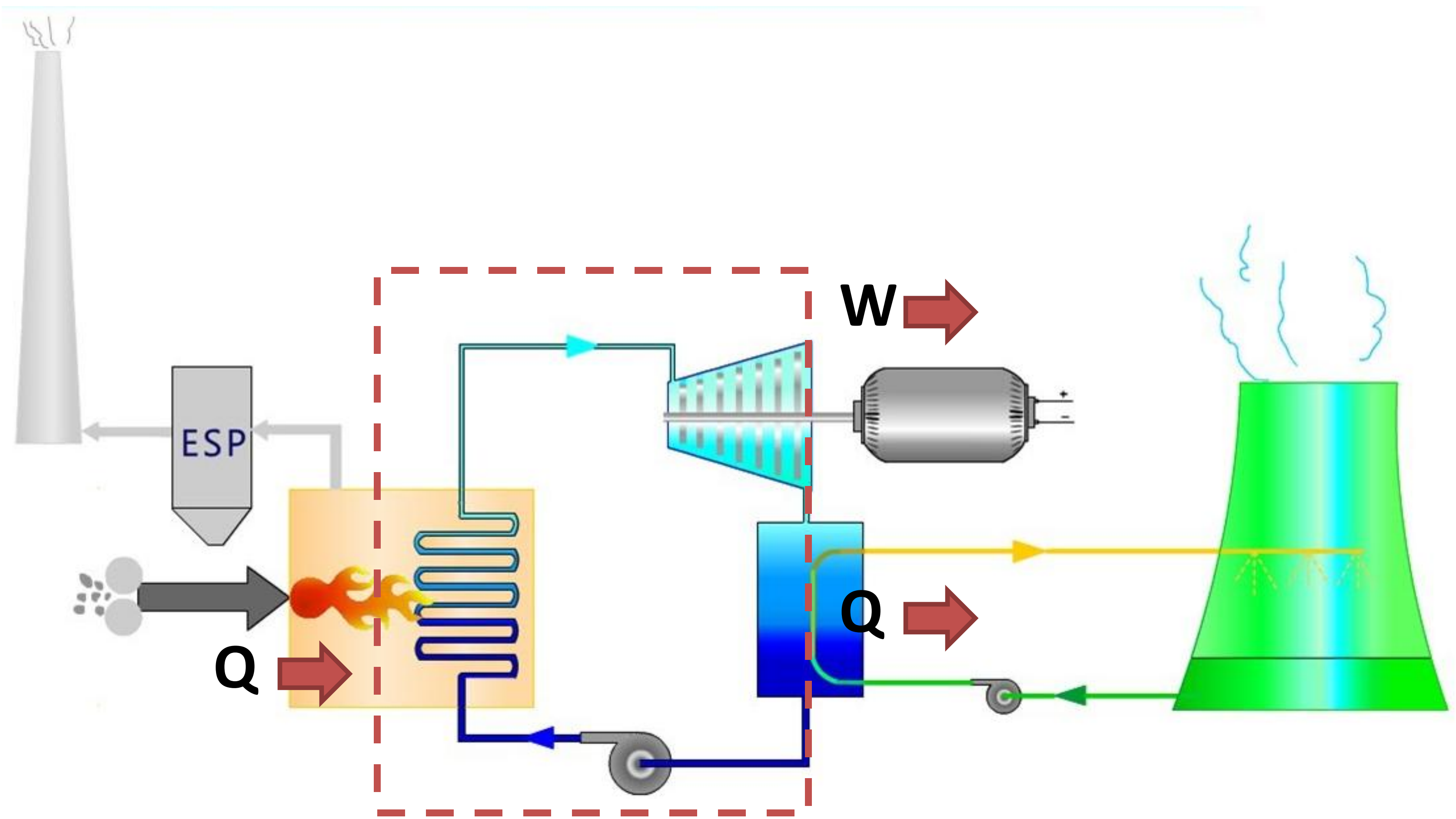
2nd Law of Thermodynamics

- No process can occur that only transfers energy from a cold body to a hot body (heat must flow from hot to cold)
- No process can occur that converts a given quantity of thermal energy into an equal quantity of mechanical work (Some energy will always end up as heat)
- Order tends to disorder

2nd Law of Thermodynamics, alternate statements:

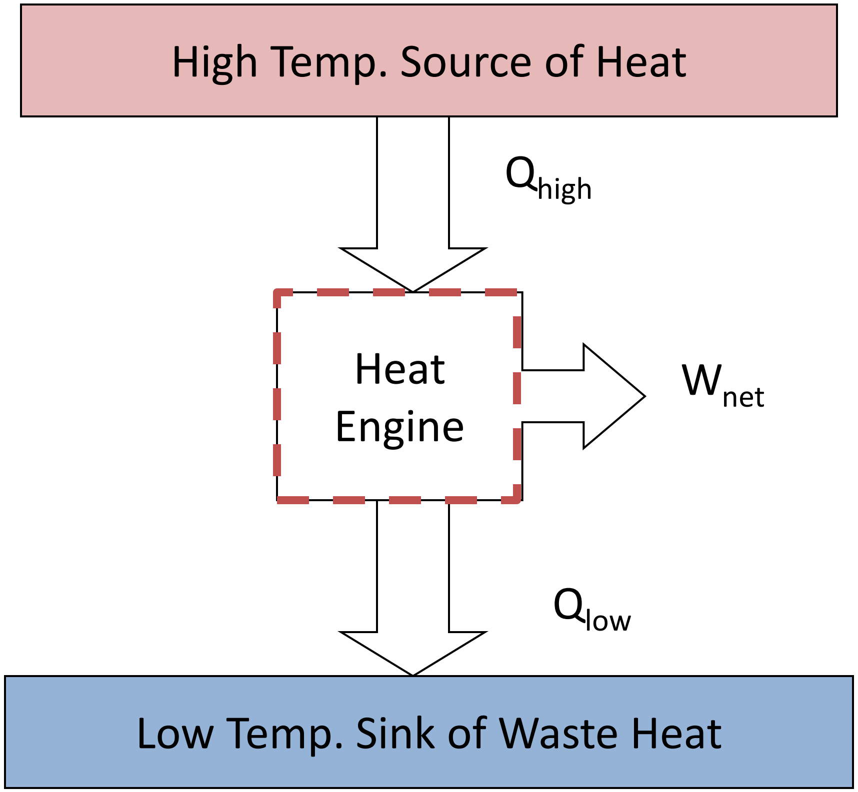
- states in which direction a process can take place
  - heat does not flow spontaneously from a cold to a hot body
  - heat cannot be transformed **completely** into mechanical work
  - it is impossible to construct an operational perpetual motion machine

Thermal power plant



Heat Engine

- Used to approximate thermal systems



Energy Balance: $Q_{high} = W_{net} + Q_{low}$

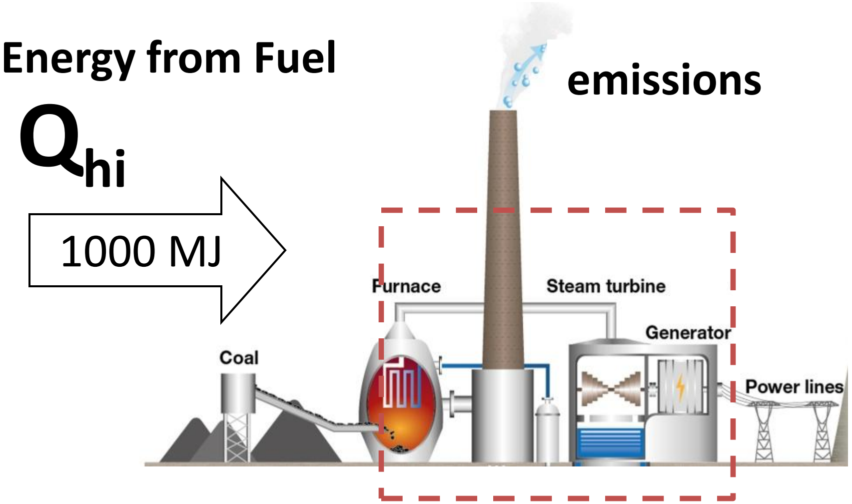
Forms of Energy

- High Temp Source of Heat: This is the source of energy that drives the power plant (heat of combustion, geothermal heat source, nuclear reactor, etc.).
- Q_{high}: This is the heat transferred from the hot source.
- Heat Engine: This includes the working parts of the power plant (including pumps, turbines, heat exchangers, condensers, etc.).
- W_{net}: This is the net amount of work that exits the power plant. A turbine generates energy, but the pumps and compressors use energy.
- Q_{low}: This is the rejected or waste heat, which is dumped to a cold source (i.e. river, atmospheric air, lake, etc.).
- Low Temp Sink of Waste Heat: This is the reservoir (river, air, lake, etc.) that the waste heat is dumped into.

<u>Energy</u> Balance for a Power Plant

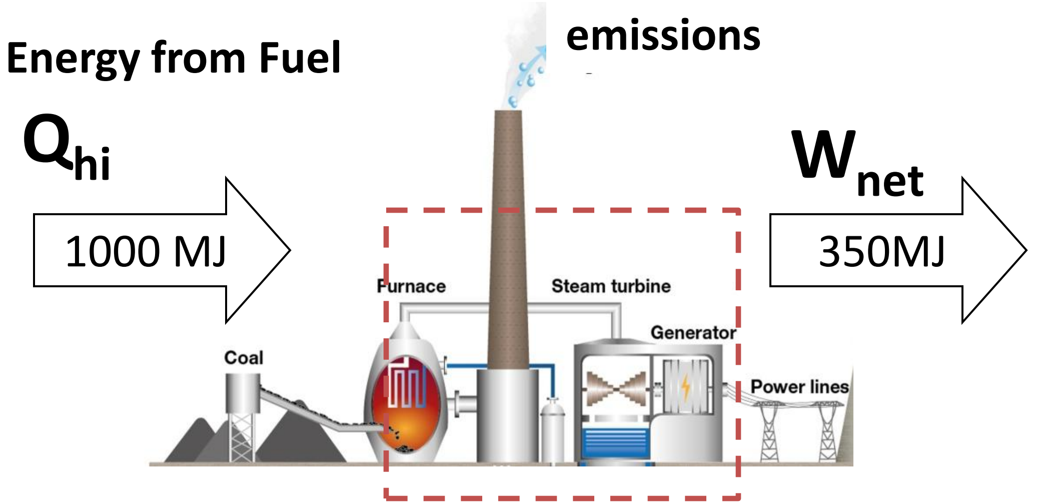
Energy from Fuel

$\mathbf{Q_{hi}}$



$\mathbf{Q_{hi} = 1000\ MJ}$

Energy Balance for a Power Plant



Q_{hi} = 1000 MJ

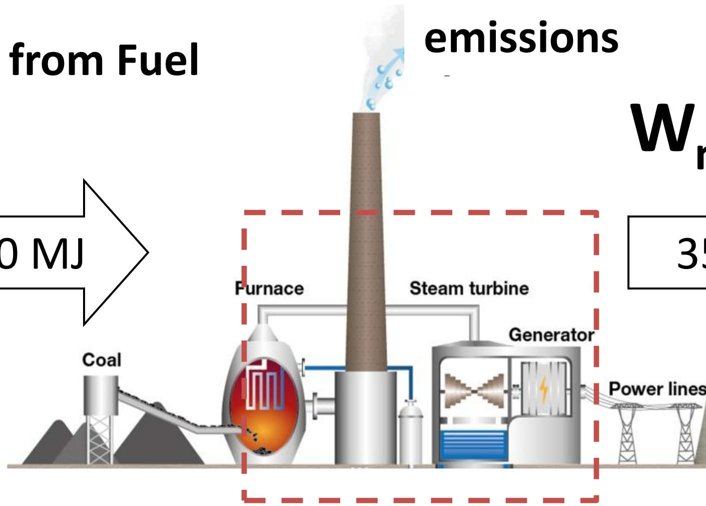
W_{net} = 350 MJ

Energy Balance for a Power Plant

Energy from Fuel

Q_{hi}

1000 MJ



W_{net}

350MJ

Q_{waste}

650 MJ

Q_{hi} = 1000 MJ

W_{net} = 350 MJ

Q_{lo} = 650 MJ

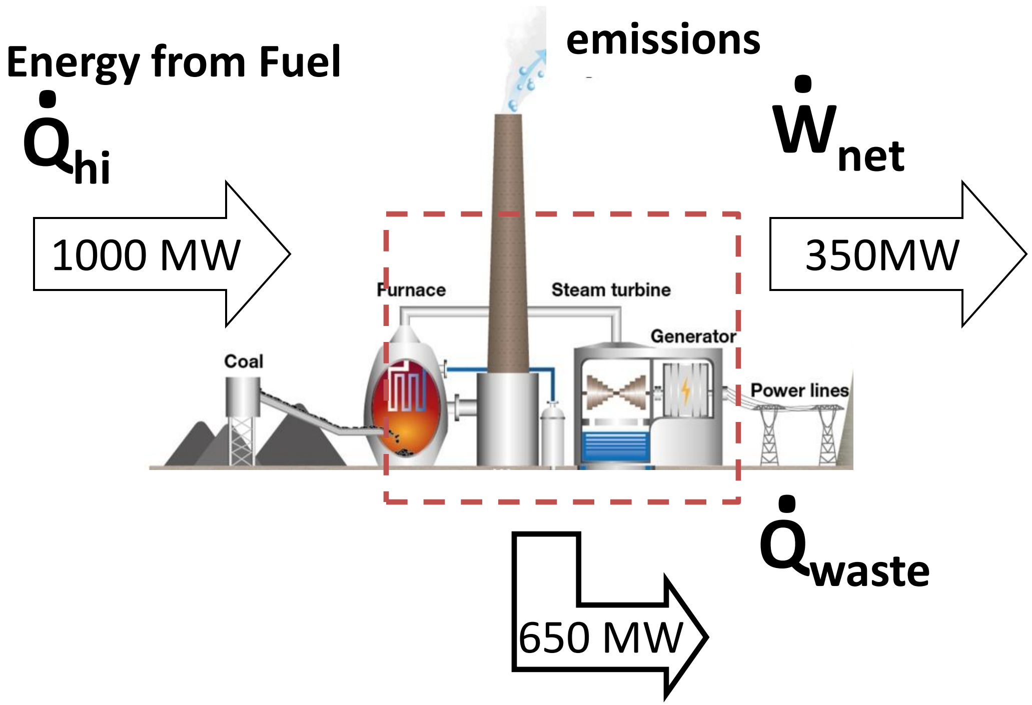
$$\Delta Q = W_{net}$$

$$Q_{hi} - Q_{lo} = W_{net}$$

$$Q_{hi} = Q_{lo} + W_{net}$$

1000 MJ = 350 MJ + 650 MJ

Power Balance for a Power Plant



$\dot{Q}_{hi} = 1000$ MW

$\dot{W}_{net} = 350$ MW

$\dot{Q}_{lo} = 650$ MW

$$P_{in} = P_{out}$$

$$P_{in} = P_{out\ 1} + P_{out\ 2}$$

$$P_{fuel} = P_{useful} + P_{waste}$$

1st Law Efficiency

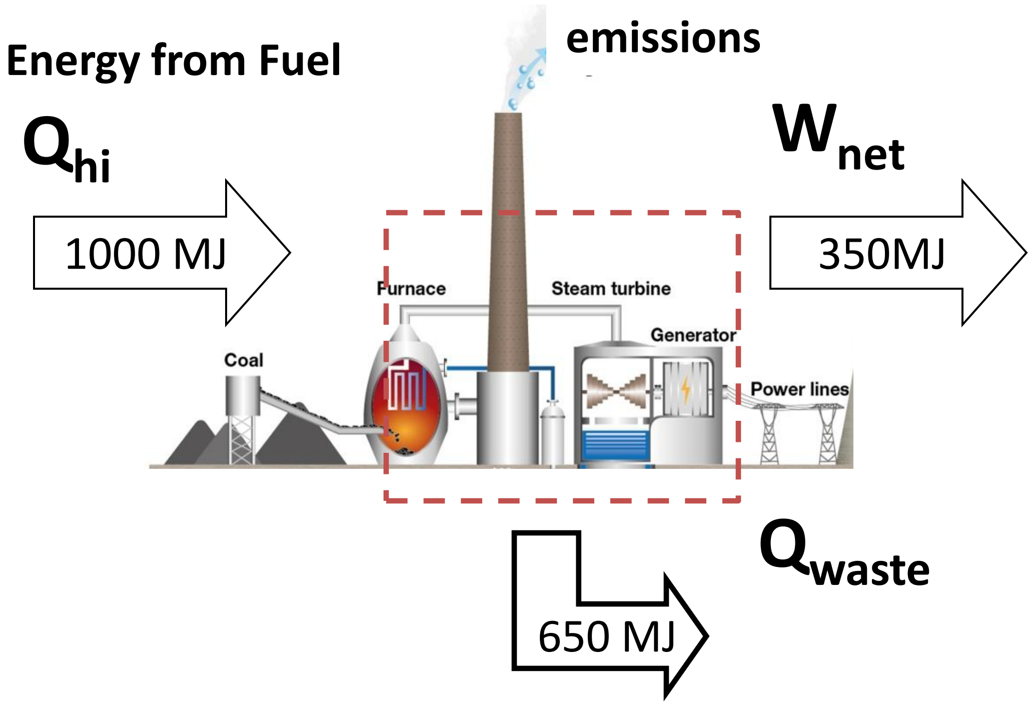
$$Efficiency = \left(\frac{what \quad you \quad want}{what \quad you \quad pay \quad for} \right)$$

Several names:

η_I =1st Law, Actual, or Thermal Efficiency

$$\eta_1 = \frac{W_{net}}{Q_{in}} = \frac{Q_{hi} - Q_{lo}}{Q_{hi}}$$

Energy Balance for a Power Plant



Q_{hi} = 1000 MJ

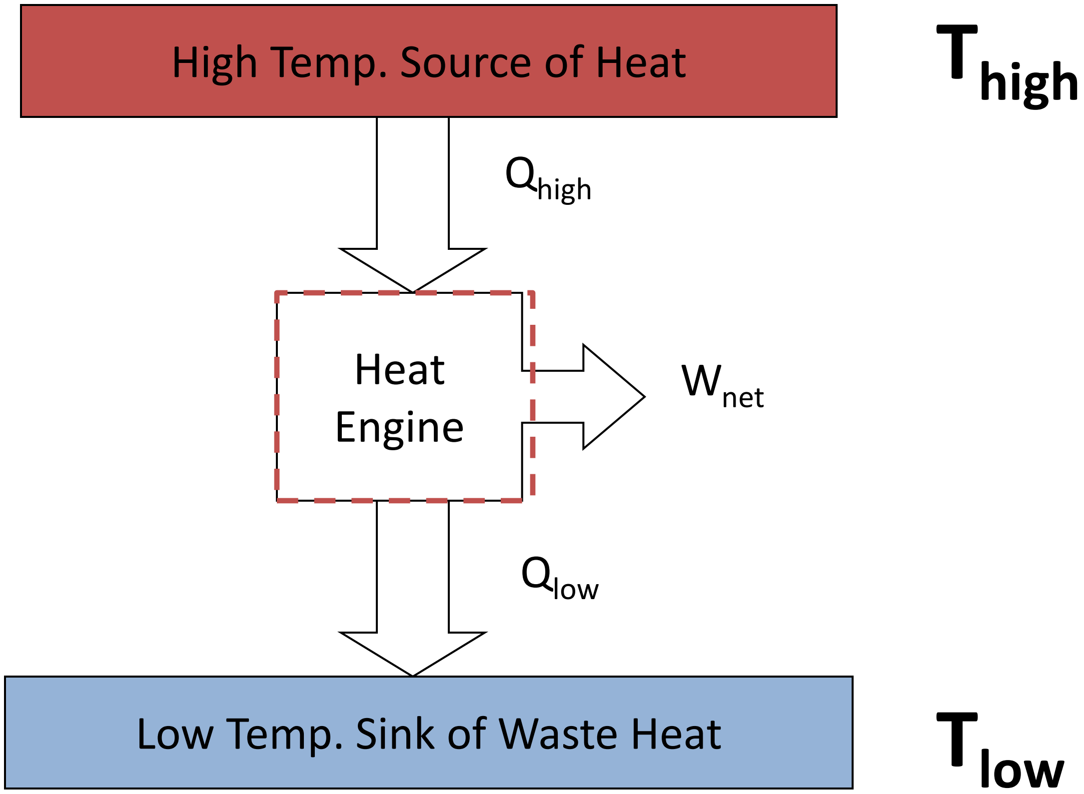
W_{net} = 350 MJ

Q_{lo} = 650 MJ

1000 MJ = 350 MJ + 650 MJ

$$\eta_1 = \frac{W_{net}}{Q_{in}} = \frac{Q_{hi} - Q_{lo}}{Q_{hi}} = \frac{350MJ}{1000MJ} = 0.35$$

Heat Engine



$$\eta_c = 1 - (T_{low}/T_{high})$$

2^{nd} Law of Thermodynamics and Carnot Efficiency

- **2nd Law:** Heat cannot be converted to work without creating some waste heat.
- **Carnot Efficiency:** The net work produced and the heat into the system only depend on temperatures. No thermal system can be more efficient than the Carnot efficiency.
- **Important:** Temperatures must be in units of Kelvin or Rankin.

$\eta_c = W_{net}/Q_{high} = (T_{high} - T_{low})/(T_{high})$

$\eta_c = 1 - (T_{low}/T_{high})$

K = ºC + 273.15

R = ºF + 459.67

2^{nd} Law Efficiency

The 2^{nd} law efficiency is a comparison of the system's thermal efficiency to the maximum possible efficiency.

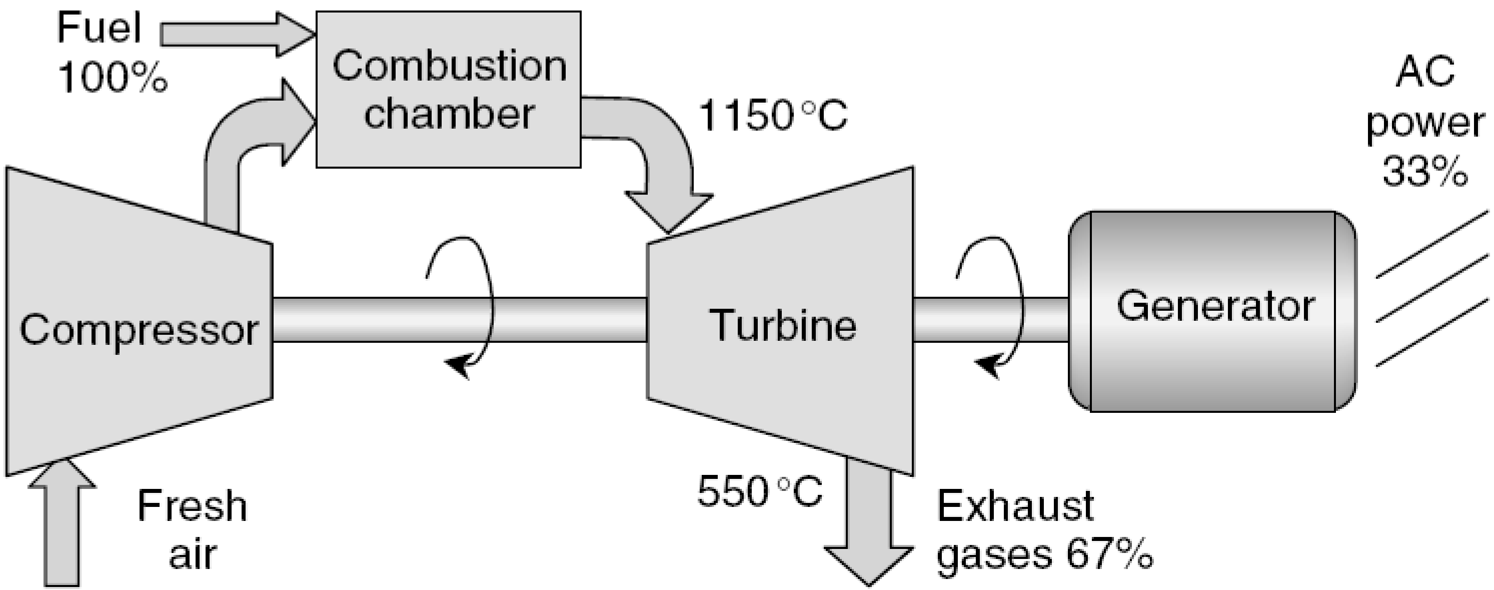
η_I = 1^{st} law efficiency or thermal efficiency

η_c = Carnot efficiency

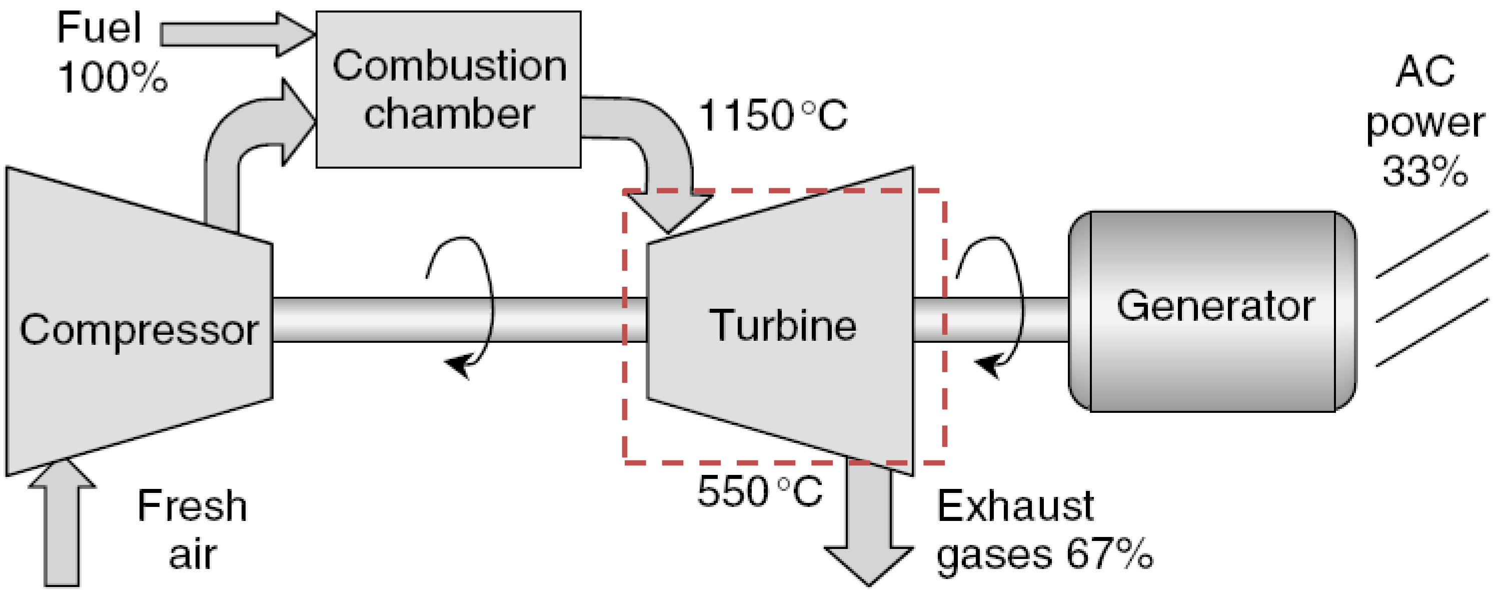
η_{II} = 2^{nd} law efficiency (effectiveness)

$$\eta_{II} = \frac{\eta_I}{\eta_C}$$

Carnot efficiency of a gas turbine

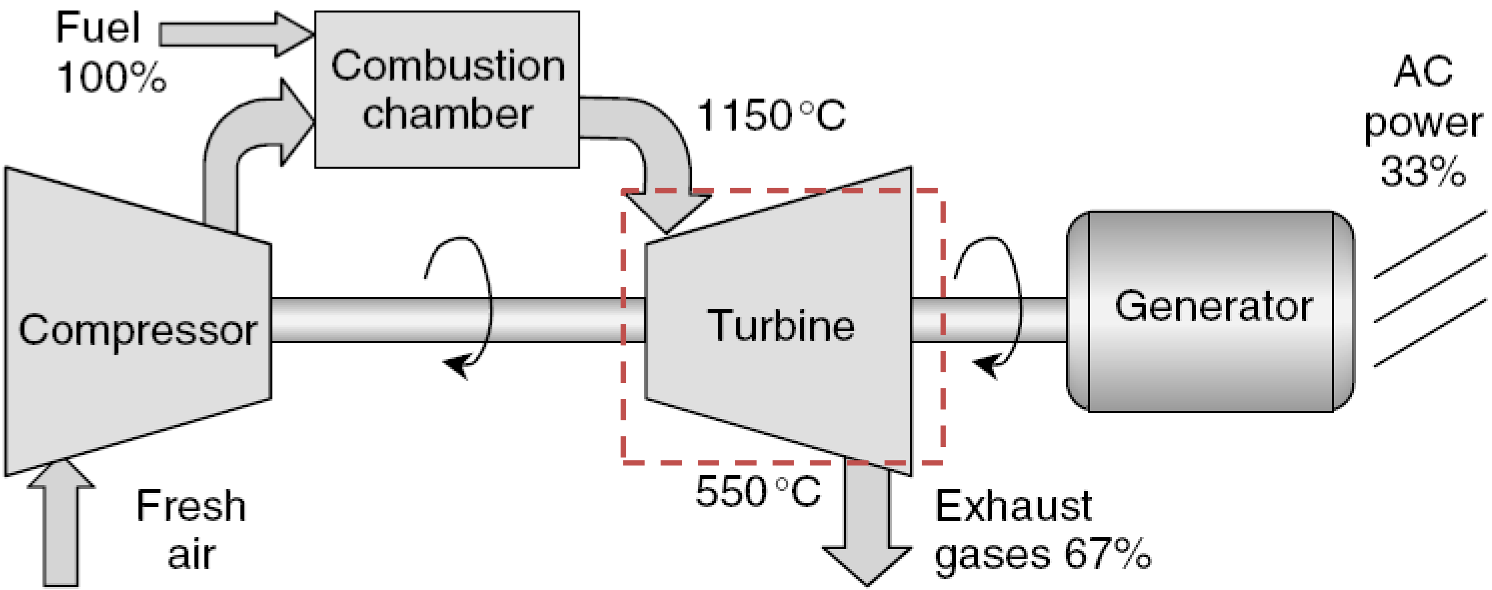


Carnot efficiency of a gas turbine



$$\eta_c = 1 - \frac{(550+273)K}{(1150+273)K} = 0.42$$

Carnot efficiency of a gas turbine



$$\eta_{II} = \frac{0.33}{0.42} = 0.78$$

Combined cycle plant

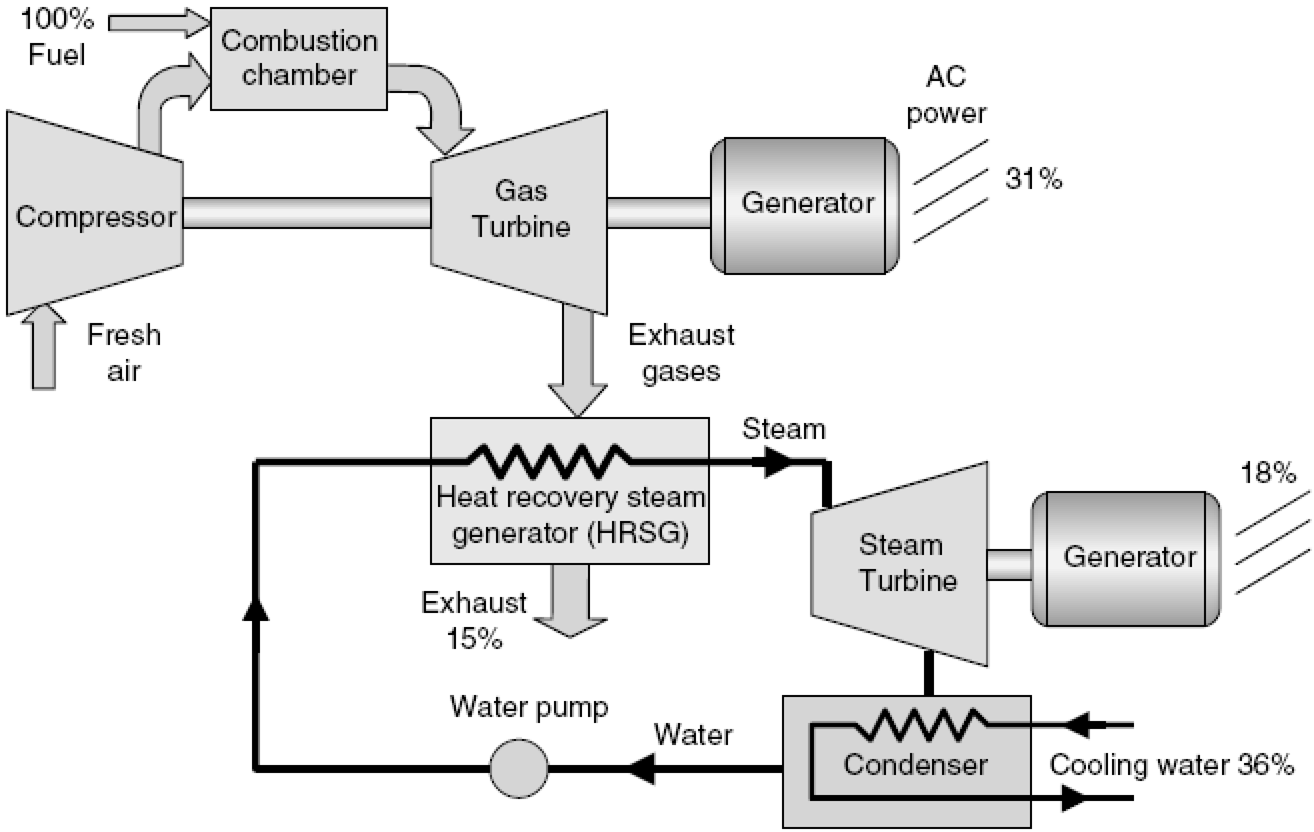
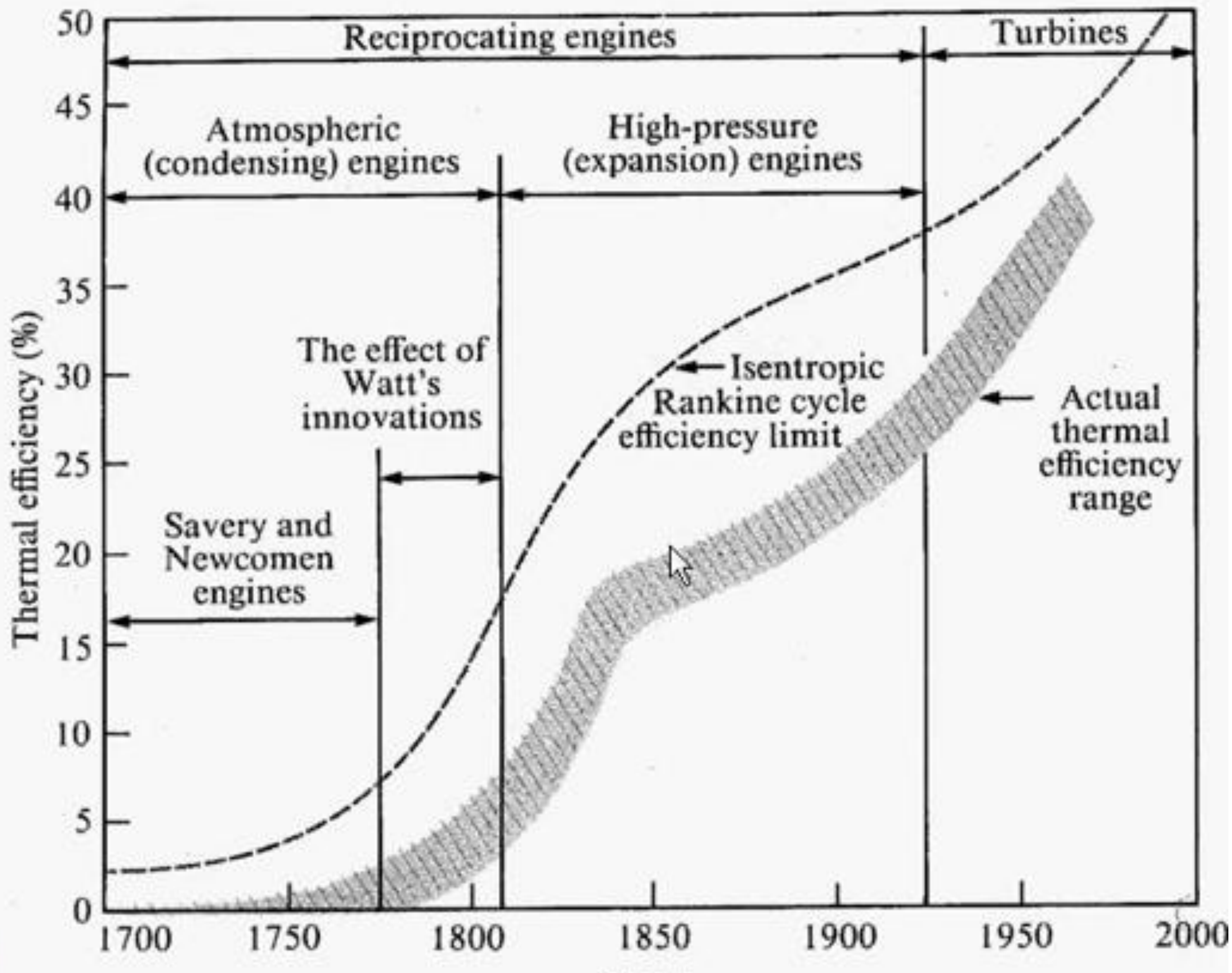


Figure 3.23 Combined-cycle power system with representative energy flows providing a total efficiency of 49%.

Thermal efficiency of steam power plant



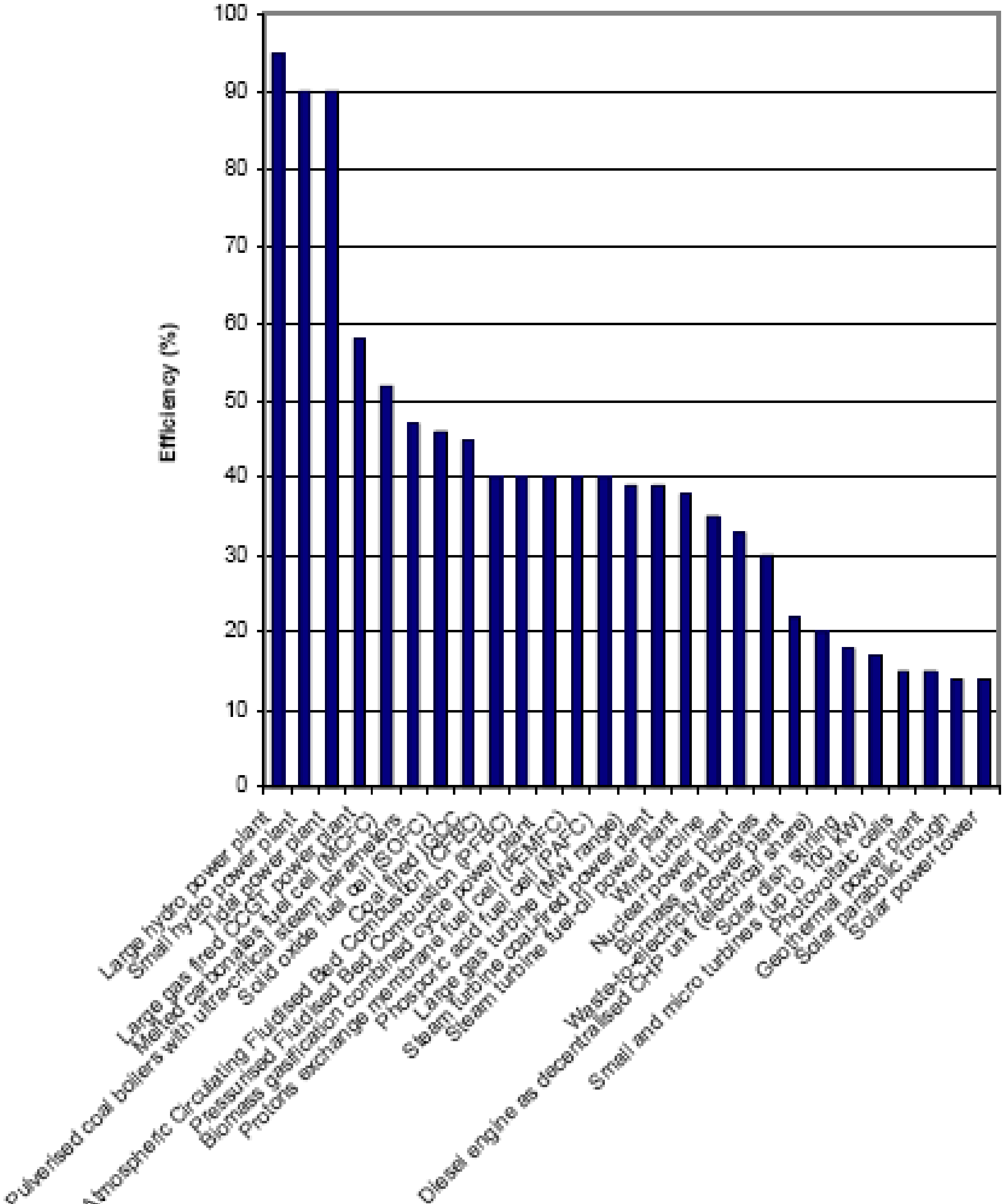
Comparison of Efficiencies

Type	T_h (K)	T_l (K)	Carnot Eff.	1st Law Eff.	2nd Law Eff.
Coal	800	300		35%	
Nuclear	1200	300		35%	
Geo-Thermal	525	350		16%	

Comparison of Efficiencies

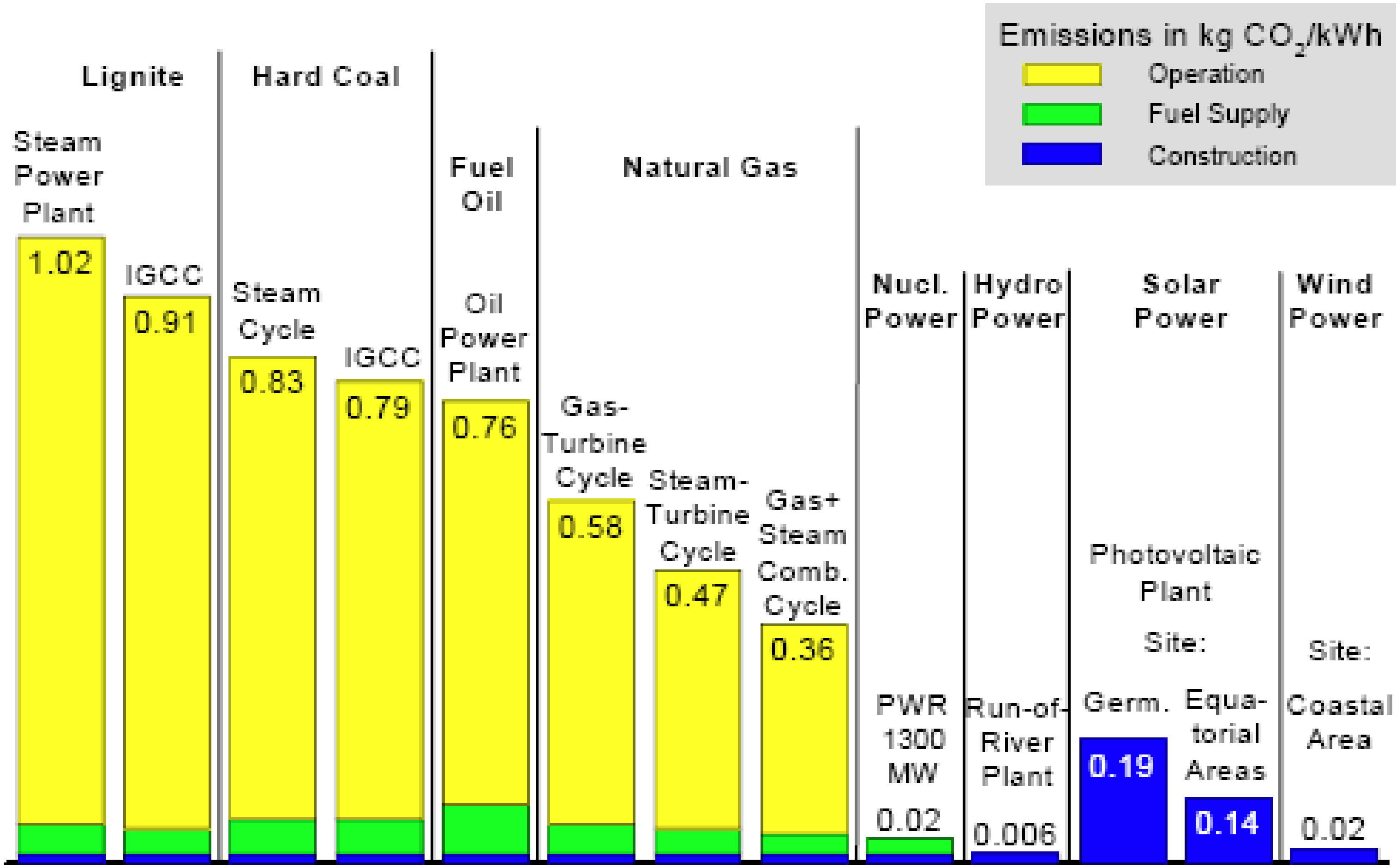
Type	T_h (K)	T_l (K)	Carnot Eff.	1st Law Eff.	2nd Law Eff.
Coal	800	300	62.5%	35%	56%
Nuclear	1200	300	75%	35%	47%
Geo-Thermal	525	350	33%	16%	48%

Efficiency in Electricity Generation



Combustion

Carbon Dioxyde Emissions per kWh



according to Siemens / Voss / VDI-GET 1999

What happens in combustion?

- Fuel + oxygen → $CO_2 + H_20$ + light + heat
- Combustion, in its simplest form, e.g: methane

$$CH_4 + O_2 \rightarrow CO_2 + H_20$$

- This idealized reaction takes place in pure oxygen and the fuel doesn't have any impurities

All equations need to be balanced

- Conservation of mass: each side of the equation need to have the same number of each element

- $CH_4 + O_2 \rightarrow CO_2 + H_20$ 1C, 4H, 2O → 1C, 2H, 3O
- $CH_4 + O_2 \rightarrow CO_2 + 2H_20$ 6C, 4H, 2O → 6C, 4H, 4O
- $CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$ 6C, 4H, 4O → 6C, 4H, 4O

How to convert # of particles to mass

- A mol contains 6.022x10^23 (Avagadro's #) particles
- Molar mass is the mass of a mol of particles
- It is the same number as the atomic weight,

Table 6 Atomic weights of common elements in combustion

Element	Symbol	Atomic Number	Atomic Weight
Hydrogen	H	1	1.008
Carbon	C	6	12.01
Nitrogen	N	7	14.01
Oxygen	O	8	16.00
Sulfur	S	16	32.06

Some common fuels

		formula
Natural Gas	Mostly CH_4; may include C_2H_6, C_3H_8, and C_4H_{10} prior to refining.	CH_4
Propane		C_3H_8
Butane		C_4H_{10}
LPG	Liquefied petroleum gas (LPG) is a mix of C_3H_8 and C_4H_{10}.	
Gasoline	Mostly C_8H_{18}, but with a mixture ranging from C_7H_{16} to $C_{12}H_{26}$.	
Wood/Cellulose		$C_6H_{12}O_6$

What is the molar mass of CO_2?

- Molar mass of C: 12 g/mol
- Molar mass of O: 16 g/mol
- Molar mass of CO_2 :
- 1 x 12g/mol + 2 x 16 g/mol = 44 g/mol

What is the molar mass of $C_6H_{12}O_6$?

- C: 12 g/mol
- H: 1 g/mol
- O: 16 g/mol
- $C_6H_{12}O_6$ molar mass:
- 6 x 12g/mol + 12 x 1 g/mol + 6 x 16g/mol
- = 180 g/mol

How many mols in a ton of wood?

- Wood has a molar mass of 180 g/mol

$$1000kgC_6H_{12}O_6 x \frac{mol}{180g} x \frac{1000g}{1kg} = 5556mol$$

How many mols of CO_2 per mol of wood ($C_6H_{12}O_6$) when combusted?

First write the stochiometric equation for combustion, and balance the equation.

1. Balance the equation (both sides of the equation have the same number of each element)

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O$$

First the carbon:

$$C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + H_2O$$

Then the hydrogen:

$$C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + 6H_2O$$

Last, the oxygen (because you can change the oxygen without altering other elements):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O,$$

Find the mol ratio between wood and CO_2

1. Mol ratio is 6 mols of CO_2 per 1 mol of wood
2. Use the mol ratio to convert the total mols of wood in a ton (5556 mol) to the total mols of CO2 that would be produced

$$5556 molC_6H_{12}O_6 x \frac{6 molCO_2}{molC_6H_{12}O_6} = 33336 molCO_2$$

3. Use the molar mass of CO2 to convert the mols of CO2 to mass of CO2

$$33336 molCO_2 x \frac{44g}{molCO_2} x \frac{ton}{1e6g} = 1.5 tonsCO_2$$

Combustion in air (78% N_2, 21% O_2)

- If combustion occurs without complete oxidation instead, we get:

$$CH_4 + O_2 + N_2 \rightarrow \text{mostly } (CO_2 + 2H_20 + N_2)$$
$$+ \text{ traces } (CO + HC + NO...)$$

- This can occur when:
  - temperature too low,
  - insufficient O,
  - combustion too rapid,
  - poor mixing of fuel and air, etc. ...

More complicated combustion

- At higher temperatures, N reacts with O:

  air(N_2 +O_2) + heat $\rightarrow$ NO_x (thermal)

- Fuels often have impurities, such as N, S, metals and ash (non-combustibles)

What we really get:

- Fuel (C, H, N, S, ash) + air (N_2 +O_2) $\rightarrow$

  (CO_2, H_2O, CO, NO_x, SO_x, VOCS, particulates) + ash

  – Volatile Organic Compounds: VOCs