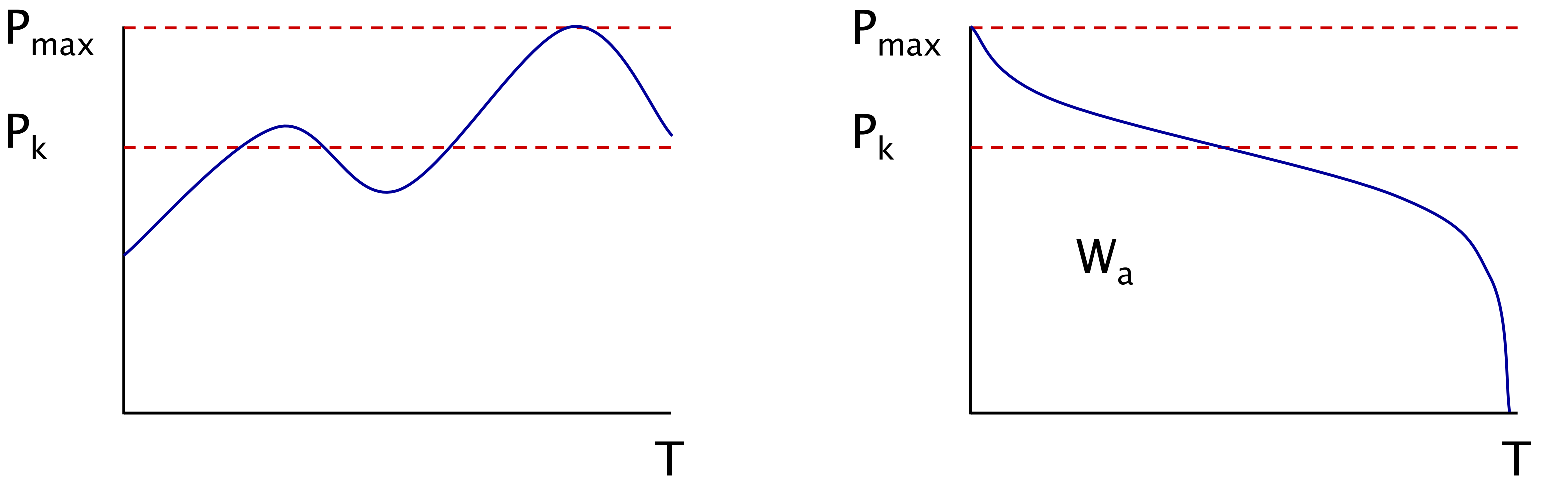
Introduction to hydrogen economy

Lecture 2

Power market & power generation

Matti Lehtonen

Load variation and load duration curve



Load duration curve is obtained by arranging the hourly demands in descending order

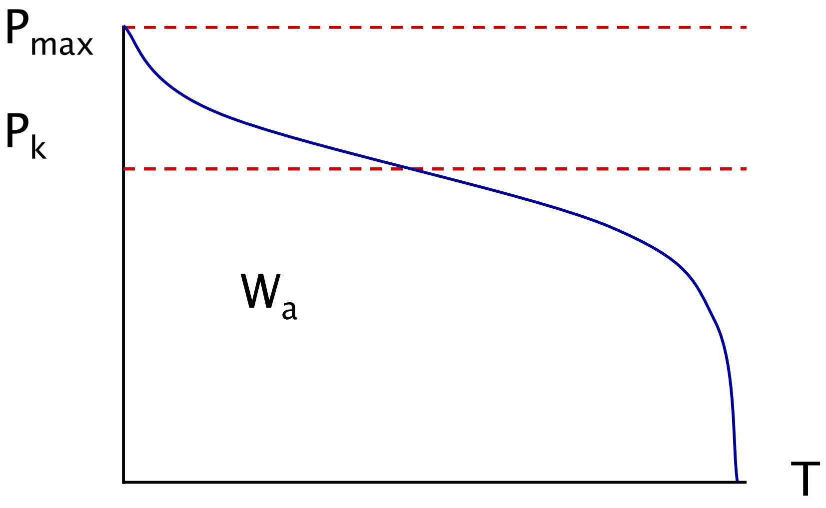
Load factor $$\varepsilon = \frac{P_k}{P_{max}}$$

Load duration time $$t_k = \frac{W_a}{P_{max}} = \frac{P_k T}{P_{max}} = \varepsilon T$$

W_a = annual energy
P_k = mean power
P_{max} = max power

Load factor is per unit load duration time

LOAD DURATION CURVE



P_{max} = max power
P_k = mean power
W_a = annual energy

Load duration time $$t_k = \frac{W_a}{P_{max}}$$

Sum of loads connected $$P_l = \sum_{i=1}^{n} P_i$$

Load factor $$\varepsilon = \frac{P_k}{P_{max}}$$

Diversity factor $$k = \frac{P_l}{P_{max}}$$

Coincidence factor $$c = \frac{P_{max}}{P_l}$$

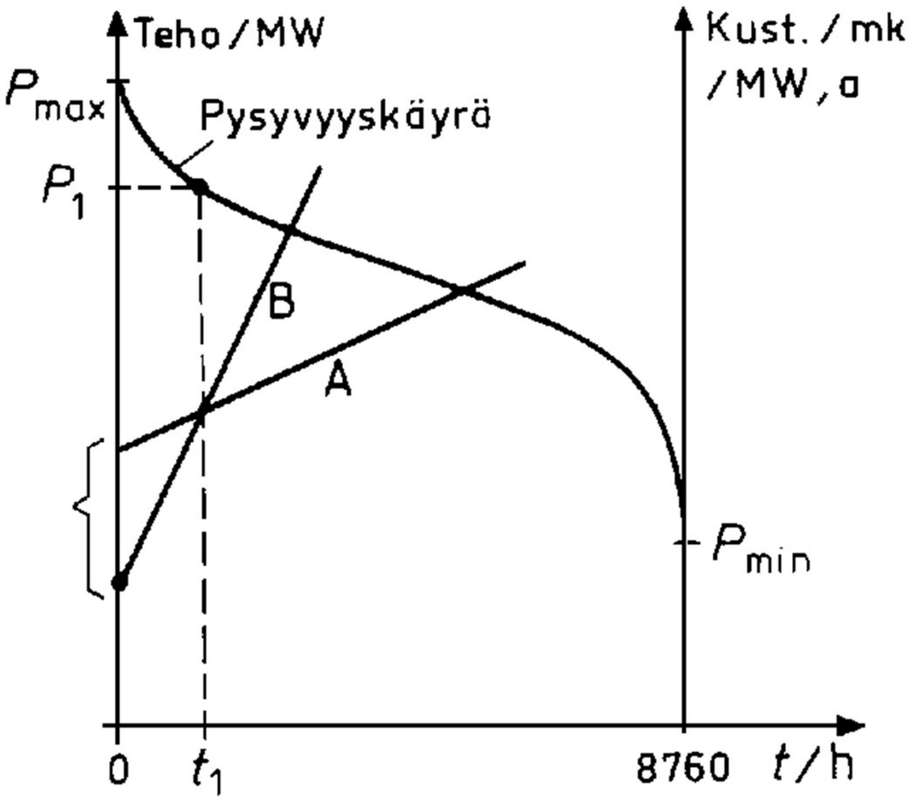
Coincidence factor = 1/Diversity factor

Power station properties & production costs

The unit costs of energy and the role of different generation units depends on:

- Timely variation of demand
- Available energy resources (water, fuels, etc.)
- Heat demand (CHP in district heating systems)
- Cost structure of the power plants

A case of two power plants illustrated by the load duration curve:
The lines A and B illustrate the total generation costs of two plants as a function of operation hours



The plant A has high investment costs but low marginal costs. Thus plant A is suitable for base generation, having operation hours more than t1 per year.

The plant B has low investment costs, but higher marginal operation costs. Thus B should be operated less than t1 per year.

The load duration curve gives the optimal sizes of the plants. At the time t1, the power demand is P1. This is the optimal rating for plant A. The size of plant B is then Pmax-P1.

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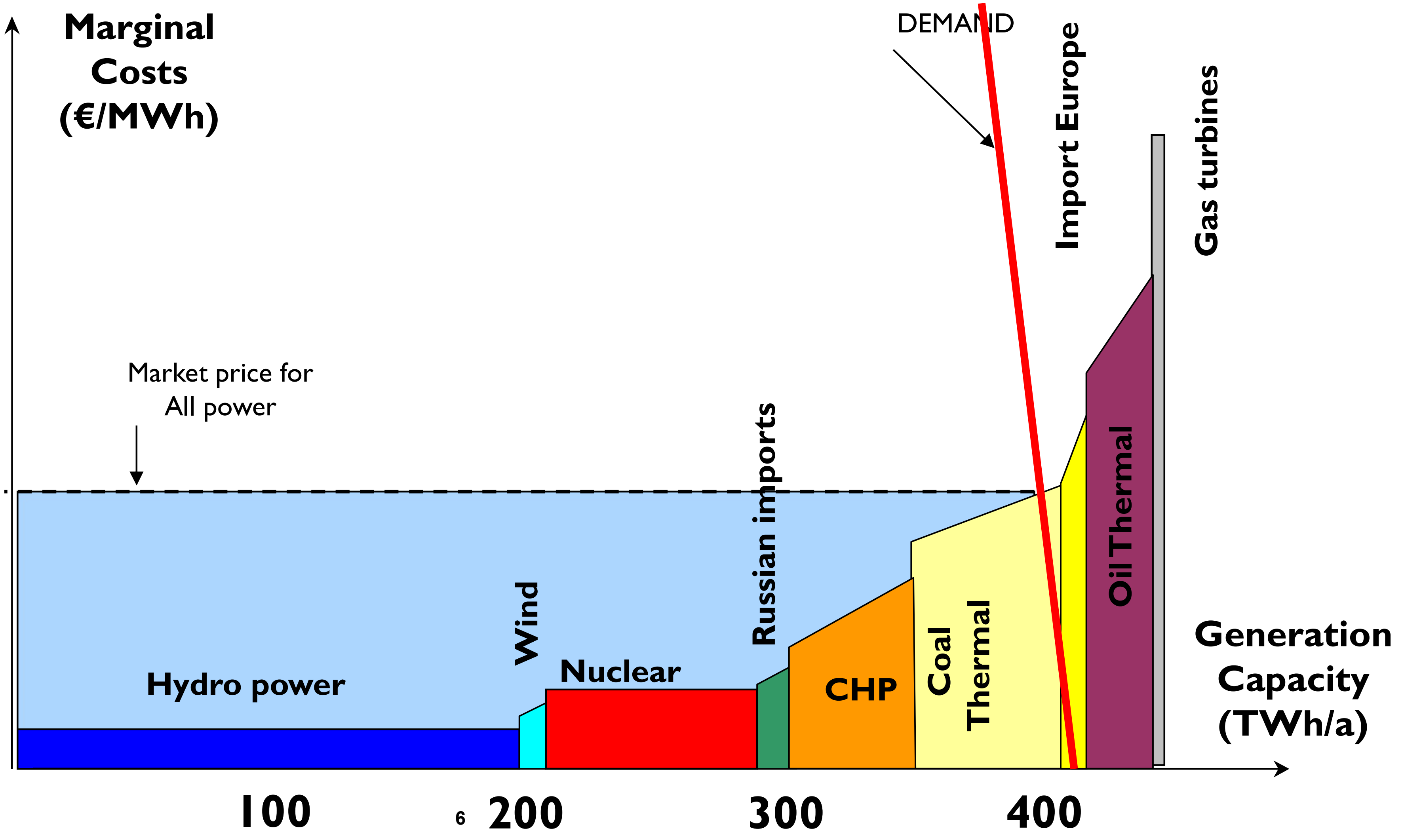
Price formation in day ahead electricity market Elspot

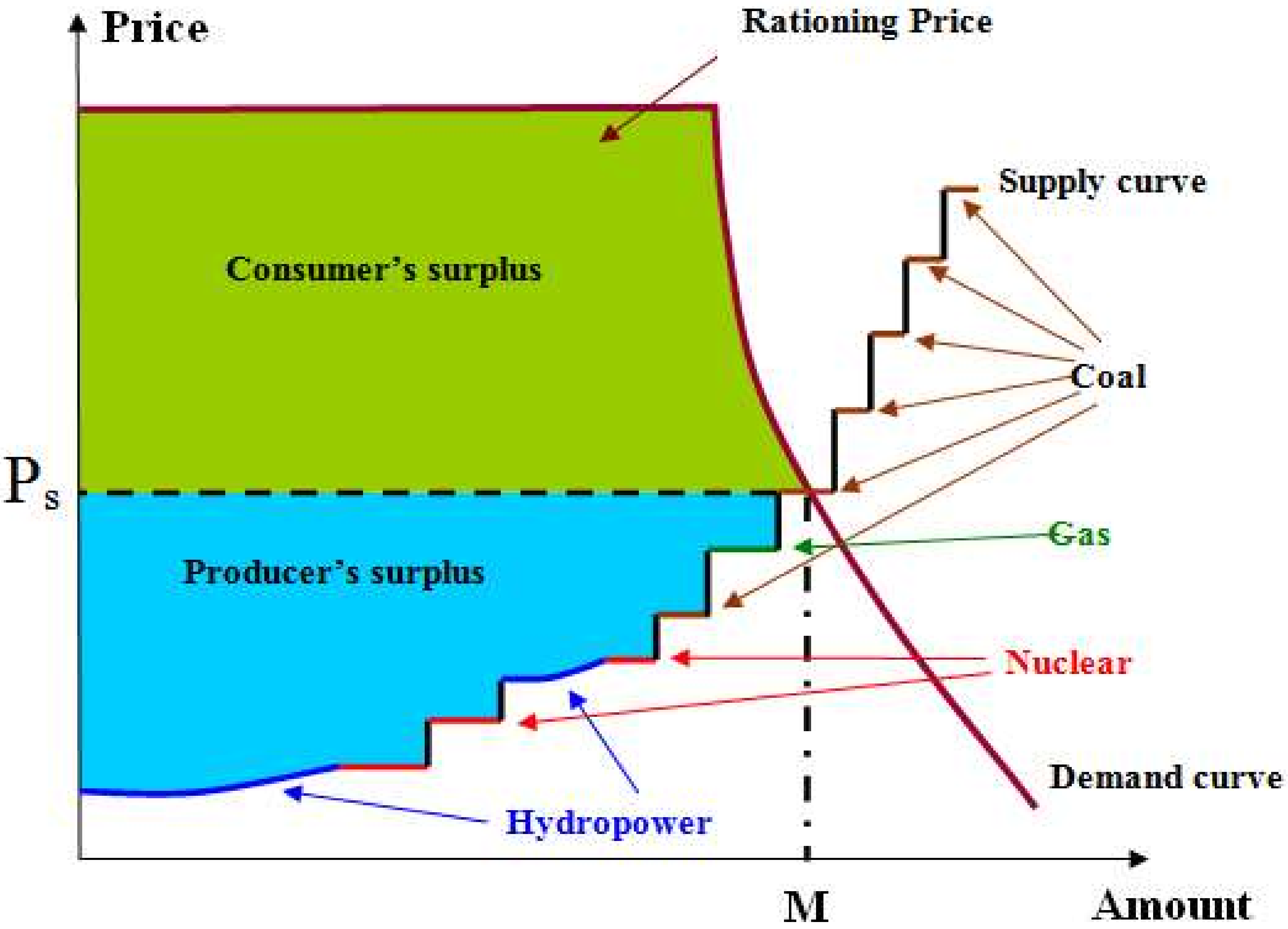
- In the following slides, the price formation of Nordic day ahead market is illustrated
- The generation offers are summed in the rising order of the prices, whereas the buying offers are summed in descending order.
- The intersection of the generation/buying curves defines the market price for all Elspot trade at the hour (5/2023 this will be 15 minutes period).
- The large variation of wind power will affect this intersection point and is expected to lead to strong price variations.

Day ahead price formation on Nordic markets



SOURCE: Federation of Finnish Technology industries

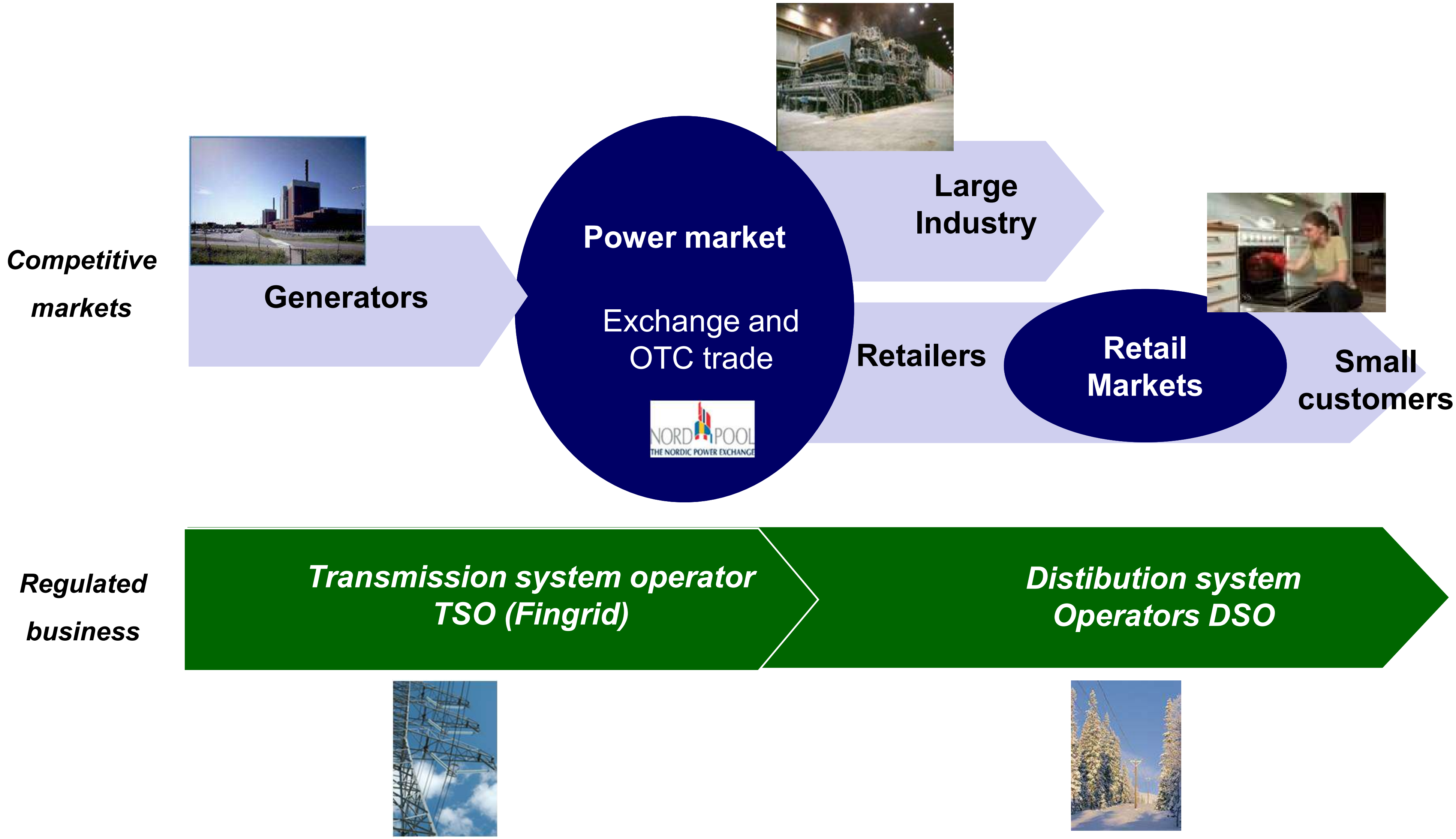
Price formation: Nord pool spot



Nordic transmission system

Nordel

Power market and power transmission



Competitive markets

Generators

Power market

Exchange and OTC trade

NORD POOL
THE NORDIC POWER EXCHANGE

Large Industry

Retailers

Retail Markets

Small customers

Regulated business

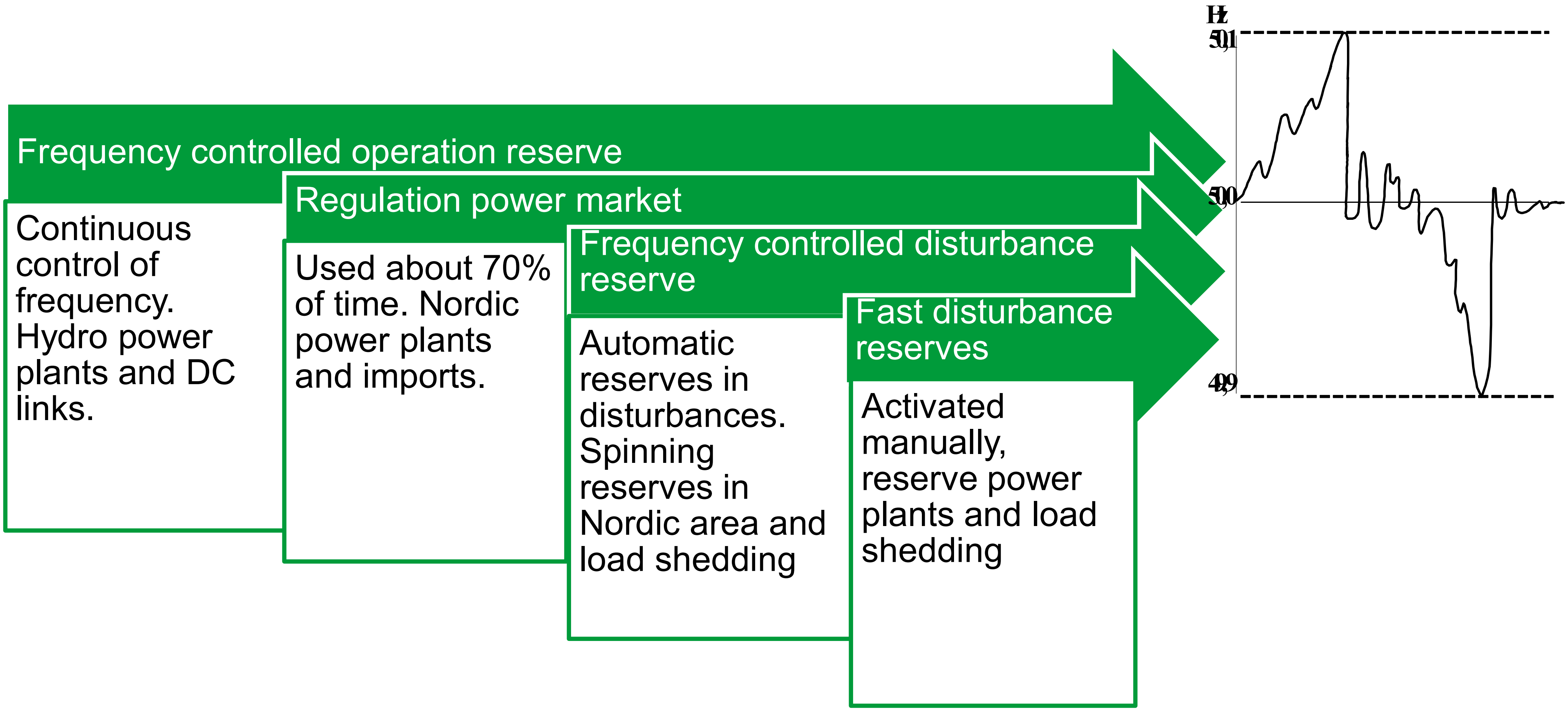
Transmission system operator TSO (Fingrid)

Distibution system Operators DSO

Deregulated versus regulated part of power system and markets

- Selling power in electricity exchange and in the retail markets is deregulated and under competition.
- Networks operated by Transmission system operator and Distribution system operators are regulated monopolies, supervised by the authorities
- TSO is also maintaining reserve markets, the purpose of which is to take case of power balance and power system security
- The technical operation of power markets is on TSO, but formation of day ahead price has been left on markets

Power balance management at the operation hour is done using power reserves and power regulation markets of TSO



Frequency controlled operation reserve

Continuous control of frequency. Hydro power plants and DC links.

Regulation power market

Used about 70% of time. Nordic power plants and imports.

Frequency controlled disturbance reserve

Automatic reserves in disturbances. Spinning reserves in Nordic area and load shedding

Fast disturbance reserves

Activated manually, reserve power plants and load shedding

Conventional steam plants

- In conventional steam plants the heat of fuel combustion is converter to mechanical energy and further electricity
- High pressure and high temperature steam produced in boiler is led to steam turbine where it expands and releases mechanical work
- The output steam of turbine is condensed back to water before it is circulated again in the boiler
- This condensing process still removes more than 50% of total energy and can be utilized it there is heat load.

POWER GENERATING STATIONS
conventional steam power plants

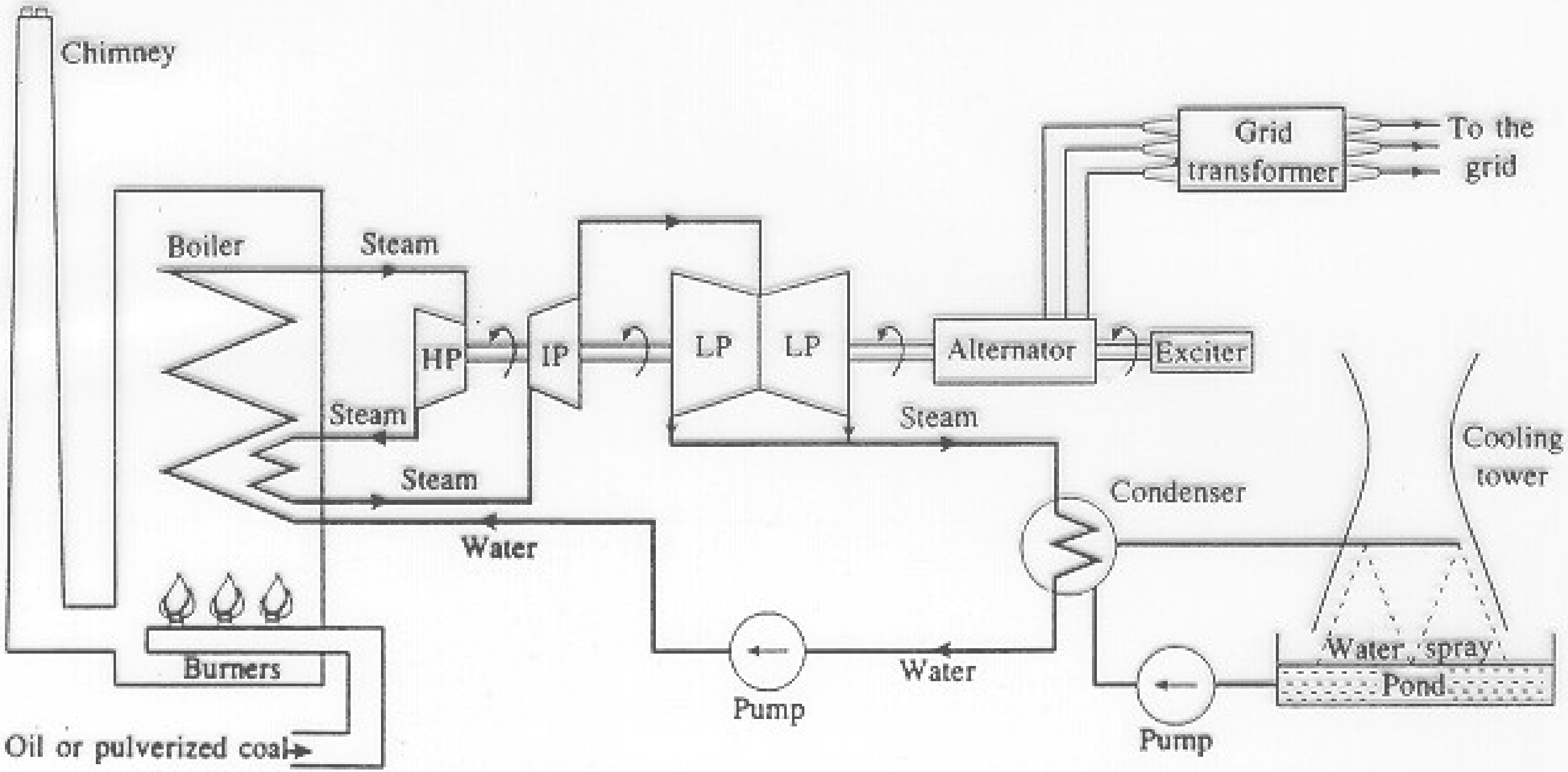


Figure 7.1 *Schematic diagram of a coal- or oil-burning power station. HP, IP and LP are the high-pressure, intermediate-pressure and low-pressure turbines respectively*

POWER GENERATING STATIONS

conventional steam power plants

Steam produced by coal, oil or peat

Efficiency at maximum about 40%

Base-load or intermediate generation

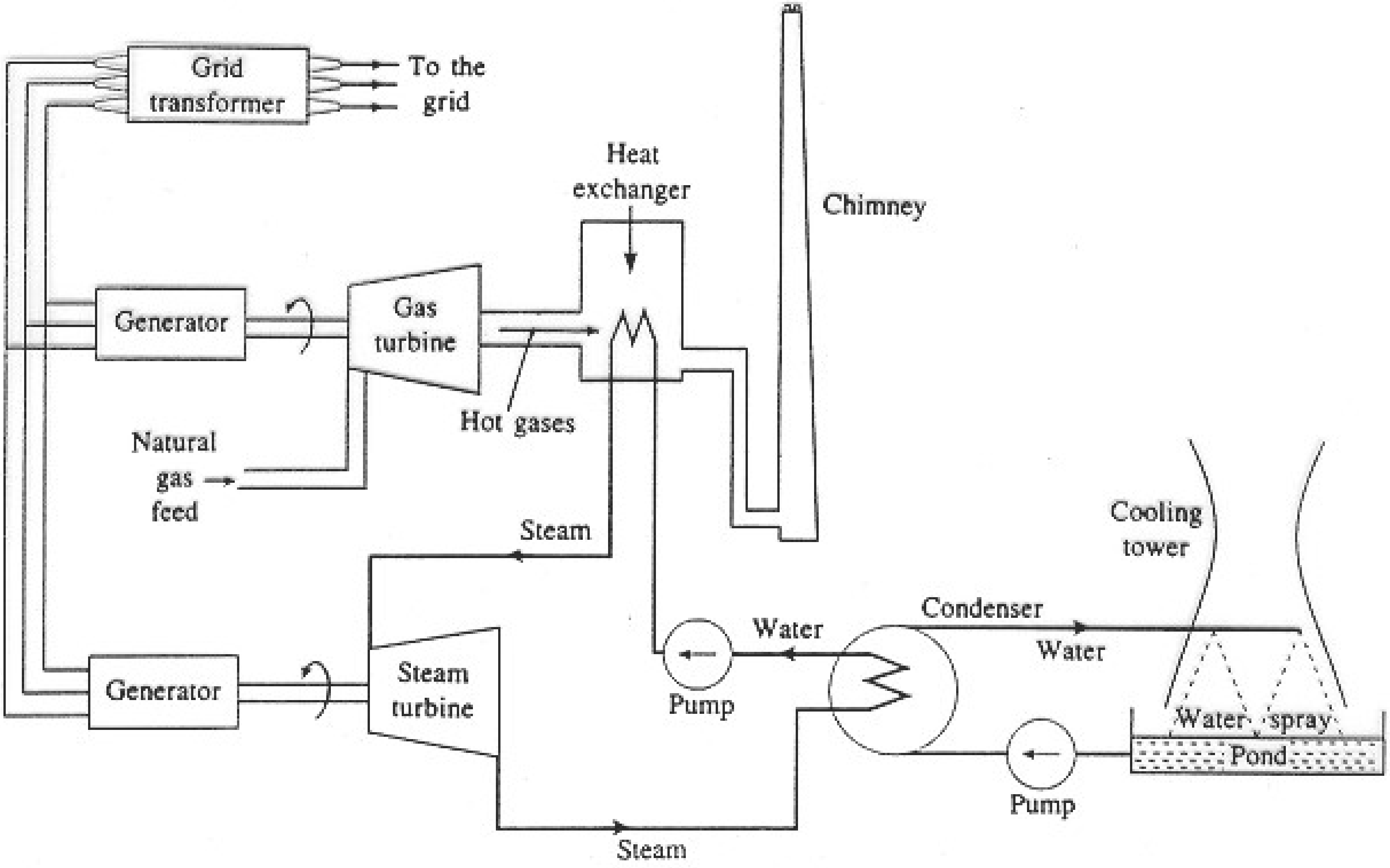
High environmental impact due to CO_2, SO_2 and NO_x

Efficiency increased if waste heat energy is used for district heating

$\Rightarrow$condenser replaced by heat exchanger

$\Rightarrow$"back-pressure power plant "

POWER GENERATING STATIONS
combined-cycle power stations



POWER GENERATING STATIONS
combined-cycle power stations

One generator driven by a gas turbine, one with steam

The exhaust heat of gas turbine is utilised in steam production

The emission of SO_2 and NOx better controlled than in conventional plants (gasification)

In back-pressure connection, thermal efficiency is very high; yield of electricity and heat about 50/50

POWER GENERATING STATIONS
Nuclear power plants

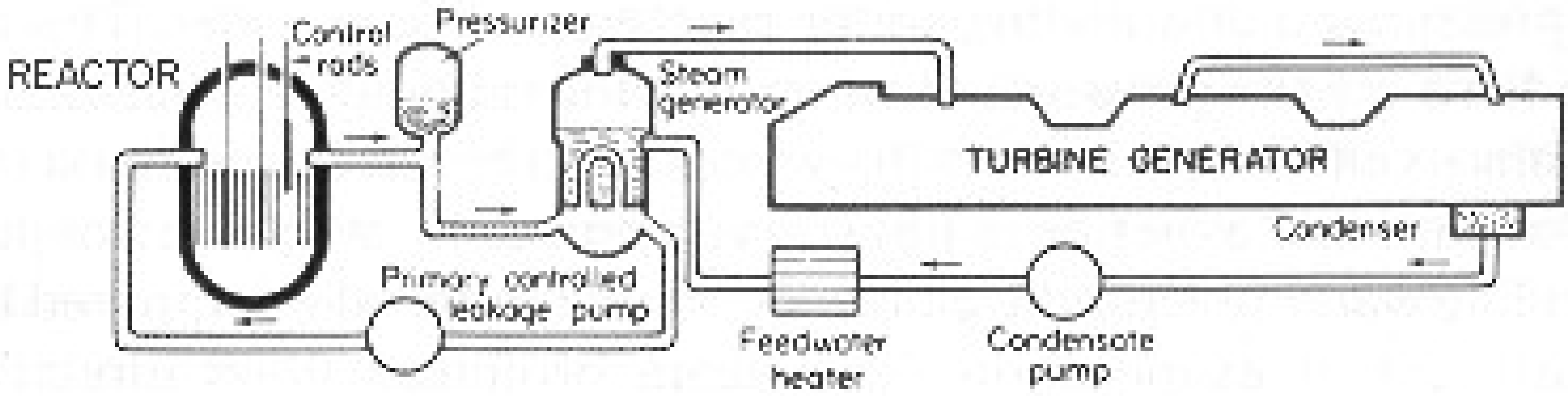


Figure 1.17 Schematic diagram of a pressurized water reactor. (*Permission of Edison Electric Institute.*)

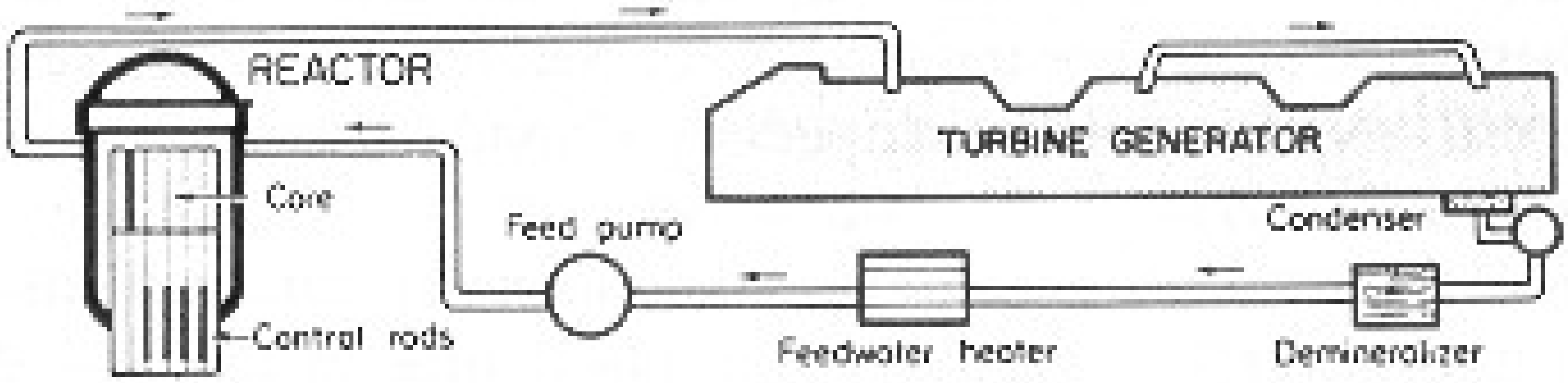


Figure 1.18 Schematic diagram of a boiling water reactor. (*Permission of Edison Electric Institute.*)

POWER GENERATING STATIONS
Nuclear power plants

Conventional steam plants beyond the heat producing reactor

High investments – low fuel costs => base load production

No emissions of CO_2 , SO_2, or NO_x

Open questions: final treatment of used fuel

Present plants based on fission of uranium-235 (0,7% of all U)

Fast-breeder reactors: uranium-238 converted to plutonium

Fusion energy: D+T= He+n or D+D=T+H or D+D=He+n

POWER GENERATING STATIONS
Hydro power plants

High investments, but no fuel costs

Variation of water flows: reservoir often needed

Limitations of operation:
⇒flood control
⇒limited variation of water level

Very good properties for generated power control
=> used for production / demand balance control

No emissions of CO_2 , SO_2, or NO_x

POWER GENERATING STATIONS
Hydro power plants

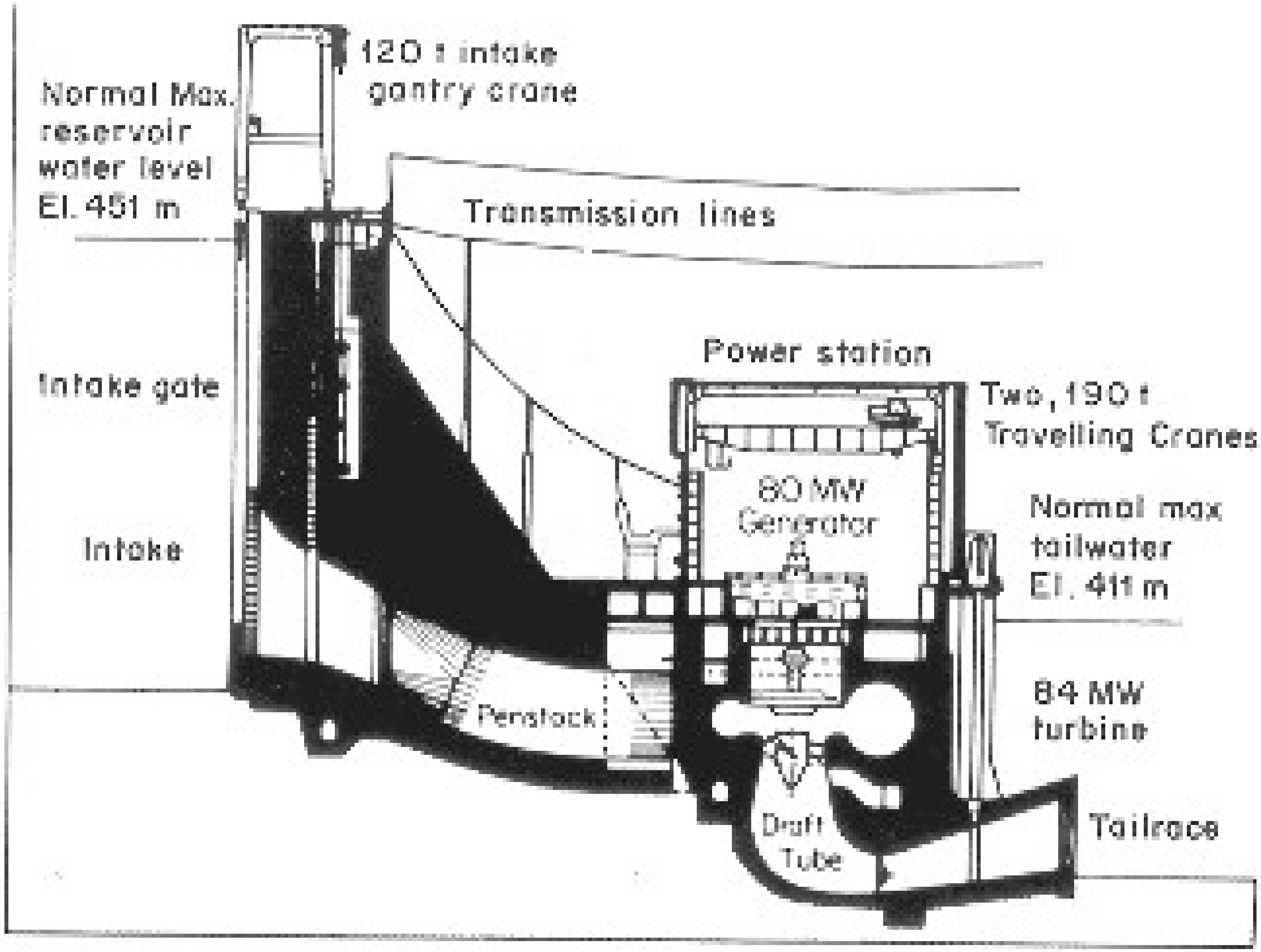


Figure 1.12 Hydroelectric scheme—Kainji, Nigeria. Section through the intake dam and power house. The scheme comprises an initial four 80 MW Kaplan turbine sets with the later installation of eight more sets. Running speed 115.4 rev/min. This is a large-flow scheme with penstocks 9 m in diameter. (*Permission of Engineering.*)

Solar Energy

- Solar radiation in space is even 1,366 kW/m²
- At earth's surface radiation is weaker because atmosphere absorps it and radiation is also reflected back
- 5-70 % of radiation in space is arriving to earth
  - Depends on month and time
  - Depends on location in the globe
  - In Finland annual radiation is about 1 000 kWh/m²
- Radiation of an hour on earth surface is more than the energy consumption of one year of the mankind

Active solar systems

- Active solar systems are based on silicon based semiconductor materials
- N-type has extra electrons, which can move, doped e.g. with Phosporous
- P-type has holes, lacking electrons, doper e.g. with Boron

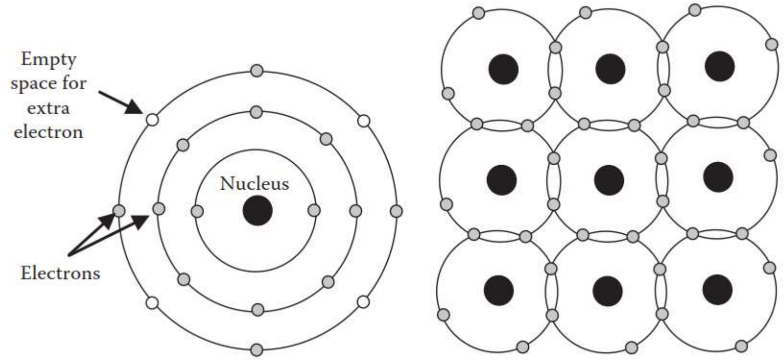
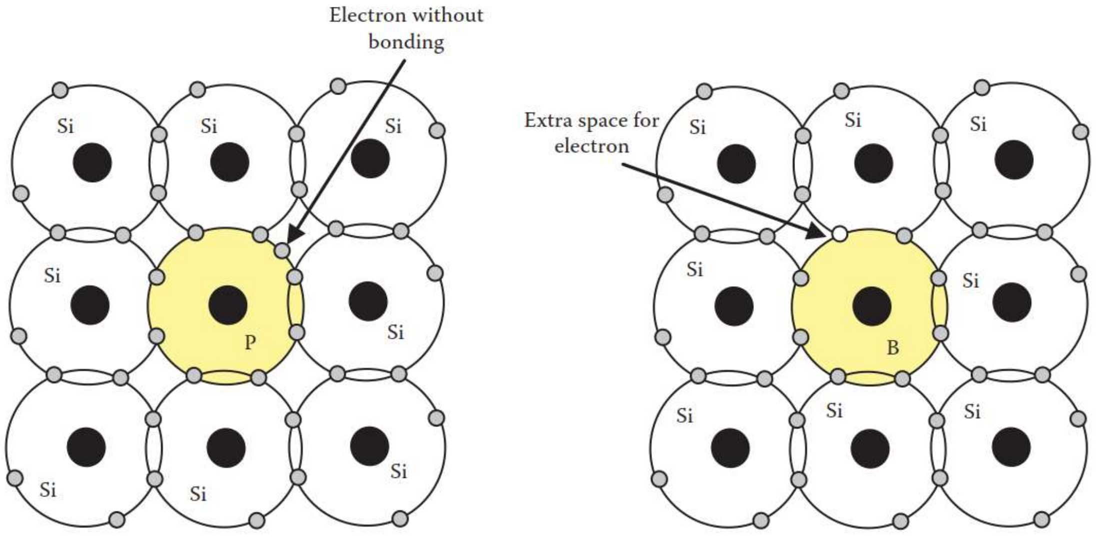


Figure 6.8 Silicon: atom and its crystal structures.



n–type

p–type

Figure 6.9 Silicon (Si) doped with phosphorus (P) and boron (B).

PV cell

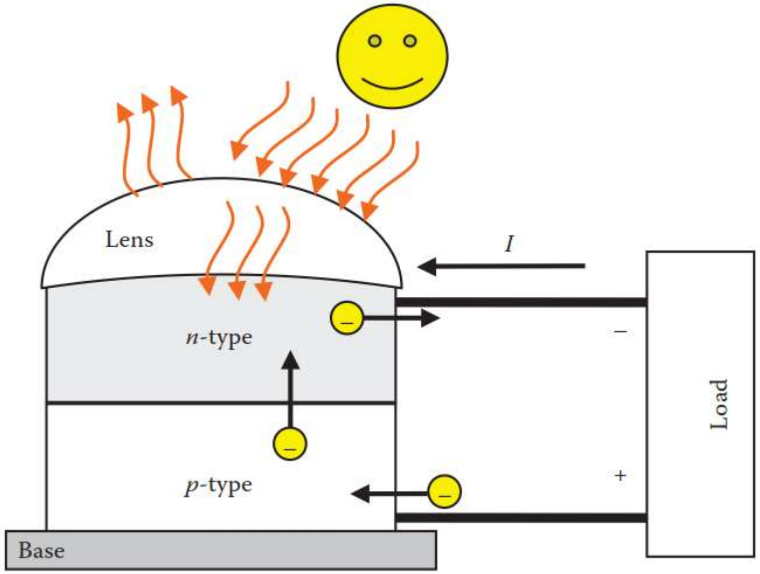


Figure 6.10 Concentrating PV cell.

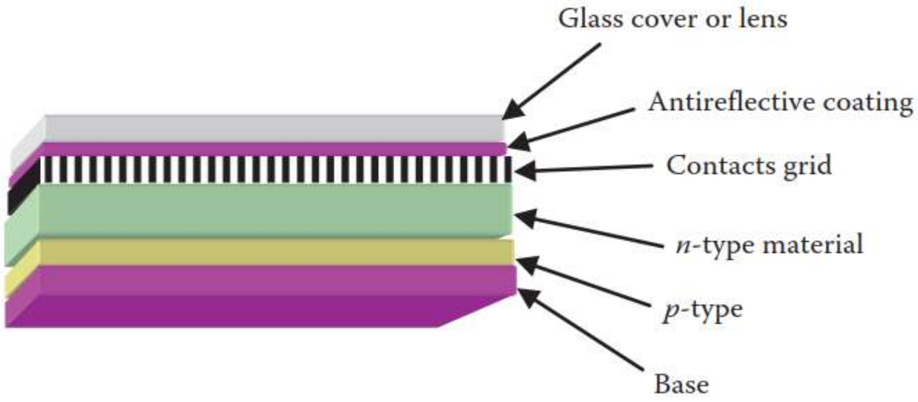


Figure 6.11 Main parts of PV cell.

P-N junction diode

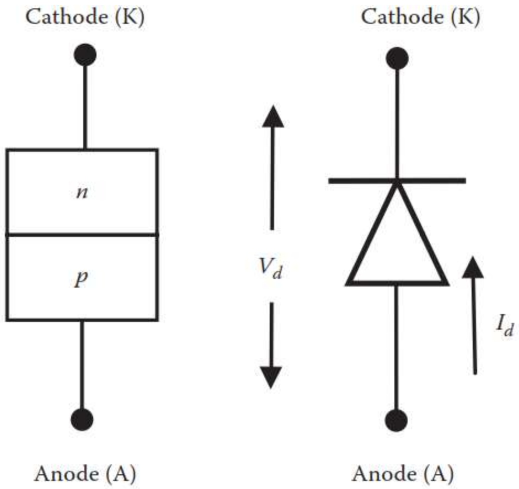
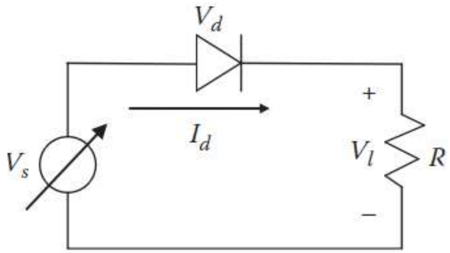
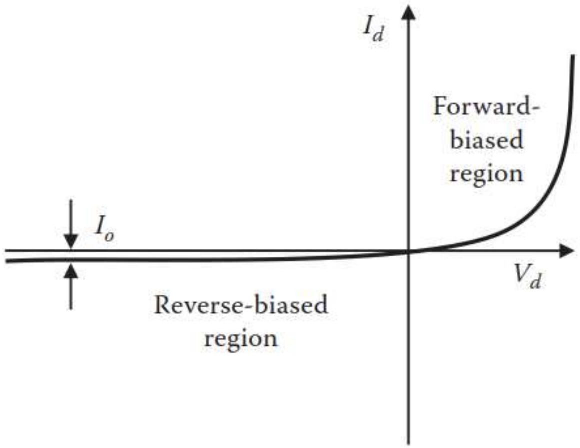


Figure 6.12 Representation of a *p*–*n* junction diode.





$$I_d = I_o\left(e^{\frac{V_d}{V_T}} - 1\right)$$

$$V_T = \frac{kT}{q}$$

I_o is the reverse saturation current of the diode
V_d is the voltage across the diode
V_T is thermal voltage
q is the charge of one electron which is known as the elementary charge constant (1.602×10^{-19} C)
T is the absolute temperature in kelvin (K); to convert from Celsius to kelvin, 273.15 is added to the Celsius value
k is the Boltzmann's constant (1.380×10^{-23} J/K)

Ideal PV cell

- Voltage of the PV cell is the diode on-state voltage => small voltage around 0,6 to 0,7 Volts and therefore series connections of cells are needed
- Output current of the cell is $I = I_s - I_d$

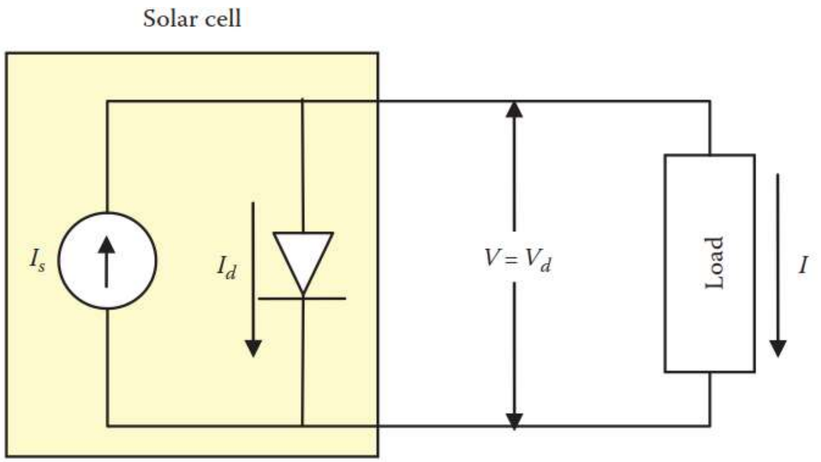


Figure 6.15 Modeling of ideal cell with current source.

Current-voltage characteristics of PV

- Solar cell is a current source with limited voltage range

$$I_d = I_o\left(e^{\frac{V_d}{V_T}} - 1\right)$$

$$V = V_d$$

$$I = I_s - I_d$$

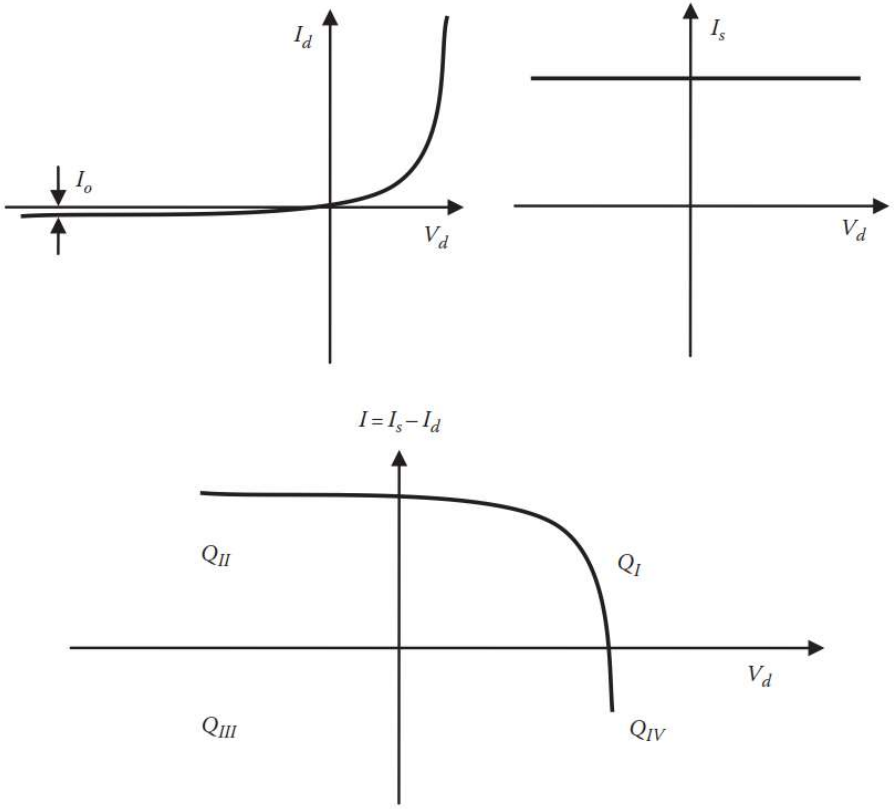


Figure 6.16 Current–volt characteristics of the PV cell.

I_o is the reverse saturation current
V_d is the voltage across the diode which is the same as the voltage across the load
V_T is the thermal voltage whose value is given in Equation 6.4

Maximum power point

- Power is obtained by multiplying voltage and current

$$P = VI = V_d I_s - V_d I_o \left(e^{\frac{V_d}{V_T}} - 1 \right)$$

- Power has maximum point and cell should be operated at this point in order to optimize its operation
- MPPT = maximum power point tracking

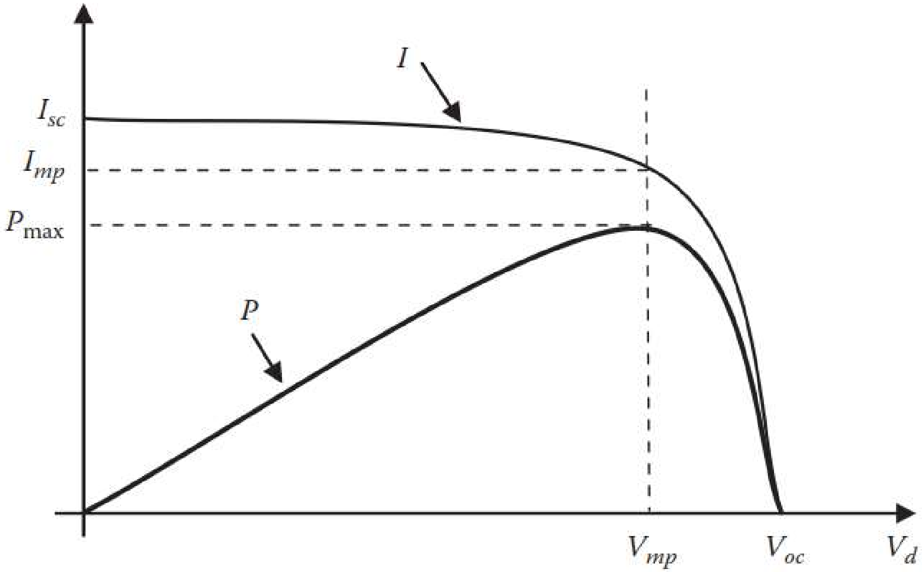


Figure 6.17 Current–voltage and power–voltage characteristics of PV cell.

Model of a real PV cell

- Efficiency of solar cells are typically around 20 % but also 40-50 % efficiency has been reported in laboratory environment
- Irradiance losses = reflections from the lences, energy level of some photons is not high enough
- Electrical losses = various resistances in the cell, wires, semiconductor material, represented with two resistors

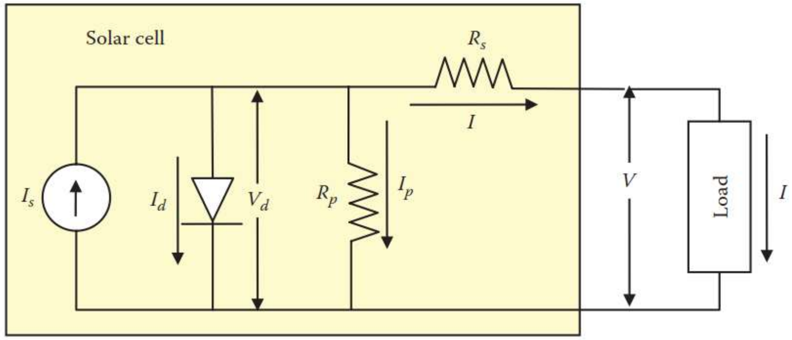


Figure 6.32 Model of real PV cell.

$$I = I_s - I_d - I_p \qquad V = V_d - IR_s$$

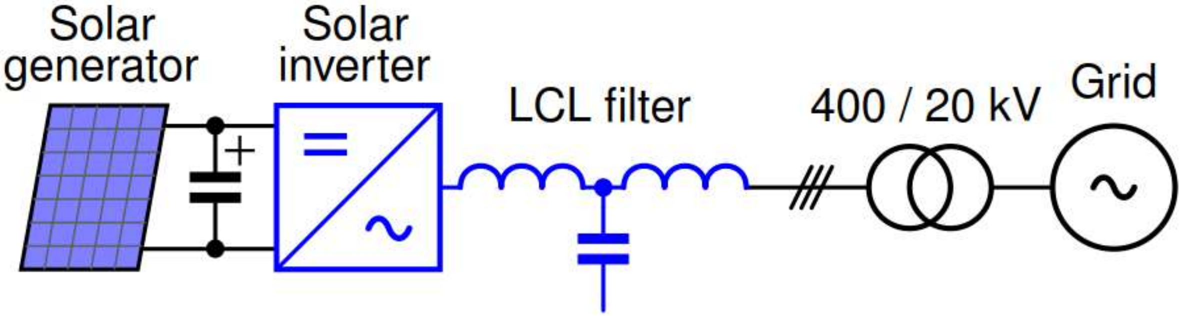
$$\eta_{irradiance} = \frac{P_{se}}{P_s} = \frac{V_d I_s}{\rho A} \qquad \eta_e = \frac{P_{out}}{P_{se}} = \frac{VI}{V_d I_s}$$

$$\eta = \eta_{irradiance}\eta_e = \frac{P_{se}}{P_s}\frac{P_{out}}{P_{se}} = \frac{P_{out}}{P_s} = \frac{VI}{\rho A}$$

P_{se} is solar power converted to electricity
P_s is solar power reaching the solar cell
P_{out} is the output power of the solar cell that is consumed by the load
ρ is the solar power density at the surface of the cell
A is the area of the PV cell facing the sun

Utility scale solar systems

- Solar panels are generating DC voltage
- DC-bus is adjusted to relative high values because of grid connection (600-850 VDC)
  - LCL-filter is a low pass filter (L inductor, C capacitor) to smooth harmonics of the inverter output voltage
- Additional DC-DC converters can be used between panels and dc-bus for better maximum power point tracking
- Power electronics is discussed more in Chapter 10

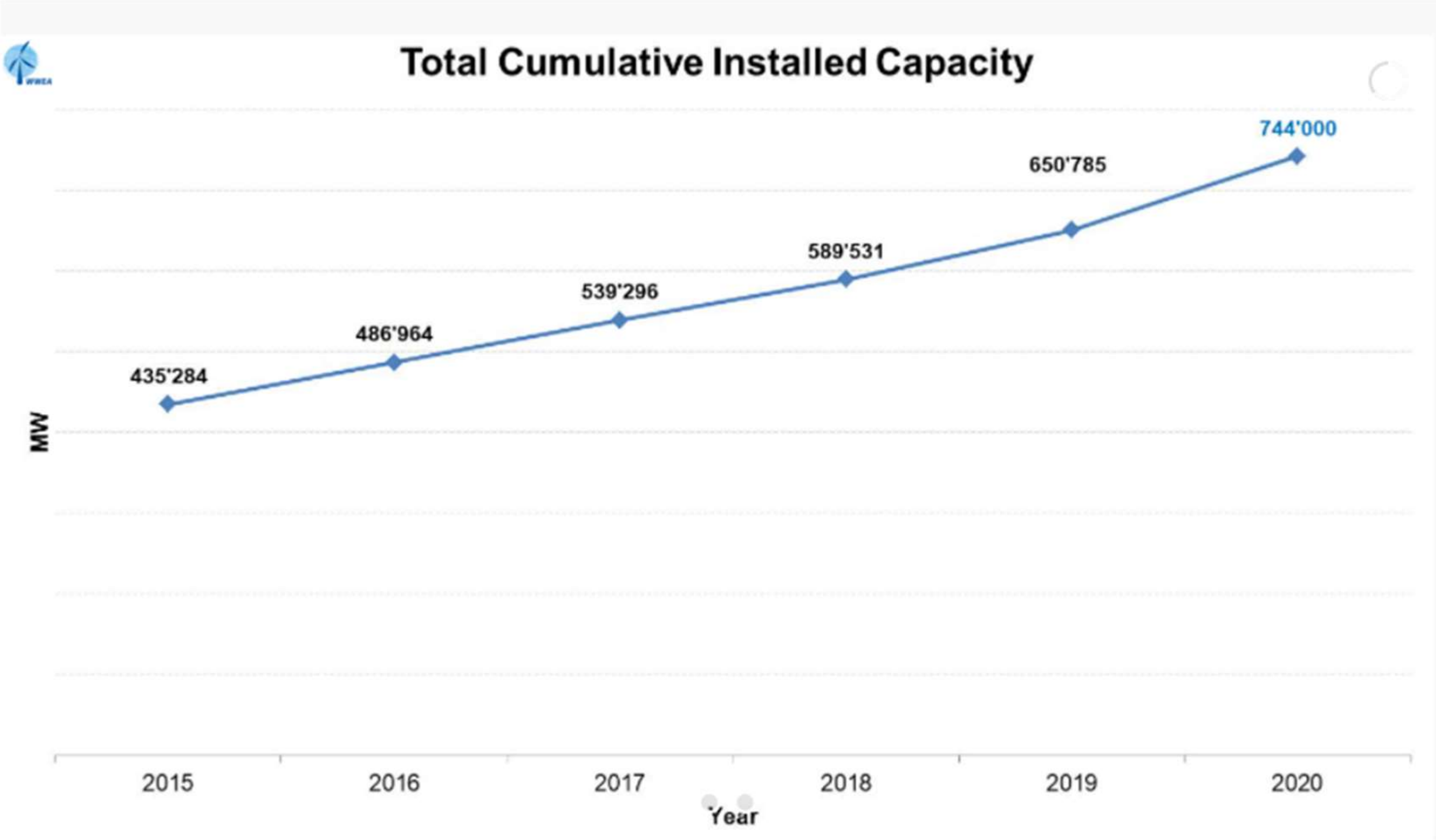


Wind Energy

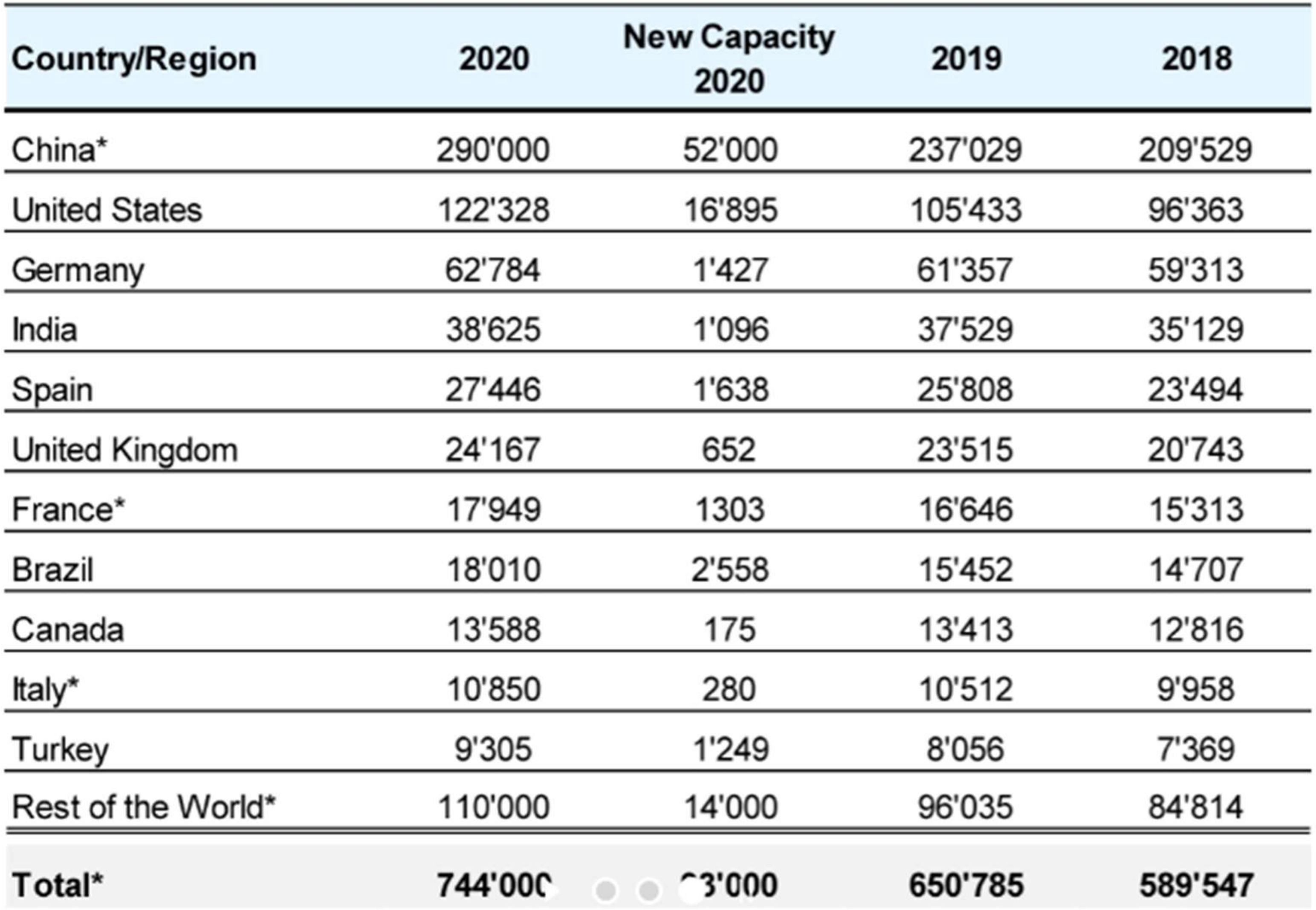
- Has been used thousand of years e.g. in sailing, about 5000 years back in Egypt
- First wind mills were used in China around 3000 BC and after that in Babylonia
- First wind turbine was constructed by Charles F. Brush in 1888
- Largest wind turbines are nowadays even 8 MW

World Wind Energy Association

- https://wwindea.org/information-2/information/



Wind energy by country

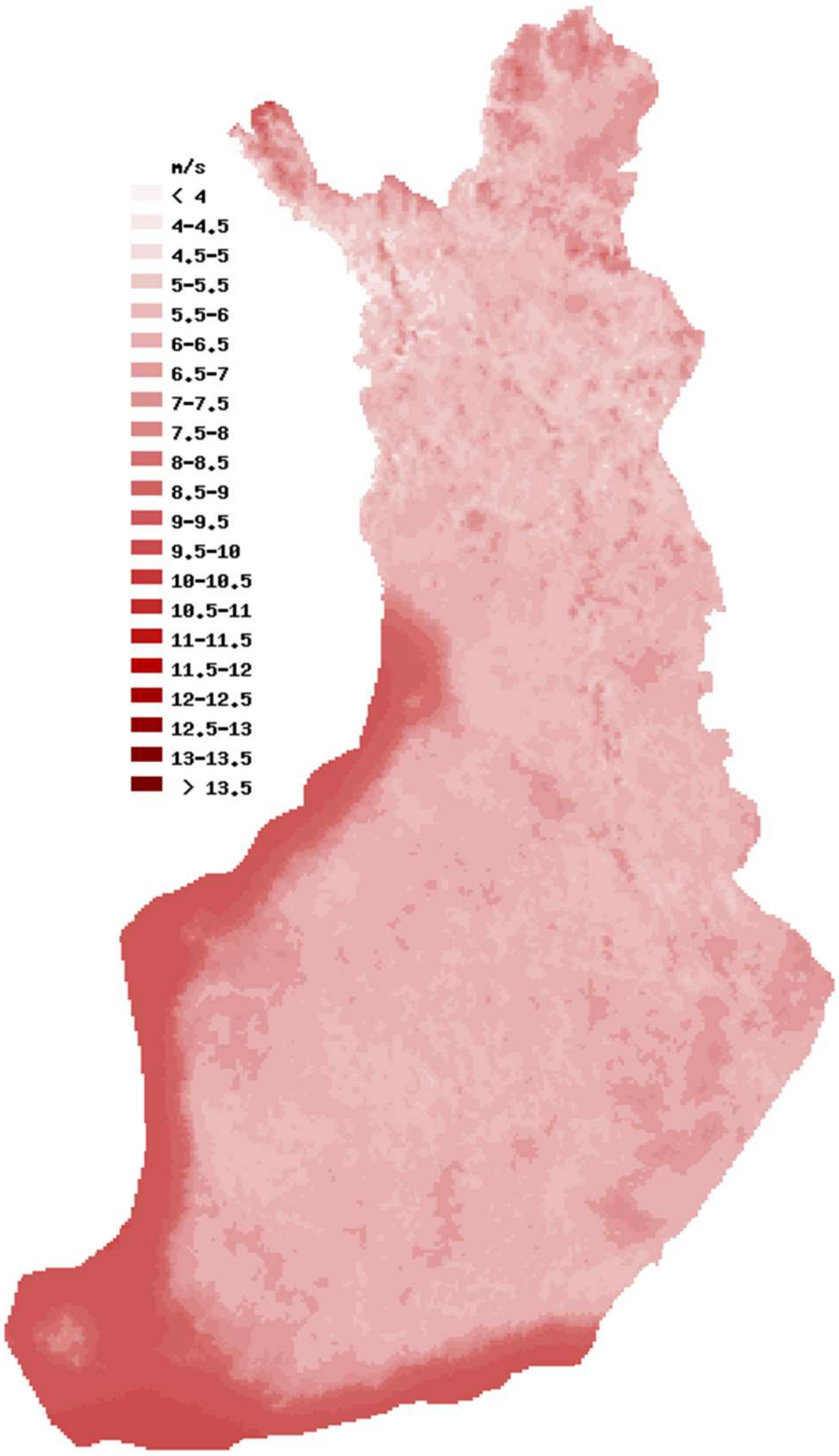


Country/Region	2020	New Capacity 2020	2019	2018
China*	290'000	52'000	237'029	209'529
United States	122'328	16'895	105'433	96'363
Germany	62'784	1'427	61'357	59'313
India	38'625	1'096	37'529	35'129
Spain	27'446	1'638	25'808	23'494
United Kingdom	24'167	652	23'515	20'743
France*	17'949	1303	16'646	15'313
Brazil	18'010	2'558	15'452	14'707
Canada	13'588	175	13'413	12'816
Italy*	10'850	280	10'512	9'958
Turkey	9'305	1'249	8'056	7'369
Rest of the World*	110'000	14'000	96'035	84'814
Total*	**744'000**	**93'000**	**650'785**	**589'547**

Finish wind atlas

- Suomen Tuuliatlas (fmi.fi) (page is only in Finnish)

The best locations for wind power
Are at the sea or on coastal line!



Definitions (1/2)

- **Energy production per wiped area of the rotor (kWh/m2)**
  - If this is calculated from annual production and result is more than 1000 kWh/m2, result can be consisered good
- **Time of nominal production (huipunkäyttöaika) th in hours**
  - Energy production of wind turbines varies between 0 % - 100 %
  - th is the time needed to produce the annual energy when turbine works with its nominal power
  - When th is more than 2400 hours production can be considered as good
- **Capacity factor, (kapasiteettikerroin) CF**
  - CF is the relation of th to the hours of one year and thus is basically same as th
  - CF is used especially in English litterature

Definitions (2/2)

- **Production index (tuotantoindeksi) IL (%)**
  - Calculated production based on measured wind data divided by the long term calculated average production data
  - At the moment in Finland the average production has been estimated by wind data between 1987 - 2001
  - Measured wind data is transferred to average produced power by using 1 500 kW wind turbine power curve and taking air density into account
  - IL is needed when we want to estimate how windy some period of time is in relation to long term conditions. This is important when doing investments, when it is necessary to estimate the lifetime production of the wind turbine

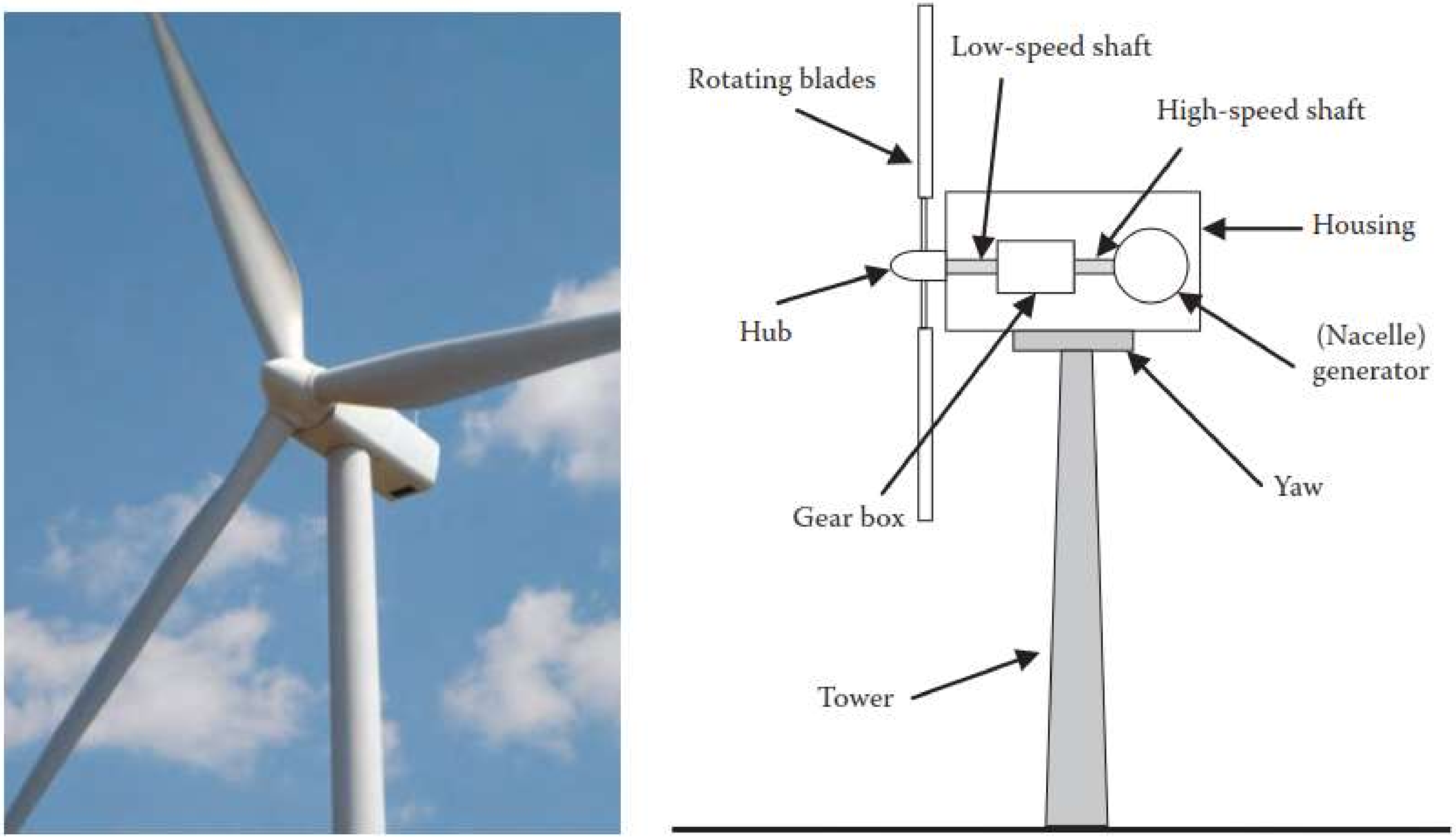
Kinetic Energy of Wind

- Energy of wind is $KE = \frac{1}{2} m w^2$ $KE = \frac{1}{2} A \delta t w^3$
  - *m*, mass of the moving object,
  - *w*, velocity in m/s,
  - δ density of air kg/m3

- And thus power is $P_{wind} = \frac{KE}{t} = \frac{1}{2} A \delta w^3$

- The power varies with the exponent 3 of wind speed

Wind generator



(a)

(b)

Figure 6.39 Basic components of a wind-generating system: (a) horizontal design and (b) main parts.

Wind turbine

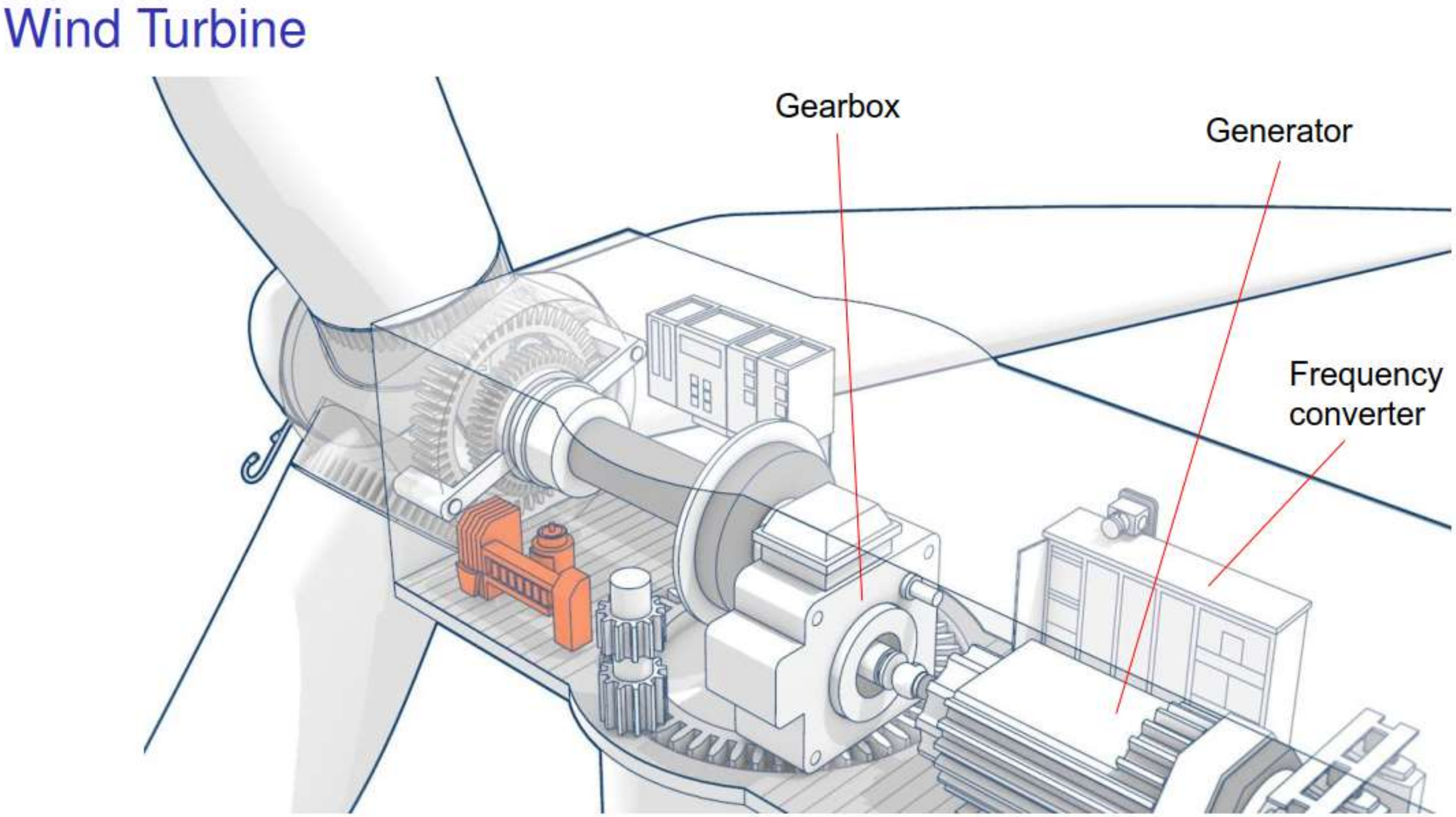


Figure: ABB (modified)

Angle of attack, α

F_L, lift force
F_D, drag force

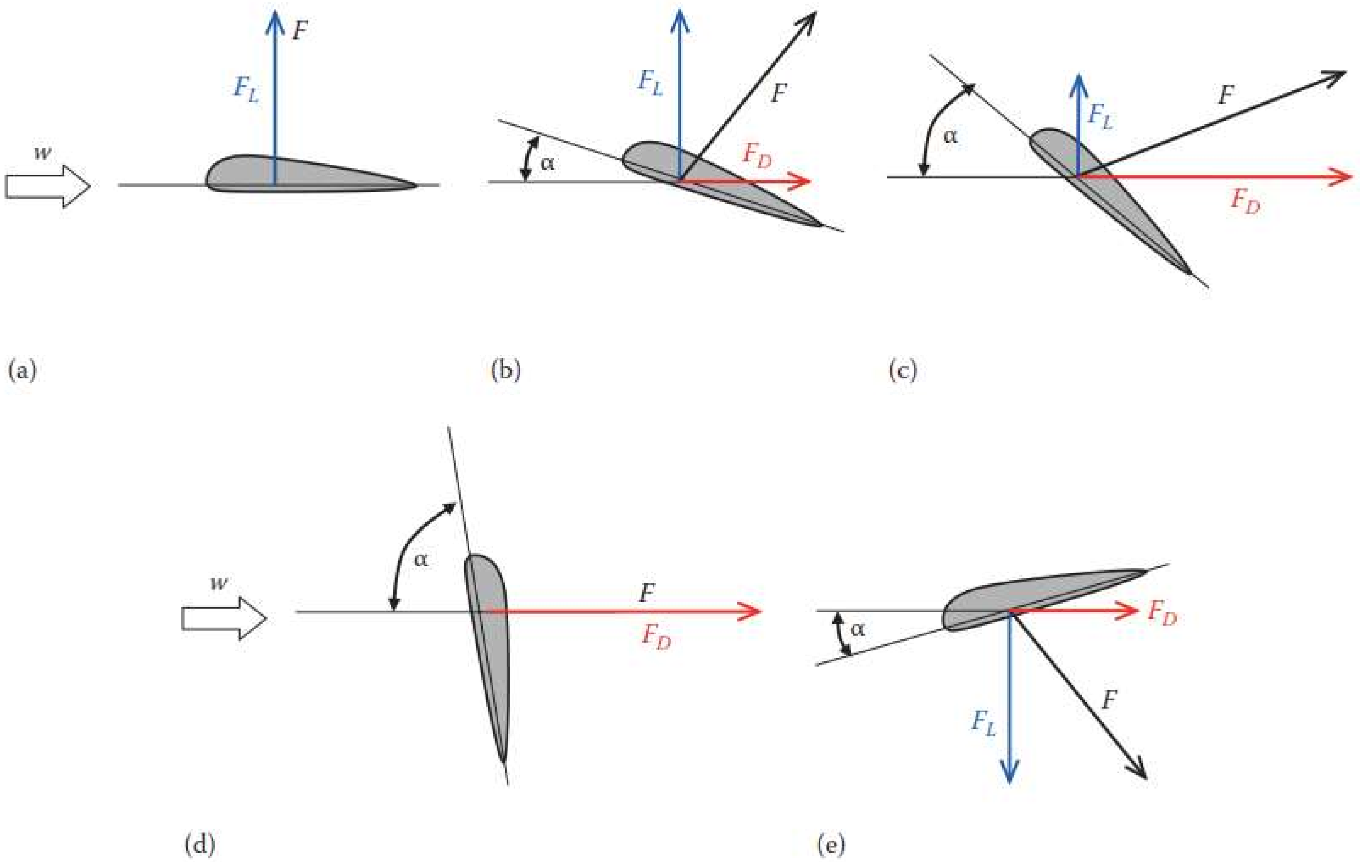


Figure 6.46 Aerodynamic forces and angle-of-attack: (a) horizontal position—all aerodynamic force is lift; (b) positive angle-of attack—aerodynamic force has lift and drag; (c) increasing positive angle-of attack, less lift, and more drag; (d) increasing positive angle-of attack until aerodynamic force is all drag; and (e) negative angle-of attack—lift is reversed.

Lift force and pitch angle β

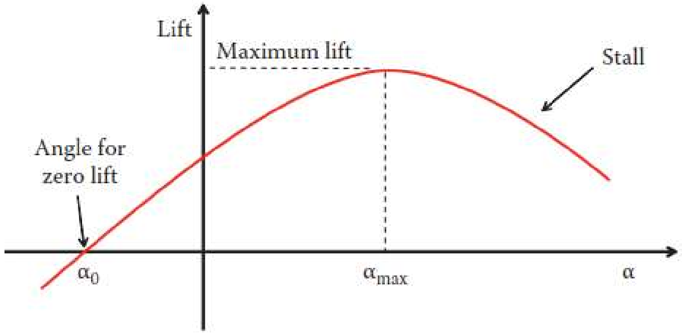


Figure 6.47 Lift force as a function of angle-of-attack.

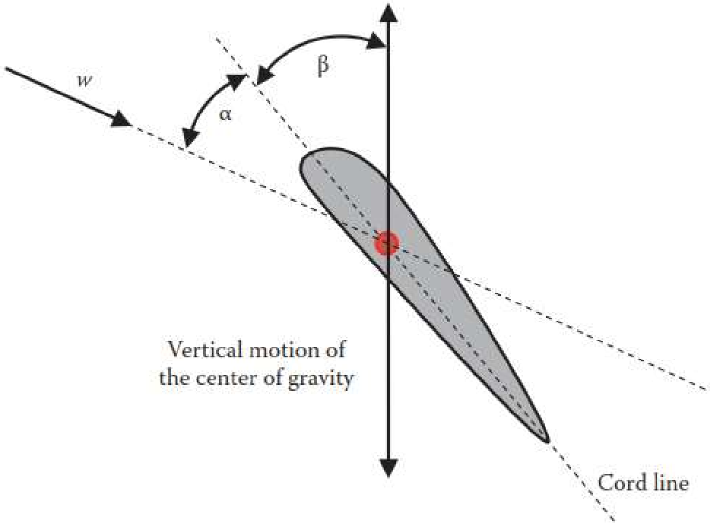


Figure 6.48 Relative wind speed, angle of attack and pitch angle.

Output power versus angular speed

- cut-in speed w_{min}, turbine starts to produce energy
- After w_B power needs to be limited by adjusting the pitch angle
- w_{max}, maximum speed, mechanical stresses limiting

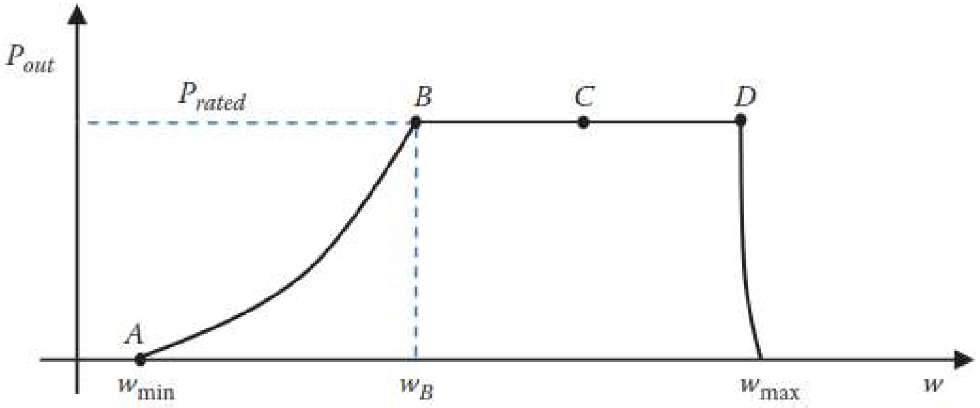


Figure 6.50 Output power of wind turbine.

Tip speed ratio, TSR

$$v_{tip} = \omega r = 2\pi \frac{n}{60} r$$

$$TSR = \frac{v_{tip}}{w}$$

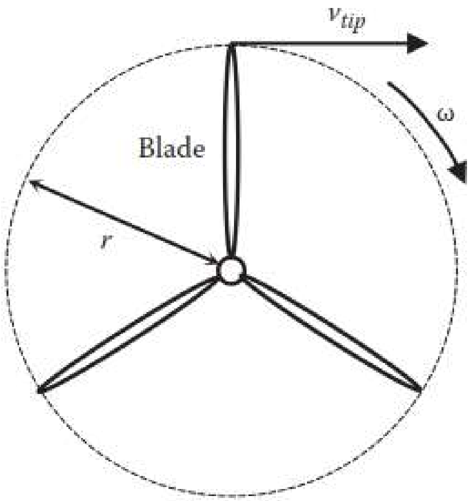


Figure 6.51 Tip velocity.

v_{tip} *is the tip speed in m/s*
ω is the angular speed of the blade (rad/s)
n *is the number of revolutions the blade makes in one minute (r/min)*
r *is the length of the blade (m)*
w is speed of wind

Cofficient of performance

$$TSR = \frac{v_{tip}}{w}$$

- Power coefficient $$C_p = \frac{P_{blade}}{P_{wind}}$$
- Describes how much of the power of the wind is converted to mechanical power in blades
- Betz limit, Cp is always less than 0,5926 and in practice less than 0,5
- In modern wind turbines TSR can be adjusted by changing the speed of the generator and the pitch angle of the blades

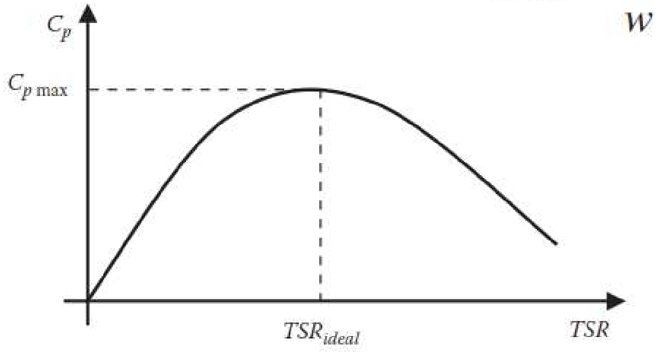


Figure 6.52 Coefficient of performance as a function of *TSR*.

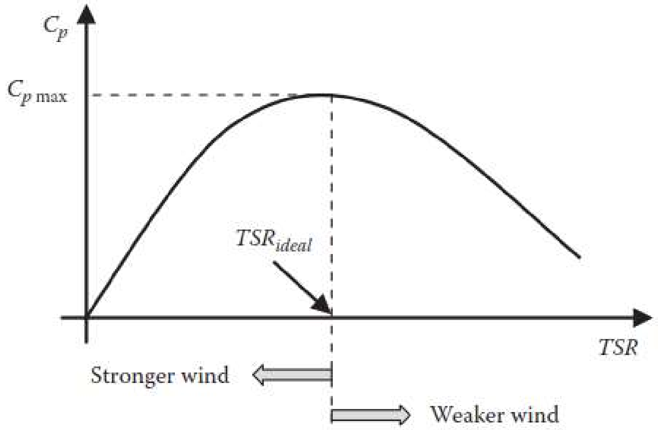


Figure 6.53 Tracking maximum C_p by adjusting the speed of the blade.

Electrical connection

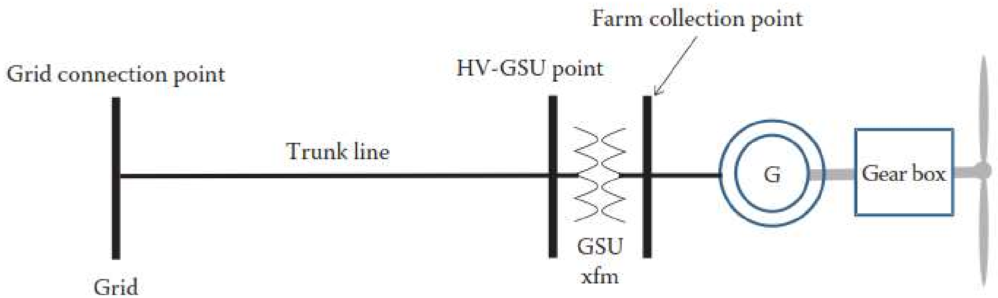


Figure 6.60 Type 1 wind turbine system.

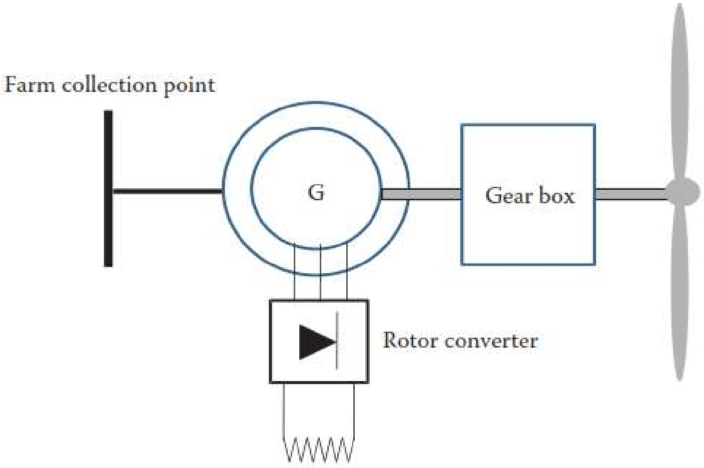


Figure 6.61 Type 2 wind turbine system.

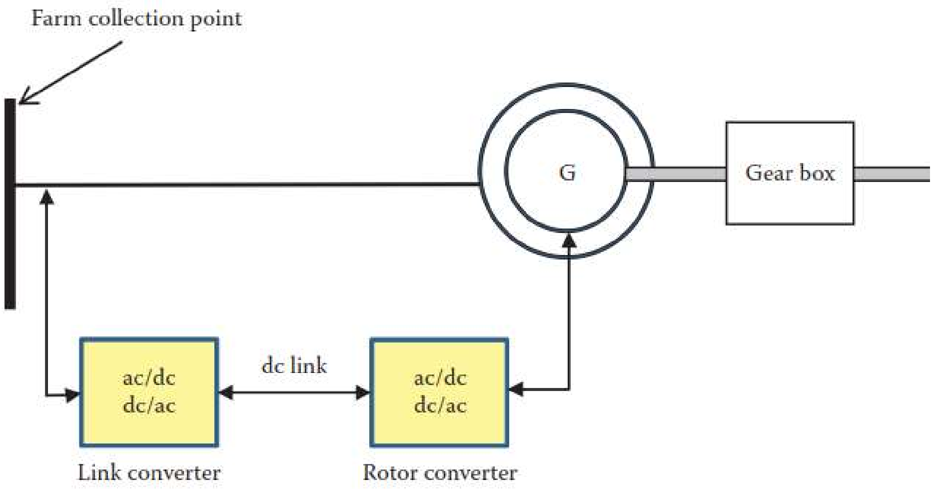


Figure 6.62 Type 3 wind turbine system.

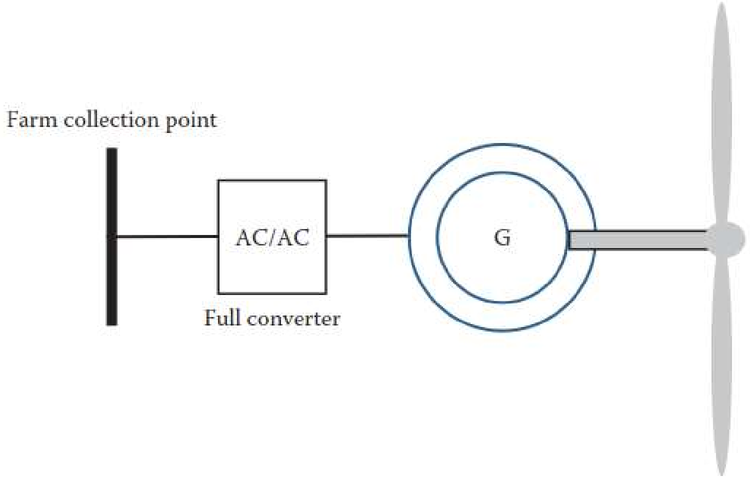


Figure 6.63 Type 4 wind turbine system.

Electrical connection of wind turbines

- First wind turbines were connected by induction generators which require almost fixed speed. To fit the propeller speed to power system frequency, a gear box was need.
- Next step was partial speed control provided by rotor resistance or by doubly fed induction machine. This provided some limited speed control range.
- Modern wind turbines use full converters, which enable decoupling of the propeller speed from power system frequency. Gear box is not needed anymore.