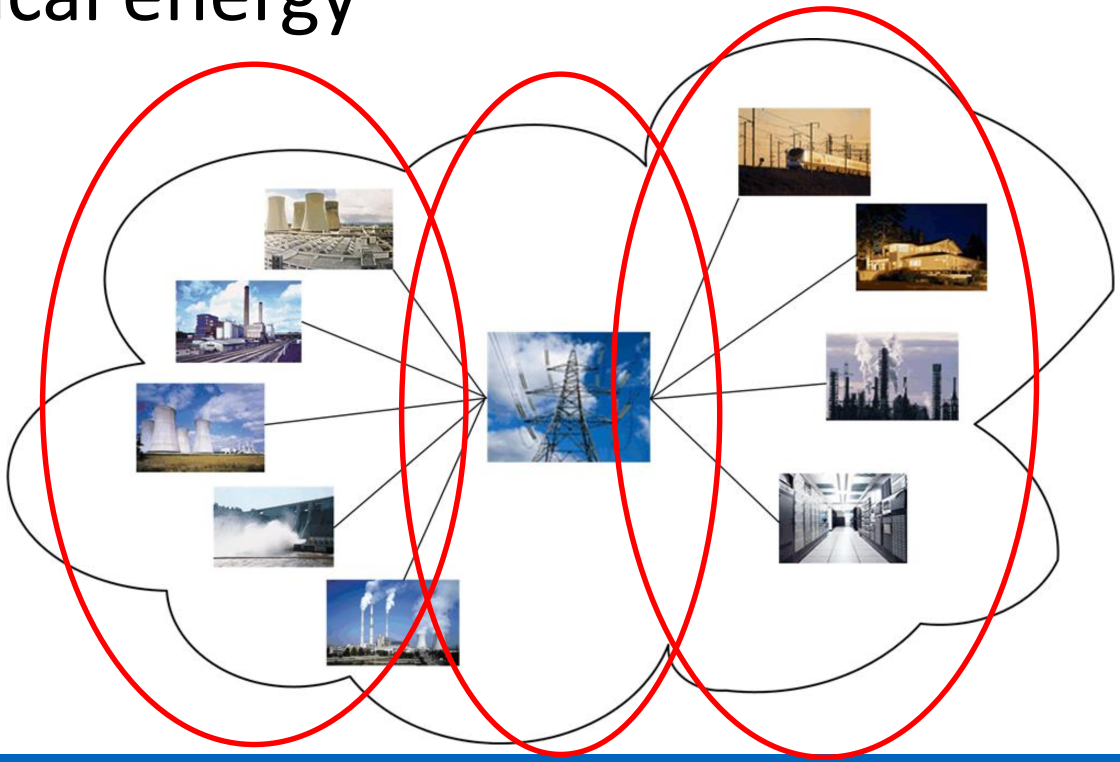
Fundamental terms and definitions

Power engineering

- A scientific discipline that focuses on:
  - Generation of electrical energy (EE)
  - Transmission and distribution of EE
  - Consumption of EE
  - Power grid operation and dispatch
  - Safety and development of the power grid

Electric power system

- A system that provides generation, transmission, distribution and consumption of electrical energy



Fundamental tasks of electric power system

- Provision of sufficient amount of electrical energy (EE) in required time
- Assurance of EE quality
- Reliability of EE delivery
- Economy optimization of EE delivery

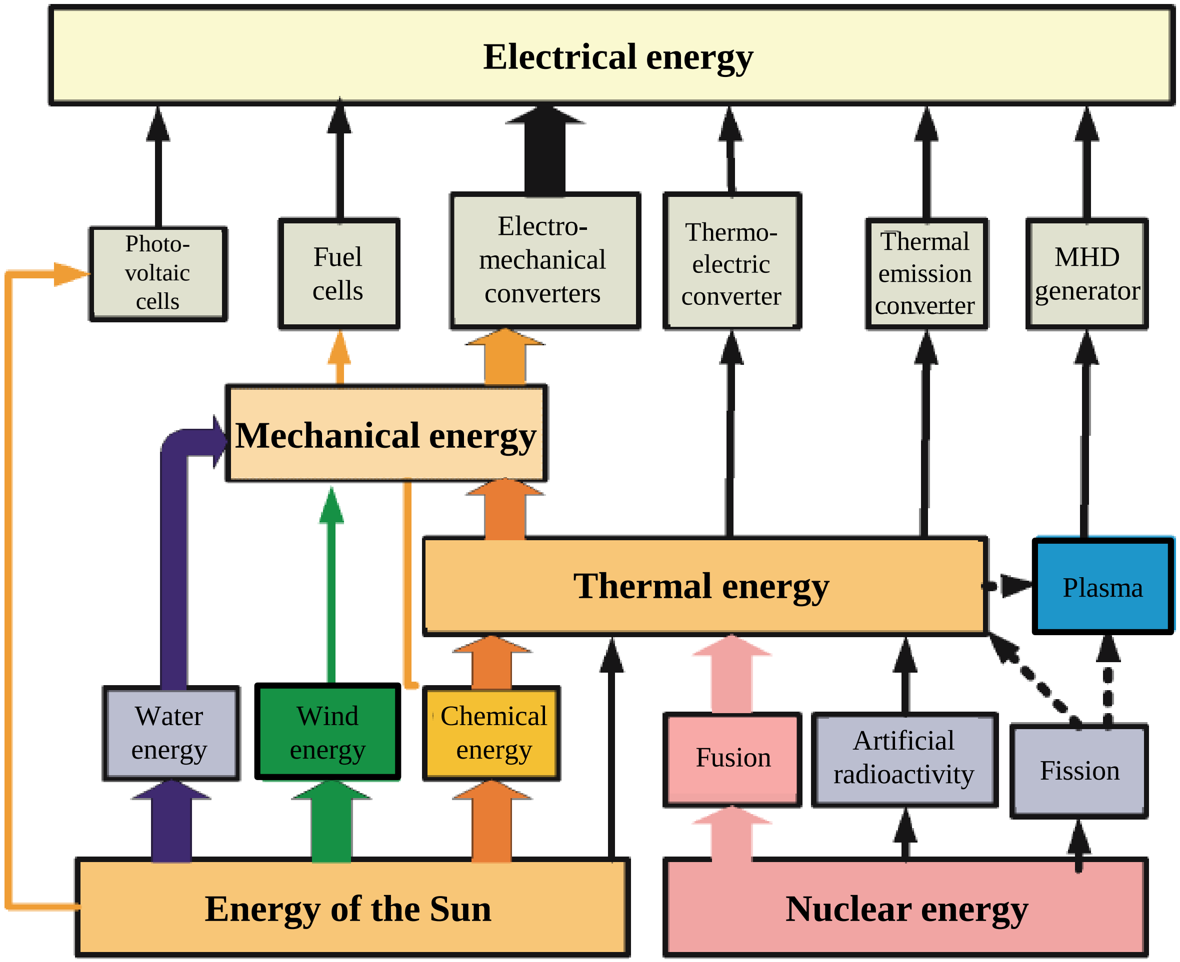
Electrical energy

- Advantages
  - Relatively simple conversion to other kinds of energy
  - Possibility of long distance transportation
  - Possibility of generation in large units
- Disadvantages
  - Difficult to store

Methods of EE acquisition

- Energy conversion from primary sources to electricity
  - Energy of the Sun
  - Energy of the Earth
  - Energy of the Earth-Moon interaction

Intermediate steps of different types of energy conversions

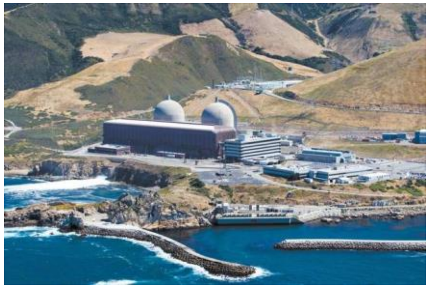


Types of electrical energy

- Based on means of production
  - Primary sources (mining, extraction)
  - Produced sources (refinement)
  - Secondary sources (from conversion losses)
- Based on renewability
  - Non-renewable sources
    - Available in finite quantity
  - Renewable sources
    - With possibility of partial or complete renewal either naturally or by human activity

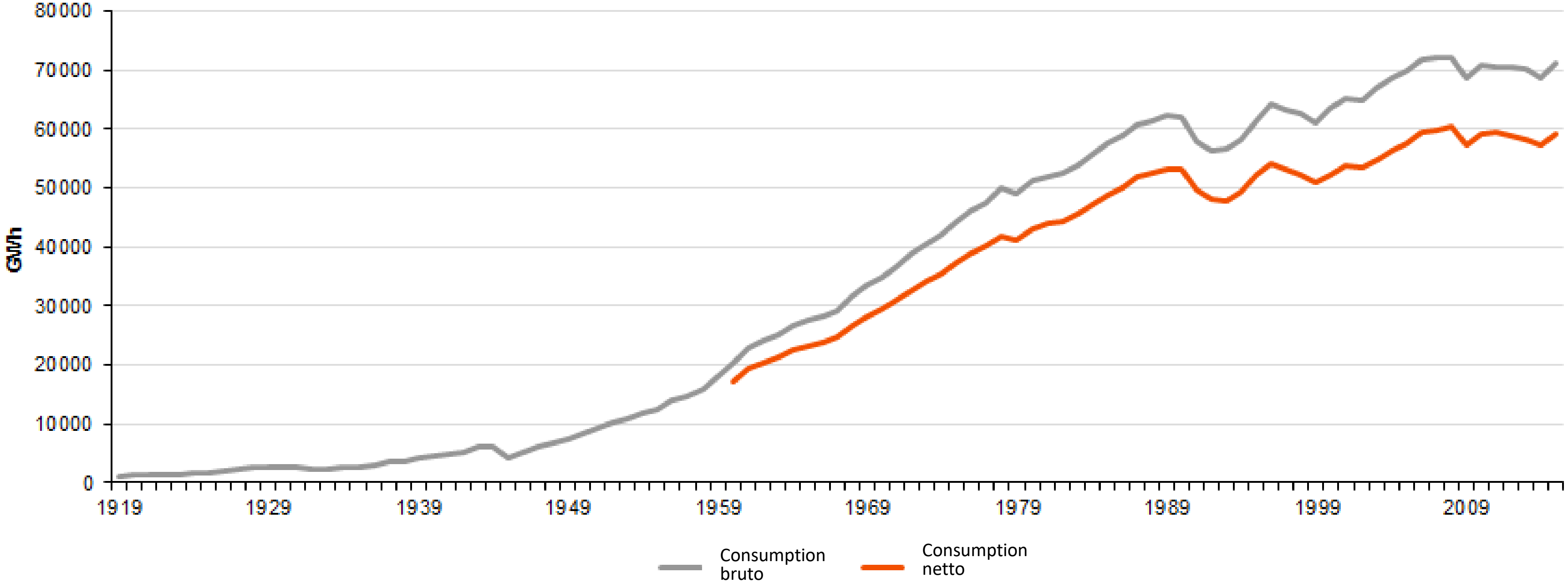
Types of electrical energy

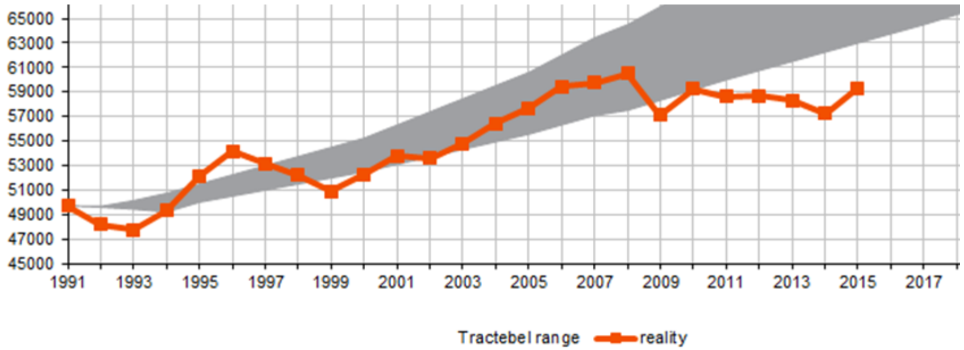
- Non-renewable
  - Fossil fuels
  - Nuclear fuels



- Renewable
  - Water energy
  - Wind energy
  - Solar irradiance
  - Biogas, biomass
  - Geothermal energy
  - Sea waves energy, tide

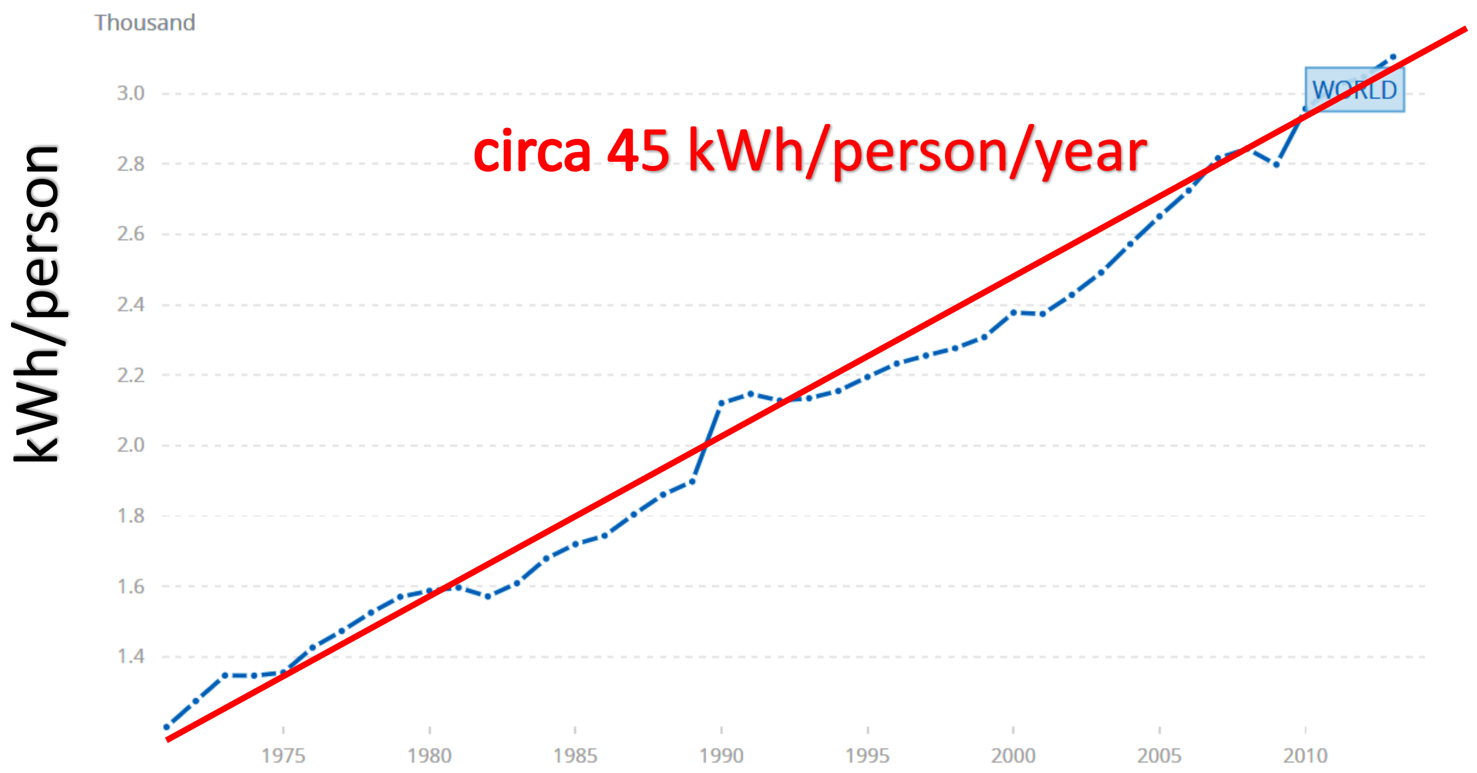
Long-term development of power consumption in CZ





ERU 2016

Long-term development of power consumption in the world



World bank 2016

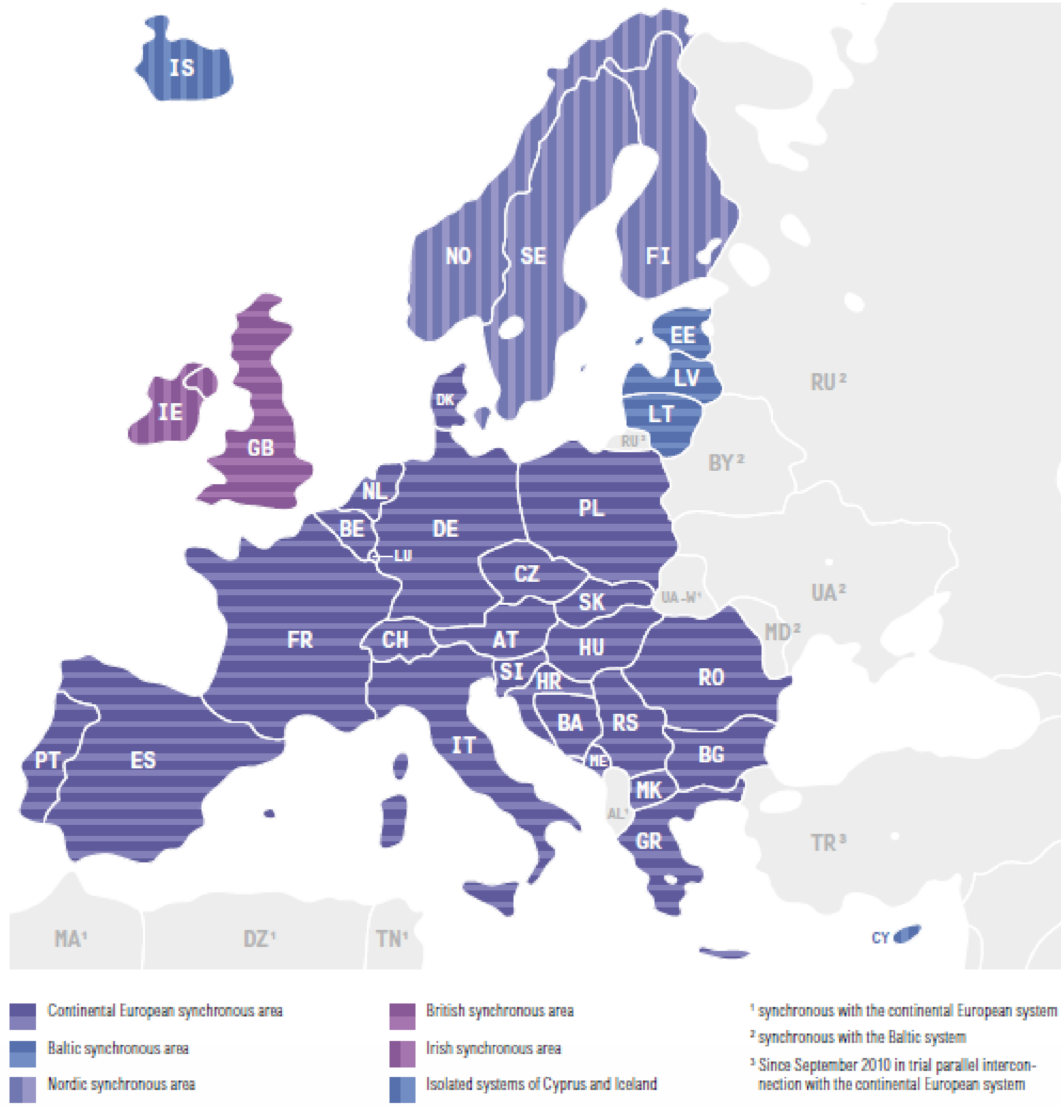
Electric power capacity terminology

- **Nominal capacity P_N** – the highest permanent electric power of a machine; determined by its design
- **Installed power capacity P_i** – the total of individual nominal capacities of all similar machines inside an object
- **Maximum achievable power P_d** - the highest electric power of a machine achievable in its normal state and normal operating conditions
- **Instantaneous power P_p** - the highest electric power of a machine achievable in its actual state and actual operating conditions
- **Technical power minimum P_{TM}** – the lowest permanent electric power at which can a machine operate without the risk of damage

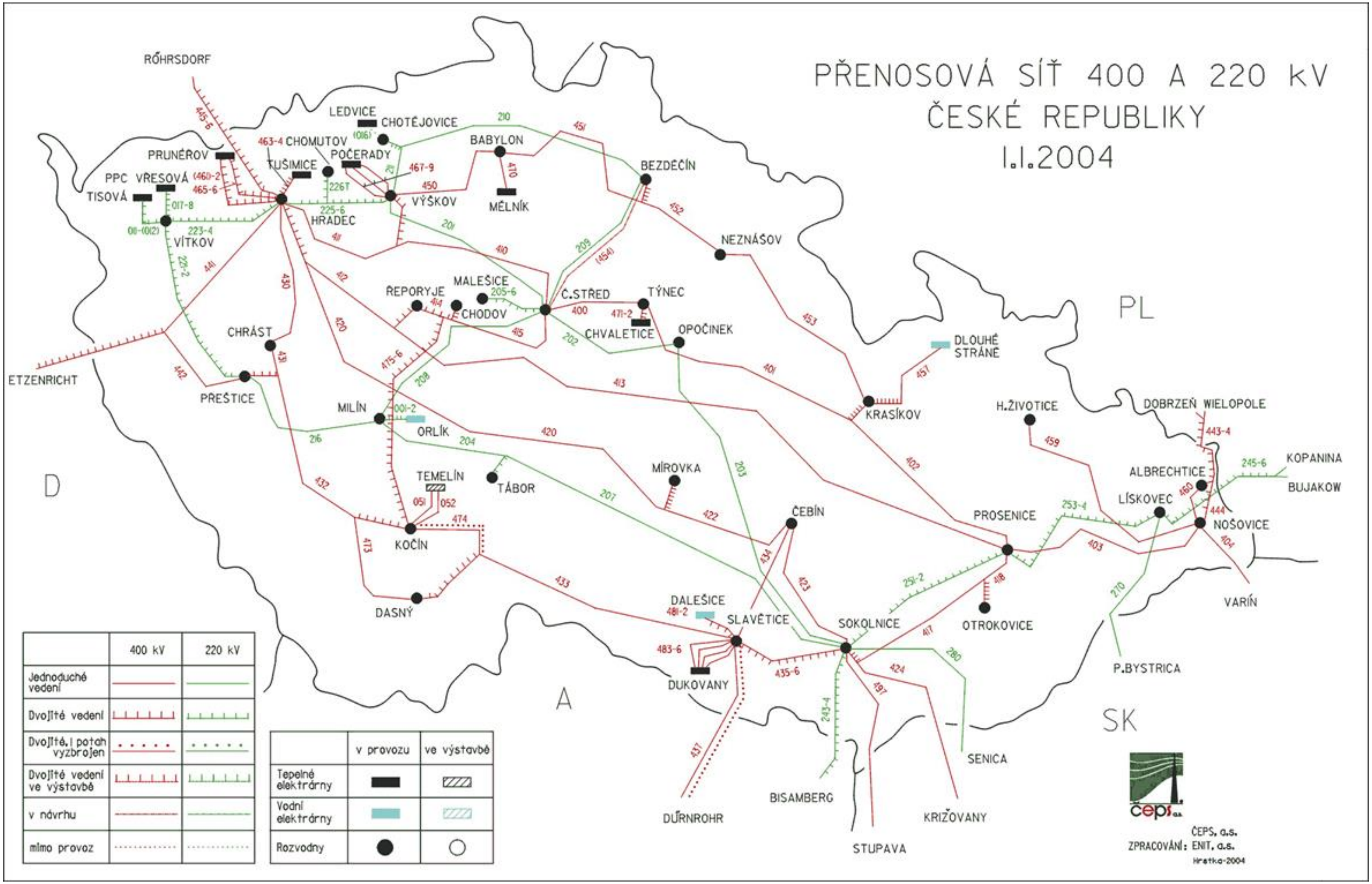
Transmission network

- Interconnected set of power lines and devices that transmits electrical energy from generating units to distribution networks
- **In CZ**: power lines, transformers and substations operating at voltage of 400 kV and 220 kV, with 2 additional substations and 105 km power lines at 110 kV.
- The transmission network operator in CZ is ČEPS, a. s.
- The Czech transmission system is integrated into European transmission system (ENTSO-E) via cross-border power lines

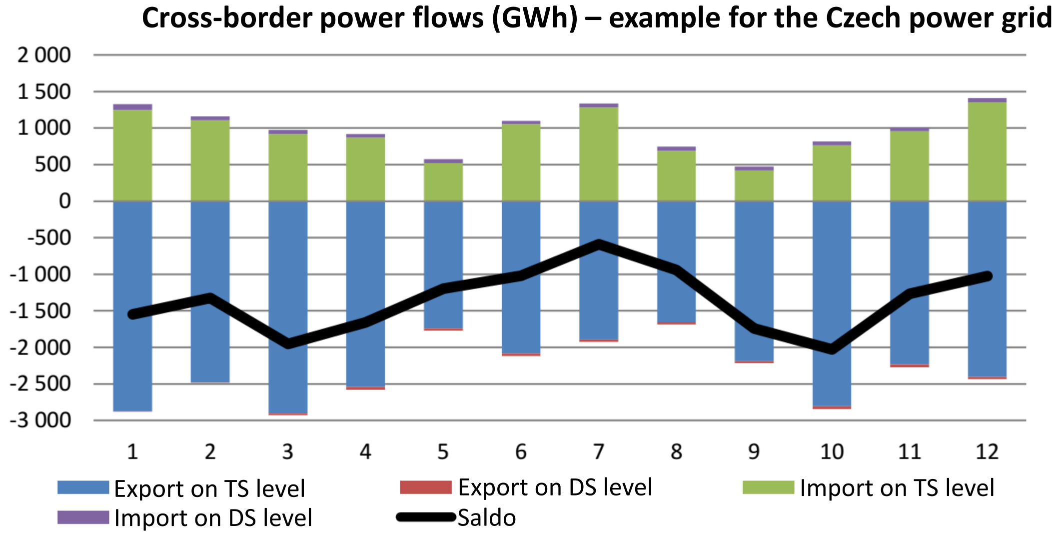
European transmission networks

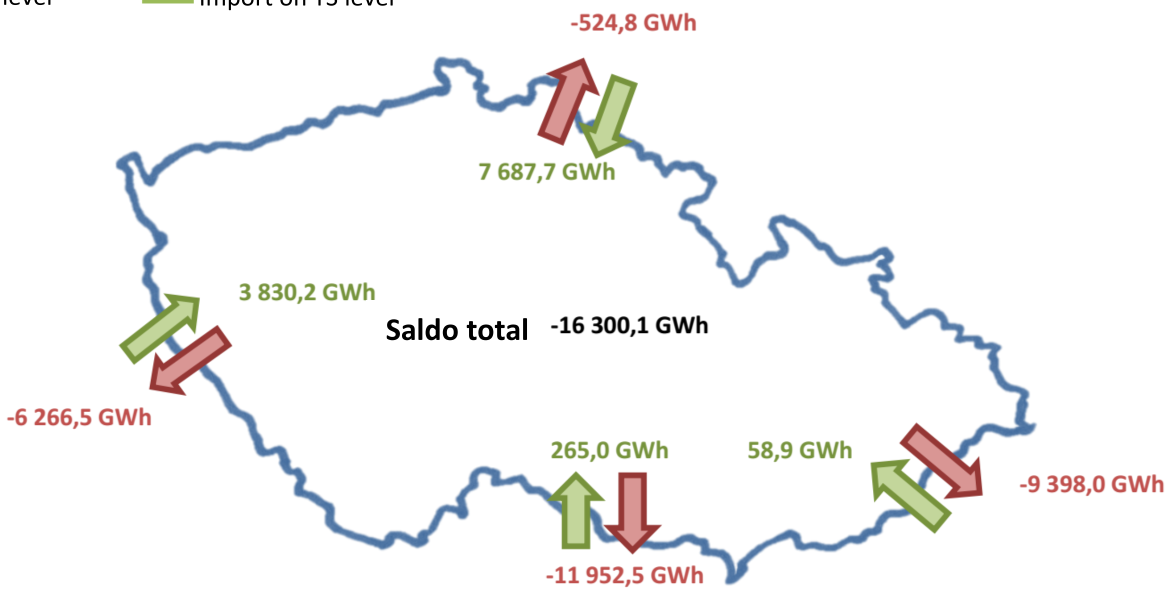


Czech transmission network



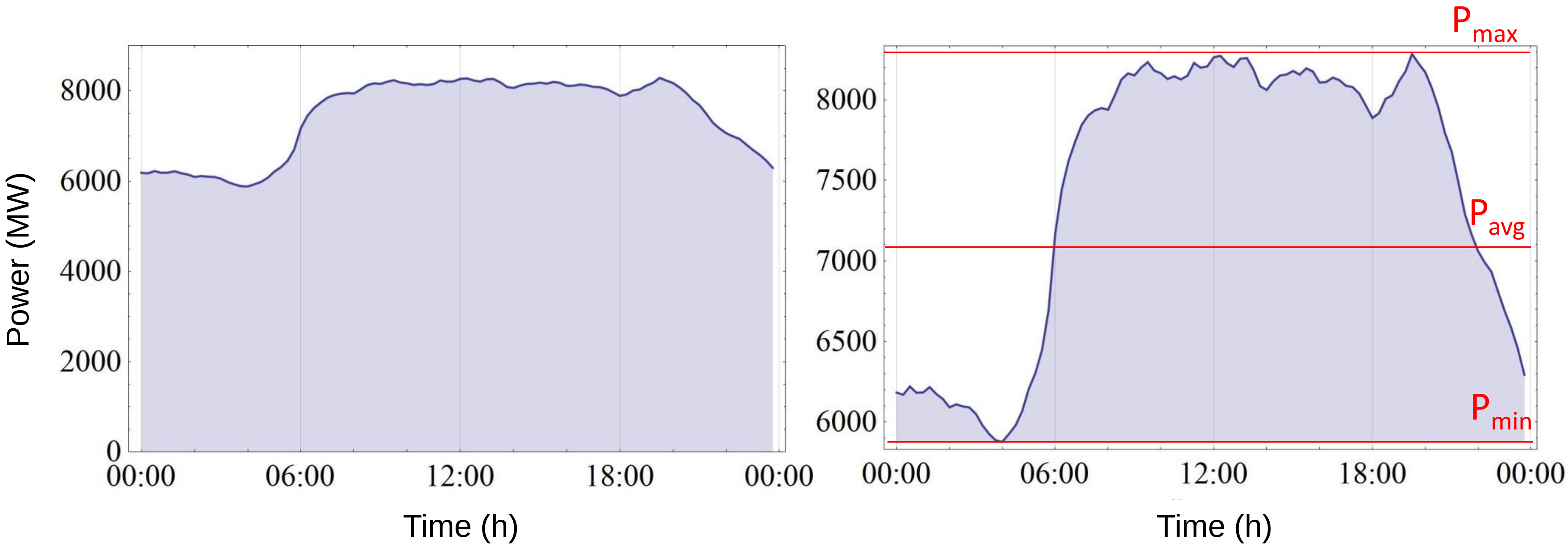
Cross-border power flows





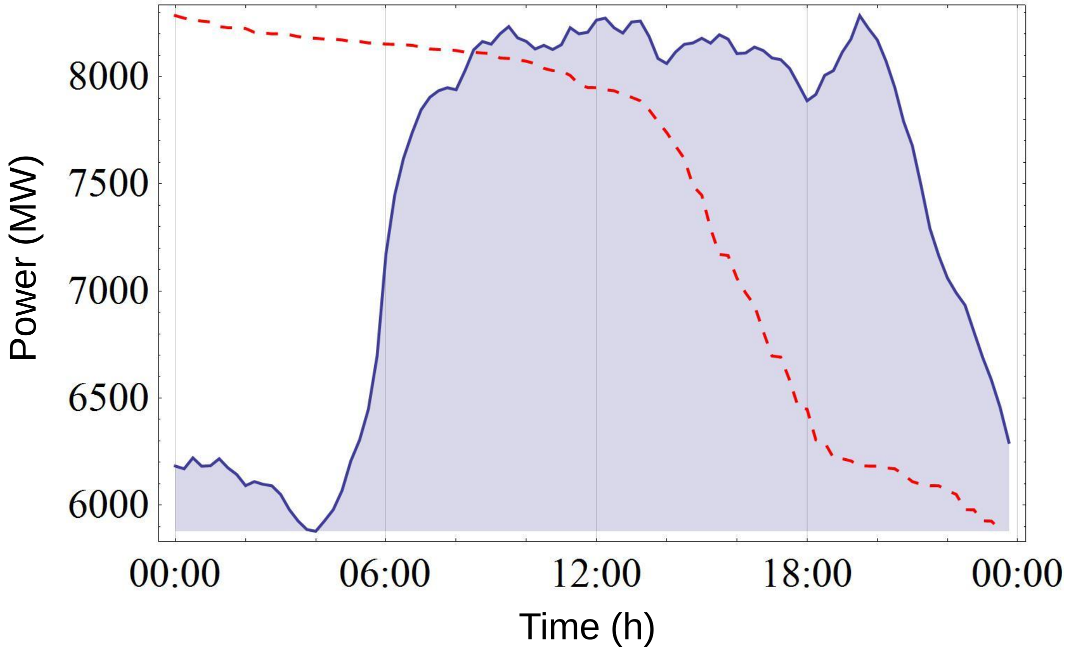
Daily load profile

- Dependency of electrical load *P* (MW) on time *t* (h). Typically processed for whole network or for single units (factories, homes)



Load duration curve

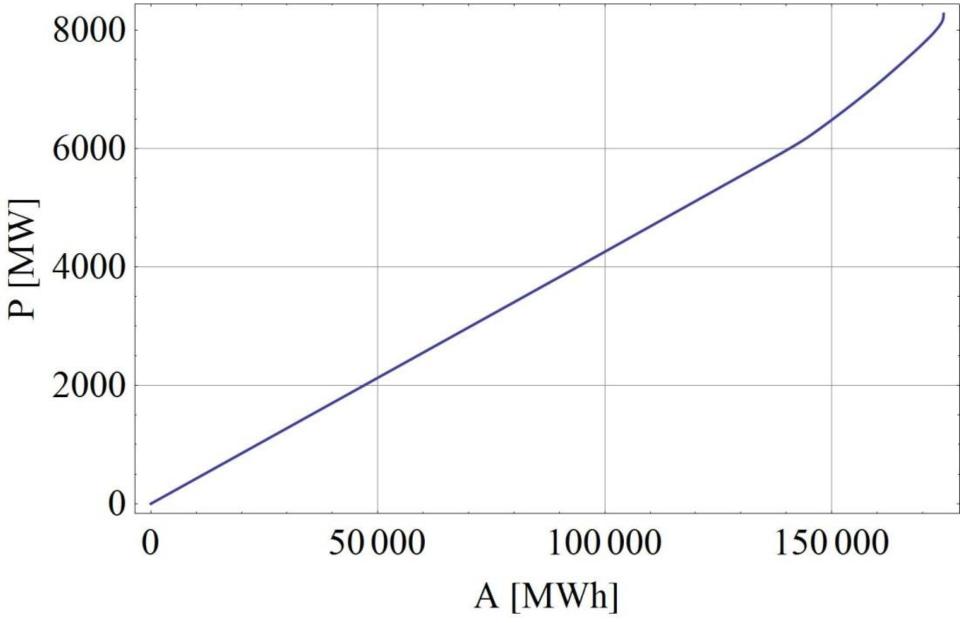
- *P* = *f*(*t*) characteristic
- Constructed by sorting electrical load values from load profile in a descending order



Production curve

- Cumulative integral of load duration curve with respect to electrical load *P*

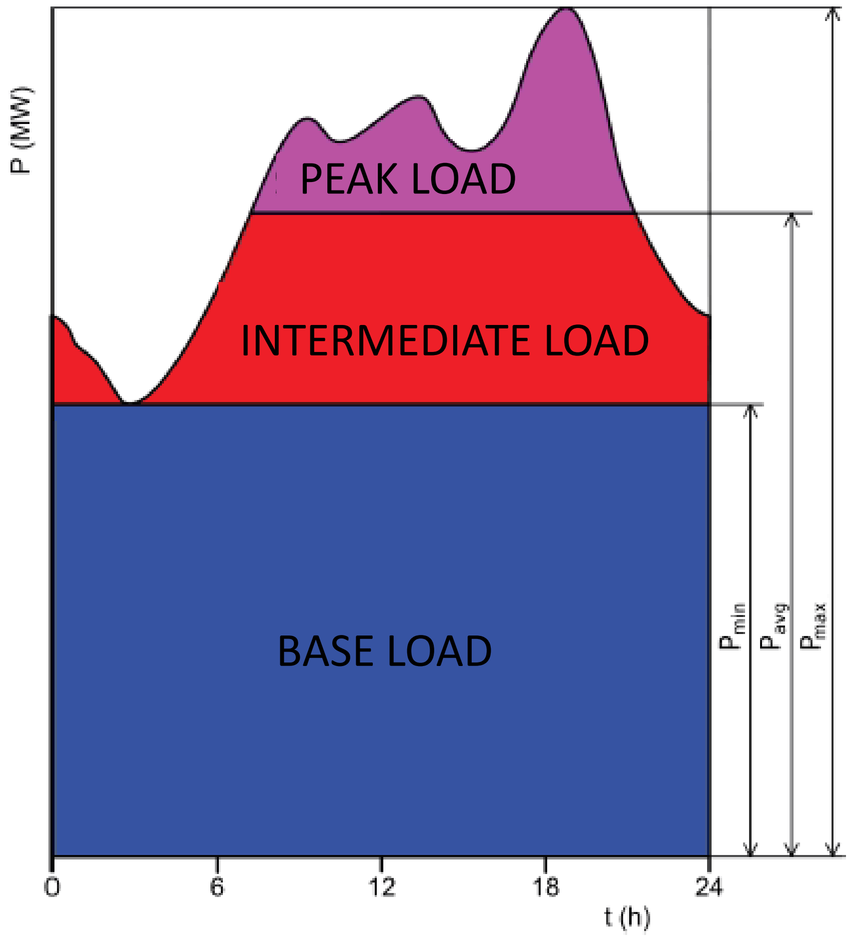
$$A_c = \int_0^{P_{max}} t(P)\, dP$$



Types of electrical load inside a load profile

- **Base load** – part of the load profile below the minimum load
- **Intermediate load** – part of the load profile between base load and average load
- **Peak load** – part of the load profile above average load
- **Average load P_{avg}** – permanent load at which a machine would produce the same amount of work as in the load diagram

Peak and load matching (load profile)

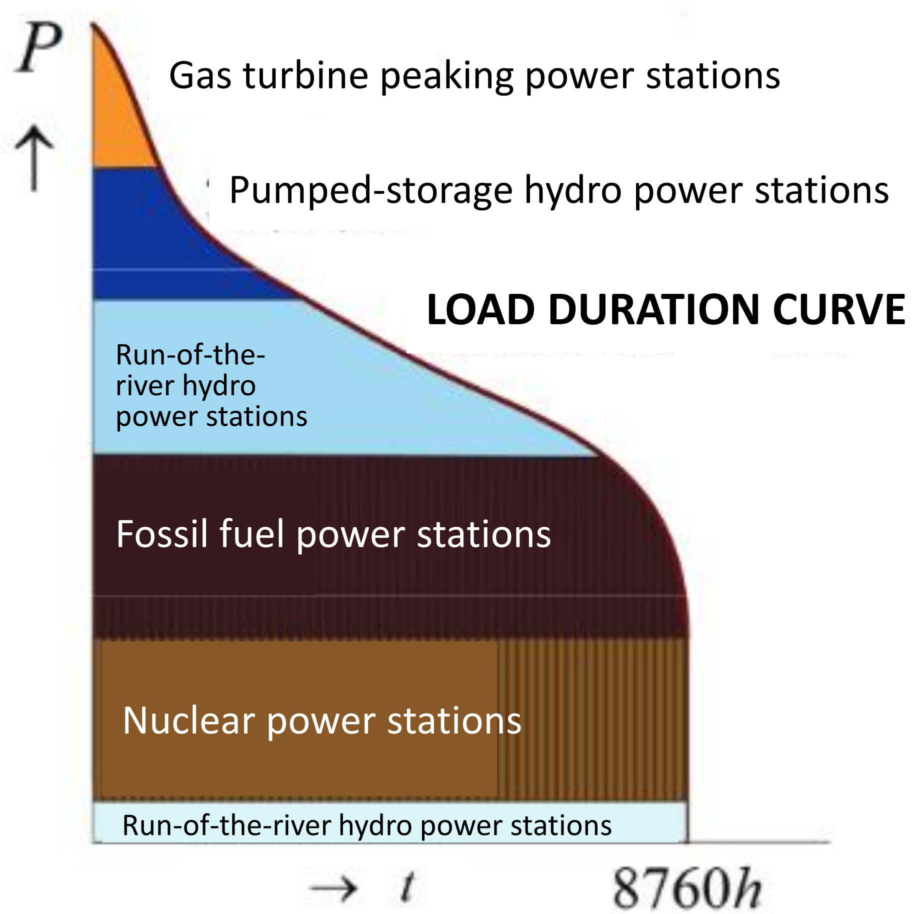


- Pumped-storage hydro power stations
- Conventional hydro power stations

- Conventional hydro power stations
- Gas turbine and combined cycle gas turbine power stations

- Coal and nuclear power stations
- Run-of-the-river hydro power stations

Peak and load matching (load duration curve)



Optimization of power station dispatch

- Optimal peak and load matching while maintaining lowest possible operating costs
- The operating costs of a power station have 2 basic components:
  - Fixed costs (**independent** on the power output)
  - Variable costs (**dependent** on the power output; typically fuel costs)
- The goal is to find the optimal power outputs of all dispatchable power stations

Optimization of power station dispatch

- Therefore, it is necessary to find the minimum of cost function *N* (the sum of the individual operating costs) with constraint *B* (power balance):

$$N = \sum_{i=1}^{M} N_i \;\&\; B = \sum_{i=1}^{M} P_i = P$$

where N_i are cost functions of individual power stations, P_i are power outputs of individual power stations and *P* is the electrical load of the electrical network

Constrained extreme values of multivariable functions

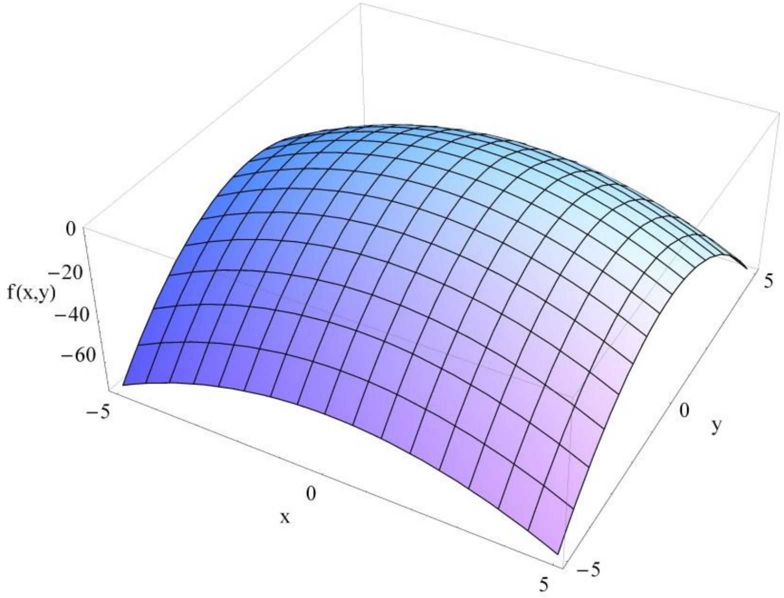
- Constrained extreme values
  - An optimization problem
    - We search for the extreme value of function *f*(x,y)
    - The extreme value is constrained by function *g*(x,y)=c
  - If we assume that *f* and *g* have continuous first order partial derivatives, then a Lagrange function

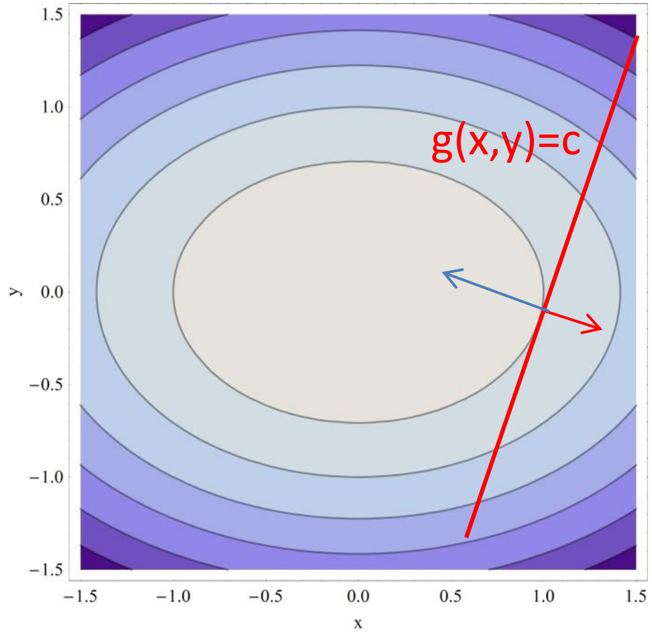
$$L(x, y, \lambda) = f(x, y) + \lambda(g(x, y) - c)$$

can be used to locate the extreme value by solving

$$\nabla L(x, y, \lambda) = 0$$

Constrained extreme values of multivariable functions – geometrical point of view





Gradient of function *f* must be parallel to the gradient of function *g* if the *f* extreme is located inside the space constrained by *g*. This is defined mathematically as:

$$\nabla f = -\lambda \nabla g$$

$$\nabla f + \lambda \nabla g = 0$$

Optimization of power station dispatch

- Lagrange function for optimal distribution of power generation is:

$$L(P_1, P_2, .. P_n, \lambda) = N + \lambda B = \sum_{i=1}^{M} N_i + \lambda(\sum_{i=1}^{M} P_i - P)$$

- The minimum must then meet the following conditions:

$$\frac{\partial L}{\partial P_1} = \frac{\partial N_1}{\partial P_1} + \lambda$$

$$\frac{\partial L}{\partial P_2} = \frac{\partial N_2}{\partial P_2} + \lambda$$

$$\vdots$$

$$\frac{\partial L}{\partial P_M} = \frac{\partial N_M}{\partial P_M} + \lambda$$

$$\Longrightarrow -\lambda = \frac{\partial N_1}{\partial P_1} = \frac{\partial N_2}{\partial P_2} = \cdots = \frac{\partial N_M}{\partial P_M}$$

Example

- A power station has two blocks with installed capacity of $P_{n1}=P_{n2}=100\pm 20$ MW. Operating costs of the first block are $N_1 = 50000 + 250P_1 + 40P_1^2$ (Kč/h) and of the second block $N_2 = 45000 + 150P_1 + 50P_2^2$(Kč/h). Find the optimal way to secure output of $P_c=210$ MW
  - Lagrange function

$$L = N_1(P_1)+N_2(P_2)+\lambda(P_1 + P_2 - P_c)$$

$$\frac{\partial L}{\partial P_1} = 250 + 80P_1 + \lambda$$

$$\frac{\partial L}{\partial P_2} = 150 + 100P_2 + \lambda$$

$$P_c = P_1 + P_2$$

Example

$$\Longrightarrow P_1 = 116\,MW, P_2 = 94\,MW, \lambda = -\,9539\,Kč/MWh$$

- The optimum is located inside the regulation ranges of both blocks.

Load factor

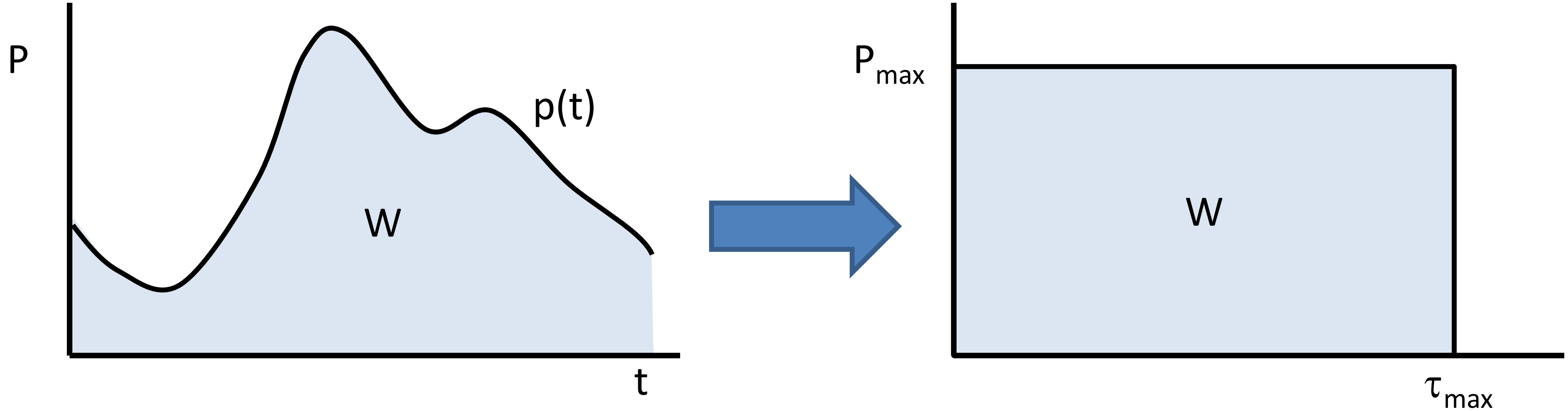
$$\xi = \frac{P_{avg}}{P_{max}} = \frac{\tau_{max}}{T}$$

- The ratio of the average electric power and the maximum electric power.
- Ideally ξ=1, the closer the load factor is to the ideal value, the more economical is the production unit

Exploitation time

- The ratio of the actual generation of a power station and its theoretical maximum over the same period.

$$\tau_{max} = \frac{W}{P_{max}} = \frac{1}{P_{max}} \int_0^T p(t)dt$$



Time of full losses

- The total time during which would a machine working at maximum load P_{max} produce the same losses of electrical energy as during the actual period T at load $p(t)$

Loss energy A_z

$$A_Z = \mathrm{R}\int_0^T I^2(t)dt = RI_{ef}{}^2T = RI_{ef}^2T\left(\frac{\xi I_{max}}{I_{avg}}\right)^2 = \overbrace{RI_{max}^2}^{P_{zm}}\overbrace{T\left(\frac{\xi I_{ef}}{I_{avg}}\right)^2}^{\tau_z}$$

Time of full losses:

$$\tau_z = T\left(\frac{\xi I_{ef}}{I_{avg}}\right)^2 = T\left(\frac{I_{ef}}{I_{max}}\right)^2 = \frac{\int_0^T i^2(t)dt}{I_{max}^2}$$

$$\xi = \frac{I_{avg}}{I_{max}}$$

If voltage U and power factor cos φ are constant:

$$\tau_z = \frac{1}{P_{max}^2}\int_0^T p(t)^2 dt$$

Utilization and diversity factor

- Since the working machines do not necessarily need to run at full load, the following factors have been introduced to incorporate that fact into the power station design
- **Utilization factor** – the ratio of the actual power input of the working machines and the total of their power ratings

$$k_z = \frac{\sum P_s}{\sum P_n} \leq 1$$

- **Diversity factor** – the ratio of power ratings of working machines and the total of power ratings of all machines

$$k_s = \frac{\sum P_{na}}{\sum P_n} \leq 1$$

Demand factor

- The ratio of maximum power output of a machine and its power rating

$$\beta = \frac{P_{max}}{P_i}$$

- Factor β can also be defined as:

$$\beta = \frac{k_s k_z}{\eta_r \eta_z}$$

where η_r is the power feed efficiency and η_z is the machine efficiency

Design load and current

- Design load is used for generator, power station, power lines and feeding transformer design

$$P_p = P_i \beta$$

- Design current can be calculated by

$$I_p = \frac{P_p}{\sqrt{3} U \cos \varphi},$$

where *U* is line voltage and cos φ is the power factor