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MENG449 INTRODUCTION TO ENERGY MANAGEMENT

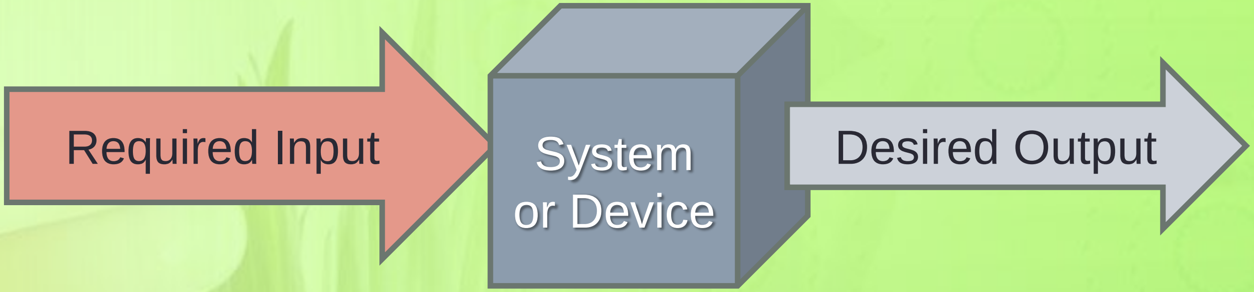
Chapter 3 – Efficiency Improvement Measures

Coverage:

- Definition of performance
- Efficiency of Boilers
- Performance of heat engines
- Performance of refrigeration systems (including air conditioners and heat pumps)
- Efficiency of electric motors
- Efficiency of water pumps
- Energy saving in air compressors
- Performance of electric lights

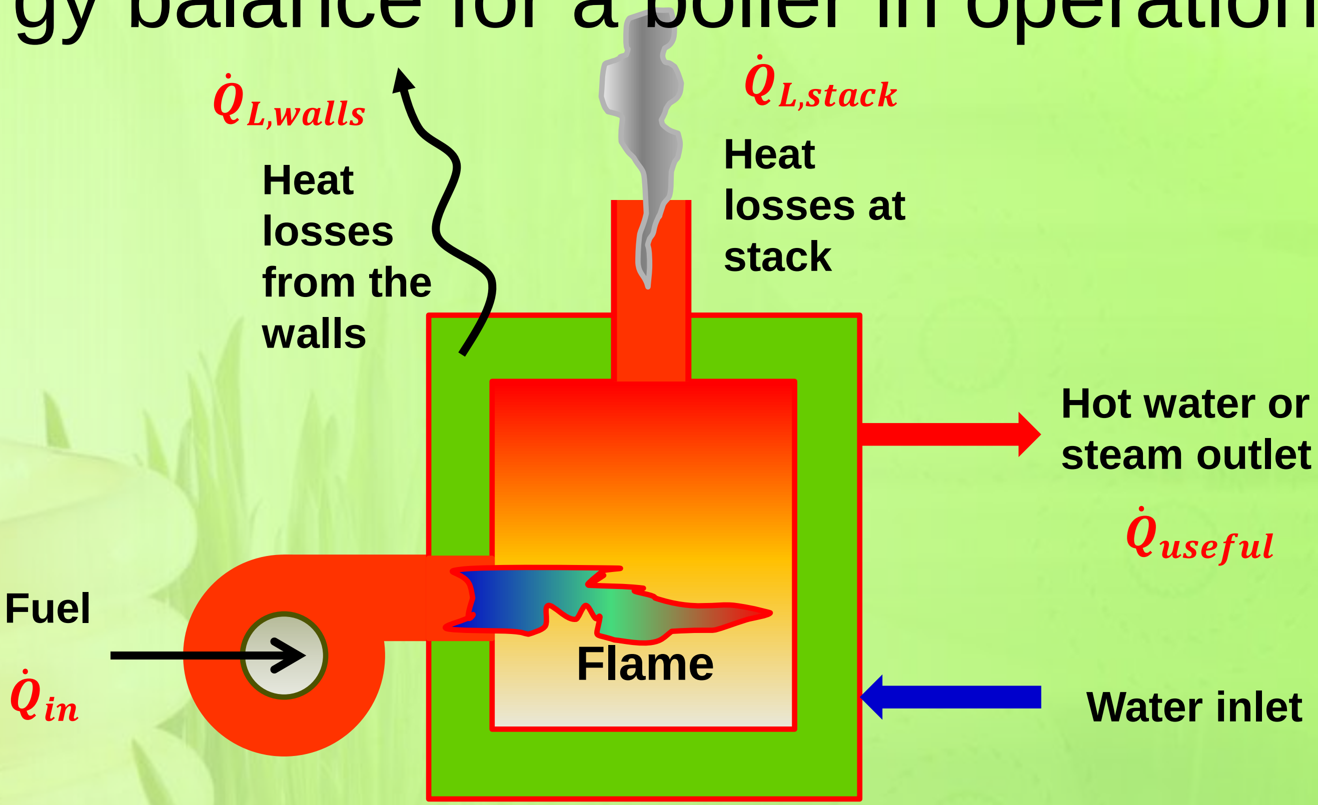
Performance of Engineering Devices

- General definition of performance:



$$\text{Performance} = \frac{\text{Desired Output}}{\text{Required Input}}$$

Energy balance for a boiler in operation



$$\dot{Q}_{useful} = \dot{Q}_{in} - \dot{Q}_{L,stack} - \dot{Q}_{L,walls}$$

$$\eta_b = \frac{\dot{Q}_{useful}}{\dot{Q}_{in}}$$

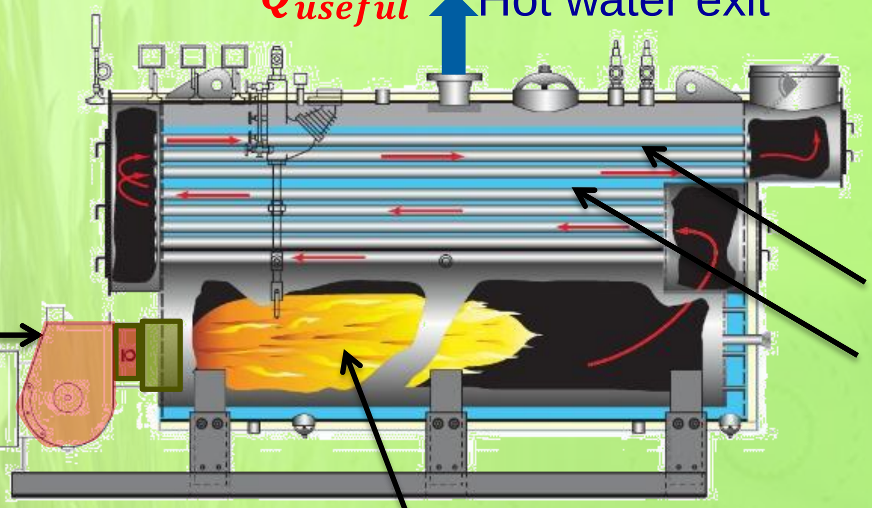
Boiler efficiency

1. Combustion efficiency

is the indication of burner's ability to burn fuel

2. Thermal efficiency

specifies the effectiveness of the heat exchanger of the boiler

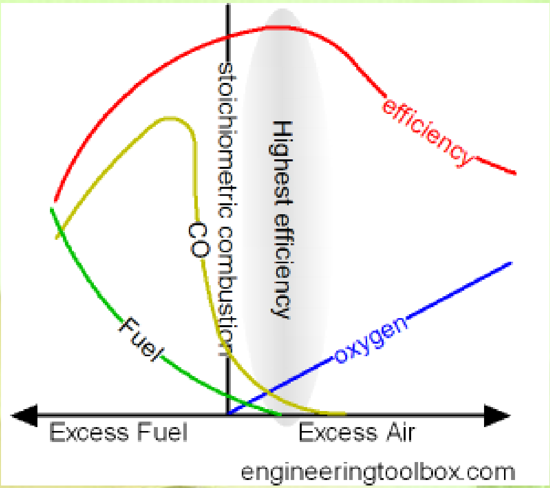


$$\eta_b = \frac{\dot{Q}_{useful}}{\dot{Q}_{in}}$$

$$\eta_b = 0.85 - 0.97$$

Boiler efficiency is a combined result of efficiencies of different components of a boiler. A boiler has many sub systems whose efficiency affects the overall boiler efficiency.

Combustion efficiency and excess air in boilers



When fuel and oxygen from the air are in perfect balance - the combustion is said to be **stoichiometric**

Natural Gas		**Combustion efficiency (%)**				
Excess (%)		**Net Stack Temperature* (°C)**				
Air	**Oxygen**	**93.3**	**149**	**204**	**260**	**316**
9.5	**2.0**	**85.4**	**83.1**	**80.8**	**78.4**	**76.0**
15	**3.0**	**85.2**	**82.8**	**80.4**	**77.9**	**75.4**
28.1	**5.0**	**84.7**	**82.1**	**79.5**	**76.7**	**74.0**
44.9	**7.0**	**84.1**	**81.2**	**78.2**	**75.2**	**72.2**
81.6	**10**	**82.8**	**79.8**	**75.6**	**71.9**	**68.2**

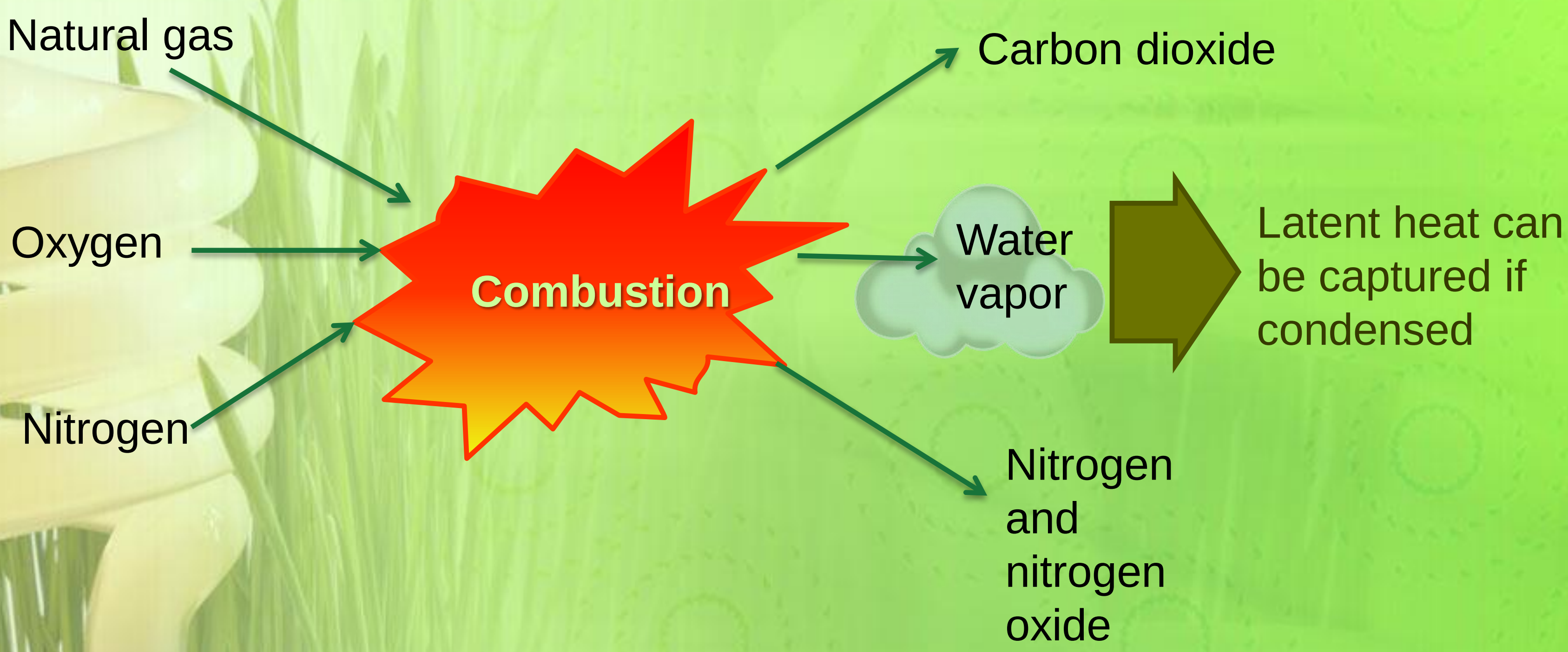
*Net stack temperature is defined as the temperature difference between flue gas temperature and room temperature

Source: https://www.engineeringtoolbox.com/boiler-combustion-efficiency-d_271.html

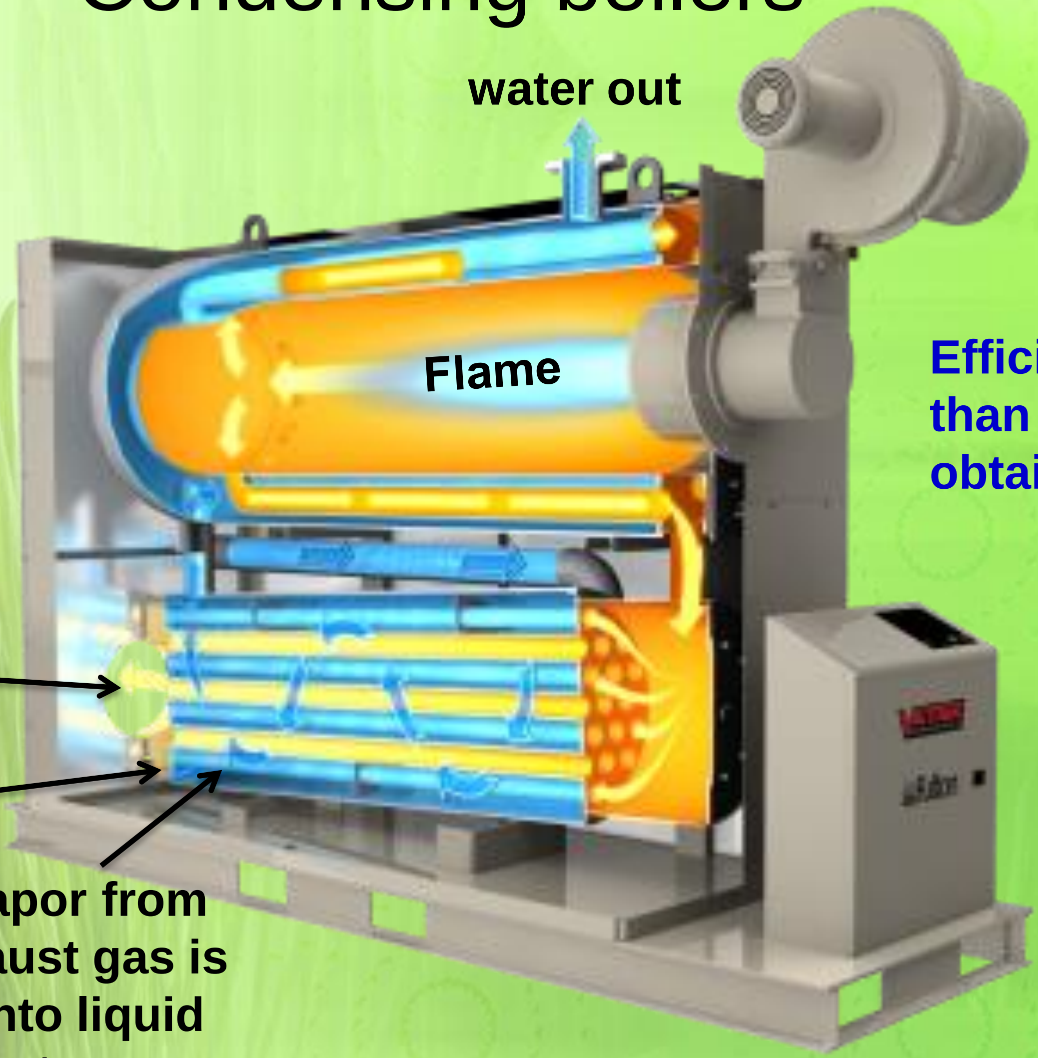
Water vapor in flue gases

Natural gas combustion:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy}$$



Condensing boilers

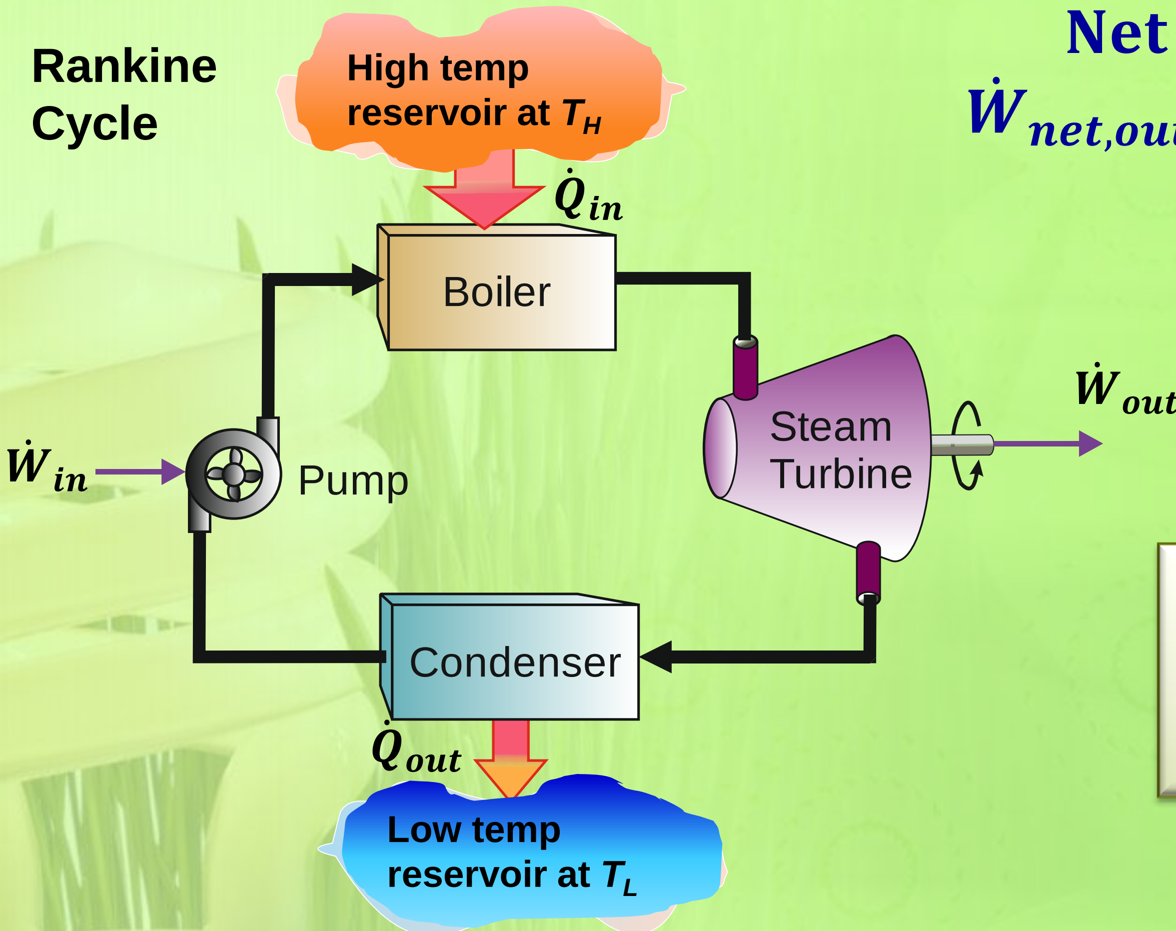


Efficiencies higher than 90% can be obtained

Source: https://www.fulton.com/

Heat Engines

Rankine Cycle

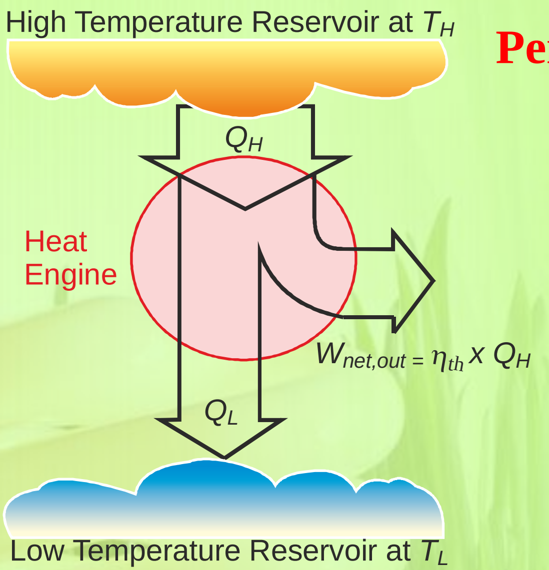


Net power out

$$\dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in}$$
$$= \dot{Q}_{in} - \dot{Q}_{out}$$

Do you know any other heat engines?

Thermal efficiency of heat engines



Performance = $\dfrac{\text{Desired output}}{\text{required input}}$ = $\dfrac{\text{What I Get}}{\text{What I pay for}}$

In heat engines:

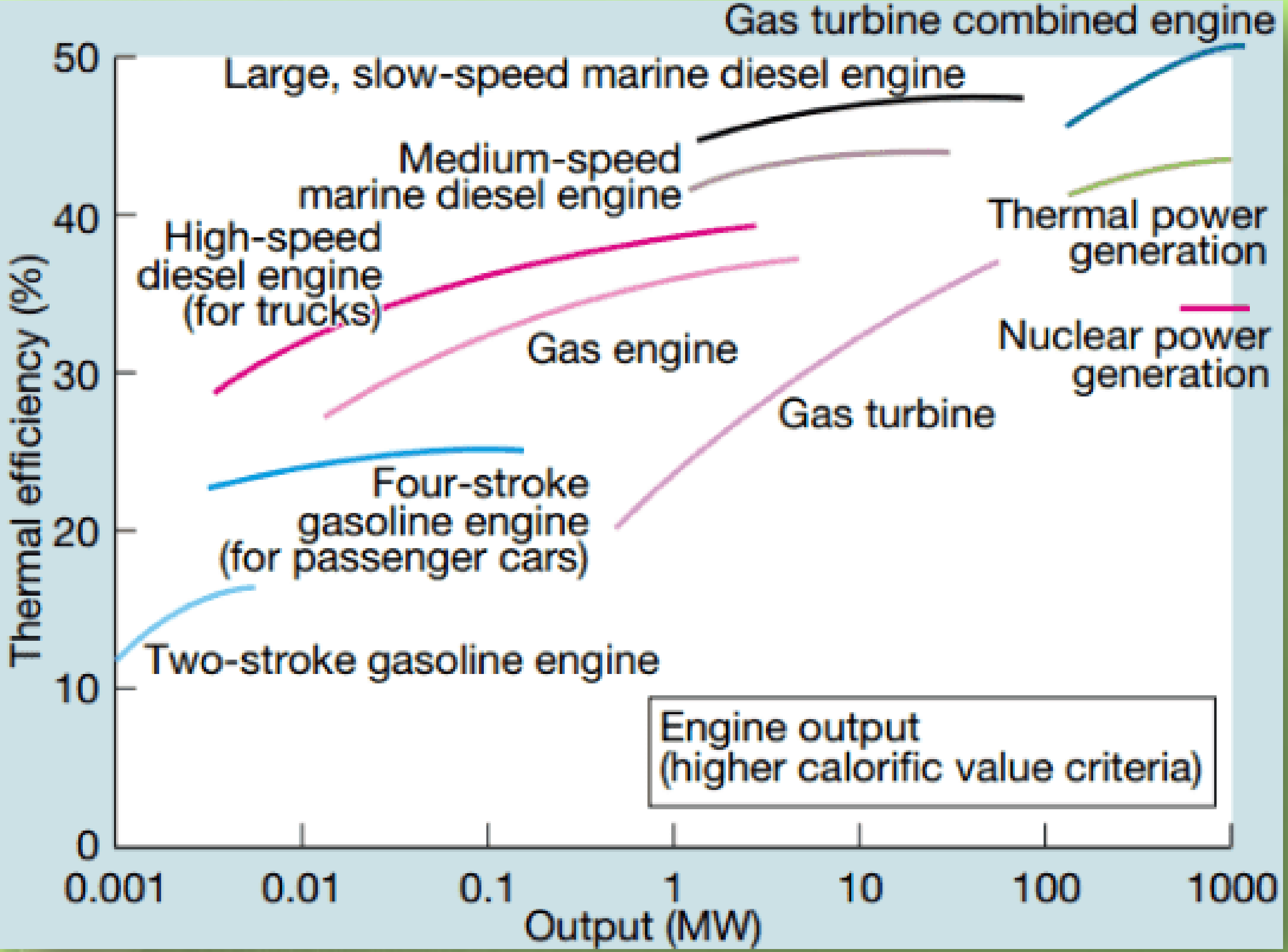
the desired output = net work output = $W_{net,out}$

the required input = heat supplied to system = Q_{in}

$$Thermal\ efficiency \quad \eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

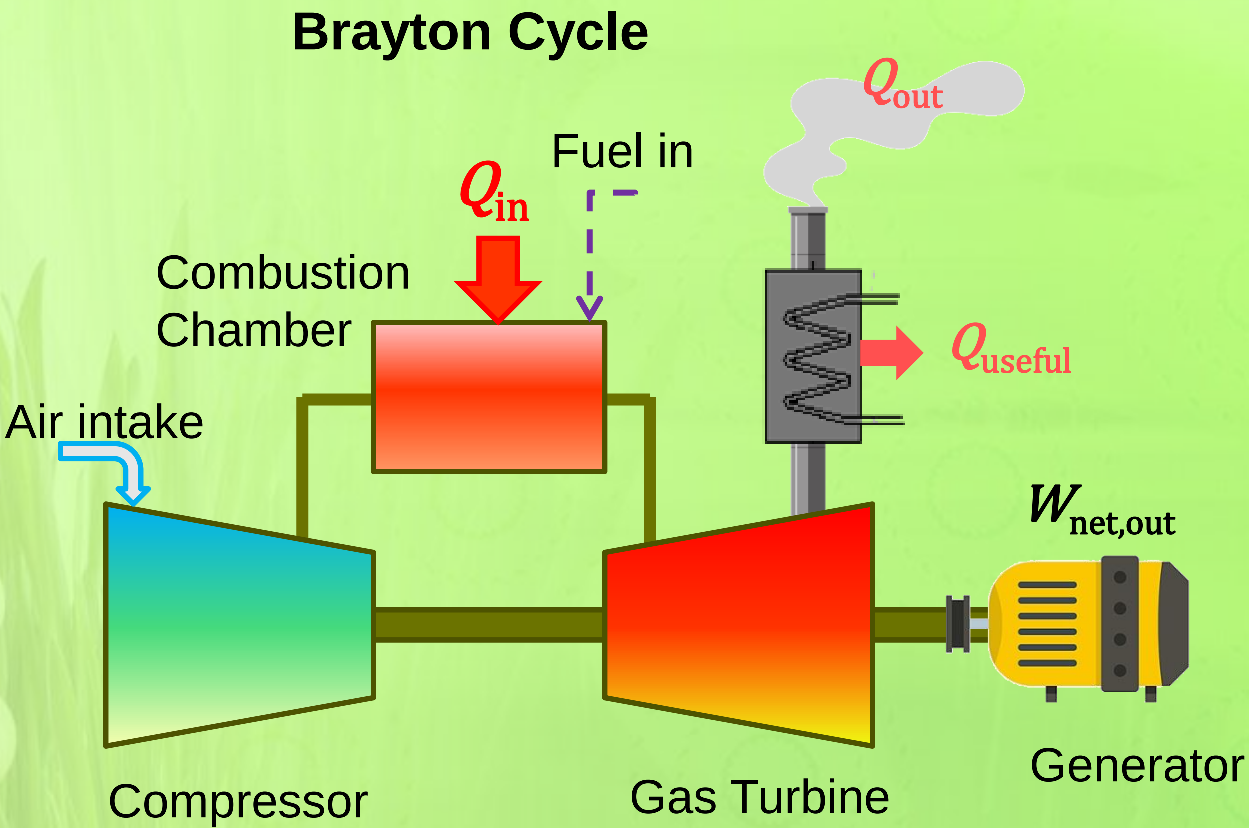
$$\text{or} \quad \eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Efficiencies of different heat engines

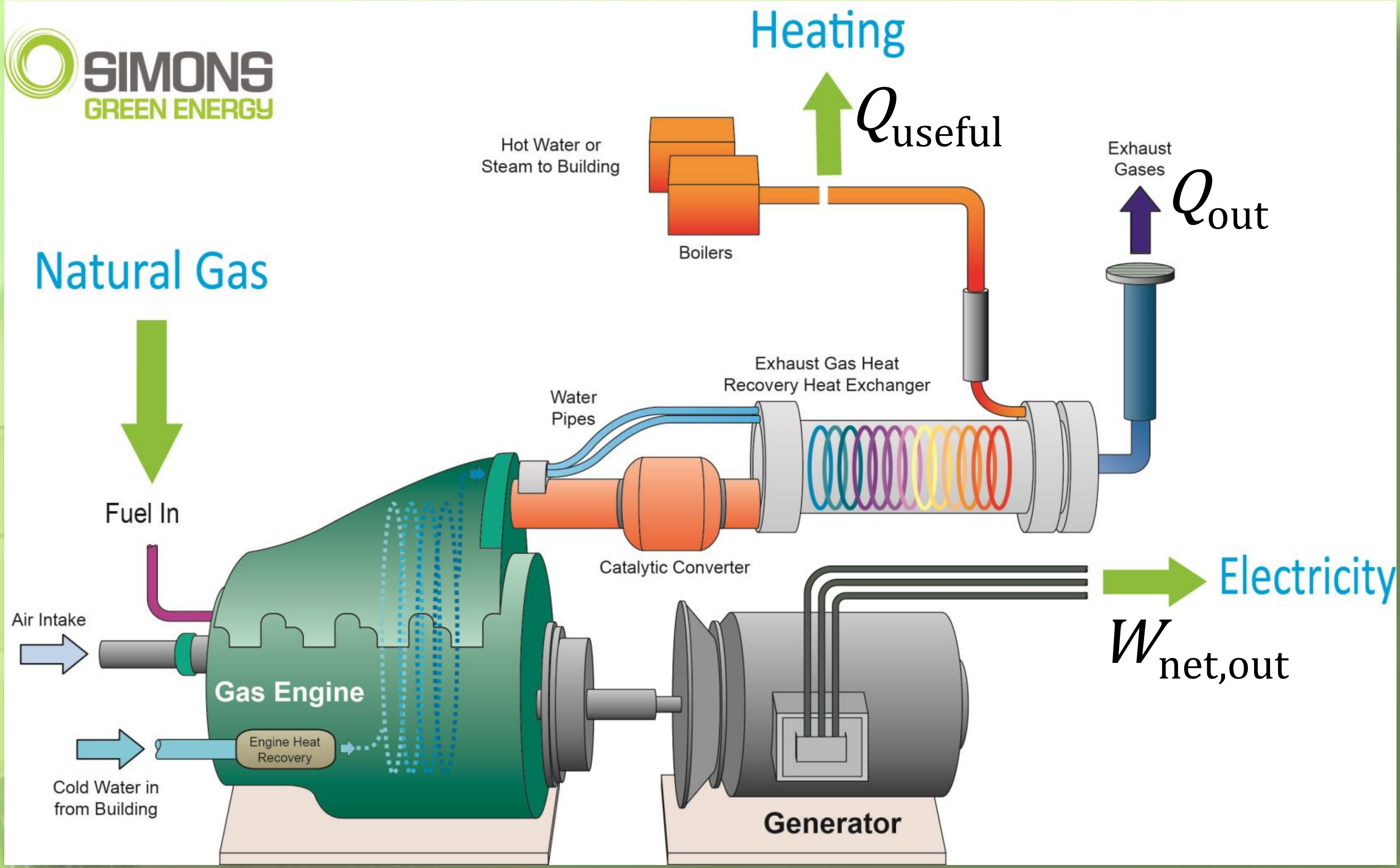


Source: Takaishi, Tatsuo; Numata, Akira; Nakano, Ryouji; Sakaguchi, Katsuhiko (March 2008). "Approach to High Efficiency Diesel and Gas Engines" (PDF). Mitsubishi Heavy Industries Technical Review. 45 (1). Retrieved 2011-02-04.

Cogeneration (or Combined Heat and Power)

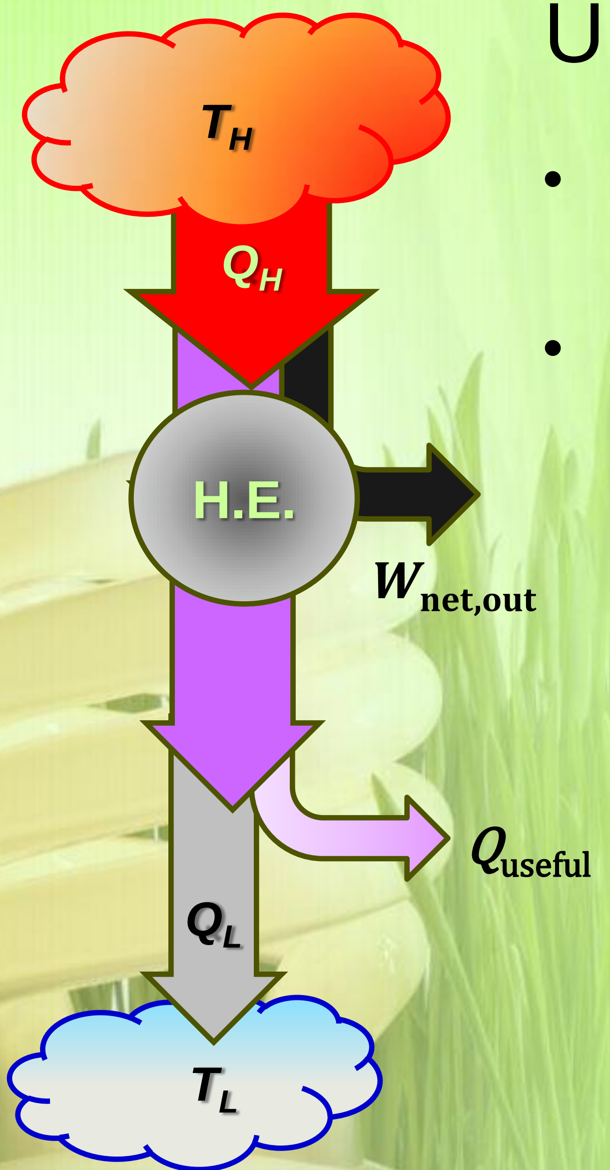


Cogeneration (or Combined Heat and Power)



Source: http://simonsboiler.com.au/product/cogeneration-combined-heat-power/

Performance of Cogeneration Units



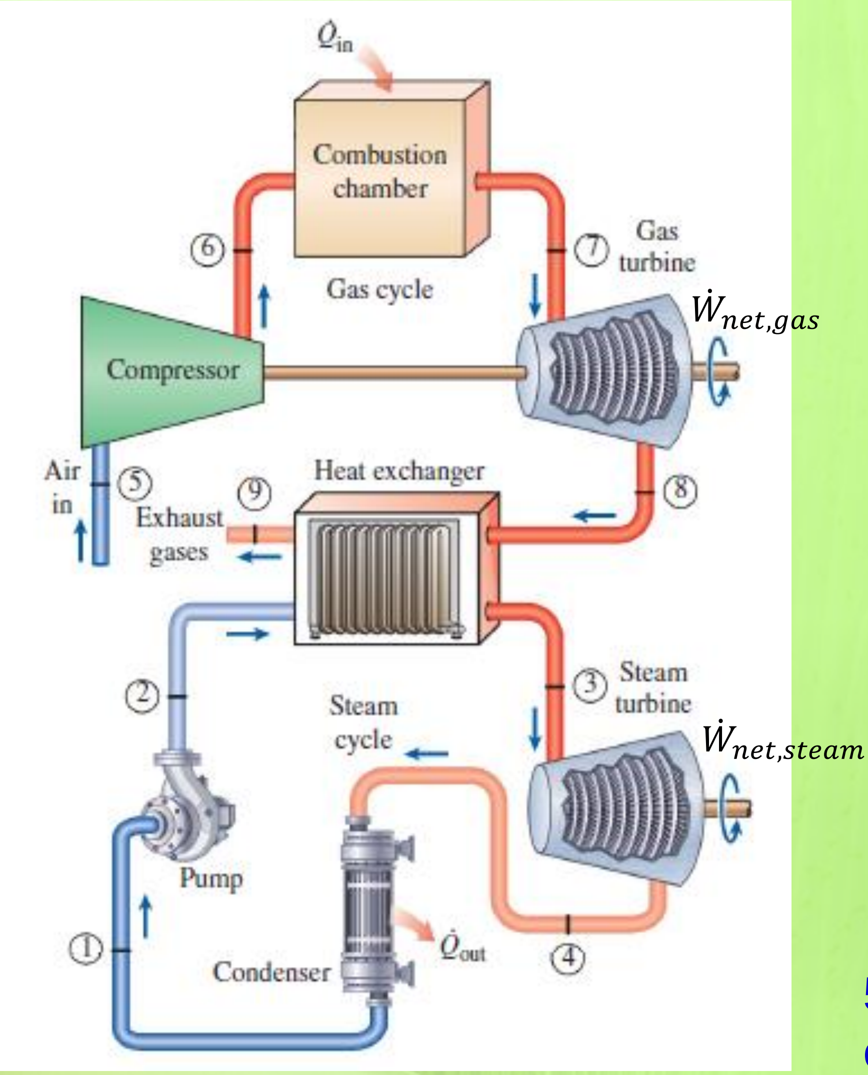
- Heat rejection from a heat engine can be utilized in heating processes
- The performance of cogeneration units are expressed as **energy utilization factor**.

Energy Utilization Factor:

$$\varepsilon = \frac{W_{\text{net, out}} + Q_{\text{useful}}}{Q_{\text{H}}}$$

In practice, utilization factors of 80% and above can be achieved.

Combined gas–steam power plant



$$\dot{W}_{net,out} = \dot{W}_{net,gas} + \dot{W}_{net,steam}$$

Thermal efficiency of the combined cycle:

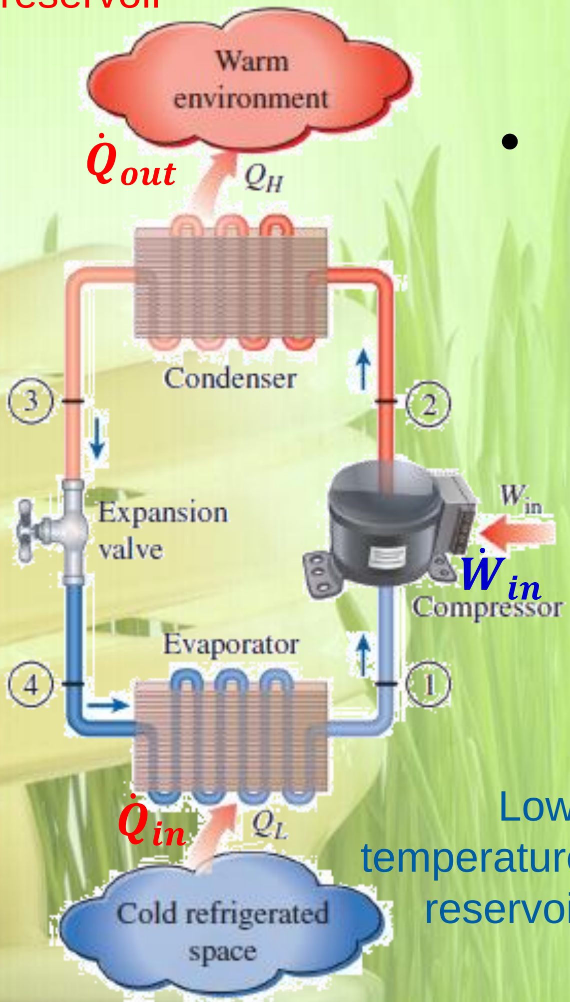
$$\eta = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}}$$

$$= \frac{\dot{W}_{net,gas} + \dot{W}_{net,steam}}{\dot{Q}_{in}}$$

50 – 60% efficiencies can be achieved with combined-cycle power plants.

Refrigerators and Air Conditioners

High-temperature reservoir



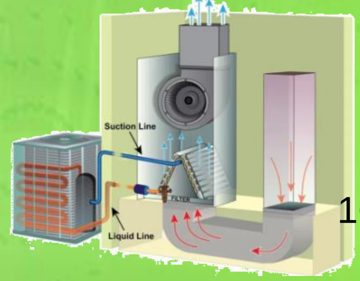
Low-temperature reservoir

- They move heat from low-temperature reservoir to high-temperature reservoir
- Different designs of air-conditioners are available:
  - Chillers
  - Single package (roof-top units)
  - Air-to-water heat pumps
  - Variable refrigerant volume (VRV) air conditioners

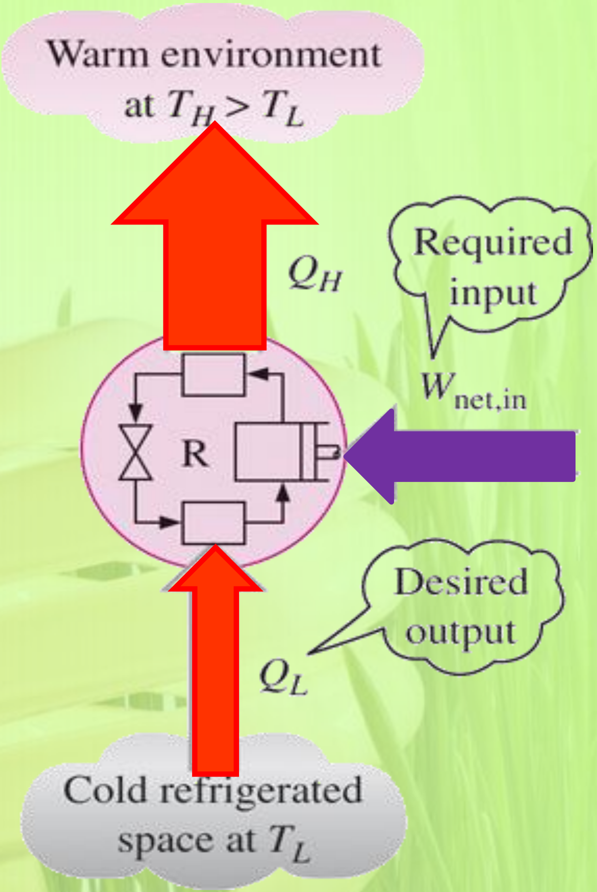
Chillers

Roof Top Units

Ducted Split-Units



Coefficient of Performance (*COP*) of refrigerators and air conditioners



- **The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (*COP*).**
- **The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.**

For a refrigerator: $COP_R = \dfrac{\text{Desired output}}{\text{Required input}}$

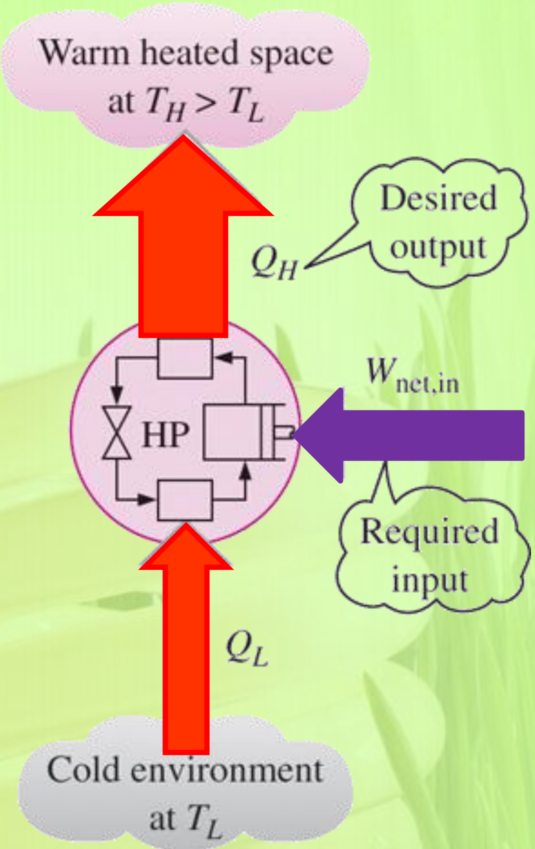
$$= \frac{Q_L}{W_{net,in}} \left(or \ \frac{\dot{Q}_L}{\dot{W}_{net,in}} \right)$$

$$W_{net,in} = Q_H - Q_L \quad (\text{ kJ })$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H / Q_L - 1}$$

Notice that COP_R, can be greater than unity.

Coefficient of Performance (*COP*) of heat pumps



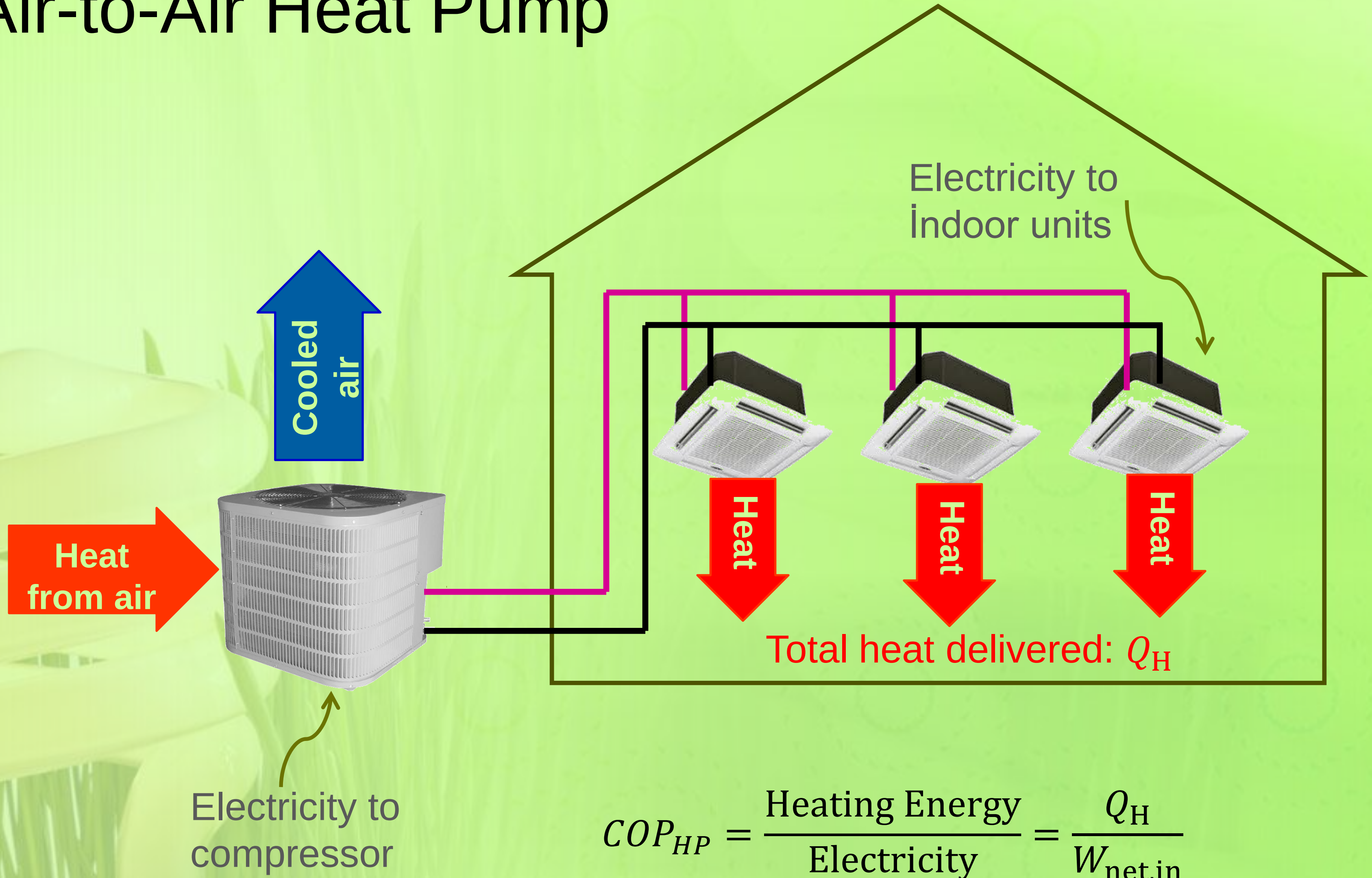
- **another device that transfer heat from T_L to T_H.**
- **objective is different : maintain a heated space at high temperature.**

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

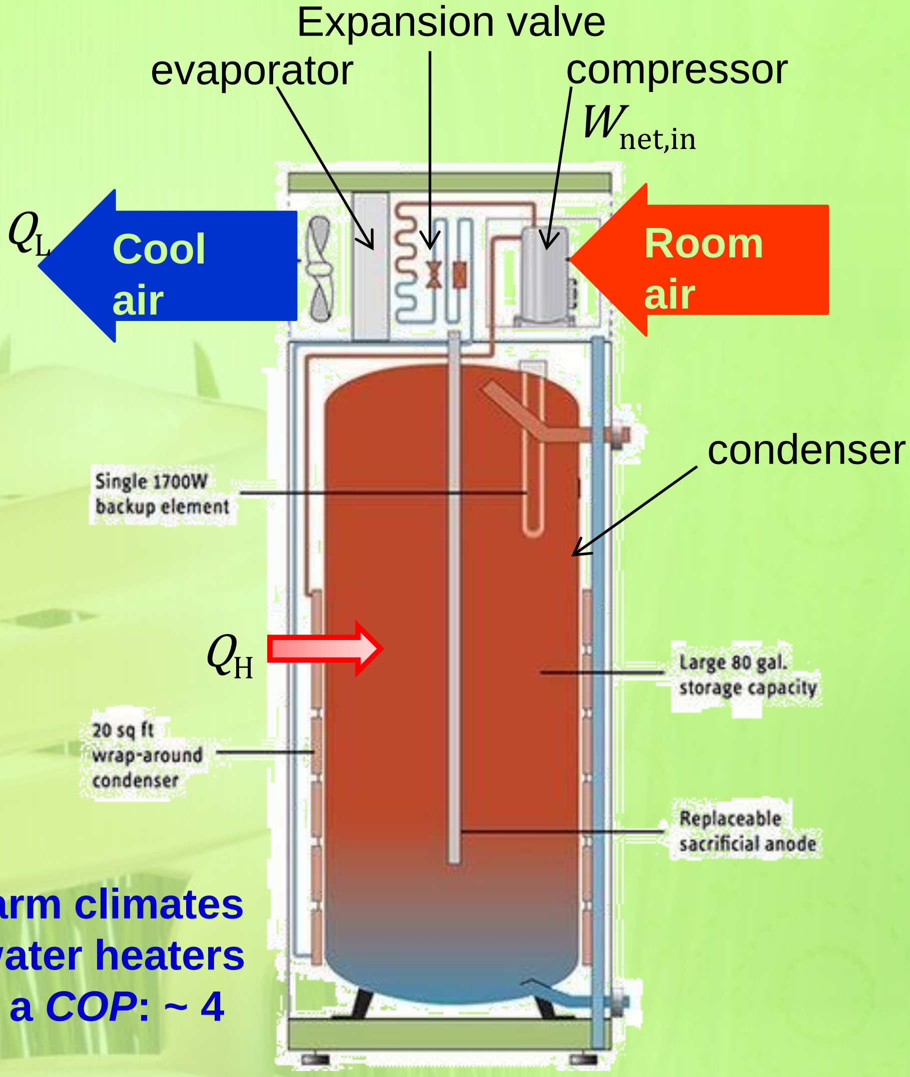
The objective of a heat pump is to supply heat Q_H into the warmer space.

Air-to-Air Heat Pump



$$COP_{HP} = \frac{\text{Heating Energy}}{\text{Electricity}} = \frac{Q_{\mathrm{H}}}{W_{\mathrm{net,in}}}$$

Air-to-water heat pump water heaters



In warm climates HP water heaters have a *COP*: ~ 4

Performance as a water heter:

$$COP_{HP} = \frac{Q_H}{W_{net,in}}$$

Performance if cool air is utilized while used as a water heater:

$$COP_{R+HP} = \frac{Q_H + Q_L}{W_{net,in}}$$

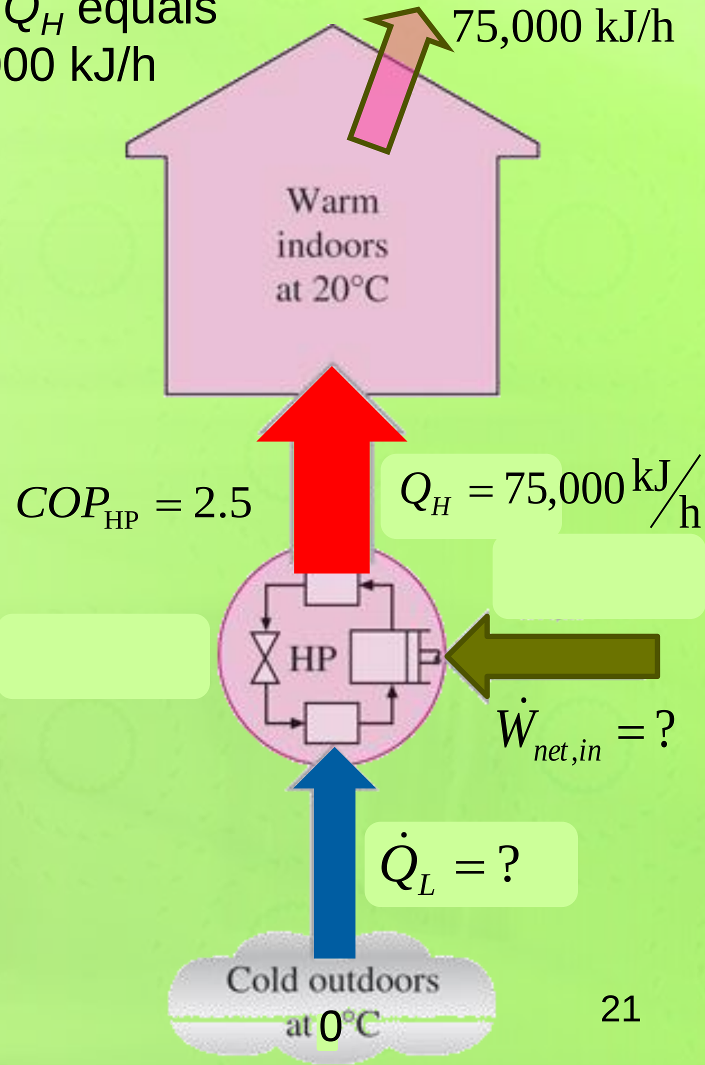
Heat Pump Example

For constant indoor temperature it is required that Q_H equals heat losses from the building. Therefore Q_H = 75,000 kJ/h

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} \rightarrow \dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{75{,}000}{2.5}$$

$$\dot{W}_{net,in} = 30{,}000 \, \mathrm{kJ/h} \; (\text{or } 8.33\,\mathrm{kW})$$

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} = (75{,}000 - 30{,}000)$$
$$= 45{,}000 \, \mathrm{kJ/h}$$



If we replace the heat pump with one that has a COP = 3.5:

$$\dot{W}_{net,in} = \frac{75{,}000}{3.5} = 21{,}429 \frac{\mathrm{kJ}}{\mathrm{h}} \; or \; \mathbf{5.95\ kW}$$

Power saved = 8.33 – 5.95 = 2.38 kW

Energy efficiency ratio (EER)

$$EER = \frac{Output\ cooling\ energy\ in\ BTU}{Input\ electric\ energy\ in\ Wh}$$

For example; a 12,000 BTU a/c powered by 1 kW will have an EER rating of 12.

- EER indicates the performance of air conditioners at peak load operations.
- EER rating is mostly used with room air conditioners.
- EER = 3.41 x COP

Seasonal energy efficiency ratio (SEER)

$$SEER = \frac{Output\ cooling\ energy\ in\ BTU\ over\ a\ season}{Input\ electric\ energy\ in\ Wh\ over\ a\ season}$$

- The SEER rating is calculated by dividing the total number of BTUs of heat removed in a cooling season from a space by the total amount of energy required in the same season by the air conditioner in watt-hours.
- In energy management calculations, it makes more sense to use SEER as performance parameter in the feasibility estimations.
- Best air conditioners have SEERs over 8.5.
- Although SEER can also be utilized for heat pumps, seasonal coefficient of performance (SCOP) is more commonly used.

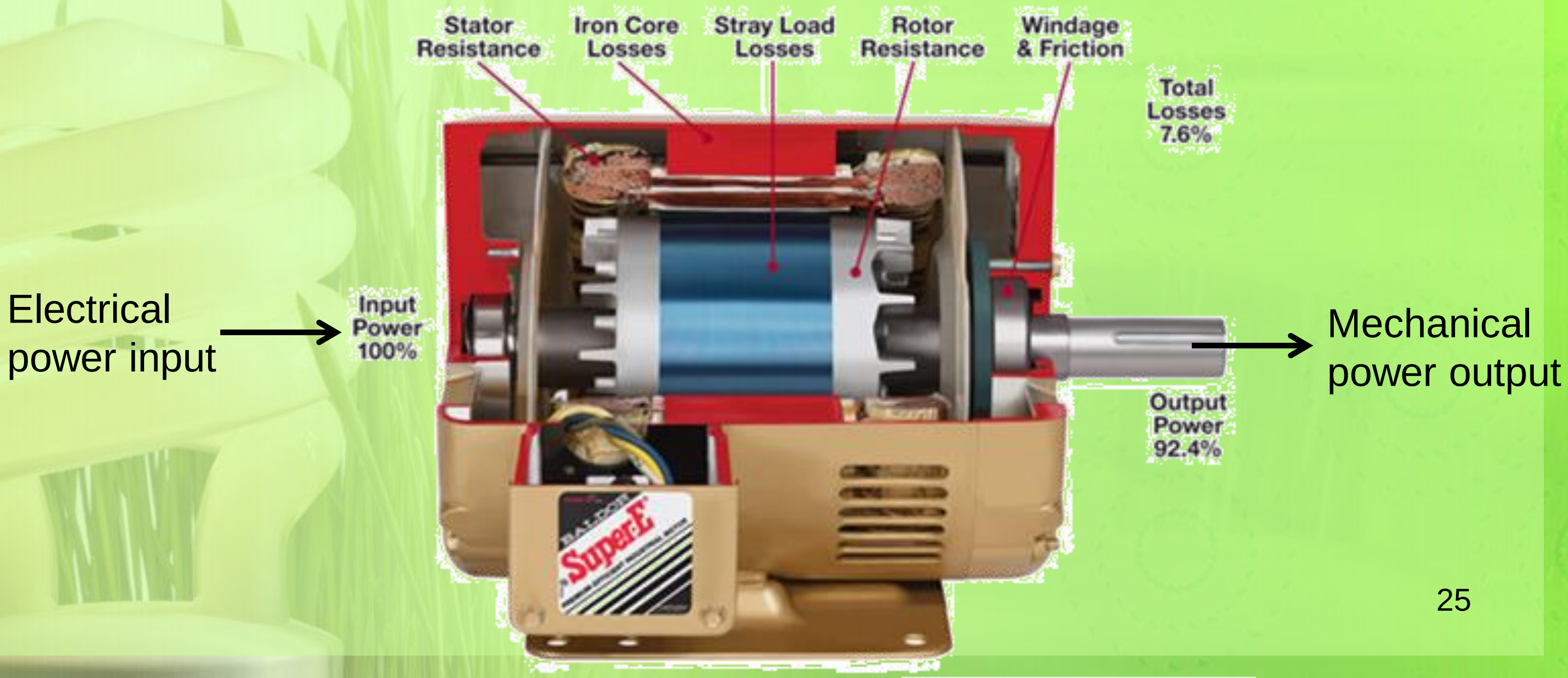
Energy labeling and SEER

Class	Cooling (SEER)	Class	Heating (SCOP)
A^{+++}	SEER ≥ 8.50	A^{+++}	SCOP ≥ 5.10
A^{++}	6.10 ≤ SEER < 8.50	A^{++}	4.60 ≤ SCOP < 5.10
A^{+}	5.60 ≤ SEER < 6.10	A^{+}	4.00 ≤ SCOP < 4.60
A	5.10 ≤ SEER < 5.60	A	3.40 ≤ SCOP < 4.00
B	4.60 ≤ SEER < 5.10	B	3.10 ≤ SCOP < 3.40
C	4.10 ≤ SEER < 4.60	C	2.80 ≤ SCOP < 3.10
D	3.60 ≤ SEER < 4.10	D	2.50 ≤ SCOP < 2.80
E	3.10 ≤ SEER < 3.60	E	2.20 ≤ SCOP < 2.50
F	2.60 ≤ SEER < 3.10	F	1.90 ≤ SCOP < 2.20
G	SEER < 2.60	G	SCOP < 1.90

Efficiency of electric motors

Efficiency (EFF) of a motor is defined as:

$$EFF = \frac{\text{Desired Output}}{\text{Required input}} = \frac{\text{Mechanical Power Output}}{\text{Electrical Power Input}}$$



Efficiency of electric motors

Many technological improvements have been made to electric motors. From new materials for inside windings to decreased friction from well-designed ball bearings, the efficiency of new motors increases almost every day.

Example

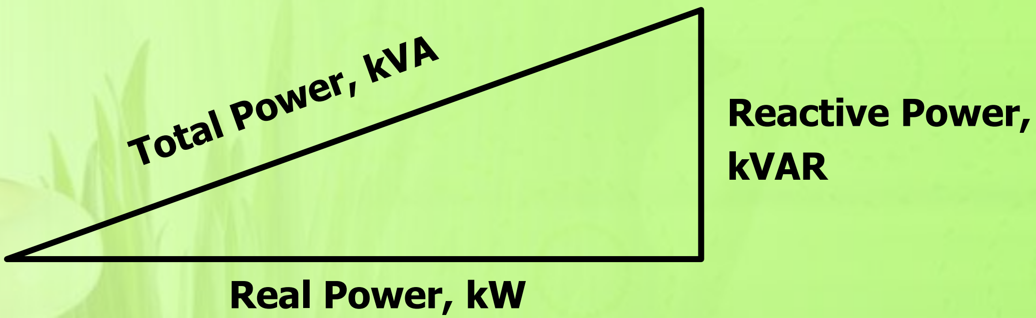
A motor delivers a shaft output power of 10 kW, and has an electrical power input of 12 kW. What is its efficiency?

Solution:

$$EFF = \frac{10\ kW}{12\ kW} = 83.3\%$$

Power factor of electric motors

- **Power Factor** – The power factor is an electrical operating parameter of a motor, and is found from the ratio of the real power input in kW to the total power input in kVA.



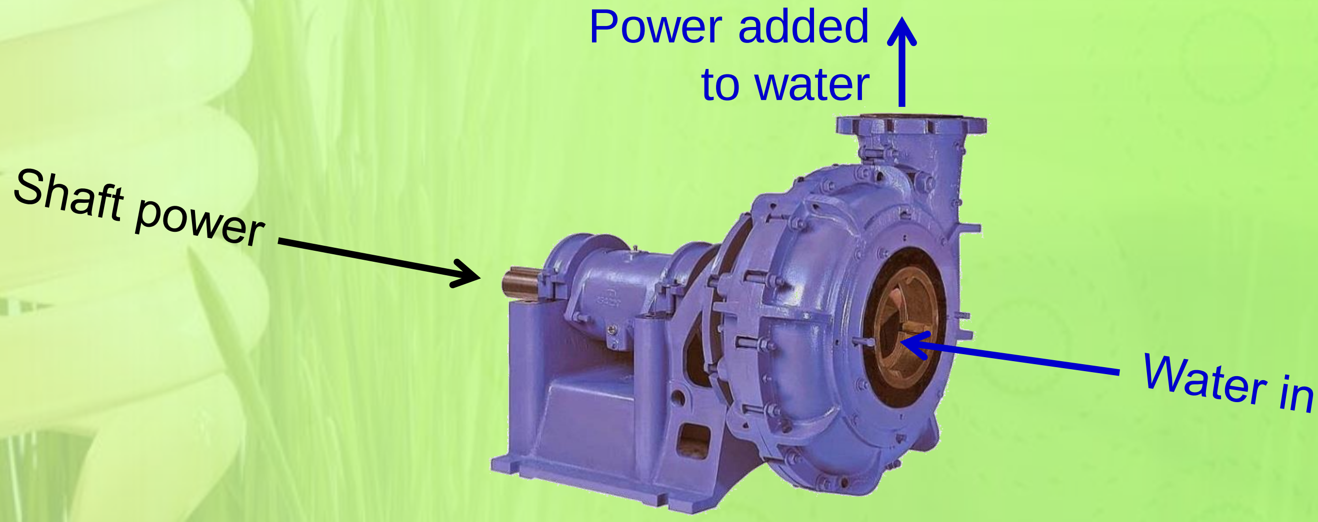
PF = kW / kVA

- Larger motors usually have higher power factors than smaller motors. Larger motors will usually have power factors around 85%.
- Sometimes, electrical capacitors are installed on motors to provide "power factor correction." This may be cost-effective for the facility if their utility charges a substantial penalty for low power factor.

Water pump efficiency

- Defined as the ratio of power delivered on the water by the pump to the shaft power input for the pump
- Such that:

$$\text{Pump efficiency} = \frac{\text{Power conveyed to water}}{\text{Shaft power}}$$



Efficiency of pumping fluids

Pump brake horse power in kW

$$P = \frac{\text{flow rate}\,(\text{m}^3/\text{s}) \times \text{pressure difference}\,(\text{N/m}^2)}{1000 \times \text{efficiency}}$$

The overall pumping efficiency refers to both the pump and motor efficiencies:

$$P = \frac{\dot{V} \times \Delta P}{1000 \times \eta_p \times \eta_m}$$

Flow rate in m^3/s

Pump head in N/m^2

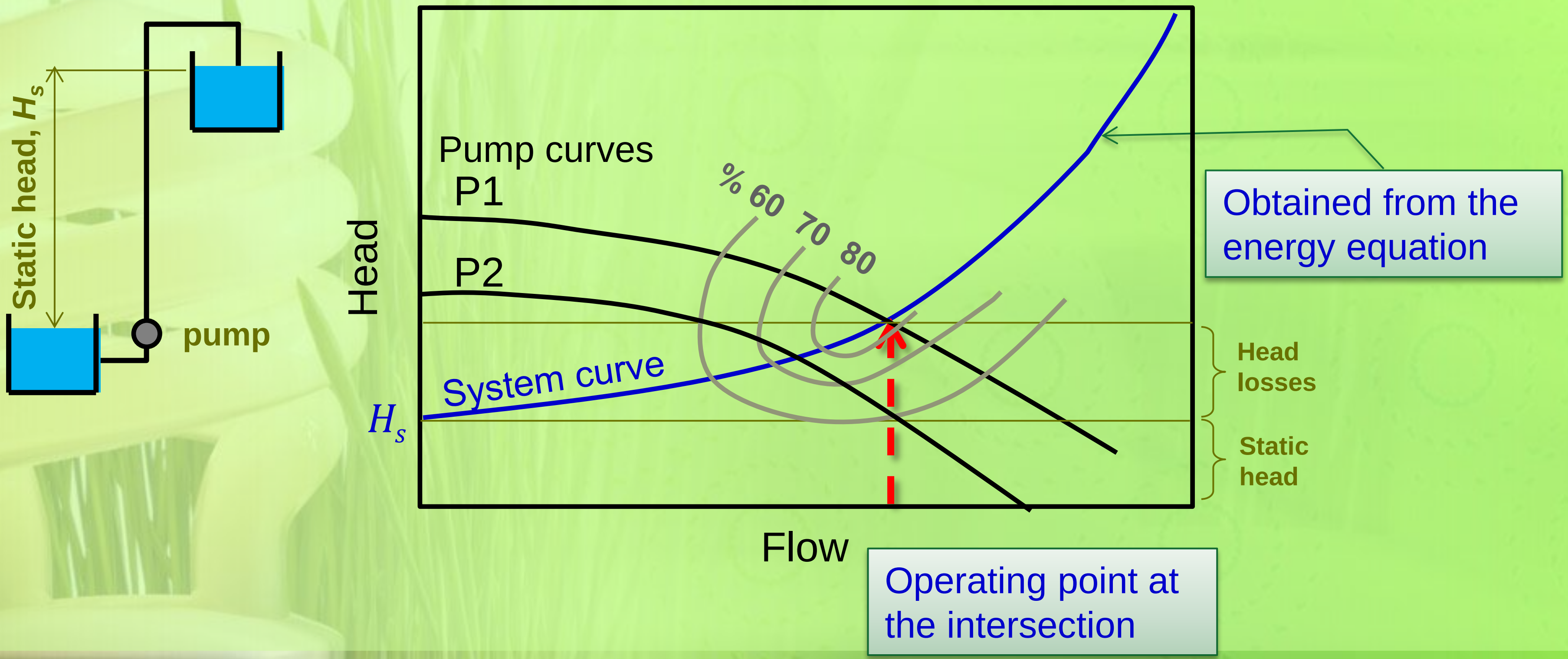
Pump power consumption in kW

Pump efficiency

Motor efficiency

Selecting the most efficient water pump

- The duty of the pump is defined by the required flow rate and pressure
- System head is usually in the form: $H_s + k\dot{V}^2$, where *k* is a constant



Pump Example

Required flow rate is 80 L/s with a head of 150 kN/m^2. What is the saving in power if a pump efficiency of 90% is preferred instead of 78%. Assume motor efficiency to be 100%.

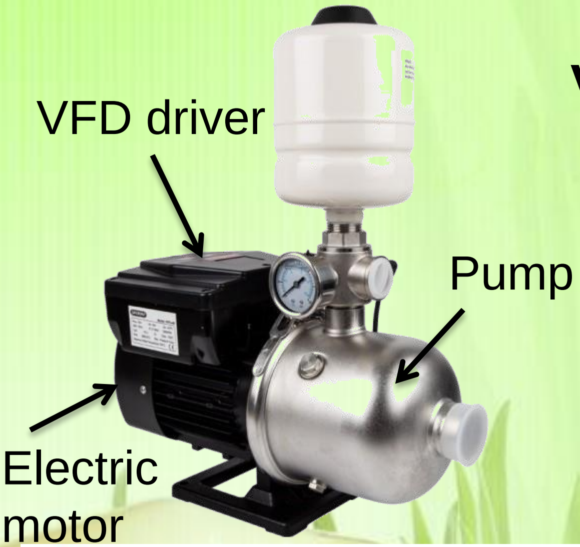
Pump power :

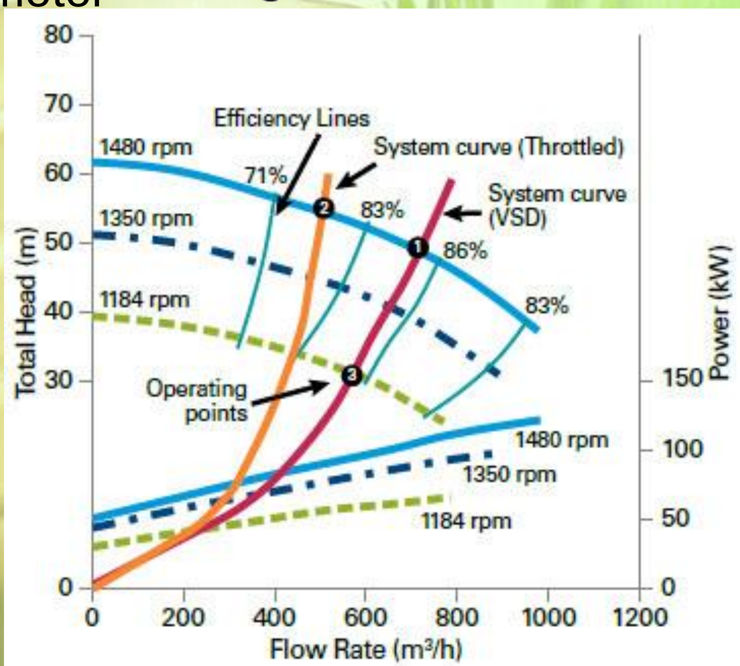
$$P = \frac{\dot{V} \times \Delta P}{1000 \times \eta_p \times \eta_m}$$

Saving in pump power :

$$= \frac{(\dot{V} \times \Delta P)}{1000}\left(\frac{1}{\eta_{78\%}} - \frac{1}{\eta_{90\%}}\right) = \frac{0.08 \times 150 \times 10^3}{1000}\left(\frac{1}{0.78} - \frac{1}{0.9}\right) = 2.05\,\text{kW}$$

Variable speed drives (VSDs) and variable frequency drives (VFDs)





- Devices that can vary speed of a fixed speed motor
- VSDs are used with both direct current (dc) and alternating current (ac) devices, whereas VFDs are used with ac devices only.
- Used in pumps, fans, HVAC systems, compressors etc.
- Cube law:

$$\frac{Power_{new}}{Power_{old}} = \frac{(Motor\ speed_{new})^3}{(Motor\ speed_{old})^3}$$

Source: http://www.gozuk.com/applications/vfd-for-pumps.html

Example of a VSD application in a fan

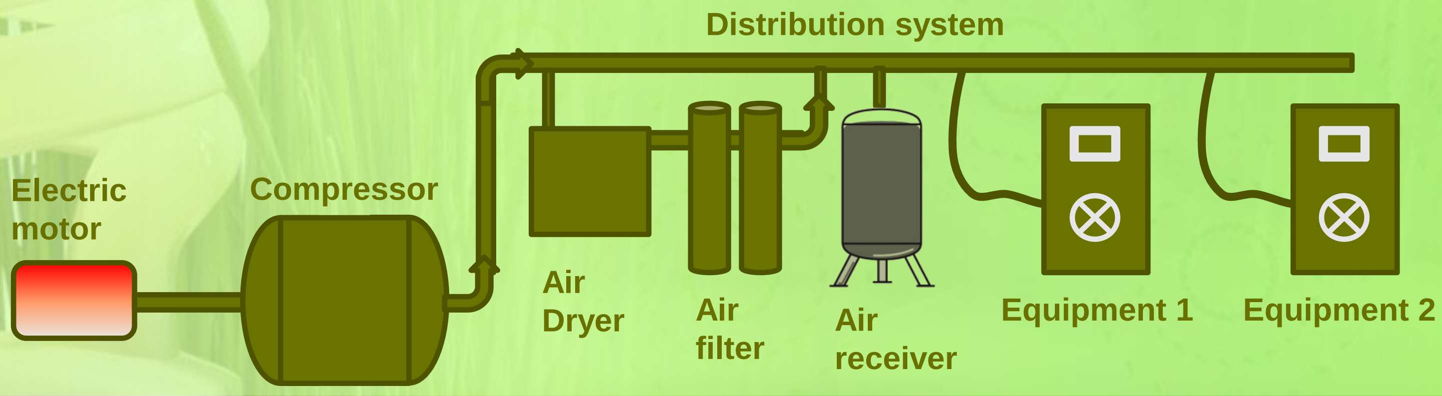
$$\frac{kW_{new}}{kW_{old}} = \frac{[RPM_{new}]^3}{[RPM_{old}]^3}$$

	Motor speed (RPM)	Power consumption (W)
(Fixed speed conditions)	1400	800
	1000	292
	700	100
	400	19

Part load speed Reduction with VSD

Compressors: *Improving compressed air energy efficiency*

- One of the significant sources of energy use in the industry is compressors
- There are three main factors causing inefficiencies in energy consumption:
  1. **Oversized compressors:** *Bigger is not better. Correct sizing is important*
  2. **Fluctuating air demand:** *Use VSD if demand is changing*
  3. **Air distribution system:** *Design shorter lengths of distribution avoiding sharp bends. Check for the leaks.*



Recovering heat dissipation from air compressors

- As much as 90% of the input energy to an air compressor becomes waste heat.
- On average 70% of the heat can be recovered from air cooled compressors. Reclaimed heat can be used for:
  - Heating a space
  - Process drying
  - Heating water
  - Bathroom use

Efficiency measures for lighting

- Energy efficient lights should be chosen
- The reflectors should be effective in fixtures
- Timer control can be used if the periods of usage is known
- Motion or occupacy sensors detect the presence of people and turn the lights on
- Daylight control can adjust the amount of light depending on the daylight level in a room

The performance measure of electric lamps: «*Efficacy*»

- Efficacy is measured in units of lumens per watt (Lu/W).
- This is not a measure of efficiency since it has units.
  - Efficiency has no units, and is either expressed as a decimal number like 0.90, or is stated in percent, like 90 %.
  - Efficacy has units of Lu/W.

Example for efficacy

A 60 watt incandescent lamp has an output of 1100 lumens (amount of light). What is the efficacy of this lamp?

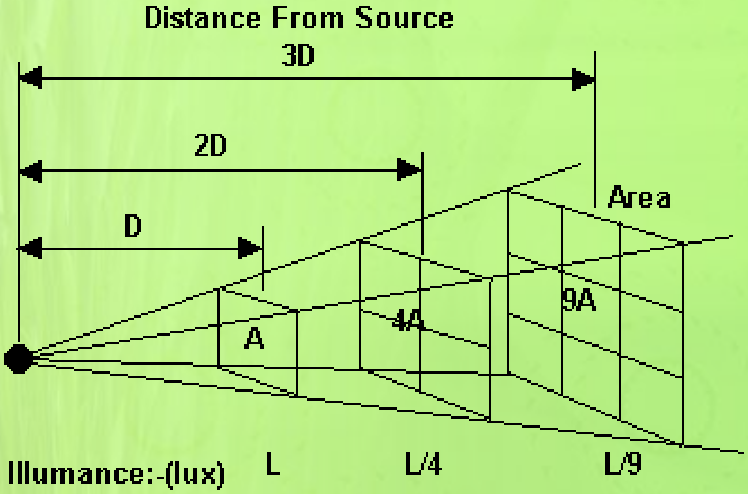
The efficacy equals 1100 lumens divided by 60 watts

$$\text{Efficacy} = \frac{\text{Light output (lumens)}}{\text{Electricity required (Watts)}}$$

$$\text{Efficacy} = \frac{1100\ \text{lumens (Lu)}}{60\ \text{Watts (W)}} = 18.3\ \text{Lu/W}$$

Task lighting

- Use lower wattage lamps at task
- Reduce number of fixtures
- Save considerable energy
- Better light

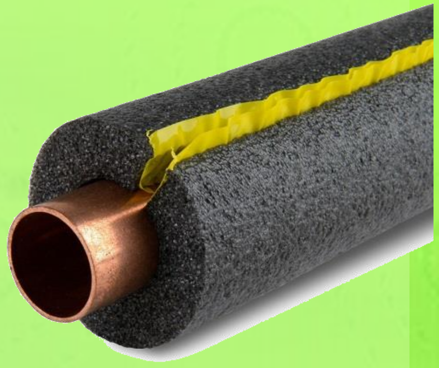


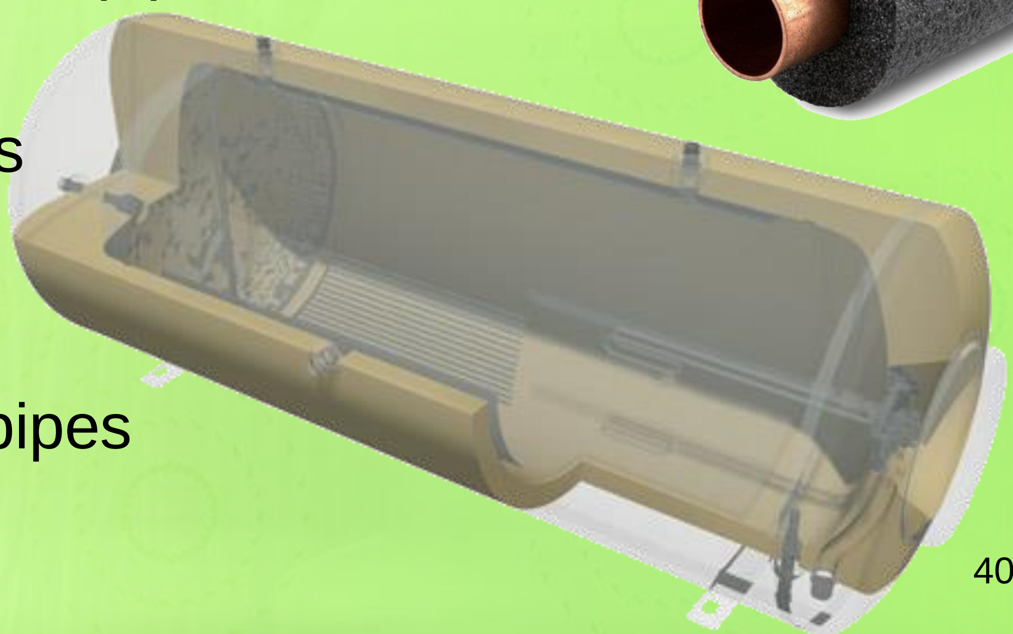
$$L = \frac{1}{D^2}$$

Light intensity falls off as the "inverse square" of the distance

Improvement of efficiency with thermal insulation

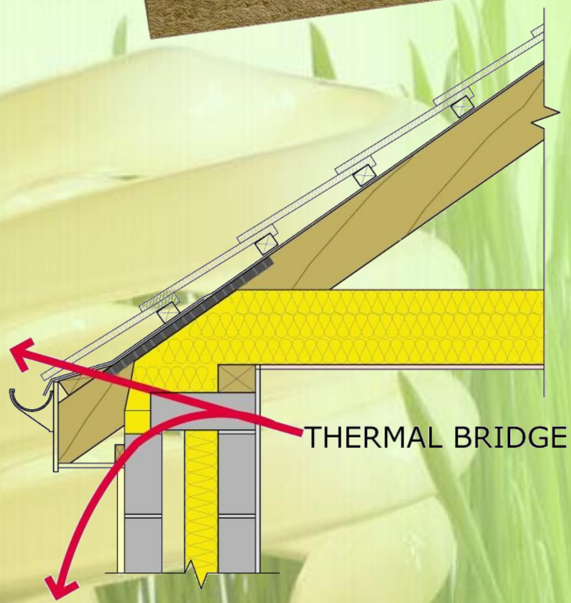
- Thermal insulation can be utilized to reduce the energy losses or gains from energy systems.
- They can be used in:
  - Buildings
  - Hot and chilled water pipes
  - Steam pipes
  - Hot water cylinders
  - Heat exchangers
  - Turbines
  - Chimneys or flue pipes
  - Air ducts





Good practice in thermal insulation

- Correct material with correct application
  - Fiberglass
  - Polystyrene board (EPS, XPS)
  - Rockwool
- Thermal insulation should cover a building or any other system all around its thermal boundary.
- Heat bridges should be avoided



Suggestion for your term assignment

- One of the measures in your assignment should be insulation of hot water pipes
- Determine the length of hot water pipes
- Estimate the annual heat losses
- Estimate the savings with thermal insulation