ENGR-3000:
Renewable Energy, Technology, and Resource Economics

# Thermal Energy Conversion

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World Learning SIT Study Abroad

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**Ísafjörður, Iceland**

1865 THE UNIVERSITY OF MAINE

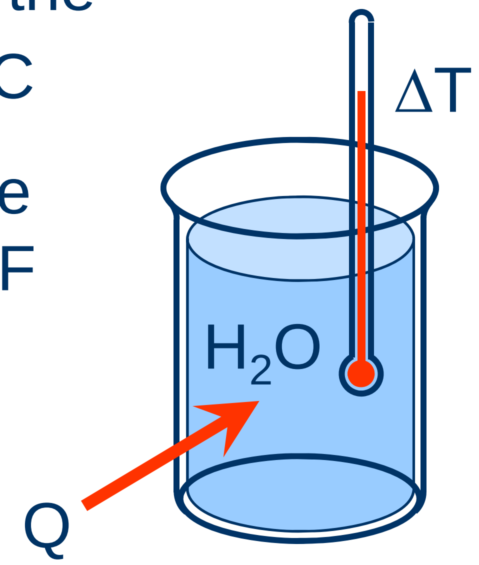
# Thermal Energy Conversion: Outline

- Thermal Energy Definitions
  - Work and heat
  - Conversion factors
- Thermal Energy Generation and Usage
- Conservation of Energy (First Law)
- Properties of water and steam
- Second Law
- Thermal Efficiency
- Power Cycles
  - Steam Plant
  - Gas Turbine Engine
- Combined Cycle

# Definitions of Thermal Energy

**1 calorie** = the energy needed to increase the temperature of 1 gram of liquid water by 1°C

**1 Btu** = the energy needed to increase the temperature of 1 pound of liquid water by 1°F




**Mechanical Equivalence of Heat:**

**1 Btu = 778 ft·lb$_f$**

1 cal = 4.12 J

1 Btu = 1.055 kJ

1 MBtu = $10^3$ Btu

1 MMBtu = $10^6$ Btu

1 **Quad** = 1 Quadrillion Btu = $10^{15}$ Btu

# Some More Energy Conversions

1 Quad = 1.055EJ

1 tons of coal = $2.5 \times 10^{7}$ Btu = 22 GJ = 1.7 MWh

1 Therm = 100 $ft^3$ natural gas = $10^5$ Btu

1 Barrel of Oil (bbl) = 42 gal = 6.12 GJ

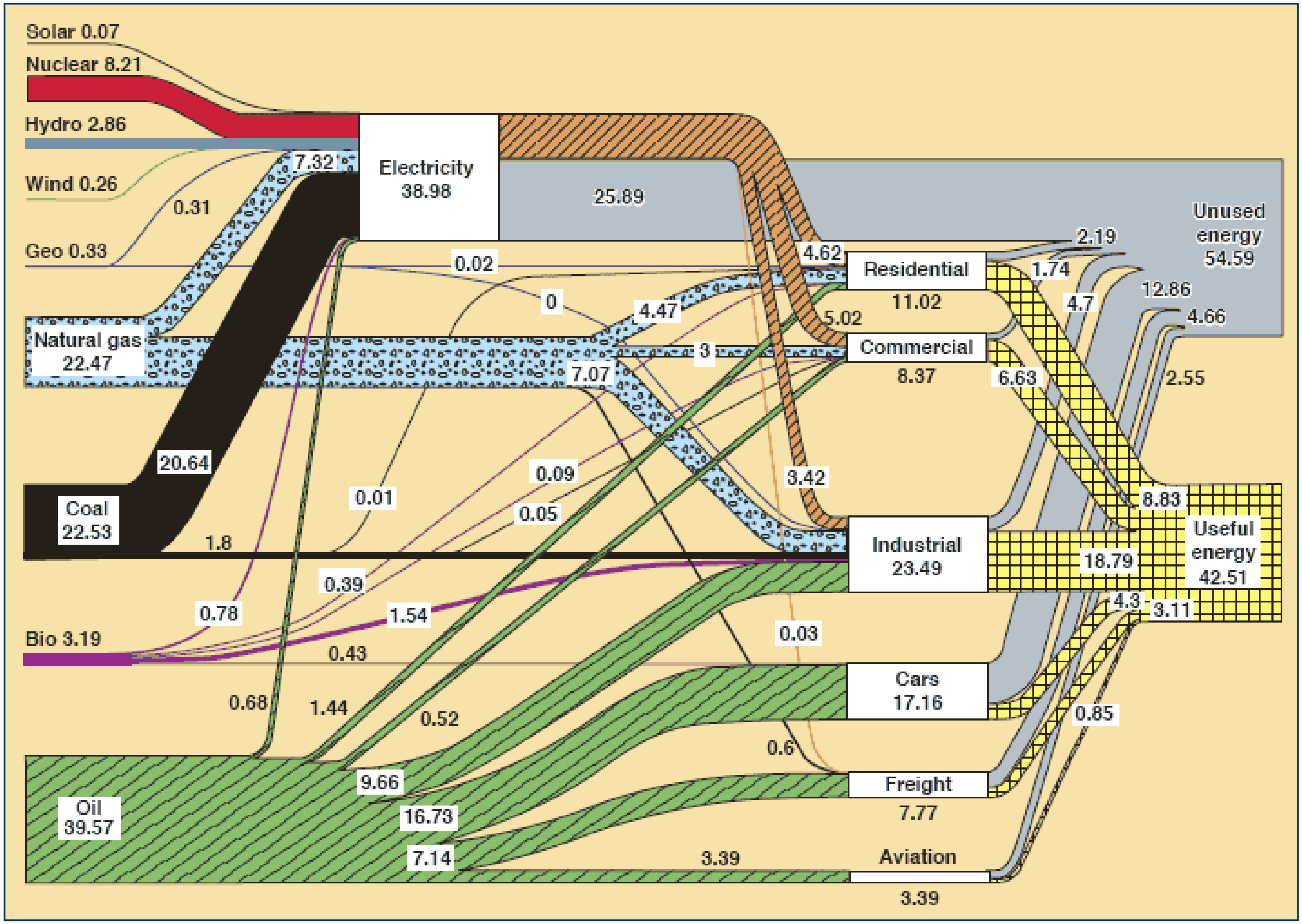
1 toe (tonnes of oil equivalent) $\cong$ 42GJ

1 toe $\cong$ 39 MMBTU = 11630 kWh

1Mtoe = $10^6$ toe

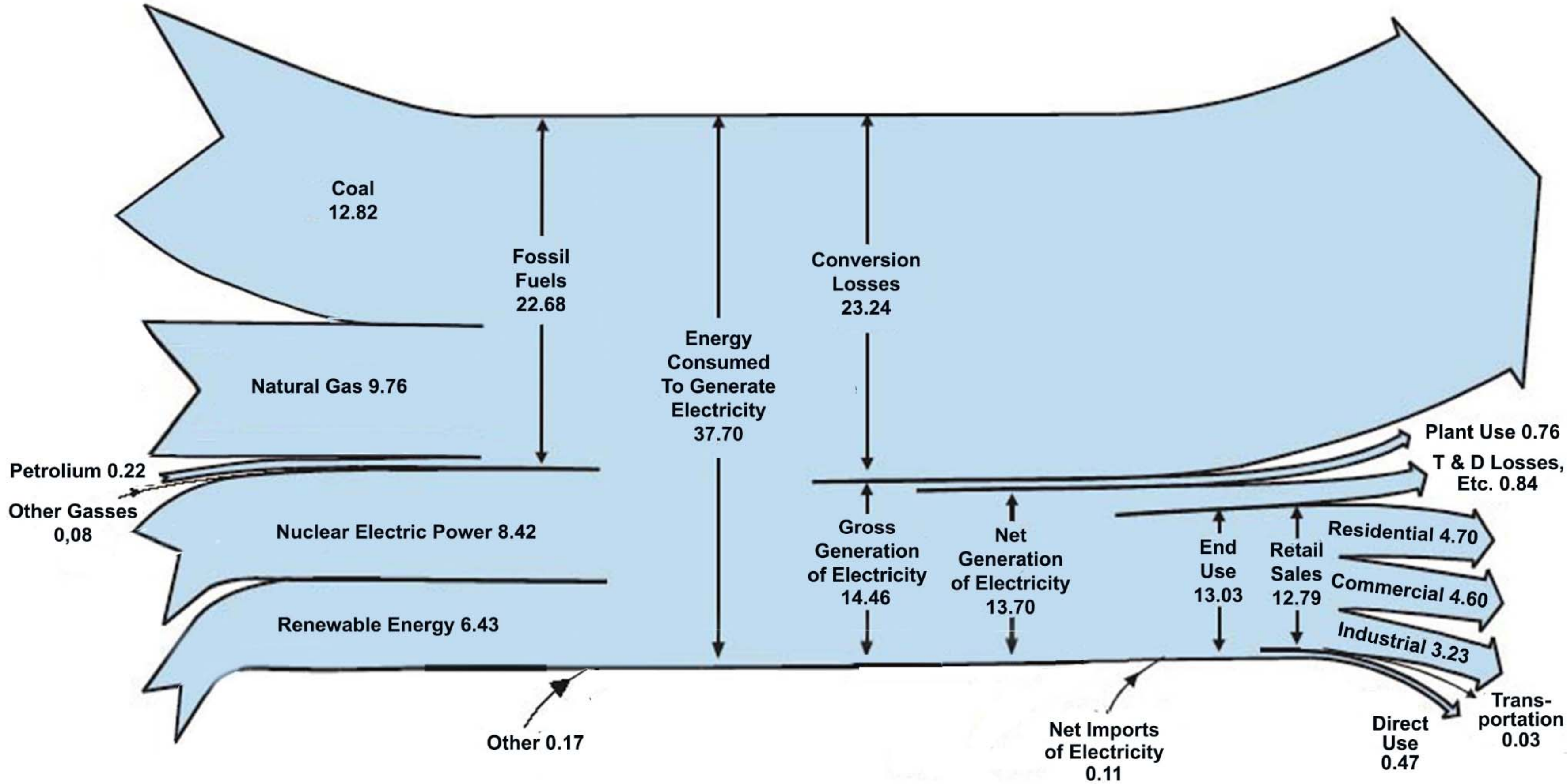
**Note: Be careful converting fuel energy units to electrical energy units!**

# Estimated Energy Usage (Quads), USA 2007




Source: LLNL

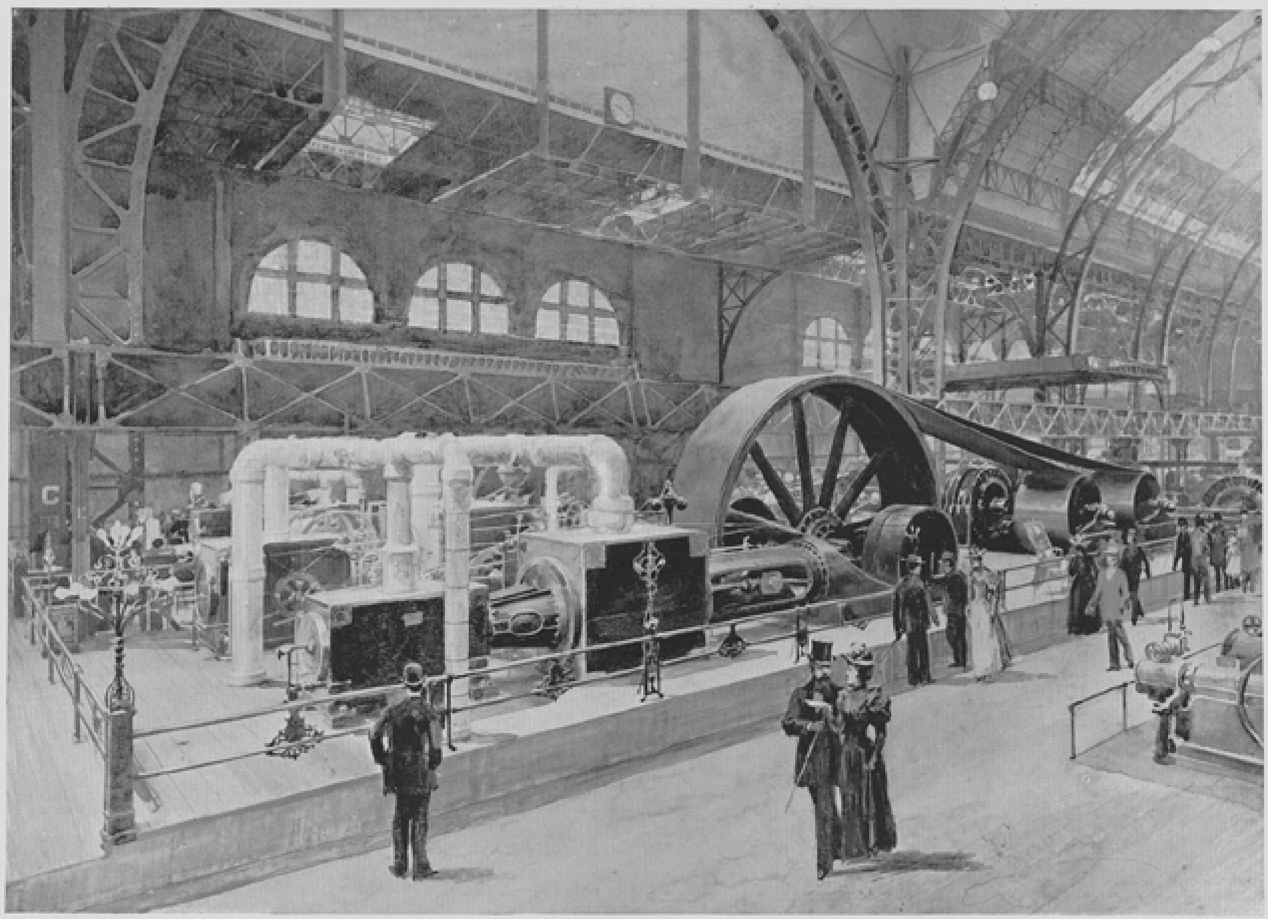
# Electricity Flow (Quads), USA, 2018




Source: EIA Monthly Energy Review April 2018

# Energy Conversion

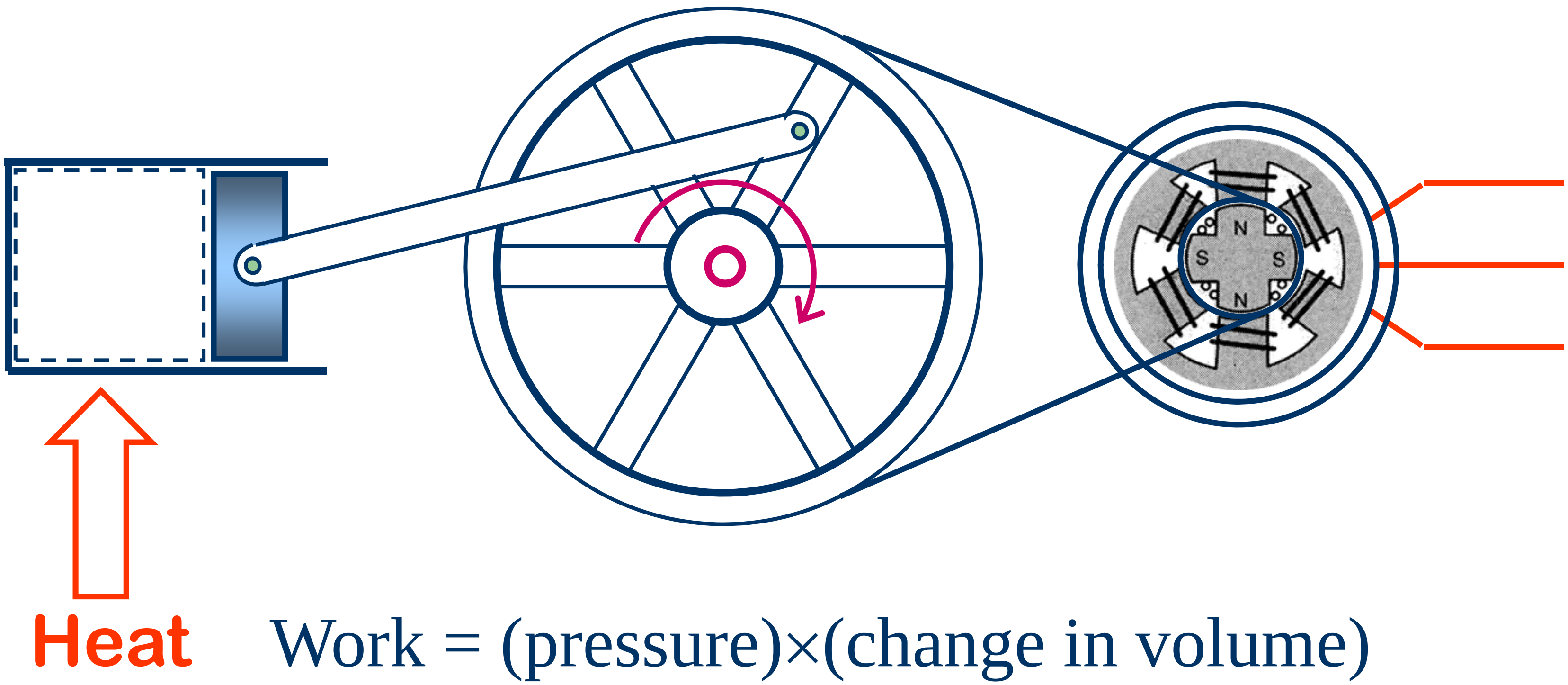
- The 2000 hp Allis-Corliss Steam Engine at the World's Columbian Exposition, Chicago 1893.



THE GREAT ALLIS-CORLISS ENGINE

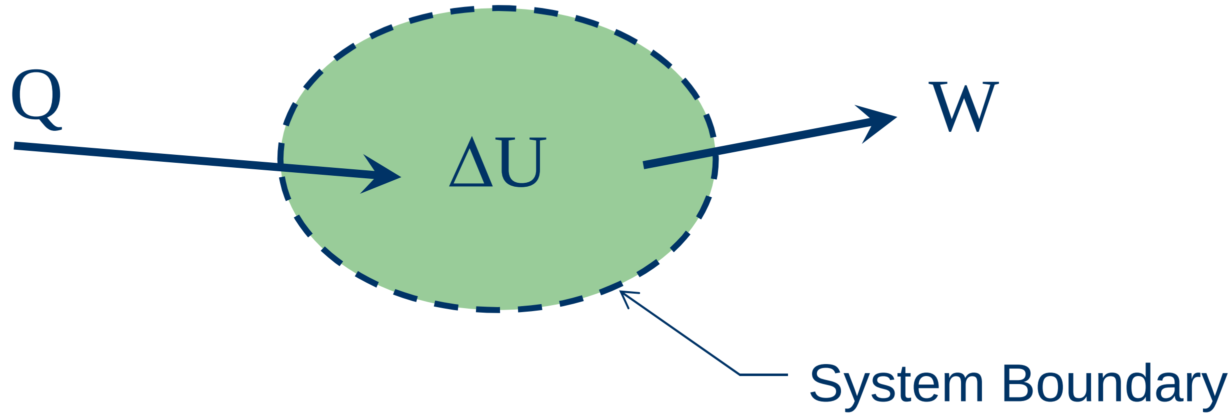
# Basic Idea of Energy Conversion

- Thermal Energy converted to mechanical energy
- Mechanical energy converted to electrical energy




Work = (pressure)×(change in volume)

# First Law of Thermodynamics



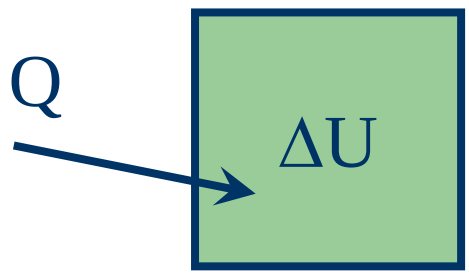

The change in internal energy of a system is equal to the heat added to the system minus the work done by the system

$$U_2 - U_1 = Q - W$$

Where, for mechanical processes: $W = \int_1^2 p\,dV$

# Energy and Enthalpy

Constant Volume System:

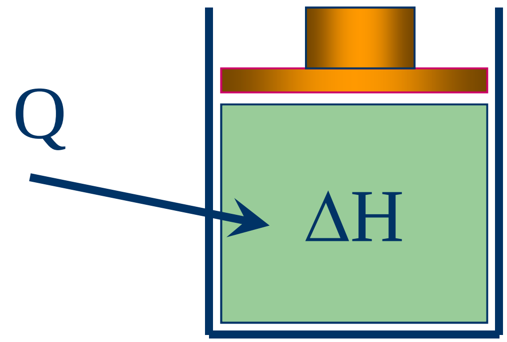



$$Q = U_2 - U_1 + W$$

$$W = 0$$

$$\boxed{Q = U_2 - U_1}$$

Constant Pressure System:




$$Q = U_2 - U_1 + W$$

$$W = p(V_2 - V_1)$$
$$= p_2V_2 - p_1V_1$$

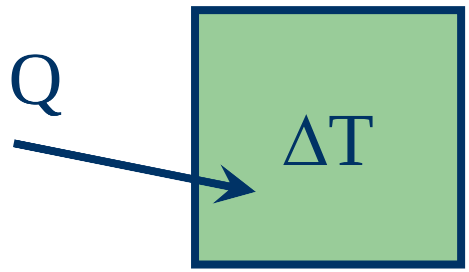
$$Q = U_2 - U_1 + p_2V_2 - p_1V_1$$

Let $H = U + pV$

$$\boxed{Q = H_2 - H_1}$$

# Internal Energy, Enthalpy and Temperature

Constant Volume System:



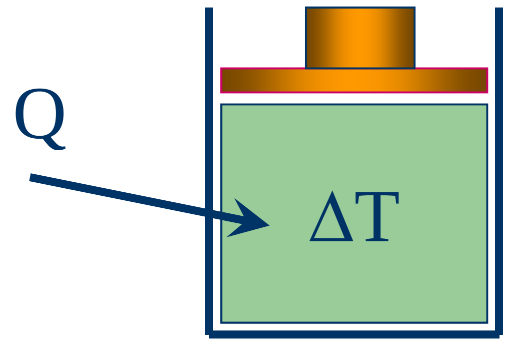

$$dq = du$$

$$du = c_v dT$$

Where $c_v$ = specific heat at constant volume

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v = \left(\frac{\partial q}{\partial T}\right)_v$$

Constant Pressure System:




$$dq = dh$$

$$dh = c_p dT$$

Where $c_p$ = specific heat at constant pressure

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p = \left(\frac{\partial q}{\partial T}\right)_p$$

# Absolute Temperature Scales

- Absolute temperature scales are based on absolute zero:

Absolute zero = -273°C = -460°F

- To convert a temperature to an absolute scale, simple add the value of absolute zero and change the units to degrees Rankine (English units) or Kelvins (SI units):

- Example: Boiling pt. of water at 1 atm:

212°F + 460 = 672°R

100°C + 273 = 373K

# Specific Heat Values

$$Q = mC_p\,(T_2 - T_1)$$

- Water

$$C_p = 1\frac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{R}} = 1\frac{\text{cal}}{\text{g}\cdot\text{K}} = 4.2\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

- Air

$$C_p = 0.24\frac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{R}} = 0.24\frac{\text{cal}}{\text{g}\cdot\text{K}} = 1.006\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

# Example: Using Specific Heats

- Determine how much heat is required to increase the temperature of 15 kg of water from 15°C to 70°C

$$Q = mC_p\left(T_2 - T_1\right)$$

$$Q = \left(15\text{kg}\right)\left(4.2\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)\left(70°\text{C} - 15°\text{C}\right)$$

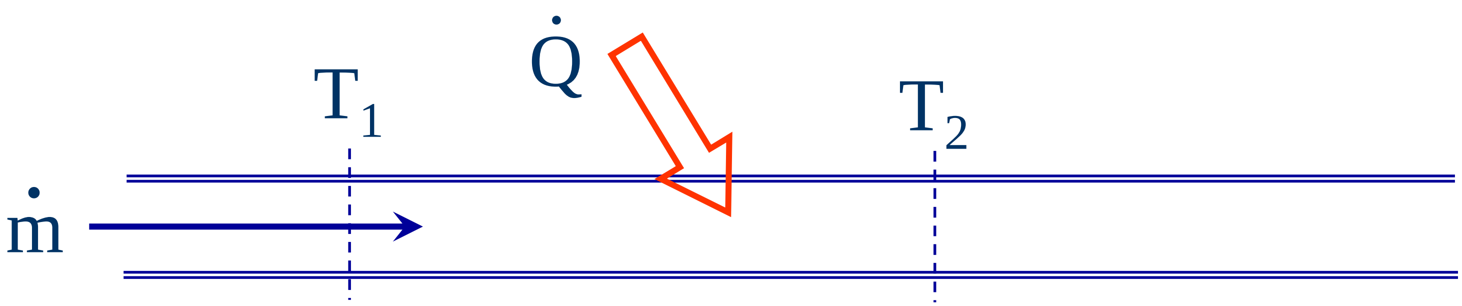
$$Q = 3465\text{kJ} = 3.47\text{MJ}$$

# Using Specific Heats in Rate Equations

- For flow systems, we look at mass flow rates and the rate of heat transfer (in Watts):

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta m}{\Delta t} C_p \left( T_2 - T_1 \right)$$

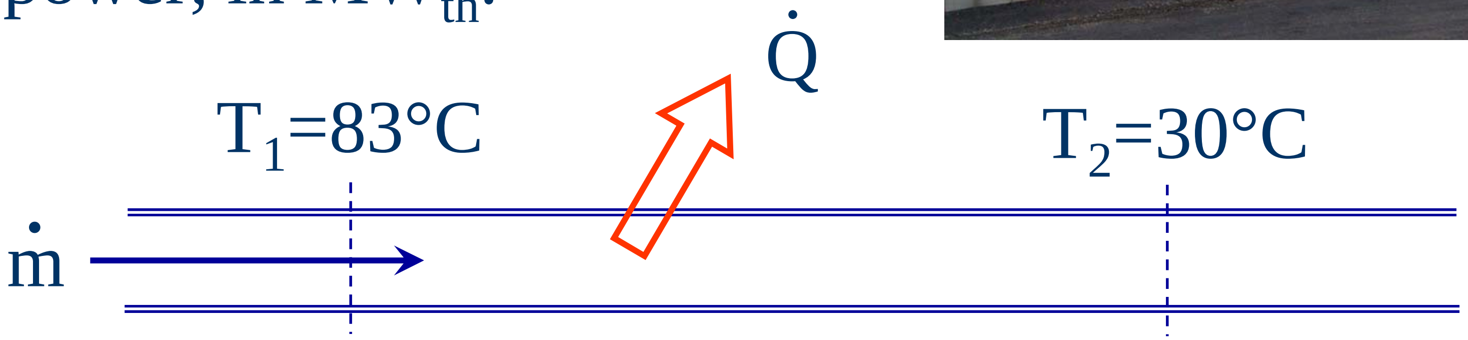
$$\dot{Q} = \dot{m} C_p \left( T_2 - T_1 \right)$$




Heat added: $T_2 > T_1$

## Example: Thermal Power for District Heating

- The geothermal power plant Hellisheiði produces 1800 l/s of water at a temperature of 83°C for district heating in Reykjavik. Using a base temp of 30°C, calculate the thermal power, in $MW_{th}$.




Heat delivered: $T_1 > T_2$

- Mass flow rate:

$$\dot{m} = 1800 \frac{\text{liter}}{\text{s}} \left( \frac{1\text{kg}}{\text{liter}} \right) = 1800 \frac{\text{kg}}{\text{s}}$$

- Thermal Power

$$\dot{Q} = \dot{m}\, C_p \left( T_1 - T_2 \right)$$

$$\dot{Q} = \left( 1800 \frac{\text{kg}}{\text{s}} \right) \left( 4.2 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right) \left( 83°\text{C} - 30°\text{C} \right)$$

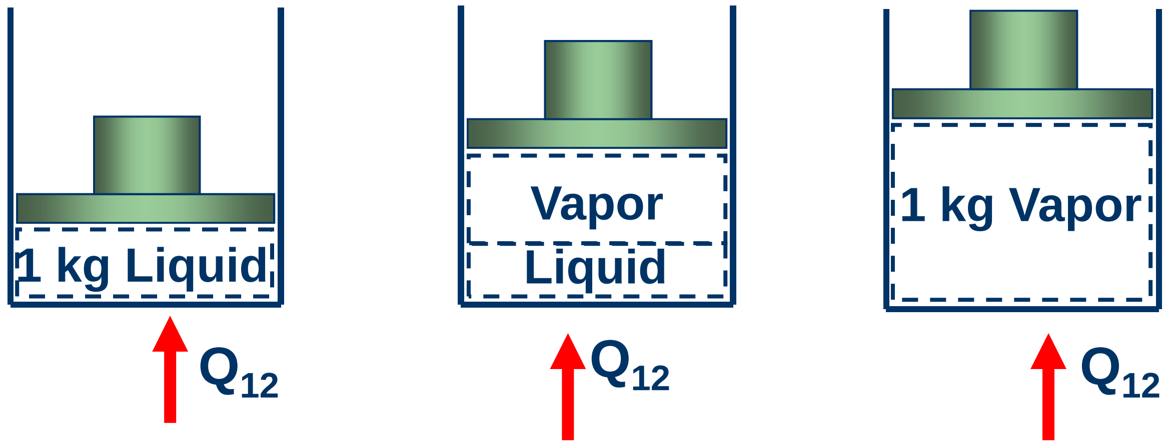
$$\dot{Q} = 401 \times 10^3 \frac{\text{kJ}}{\text{s}} = 401\text{MW}_{\text{th}}$$

# Reversible Process: Isothermal Heat Addition

Initial State (1): Saturated Liquid

Saturated Mixture

Final State (2): Saturated Vapor




Steam Properties at 1 atmosphere (1.01bar): $T_{sat} = 100°C$

Enthalpy $$Q_{12} = H_2 - H_1 = 2257 kJ$$

Entropy $$\Delta S = S_2 - S_1 = 6.05 \frac{kJ}{K}$$

# Steam Properties: Pressure Variations

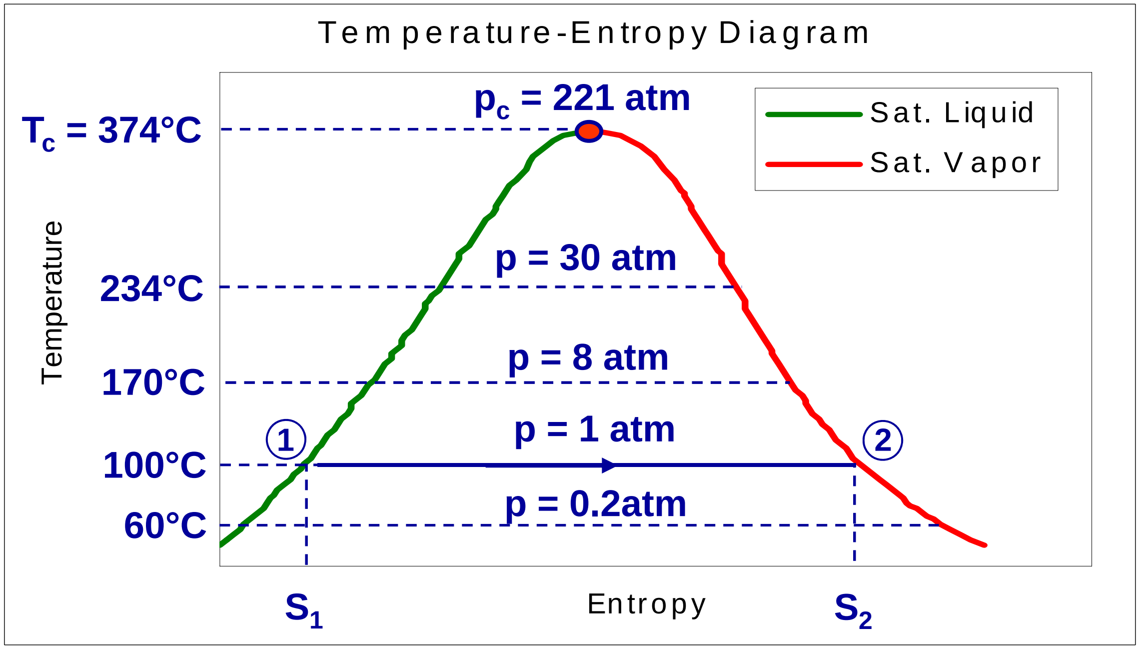
- At low pressure (cooking at high elevations)
- At an elevation of 2110m, $P_{atm}$ = 78.4 kPa
- At 0.784 bar: Tsat = 93°C
- Food cooks *slower*

$$Q_{12} = 2276\text{kJ}$$

- At high pressure  (pressure cooker)
- At 2 bar: $T_{sat}$ = 120°C
- Food cooks *faster*


$$Q_{12} = 2202\text{kJ}$$

# Saturated Steam Properties: the "Vapor Dome"



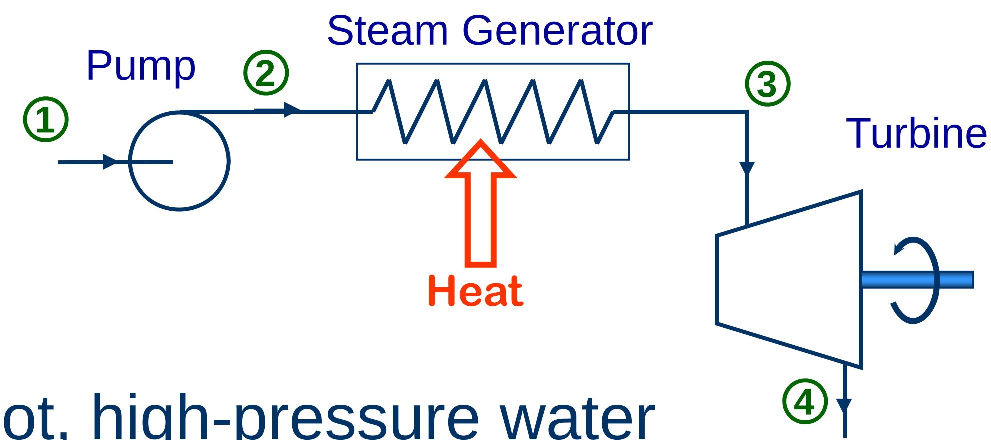

For a reversible process: $$S_2 - S_2 = \int_1^2 \frac{\delta Q}{T} \quad \Rightarrow \quad Q_{12} = \int_1^2 T dS$$

For T = Const: $$\Delta S = S_2 - S_1 = \frac{Q_{12}}{T} \quad \Rightarrow \quad Q_{12} = T\Delta S$$

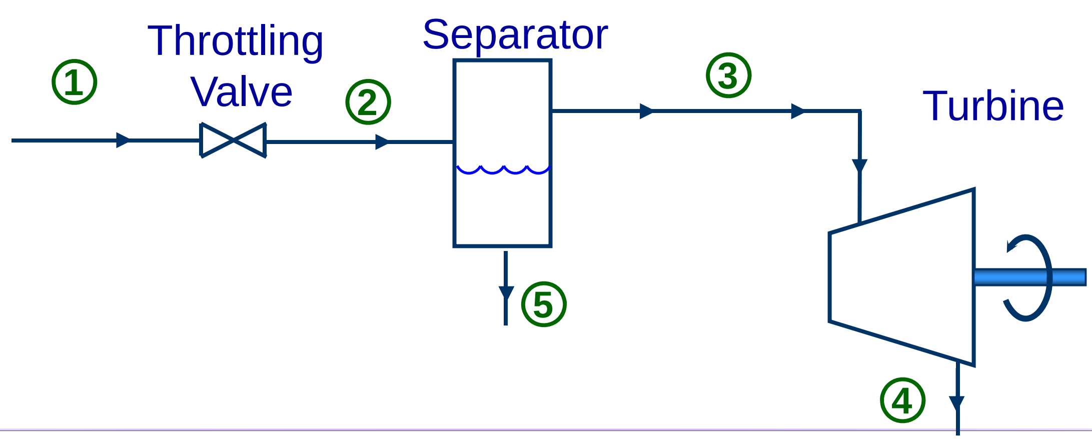
For p = 1 atm: $$Q_{12} = T\Delta S = (373\text{K})\left(6.05\frac{\text{kJ}}{\text{K}}\right) = 2257\text{kJ}$$

# Power from Steam

- Start with cold, low-pressure water
- Increase pressure (pump), add heat

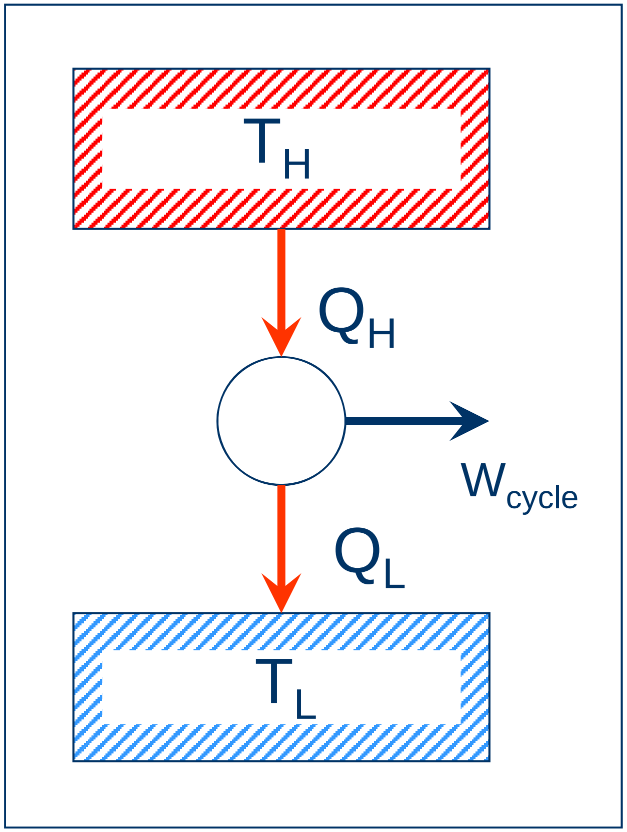


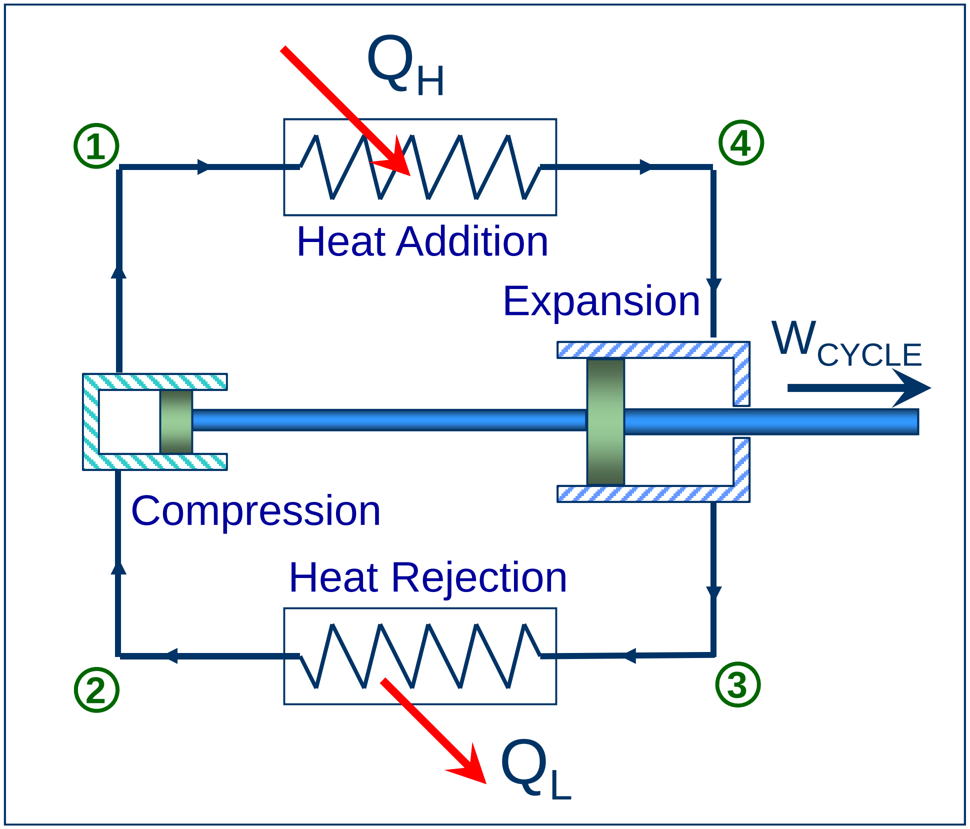

- Start with hot, high-pressure water
- Decrease pressure (flash), separate moisture



# Thermodynamic Cycle

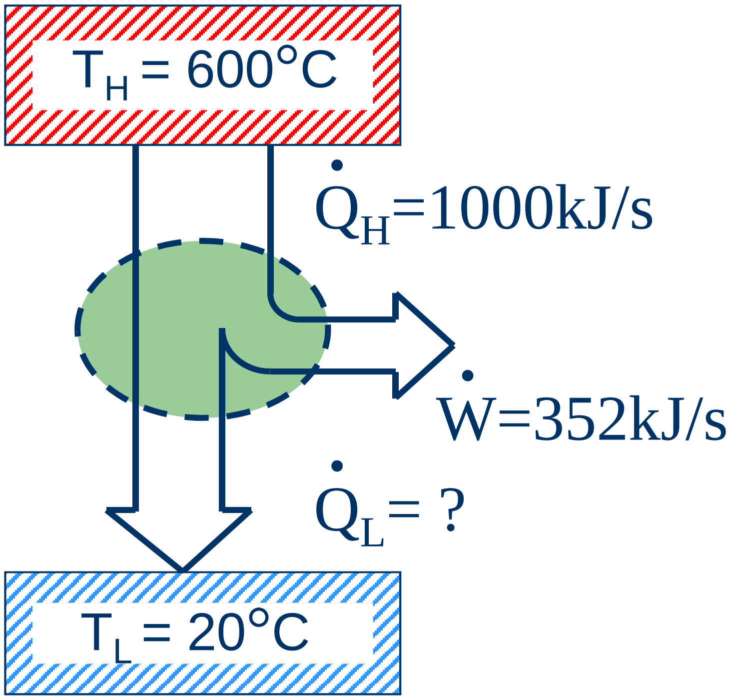
- A heat engine uses heat from a hot thermal reservoir, extracting shaft work and rejecting waste heat to a cold thermal reservoir.




**First Law: $Q_H = Q_L + W$ (no energy stored in system)**

# Example: Thermal Efficiency




- Heat rejected to low-temperature sink

From 1st Law:

$$\dot{Q}_L = \dot{Q}_H - \dot{W}$$

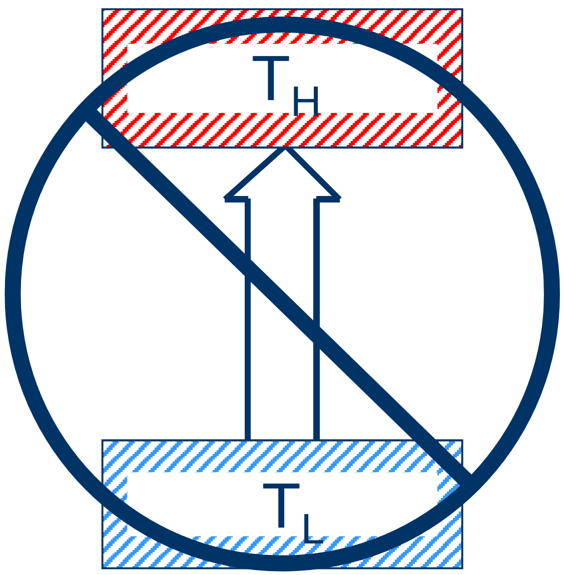
$$\dot{Q}_L = 1000\frac{kJ}{s} - 352\frac{kJ}{s} = 648\frac{kJ}{s}$$

- Calculate Efficiency

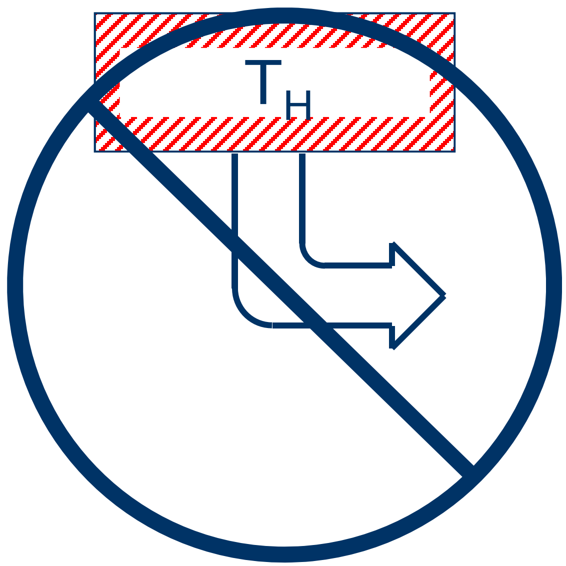
$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_H} = \frac{352kJ/s}{1000kJ/s} = 35.2\%$$

# Statements of The Second Law of Thermodynamics

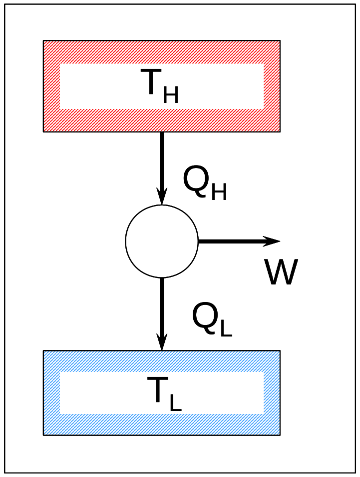
- **Clausius:**
  - It is impossible to construct a device that operates in a cycle and produces no other effect than the transfer of heat from a cooler body to a hotter body:

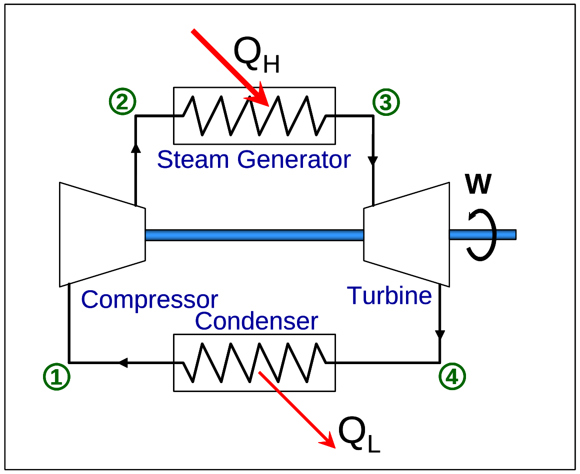


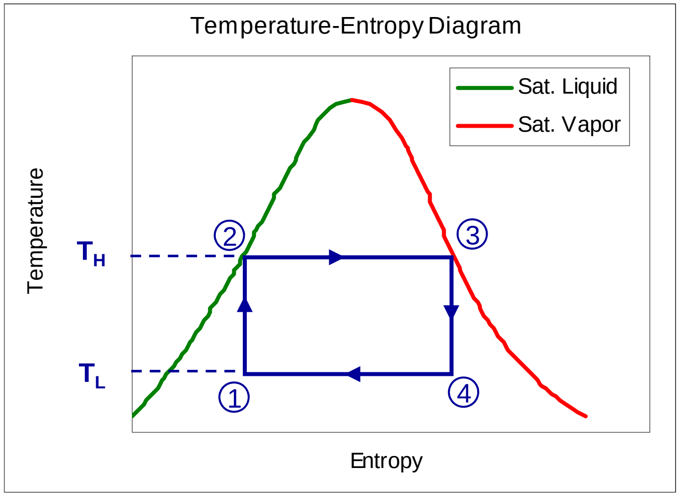

- **Kelvin-Planck:**
  - It is impossible to construct a device that operates in a cycle and produces no other effect than the raising of a weight and the exchange of heat with a single reservoir:



# Carnot Cycle Efficiency




First Law: $Q_H = Q_L + W$

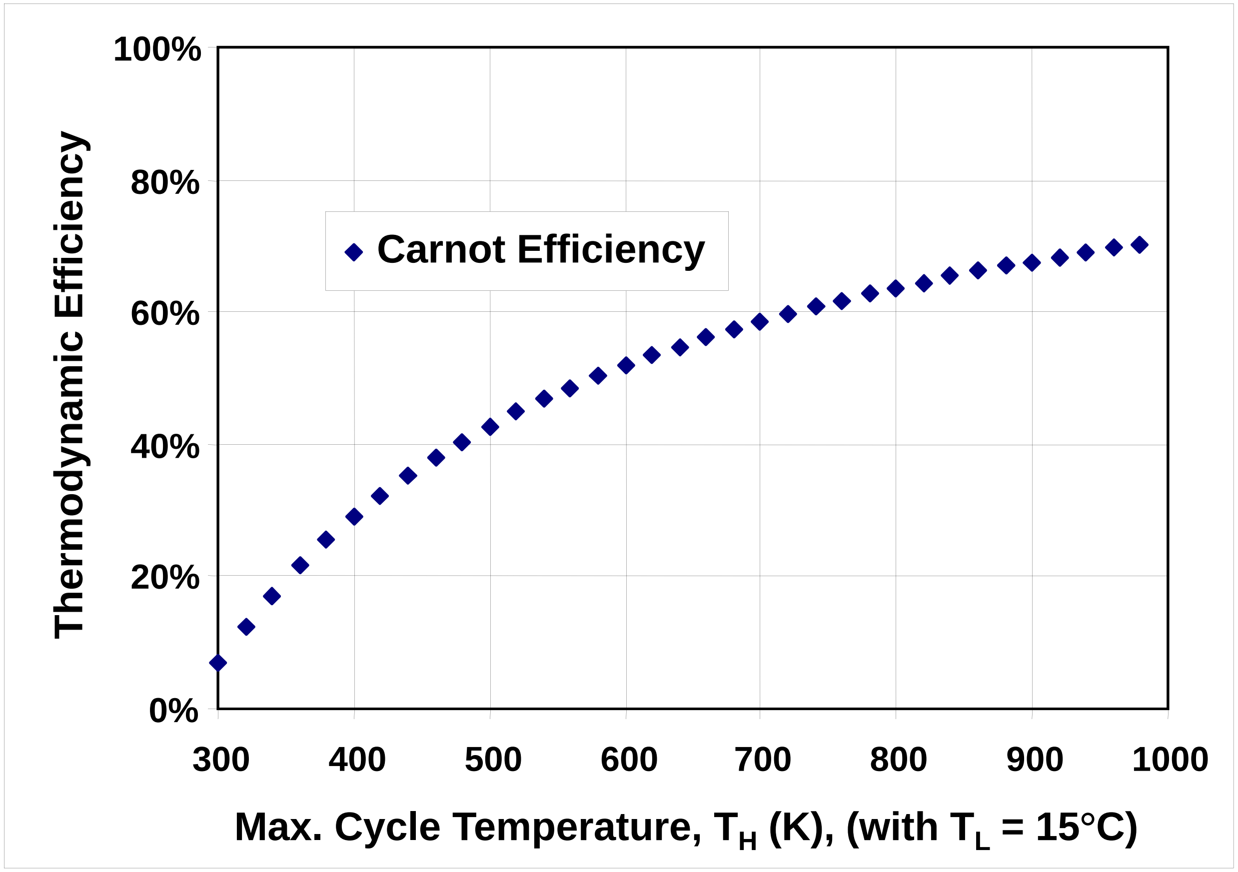
Thermodynamic Efficiency: $$\eta_{thermo} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

For a reversible cycle: $$\Delta S = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = 0 \qquad \frac{Q_H}{T_H} = \frac{Q_L}{T_L}$$

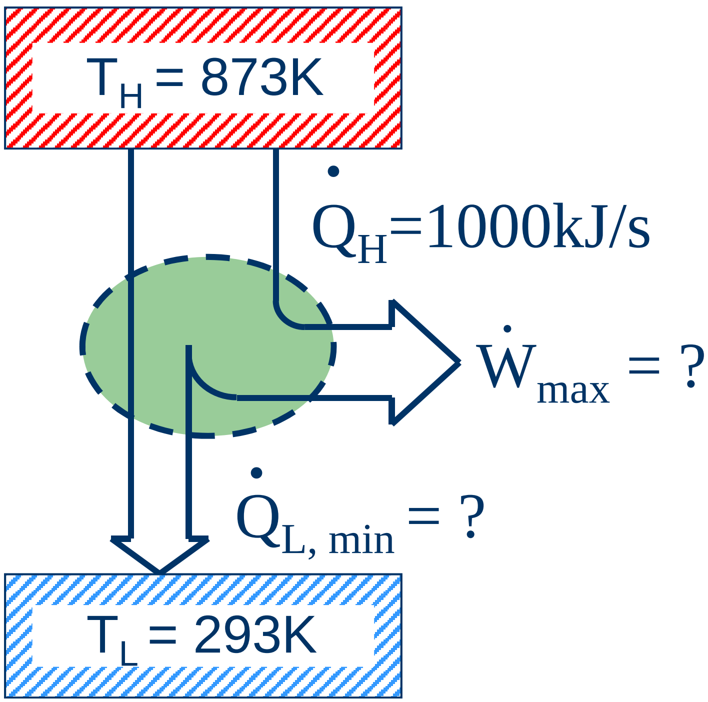
Carnot Efficiency $$\eta_{carnot} = 1 - \frac{T_L}{T_H}$$

# Carnot Cycle Efficiency

$$\eta_{carnot} = 1 - \frac{T_L}{T_H}$$



# Example: Carnot Cycle Efficiency




- Calculate max. theoretical efficiency:

$$\eta_{carnot} = 1 - \frac{T_L}{T_H}$$

$$\eta_{carnot} = 1 - \frac{293K}{873K} = 66.4\%$$

- Using the Carnot cycle efficiency, calculate max theoretical power output and heat rejected:

$$\dot{W}_{max} = \eta_{carnot}\,\dot{Q}_H$$

$$\dot{W}_{max} = (0.664)1000\frac{kJ}{s} = 664kW$$

$$\dot{Q}_{L,min} = \dot{Q}_H - \dot{W}_{max}$$

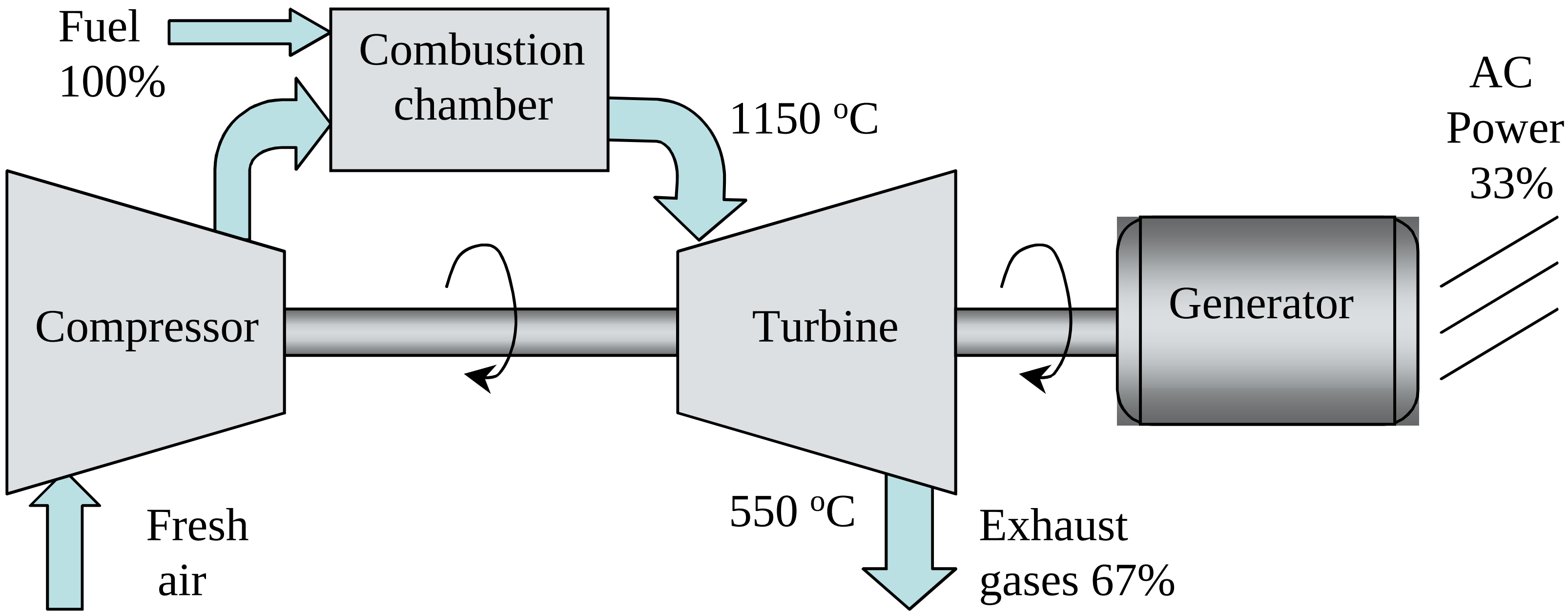
$$\dot{Q}_{L,min} = 1000\frac{kJ}{s} - 664\frac{kJ}{s} = 336\frac{kJ}{s}$$

# Exercise: Power Plant

- A 1500 MW steam power plant burns 157 kg/s of bituminous coal, which has a heating value of 27,300 kJ/kg. What is the actual efficiency of this power plant?
- The power plant has a maximum steam temperature of 640°C, and the power plant rejects heat to the surroundings at an average temperature of 15°C. What is the maximum theoretical output of this power plant?

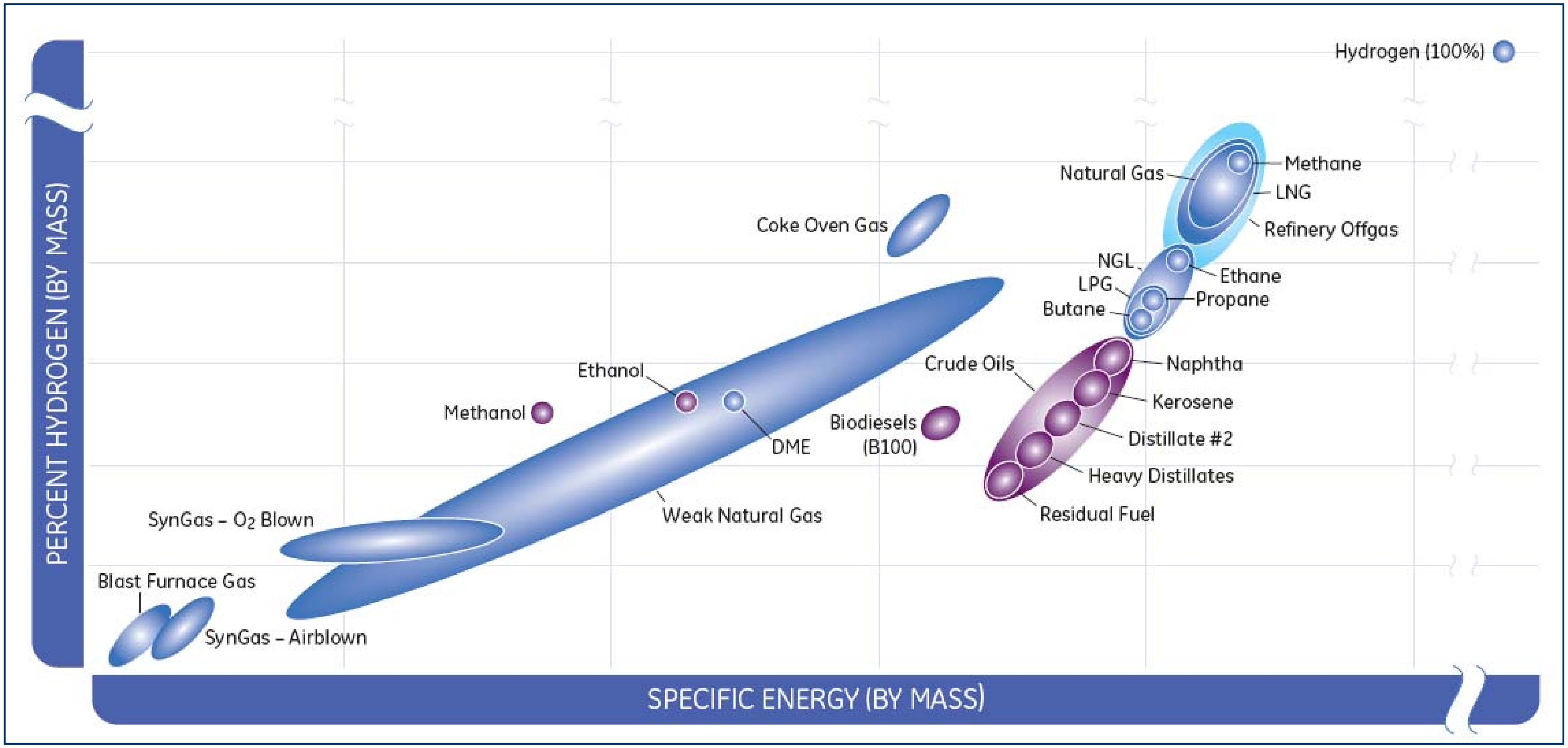
# Basic Gas Turbine (Simple Cycle)

- Most common fuel is natural gas
- Typical efficiency is around 30 to 35%




$$\eta_{Carnot} = 1 - \frac{15 + 273}{1150 + 273} = 80\%$$

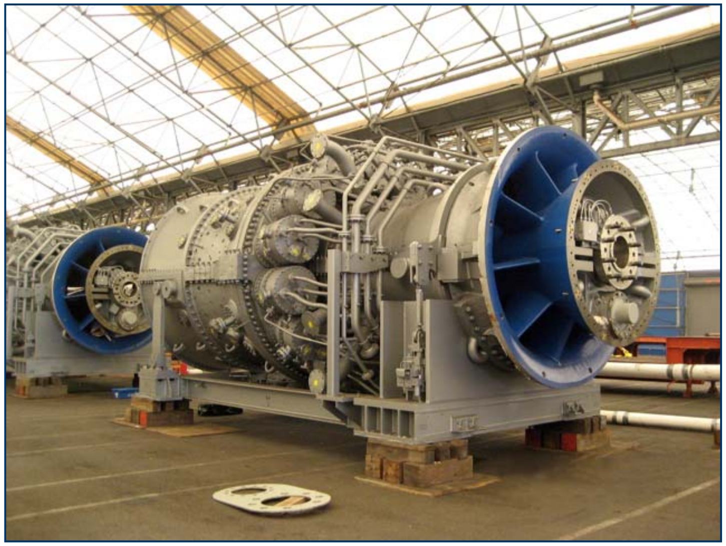
# Gas Turbine Multifuel Capability




www.gepower.com

# Types of Industrial Gas Turbines

- Industrial Gas Turbines
  - Large and heavy
  - High termal and mechanical inertia
  - Adjust slowly to changing loads
- Aeroderivative Gas Turbines
  - Derived from aircraft engines
  - Lightweight, low thermal and mechanical inertia
  - Adjust rapidly to changing loads



183MW GE 7FA

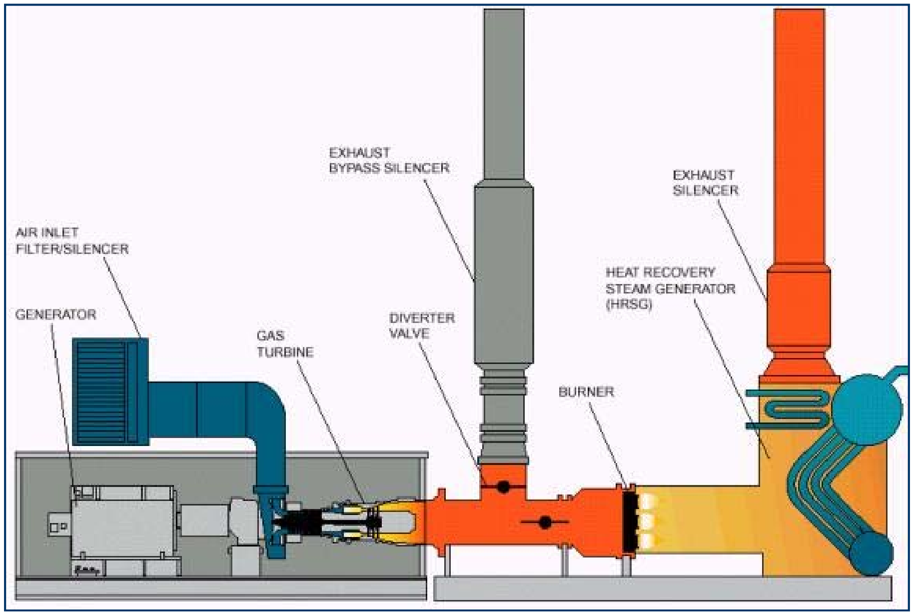
www.gepower.com

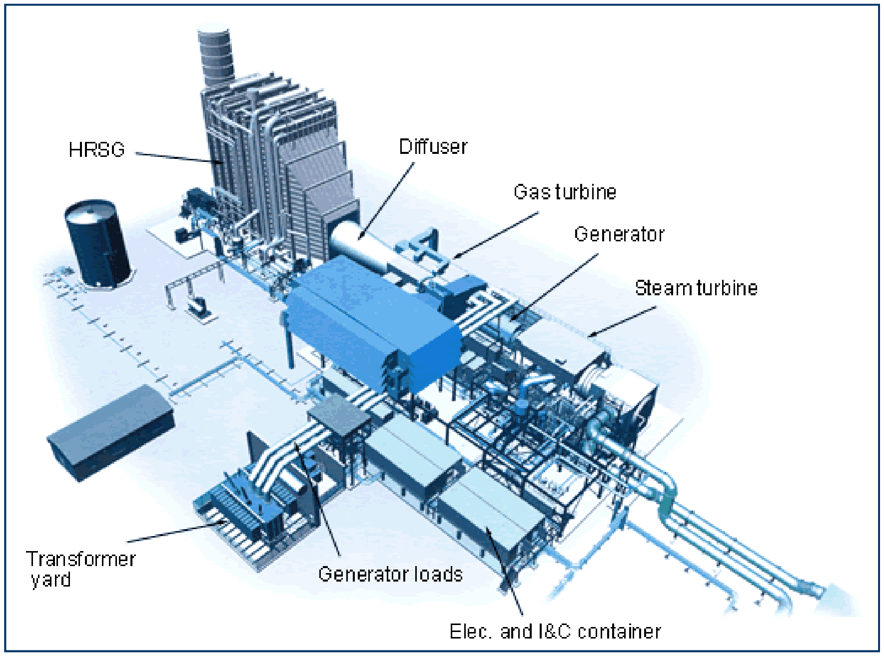
29.5MW Rolls Royce RB211

www.rolls-royce.com

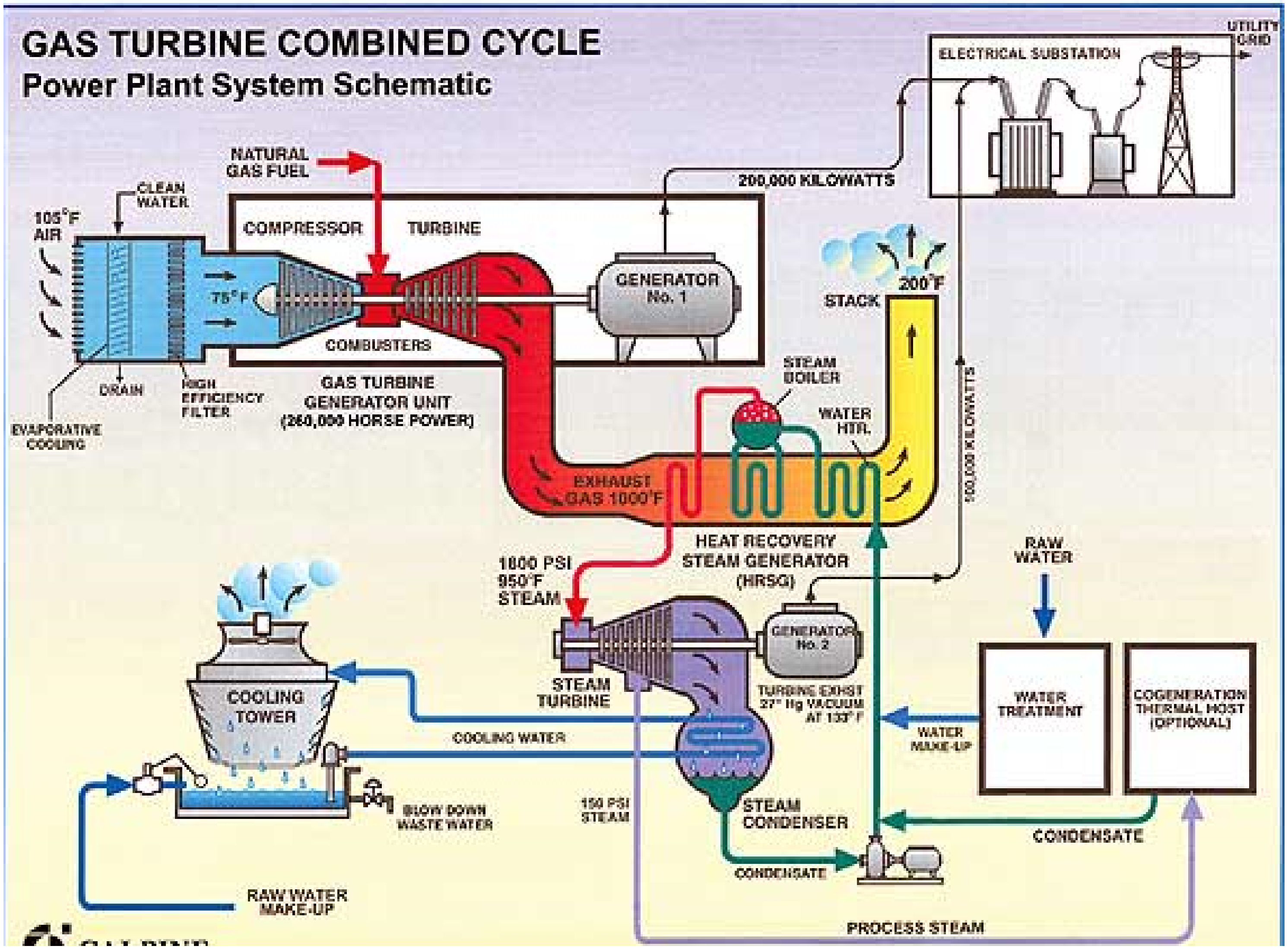
# Combined Cycle Power Plant

- Capture exhaust heat in a “heat recovery steam generator” (HRSG).

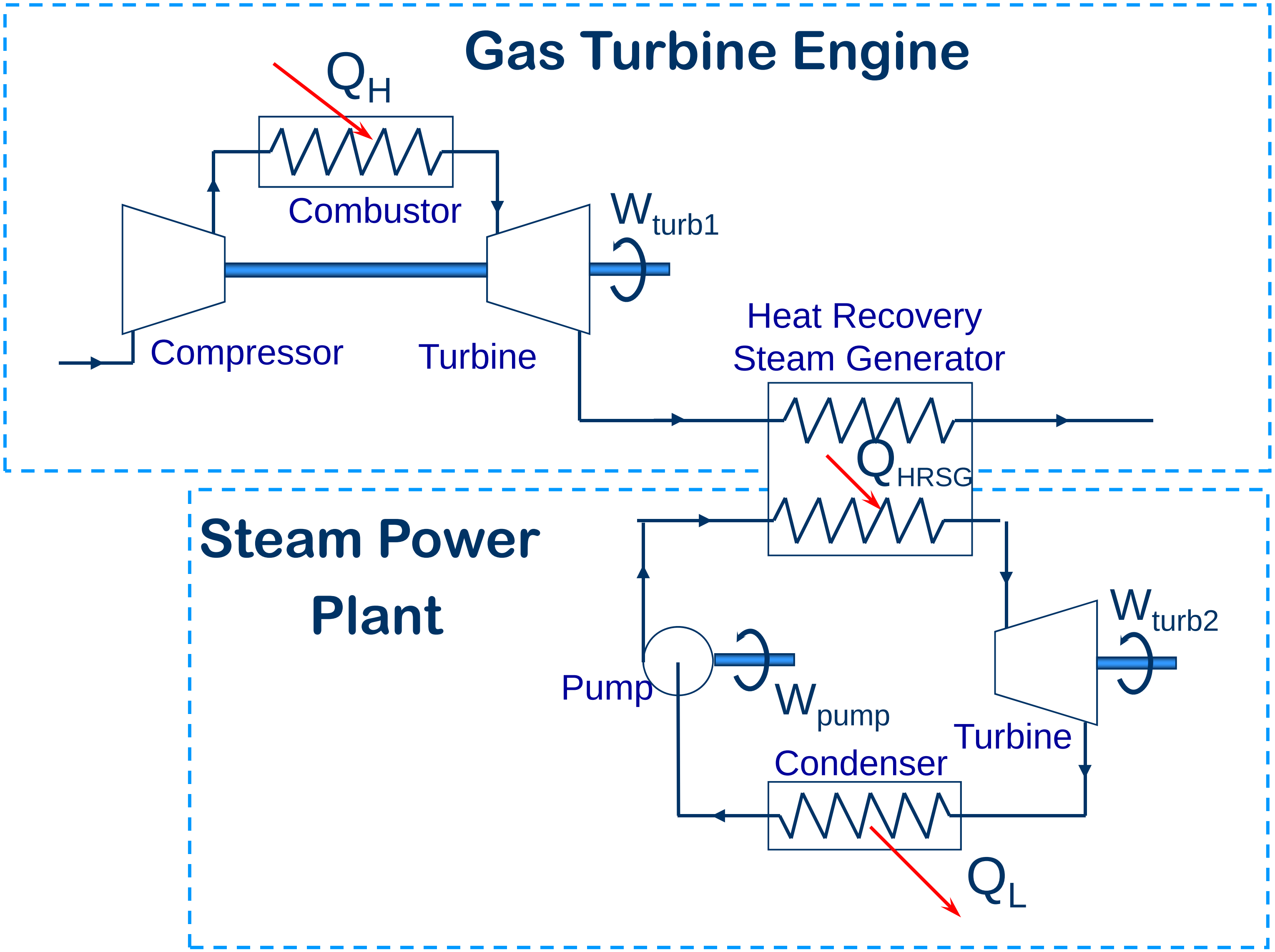


# Combined Cycle Gas Fired Turbine



# Combined Cycle Schematic



# Example: Combined Cycle

- Irsching-4 Power Plant, Bavaria Germany

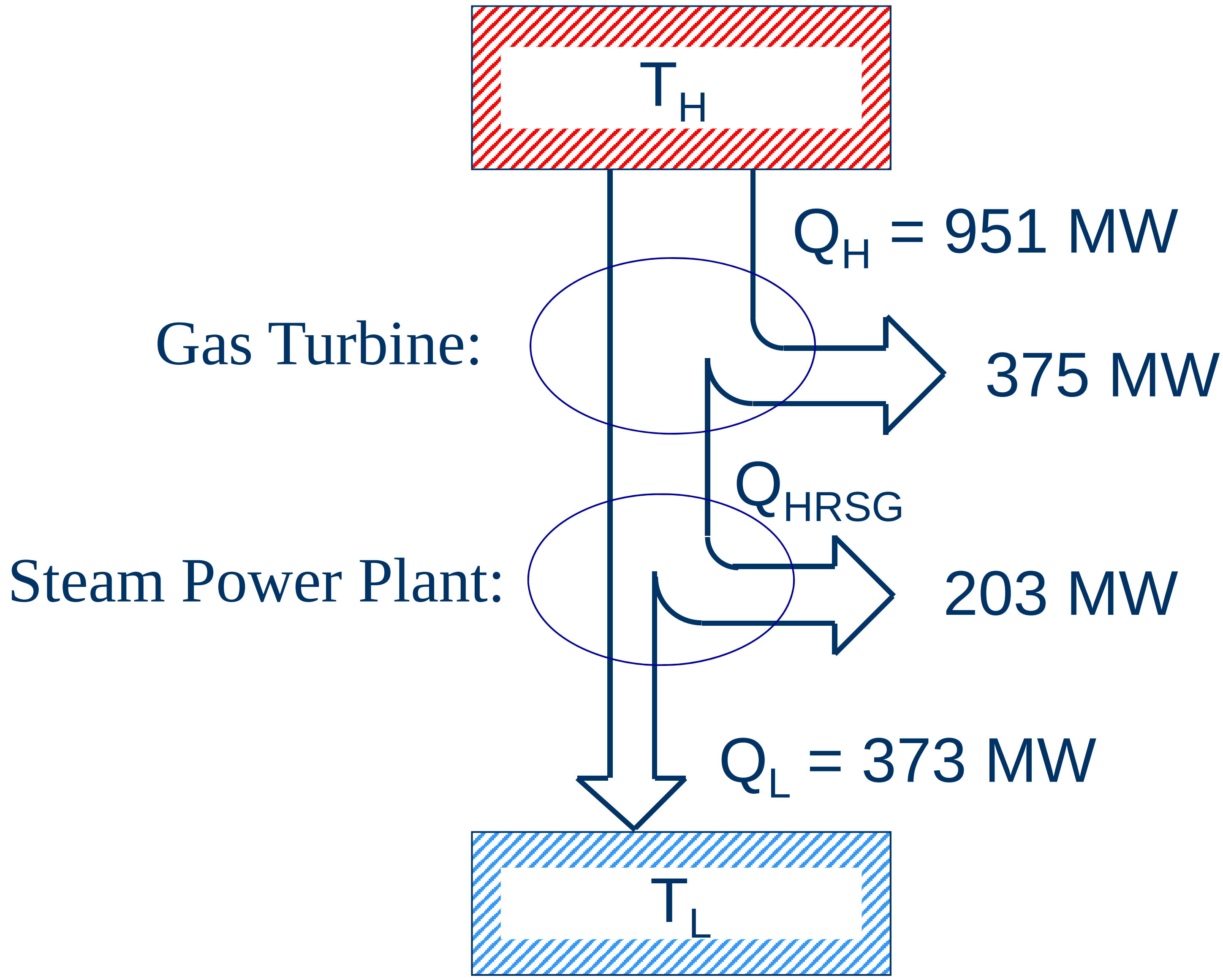
Siemens SGT5-8000H Gas Turbine

Gas Turbine and Steam Turbine

www.energy.siemens.com

www.eon.com/de/ueber-uns/struktur/asset-finder/irsching.html

# Irsching 4 Combined Cycle Power Plant



## Exercise: Irsching-4 Combined Cycle

- Determine the efficiency of the gas turbine
- Calculate the heat rejected by the gas turbine, which is also the heat input to the steam plant ($Q_{HRSG}$)
- Determine the efficiency of the steam plant
- Calculate the overall efficiency of the combined cycle system