THE ELECTRICAL POWER SYSTEM

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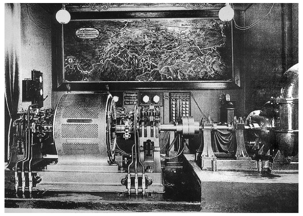
History of the power systems

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



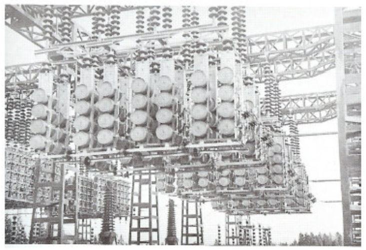
170 kW transferred 175 km from Lauffen hydropower station to the exhibition area at 13000-14700 V

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

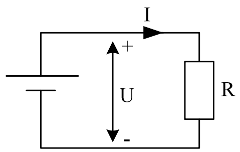
First 400 kV system Harsprånget Hallsberg 1952

Series compensation introduced 1954

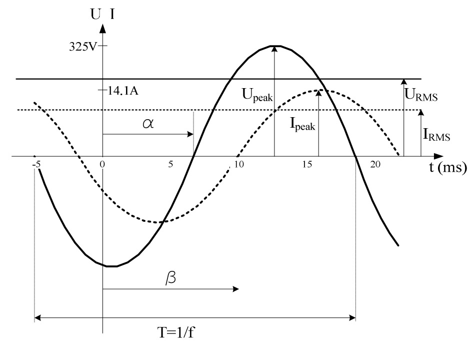


Fundamentals of Electric Power

- 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



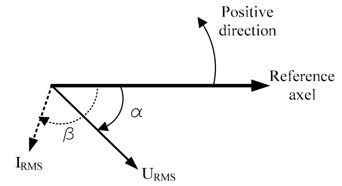
Direct Current (DC) / Alternating Current (AC)



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

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

$$\omega = 2\pi f$$



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

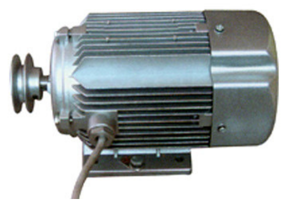
$$\underline{U} = U_{RMS} \angle \alpha$$

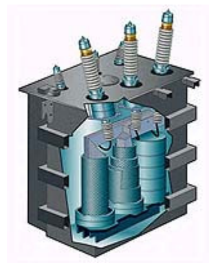
$$\underline{I} = I_{RMS} \angle \beta$$

Why is AC used?

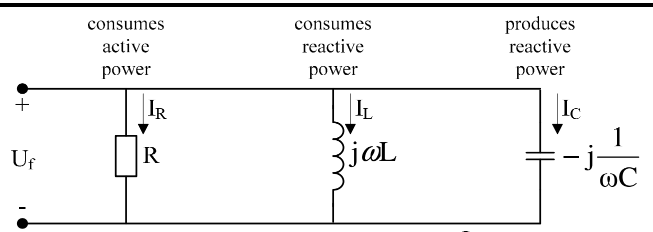
The two main factors that formed the power system

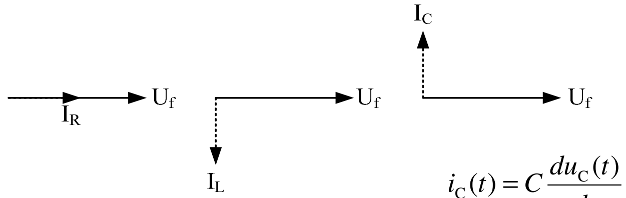
- Transformer (only works on AC)
- Robust and cheep motor (rotating flux)





Impedance





$$u_R(t) = R i_R(t)$$

$$\underline{U}_R = R \underline{I}_R$$

$$u_L(t) = L \frac{di_L(t)}{dt}$$

$$\underline{U}_L = j\omega L \underline{I}_L = jX_L \underline{I}_L$$

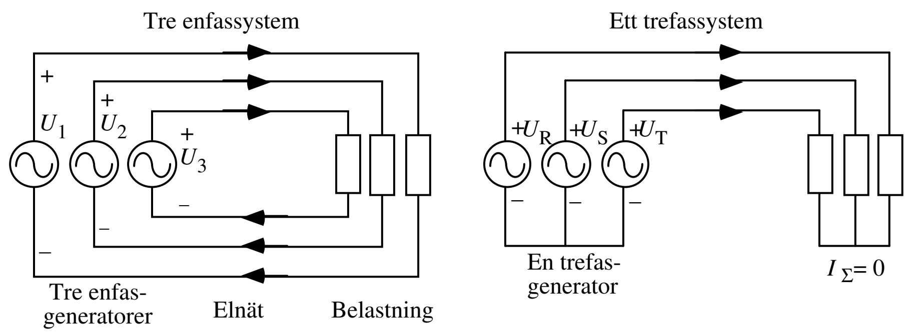
$$X_L = \omega L$$

$$i_C(t) = C \frac{du_C(t)}{dt}$$

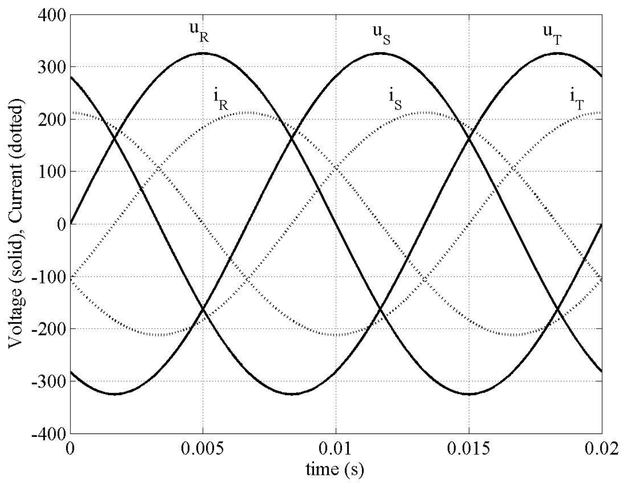
$$\underline{U}_C = -j\frac{1}{\omega C}\underline{I}_C = -jX_C \underline{I}_L$$

$$X_C = \frac{1}{\omega C}$$

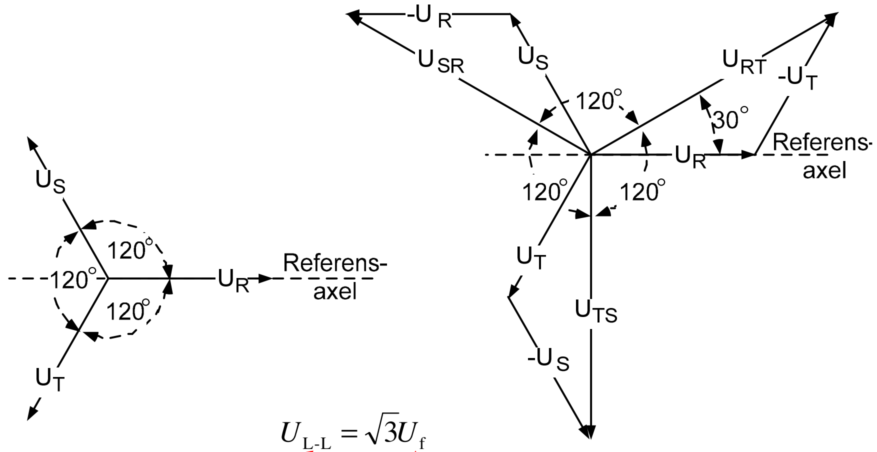
Why three phase system?



Three phase voltage and current



Phasors for the voltages



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

Line to Line

Phase (to ground)

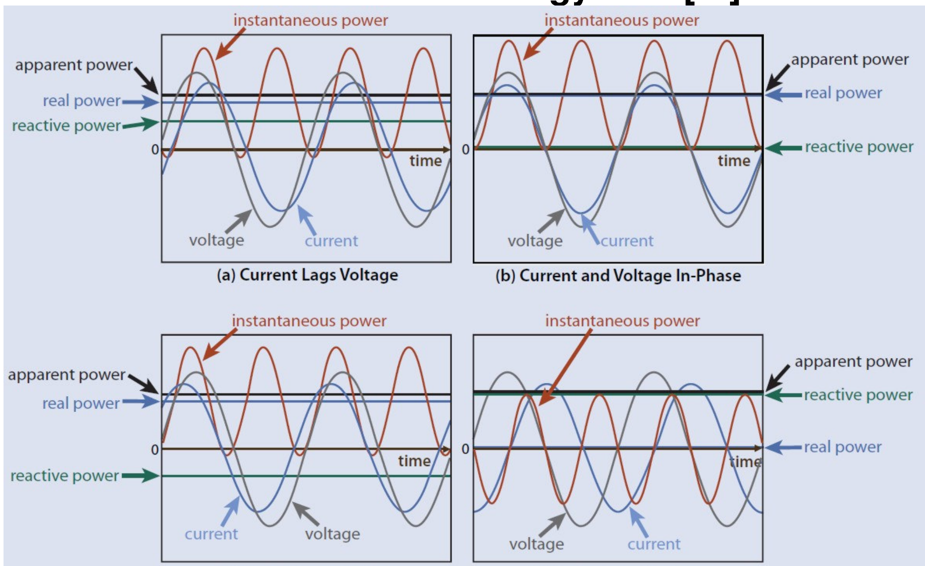
Power – Rate of energy flow [W]

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

Angle between voltage and current
$$\varphi = \alpha - \beta$$

Single phase	Three phase
$p(t) = u(t)i(t)dt$ $P = \frac{1}{T}\int_0^T u(t)i(t)dt$	$p(t) = u_R(t)i_R(t) + u_S(t)i_S(t) + u_T(t)i_T(t)$ $P = \frac{1}{T}\int_0^T \{u_R(t)i_R(t) + u_S(t)i_S(t) + u_T(t)i_T(t)\}dt$
$S = \underline{U}\,\underline{I}^* = P + jQ$ $P = \lvert U_{RMS}\rvert\lvert I_{RMS}\rvert\cos\varphi$ $Q = \lvert U_{RMS}\rvert\lvert I_{RMS}\rvert\sin\varphi$	$S = 3\underline{U}\,\underline{I}^* = \sqrt{3}\underline{U}_{L-L}\underline{I}^* = P + jQ$ $P = 3\lvert U_{RMS}\rvert\lvert I_{RMS}\rvert\cos\varphi = \sqrt{3}\lvert U_{L-L,RMS}\rvert\lvert I_{RMS}\rvert\cos\varphi$ $Q = 3\lvert U_{RMS}\rvert\lvert I_{RMS}\rvert\sin\varphi = \sqrt{3}\lvert U_{L-L,RMS}\rvert\lvert I_{RMS}\rvert\sin\varphi$

Power – Rate of energy flow [W]



(a) Current Lags Voltage

(b) Current and Voltage In-Phase

(c) Current Leads Voltage

(d) Current and Voltage Out-of-Phase by 90 Degrees

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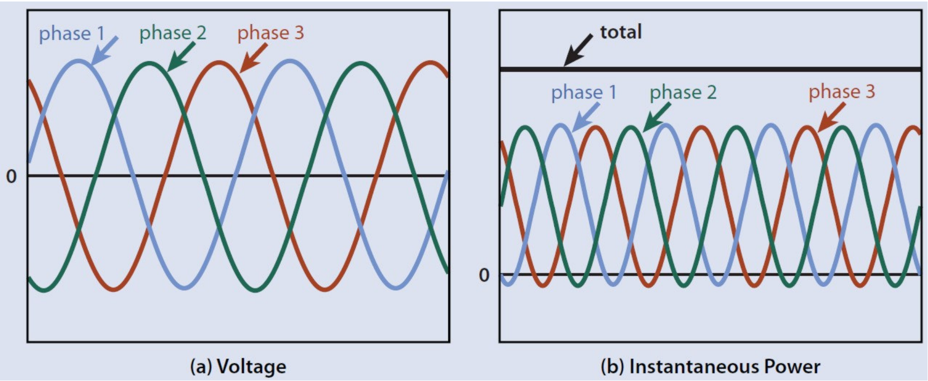
Power – Rate of energy flow [W]

3-phase Power [W]



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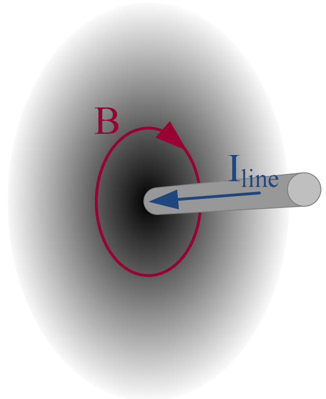
Reactive power flow – What is reactive power?

Consider an alternating current I_{line} flowing in a line

- The current causes a magnetic field around the conductor
- The field strength is highest close to the conductor surface
- The field energy density is proportional to the square of the field strenght
- The field is built up and eleminated with the double of the network frequency in each phase



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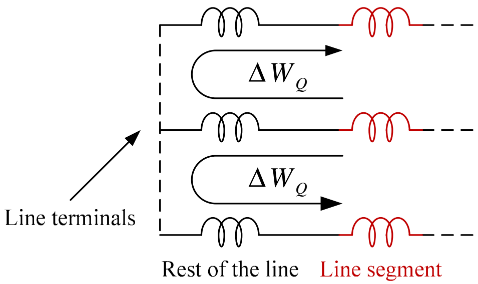
Reactive power flow – What is reactive power?

Consider a line segment of, for example, 100 km in a long transmission line



- The distance between the phases is about 10 m.
- It is not possible to transfer the energy directly between the neighboring phases.
- The energy must be transported to some place where the conductors are connected (a generator or a transformer).

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Reactive power flow – What is reactive power?

How much energy is involved?

Consider a line segment of 100 km and a current of 1 kA (rms value); the energy at the current peak is

$$W_Q = \frac{1}{2} L \hat{i}_{line}^2 = \frac{1}{2} 0.1 (1000\sqrt{2})^2 = 100kJ$$

It is the same energy needed to lift a 1500 kg car up to 7 meters.

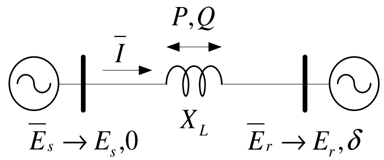
This is done each 10 ms, in each phase.

Reactive power flow – What is reactive power?

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

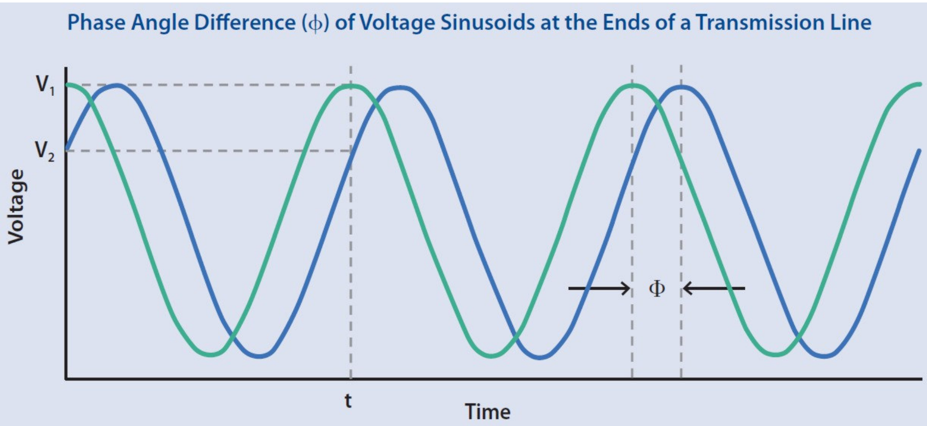
Need for reactive power compensation for better utilization of the system

Power flow



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

Voltages at the ends of a transmission line



s = 1
r = 2

Power flow

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

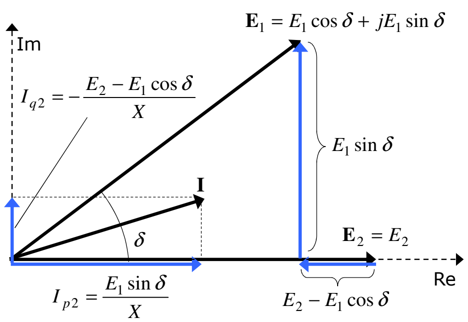
Complex power to E_2:

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

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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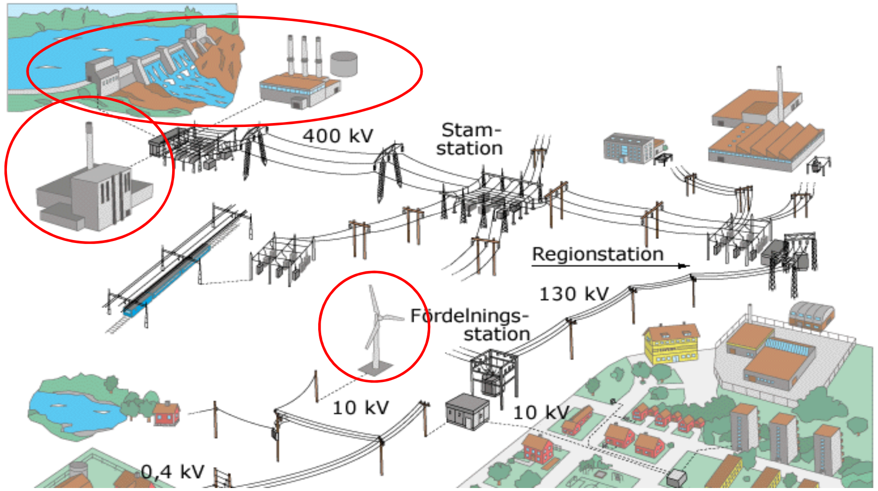
Structure of the Electric Power System



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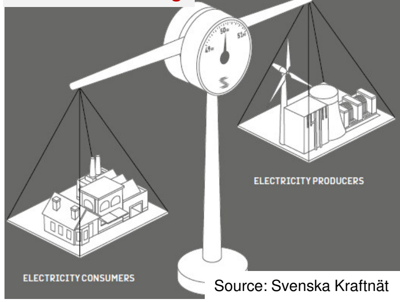
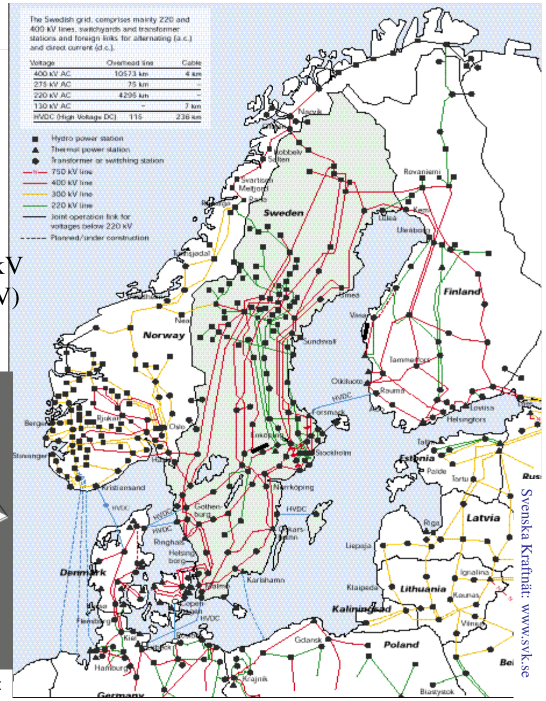
- Transmission 400, 220 kV
- Regionalnät 130 kV
- Distributionsnät *70*, 40, *30*, 20,10 kV
- Kunder 400 V (Industri 10-130 kV)

Power balancing



Source: Svenska Kraftnät



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Vattenkraft

Vatten trycker på från reservoiren

Generatorn omvandlar den mekaniska energin till elektrisk energi.

Ett spjäll ställer in vatten-flödet

Galler för att hindra skräp

Vattnets rörelseenergi omvandlas till mekanisk effekt på

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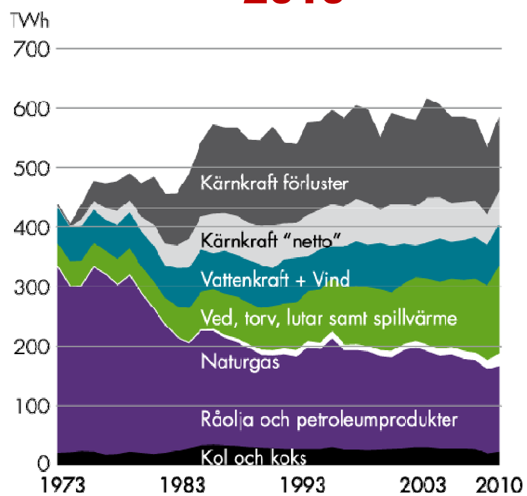
Total energitillförsel i Sverige 1973–2010



Källa: SCB

Elåret 2010

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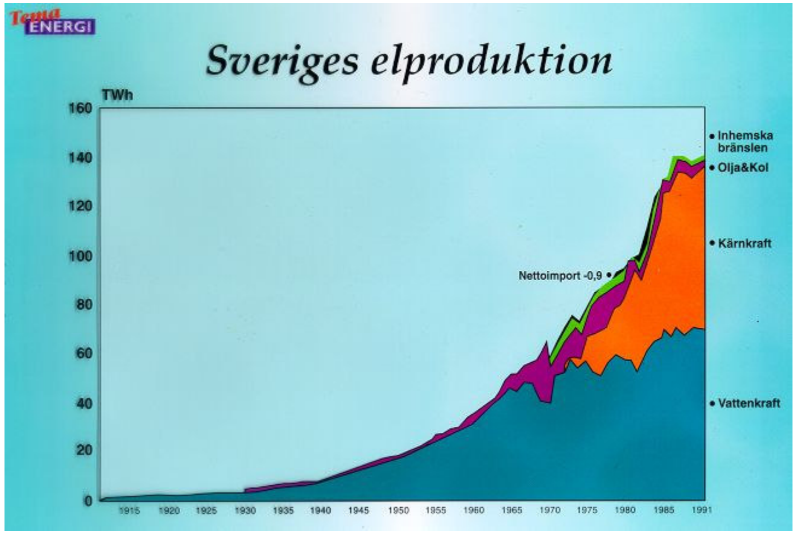

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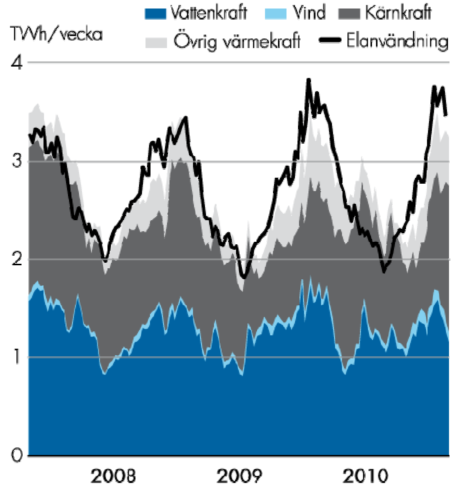
Elproduktion och elanvändning i Sverige under åren 2008–2010, TWh/vecka



Elåret 2010

Källa: Svensk Energi

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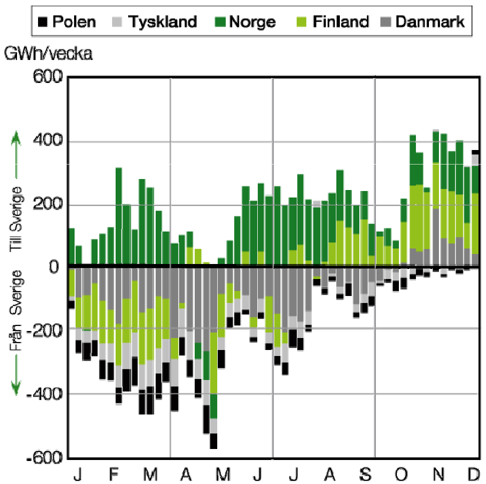
Nettoflöde av el per grannland till och från Sverige år 2008, GWh



Källa: Svenska Kraftnät och Svensk Energi

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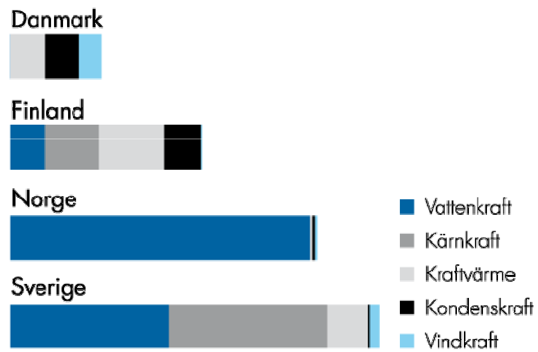
Normaliserad elproduktionsmix i Norden



Källa: Svensk Energi

Elåret 2010

Netto elproduktionen i Sverige uppgick till:

145,0 TWh år **2007** **(v 65,5; k 64,3)**

146,0 TWh år **2008** **(v 68,6; k 61,3; v 2,0)**

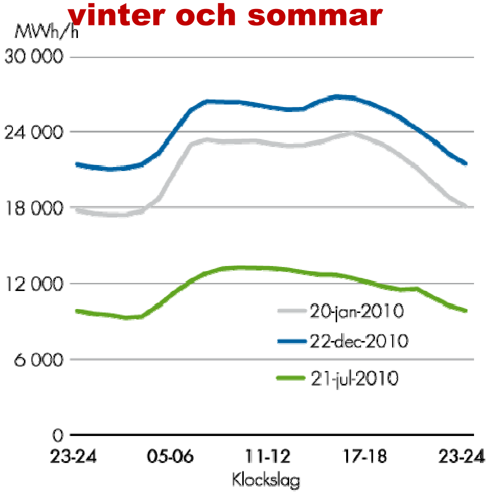
133,7 TWh år **2009** **(v 65,3; k 50,0; v 2,5)**

144,9 TWh år **2010** **(v 66,8; k 55,6; v 3,5)**

146,9 TWh år **2011** **(v 66,0; k 58,0; v 6,1)**

Profil över elförbrukning för dygn med högsta elförbrukning år 2010 (22 dec) respektive typdygn vinter och sommar

2011
23 februari
mellan kl.08-09
26 000 MW

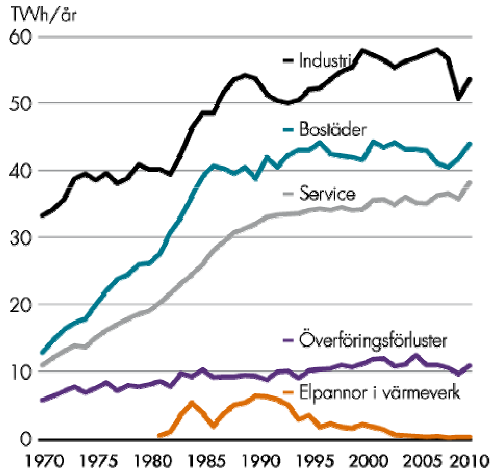


Källa: Svenska Kraftnät och Svensk Energi

Installerad effekt per den 2011.12.31, MWel

Vattenkraft	**16 197**
Vindkraft	**2 899**
Kärnkraft	**9 363**
Övrig värmekraft	**7 988**
∑	**36 447**

Elanvändningen fördelad på olika användare 1970–2010



Källa: SCB

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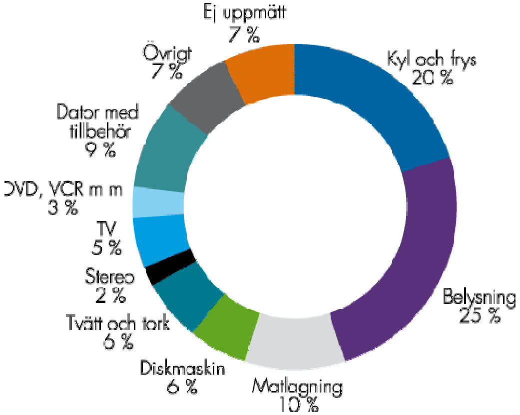
Relativ fördelning av hushållsel (undersökning år 2007)



Elåret 2010

Källa: Energimyndigheten

The End

Do you have any questions?