# DAT300
# THE ELECTRICAL POWER SYSTEM

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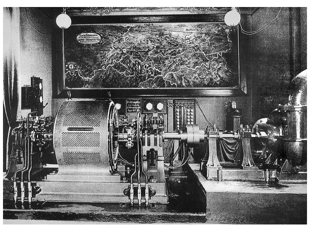
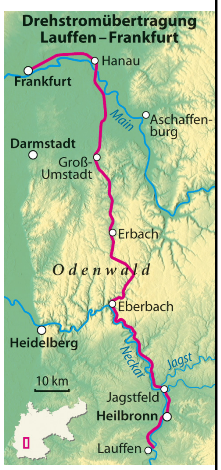
## History of the power systems

AC transmission was first demonstrated at an exhibition in Frankfurt am Main 1891



170 kW transferred 175 km from Lauffen hydropower station to the exhibition area at 13000-14700 V



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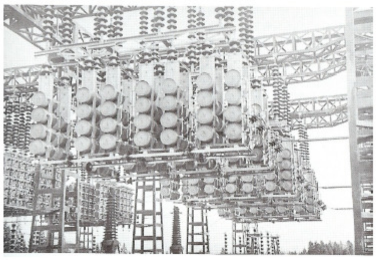
# History of the power systems in Sweden

First 3-phase transmission system installed in Sweden between Hellsjön and Grängesberg 1893
voltage 9650 V, 70 Hz, 70 kW

First 400 kV system Harsprånget Hallsberg 1952

Series compensation introduced 1954



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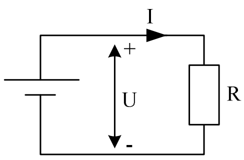
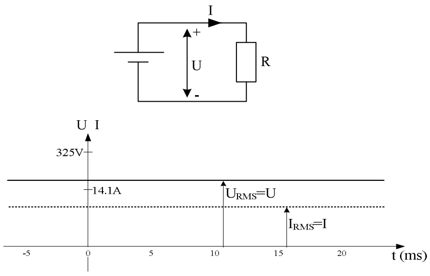
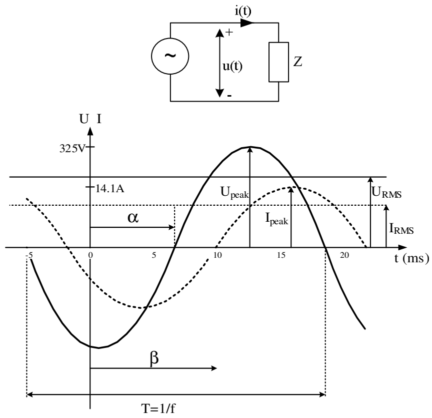
# Fundamentals of Electric Power

- Energy
  - Ability to perform work, [J], [Ws], [kWh] (1 kWh = 3.6 MJ)
- Voltage
  - Measured between two points [V], [kV]
  - Equivalent to pressure in a water pipe
- Current
  - Measure of rate of flow of charge through a conductor [A], [kA]
  - Equivalent to the rate of flow of water through a pipe.
  - Must have a closed circuit to have a current



# Direct Current (DC) / Alternating Current (AC)




$$u(t) = U$$

$$i(t) = I$$

$$u(t) = U_{peak} \cos(\omega t - \alpha)$$

$$i(t) = I_{peak} \cos(\omega t - \beta)$$

$$\omega = 2\pi f$$

RMS = Root-Mean-Square

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\, dt} = \frac{I_{peak}}{\sqrt{2}}$$

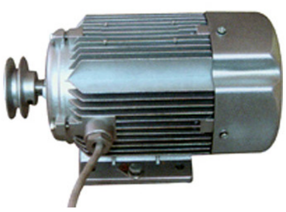
Only for sinusoidal waveforms

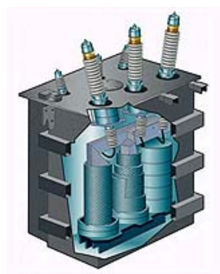


# Why is AC used?

The two main factors that formed the power system

- Transformer (only works on AC)
- Robust and cheep motor (rotating flux)





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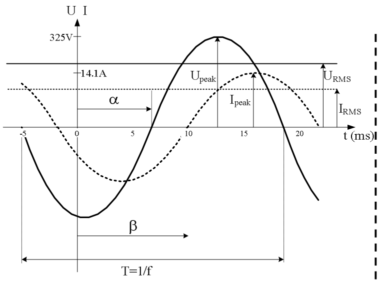
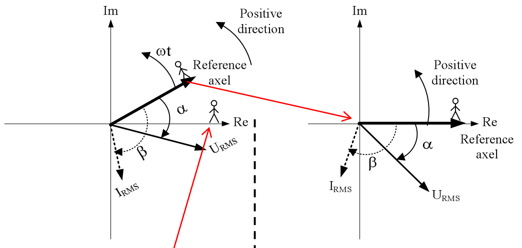
# Alternating Current (AC)




$$u(t) = U_{peak}\cos(\omega t - \alpha)$$
$$i(t) = I_{peak}\cos(\omega t - \beta)$$
$$\omega = 2\pi f$$

Express the sinusoidal voltage and current as complex rotating phasors and use RMS values for the amplitude

$$u(t) = \sqrt{2}\,\mathrm{Re}\{U_{RMS}e^{j(\omega t-\alpha)}\} \Rightarrow$$
$$u(t) = \sqrt{2}\,\mathrm{Re}\{\underbrace{U_{RMS}e^{j(-\alpha)}}_{\underline{U}}e^{j\omega t}\}$$
$$i(t) = \sqrt{2}\,\mathrm{Re}\{I_{RMS}e^{j(\omega t-\beta)}\} \Rightarrow$$
$$i(t) = \sqrt{2}\,\mathrm{Re}\{\underbrace{I_{RMS}e^{j(-\beta)}}_{\underline{I}}e^{j\omega t}\}$$

Since all phasors are rotating with the same speed, we select one as the reference and observe all others relative to this one. This gives that the rotation disappears and the voltage and currents can be expressed as complex number (constant)

$$\underline{U} = U_{RMS}\angle\alpha$$
$$\underline{I} = I_{RMS}\angle\beta$$

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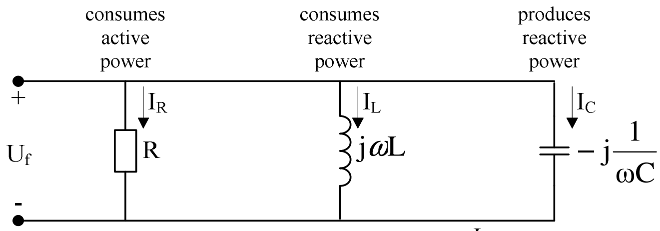
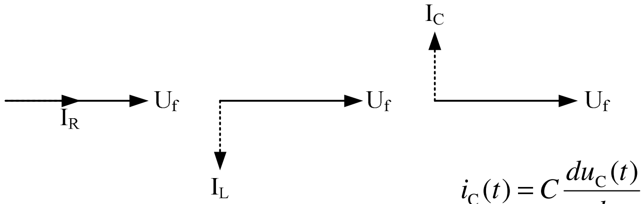
# Impedance




$$u_R(t) = Ri_R(t)$$
$$\underline{U}_R = R\underline{I}_R$$

$$u_L(t) = L\frac{di_L(t)}{dt}$$
$$\underline{U}_L = j\omega L\underline{I}_L = jX_L\underline{I}_L$$
$$X_L = \omega L$$

$$i_C(t) = C\frac{du_C(t)}{dt}$$
$$\underline{U}_C = -j\frac{1}{\omega C}\underline{I}_C = -jX_C\underline{I}_L$$
$$X_C = \frac{1}{\omega C}$$

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## Reactive power (Q) flow – What is reactive power?

A mathematical description of the phase shift between voltage and current

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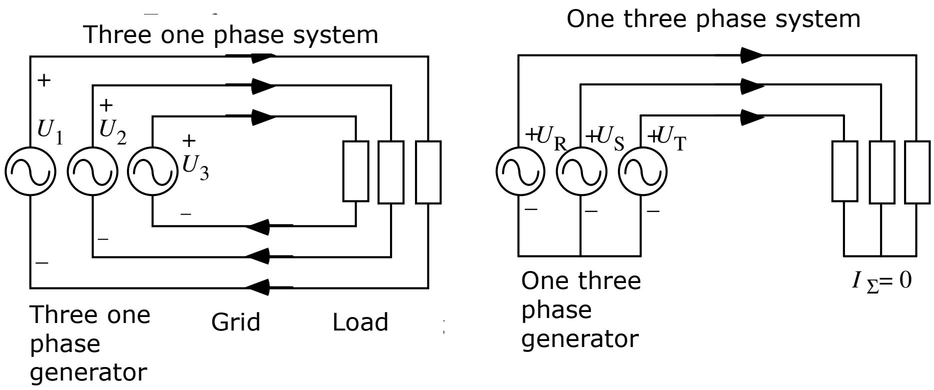
## Reactive power (Q) flow – Why care?

Due to the presence of the reactive power, the system cannot be used up to its thermal limit and its voltage variation limits

*Need for reactive power compensation for better utilization of the system*

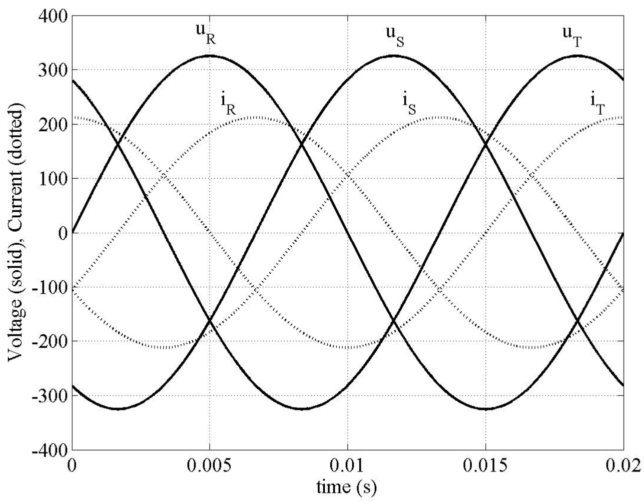
# Why three phase system?




The lowest number of phases that could create a rotating electric field



# Three phase voltage and current



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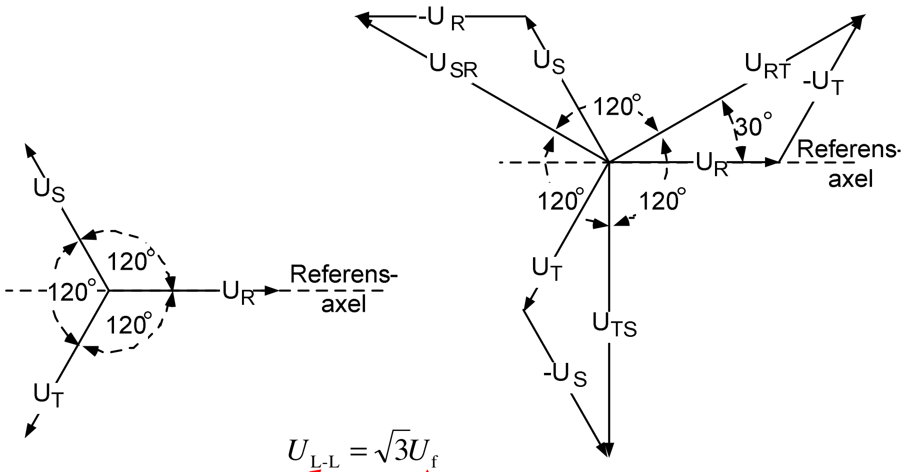
# Line-to-line phasors for the voltages




$$U_{\text{L-L}} = \sqrt{3} U_{\text{f}}$$

Line to Line — Phase (to ground)

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# Power – Rate of energy flow [W]

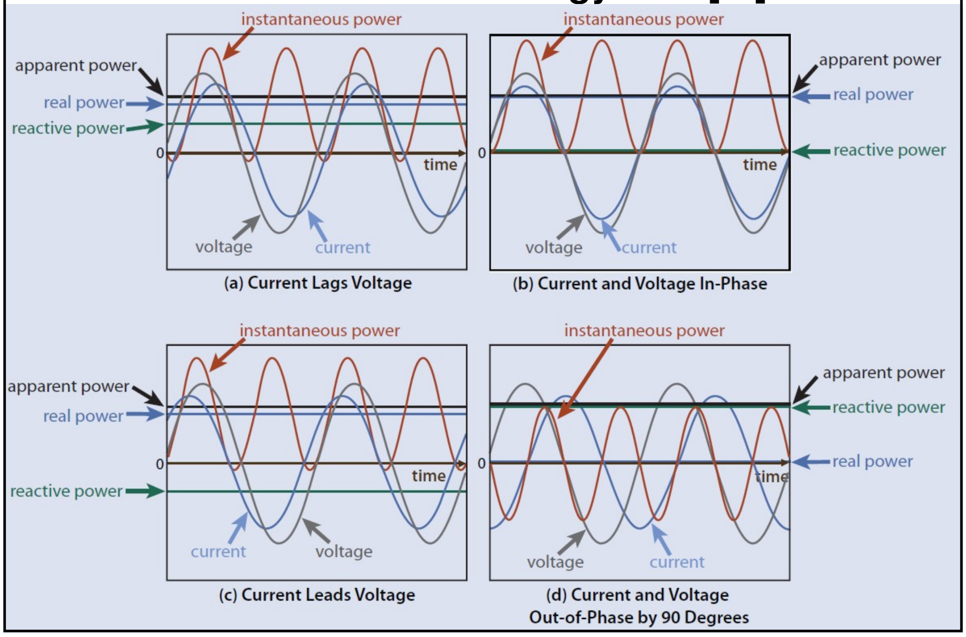
$$u(t) = \sqrt{2} U_{RMS} \cos(\omega t)$$
$$i(t) = \sqrt{2} I_{RMS} \cos(\omega t - \varphi)$$

Angle between voltage and current

$$\varphi = \beta - \alpha$$

| Single phase | Three phase |
|---|---|
| $p(t) = u(t) i(t) dt$ ← Instantaneous power → | $p(t) = u_R(t) i_R(t) + u_S(t) i_S(t) + u_T(t) i_T(t)$ |
| $P = \frac{1}{T}\int_0^T u(t) i(t) dt$ ← average → | $P = \frac{1}{T}\int_0^T \{u_R(t) i_R(t) + u_S(t) i_S(t) + u_T(t) i_T(t)\} dt$ |
| Apparent power $S = \underline{U}_{RMS} \underline{I}_{RMS}^* = P + jQ$ [VA] | $S = 3\underline{U}_{RMS} \underline{I}_{RMS}^* = \sqrt{3} \underline{U}_{L-L,RMS} \underline{I}_{RMS}^* = P + jQ$ |
| Active power $P = \lvert\underline{U}_{RMS}\rvert \lvert\underline{I}_{RMS}\rvert \cos\varphi$ [W] | $P = 3\lvert\underline{U}_{RMS}\rvert \lvert\underline{I}_{RMS}\rvert \cos\varphi = \sqrt{3}\lvert\underline{U}_{L-L,RMS}\rvert \lvert\underline{I}_{RMS}\rvert \cos\varphi$ |
| Reactive power $Q = \lvert\underline{U}_{RMS}\rvert \lvert\underline{I}_{RMS}\rvert \sin\varphi$ [VAr] | $Q = 3\lvert\underline{U}_{RMS}\rvert \lvert\underline{I}_{RMS}\rvert \sin\varphi = \sqrt{3}\lvert\underline{U}_{L-L,RMS}\rvert \lvert\underline{I}_{RMS}\rvert \sin\varphi$ |

# Power – Rate of energy flow [W]

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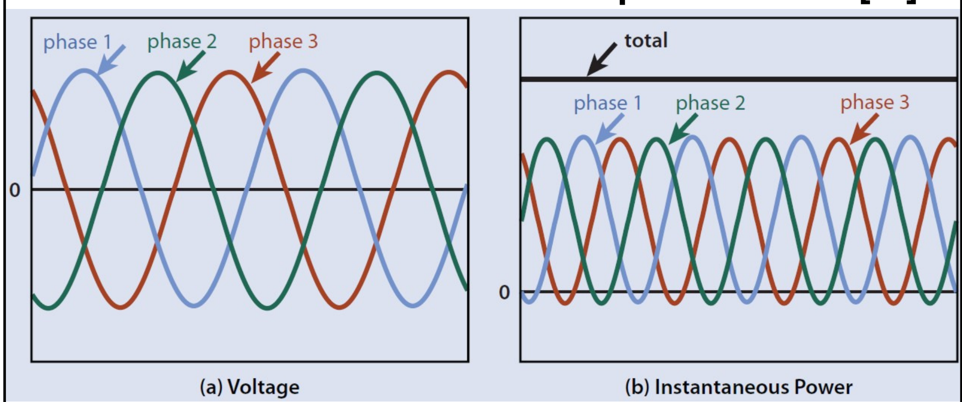
# Power – Rate of energy flow [W]

## 3-phase Power [W]



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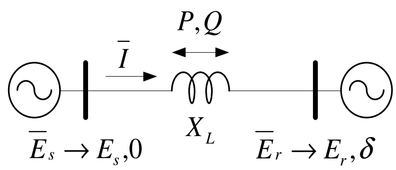
## Power flow




| Active/reactive power at sending end $E_s$ | Active/reactive power at receiving end $E_r$ |
|---|---|
| $P_s = \text{real}\left(\bar{E}_s \bar{I}^*\right) = E_s I_p = \dfrac{E_s E_r \sin\delta}{X_L}$ | $P_r = \text{real}\left(\bar{E}_r \bar{I}^*\right) = \dfrac{E_r E_s \sin\delta}{X_L}$ |
| $Q_s = \text{imag}\left(\bar{E}_s \bar{I}^*\right) = E_s I_q = \dfrac{E_s (E_s - E_r \cos\delta)}{X_L}$ | $Q_r = \text{imag}\left(\bar{E}_r \bar{I}^*\right) = -\dfrac{E_r (E_r - E_s \cos\delta)}{X_L}$ |

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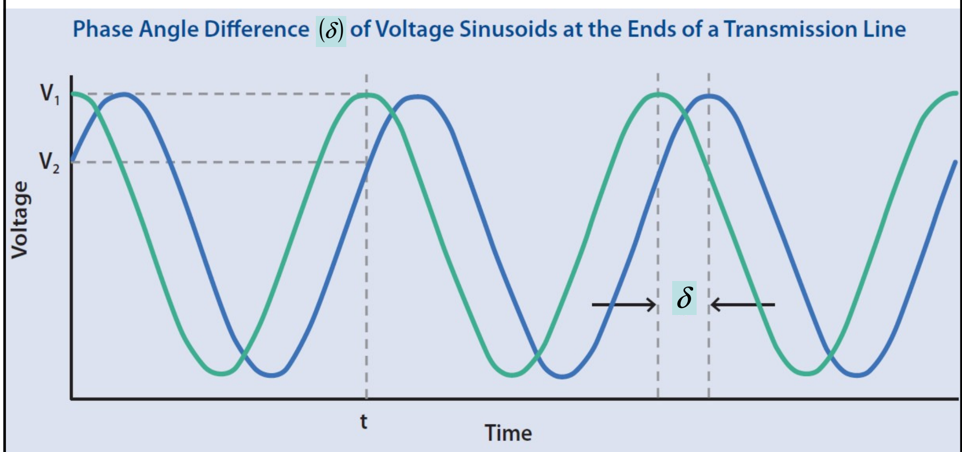
## Voltages at the ends of a transmission line (same phase)




s = 1 (sending end)
r = 2 (receiving end)

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s = 1 (sending end)
r = 2 (receiving end)

# Power flow

$$\bar{I} = \frac{\bar{E}_1 - \bar{E}_2}{jX} = \frac{E_1 \sin\delta}{X} + \mathrm{j}\frac{E_2 - E_1\cos\delta}{X} = I_{p2} - \mathrm{j}I_{q2}$$

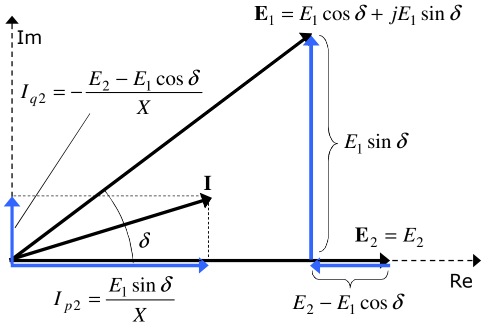
Complex power to $E_2$:

$$\bar{S}_2 = \bar{E}_2 \bar{I}^* = E_2(I_{p2} + \mathrm{j}I_{q2}) = P_2 + \mathrm{j}Q_2$$

Active/reactive power to $E_2$:

$$P_2 = E_2 I_{p2} = \frac{E_2 E_1 \sin\delta}{X}$$

$$Q_2 = E_2 I_{q2} = -\frac{E_2(E_2 - E_1\cos\delta)}{X}$$




Active power from $E_1$ to $E_2$ :

$$P = P_1 = P_2 = \frac{E_2 E_1 \sin\delta}{X}$$

Reactive power consumption of the transmission line:

$$\Delta Q = Q_1 - Q_2 = \frac{1}{X}\left(E_1^2 + E_2^2 - 2E_1E_2\cos\delta\right) = \frac{E_L^2}{X}$$

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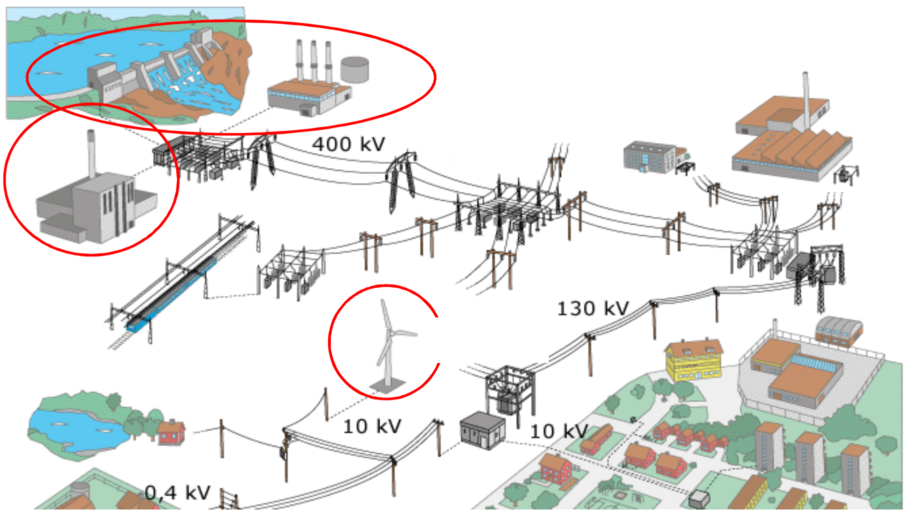
# Structure of the Electric Power System



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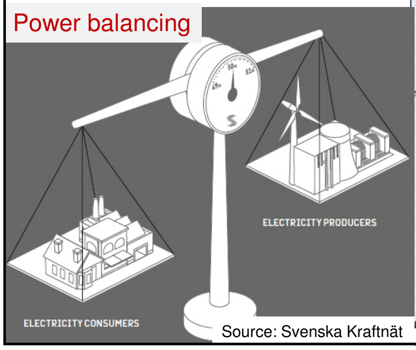
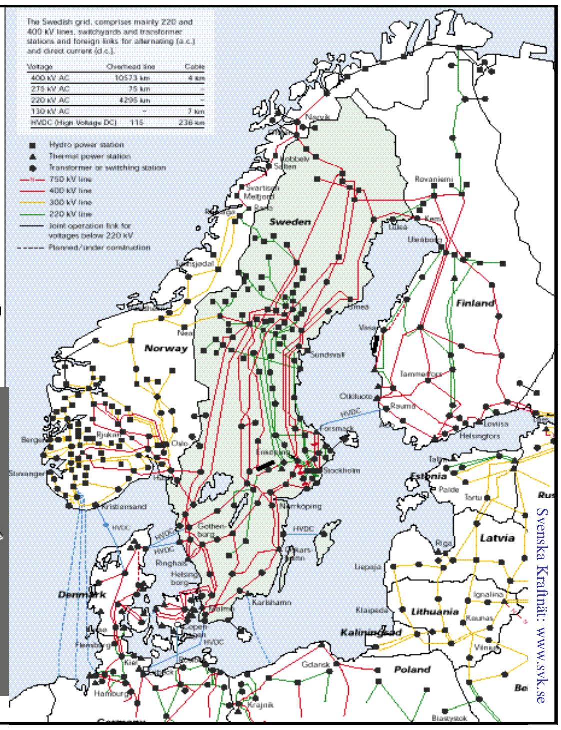
- Transmission 400, 220 kV
- Regional 130 kV
- Distribution *70*, 40, 30, 20,10 kV
- Local 400 V (Industry 10-130 kV)

Power balancing




Source: Svenska Kraftnät




Svenska Kraftnät: www.svk.se

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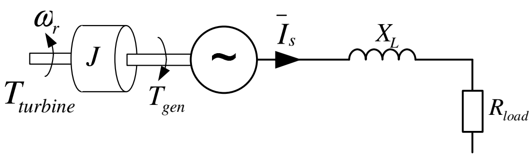
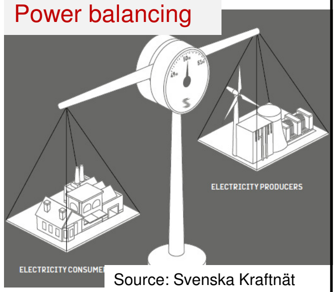
# What happens if the turbine power does not match the load power?



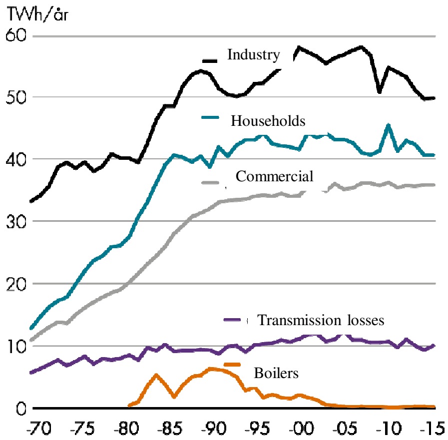

Power balancing




Source: Svenska Kraftnät

$$\left.\begin{aligned} J\frac{d\omega_r}{dt} &= T_{turbine} - T_{gen} \\ P_{turbine} &= \omega_r T_{turbine} \\ P_{gen} &= \omega_r T_{gen} \\ P_{load} &\approx P_{gen} \\ \omega_r &= \frac{2\pi f_{grid}}{n_p} \end{aligned}\right\} \Rightarrow J\frac{4\pi^2}{n_p^2}\frac{df_{grid}}{dt} = \frac{P_{turbine} - P_{gen}}{f_{grid}}$$

# Electric energy consumption in Sweden divided on different consumers 1970–2015




Källa: SCB

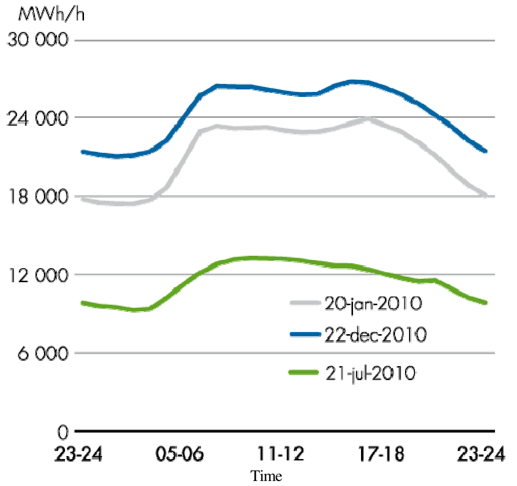
Elåret 2015



# Profile over the electric energy consumption in Sweden for a typical summer day, winter day and the highest consumption day 22th of December 2010

**On the 23rd of February 2011 Sweden used**
**26 000 MW**
**between 08-09**

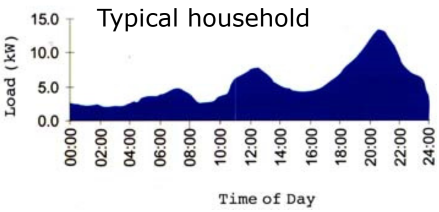
The consumption is higher in winter time in the Nordic countries, but in warm countries it is opposite




Källa: Svenska Kraftnät och Svensk Energi

Elåret 2010

# Electric energy consumption for households in Sweden (investigated 2007)

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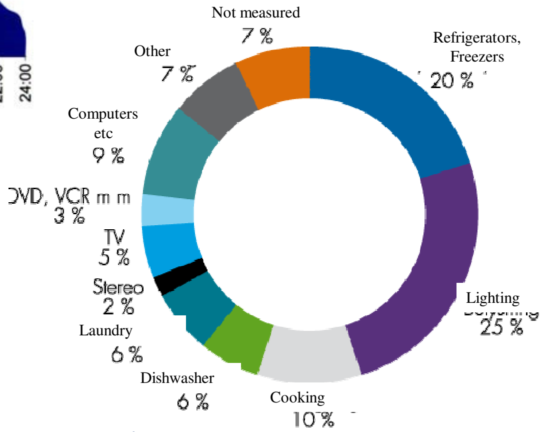


Elåret 2010

Källa: Energimyndigheten

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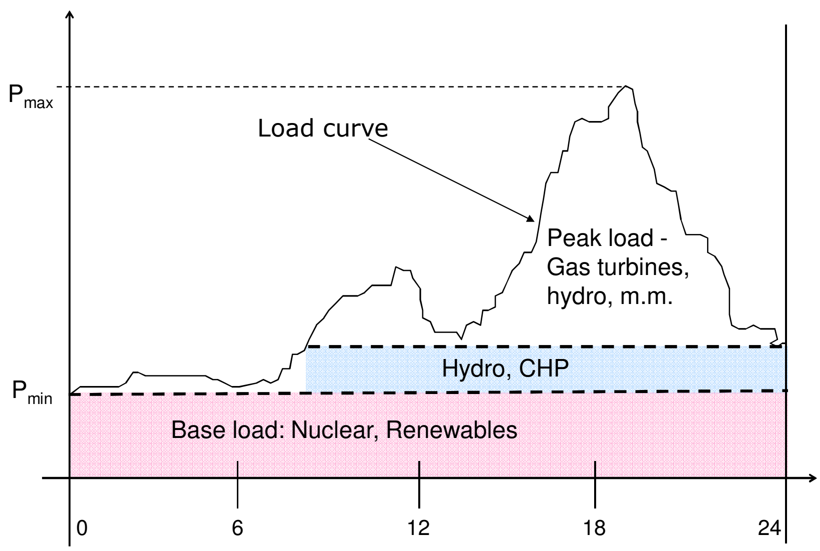
# Production planing



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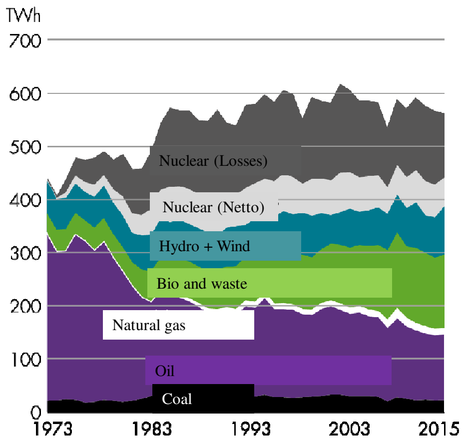
# Total input energy to Sweden 1973–2015




Källa: SCB



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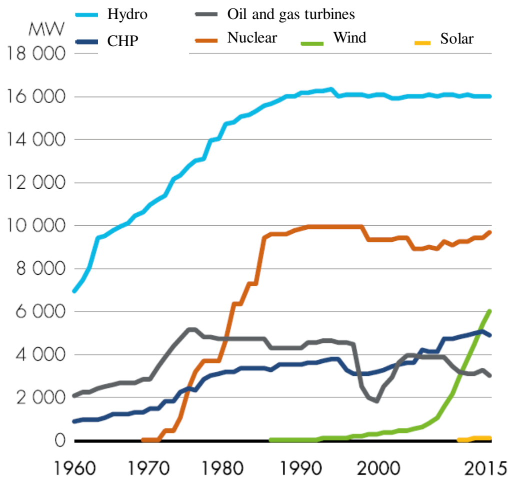
# Installed peak power in Sweden, MWel




Source: *Svensk Energi*

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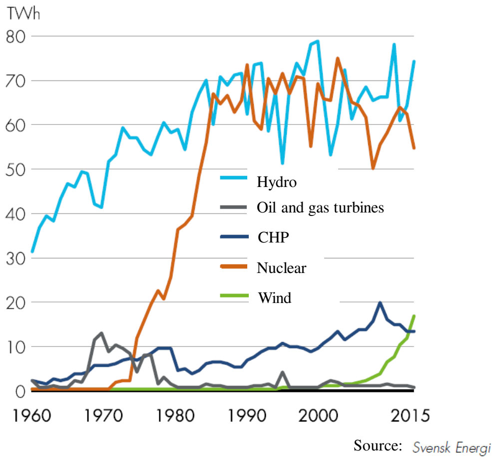
## Electricity production in Sweden, TWh$_{el}$

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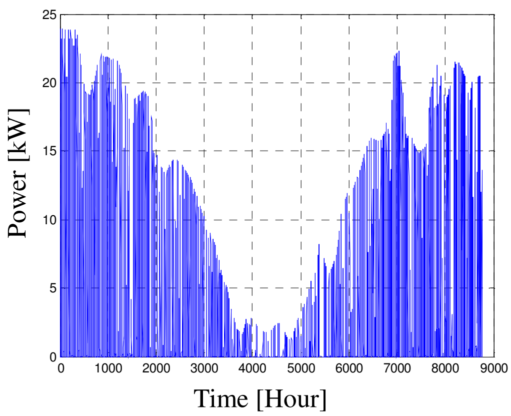
## Solar Plant

<u>Göteborg</u>
Latitude 57.7 °
200 m$^2$ of solar cells
Statistical cloudiness
Sun tracking

*<u>Efficiency</u>*:

| | |
|---|---|
| MPP | 0.95 |
| Power electronics | 0.95 |
| Solar cells | 0.15 |




Integrated power during 1 year
**24 000 kWh**

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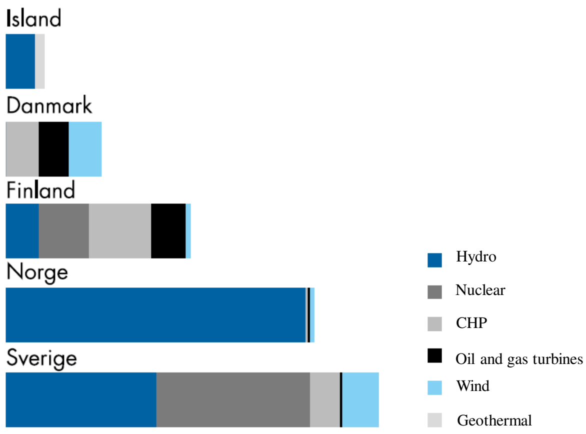
# Normalized electric production mix for the Nordic countries




Source: *Svensk Energi*

Elåret 2013

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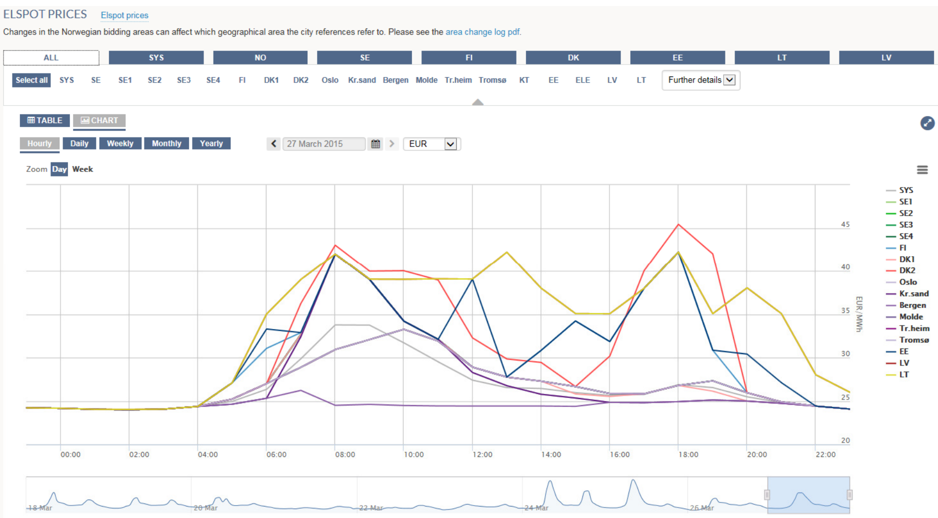
# Spot market price for 2015-03-27



# The End

*Do you have any questions?*