EEE210:
Energy Conversion and Power Systems

Necessary power system components and concepts-Part I

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Highlights

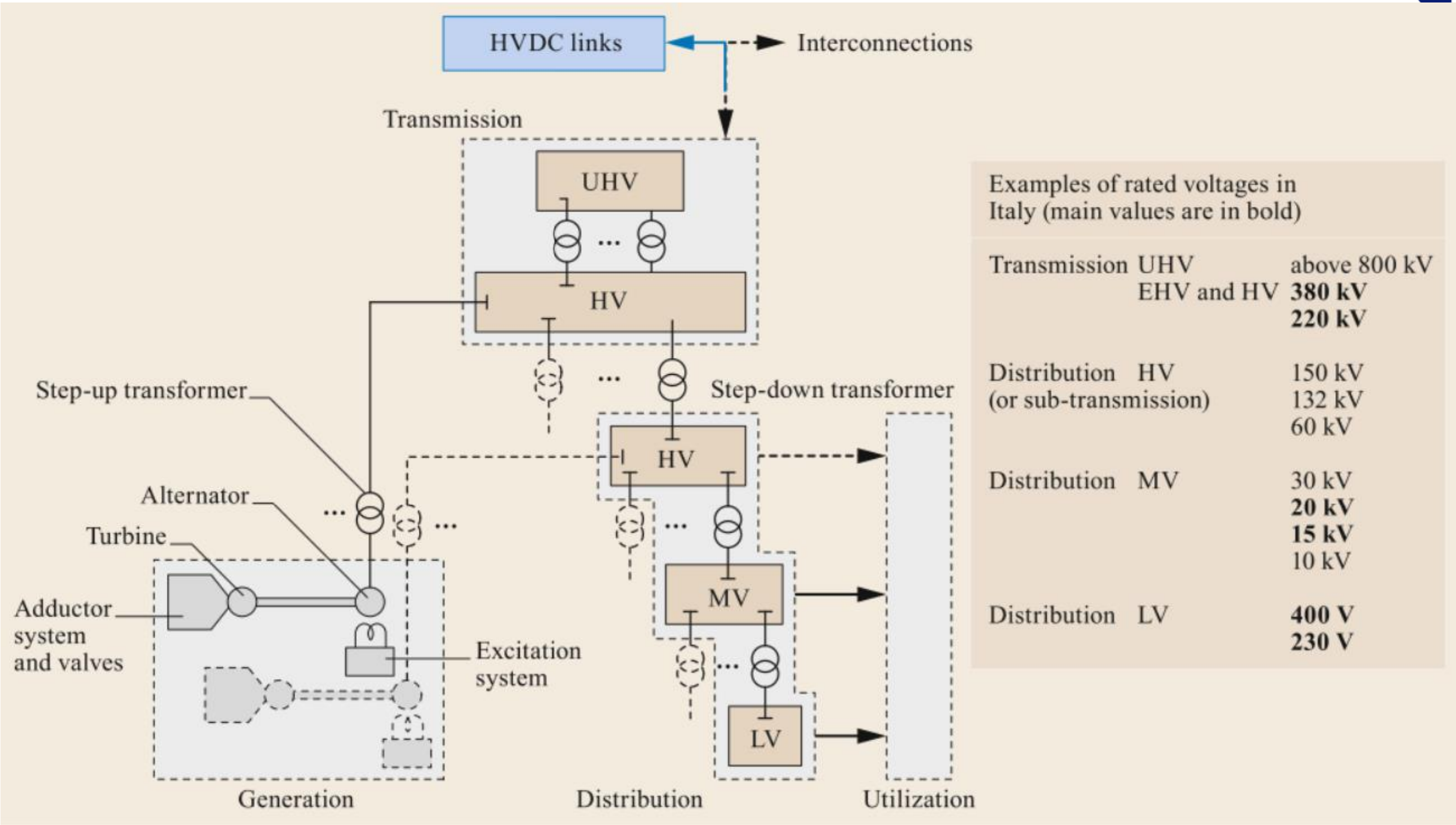
- **Generation mixes**
- **Delivery systems and consumptions**
- Essence of the power system control
- Smart Grids

Review of the power system structure

Generation

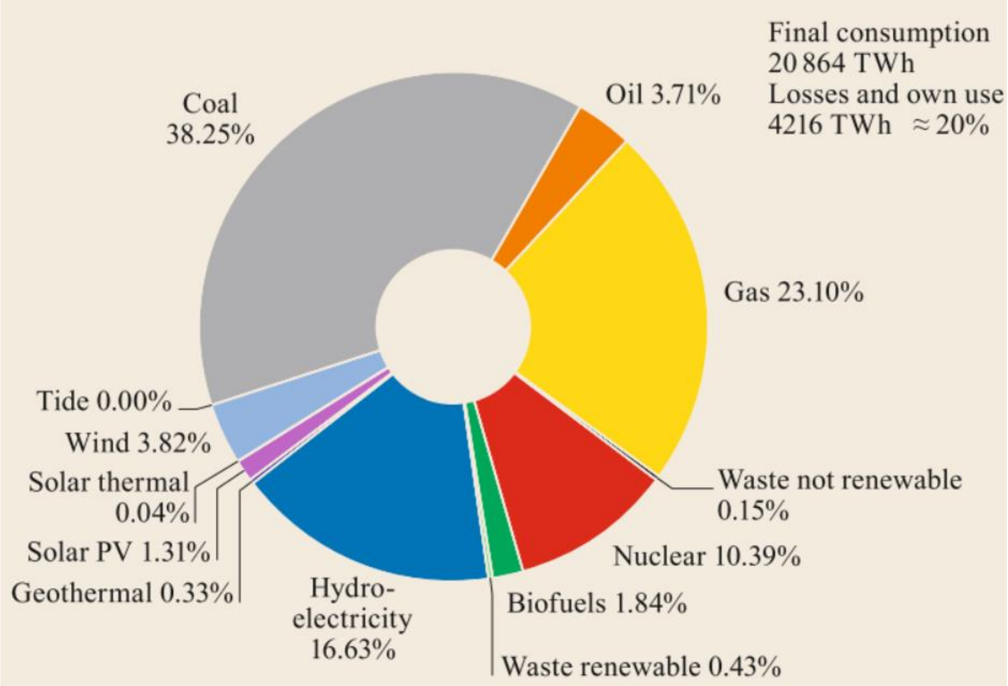
Delivery

Customers



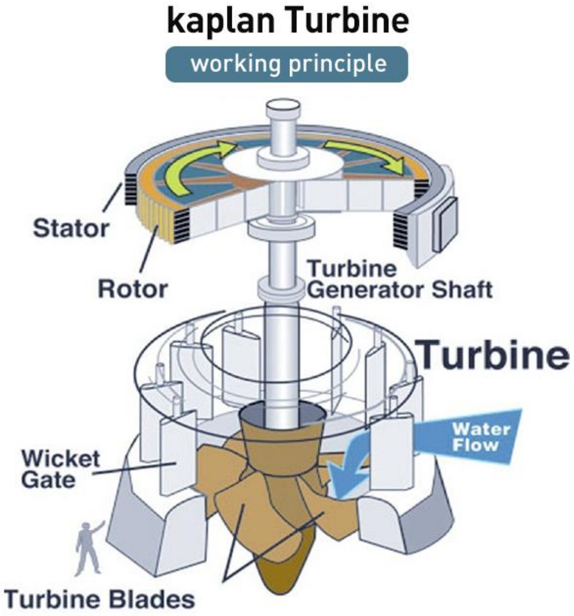
Generation Mixes

Energy sources used for electricity production worldwide in 2016



Until now, the most used generation tech -- Turbine-Generators

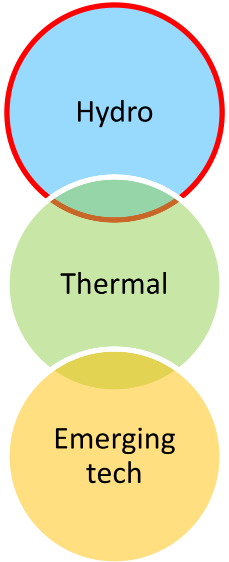
For example:

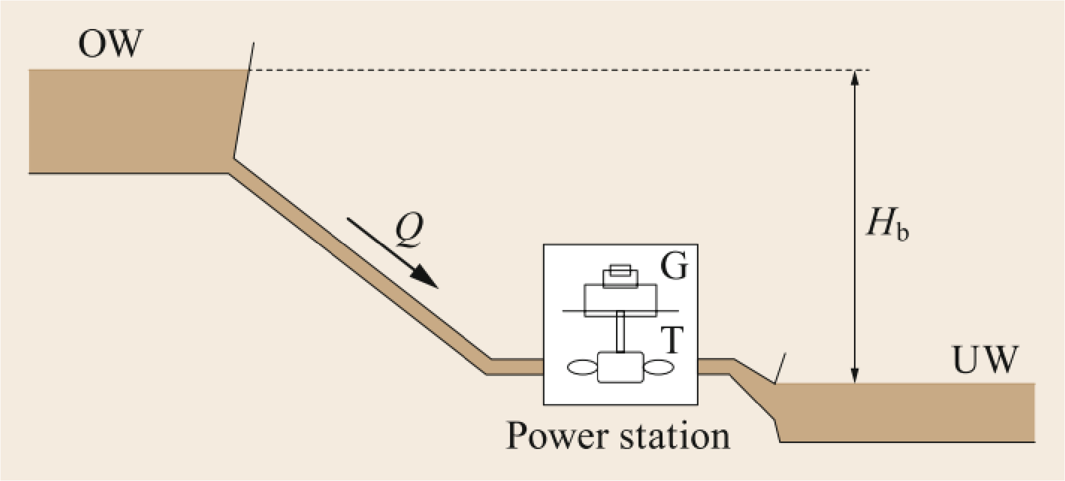


https://www.youtube.com/results?search_query=kaplan+turbine

Generation Mixes

Hydro stations





- OW: the upper pool (head water)
- UW: the lower pool (the tailwater)
- H_{b}: fall height or gross head (m) between OW and UW
- Q: the maximum quantity of usable water (m^3/s)
- G indicates the generator
- T indicates the water turbine

*

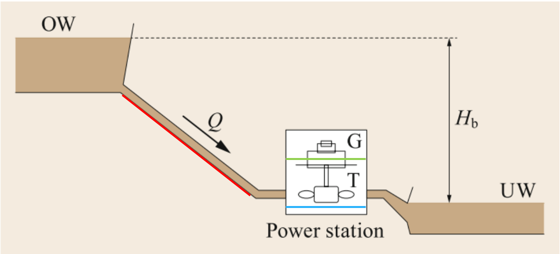
Whether Hydro power is a clean energy is still controversial.

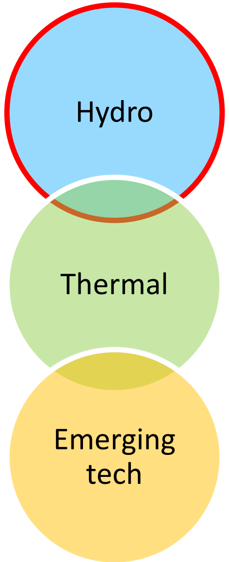
Dams and Reservoirs create environment problems.

How to calculate the power output for a hydro power station?

Generation Mixes

Hydro stations





The theoretical gross power is given by:

$$P_b = \rho * Q * g * H_b$$

where

ρ is the unit weight of water (998 or 1000 kg/m^3)

Q is the maximum quantity of usable water/ nominal water flow

g is the acceleration of gravity (9.81 m/s^2)

H_b is the fall height or gross head (m) between OW and UW

In reality, this theoretical height should be weighted, considering the friction in the supply and discharge line

The effective height:

$$H = H_b * \eta_h$$

Where η_h is the efficiency of the hydraulic system or the hydraulic efficiency.

The hydraulic power $P_h = \rho * Q * g * H$

In addition, there are also power losses on the turbine. Thus the turbine power should be

$$P_t = \eta_t * P_h = \eta_t * \rho * Q * g * H$$

Where η_t is the turbine efficiency

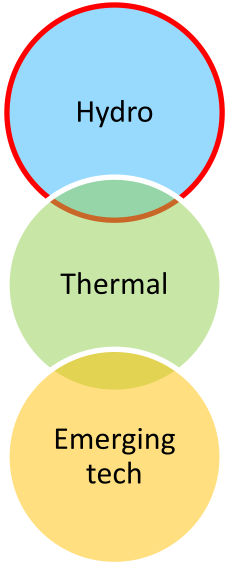
Turbine power to generator power incurs losses. The net output of the power plant is

$$P = \eta_e * P_t = \eta_e * \eta_t * \rho * Q * g * H$$

Where η_e is the efficiency of the electrical device

Generation Mixes

Hydro stations



Example questions:

A power plant with a net output of 100MW and a gross head of 500m has the following efficiencies: η_h = 0.92; η_t = 0.85; η_e = 0.96. Also, ρ = 1000 kg/m3 and g = 9. 81m/s2. Determine:

(a) The turbine and hydraulic power
(b) The effective head and the nominal water flow
(c) The diameter of the circular feed gallery if the optimal water speed is 4m/s

Generation Mixes

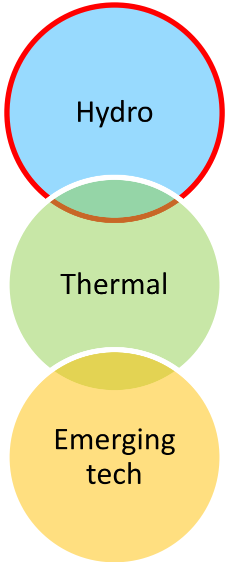
Hydro stations

(a) The turbine and hydraulic power

$$P_h = \rho * Q * g * H$$

$$P_t = \eta_t * P_h = \rho * Q * g * H$$

Unknown Q



Other equations related to P_h and P_t:

$$P = \eta_e * P_t = \eta_e * \eta_t * P_h$$

Thus

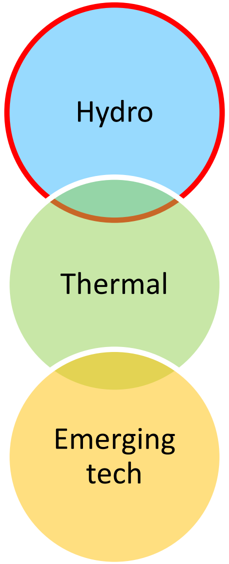
$$P_t = \frac{P}{\eta_e} = \frac{100\ MW}{0.96} = 104.2\ MW$$

$$P_h = \frac{P}{\eta_e * \eta_t} = \frac{100\ MW}{0.96 * 0.85} = 122.6\ MW$$

Generation Mixes

Hydro stations

(b) The effective head and the nominal water flow



$$H = H_b * \eta_h$$

In (a), $P_h = 122.6\ MW = \rho * Q * g * H$

The effective head:

$$H = H_b * \eta_h = 500\text{m} * 0.92 = 460\ \text{m}$$

The nominal water flow：

$$Q = \frac{P_h}{\rho * g * H} = \frac{122.6 * 10^6\ W}{1000\ kg/m^3 * 9.81 m/S^2 * 460m} = 27.2 \frac{m^3}{s}$$

Generation Mixes

Hydro stations

(c) The diameter of the circular feed gallery if the optimal water speed is 4m/s

Hydro

Thermal

Emerging tech

- Extra knowledge:

The flow rate equation -- the flow rate of water through a specific pipe diameter – also called the discharge equation

$$Q = A * v$$

where Q is the flow rate, A is the flow area, v is the velocity.

Considering the cross section of the feed gallery is a circle, the diameter is given by:

D = $\sqrt{\frac{4A}{\pi}}$

The flow area is:

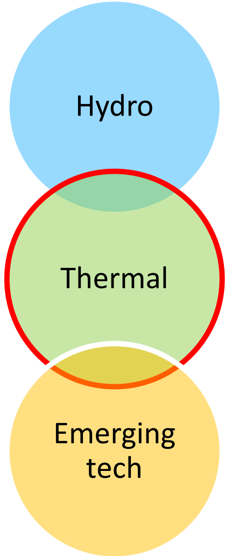
$$A = \frac{Q}{v} = \frac{27.2\ m^3/s}{4\ m/s} = 6.8\ m^2$$

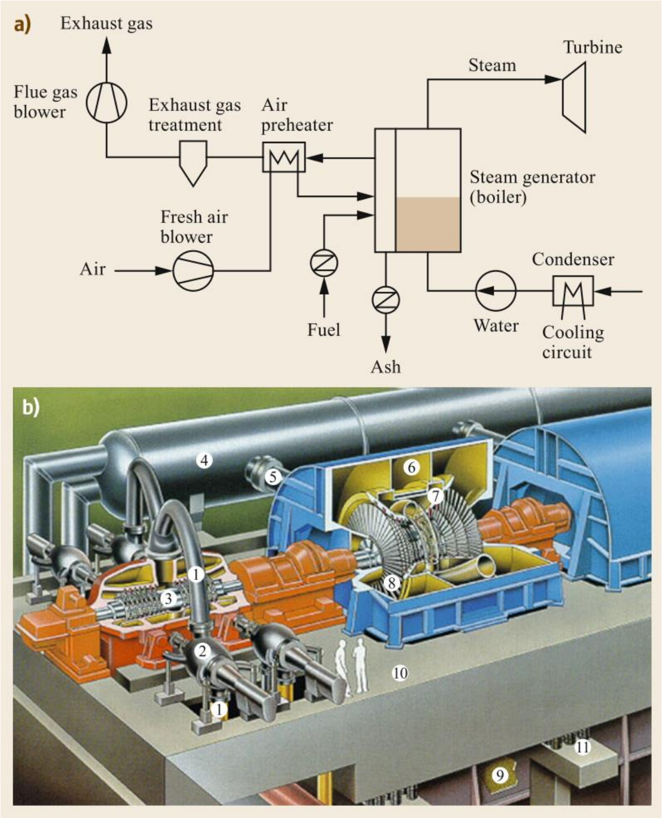
The diameter is

D = $\sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 * 6.8\ m^2}{3.14}} = 2.94\ m$

Generation Mixes

Steam power plant



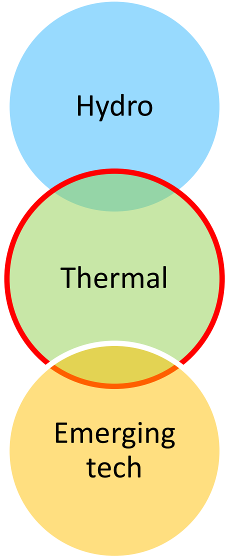


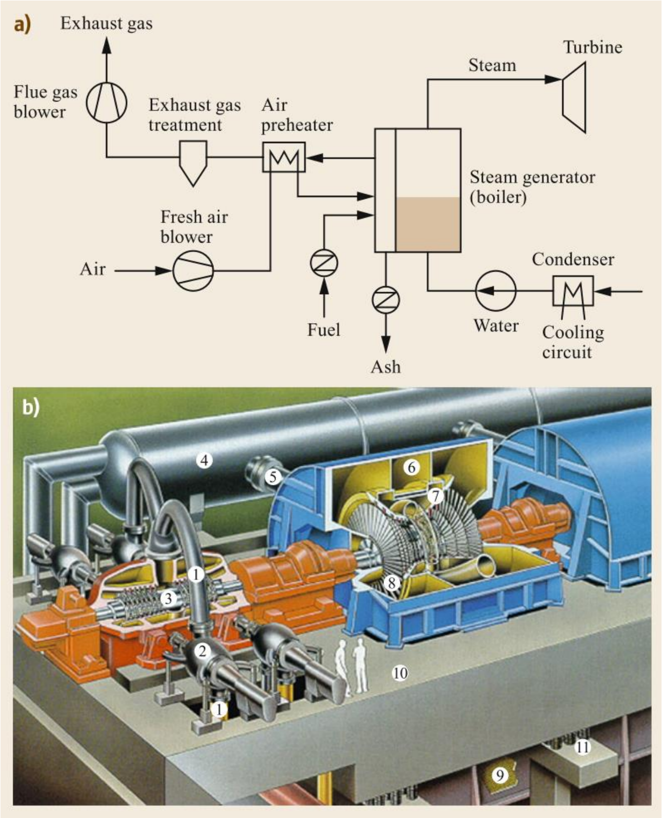
Main circuits in a fossil fired steam power plant (principle)

- 1 live steam line
- 2 stop and control valve
- 3 high pressure turbine
- 4 water separator/ reheater
- 5 steam line, 6 low pressure turbine
- 7 guide vanes
- 8 rotor blades
- 9 condenser
- 10 support plate
- 11 vibration dampers

Generation Mixes

Steam power plant



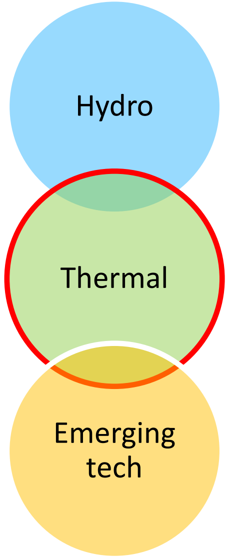


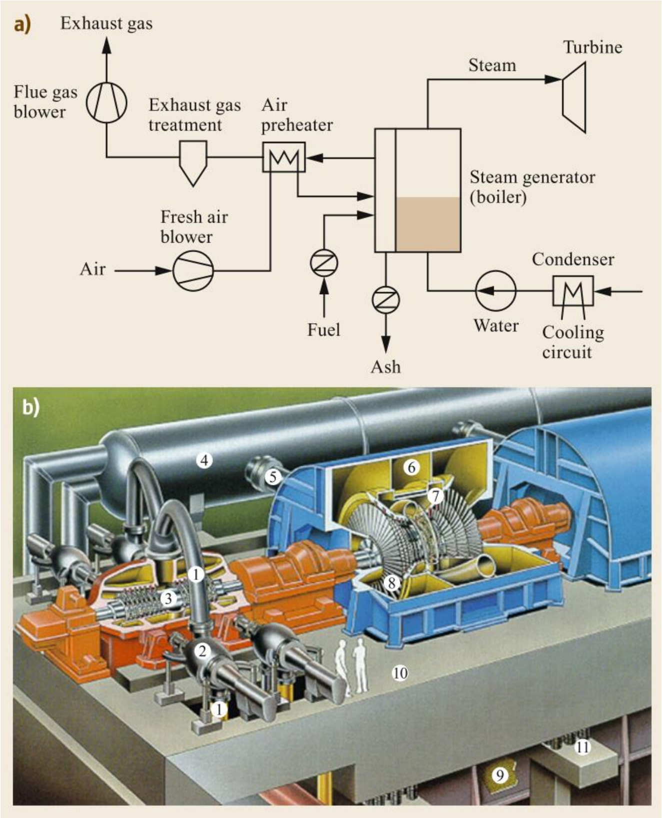
The fossil-fired steam power plants includes three typical systems, where the last two also occur in nuclear power plants:

- Air–fuel–flue gas/ash circuit
- Water–steam cycle
- Cooling water circuit

Generation Mixes

Steam power plant





- Air–fuel–flue gas/ash circuit

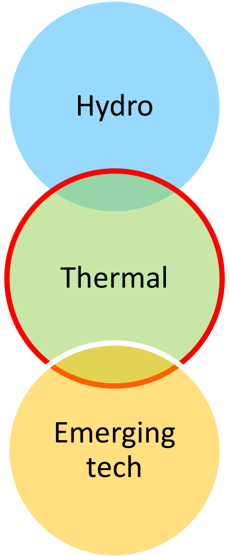
The fuel and the air preheated by the flue gases are fed into the combustion chamber.

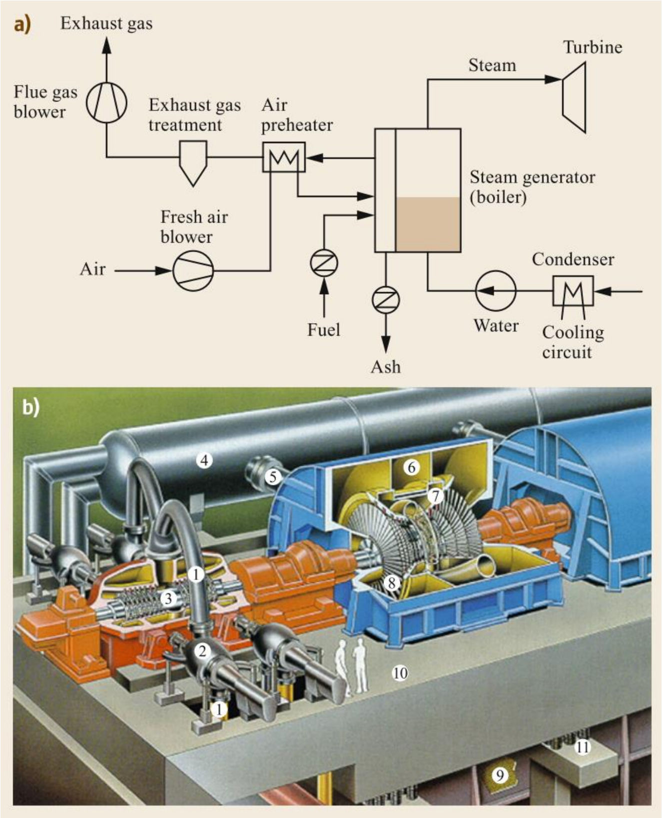
Flue gas cleaning (flue gas treatment) includes, among other things, denitrification, desulfurization and dust removal.

An ash extractor is required for coal fired systems.

Generation Mixes

Steam power plant

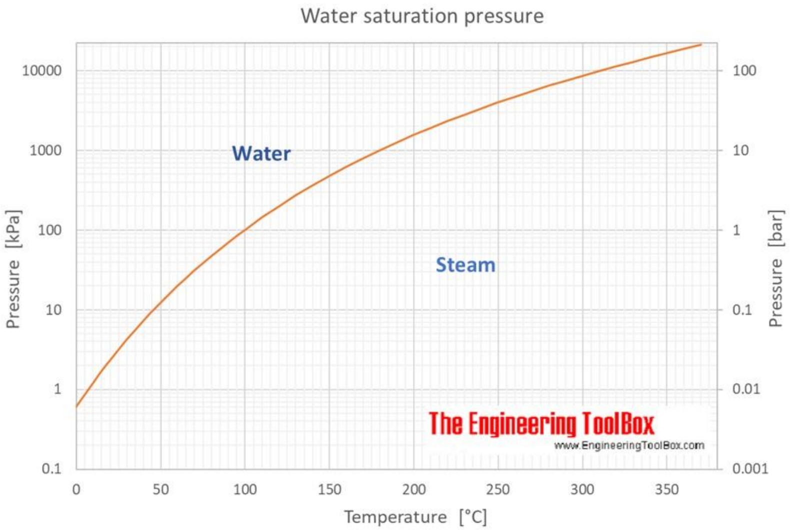




- Water–steam cycle

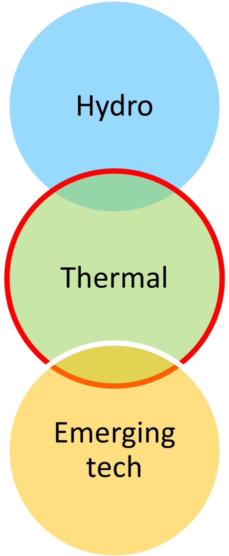
Condensation process:

In modern power plants, the condensation pressure is selected as 0.04 – 0.1 bar, because:

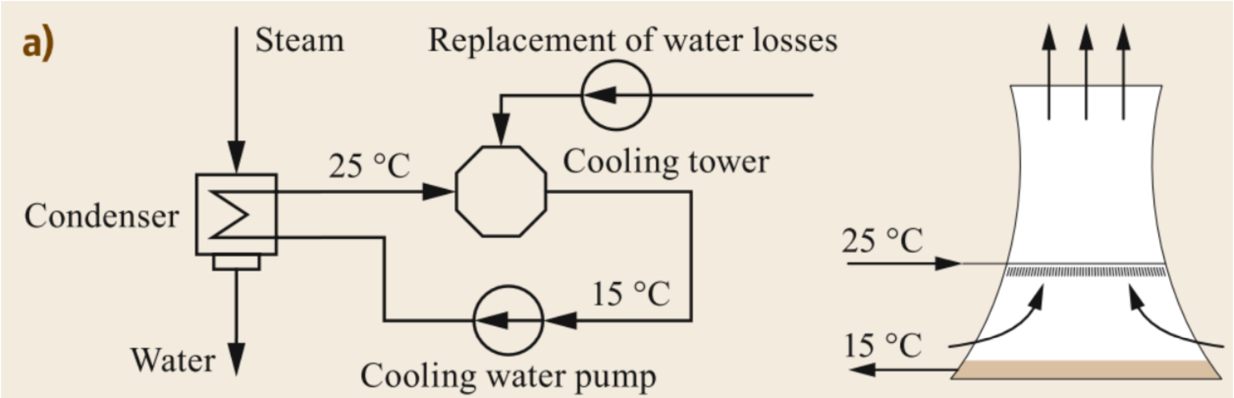


Generation Mixes

Steam power plant

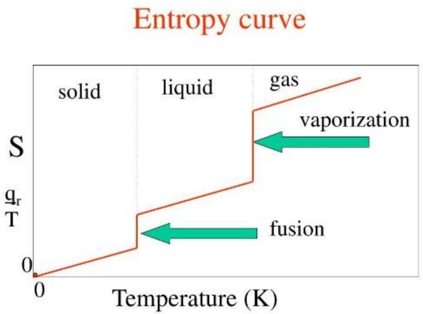


- Cooling water circuit (wet tower cooling)



- The necessary cooling water quantity is about 50 -- 70 times the steam weight, if cooling water heating of approximately 10 degree is permitted

- As the river temperature should only rise slightly for ecological reasons, large rivers are needed even for these relatively small quantities of water



Generation Mixes

Wind power

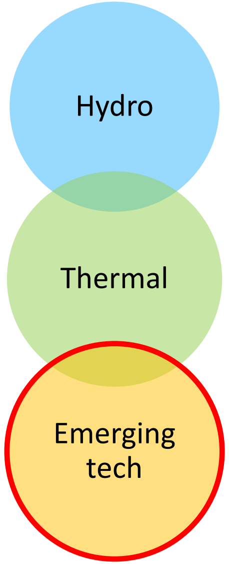
- Hydro
- Thermal
- Emerging tech

Traditional wind turbines

Vertical axis spiral turbines

Generation Mixes

Wind power



1. Given an air mass m moving with speed v_0, this air mass should have the kinetic power:

$$E_{kin} = \frac{1}{2} * m * v_0^2 \text{ (J)}$$

2. If the air density is ρ and the cross section of this air mass is A, the air mass/second should be:

$$m' = A * \rho * v_0 \text{ (kg/s)}$$

3 the theoretical wind power is:

$$P_0 = \frac{1}{2} * m' * v_0^2 = \frac{1}{2} * A * \rho * v_0 * v_0^2$$

$$= \frac{1}{2} * A * \rho * v_0^3$$

* From the equation of P_0:

- wind speed and air density are two factors to P_0

For air density, it changes with the varying of the ambient temperature and pressure. By taking the barometric formula (not important, refer to physics books), the theoretical wind power at different altitude and temperature:

Only temperature $\rho = \rho_0 * \frac{T_0}{T_{new}}$

Only altitude $\rho = \rho_0 e^{-\frac{h-h_0}{aT}}$

where h is the alternative m a.s.l (meter above sea level)

h_0 is the base m a.s.l

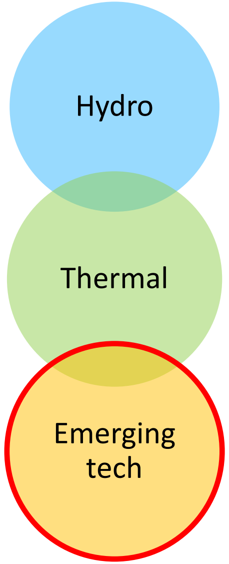
T is the temperature in K

a is a constant equals 29.27 m/K

Generation Mixes

Wind power

* Due to the ground friction, wind speed is not always constant



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$$= \frac{1}{2} * A * \rho * v_0^3$$

Wind speed at different altitude is given by :

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{\alpha}$$

Where

$\alpha = 0.16$ *above the sea*

$\alpha = 0.17 \sim 0.2$

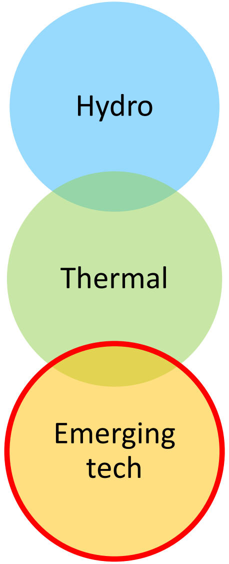
above plain ground without obstacles

V is the wind speed at a different altitude

V_0 is the base wind speed

Generation Mixes

Wind power



Example questions:

Calculate the theoretical power per m^2 of area for v_0=4m/s and 7m/s and the corresponding theoretical power with constant wind conditions $\rho = 1.292\ kg/m^3$ at 0 °C and normal pressure (0 m a.s.l)

a) For 0 ma.s.l. at standard pressure and 20 °C
b) At 2000 ma.s.l. at the corresponding pressure and 10 °C at a wind speed of v_0. The velocity of height change is ignored.
c) Assuming that the above speed values apply to a height of 10m above the ground, how does the power change in % if the wind turbine is installed 20m above the ground (ground without obstacles). The air density of height change is ignored.

Generation Mixes

Wind power

Hydro

Thermal

Emerging tech

a) For 0 m a.s.l. at standard pressure and 20 °C

- Scale the air density to 20 °C

$$\rho_{20C} = \rho * \frac{T_0}{T_{new}} = 1.292 * \frac{273}{293} = 1.205\ kg/m^3$$

- For 4 m/s

The theoretical power :

$$P_0 = \frac{1}{2} * A * \rho_{20C} * v_0^3 = \frac{1}{2} * 1 * 1.205 * 4^3 = 38.6\ W/m^2$$

- For 7 m/s

The theoretical power :

$$P_0 = \frac{1}{2} * A * \rho_{20C} * v_0^3 = \frac{1}{2} * 1 * 1.205 * 7^3 = 207\ W/m^2$$

Generation Mixes

Wind power

Hydro

Thermal

Emerging tech

b) At 2000 m a.s.l. at the corresponding pressure and 10 °C at a wind speed of v_0.

The velocity of height change is ignored.

- Define variables:

$$h_0 = 0\,m; h = 2000\,m; T = 273 + 10 = 283\,K$$

- Derive air density at 10 °C

$$\rho_{10C} = \rho_{20C} * \frac{T_{20C}}{T_{10C}} = 1.205 * \frac{293}{283} = 1.248\,kg/m^3$$

- Derive theoretical power at 0 m a.s.l

$$P_0 = \frac{1}{2} * A * \rho * v_0^3 = \frac{1}{2} * 1 * 1.248 * v_0^3 = 0.624 v_0^3\,W/m^2$$

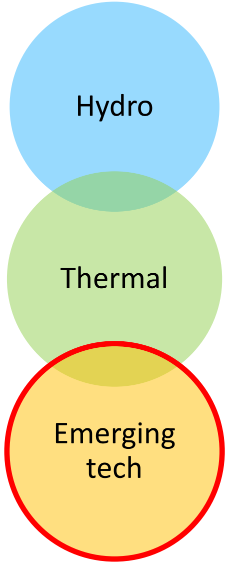
- *Derive* theoretical power at 2000 m a.s.l

$$P = P_0 e^{-\frac{h-h_0}{aT_{10C}}} = 0.624 v_0^3 * e^{-\frac{2000-0}{29.27*283}} = 0.624 v_0^3 * 0.7855 = 0.49 v_0^3\,W/m^2$$

The theoretical power reduced by 19% (in Question a) $P = 0.60\, v_0^3\, W/m^2$)

Generation Mixes

Wind power



c) Assuming that the above speed values apply to a height of 10m above the ground, how does the power change in % if the wind turbine is installed 20m above the ground (ground without obstacles). The air density of height change is ignored.

- Define variables:

$$h_0 = 10\ m; h = 20\ m$$

- Take variables into the equation:

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{\alpha} = \left(\frac{20}{10}\right)^{\alpha}$$ considering $\alpha = 0.17\sim 0.2$ on ground without obstacles

$$V = 1.125\sim1.149\ V_0,$$

$$P_0 = \frac{1}{2} * A * \rho * v_0^3\ thus\ v^3\ = 1.42\sim1.52 v_0^3$$

The theoretical power would increase by 42~52%.

Generation Mixes

Solar power

Hydro

Thermal

Emerging tech

	PV panels	PV glasses
		
Efficiency	15-20%	9-10%

Generation Mixes

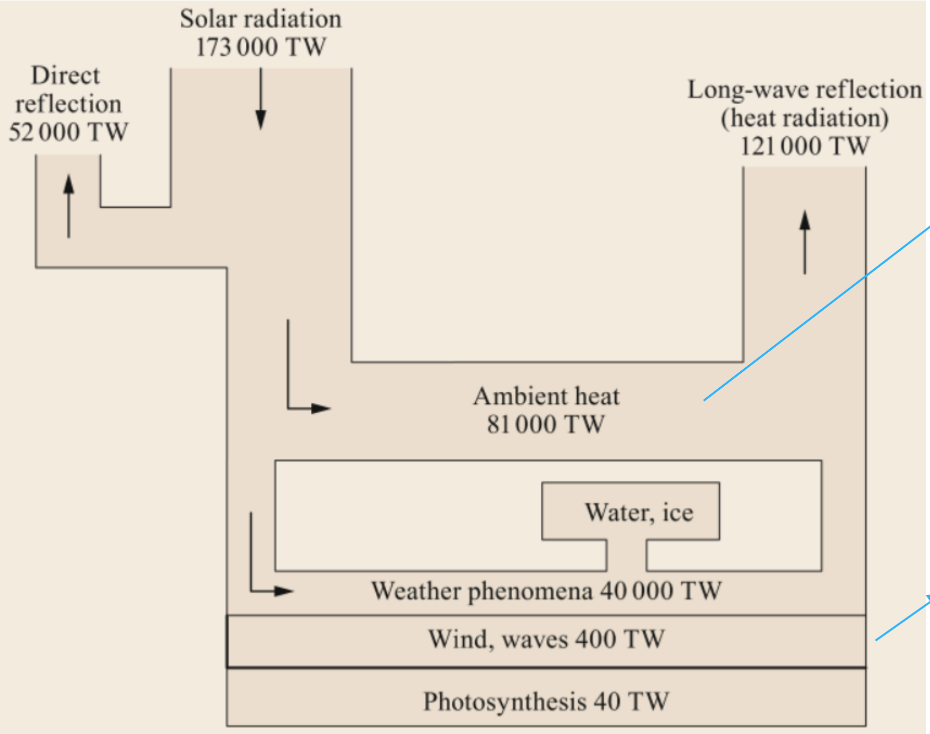
Solar power ---- Specific Availability of Solar Energy

Hydro

Thermal

Emerging tech

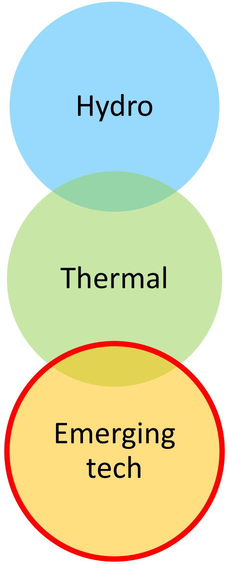
Solar energy balance of the world

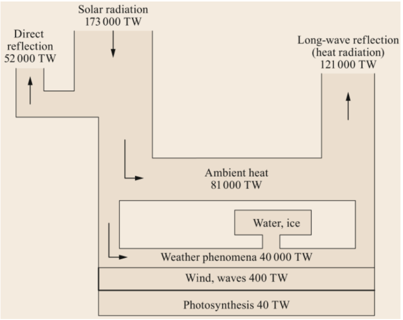


the absorbed radiation is stored in air, water and the ground as low-temperature heat and, as such, it can be made use of, e.g., by means of heat pumps

Drives the world's weather by evaporating water and creating differences of pressure and temperature; this energy occurs as potential energy (water content of clouds, flowing water and glaciers) and as kinetic energy (wind, ocean currents, waves)

Generation Mixes





Solar power ---- Specific Availability of Solar Energy

If the 121 000TW that reaches the earth is distributed uniformly over the earth's surface, the result for a horizontal surface is

$$Mean\ annual\ power = \frac{P_{s\_radiation}}{A_{earth}} = \frac{121\ 000\mathrm{TW}}{510 * 10^6\ km^2} = 237\ W/\mathrm{m}^2$$

If we consider only daylight hours, the result will double to 474 W/m^2

If we multiply the annual mean power by 8760 h/a, the solar energy throughout a year would be:

$$The\ annual\ mean\ energy\ = Mean\ annual\ power * T_a$$
$$= 237 * 8760 = 2076\ kWh/a \cdot \mathrm{m}^2$$

Will this value change because of different climate conditions on earth?

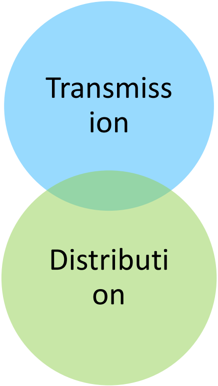
Delivery systems and consumptions

Example cases

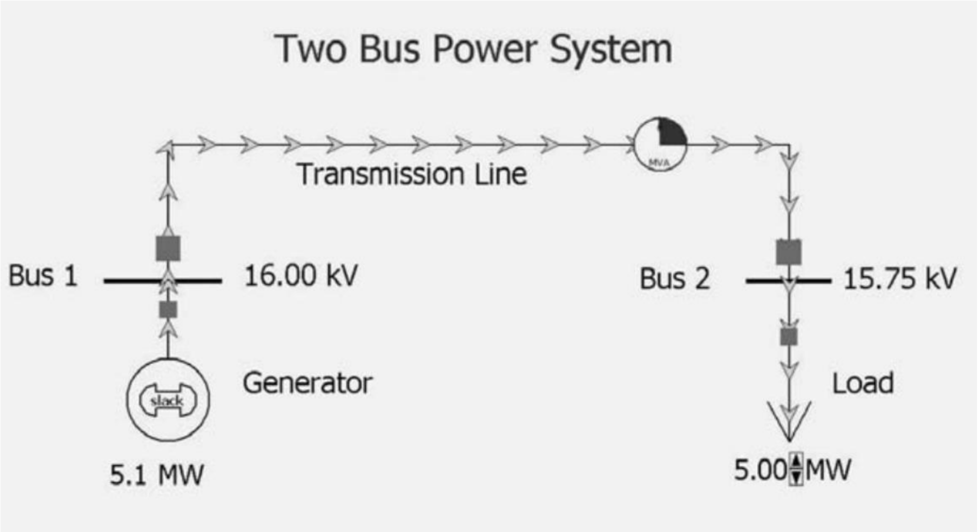
Questions:

If the load cannot connect to 15KV, what should we do?

If the generator is 100 times of the example away from the load, what should we do?

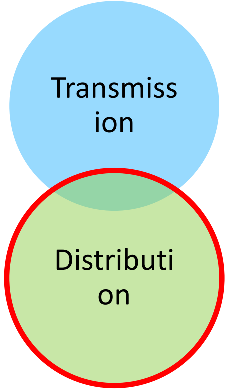


- Power transmitted from bus 1 to bus 2
- Voltage drops by 0.25 kV
- 0.1 MW lost on the delivery system

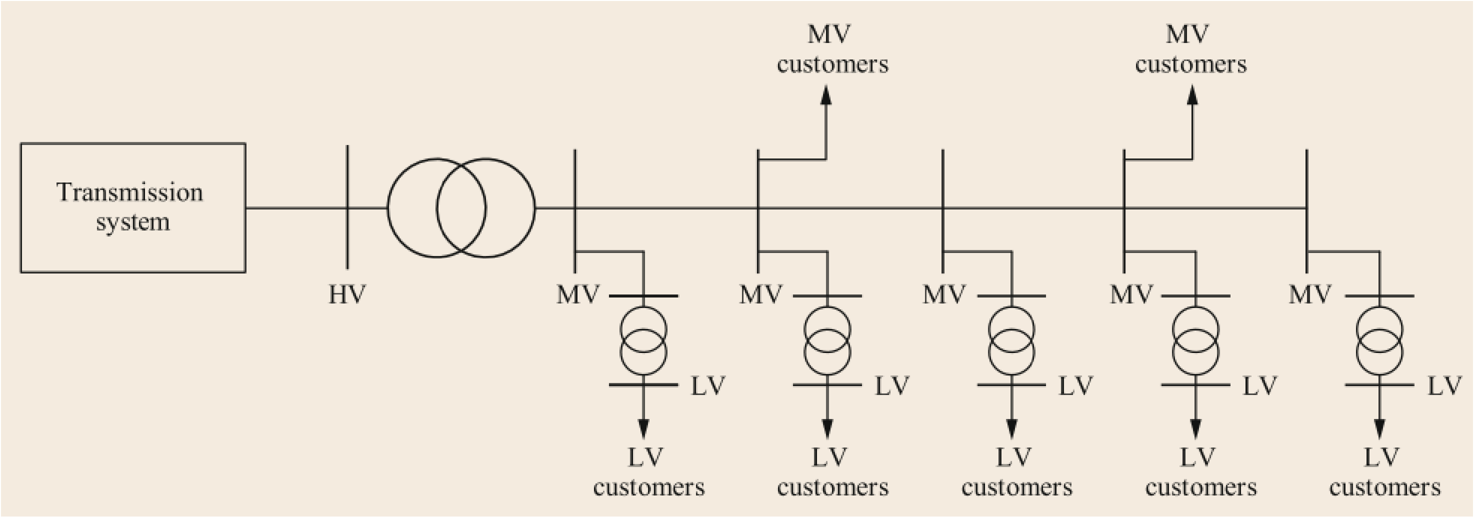


Delivery systems and consumptions

If the load cannot connect to 15KV, what should we do?



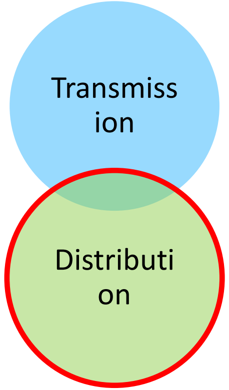
Lower the voltage level



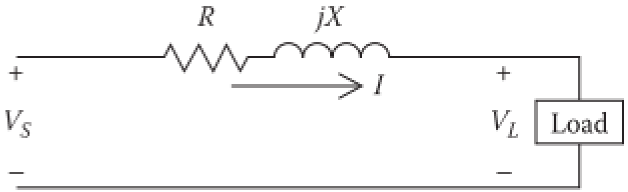
High Voltage → Medium Voltage → Low Voltage

Delivery systems and consumptions

Distribution networks— Voltage variations:



it can cause damage to electrical / electronic equipment as well as significant inefficiencies



By applying the Kirchhoff's Voltage Law

$$V_s = V_L + (R + jX) * I$$

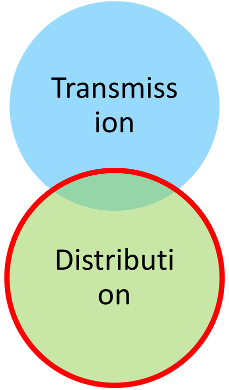
$$V_{drop/rise}\% = \frac{V_s - V_L}{V_{nominal}}$$

VARIATION RANGES OF THE SERVICE VOLTAGE

Country	Nominal Voltage(V)	Voltage variation range (min./max.)
Australia	230	-6.1%/+10%
Canada	120	-8.3%/+4.2%
Germany	230	±10.0%
Japan	100	±6.0%
Korea	220	±5.9%
U.K.	230	-6.0%/+10%
U.S.	120	±5.0%

Delivery systems and consumptions

Distribution networks— Voltage variations:

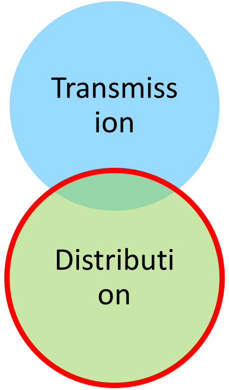


If the resistivity for a 200 m single-phase distribution wire is 0.6 Ω/km, the nominal voltage level is 230V at the beginning of the distribution wire. A demand of 6.9 kW is connected at the end of the distribution wire:

a) Calculate the voltage drops at the end of the distribution wire (wire reactance is neglected)
b) Derive the maximum supply distance of this wire at 230V if the voltage variation limits is $\pm 5.0\%$
c) Develop a scheme to double the maximum supply distance

Delivery systems and consumptions

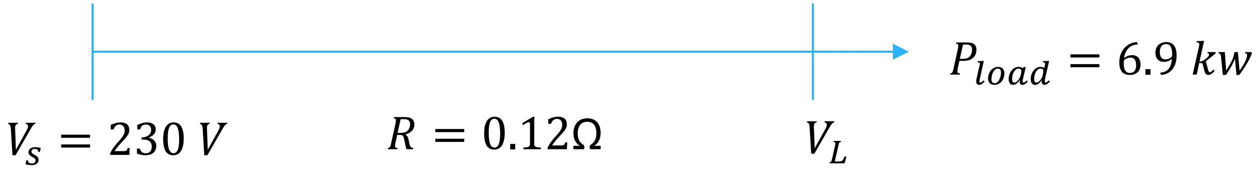
Distribution networks— Voltage variations:



a) Calculate the voltage drops at the end of the distribution wire (wire reactance is neglected)

- According to the problem statement:

$$R = r * L = 0.6\ \Omega/\text{km} * 0.2\ \text{km} = 0.12\ \Omega$$



- Reviewing the equation:

$$V_s = V_L + (R + jX) * I$$
$$P_{load} = V_L * I$$

- Taking the equation of P into V_s

$$V_s = \frac{P_{load}}{I} + (R + jX) * I$$

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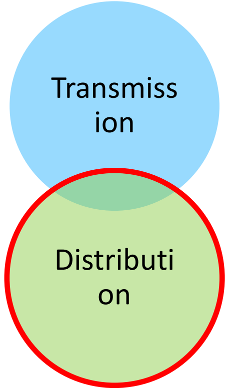

a) Calculate the voltage drops at the end of the distribution wire (wire reactance is neglected)

$$V_s = \frac{P_{load}}{I} + (R + jX) * I$$

$$V_s * I = P_{load} + R * I^2$$

$$0.12I^2 - 230I + 6900 = 0$$

$$I = 30.485 \text{ A or } 1886.185 \text{ A}$$

If $I = 1886.185$ A, V_L equals 3.65 V, impossible answer in the reality.

Thus, $I = 30.485$ A

$$V_L = \frac{P_{load}}{I} = \frac{6900}{30.485} = 226.34\,V$$

$$V_{drop} = V_s - V_L = 230 - 226.34 = 3.66V$$

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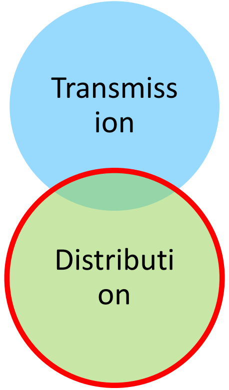


b) Derive the maximum supply distance of this wire if the voltage variation limits is $\pm 5.0\%$

- The connected load is a pure resistive load, voltage should drop at the end.

* If the loads are shunt capacitors, things would be different.

- Calculate the permittable voltage margin

$$V_{Lm} = (100\% - 5\%) * V_S = 0.95 * 230 = 218.5\ \mathrm{V}$$

- Calculate the current that flows through the wire

$$I_{Lm} = \frac{P_{load}}{V_{Lm}} = \frac{6900}{218.5} = 31.58\ A$$

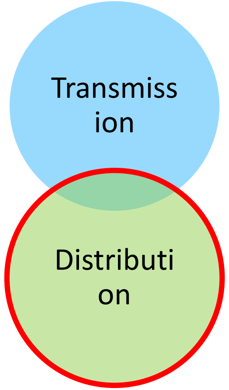
- Calculate the voltage drops and maximum supply distance

$$V_S - V_L = V_{dropm} = I_{Lm} * \mathrm{R} = I_{Lm} * \mathrm{r} * L_m$$

Thus, $L_m = \frac{V_S - V_{Lm}}{I_{Lm} * \mathrm{r}} = \frac{230-218.5}{31.58*0.6} = 607\ m$

Delivery systems and consumptions

Distribution networks— Voltage variations:



c) Develop a reinforcement plan to double the maximum supply distance

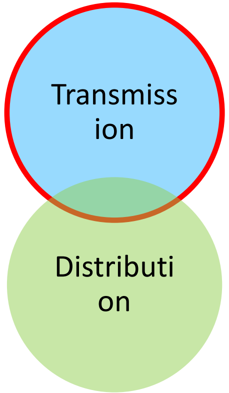
- Now, the maximum supply distance L_m = 607 m

The doubled supply distance L_{dm} = $2 * L_m$ = 2*607 = 1214 m

The answer will be discussed in following classes.

Delivery systems and consumptions

If the generator is 100 times of the distance away from the load, what should we do?



Voltage drops: $V_s = V_L + (R + jX) * I$ Power losses $P_{loss} = R * I^2$

Typical electrical characteristics of various overhead distribution lines

Material and cross-sectional area (mm^2)	R (Ω/km)	X (Ω/km)	Ampacity (A)	Voltage (kV)
ACSR–16	1.268	0.422	136	20
ACSR–95	0.215	0.334	448	20
Cu–95	0.220	0.358	352	20
Cu–16	1.274	0.334	115	0.4
Cu–35	0.596	0.309	185	0.4

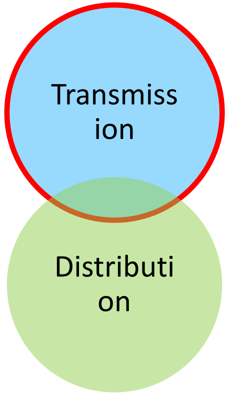
The reduction of the losses requires a larger cross section of the conductor

- Electric power generated is given by:

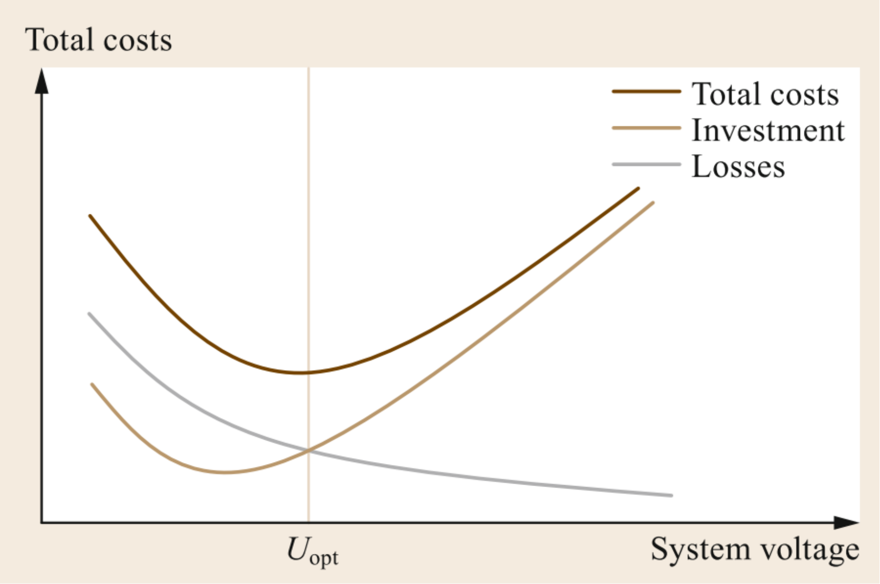
$$S = U\uparrow * I\downarrow$$

Delivery systems and consumptions

If the generator is 100 times of the distance away from the load, what should we do?



Typical total costs for an electric power transmission system as function of the system voltage



P = 9.6 kW in the previous example:
The maximum supply distance is 607 m

If the voltage at the beginning of the wire is 10 kV with ±5.0% variation limit
The current reduces to 1.01 A

The maximum distance could achieve almost 825 km

Next Lecture

Necessary power system components and concepts (2)

Thanks for your attendance!