Aalto University
School of Electrical
Engineering

Chapter 6
Renewable Energy

ELEC-E8422 - An Introduction to Electric Energy

20.9.2022 and 27.9.2022

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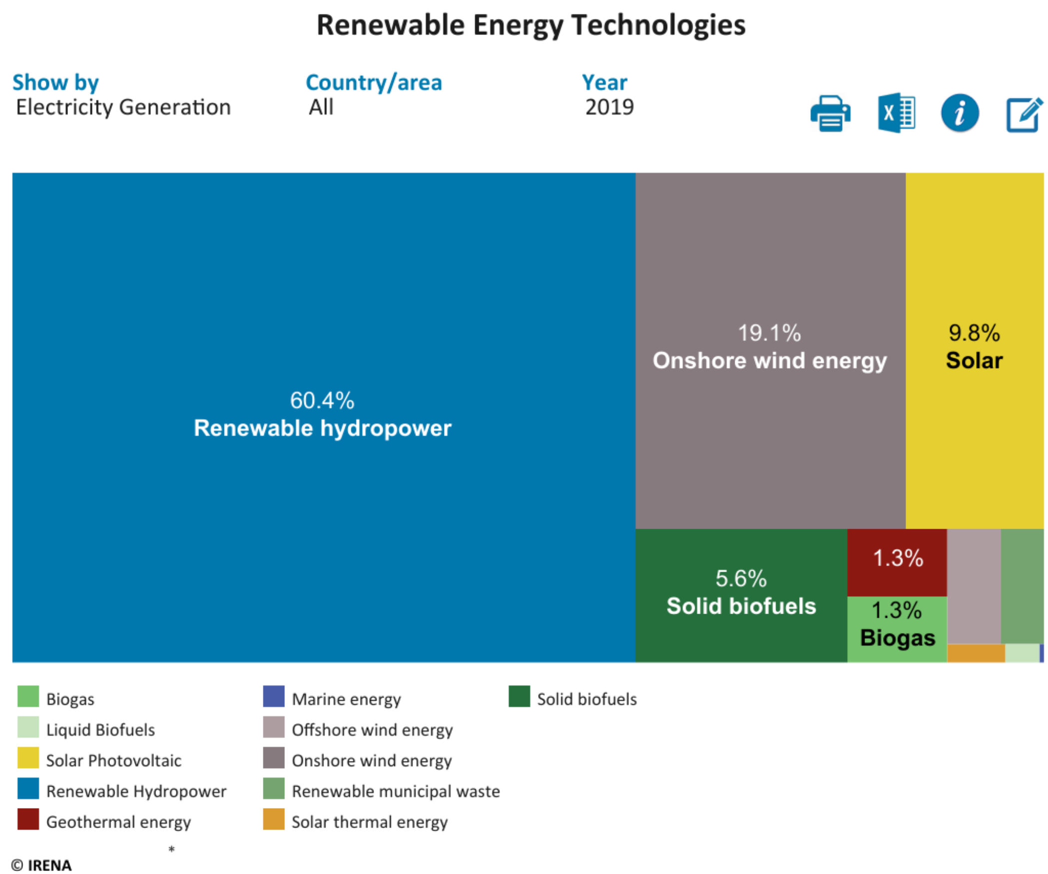
Content

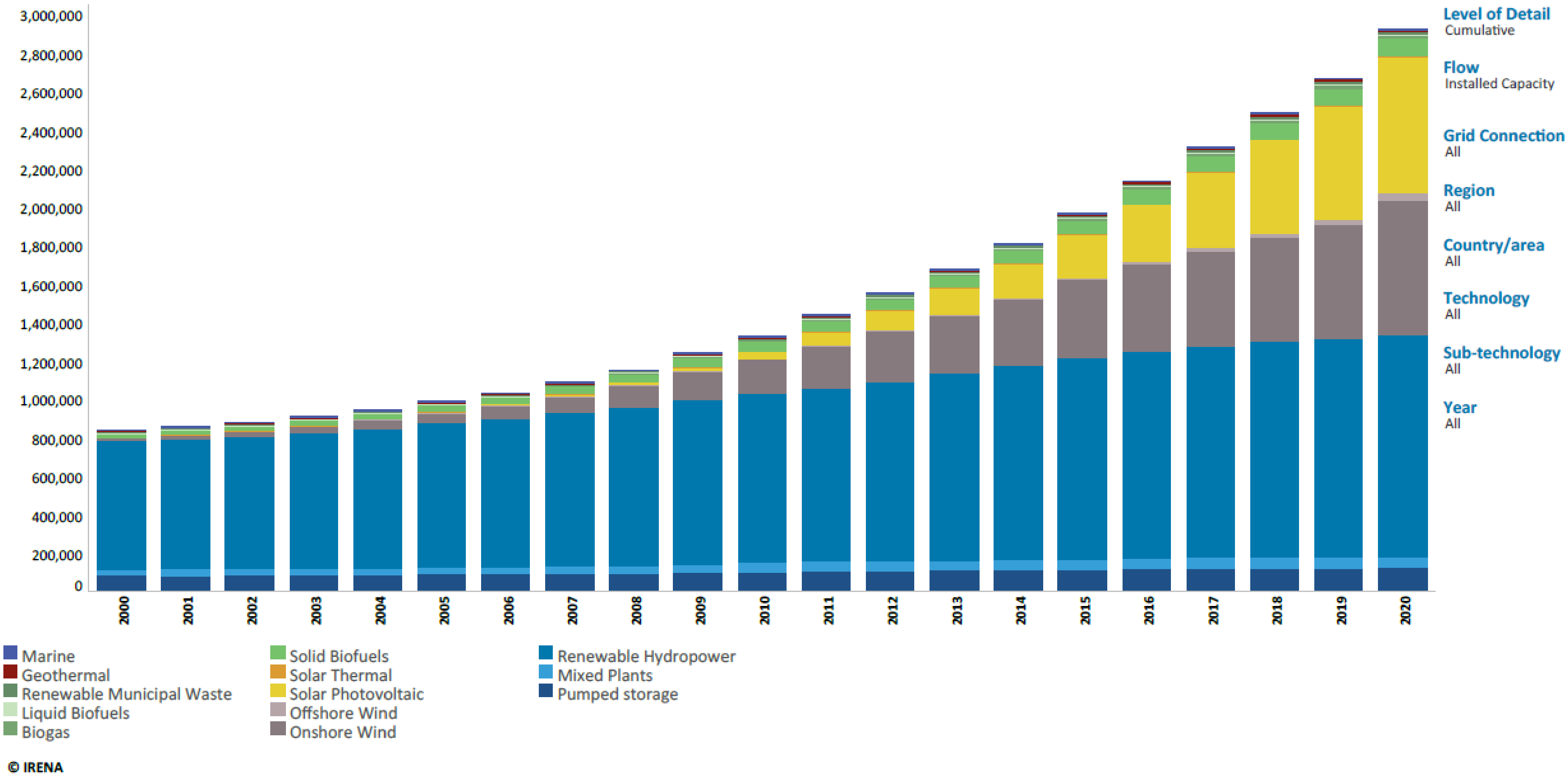
- Solar Energy
- Wind Energy
  - 6.2.1, 6.2.2, 6.2-6.2.13, other Chapters extra
- Hydrokinetic Systems
- Geothermal Energy
- Biomass Energy
- Fuell Cells
  - Chemistry in Chapter 6.6 extra
- Intermittency of Renewable Systems
- Energy Storage Systems

Production of renewable energy in the World, 2019



Source: IRENA, International Renewable Energy

World Installed capacity in renewables



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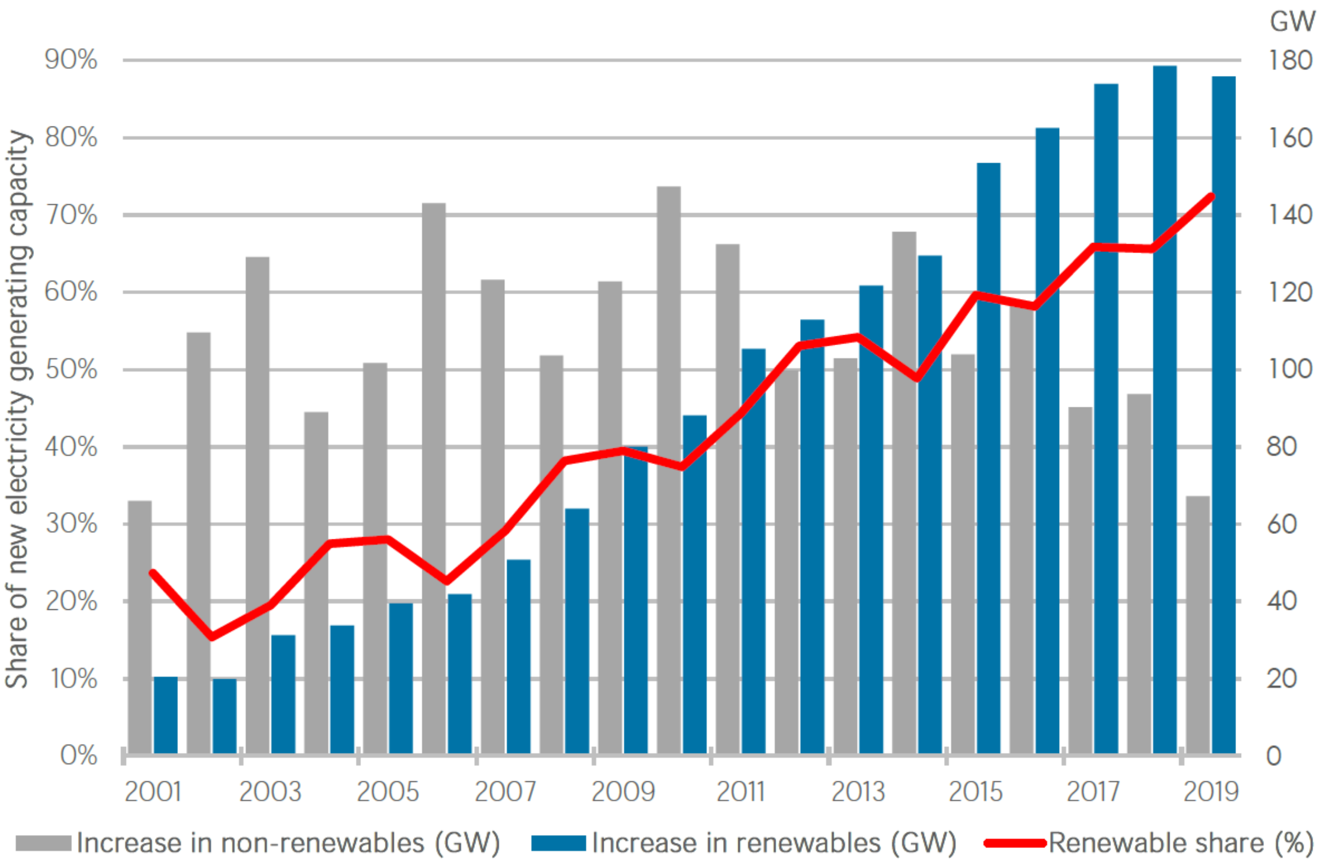
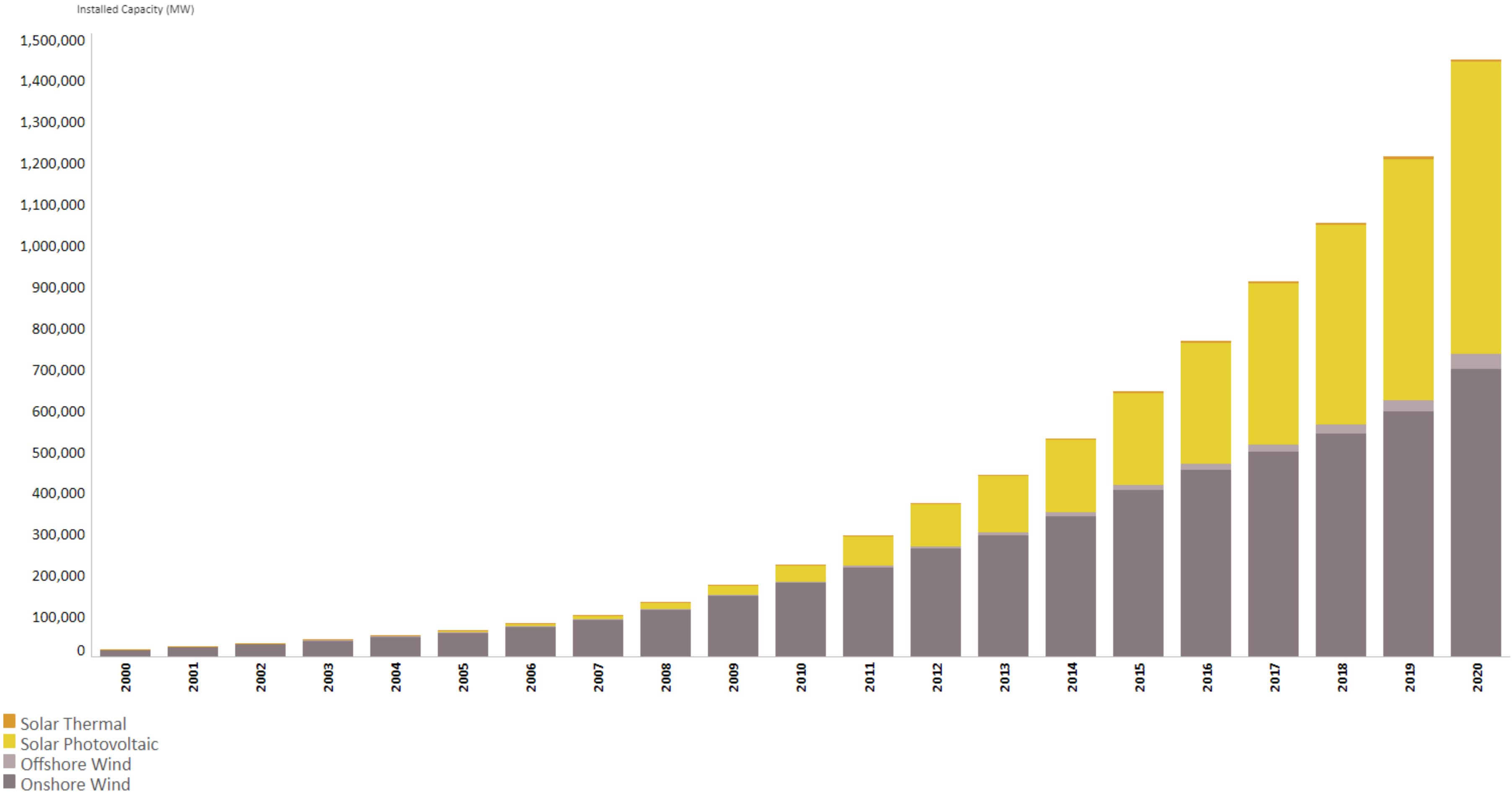
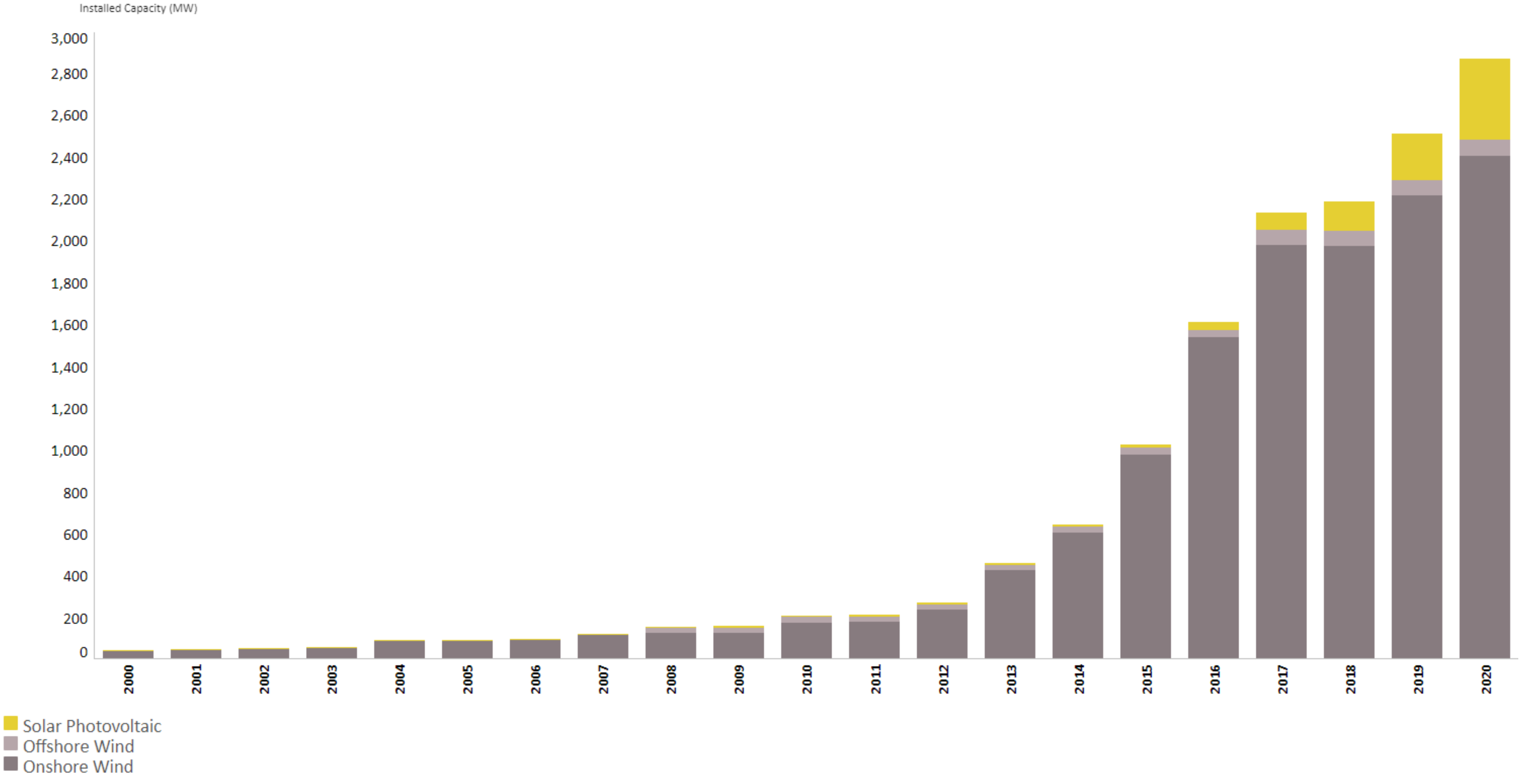
Since 2011 installed capacity on renewables has been higher than 50 %



World Installed Capacity (MW) in Wind and Solar



Installed Capacity (MW) in Wind and Solar, Finland



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

Worldwide solar insolation

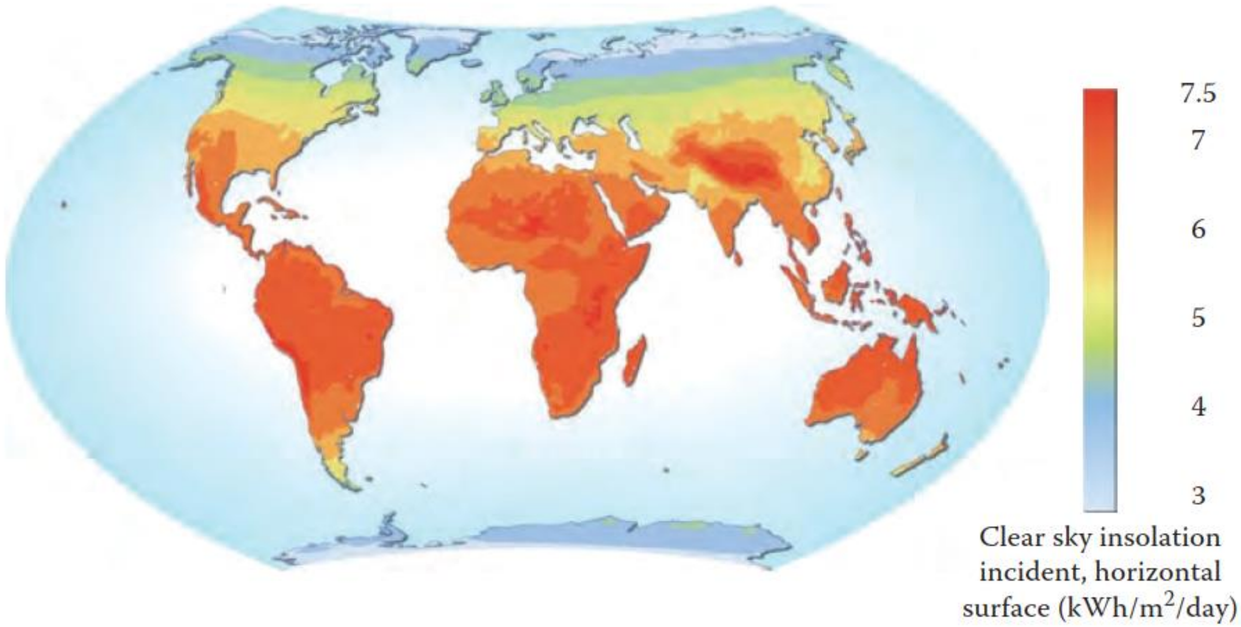
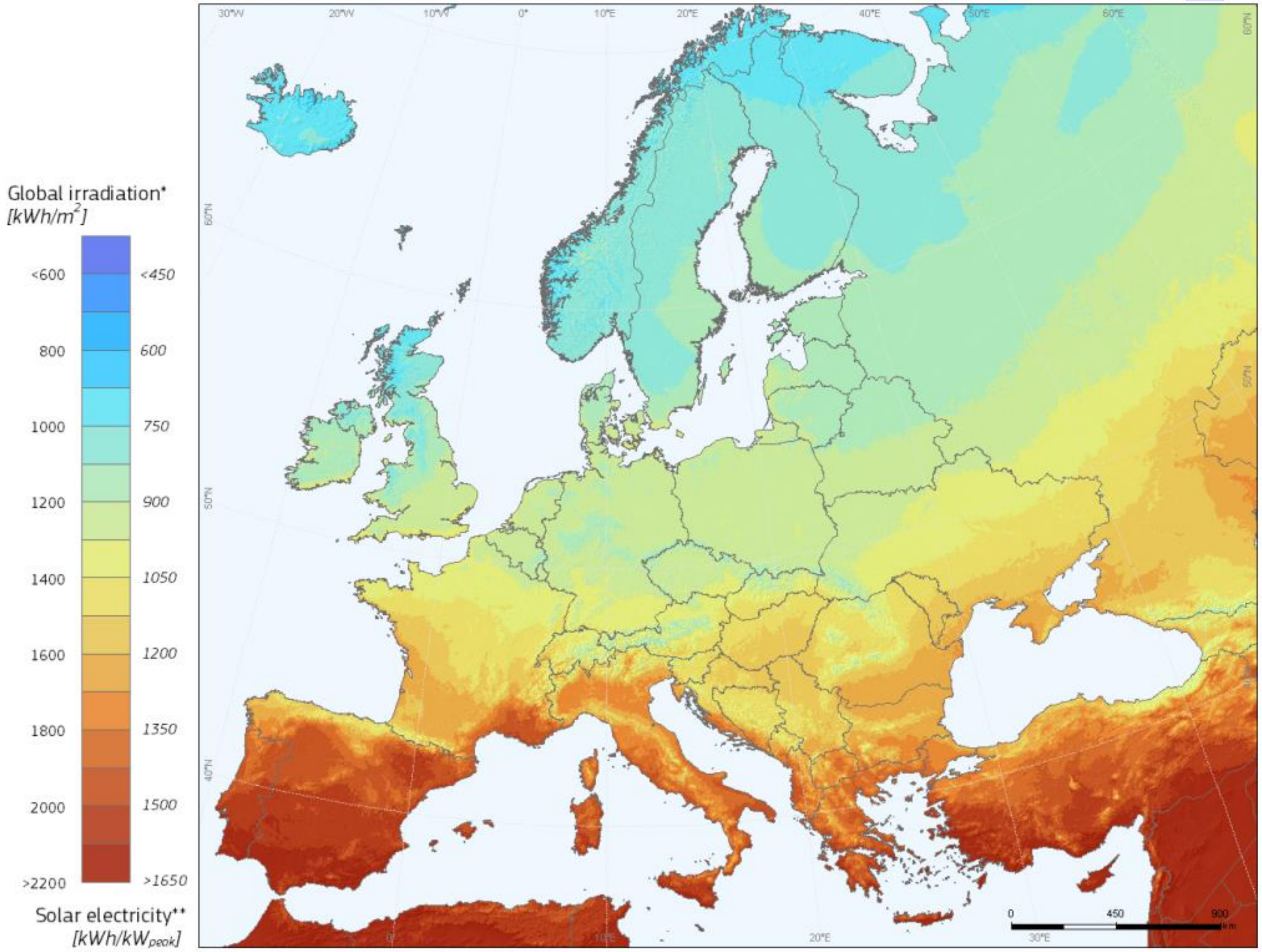


Figure 6.3 Average annual solar energy worldwide. (Courtesy of the National Aeronautic and Space Administration NASA.)

Photovoltaic Solar Electricity Potential in European Countries



* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

**Yearly sum of solar electricity generated by optimally-inclined $1kW_p$ system with a performance ratio of 0.75

PVGIS http://re.jrc.ec.europa.eu/pvgis/

Authors: Thomas Huld, Irene Pinedo-Pascua
EC • Joint Research Centre
In collaboration with: CM SAF, www.cmsaf.eu

Distribution of solar energy in 24 hours

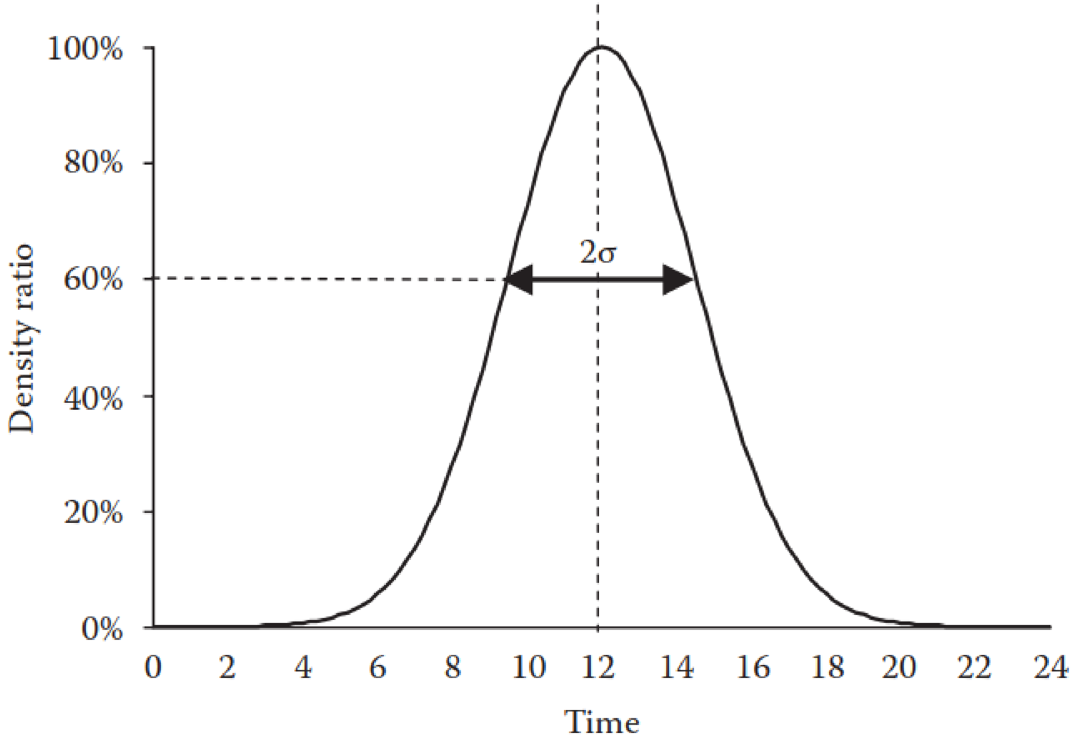


Figure 6.4 A typical solar distribution function (solar power density in 24 h period).

Hot water solar systems

Figure 6.5 Passive thermosiphon hot water solar system.

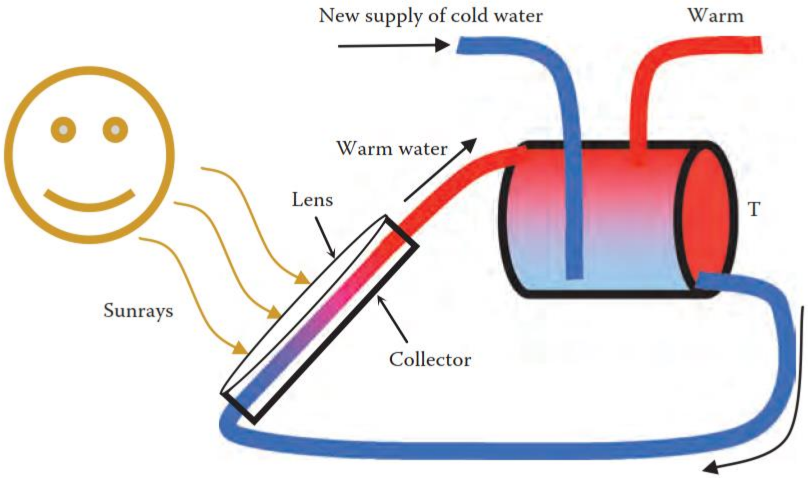


Figure 6.6 Thermosiphon hot water system.

Integrated systems

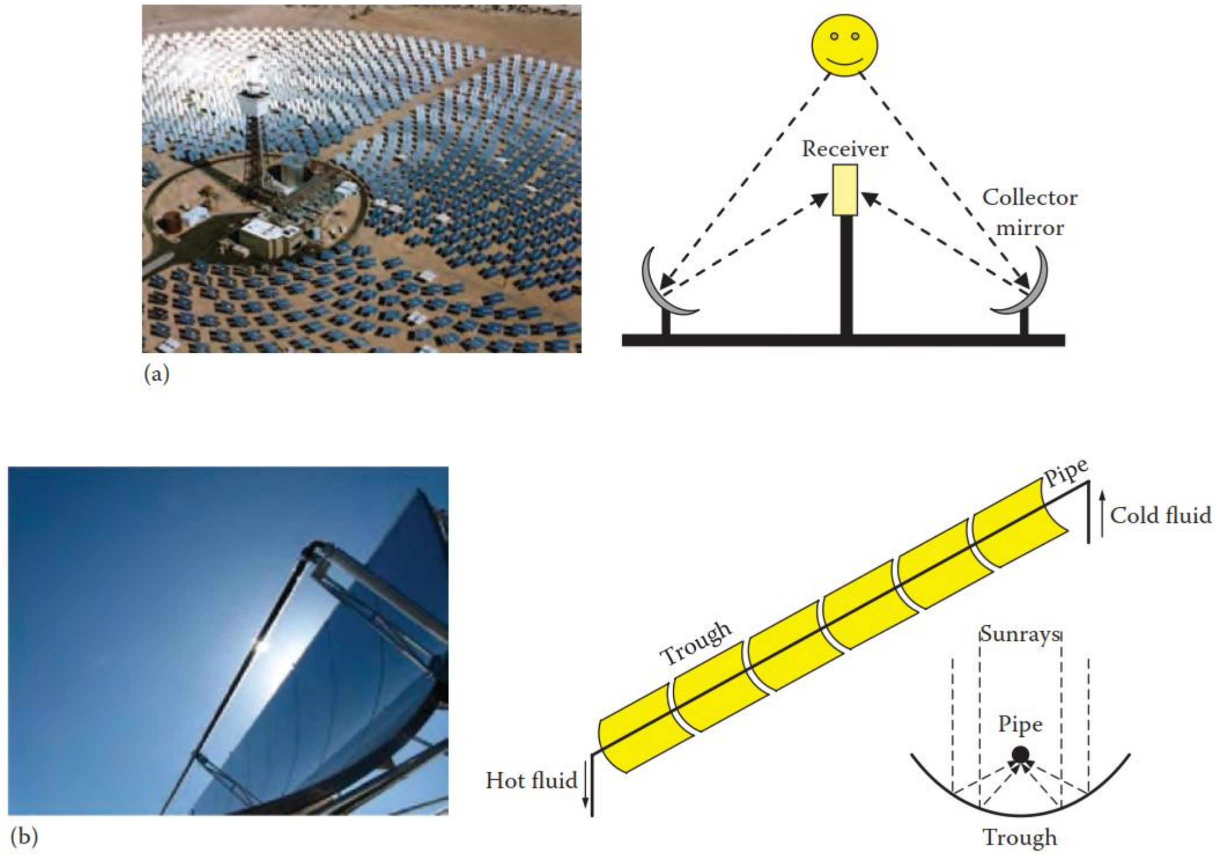


Figure 6.7 Solar systems: (a) integrated solar combined cycle system and (b) concentrated trough. (Images are courtesy of the US Department of Energy, Washington, DC.)

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

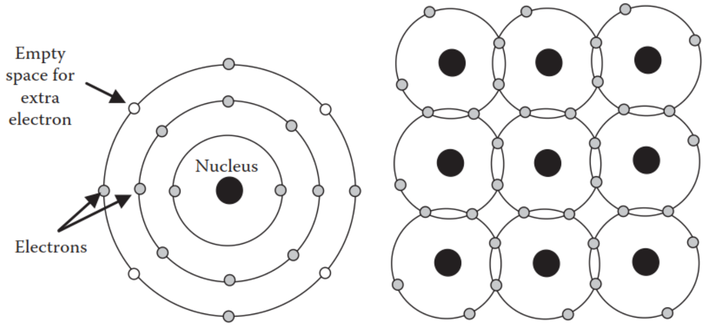


Figure 6.8 Silicon: atom and its crystal structures.

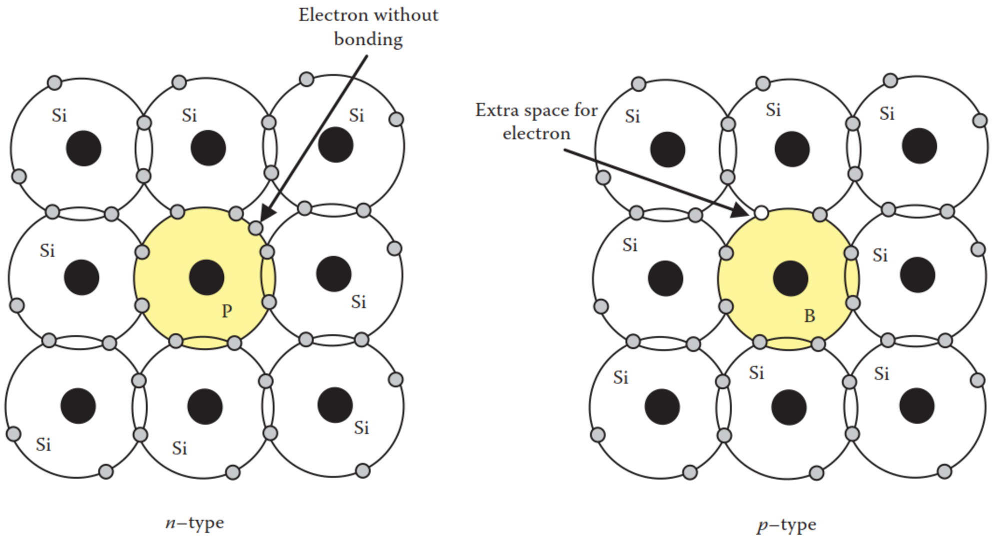


Figure 6.9 Silicon (Si) doped with phosphorus (P) and boron (B).

PV cell

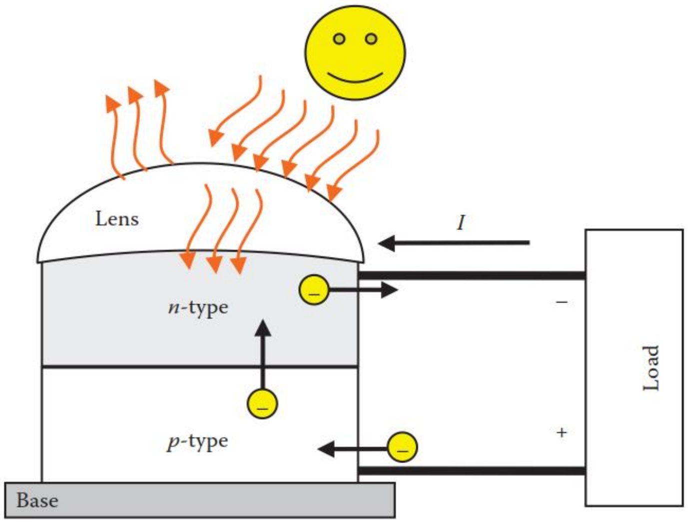


Figure 6.10 Concentrating PV cell.

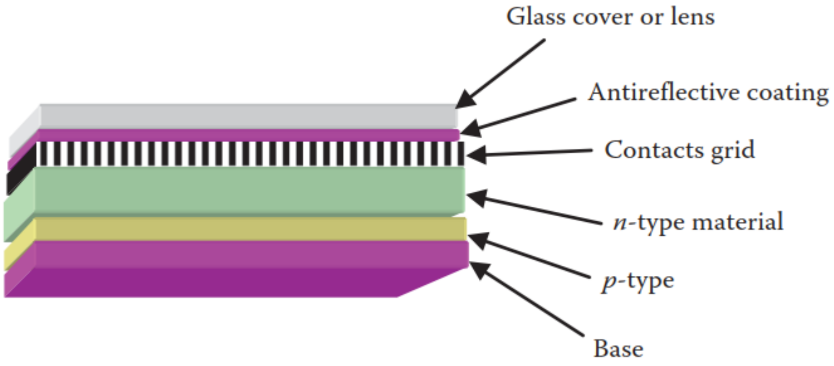


Figure 6.11 Main parts of PV cell.

P-N junction diode

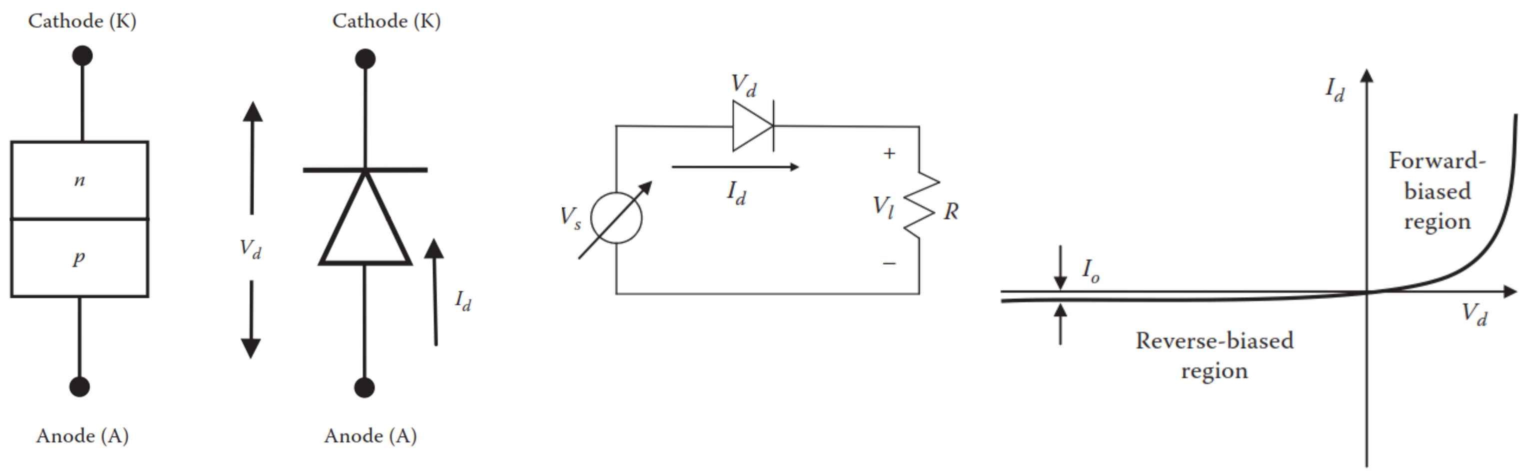


Figure 6.12 Representation of a *p*–*n* junction diode.

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

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

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 $I = I_s - I_d$

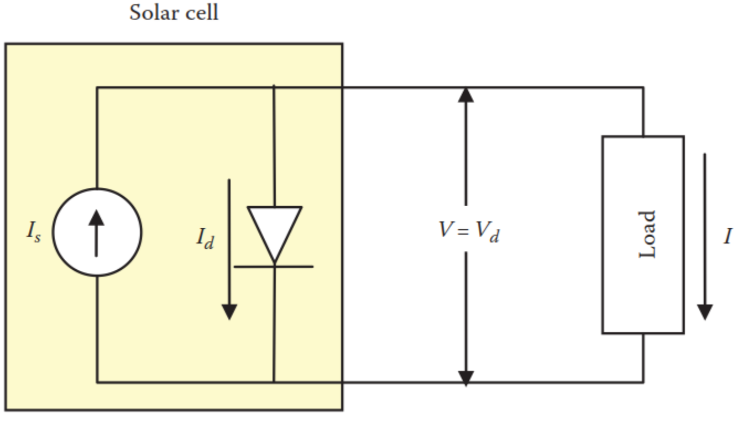


Figure 6.15 Modeling of ideal cell with current source.

Current-voltage characteristics of PV

- Solar cell is a current source with limited voltage range

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

$$V = V_d$$

$$I = I_s - I_d$$

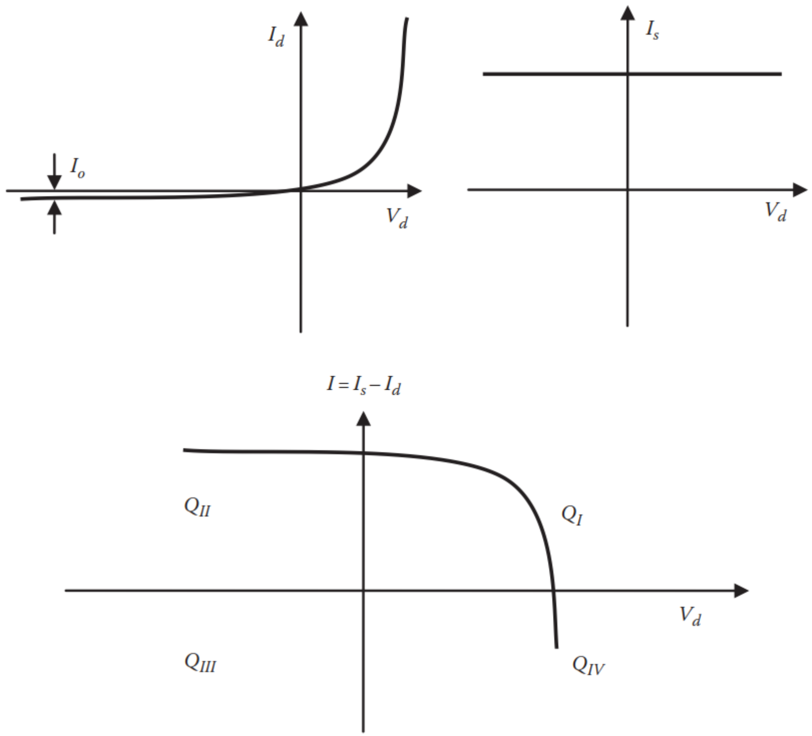


Figure 6.16 Current–volt characteristics of the PV cell.

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

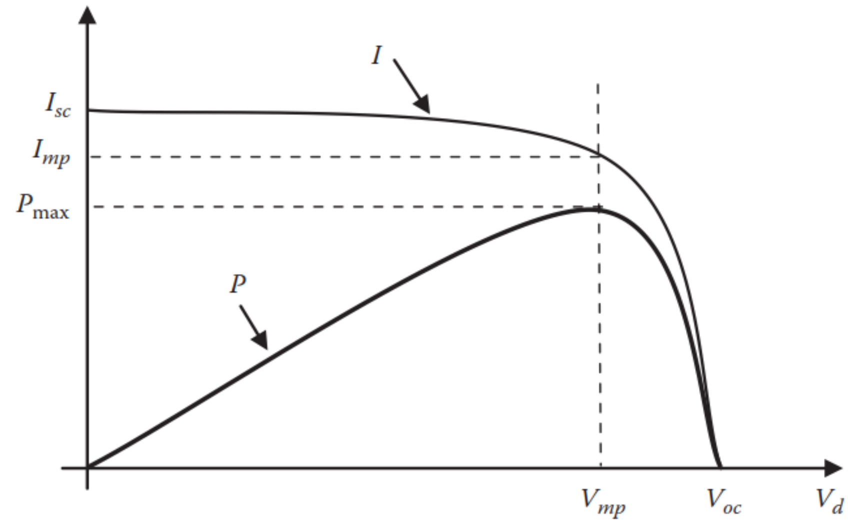


Figure 6.17 Current–voltage and power–voltage characteristics of PV cell.

Operating points of the cell

- Different load resistances
  - R1 is the smallest resistance
  - Power is maximum at R2
  - R3 is largest resistance and current has dropped because voltage is limited
- In practice controllable load resistance can be realized with dc-dc converters, Chapter 10

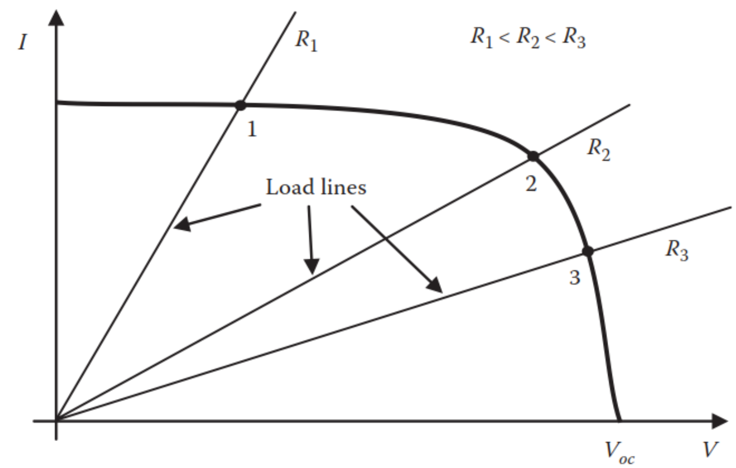


Figure 6.20 Operating points of the solar cell connected to a resistive load.

Changing irradiance

- Changes in solar radiation changes current output of the cell and also the maximum power point
- For maximum output power point, i.e. load should be adjusted and should not be kept constant

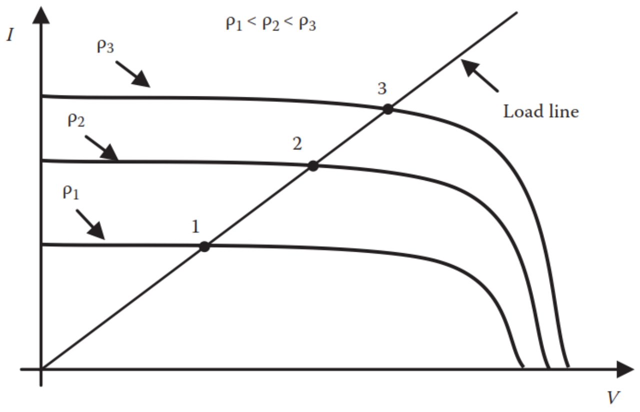


Figure 6.21 Effect of irradiance on the operating point.

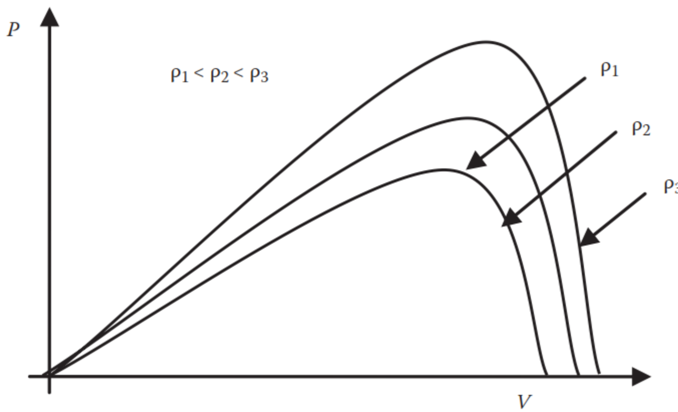


Figure 6.22 Effect of irradiance on PV output power.

Temperature

- Inceasing temperature
  - Reduces open circuit voltage of the cell
  - Increases output current of the cell
  - Reduces maximum power point of the cell
- Solar cell should be operated in a cool environment with high irradiation

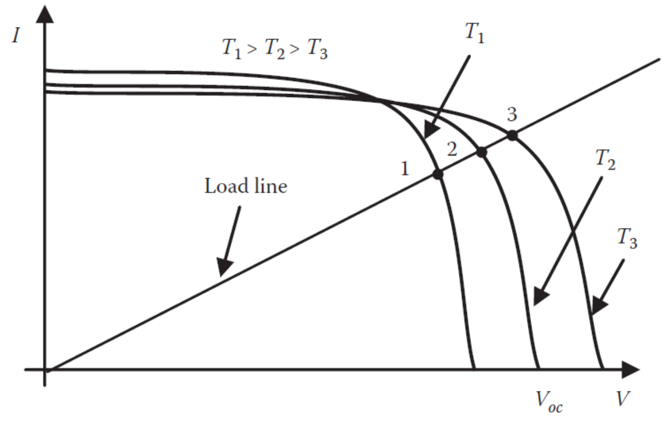


FIGURE 6.23 Effect of temperature on the operating point.

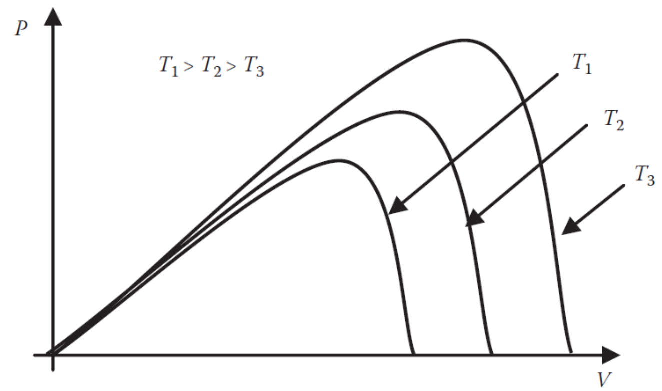


FIGURE 6.24 Effect of temperature on PV output power.

PV modules or panels

- Several cells are connected in series and parallel to make panels

Module or panel Array System

Figure 6.25 PV module, PV array, and PV system. (Images courtesy of the US Department of Energy, Washington, DC.)

Series connections

- Series connection increases voltage
- Same current flows through all cells
- Shading has an effect on the current of the whole panel, i.e. current is the lowest one

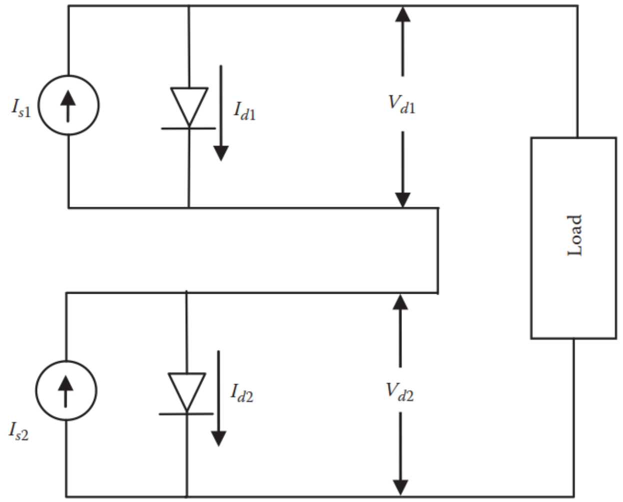


Figure 6.26 Solar cells in series.

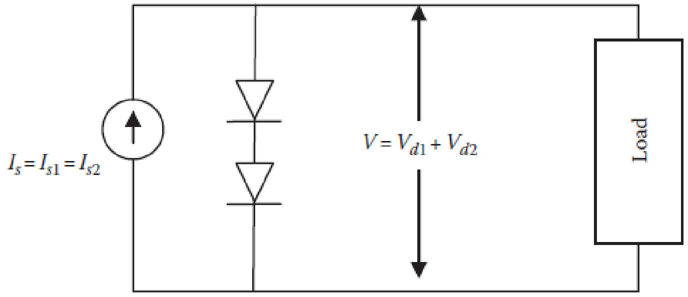


FIGURE 6.27 Equivalent circuit for solar cells in series.

Parallel connection

- Parallel connection increases the current of the panel
- Voltage is the voltage of a single cell, i.e. low
- In practice both series and paralle connections of cells is used

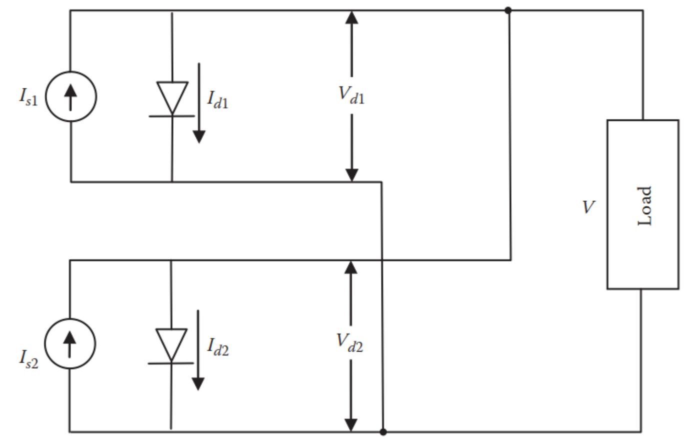


Figure 6.28 Solar cells in parallel.

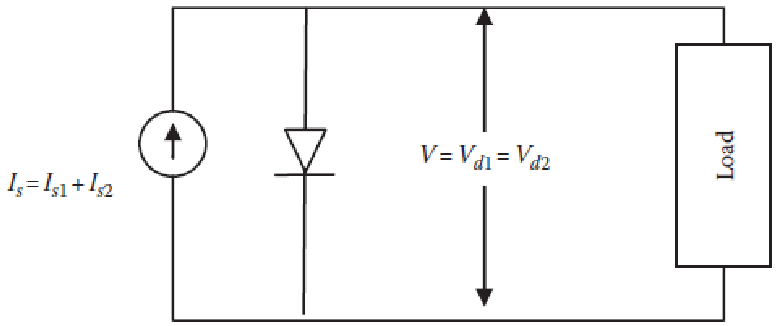


FIGURE 6.29 Equivalent circuit of solar cells in parallel.

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

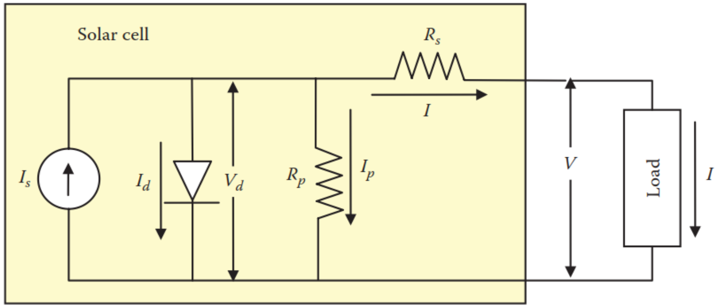


Figure 6.32 Model of real PV cell.

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

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

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

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

Photovoltaic systems

Figure 6.33 Various photovoltaic systems. (Image courtesy of the US Department of Energy, Washington, DC.)

PV systems

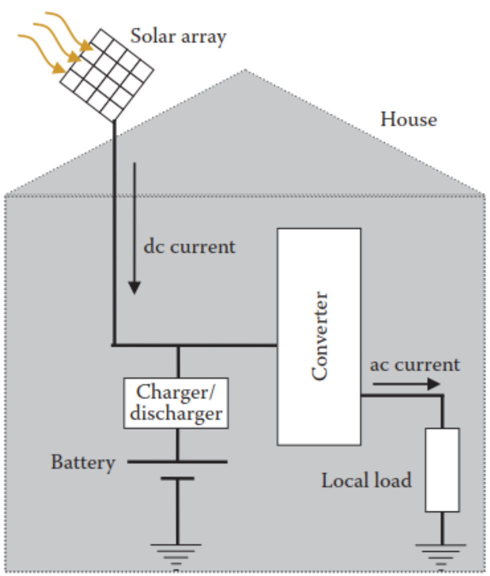


Figure 6.34 Storage PV system.

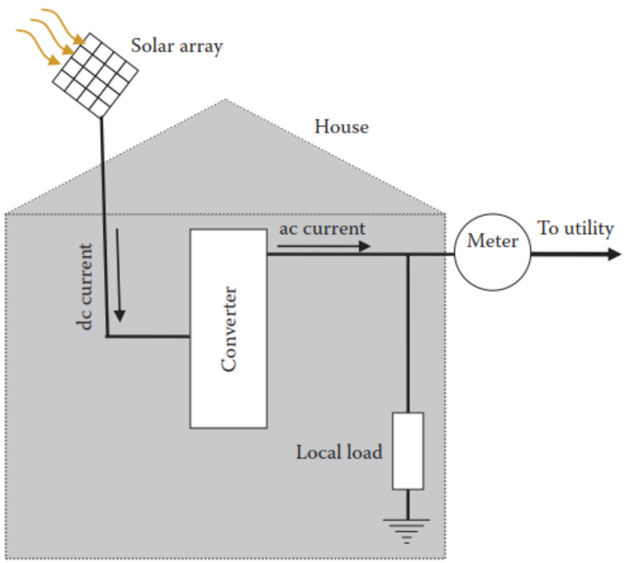
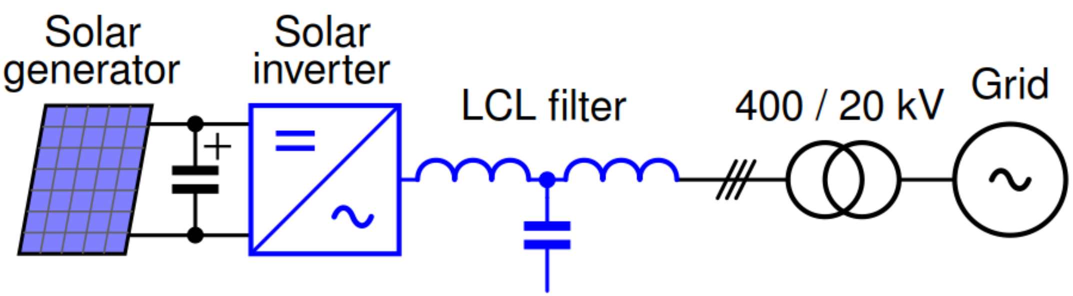


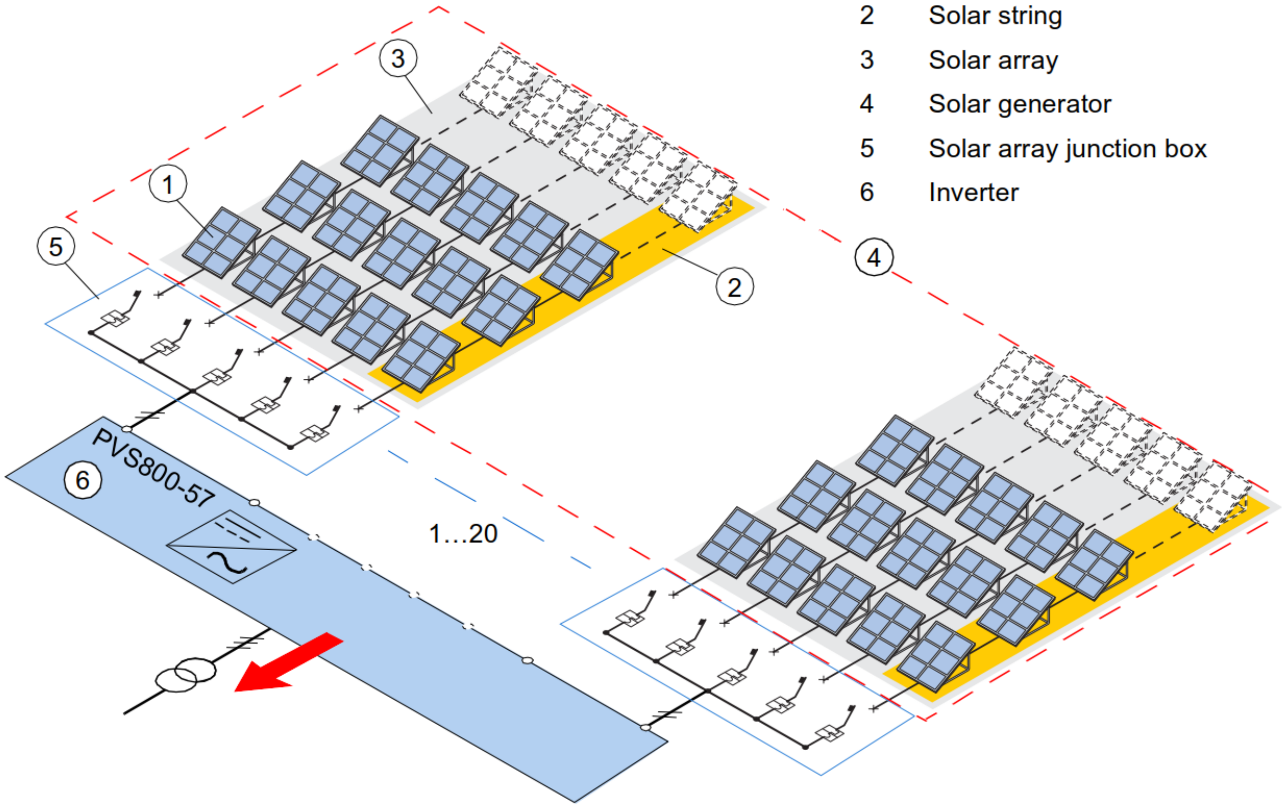
Figure 6.35 Direct PV system.

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



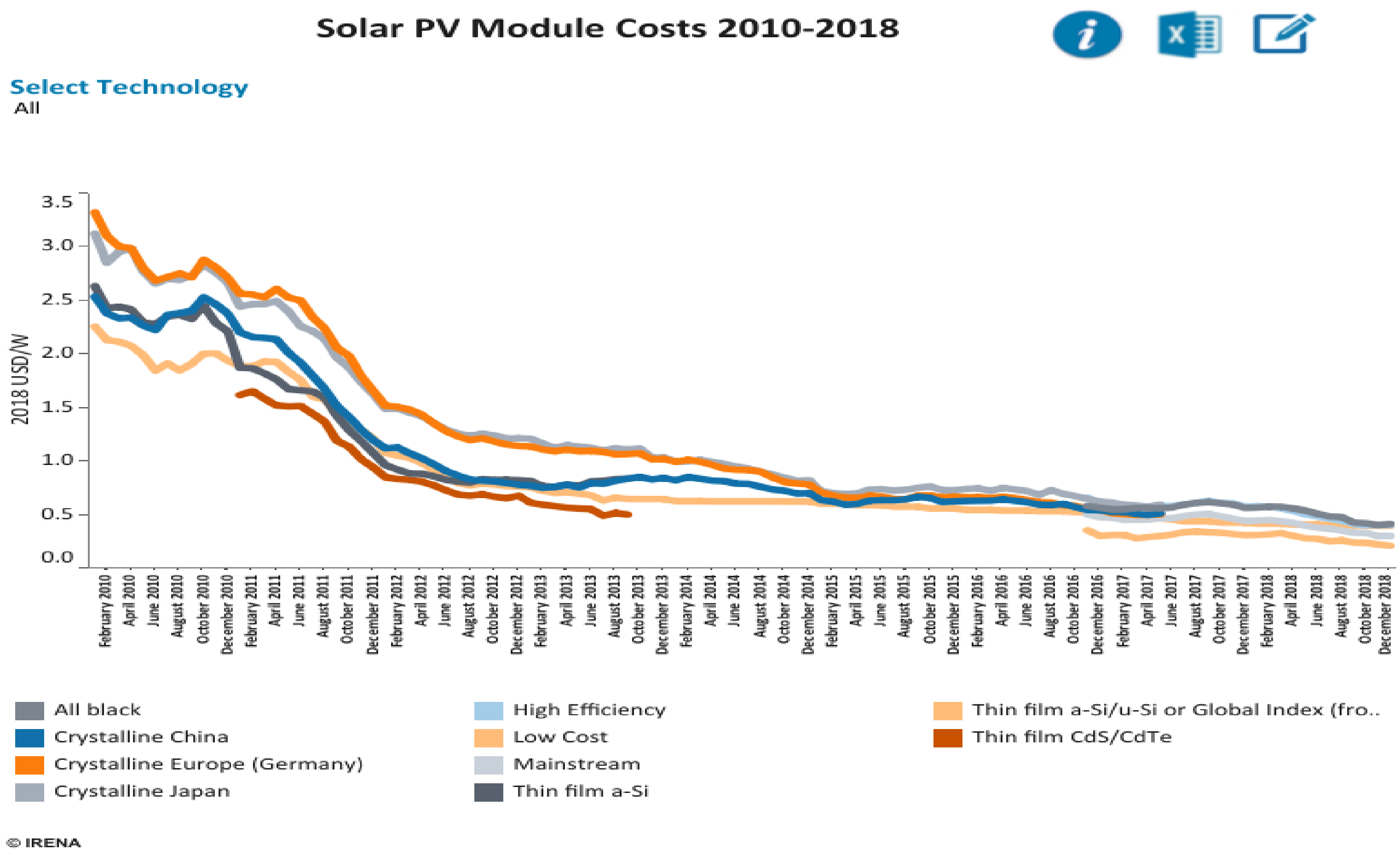
Central Inverter



1 Solar module (photovoltaic module)
2 Solar string
3 Solar array
4 Solar generator
5 Solar array junction box
6 Inverter

Figure: ABB

Solar PV Module Prices

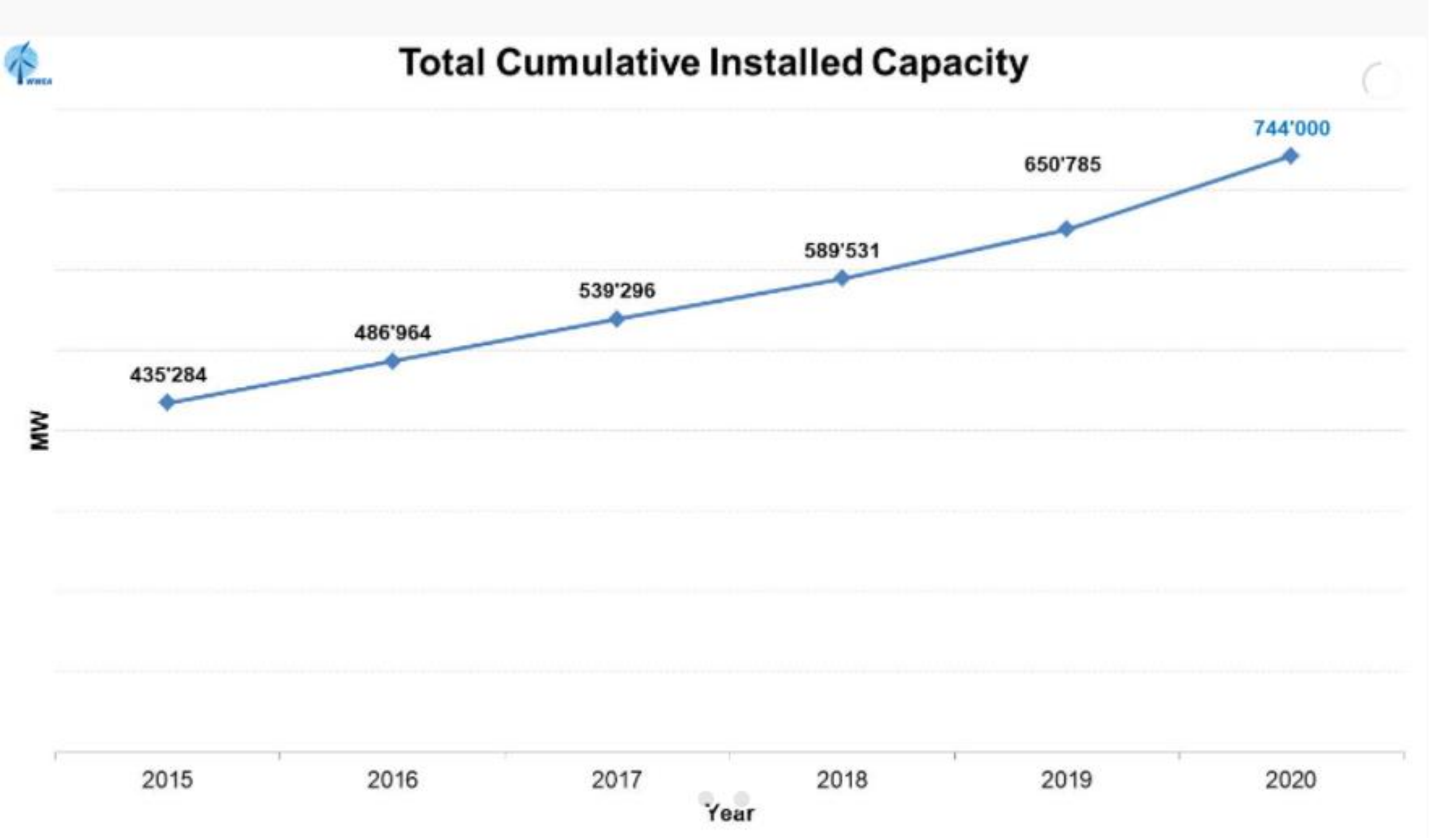


6.2 Wind Energy

- 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

- http://www.wwindea.org

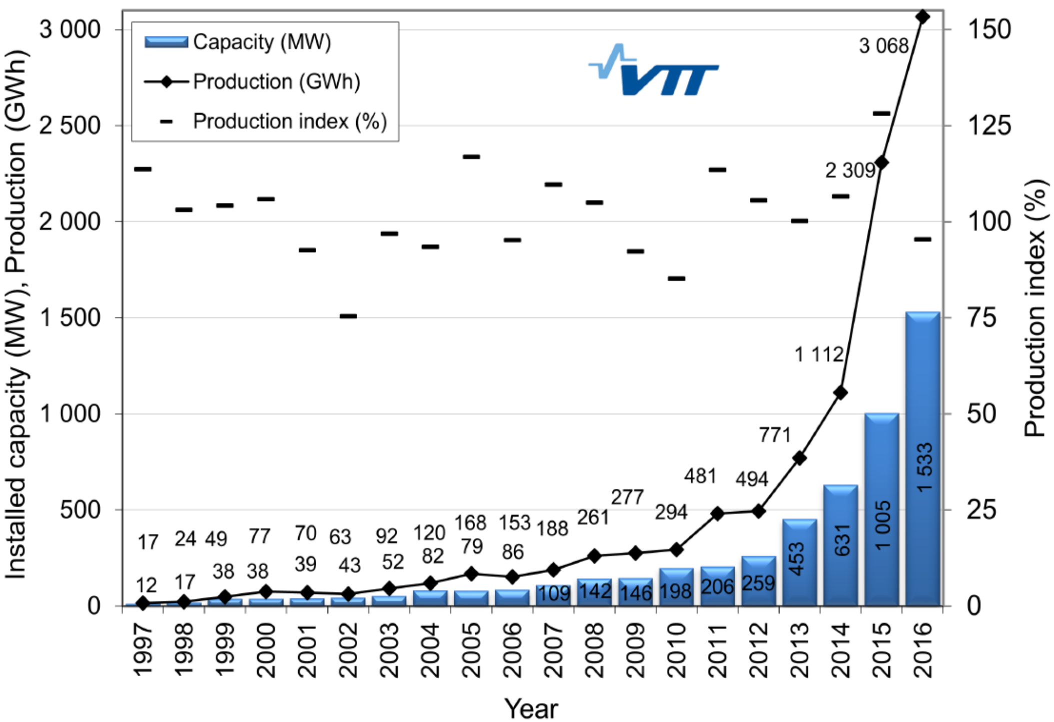


Wind energy by country

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**	**[illegible]3'000**	**650'785**	**589'547**

Finish Wind Energy Statistics

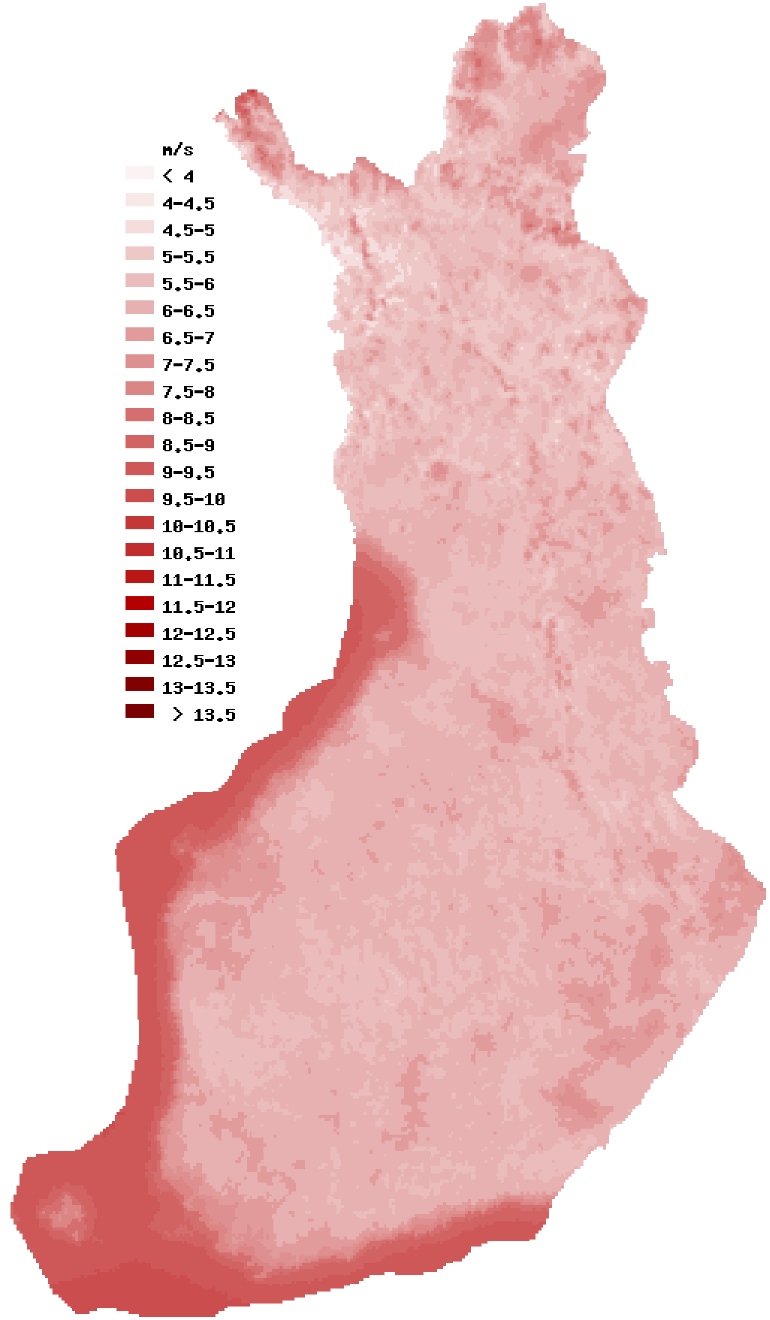
- https://tuulivoimayhdistys.fi/en/wind-power-in-finland/projects-under-planning
- Locations of current and planned turbines turbines



Production index is explained in slide 39

Finish wind atlas

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



Definitions (1/2)

- **Energy production per wiped area of the rotor (kWh/m2)**
  - If this is calulated from annual production and result is more than 1000 kWh/m2, result can be conisered 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)

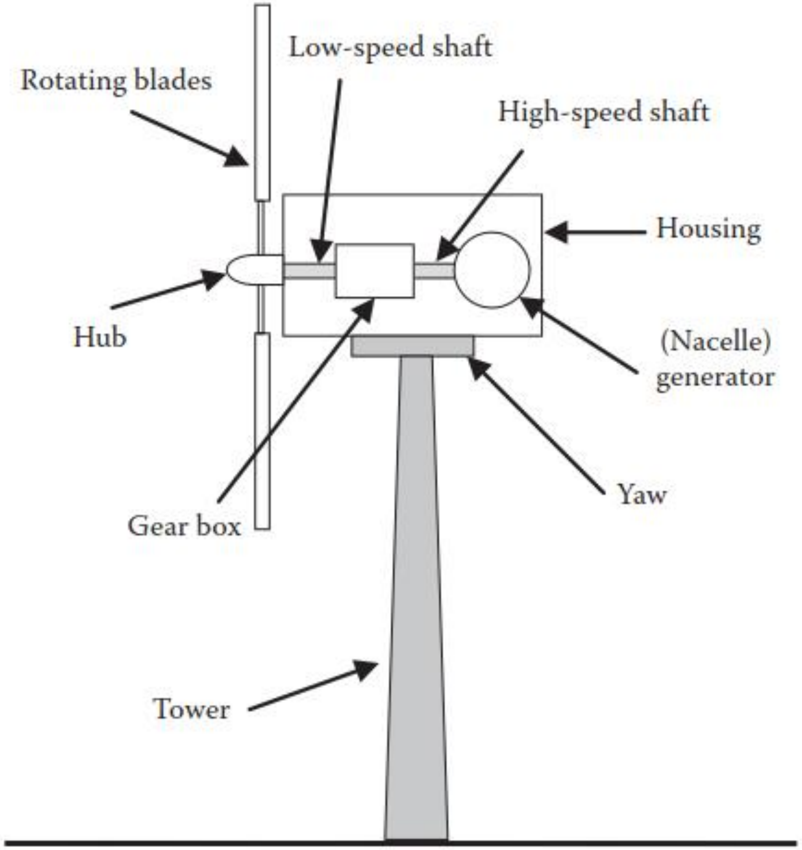
- **Production index (tuotantoindeksi) IL (%)**
  – Calculated production based on measured wind data divided by the long term calculated average production data
  – At the moment in Finland the average production has been estimated by wind data between 1987 - 2001
  – Measured wind data is transferred 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 $$KE = \frac{1}{2} m w^2 \qquad KE = \frac{1}{2} A \delta t w^3$$
  - *m*, mass of the moving object,
  - *w*, velocity in m/s,
  - δ density of air kg/m3

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

Wind generator



(a) (b)

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

Wind turbine

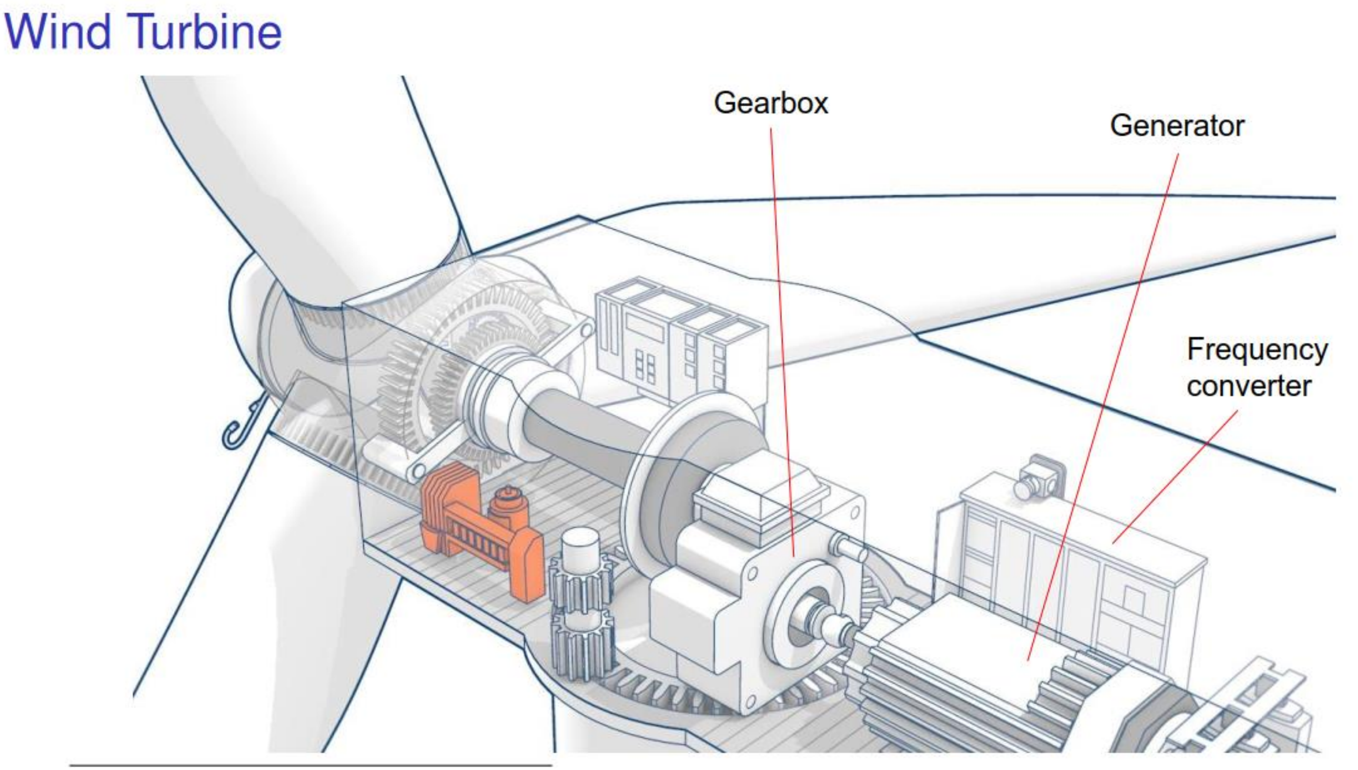


Figure: ABB (modified)

Blades

(a) (b)

Figure 6.40 (a) Housing and (b) blade of a 1.8 MW wind generating system.

Generation of aerodynamic force

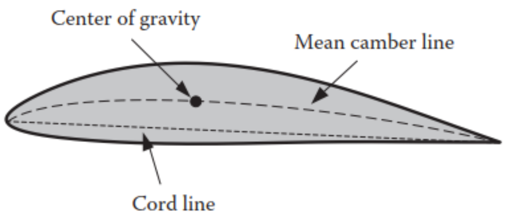


Figure 6.42 Mean camber line, center of gravity of airfoil, and cord line.

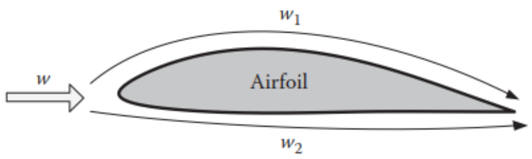


Figure 6.43 Flow of air around airfoil.

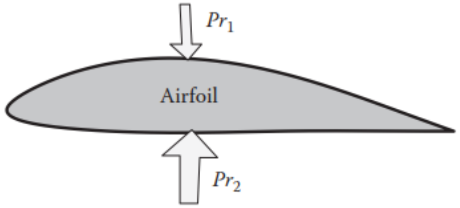


Figure 6.44 Bernoulli's principle.

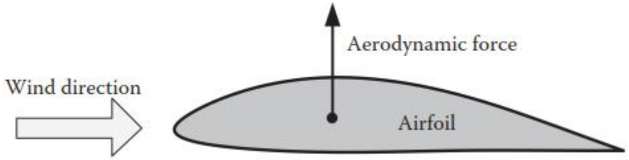


Figure 6.45 Aerodynamic force.

Angle of attack, α

F_L, lift force
F_D, drag force

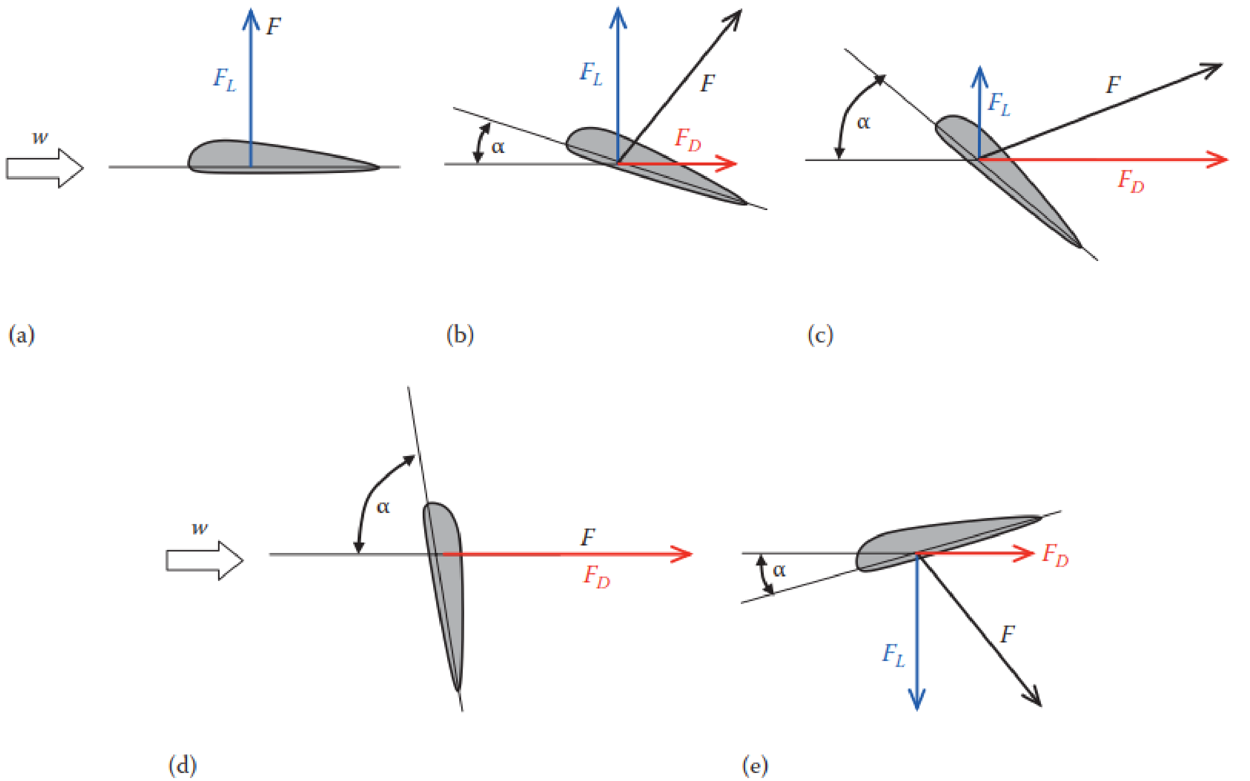


Figure 6.46 Aerodynamic forces and angle-of-attack: (a) horizontal position—all aerodynamic force is lift; (b) positive angle-of attack—aerodynamic force has lift and drag; (c) increasing positive angle-of attack, less lift, and more drag; (d) increasing positive angle-of attack until aerodynamic force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

Lift force and pitch angle β

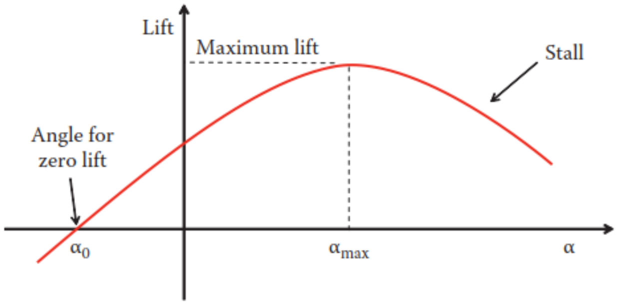


Figure 6.47 Lift force as a function of angle-of-attack.

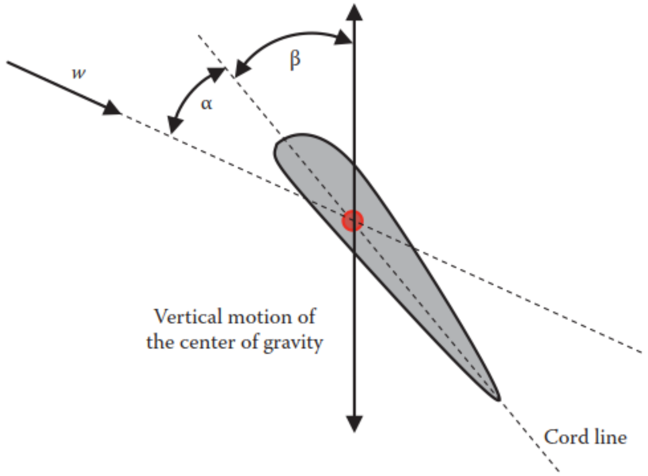


Figure 6.48 Relative wind speed, angle of attack and pitch angle.

Losses in wind turbine

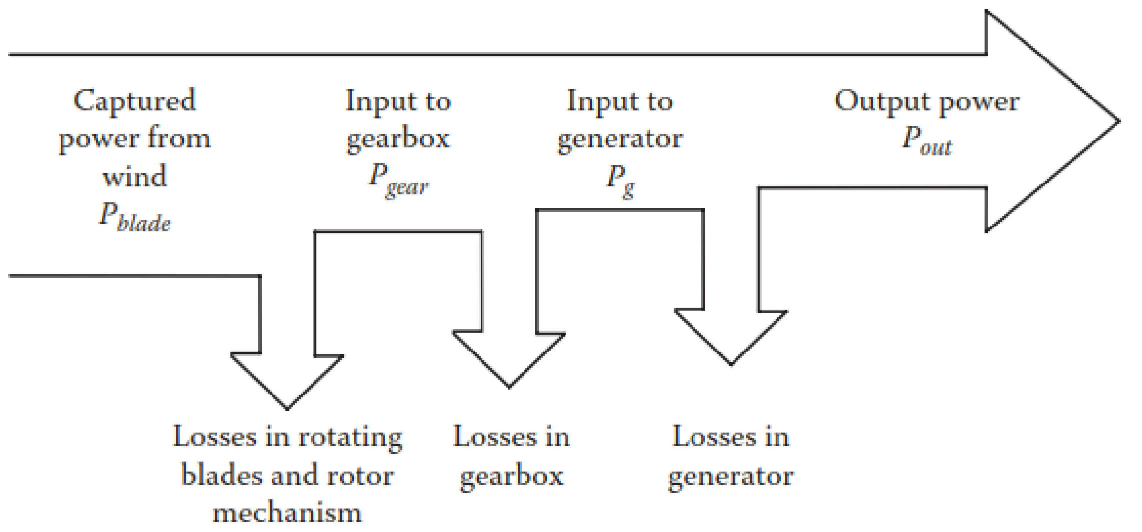


Figure 6.49 Power flow of a wind turbine.

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

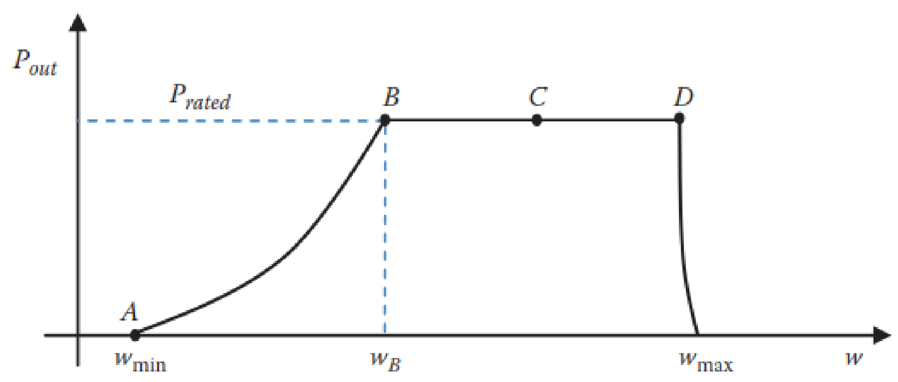


Figure 6.50 Output power of wind turbine.

Tip speed ratio, TSR

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

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

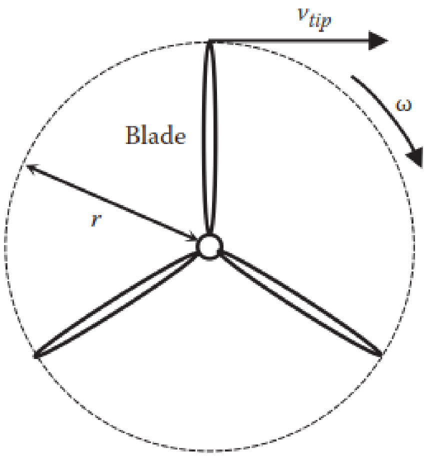


Figure 6.51 Tip velocity.

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

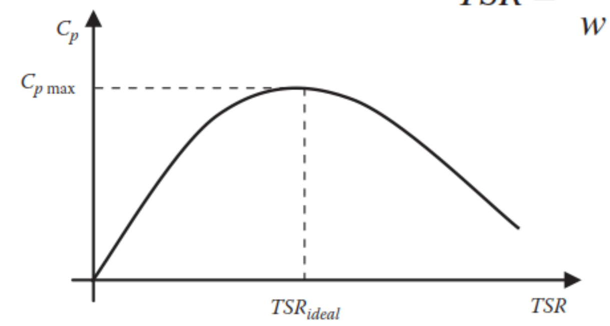


Figure 6.52 Coefficient of performance as a function of *TSR*.

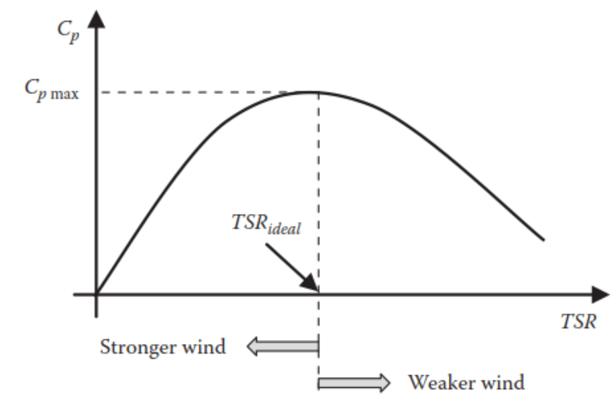


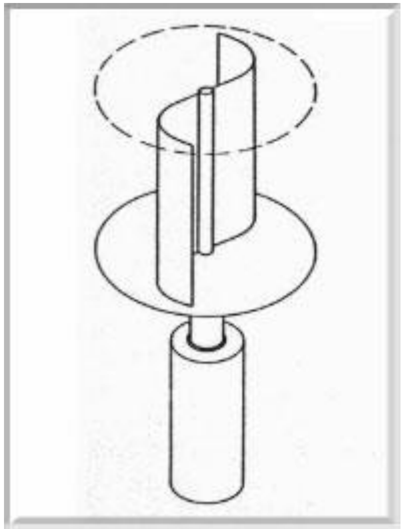
Figure 6.53 Tracking maximum C_p by adjusting the speed of the blade.

Horizontal axis

Figure 6.57 Horizontal axis wind turbines.

Figure 6.58 Lifting of gearbox and brakes of HAWT. (Courtesy of Paul Anderson through Wikipedia.)

Vertical axis



Savonius
rotor

Figure 6.59 Vertical axis wind turbine. (Courtesy of US National Renewable Energy Lab.)

Electrical connection

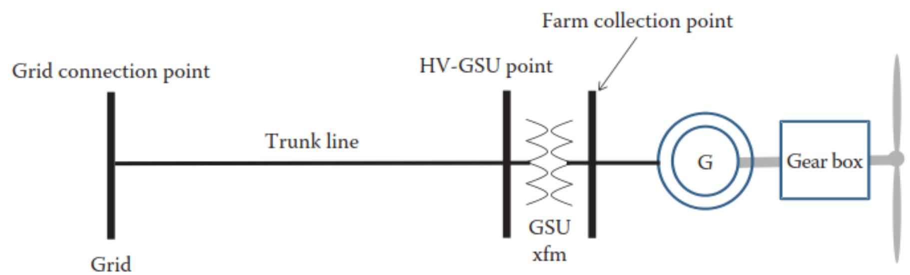


Figure 6.60 Type 1 wind turbine system.

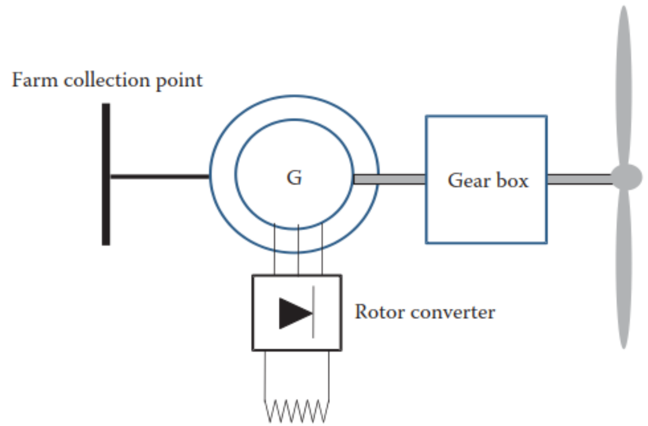


Figure 6.61 Type 2 wind turbine system.

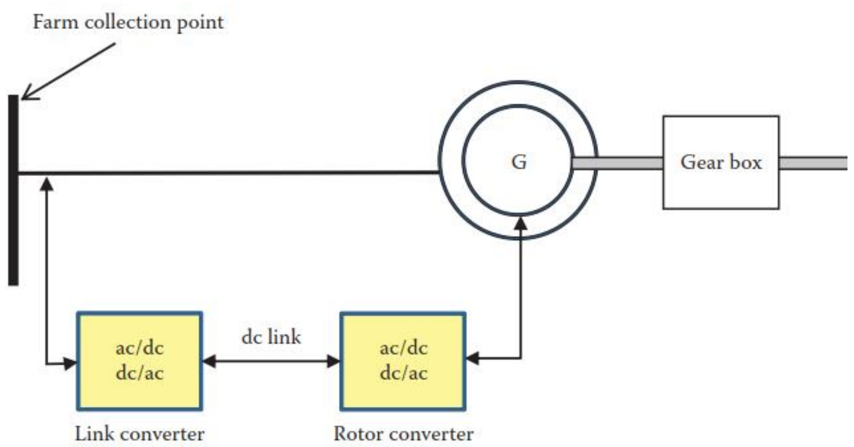


Figure 6.62 Type 3 wind turbine system.

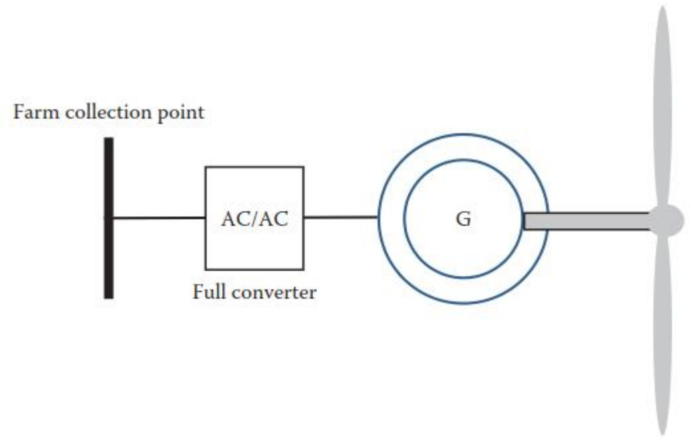


Figure 6.63 Type 4 wind turbine system.

Wind farms

Figure 6.65 Wind farm located in California. (Images are courtesy of the U.S. Department of Energy, Washington, DC.)

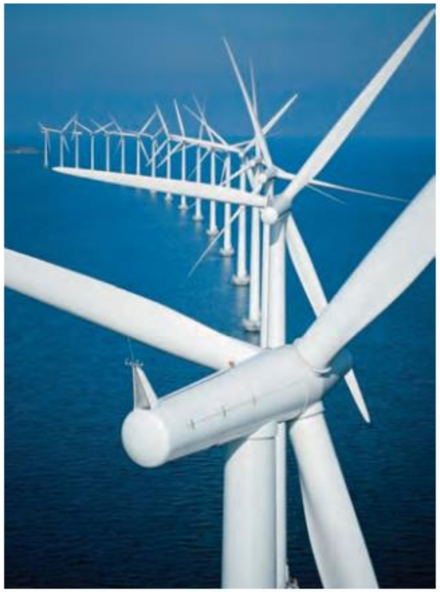


Figure 6.66 Two megawatt offshore wind turbine farm in Denmark. (Image courtesy of LM Glasfiber Group.)

Future Concepts: Superconducting Direct-Drive Generators

High Temperature Superconductor (HTS), Operated at 30. . . 50 K

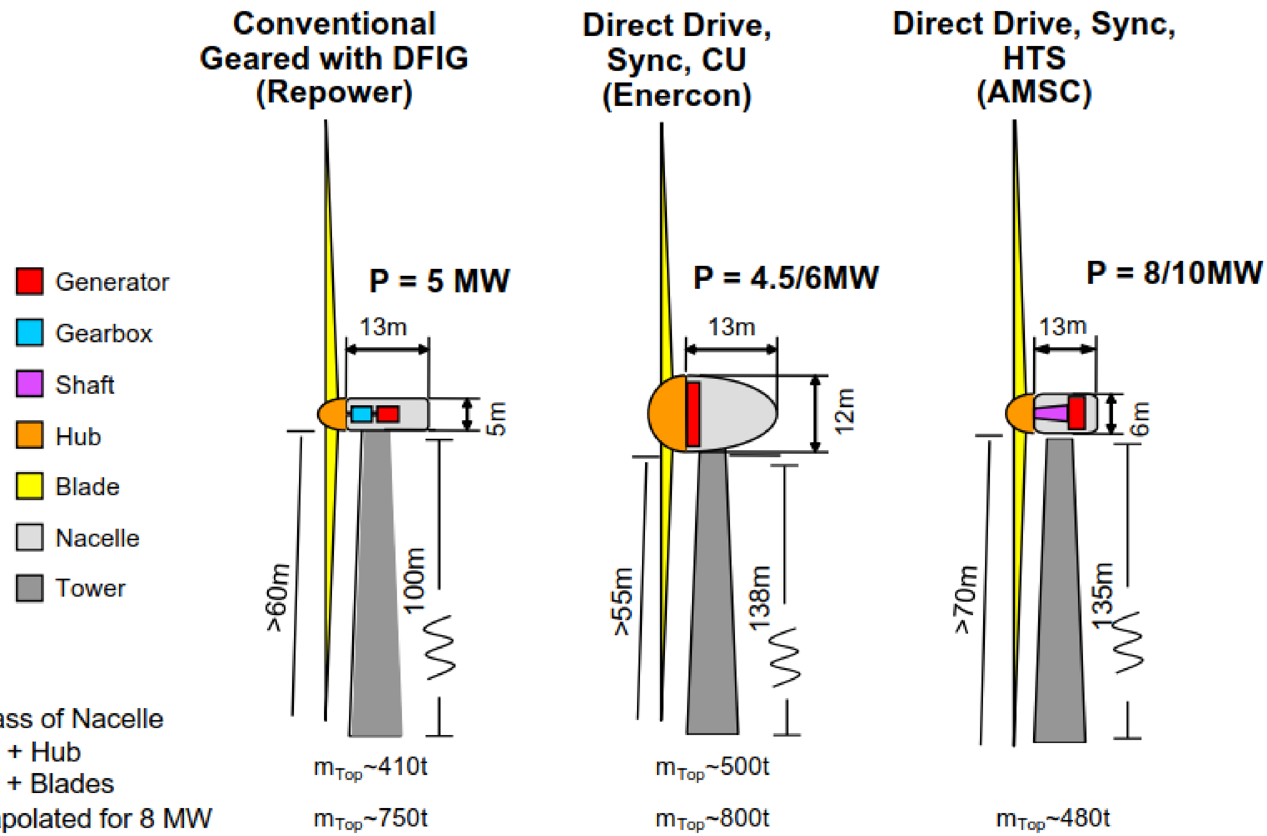
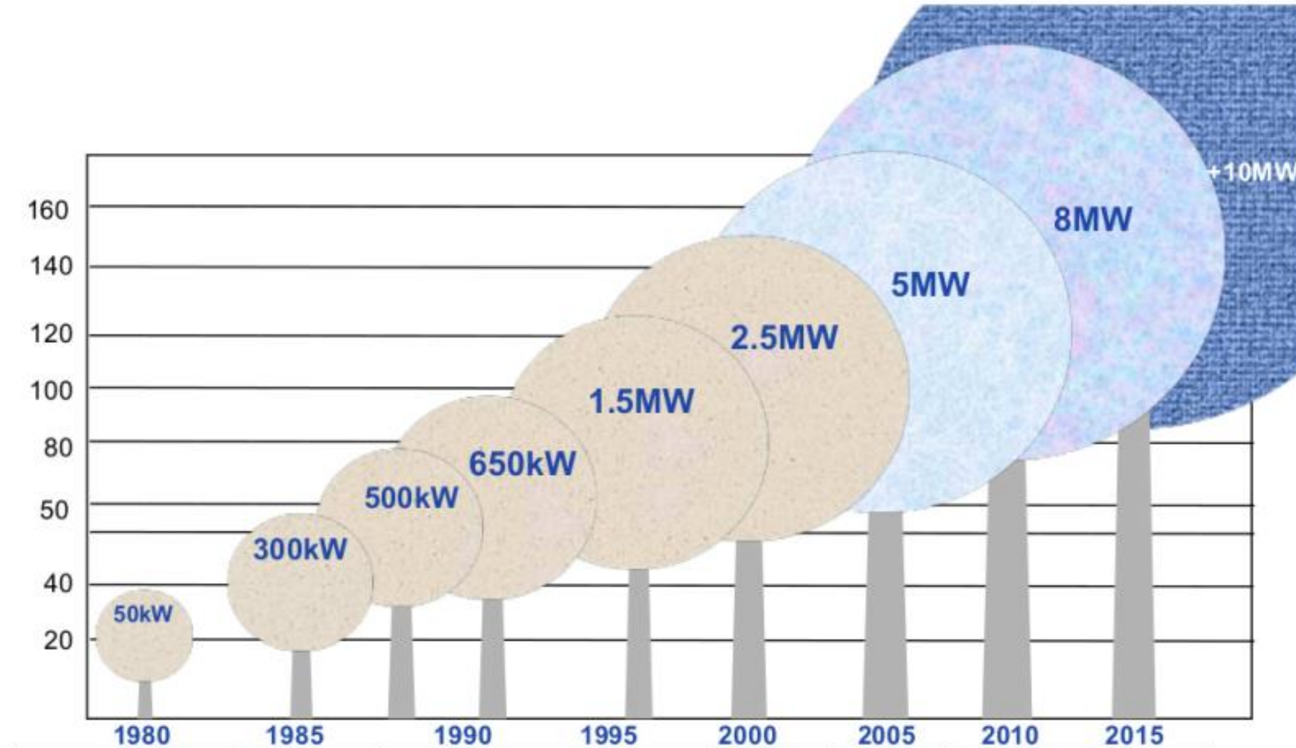


Figure (modified): D. McGahn, "Drivetrains: direct drive generators and high temperature superconductor based machines," MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

Growth in Turbine Size



Drive Train	Induction	DFIG	DFIG	DFIG	Full Conv.	PM	FC HTS
Tower Height (m)	60	70	75	80	100	120	140
Top Weight (Metric Tons)	50	100		200		400	450

DFIG = Doubly Fed Induction Generator

PM = Permanent Magnet Machine

FC HTS = Full Converter High Temperature Superconductor (Note: HTS not reality even today in industrial scale)

Figure (modified): D. McGahn, "Drivetrains: direct drive generators and high temperature superconductor based machines," MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

6.3 Hydrokinetic Systems

- Small Hydro Systems
- Tidal and Stream Energy Systems
- Wave Energy

- Textbook includes a lot details on mechanics, no need to go through

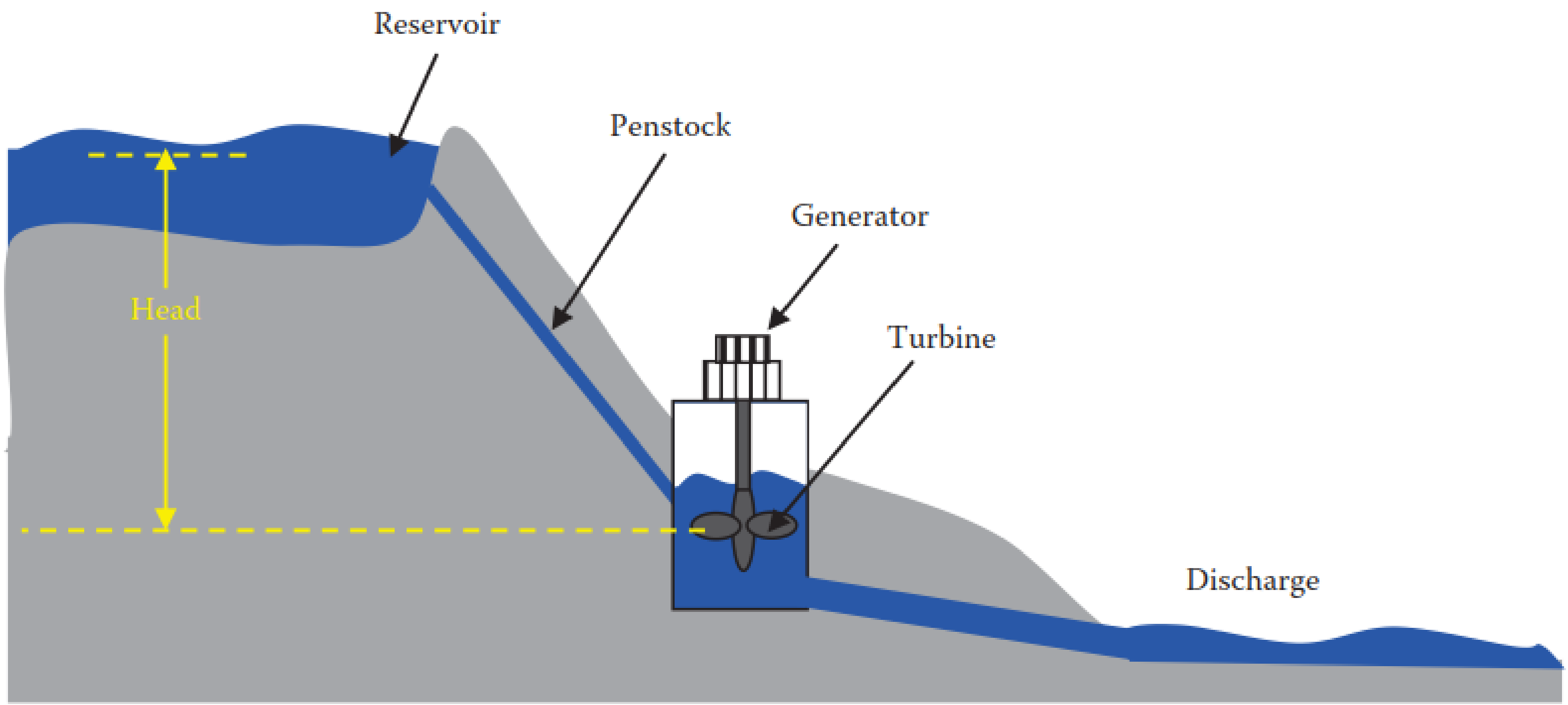


Figure 6.69 Small hydroelectric system with reservoir.

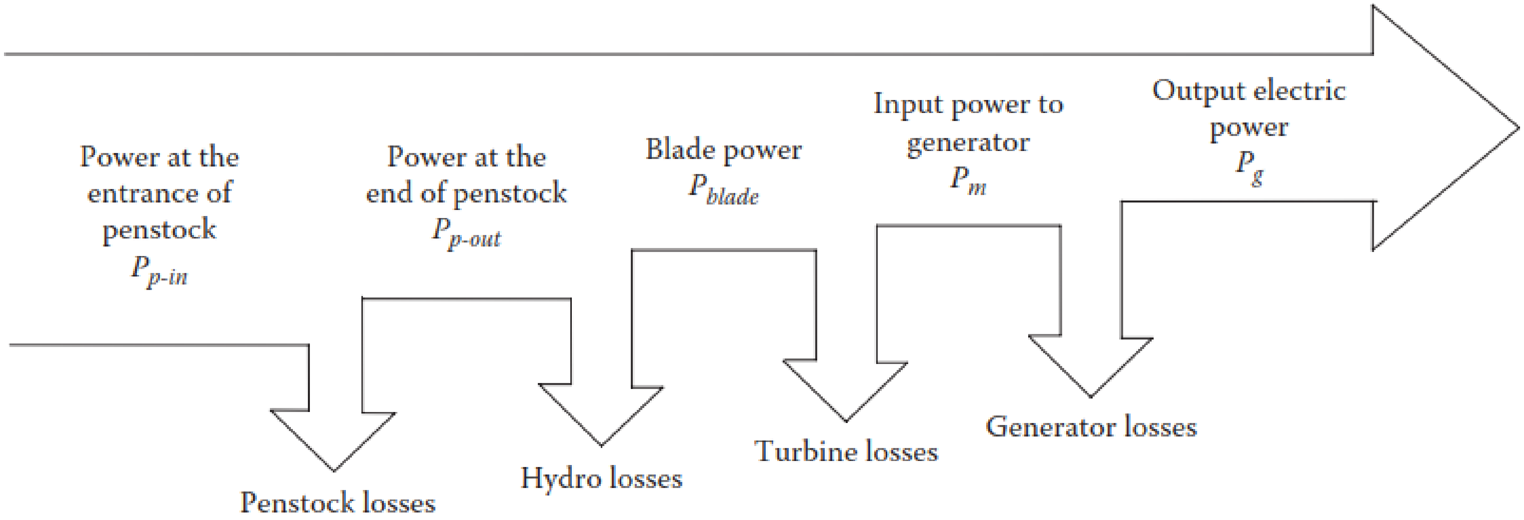


Figure 6.70 Power flow in small hydroelectric system.

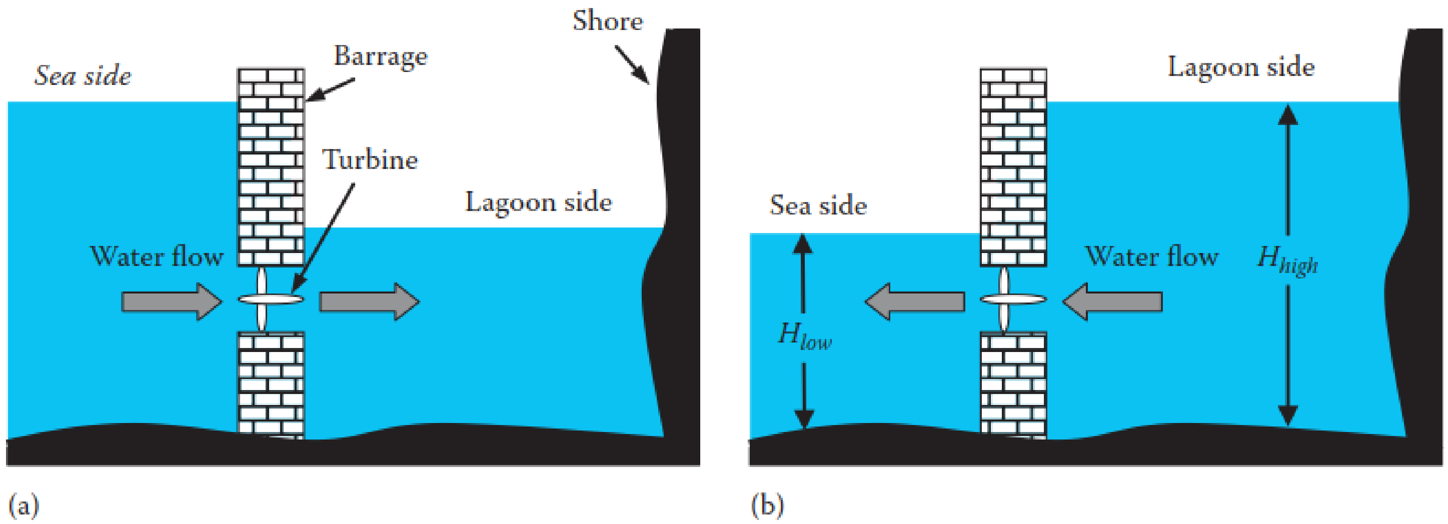


Figure 6.71 Barrage tidal energy system: (a) high tide and (b) low tide.

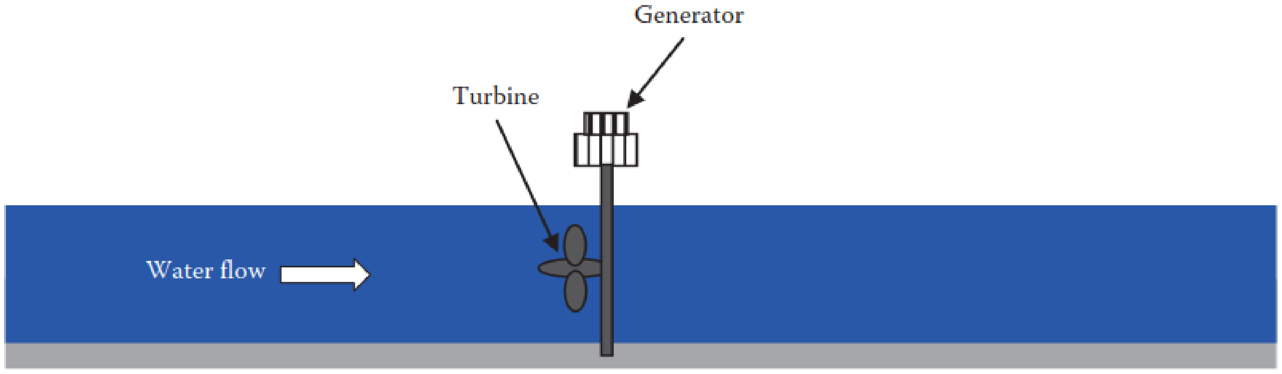


Figure 6.73 Diversion-type small hydroelectric system.

(a) (b)

Figure 6.74 WS energy system: (a) turbine and (b) conceptual design of a farm. (Images courtesy of Marine Current Turbines Limited.)

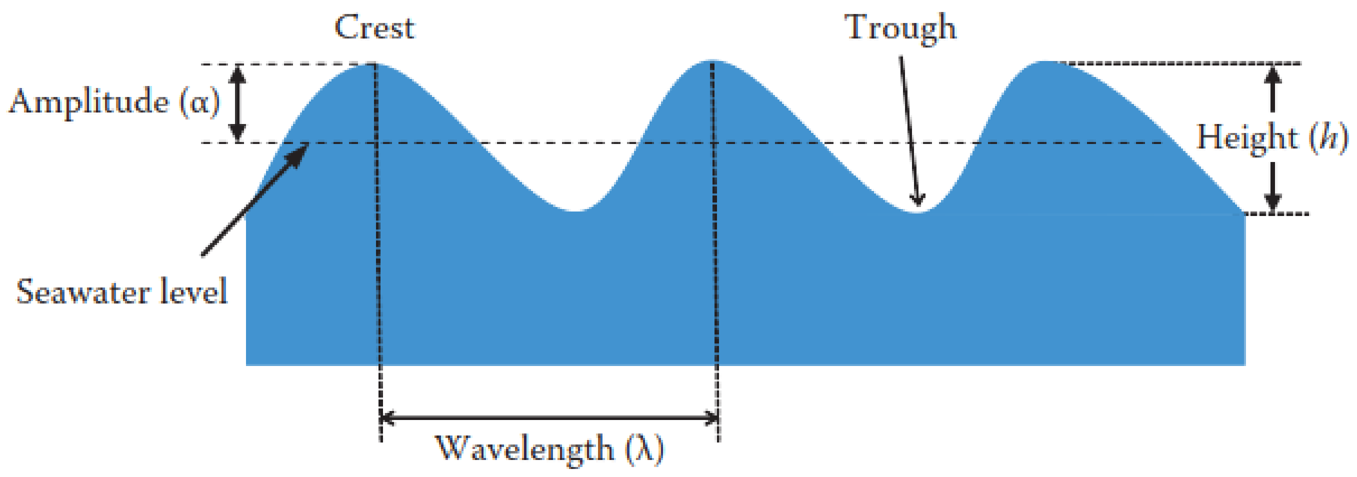


Figure 6.75 Wave parameters.

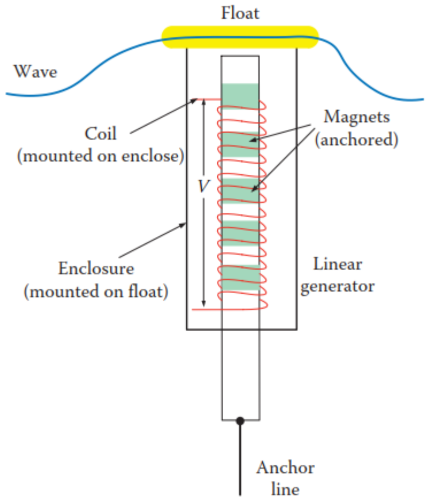


Figure 6.76 Buoyant moored system.

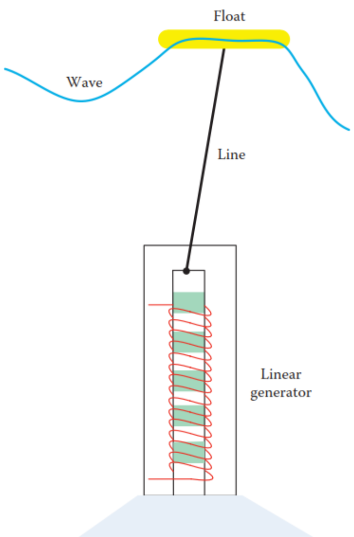


Figure 6.78 Buoyant moored system anchored on ocean floor.

Figure 6.77 Buoyant actuator during the installation. (Courtesy of Carnegie Wave Energy through Wikipedia.)

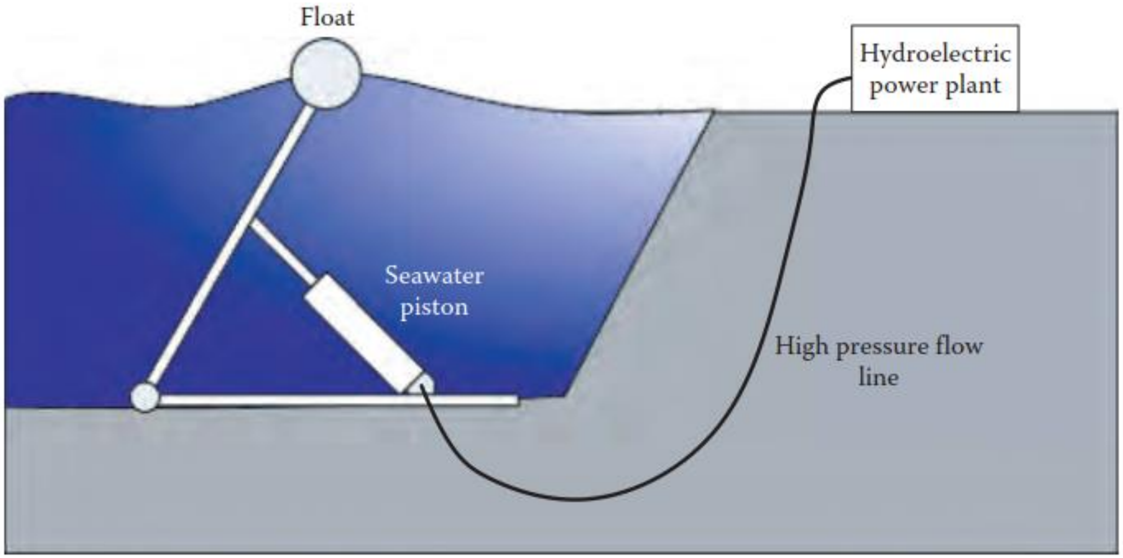


Figure 6.79 Oyster system.

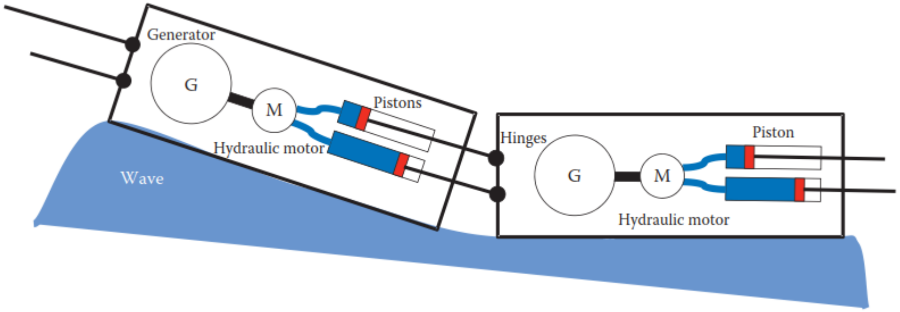


Figure 6.80 Main components of hinged contour system.

Figure 6.82 The front pontoon. (Courtesy of Pelamis Wave Energy through Wikipedia.)

Figure 6.81 HC system. (Courtesy of Pelamis Wave Energy through Wikipedia.)

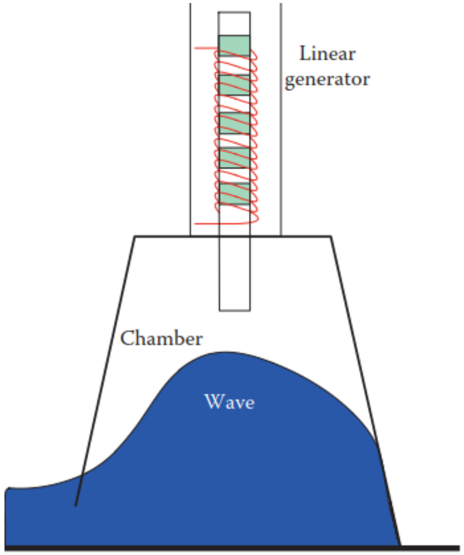


Figure 6.83 Oscillating column system.

6.4 Geothermal Energy

- Heat Pumps
- Electricity production

Earth temperature profile

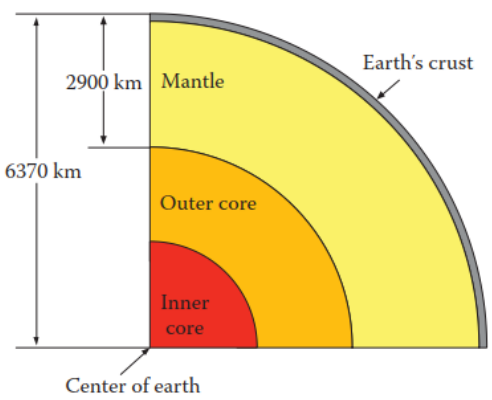


Figure 6.84 Cross section of Earth.

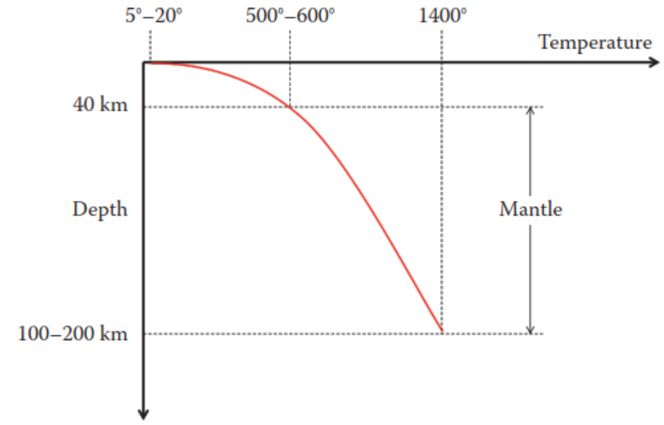


Figure 6.85 Geothermal gradient of Earth.

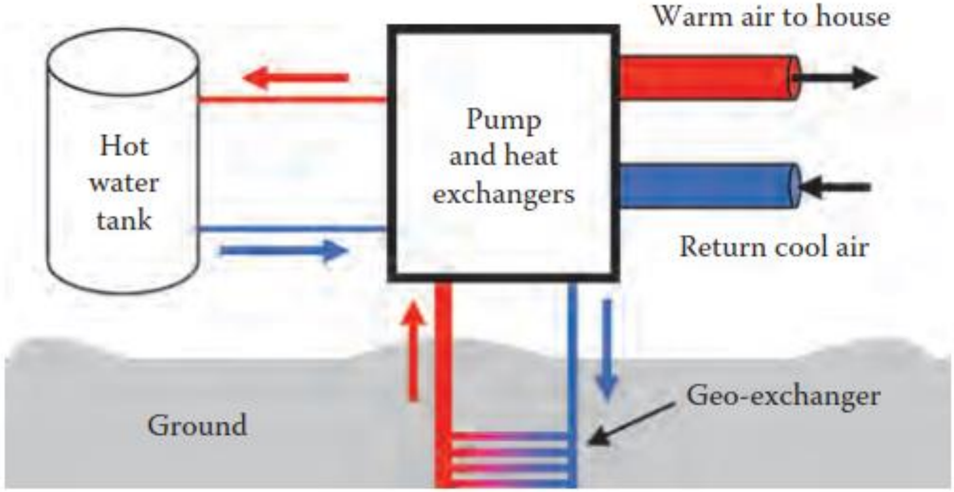


Figure 6.87 Heat pump system.

Figure 6.88 Steam generated from rain even in cold environment.

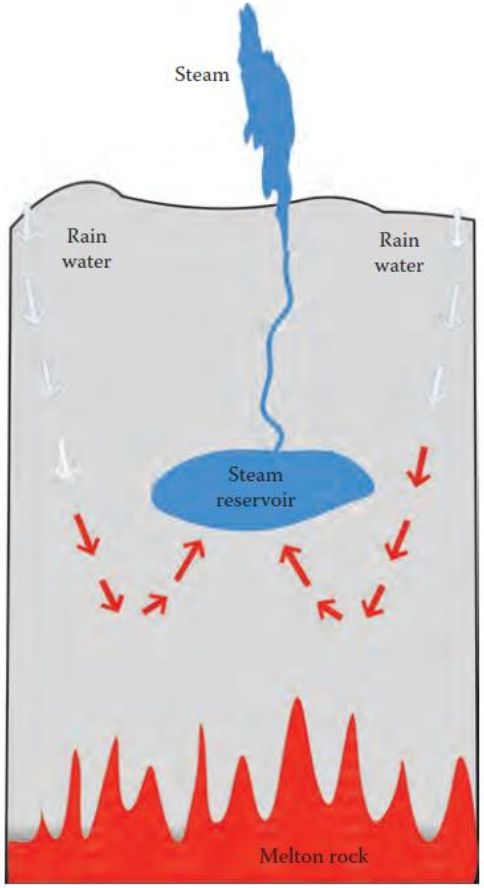


Figure 6.89 Geothermal reservoir.

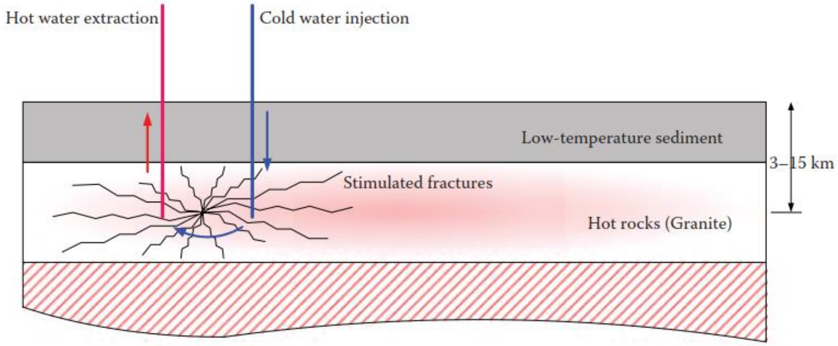


Figure 6.90 Hot dry rock site.

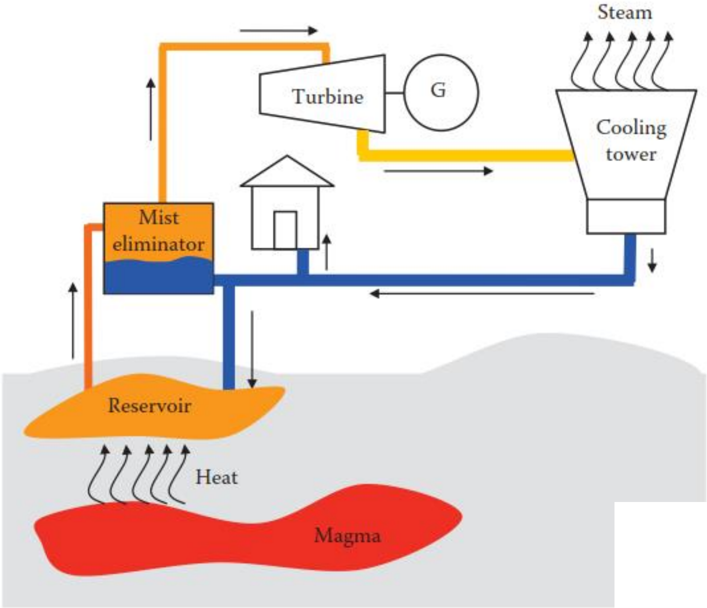


Figure 6.91 Reservoir type geothermal power plant.

Figure 6.93 The Geyser's in northern California—the first geothermal power plant in the United States.

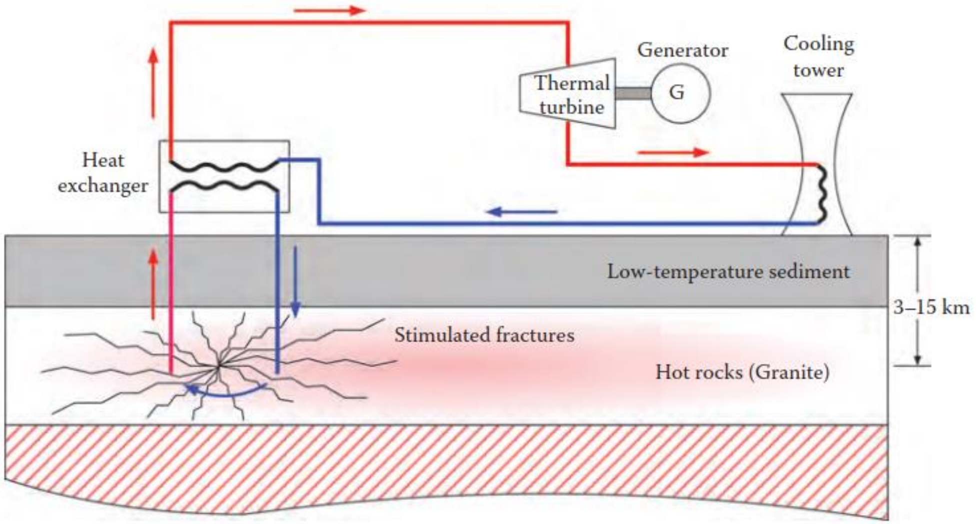
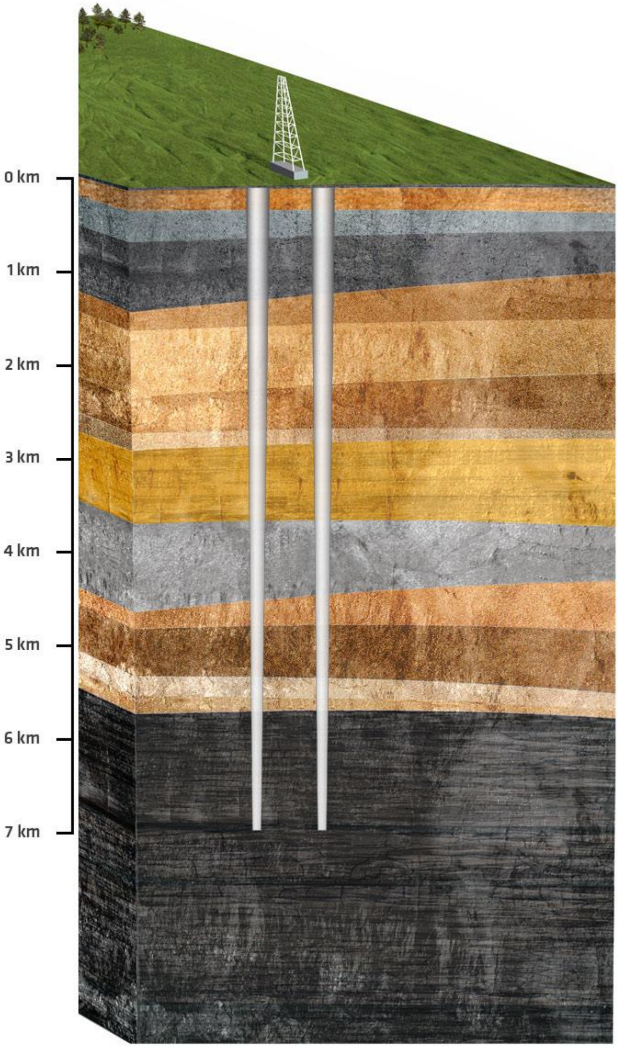


Figure 6.92 Hot dry rock geothermal power plant.

Deep Heat, ST1, Otaniemi

http://www.st1.fi/deepheat
40 MW of heat



Biomass

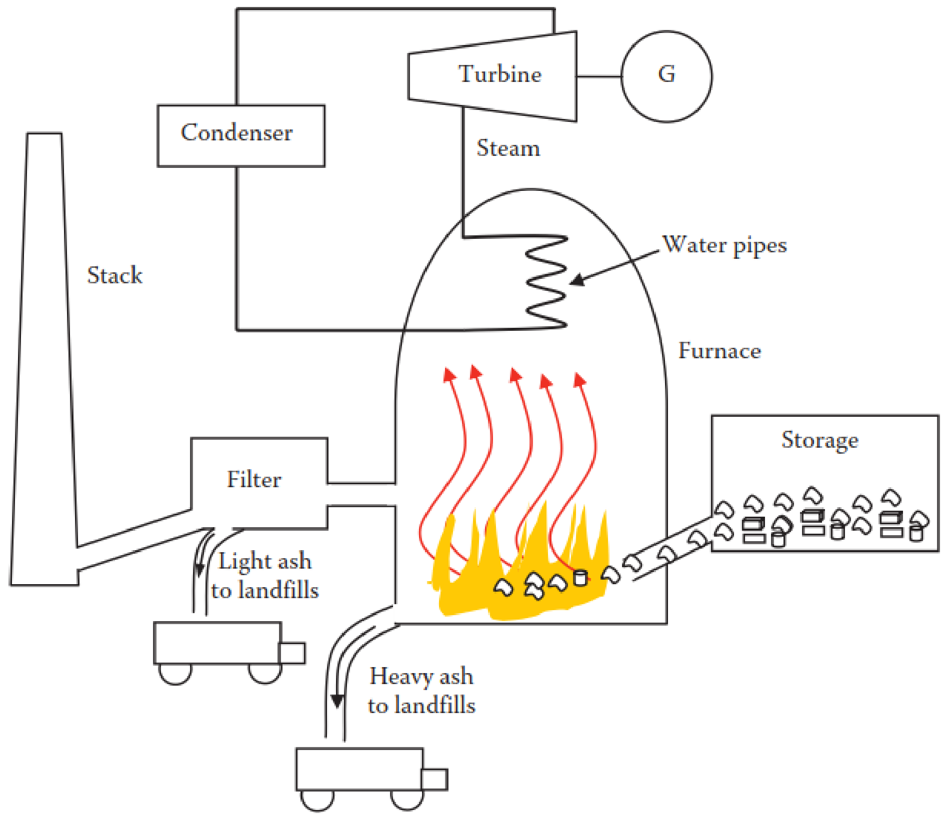


Figure 6.95 Biomass incineration power plant.

6.6 Fuel Cells

- First fuel cells were developed already 1839
- Francis Bacon created nickel based electrodes1939 and later used by NASA in spacecrafts
- Most fuel cels are using hydrogen and oxygen to produce electricity, side product is water
- Some FCs use methanol directly as fuel and do not need separate reformer to produce hydrogen

Fuel Cell Types

TABLE 6.2

Main Types of FCs and Their Operating Characteristics

Fuel Cell	Electrolyte	Anode Gas	Cathode Gas	Approximate Temperature (°C)	Typical Efficiency (%)
Proton exchange membrane (PEM)	Solid polymer membrane	Hydrogen	Pure or atmospheric oxygen	80	35–60
Alkaline (AFC)	Potassium hydroxide	Hydrogen	Pure oxygen	65–220	50–70
Phosphoric acid (PAFC)	Phosphorous	Hydrogen	Atmospheric oxygen	150–210	35–50
Solid oxide (SOFC)	Ceramic oxide	Hydrogen, methane	Atmospheric oxygen	600–1000	45–60
Molten carbonate (MCFC)	Alkali-carbonates	Hydrogen, methane	Atmospheric oxygen	600–650	40–55
Direct methanol (DMFC)	Solid polymer membrane	Methanol solution in water	Atmospheric oxygen	50–120	35–40

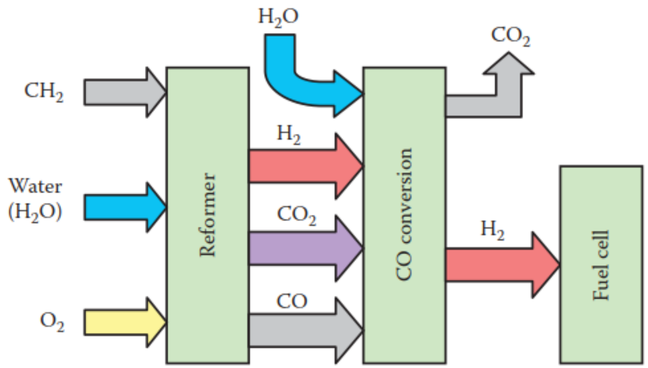


Figure 6.96 Generation of hydrogen.

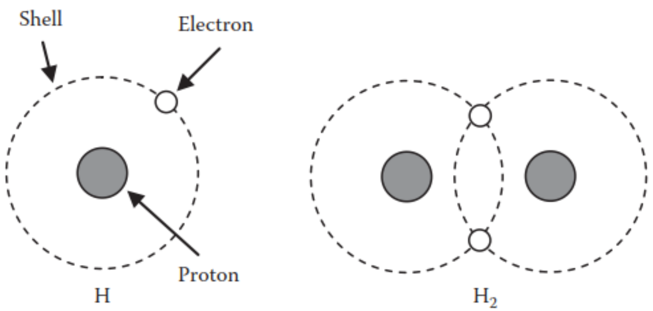


Figure 6.97 Hydrogen atom and hydrogen gas.

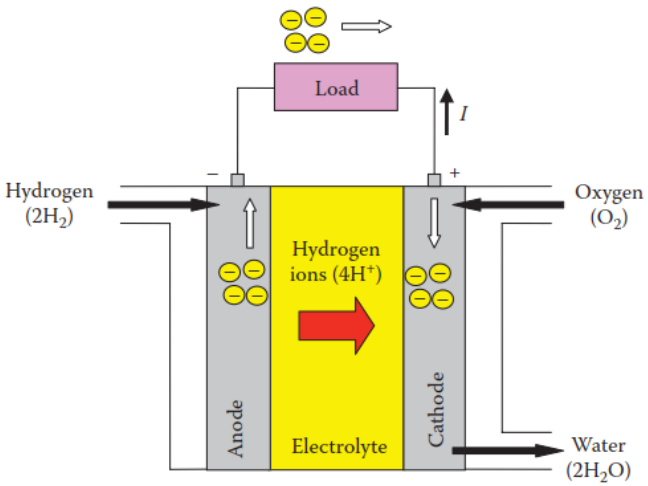


Figure 6.98 PEM FC.

Figure 6.99 PEM fuel cell.

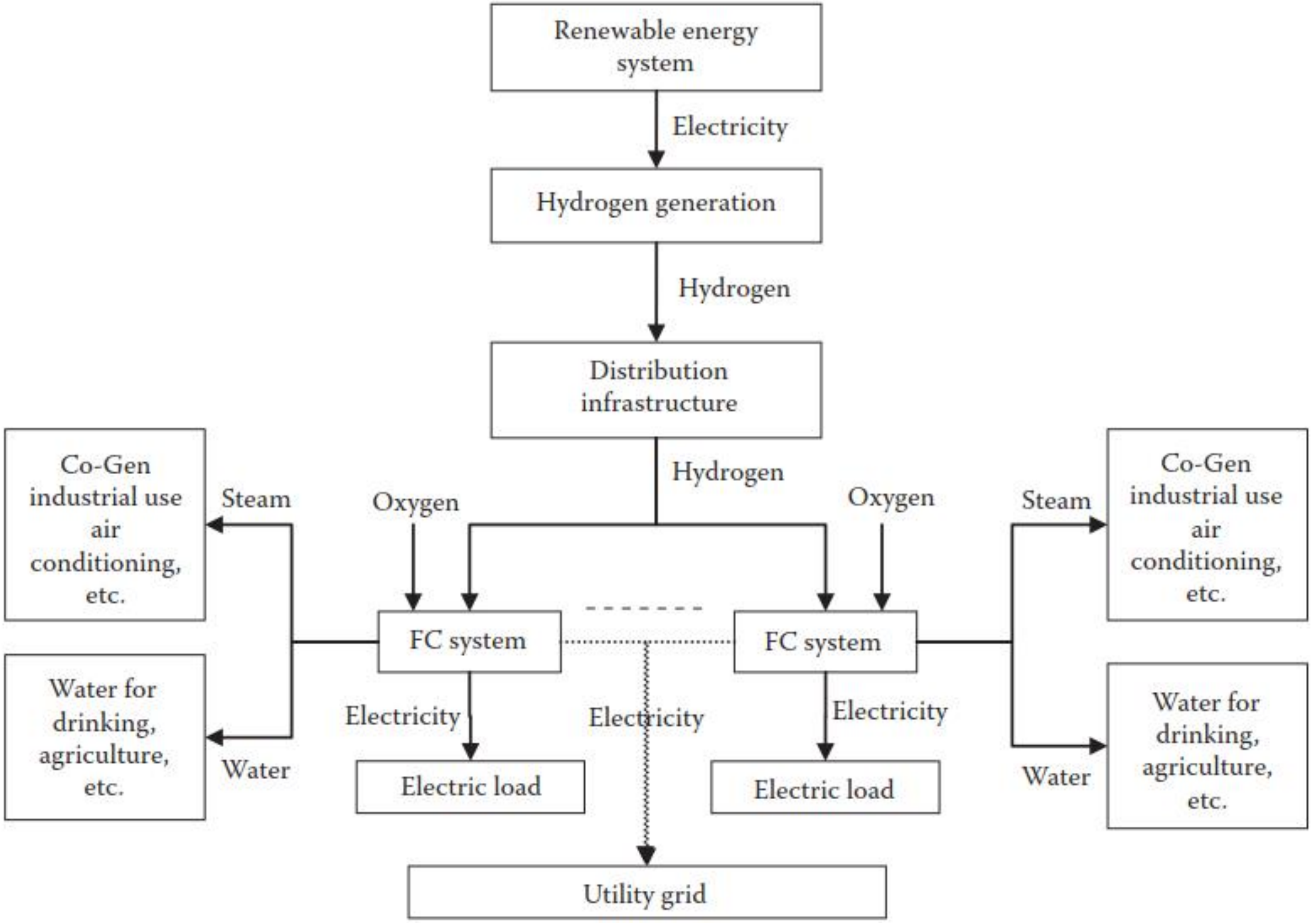


Figure 6.105 Hydrogen-based energy system.

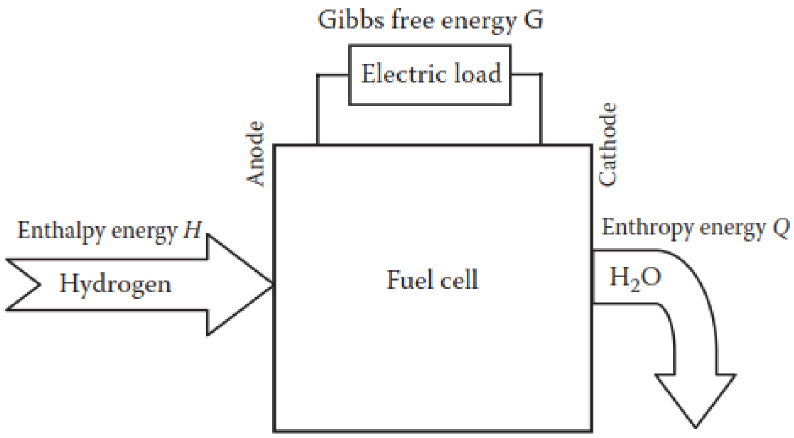


Figure 6.106 Gibbs free energy.

Power Curve of Fuel Cells

- Power curve of FC has similar shape as that of photovoltaic cells though the underlying phenomena are quite different

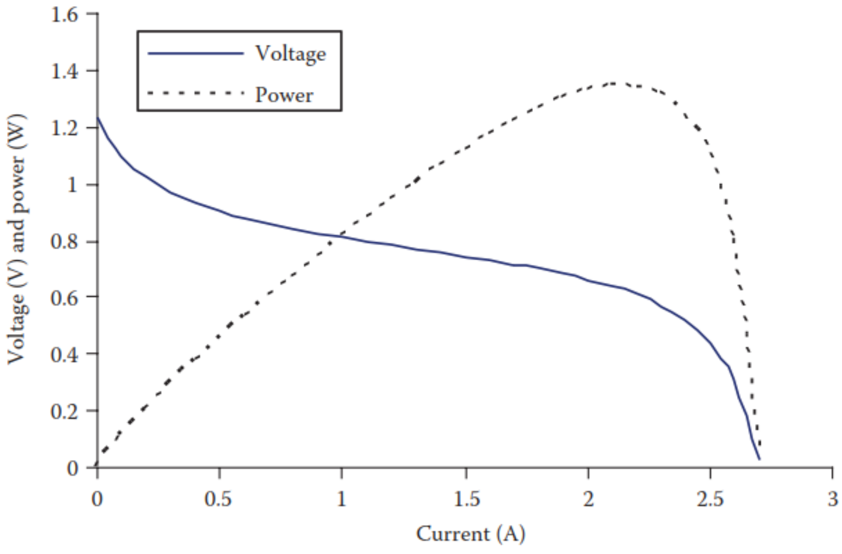


Figure 6.108 Polarization and power curves of FC in Example 6.35.

6.8 Energy Storage Systems

- Production of renewable energy is intermittent and often also very difficult to predict
- Changing production requires
  - Reserve production
  - Storage systems
  - Adjusting consumption, demand side management
- Alessandro Volta developed the first battery already1800, but economic storage in large scale is still one of the big open questions

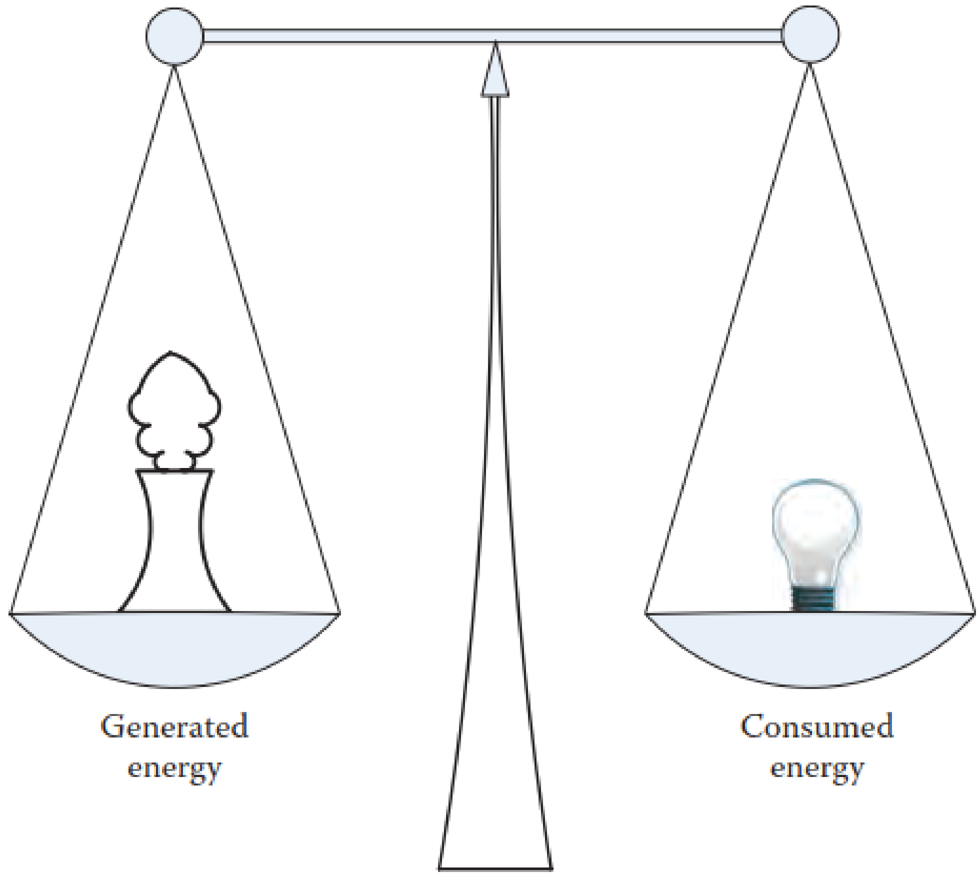


Figure 6.109 Balance of electric energy.

Figure 6.110 PHS system. (Courtesy of the United States Army Corps of Engineers.)

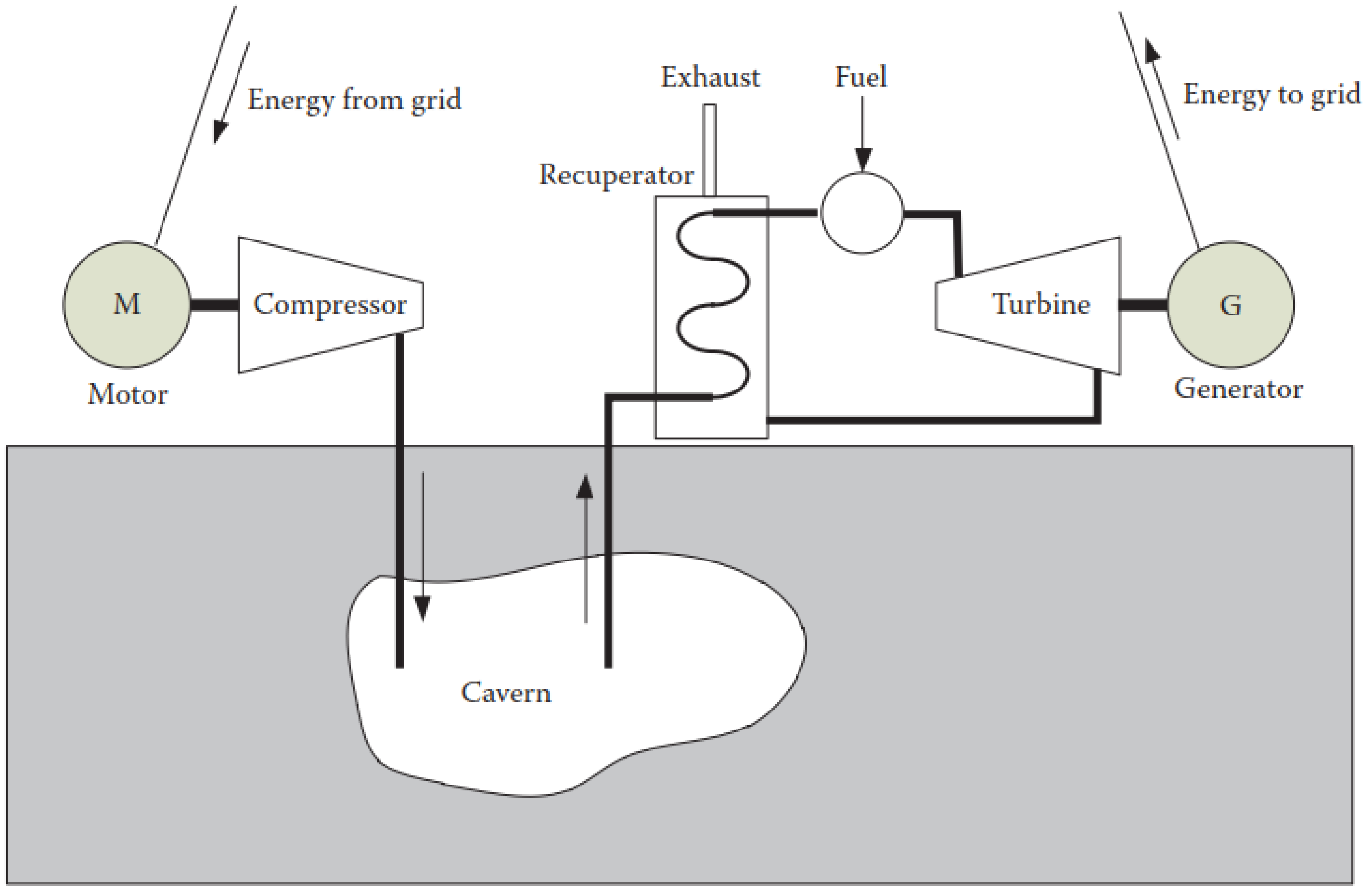


Figure 6.111 Main components of compressed air energy storage system.

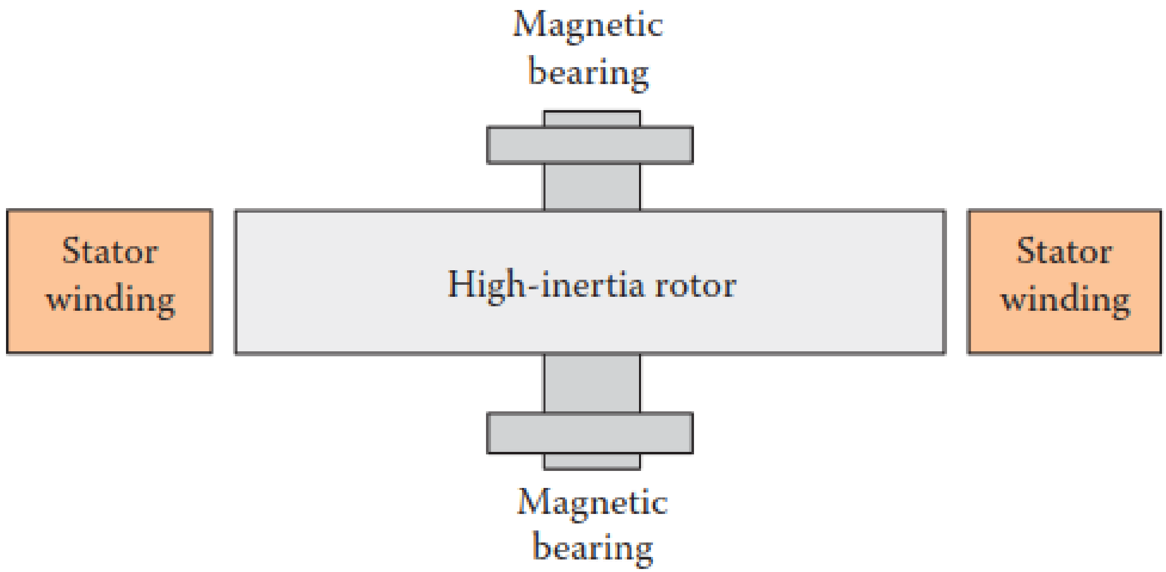


Figure 6.112 Main components of flywheel.