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POWER PLANT

INTRODUCTION

Lecturer

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SYLLABUS

1. Introduction
   - Classification of power plant
   - Comparison between power plant
2. Steam cycles, Cogeneration plant (combined power and heat plant)
3. Gas power plants
4. Steam boilers
5. Steam nozzles
6. Steam turbines
7. Economics of power plant

REFERENCES

1. Applied thermodynamic By Eastop & Mcconkey
2. Engineering thermodynamics work and heat transfer By Rogers & Myhew
3. Power plant technology By M.M. EL. Wakil
4. Steam turbine theory and practice By W.J. Kearton
5. A course in power plant engineering By Arora

2. Steam Cycles:

2.1 Definition

2.2 Carnot cycle

2.3 Rankine cycle

- **Simple Rankin cycle**
- **Modified Rankin cycle** →
  - **Superheat**
  - **Reheat**
  - **Regeneration**

2.4 Cogeneration Plant

- **The Bottoming cycle**
- **The Topping cycle** →
  - **Back pressure turbine**
  - **Extraction turbine**

3. Gas turbine power plants:

3.1 Open cycle gas turbine

3.2 Closed cycle gas turbine

3.3 Analysis of closed cycle gas turbine

3.4 Analysis of open cycle gas turbine

3.5 Improvement the performance of gas turbine

3.6 Gas and steam cycle (combined cycle)

4. Stem boilers:

4.1 Feed water treatment

4.2 Classification of boilers

4.3 Boiler mountings

4.4 Boiler accessories

4.5 Combustion calculations

4.6 Boiler performance

4.7 Boiler heat balance

5. Steam nozzles:

5.1 Types of nozzles

5.2 Off-design condition

5.3 Basic equation for nozzle

5.4 Super saturation (metastable) expansion

6. Steam turbine:

6.1 Types of steam turbine

6.2 Impulse turbine

6.2.1 Simple impulse

6.2.2 Compound impulse

6.3 Flow of steam through impulse turbine

6.3.1 Simple impulse

6.3.2 Compound impulse turbine

6.4 a. velocity diagram b. degree of reaction

c. parsons turbine d. blade efficiency

e. stage efficiency f. blade height

6.5 Losses in steam turbine (steam distribution)

6.6 Steam turbine governing

6.7 stage efficiency, overall efficiency and reheat factor

7. Economics of power plant:

7.1 Coast of electrical energy

7.2 Selection generating type

7.3 Load curve and load duration curve

7.4 Different terms and definition

7.5 Peak load plants

7.6 Pump storage plants

7.7 Air storage plants

What is Power Plant?

A **power plant** or a **power generating station**, is basically an industrial location that is utilized for the generation and distribution of electric power in mass scale, usually in the order of several 1000 Watts.

Location

At the sub-urban regions or several kilometers away from the cities or, the load centers, because of its requisites like huge land and water demand along with several operating constraints like the waste disposal etc.

Classification of power plans

Power plants using conventional (non-renewable) source of energy

- Steam power plant
- Nuclear (Atomic) power plant
- Diesel power plant
- Gas power plant
- Hydro electrical (Hydel) power plant

Power plants using Non-conventional (renewable) source of energy

- Solar thermal power plant
- Wind powered generation(aero generation)
- Wave power plant
- Tidal power plant
- Geothermal power plant
- Bio-mass power plant
- Ocean thermal power plant

Other Classifications

Based on Fuel Type:

1. **Coal Fired Power Plant**
2. **Diesel/HFO Power Plant**
3. **GAS Power Plant**
4. **Nuclear Power Plant**

Based on place

1. **Central Power Plant:** connected with national grid system
2. **Isolated Power Plant:** for supply electricity to a limited number of consumers in a remote place

Based on Load Type:

1. **Base Load Power Plant:** Provides a continuous supply of electricity
2. **Peak Load Power Plant:** when we use much electricity like 2pm–8pm

Efficiencies of Different types of Power generation sources:

Type	Efficiency	Operating Condition
Sub Critical Thermal plant	35-38%	170 bar , 570˚C
Super Critical Thermal Plant	42%	220 bar, 600˚C
Ultra Super Critical	45-48%	300 bar,600˚C
IGCC	45-55%	
Hydro Power Plant	85-90%	
Wind turbine	30-45%	
Solar Thermal System	12% annually	
Geo Thermal System	35%	
Nuclear Power Plant	0.27%	
Diesel Engines	35-42%	

IGCC (Integrated Gasification Combined Cycle)

Source EnggCyclopedia

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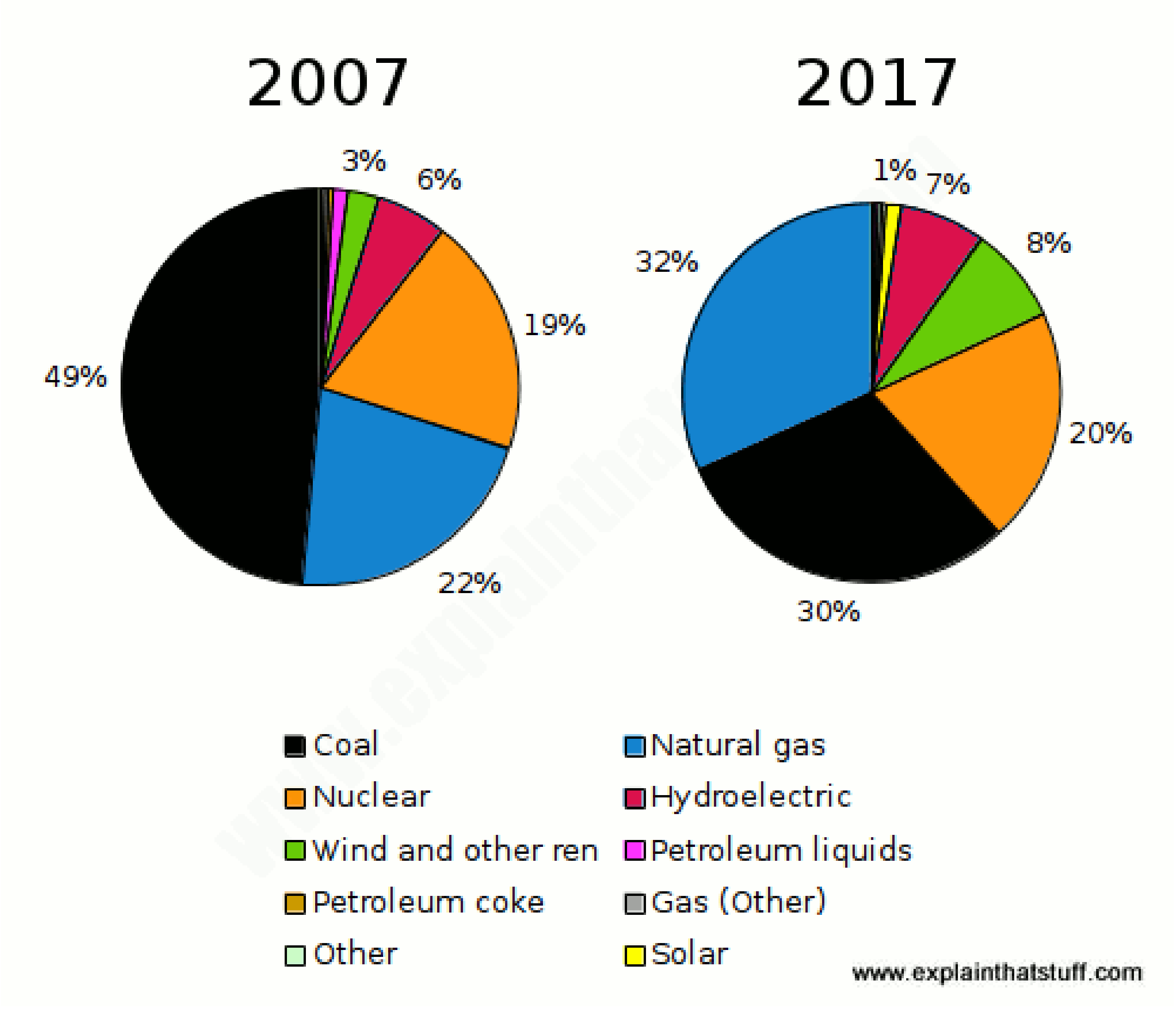
Types of Power Generation

depending on the type of fuel used
3 major classifications for power production in reasonably large scale are :-

Thermal power generation.

Nuclear power generation.

Hydro-electric power generation.



Thermal power generation

Thermal power plants use **water** as **working** fluid.
Nuclear and coal based **power** plants fall under this category.

In a **thermal power plant** a **steam turbine** is rotated with help of high pressure and high temperature steam.

Diesel power station

For small scale production of electric power, and where ?

There is no other easily available alternatives of producing electric power, **diesel power station** are used

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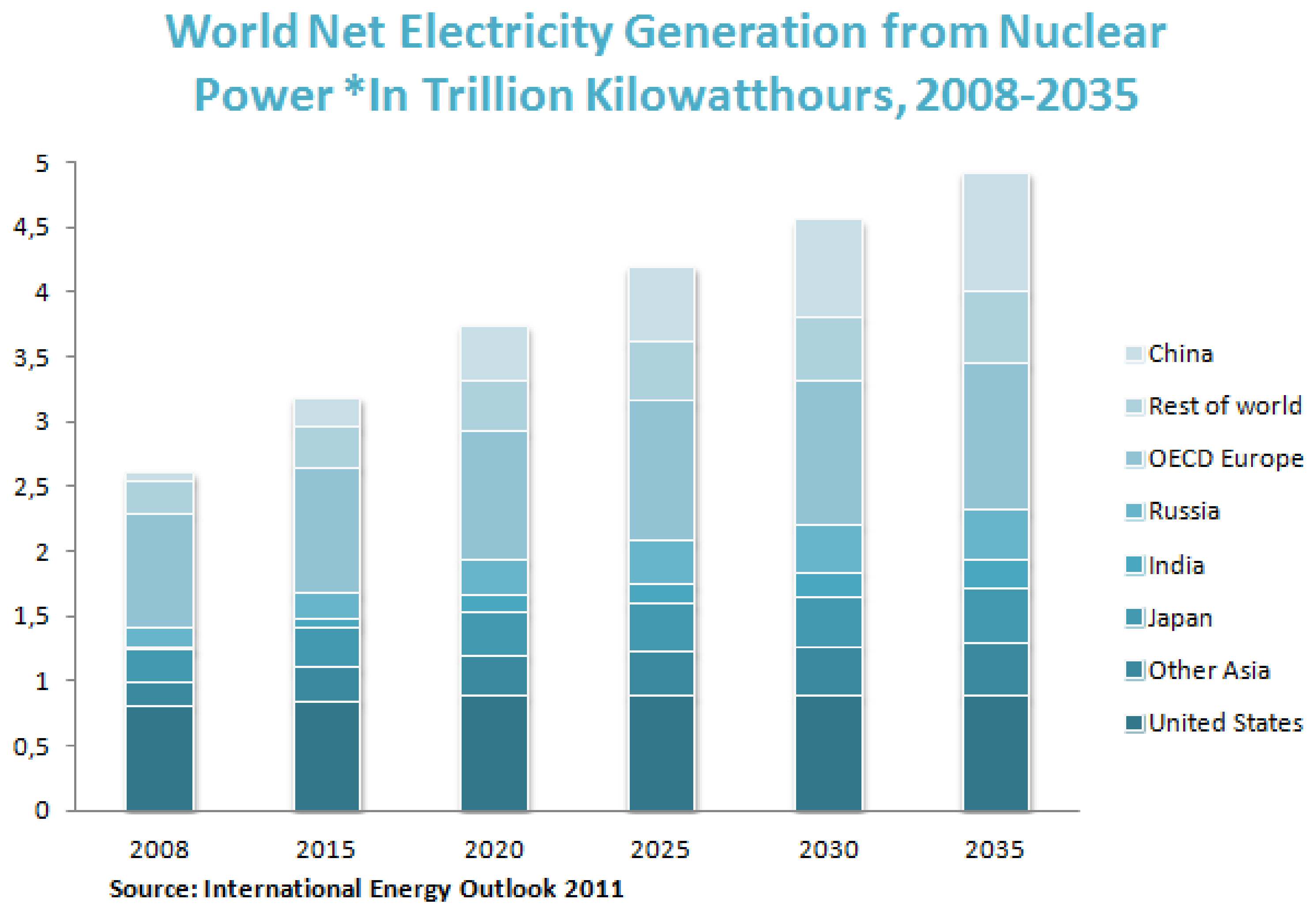
Nuclear power generation



Risk

Dissemination of radioactive products

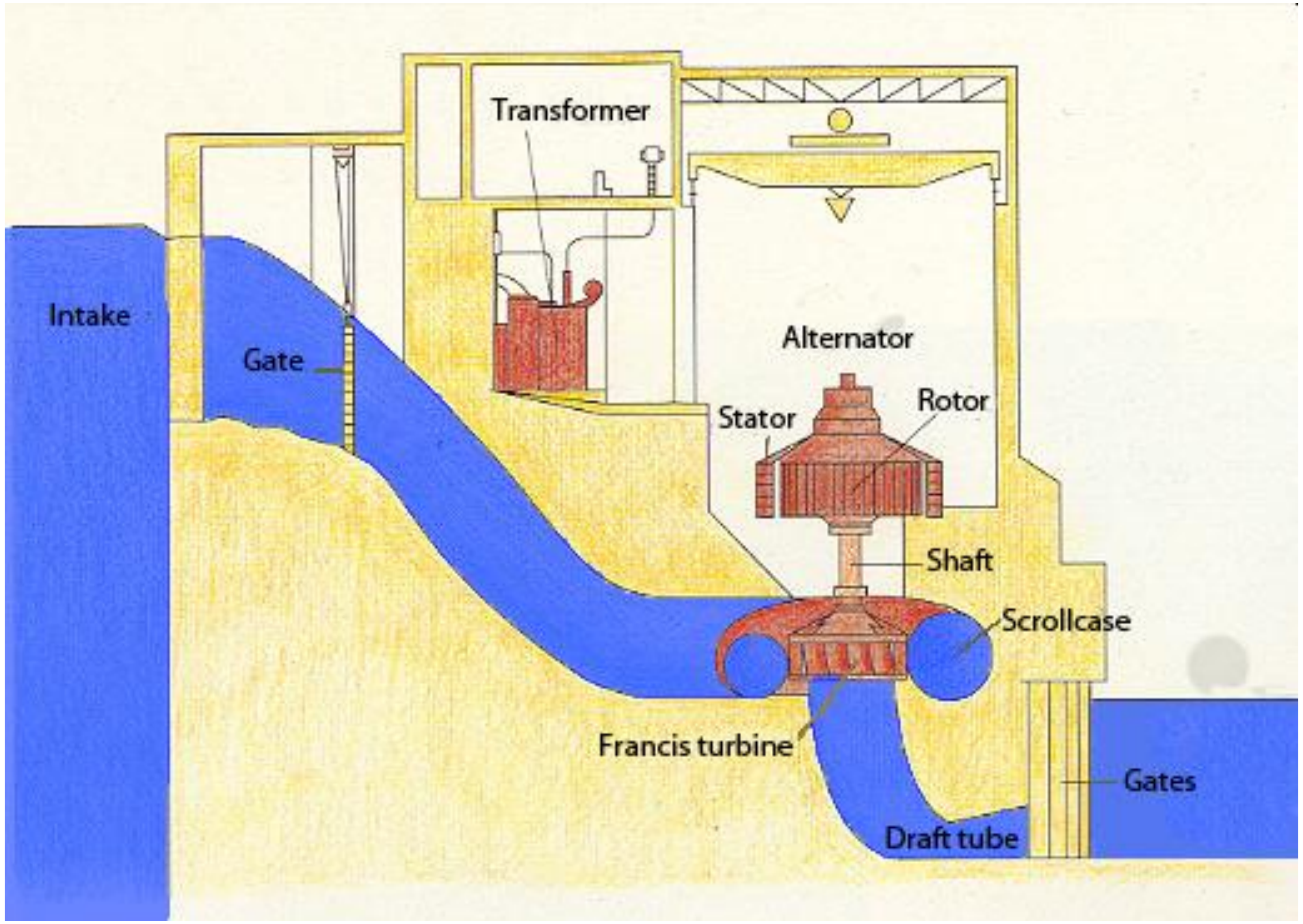
Exposure to radioactivity on plant components

Hydro-electric power generation.

This type of power plant is CO_2 free because no **fossil fuel** is used

In 2015 hydropower generated **16.6%** of the world's total electricity

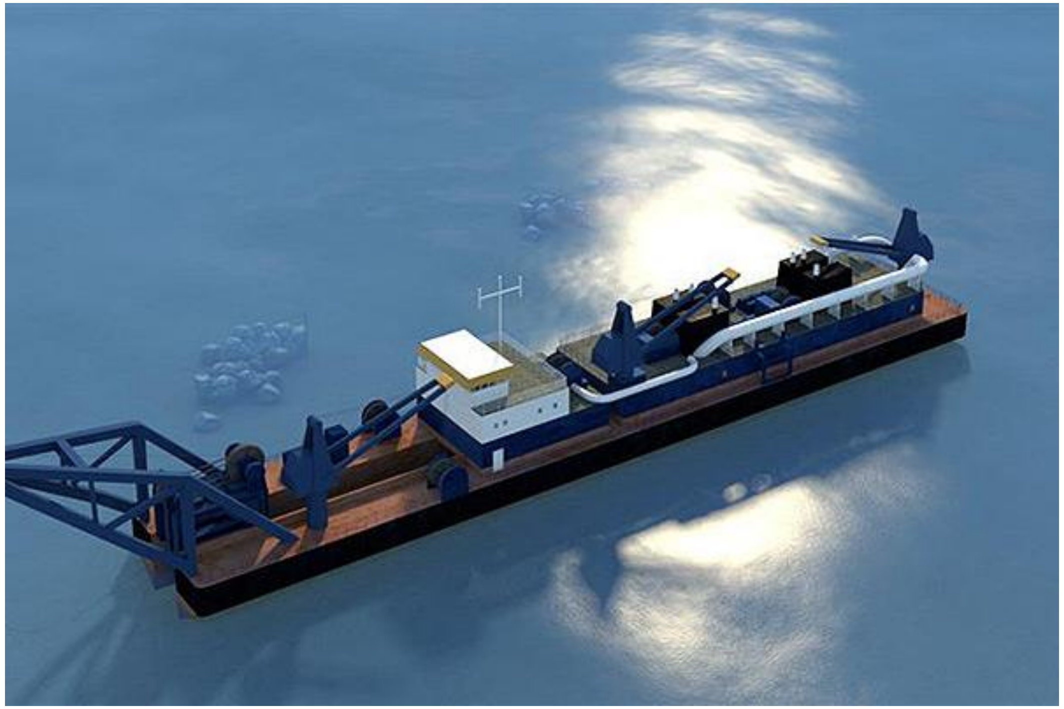
China is the largest hydroelectricity producer, with **920 TWh** of production in 2013, representing 16.9 percent of domestic electricity use

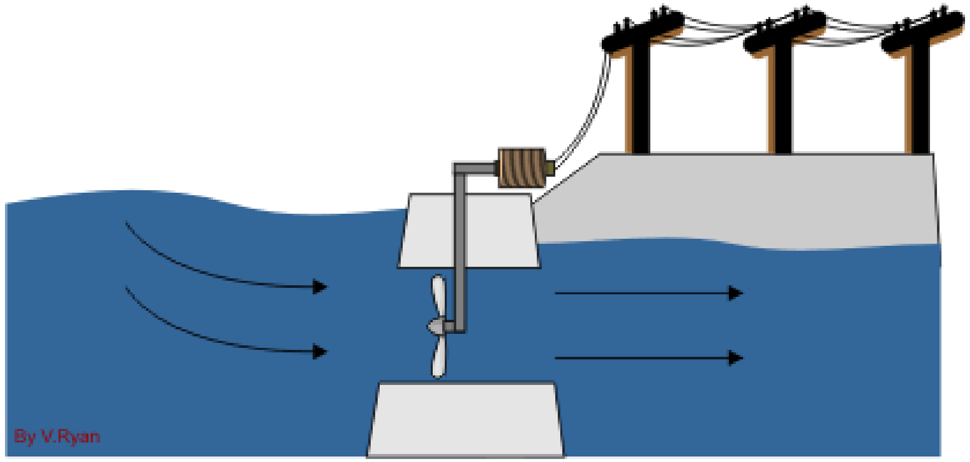


Ocean Water (Tidal Power Plant):

Converts the **tidal** flows energy into electricity

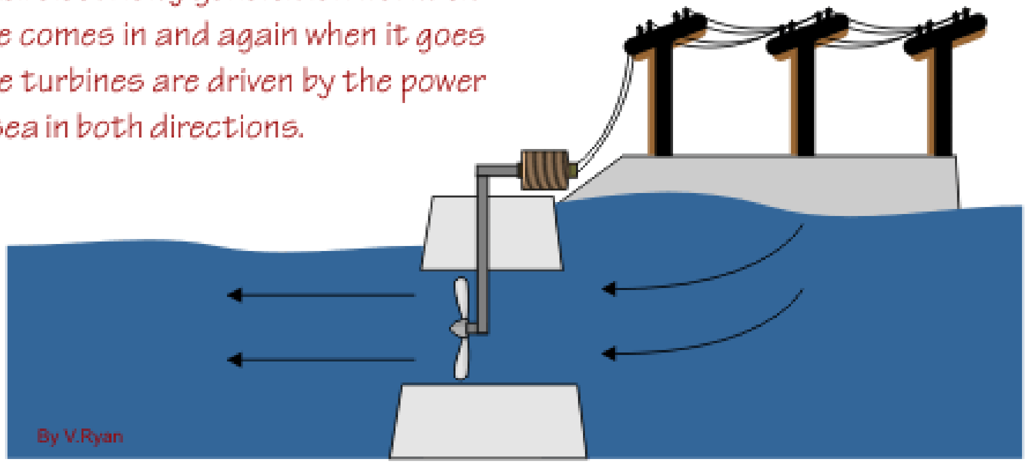
La Rance Tidal Power Plant,
France – 240MW





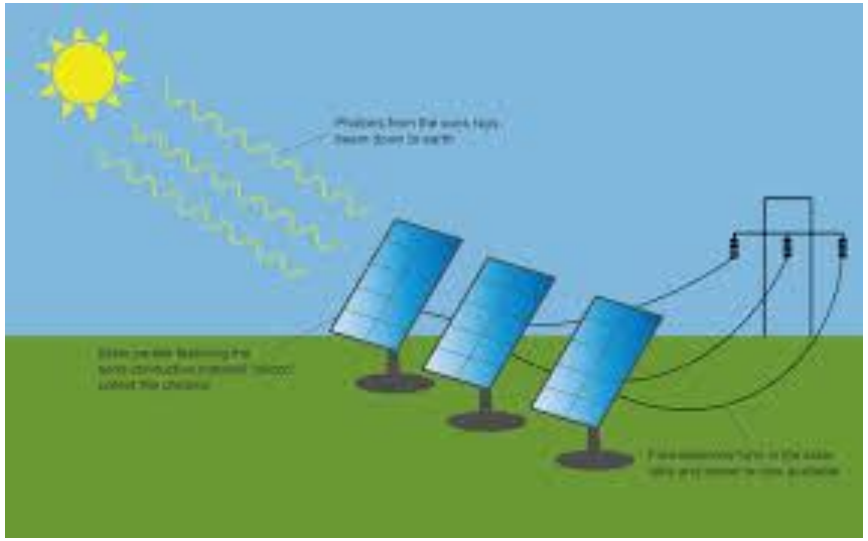
TIDE COMING IN

This tidal electricity generation works as the tide comes in and again when it goes out. The turbines are driven by the power of the sea in both directions.



TIDE GOING OUT

Sun Light (Solar Power Plant):



Now a day's solar power is one of the favorite power sources.

Solar Powered Car, Cell Phone is getting more popularity day by day.

We cannot use direct sunlight to electricity

The system called **Photovoltaic (PV) technology** is used to convert sunlight to electricity.

List of Top Five Solar Power Stations

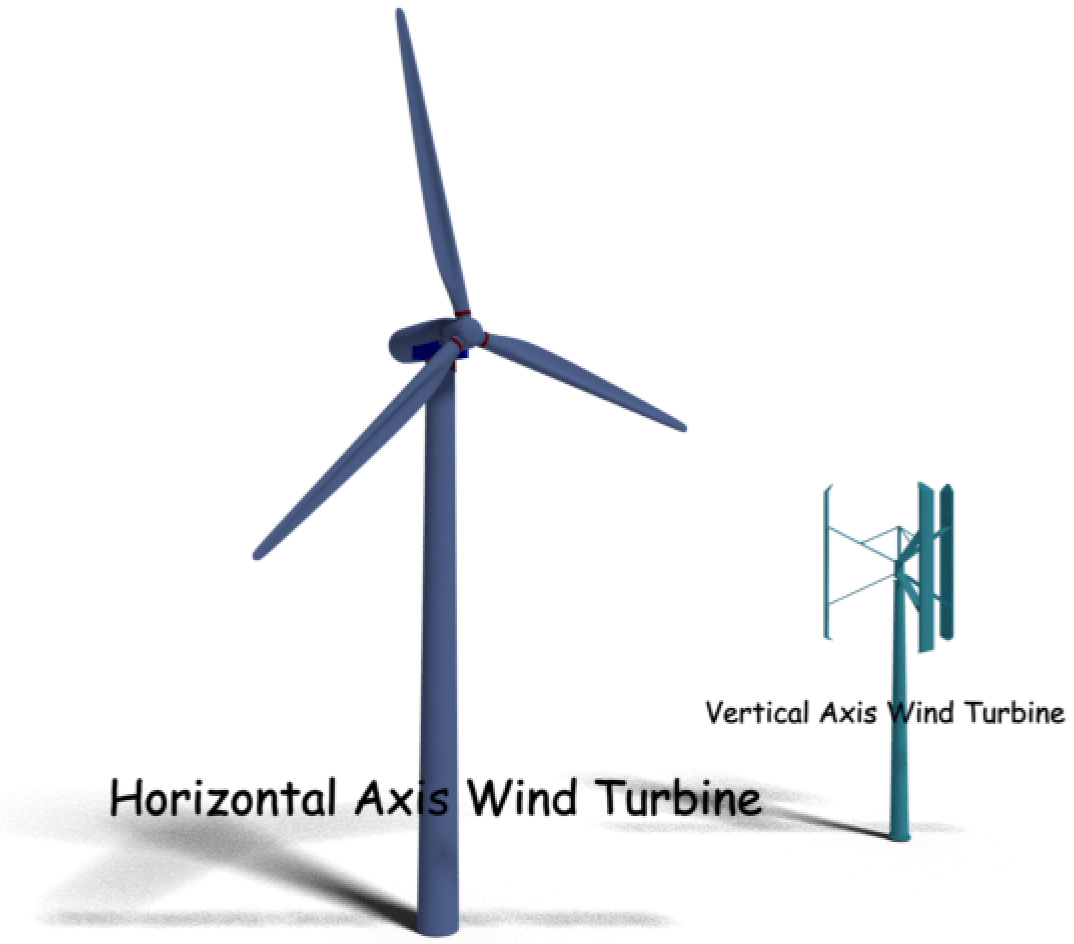
Ivanpah Solar Power Facility	California,USA	392 MW
Solar Enargy Generating System (SEGS)	California,USA	354 MW
Mojave Solar Project	California,USA	280 MW
Solana Generating Station	Arizona,USA	280 MW
Genesis Solar Energy Project	California,USA	250 MW

Wind Energy Electricity Generation

It is now the fastest growing electricity resource in the world.

Wind energy simply means kinetic energy of air in motion

The **Betz limit** is the theoretical maximum efficiency for a wind turbine, conjectured by German physicist Albert Betz in 1919. Betz concluded that this value is **59.3%**



GE Renewable Energy this week announced what it calls the world's **most powerful wind turbine**– 12-megawatt

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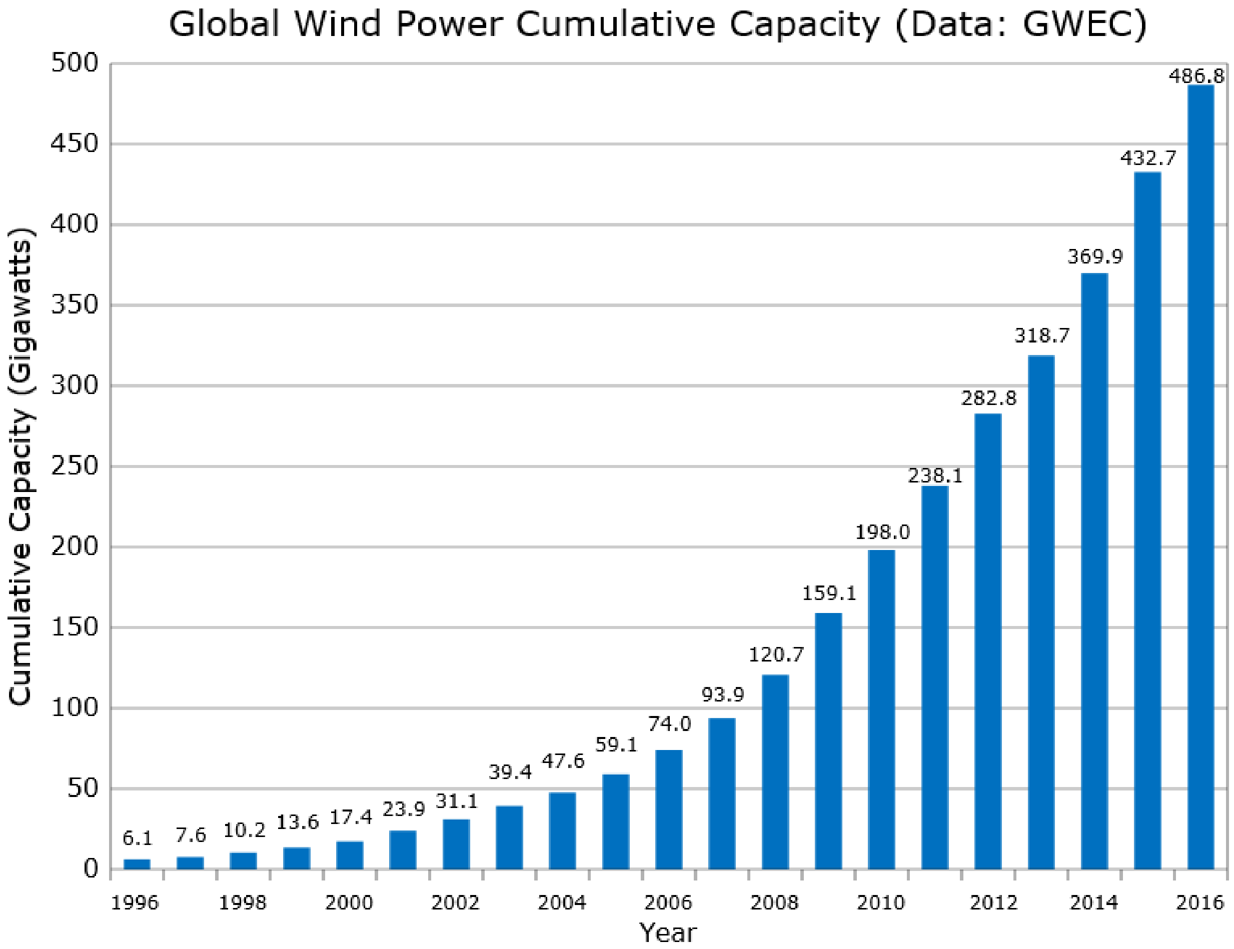
The output of a **wind turbine** depends on the **turbine's** size and the **wind's** speed through the rotor.

An **average** onshore **wind turbine** with a capacity of 2.5–3 MW **can produce more** than 6 million kWh in a year – enough to supply 1,500 **average** EU households with **electricity**.

The Gansu **Wind Farm** in China is the **largest wind farm in the world**, with a target capacity of 20,000 MW by 2020.



most powerful wind turbine

GE Renewable Energy announced at Mar 2, 2018,

What it calls the world's **most powerful wind turbine**– 12-megawatt Haliade-X. And it's a whopper. At 853 feet high, it's roughly three times the size of New York City's Flatiron Building (which has 21 floors).

Comparison between power plans

No	parameter	Power Plant Type			
		Hydro-Plant	Thermal	Gas	Nuclear
1	Size and weight	Large	Large	Small	Large
2	Life (Year)	100-125	20-25	↓	↑
3	Initial cost	High	High	Low	Very high
4	Time for construction	Very long	Long	Short	Very long
5	Capacity (MW)	~ 700	1000-1200	100-150	1300
6	Maintenance	Easy	Difficult	Easy	Difficult
7	Water requirement	Large	Large	Small	Large
8	Efficiency	Very high	~ 40%	25-30%	~ 30%
9	Time for starting	Short	Long	Short	Very long
10	Response to the load eff.	Very high	Low	Very high	Low
11	Pollution	Nothing	There is Poll.	There is Poll.	Lower than thermal

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1. History and general survey

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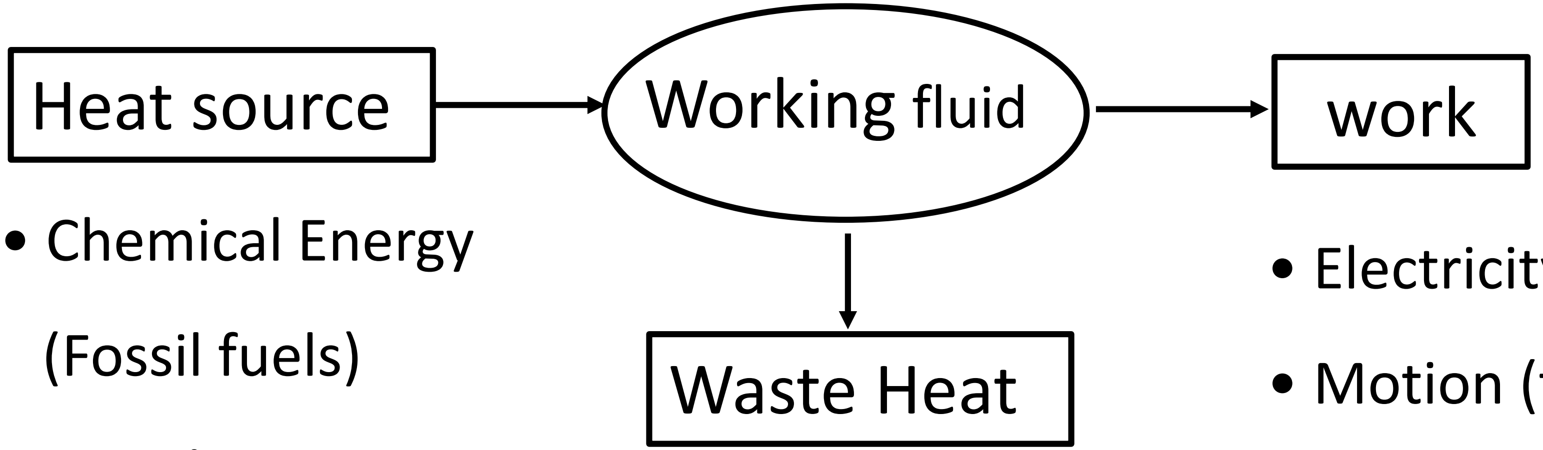
Types of Thermal power plants

- Gases (e.g. Air)
- Water/Steam



- Chemical Energy (Fossil fuels)
- Atomic Energy (Nuclear fuels)
- Solar Radiation

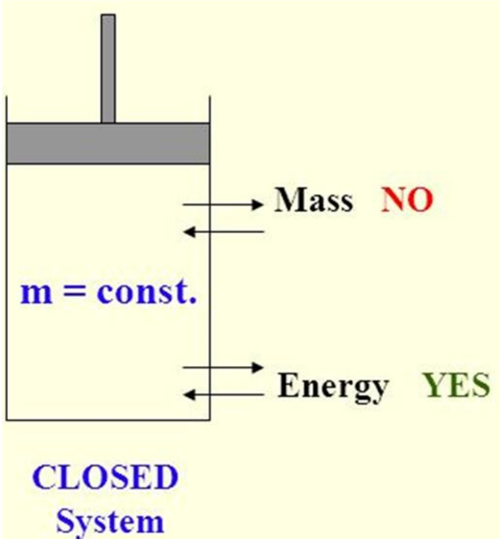
- Cooling tower
- Exhaust duct

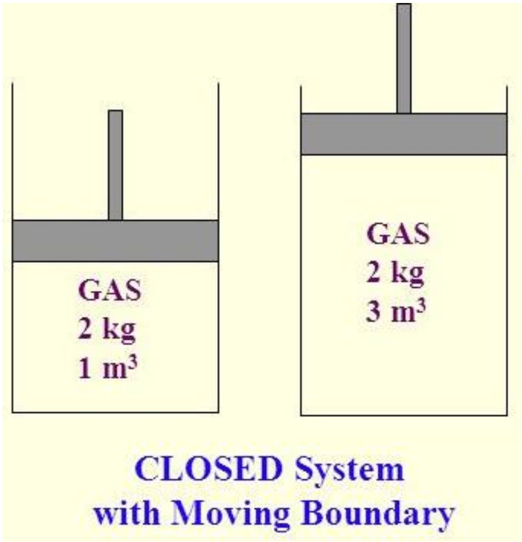
- Electricity
- Motion (transport)

Ideal cycles

Closed systems (Fixed mass)

- Otto cycle (Air)
- Diesel cycle (Air)

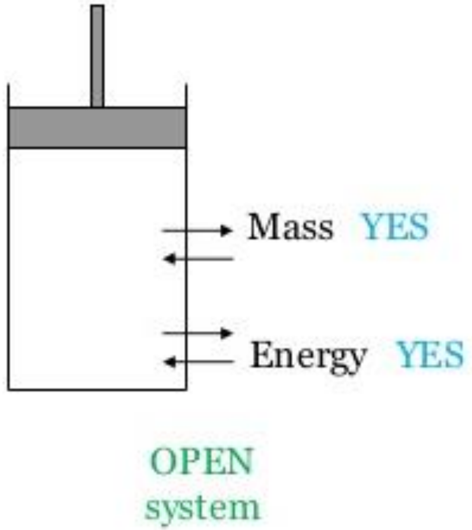




$$W = -\int PdV$$

Open systems (Fixed region in space)

- Rankine cycle (Liquid/ Vapour)
- Brayton or Joule cycle (Air)

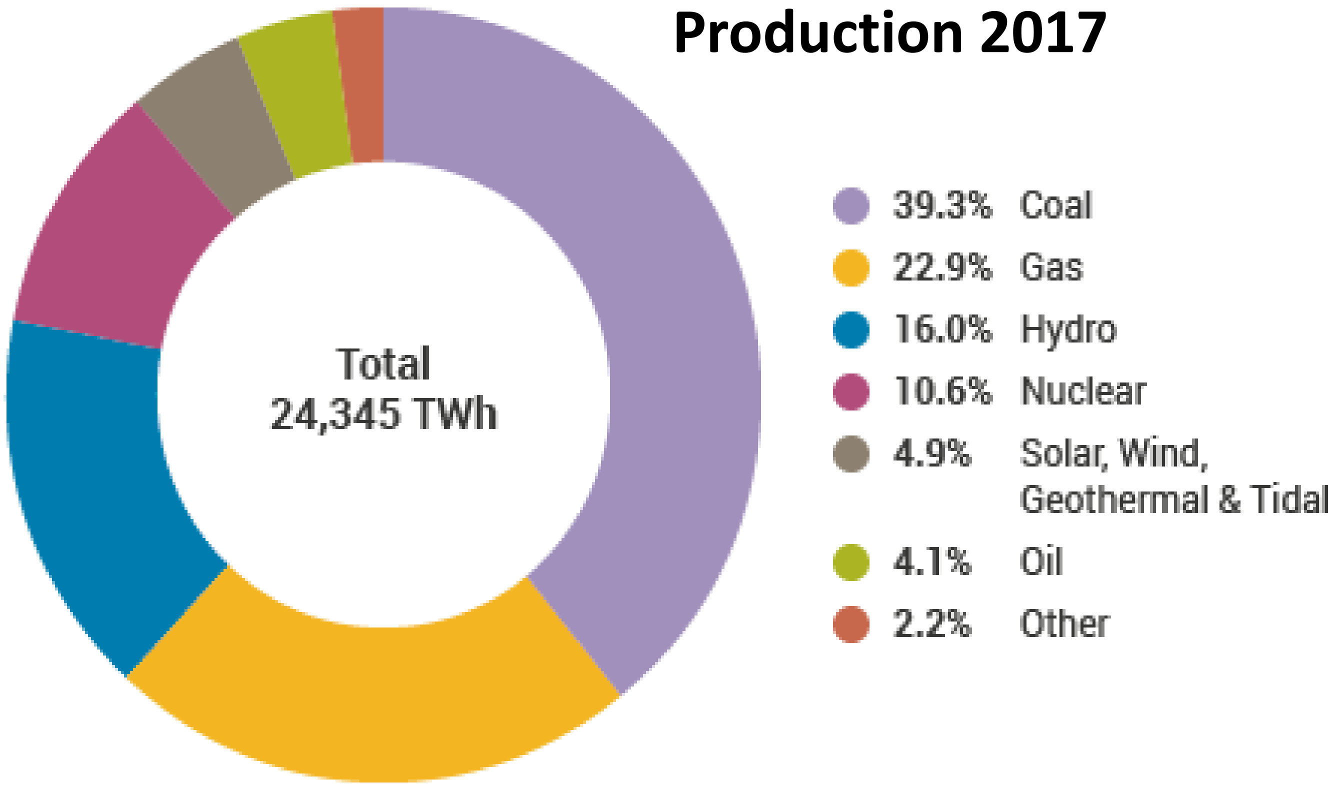


$$W \neq -\int PdV$$

Energy Data

- Steam power plants (Coal, Biomass, Nuclear, Solar thermal)
- Gas turbines (Gas)
- Reciprocating engines (Oil)

World Electricity Production 2017

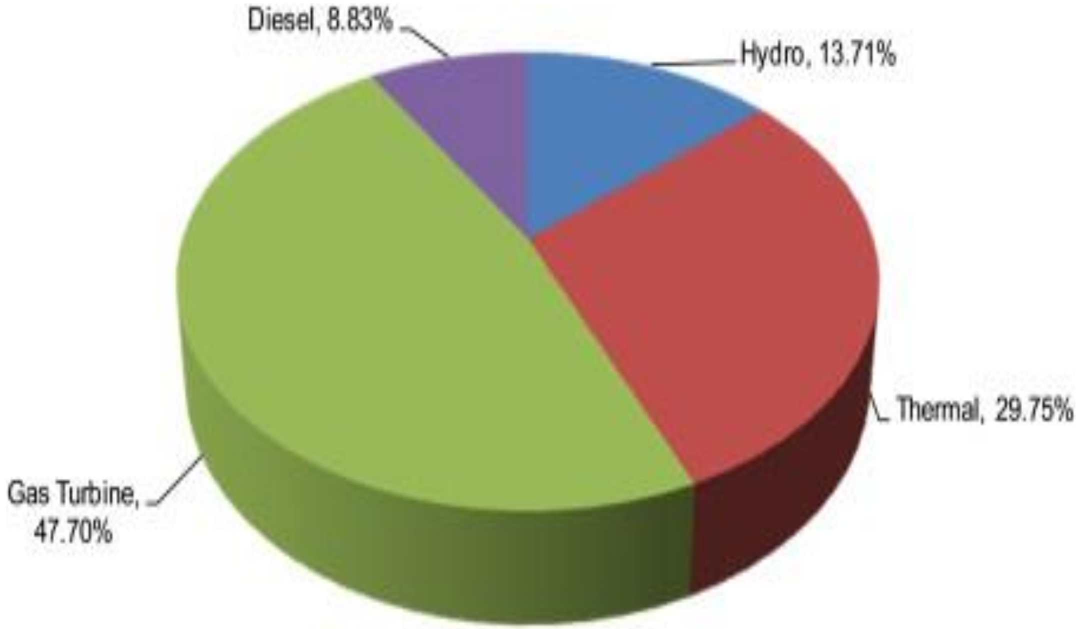


Source: IEA Electricity Information 2017

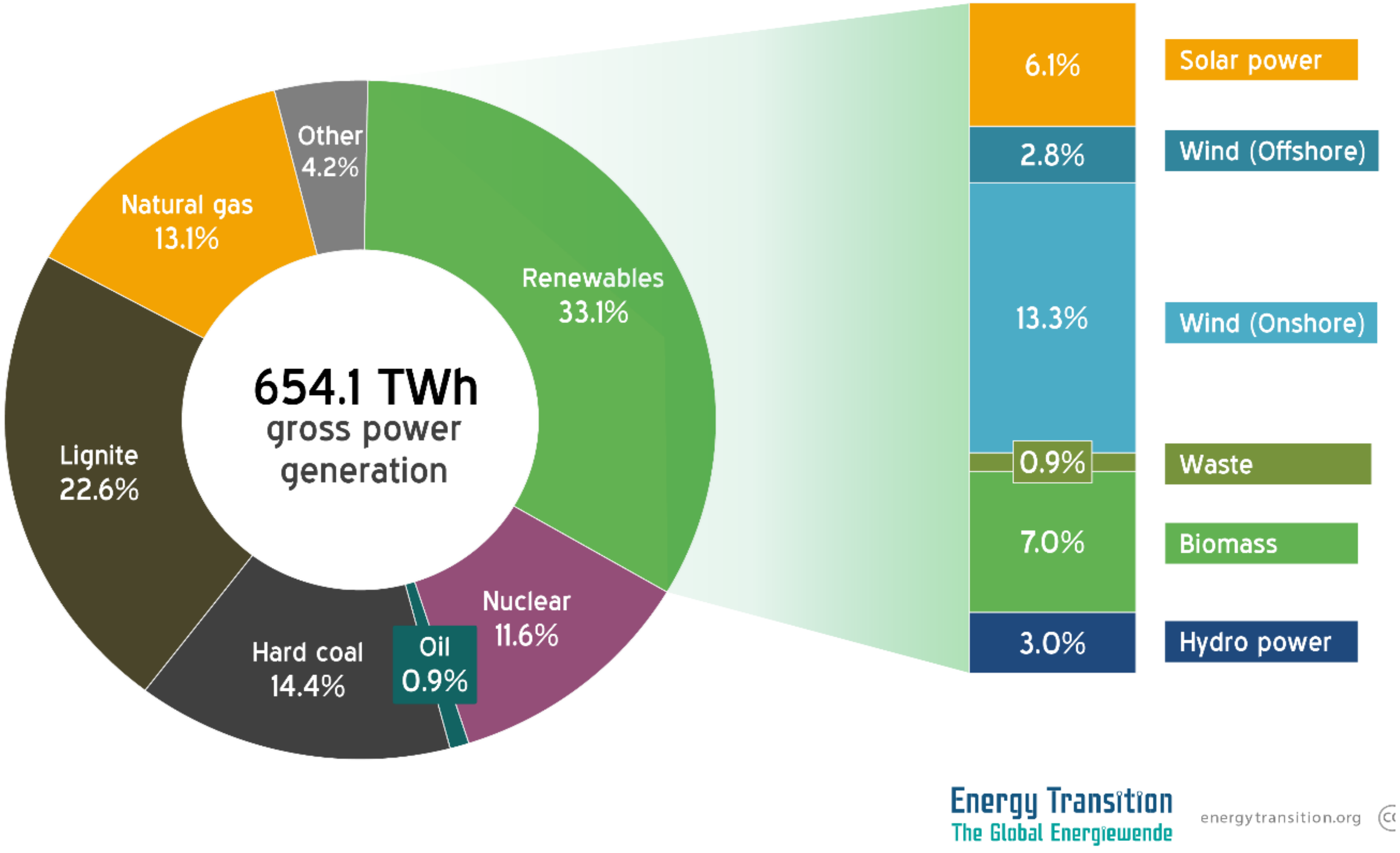
Steam power plants include :

- Coal power plant
- Nuclear power plant
- Biomass power plant
- Some solar power plant

Electricity production in Iraq 2014



Electricity production in Germany 2017

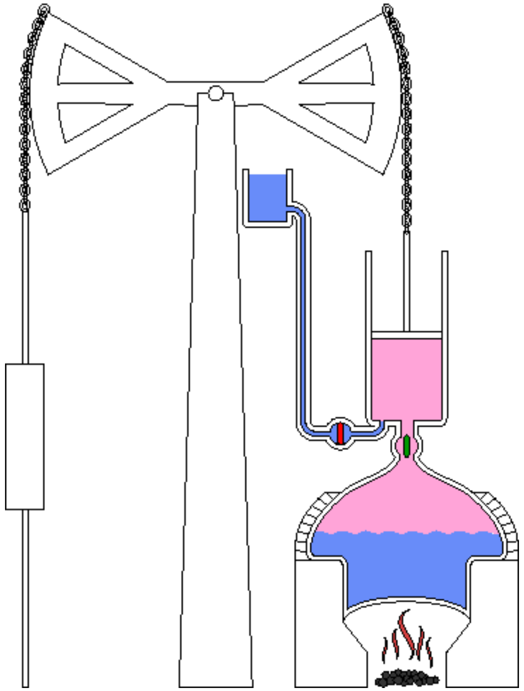


First steam engine: Aeolipile (Heronsball)

Heron von Alexander 1.Century. A.D.

Evolution of steam engine

1712: First steam engine by **Thomas Newcomen** so called atmospheric operated with condensation inside the cylinder



Power of the first engine: 50 hp! (1 hp = 735 W)

Thermal efficiency about 0,5%

Draining of coal mines in England

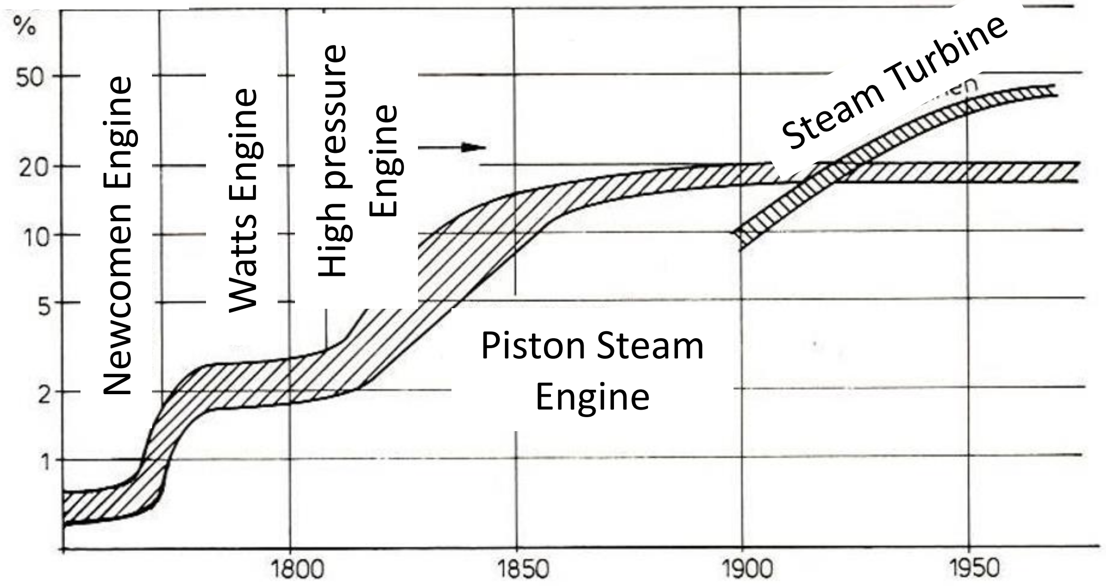
Evolution of steam engine

ca. 1770: Low pressure piston steam engine developed by James Watt

1769: first Patent: condensation separated from cylinder leads to lower condensation pressure and temperature

1782: Patent on a double acting piston steam engine

Efficiency



ca. : arround

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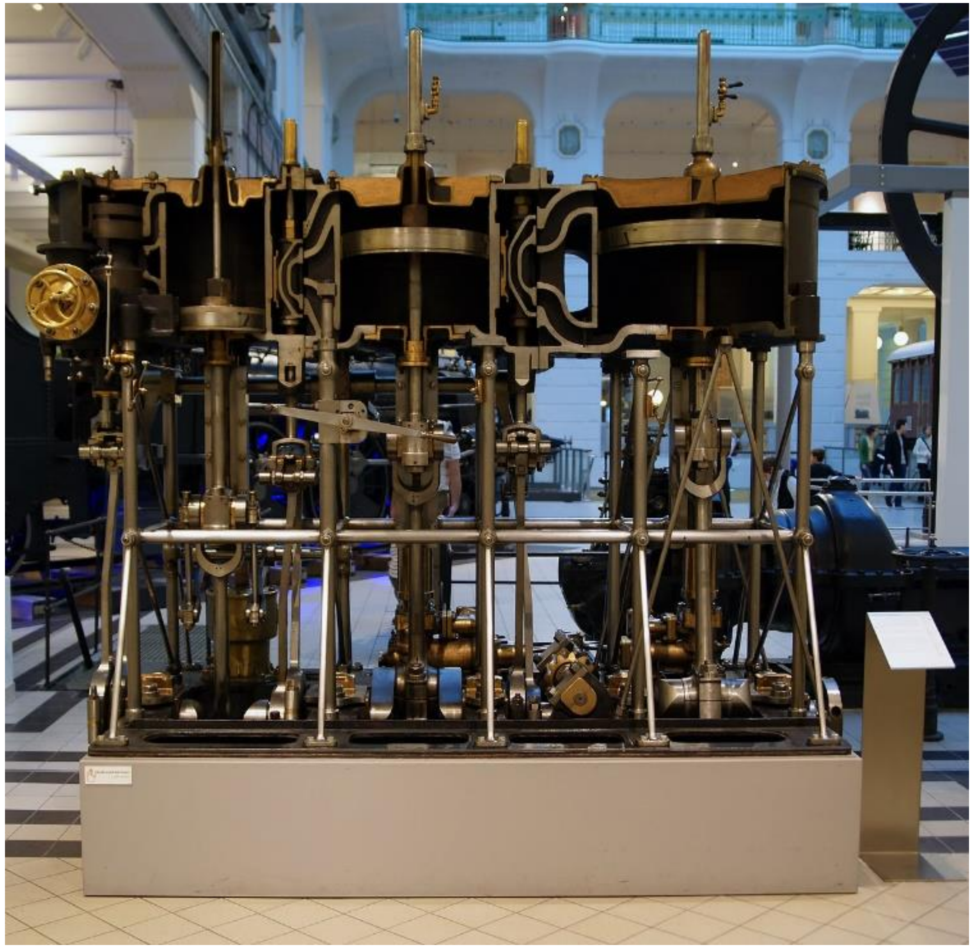
Evolution of piston steam engine

Performance:
1840: 20 h
1900: 3000 hp build by Borsig for Paris world exhibition
ever larges piston steam engine: 30000 hp by DEMAG

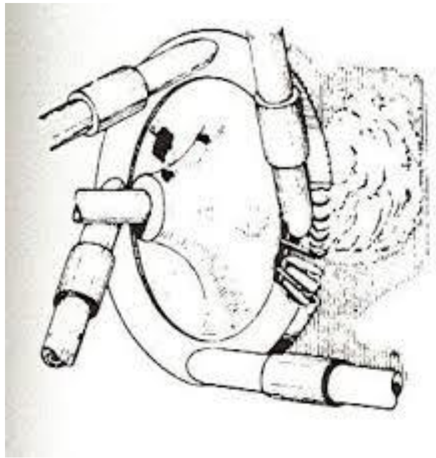
Climax of evolution for piston steam engine
Triple-Expansion-Superheated Steam Engine
separation in high, medium and low pressure expansion

Today relevance: fast rotating steam engines for power-heat cogeneration

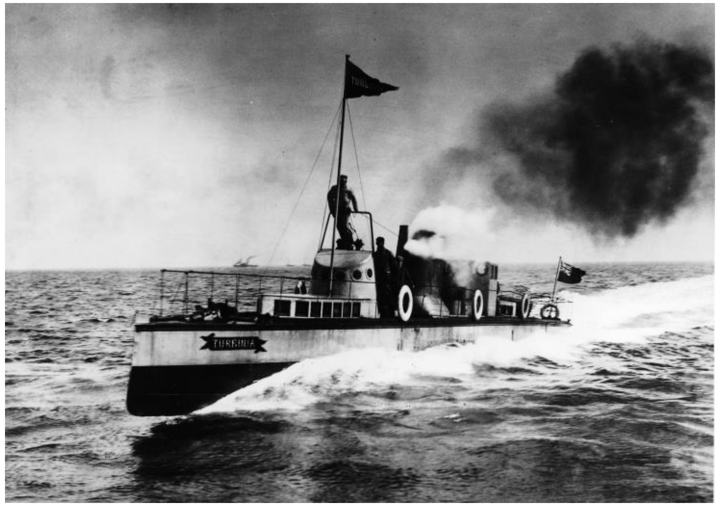


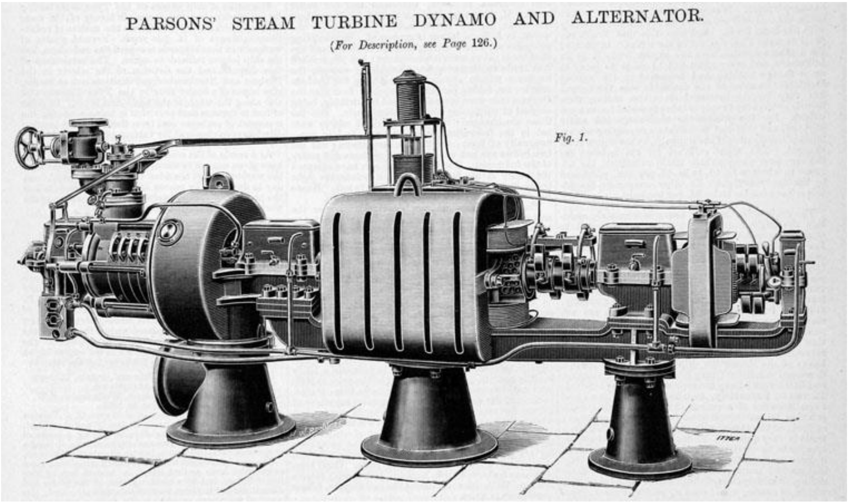
Technisches Museum Wien

Evolution of steam turbines



First turbine: see Herons ball
1883: principle of turbines published by C.G.P. de Laval
(impulse or constant pressure and reaction turbine)
1884: acquisition of patents by C.A. Parson, development of multistage turbines
1894: launching Turbine, speed record: 34,5 kn, 960 hp





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Evolution of steam boiler

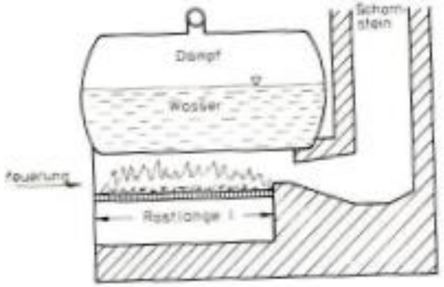
at the beginning: wagon type boiler p_{max}: 1,5 bar at 110°C

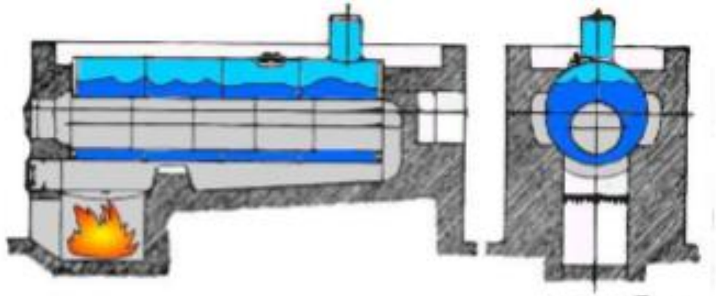
by 1804: cylindrical fire tube boiler: all shell boiler

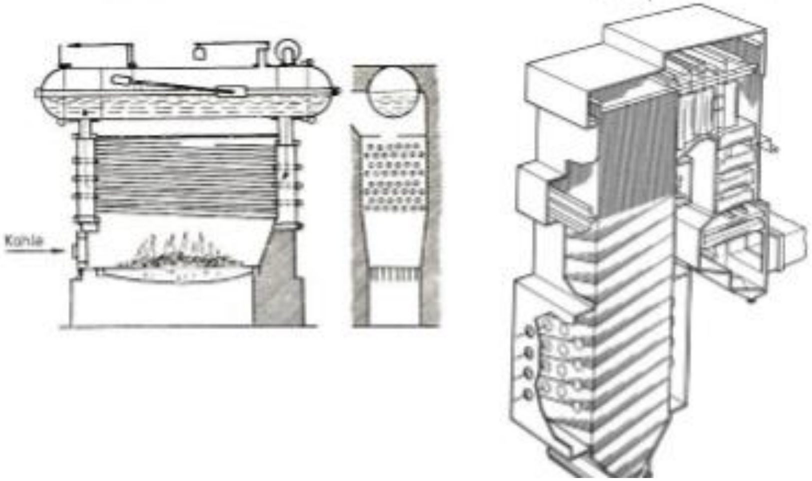
from 1885: angular water tube boiler, saturated steam 10bar, 180°C

1895: Boiler with superheated steam by W. Schmidt 16bar, 450°C

followed by: once-trough steam boiler by Mark Benson







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1770	1769	patent application by James Watt
		copper kettle 1,5bar/110°C
1800	1801	steam automobile by R. Trevithick
	1803	water boiler by Stevens
	1811	Flame tube boiler by R. Trevithick (corn wall-boiler) 8bar/170°C
	1826	High pressure piston steam engine, R. Trevithick
	1832	Superheated steam boiler , R. Trevithick
	1847	E. Albans: dual chamber boiler, angular water tubes
	1860	G.A. Hirn: Super heater with 253°C/6bar 1885 First power plant in Germany
	1895	W. Schmidt: superheated steam 350°C
1900	1901	Introducing of superheating and water preheating (Economizer) to power plan
	1911	W. Schmidt: 450°C/60bar 1918 First pulverised coal furnace in USA, Benson
	1927	Benson steam boiler, 180bar, 30t/h 1938 electrostatic precipitator (soot)

by 1950 once-trough steam boilers benson or sulzer type

Today up to 2500 t/h at 270bar, 600°C, thermal efficiency: 44%, 1000MWel

The ideal thermal power plant

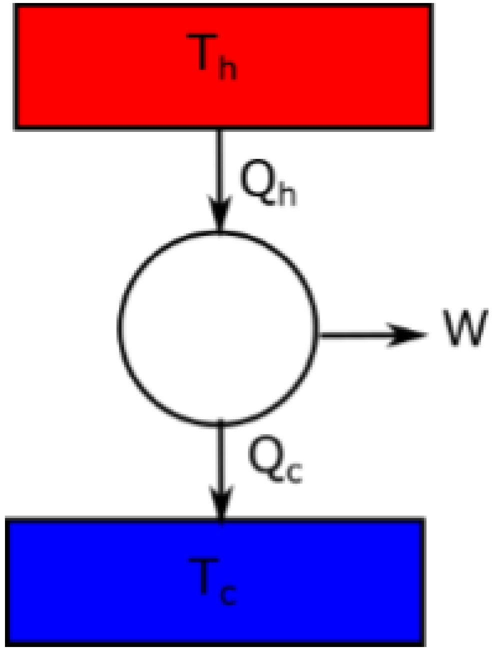
Carnot cycle – Fully reversible cycle

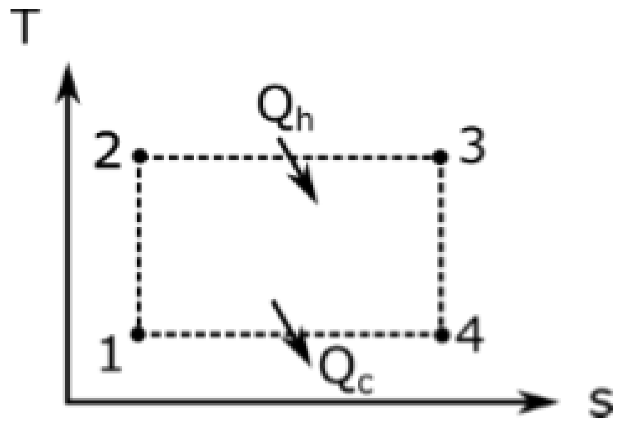
- Heat exchange at fixed temperature
- All reversible processes

$$\frac{Q_h}{Q_c} = \frac{T_h}{T_c}$$ By definition of temperature scale

- The most efficient cycle to convert heat into work between two given temperature.
- Efficiency only depends on Th and Tc

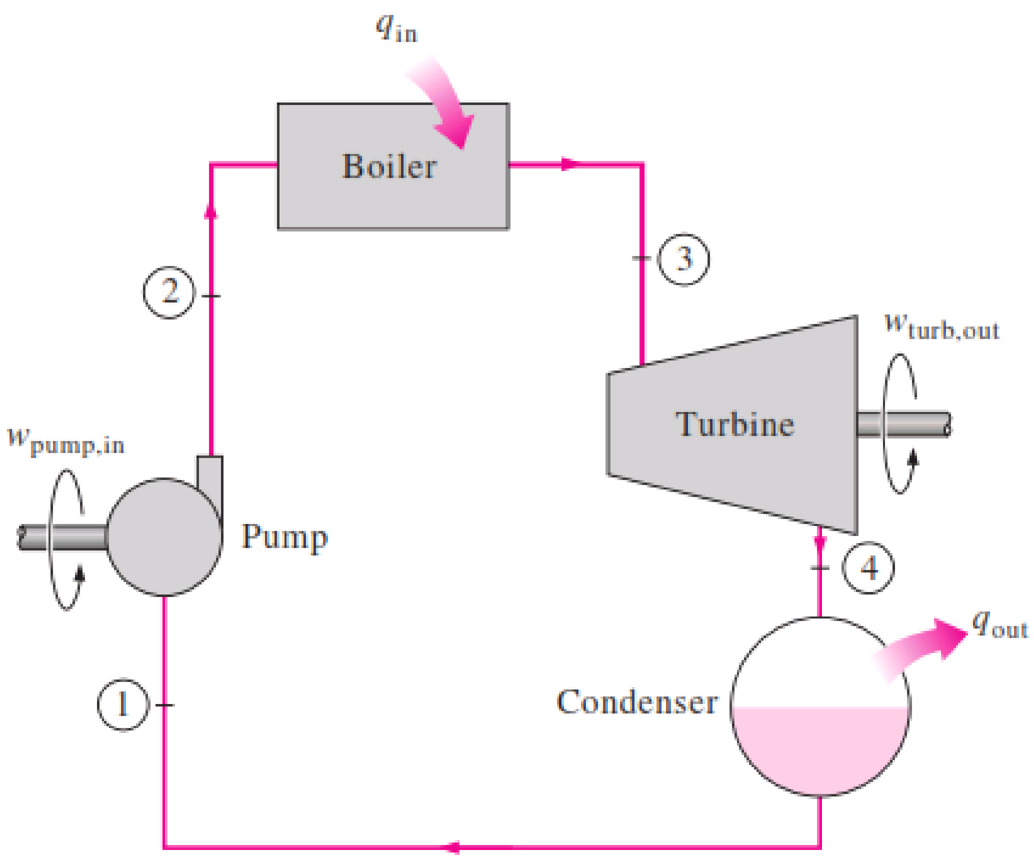
$$\eta = \frac{W}{Q_h} = \frac{1 - Tc}{T_h}$$





The steam power plant

- Working fluid is water/steam
- ⚠ Ideal gas law does **not** apply
- **Truly closed cycle** – the water/steam in closed circuit
- **Heat addition from variety of sources, e.g.**
    - **Burning coal or biomass particles**
    - **Nuclear reactions**
    - **Waste Heat**
- Turbine transfers shaft work to generator

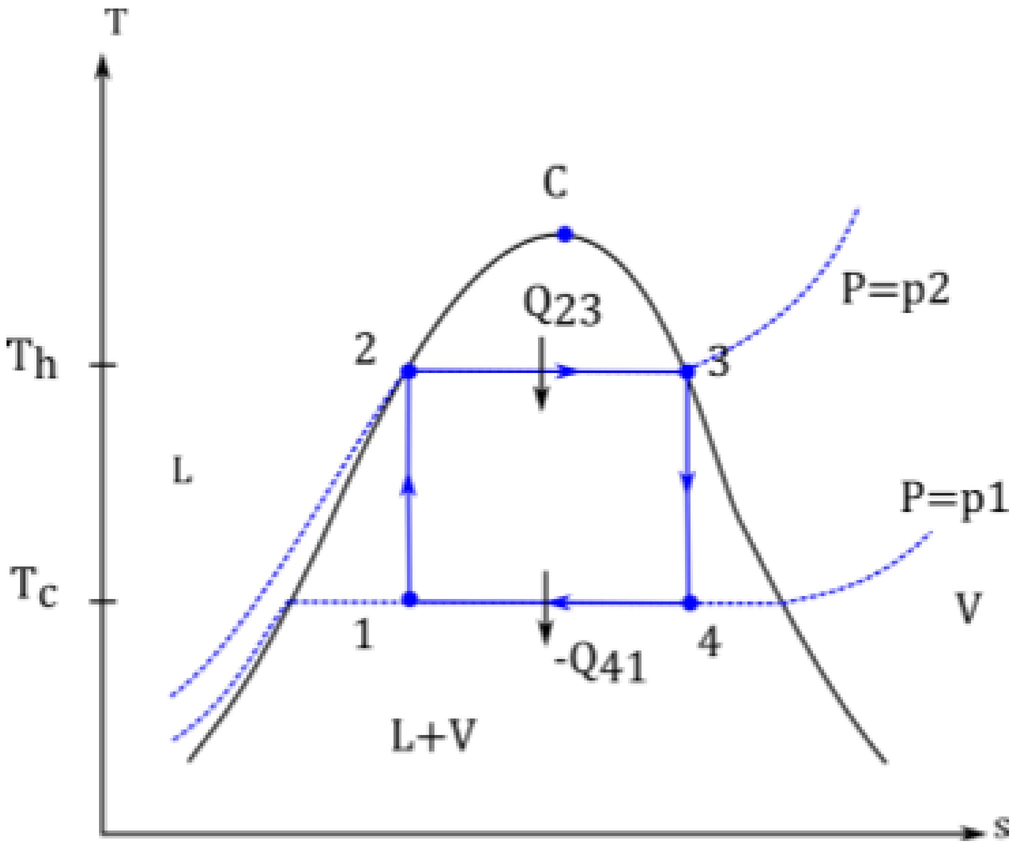


Basic steam plant elements

Why not a Carnot cycle ?

-> Carnot Cycle has maximum efficiency

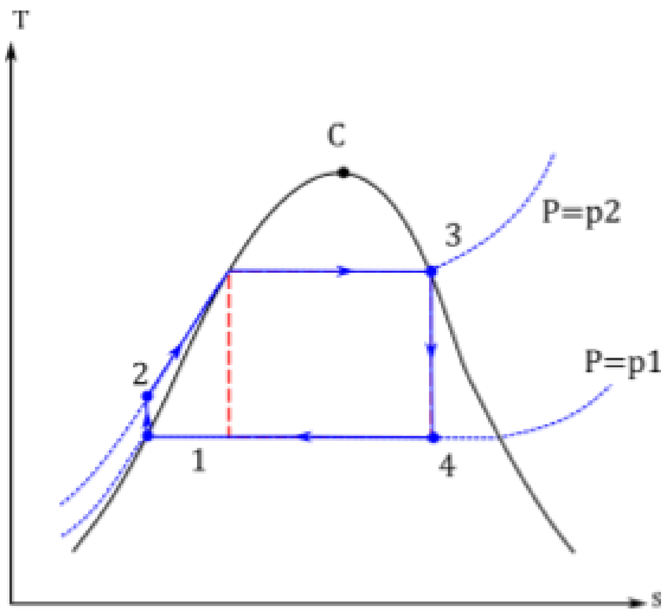
- Evaporation and Condensation : Constant temperature heat rejection
- Why can’t we use a Carnot Cycle.
  1. Stopping condensation at state 1 where s is precisely s2 (=s’(T_h)).
  2. Compressing liquid/vapour is difficult
- Condensation to saturation liquid is needed Clausius Rankine Cycle

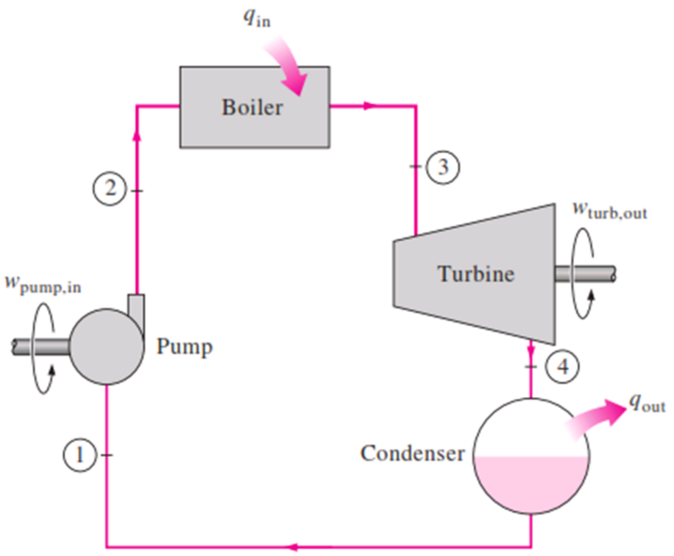


$$\eta_{th} = 1 - \frac{T_H}{T_C}$$

Rankine cycle

- Rudolf **Clausius** (1822 – 1888)
- William **Rankine** (1820 – 1878)





Basic steam plant elements

Four processes :

- 1 – 2 : Isentropic compression – Pump
- 2 – 3 : Constant pressure (and temperature) heat addition – Boiler
- 3 – 4 : Isentropic expansion – Turbine
- 4 – 1 : Constant pressure (and temperature) heat rejection – Condenser

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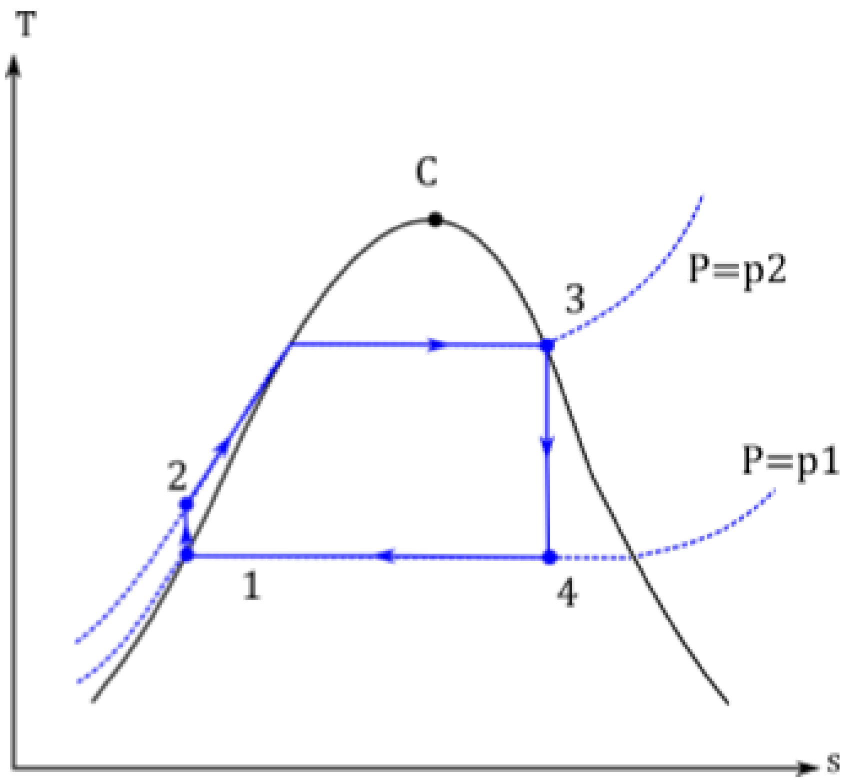
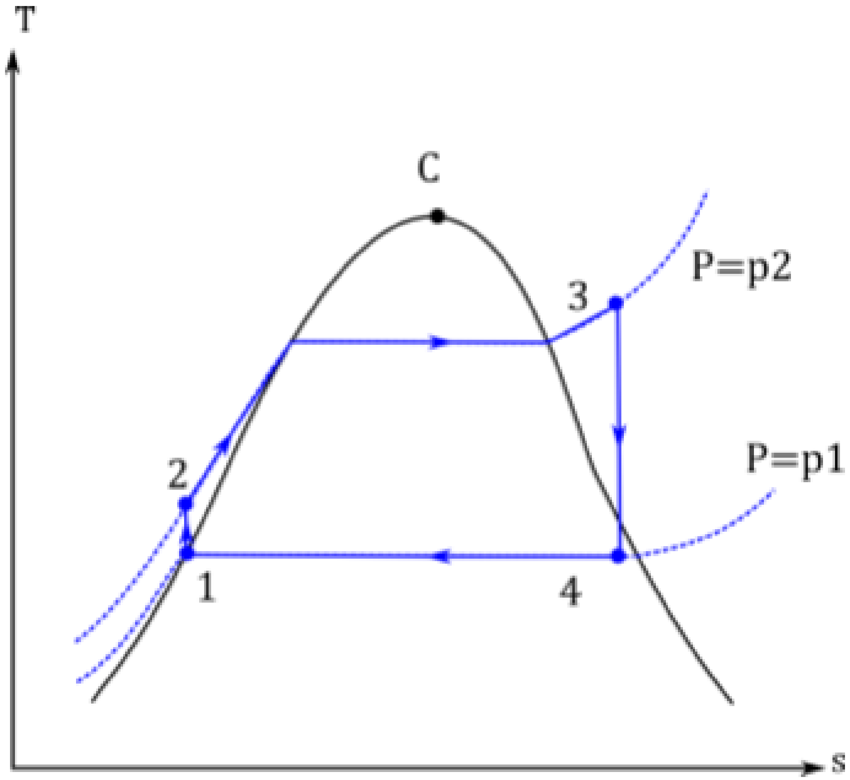
Rankine cycle with superheat

- Droplets in state 4 lead to blade damage
- Superheating increases x_4



Basic Clausius-Rankine cycle



Clausius-Rankine cycle with superheat

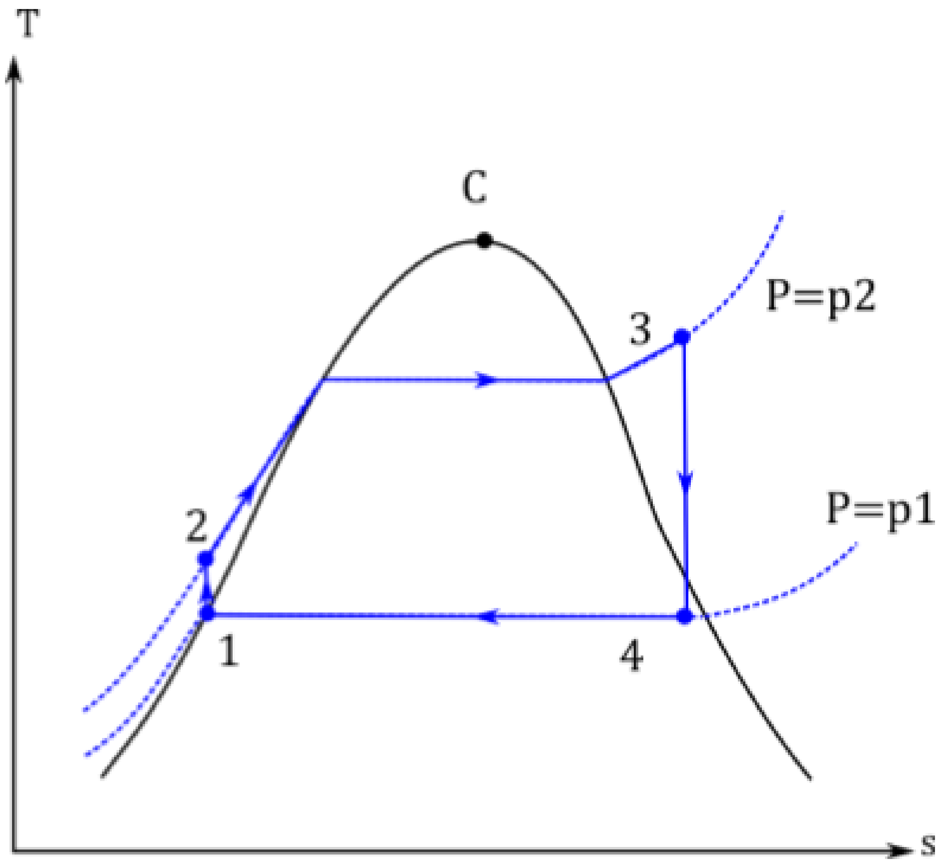
Cycle Efficiency

- Calculate cycle efficiency

$$\eta_{th} = \frac{\left|\dot{W}_{12} + \dot{W}_{34}\right|}{\dot{Q}_{23}} = \frac{\left|h_2 - h_1 + h_4 + \frac{c_4^2}{2} - h_3\right|}{h_3 - h_2} = \frac{h_1 + h_3 - h_2 - h_4 - \frac{c_4^2}{2}}{h_3 - h_2}$$

$$\eta_{th} \approx \frac{h_3 - h_4}{h_3 - h_2}$$

If we neglect pump work and kinetic energy



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3. Steam Cycles

Rankine cycle

Objectives :

- Apply thermodynamic principles to improve the Rankine cycle, via additional components (feed water heaters, reheating, combined cycle)
- Understand heat transfer limitations
- Understand the process diagram of large scale steam power plant

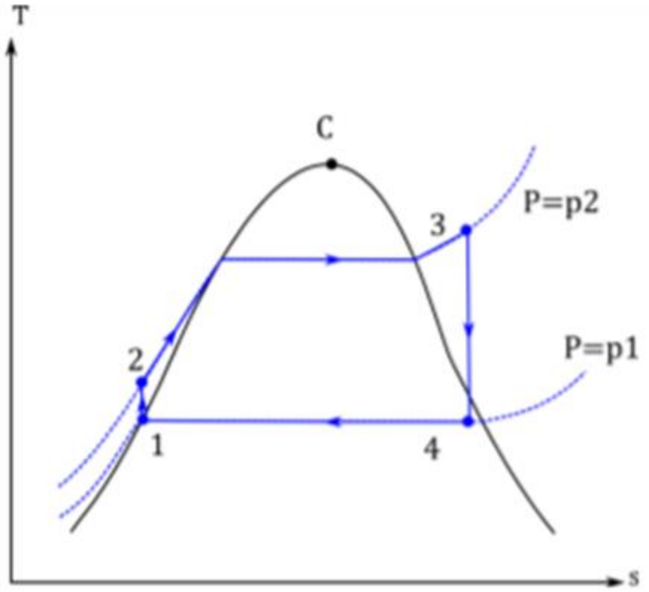
Ideal Rankine cycle

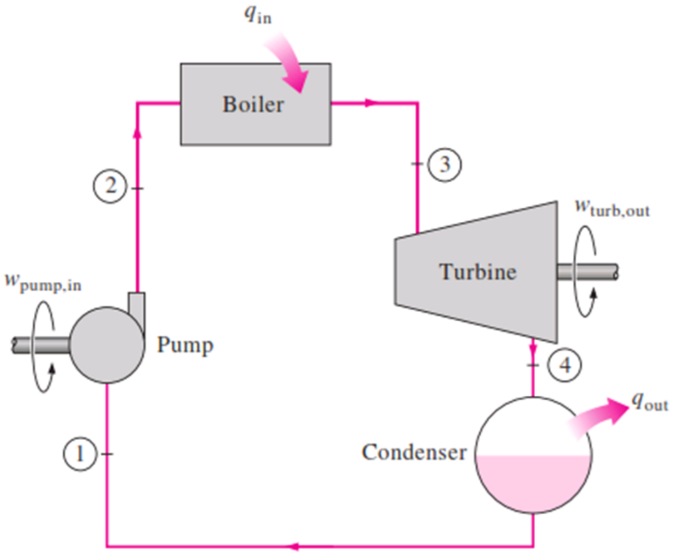
Four processes:

- 1 – 2 : Isentropic compression – Pump
- 2 – 3 : Constant Pressure (and temperature) heat addition – Boiler
- 3 – 4 : Isentropic expansion – Turbine
- 4 – 1 : Constant pressure (and temperature) heat rejection – Condenser

$$\eta_{th} < 1- \frac{T_3}{T_4}$$

How to increase efficiency ?





Efficiency improvement

1. Simple Rankine cycle:

   Increase maximum temperature (superheat)

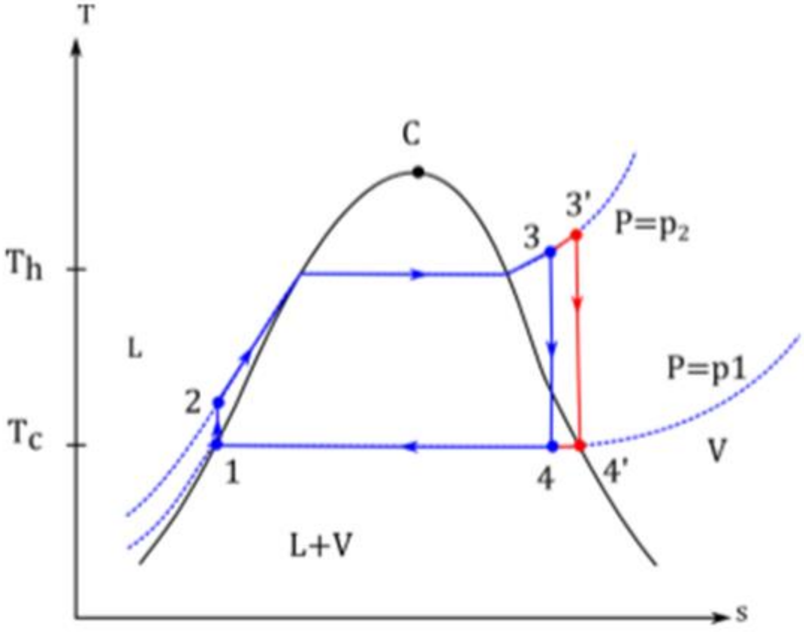
   Increase boiler pressure (or maximum average temperature)

   Decrease condenser temperature (and pressure)
2. Regenerative feed water heating
3. Reheating
4. Combined cycle
5. Heat and power (cogeneration)

1. Simple cycle

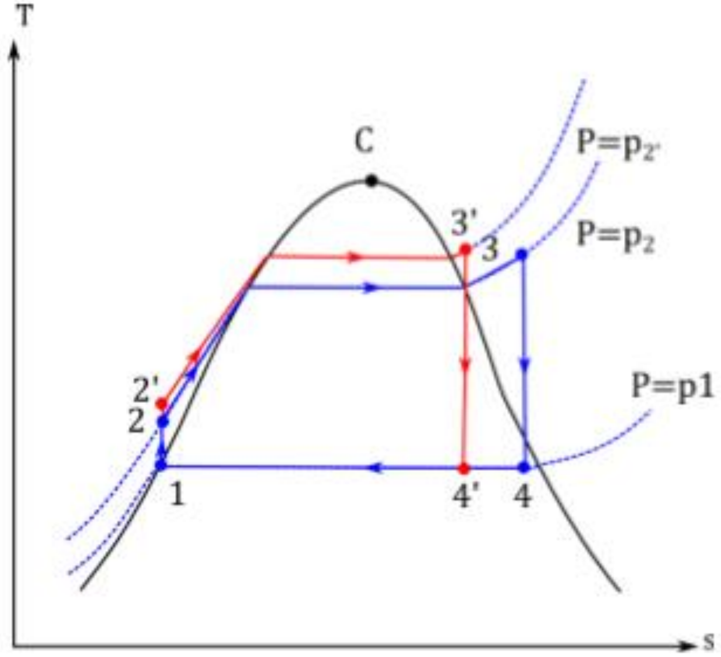
Increase maximum temperature

Limited by temperature of steel to be used (≈**600 c**). Increase steam quality at 4, decreasing erosion damage of blades



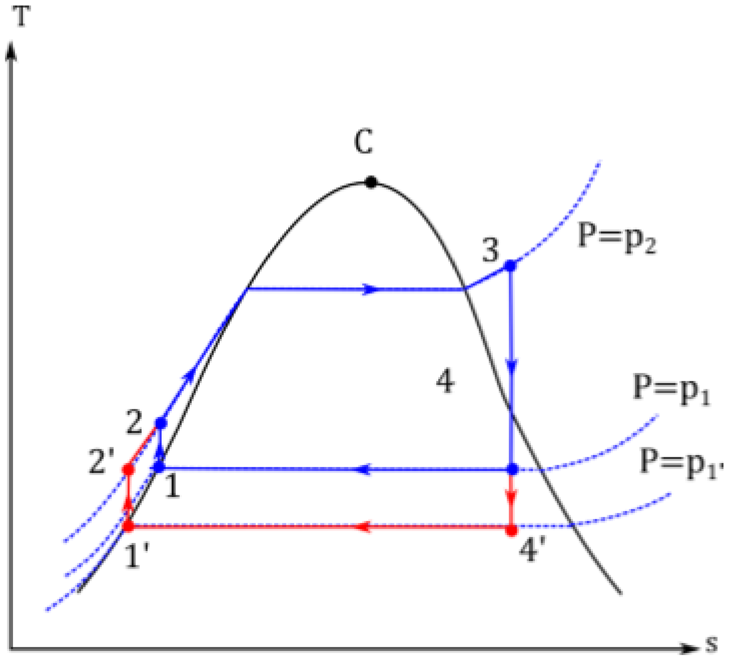
Increase boiler pressure

at fixed max. T → increases average temperature of heat addition will decrease steam quality if no increase in max. T



Decrease minimum temperature

Less heat rejected → higher efficiency. Limited by available cold source. Adverse effect: Lower steam quality



Regenerative Heat exchange

Regeneration : Heat exchange between the fluid in one process during the power cycle and the working fluid in another process of the cycle

- Idea : -> Carnotisation of process.

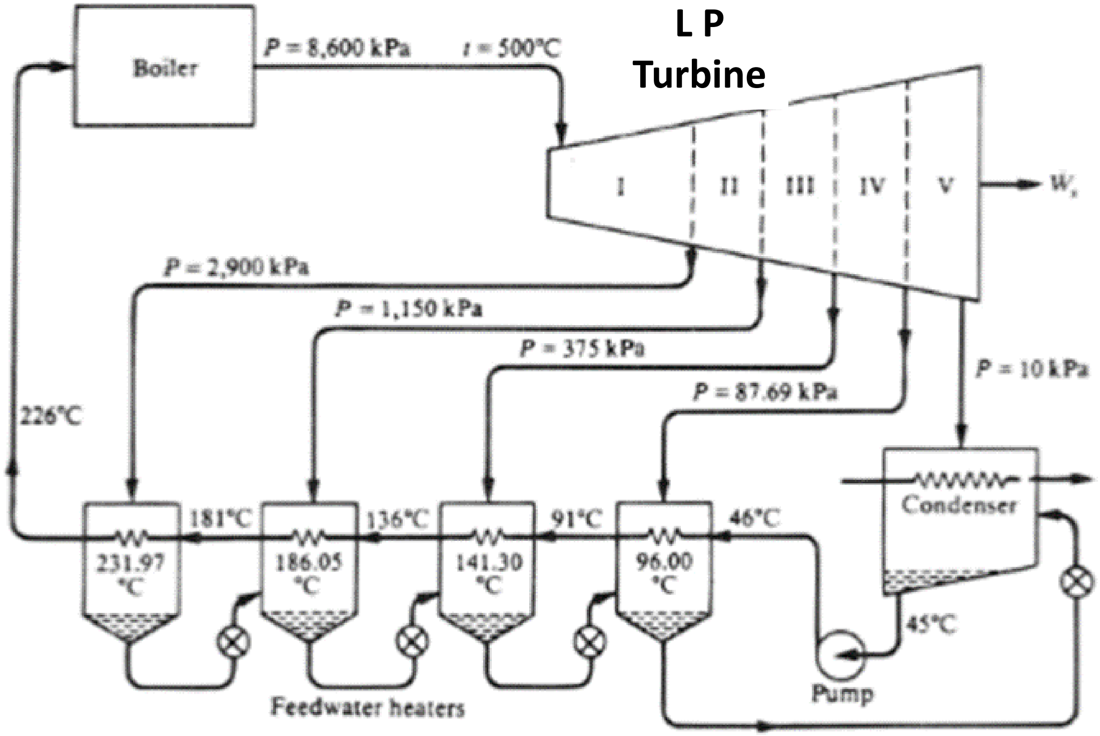
- Heat transfer during expansion recovered during boiling. For infinite number of heat exchange steps : -> Carnot cycle

- With only heat exchange between steam and water, the main problem is decrease in steam quality during expansion

- Solution : Bleed steam -> The steam is extracted at intermediate pressure and condensed. Latent heat of condensation converted into sensible heat of condensate
- On the board …

Feed water heaters (FWH)

- The more feed water heaters the closer the cycle to Carnot cycle.



Unit size (MW)	Number of heaters
0-50	3-5
50-100	5 or 6
100-200	5-7
Over 200	6-8

Power plant Engineering & Veath

- **Non contact heaters (NCFWH):** Only need one pump on condensate loop
- **Direct contact heaters:** Pressure must be equal : additional pump.
  However it allows deaeration of dissolved gas, e.g. O2 that leads to corrosion.

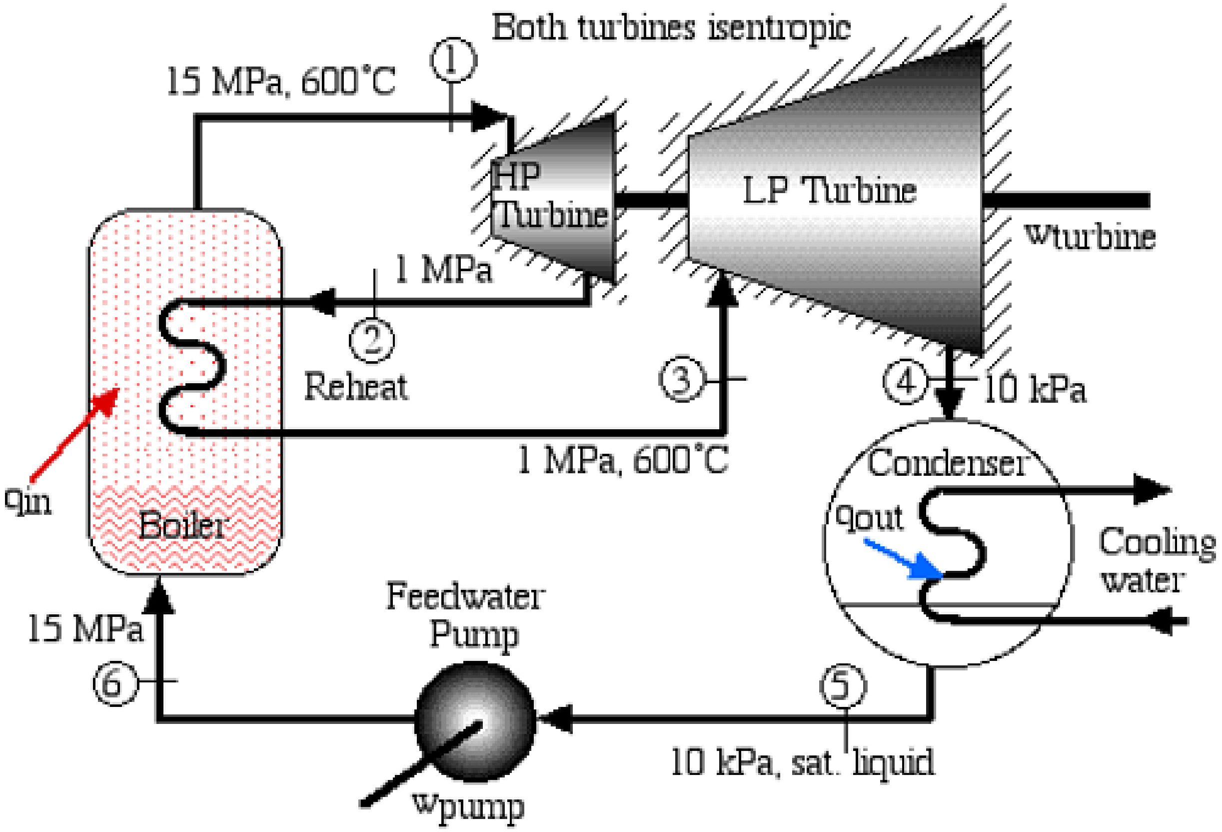
Source: Thermopedia

Reheating

- Steam is sent back to boiler after first expansion
- Can increase efficiency depending on Point of reheating

- High steam quality after reheating

- Single stage reheat in normal power plant, and double stage reheat in supercritical power plant



Source Ohio.edu

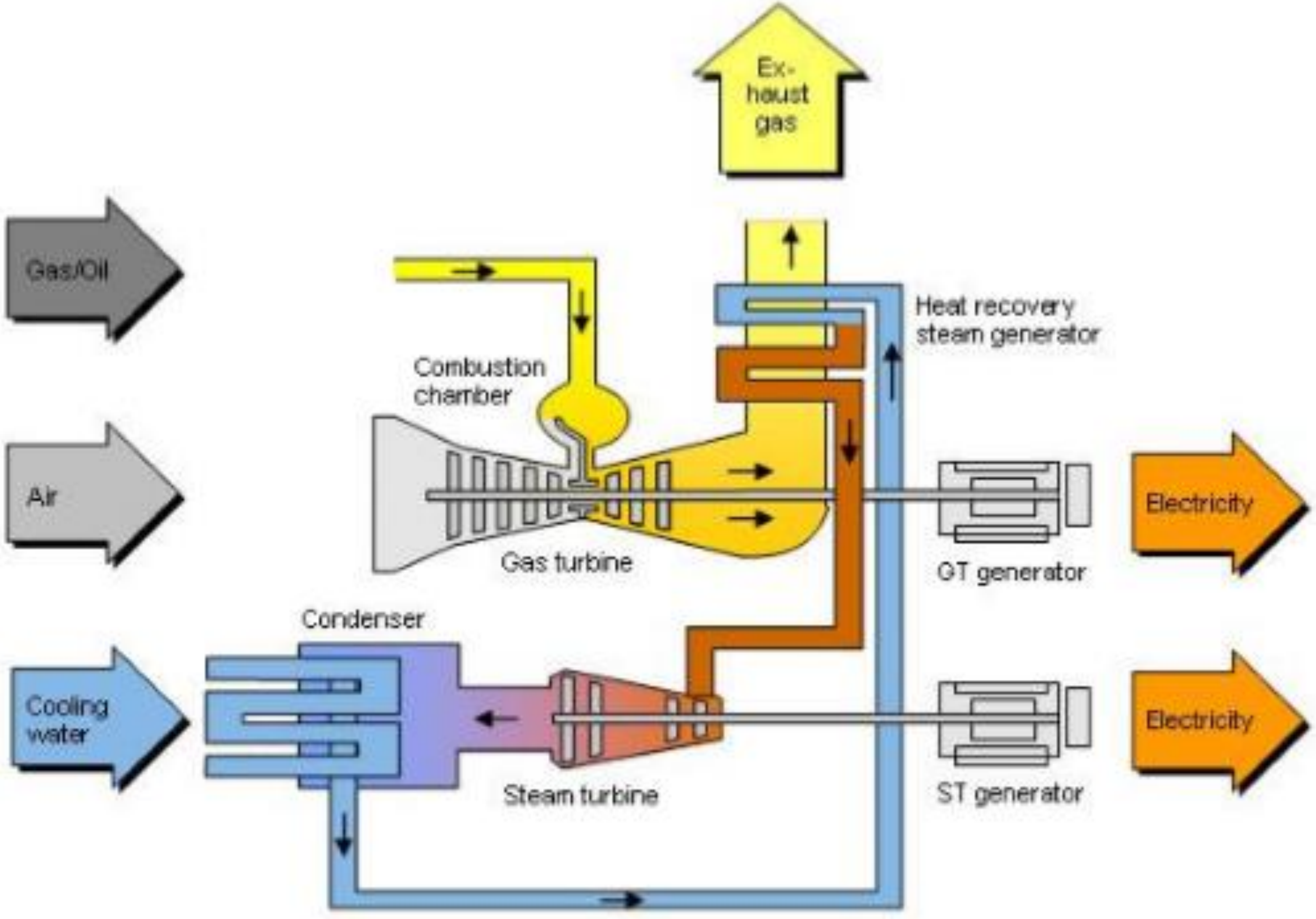
Combined cycle

<u>Top and bottom cycle</u>

Heat rejected from top cycle at T_{min} is used as high temperature heat source of bottom cycle

- Water/steam and organic fluid
- Joule cycle + Rankine cycle

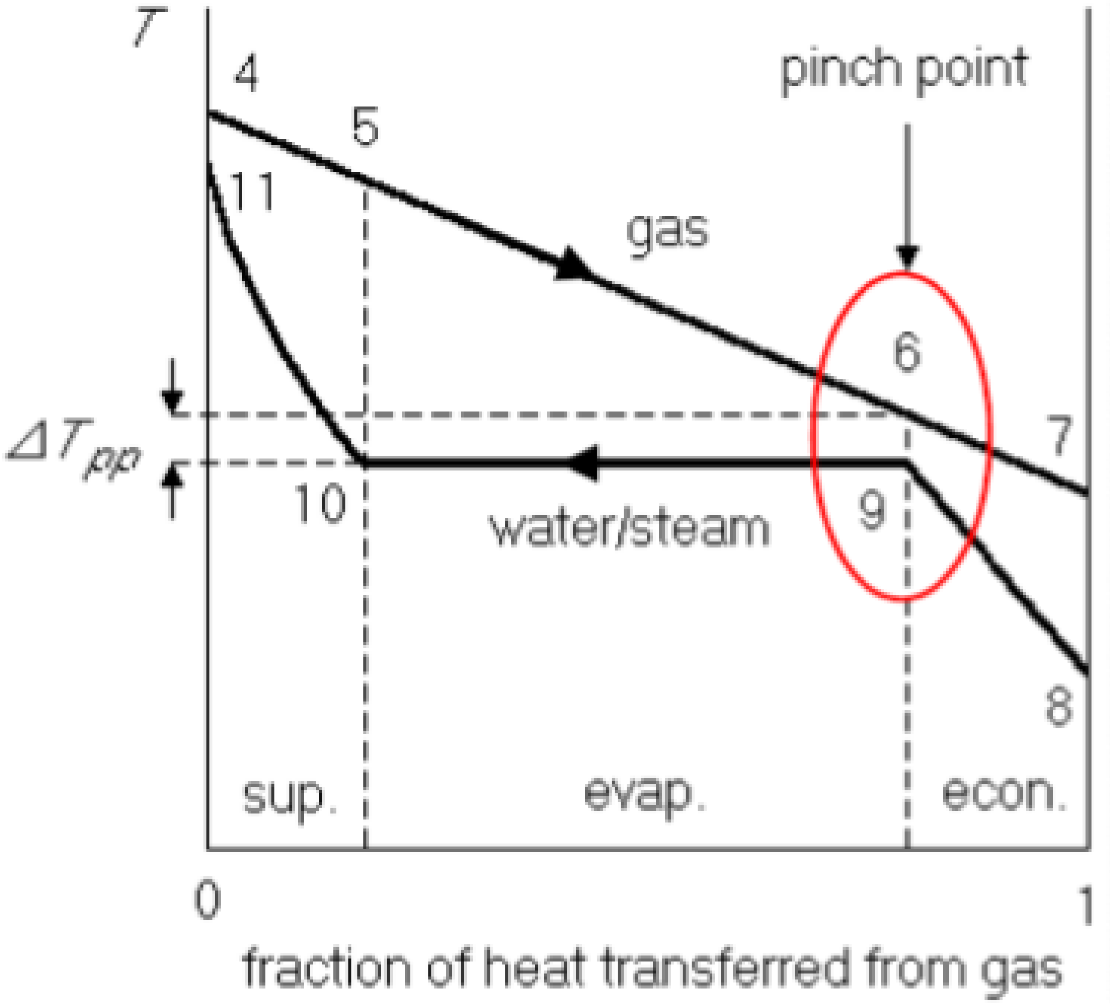
	Gas turbine	Steam Plant	Combined cycle
T_{max}(K)	1500	700	1500
T_{min}(K)	800	300	300
η_{carnot}			



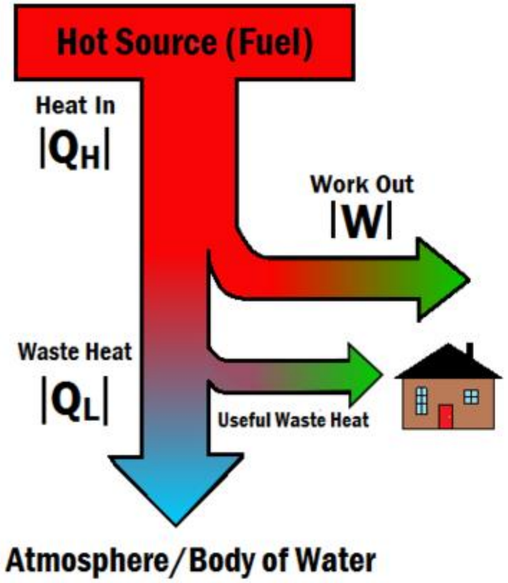
http://www.zeroco2.no/

Heat recovery steam generator

- Pinch point temperature difference.
- Compromise on size of heat exchanger and efficiency of the cycle
- The lower the temperature difference, the lower the irreversibility in heat transfer
- CC cycle efficiency can be as high as 55-60 % compared to 45-48 % for supercritical steam cycle.
- Sometimes HRSG have gas burners as boosters



Combined Heat and Power – Cogeneration (CHP)



- Heat rejection typ. >40 %

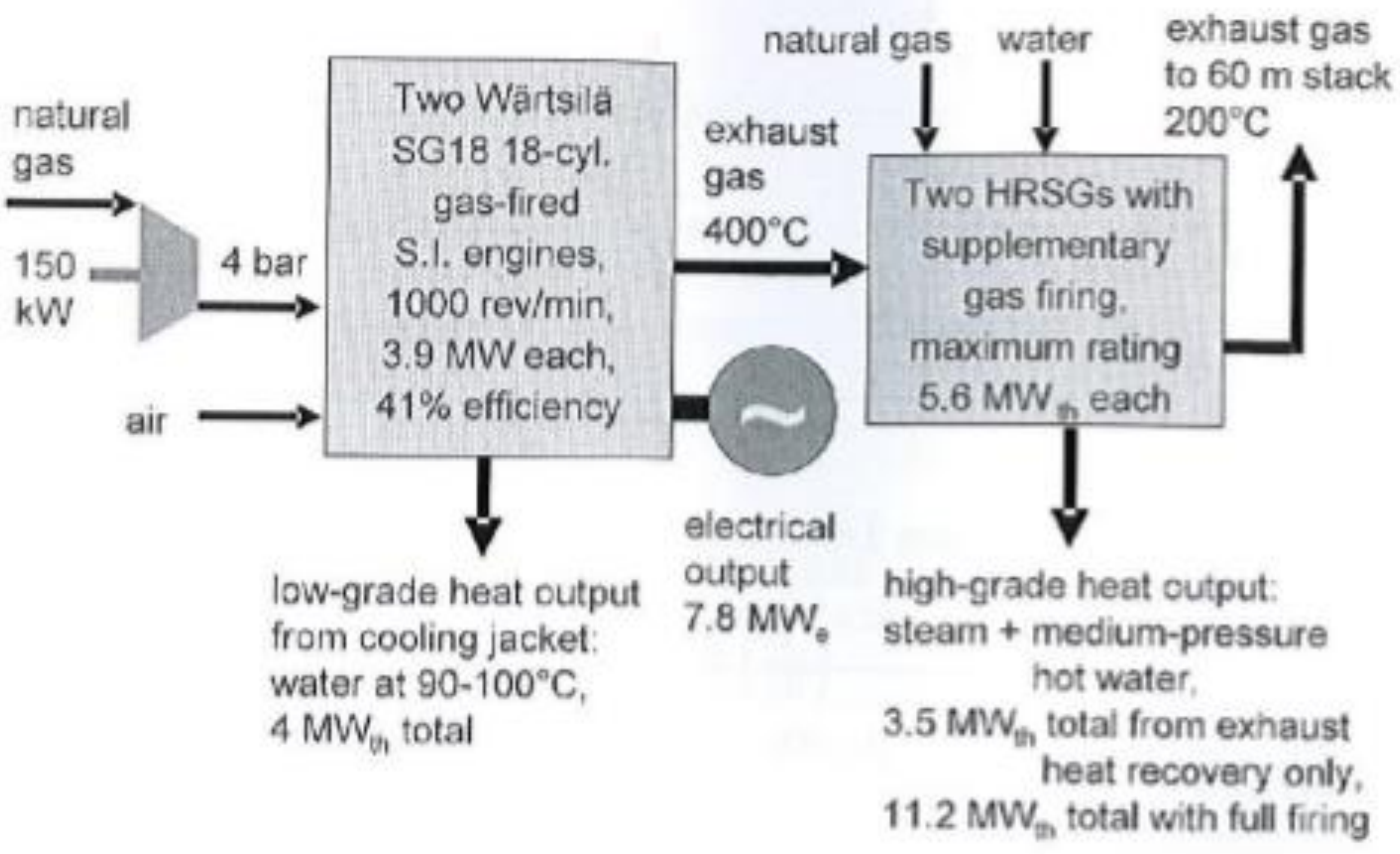
- Can be used for heating, or processes (hospital, industry)

$$Energy\ Utilisation\ factor\ EUF = \frac{electricity + useful\ heat}{output\ external\ heat\ addition}$$

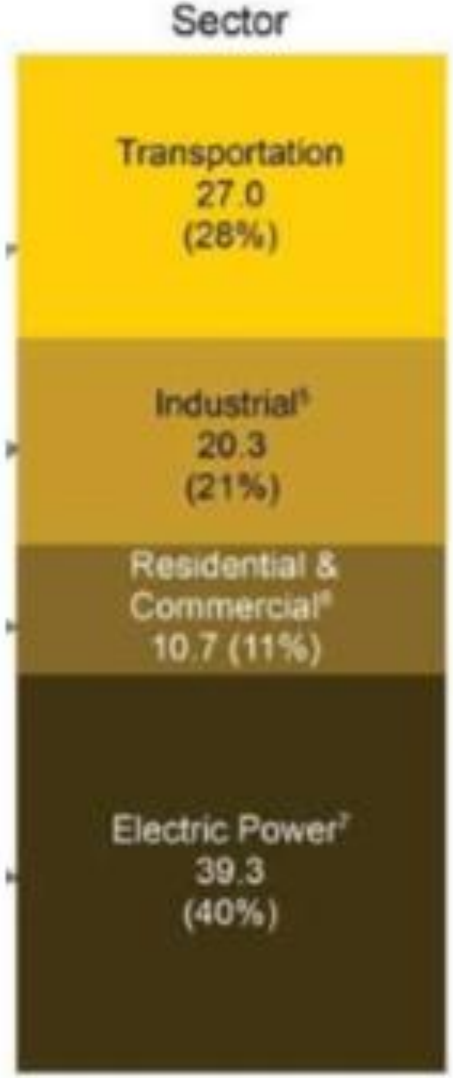
- Industrial site : Local CHP to replace electricity purchase and on-plant boiler means less transmission distribution loss

- Thermal efficiency could be **80%**

Mechanical Engineering Department



Imperial College CHP plant

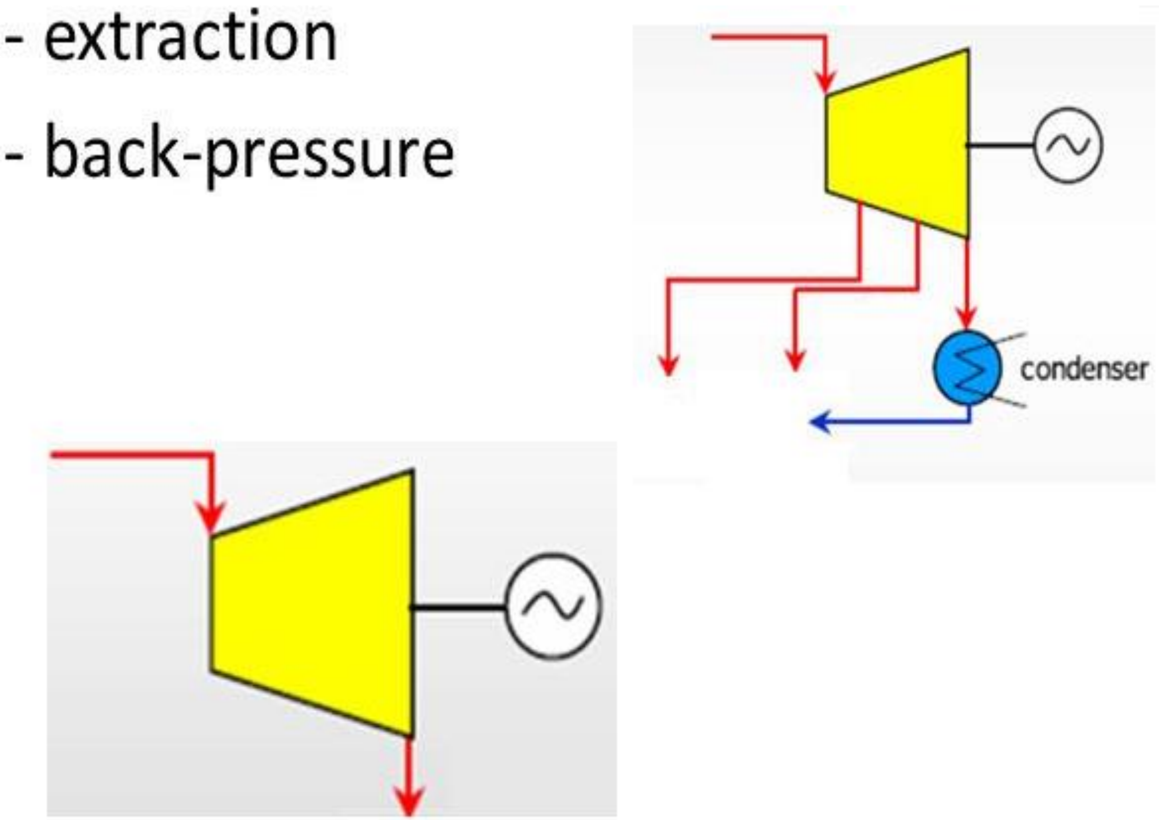


US Energy Info Administration

Types of Cogeneration systems

Number of different cogeneration systems are used, namely the following:

- Steam Turbine Cogeneration System
  - The backpressure steam turbine
  - The extraction condensing type steam turbine
- Internal Combustion Engine Cogeneratio System
- Gas Turbine Cogeneration System



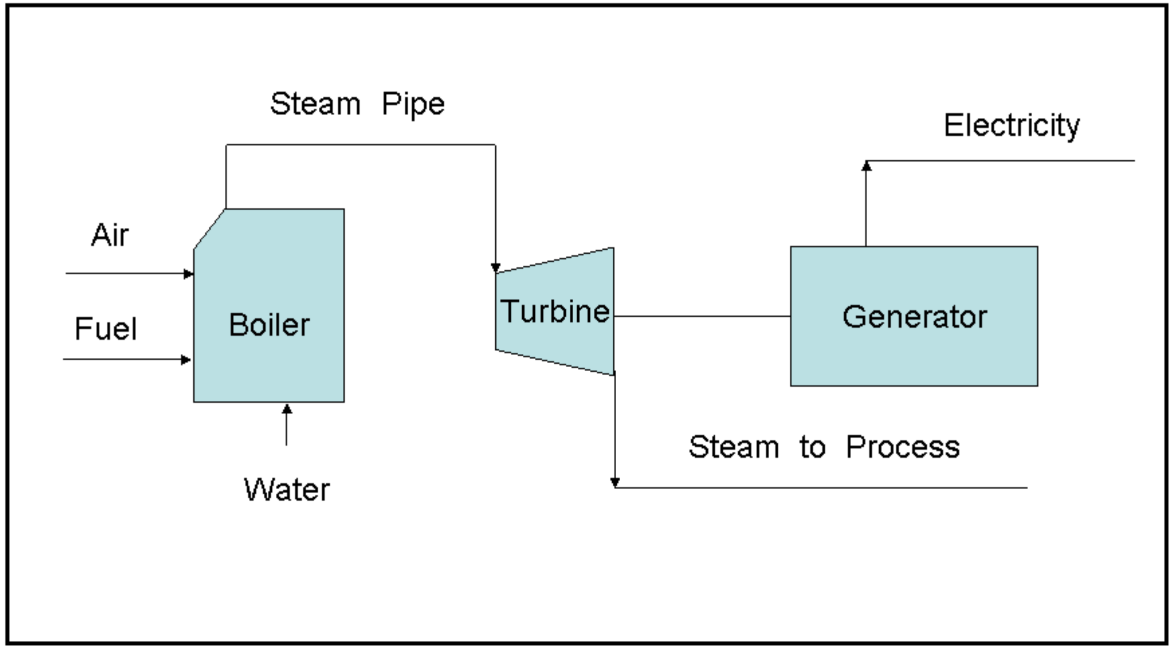
Classification of system

According to the sequence of energy use as well as the operating procedure used.

- **A topping cycle**

fuel supplied first to produce power and then in the process to produce thermal energy

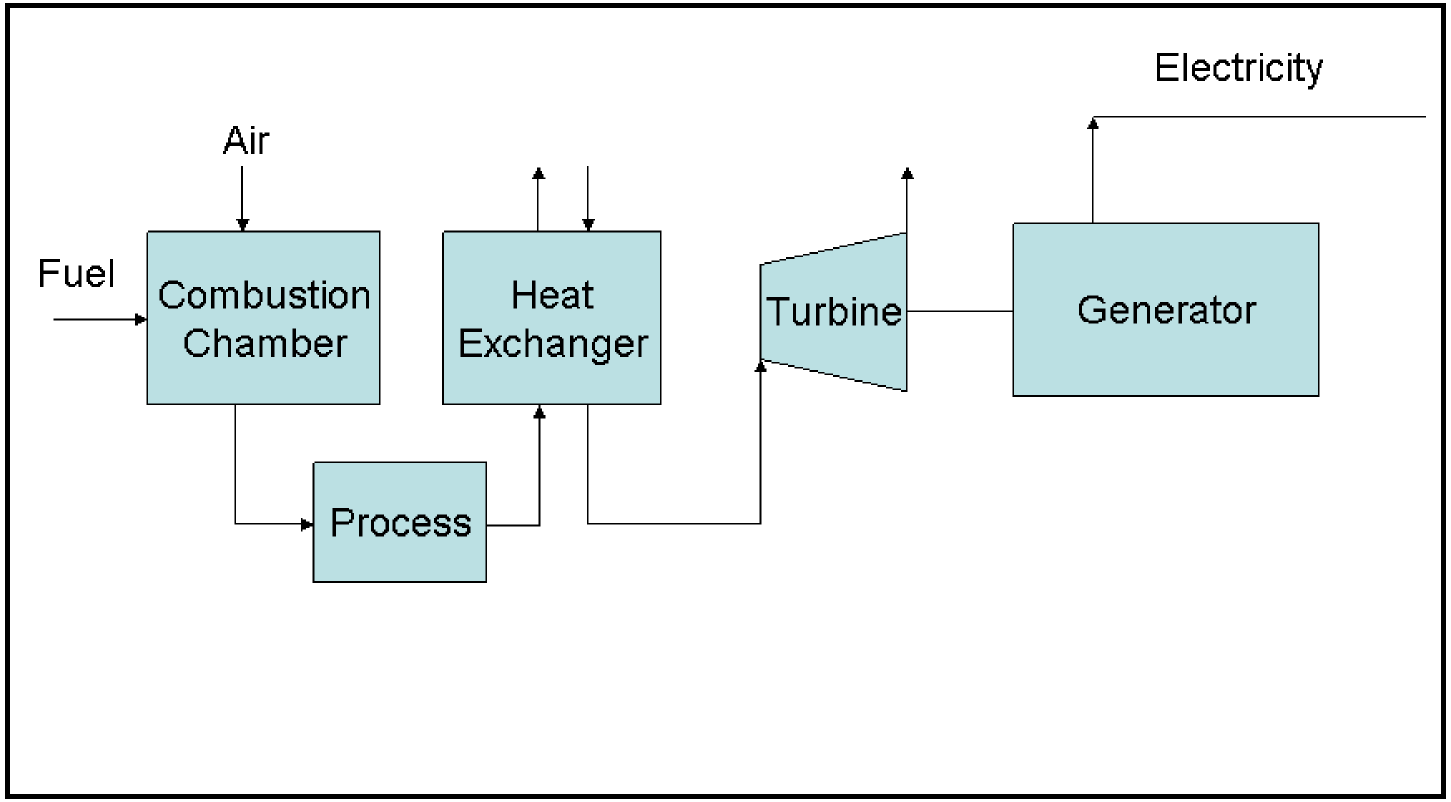
Topping Cycle



Bottoming Cycle

- **A bottoming cycle**

fuel supplied first to produce thermal energy at a high temperature. The heat rejected in the process is then further used to generate power



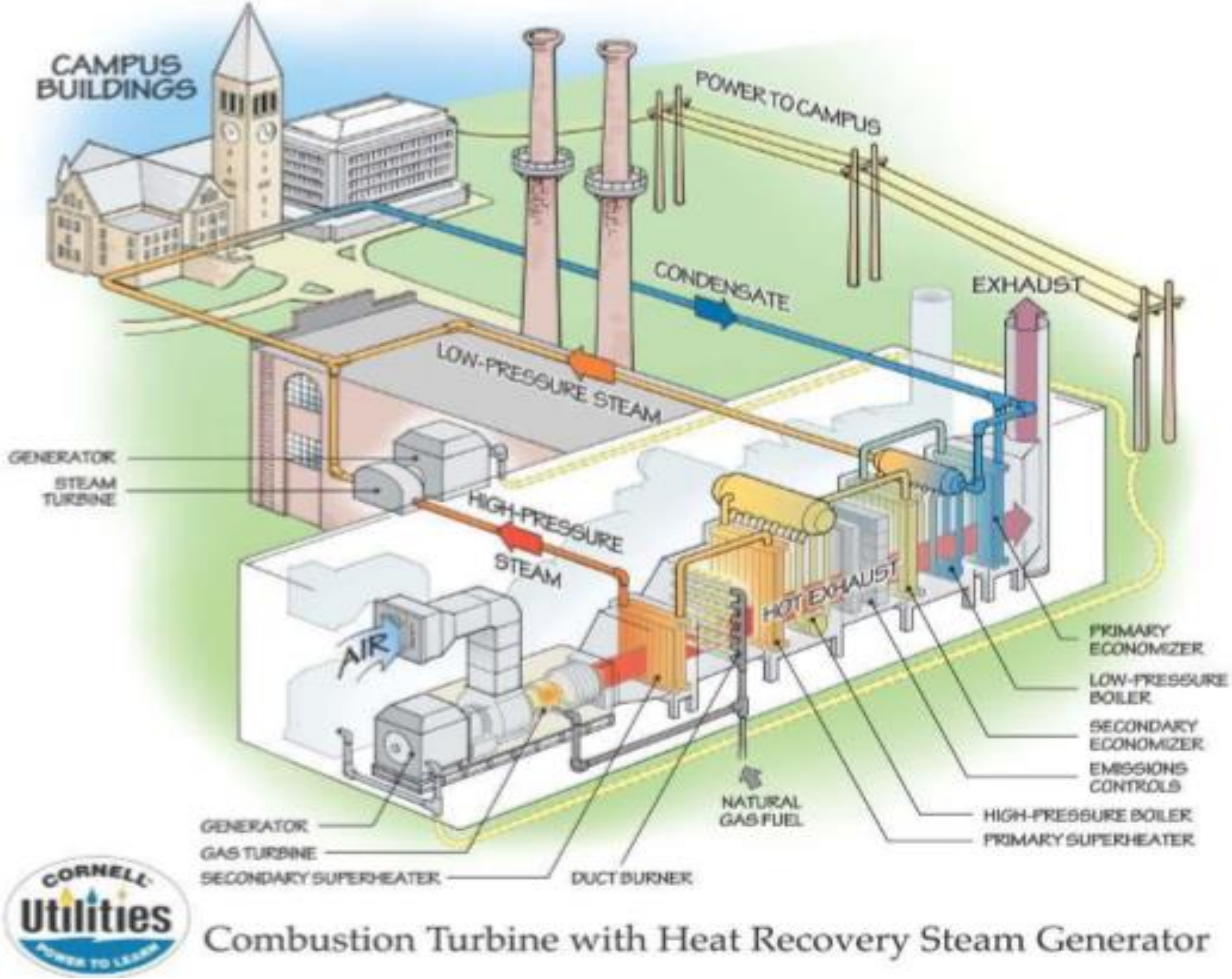
Combined cycle + Cogeneration

- Combined Cycle Heat and Power (CCHP)

<u>Cornell university</u>

2 x 15 MW gas turbine
Double stage HRSG

As compared to on-site (central heating) and off-site (electricity sources):
-20 % CO2, -55% NOx,
- 55% SO2.



Conclusions

1. Typical steam power plants have multiple feed water heaters including a de-aerator, and at least a re heater
2. Additional utility gain by combined cycles, or combined heat and power
3. Next lecture : focus on steam generators and combustor from heat and mass transfer standpoint