Primary energy sources

- Renewable sources
  - Wind
  - Solar
  - Geothermal
  - Wave
  - Tidal
- Fossil fuels
  - Nuclear
  - Coal
  - Gas
  - Oil

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Wind generation



How much energy is there in the wind?

- Area swept by the blades:

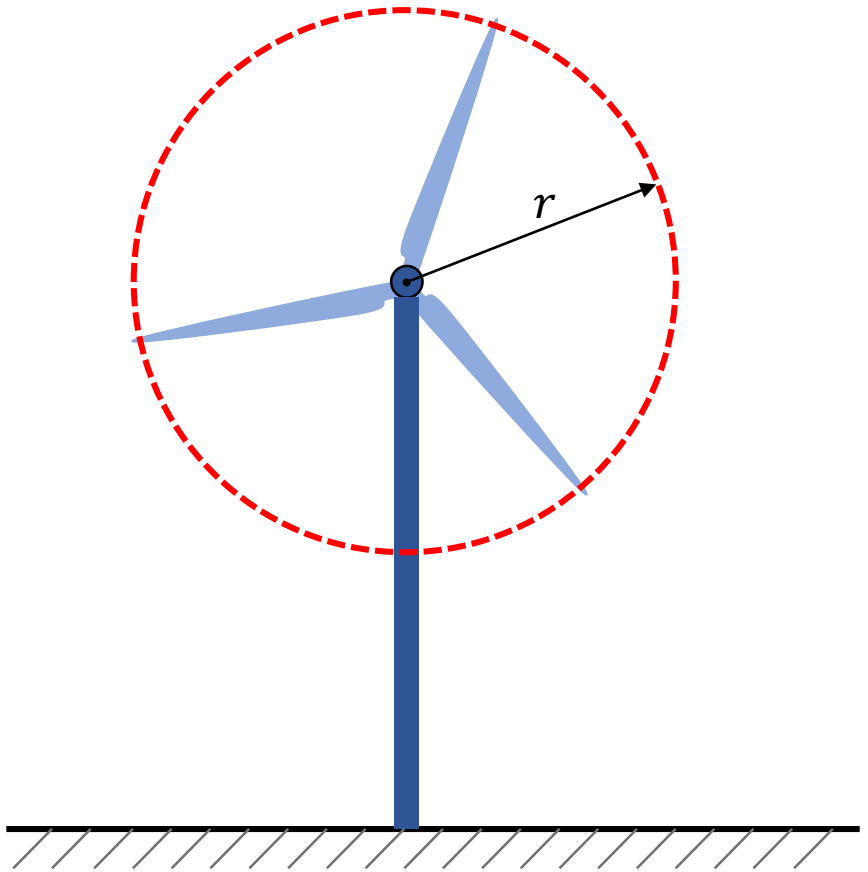
$$A = \pi r^2$$

- Mass of air passing through this area in time t:

$$m = \rho_a A v t$$

- ρ_a: specific mass of air
- v: wind speed
- Kinetic energy in this mass:

$$E_k = \frac{1}{2} m v^2 = \frac{\pi}{2} \rho_a r^2 v^3 t$$



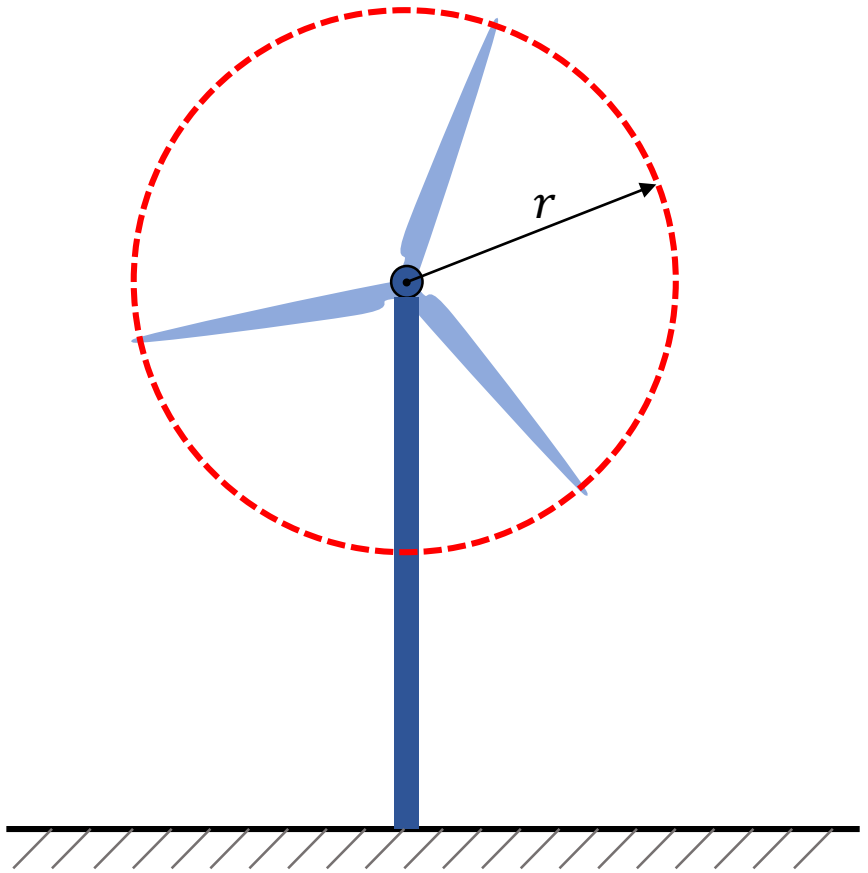
How much power is there in the wind?

$$E_k = \frac{1}{2} m v^2 = \frac{\pi}{2} \rho_a r^2 v^3 t$$

- Power in this wind:

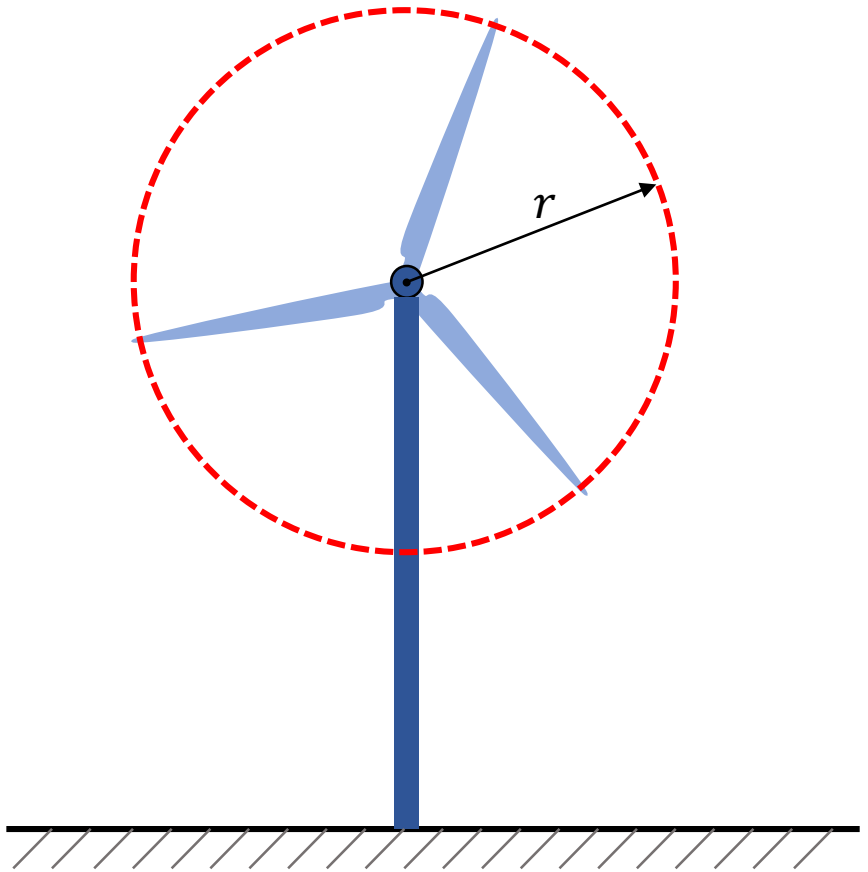
$$P_w = \frac{dE_k}{dt} = \frac{\pi}{2} \rho_a r^2 v^3$$

- Increases rapidly with:
  - The wind speed
  - The length of the blades

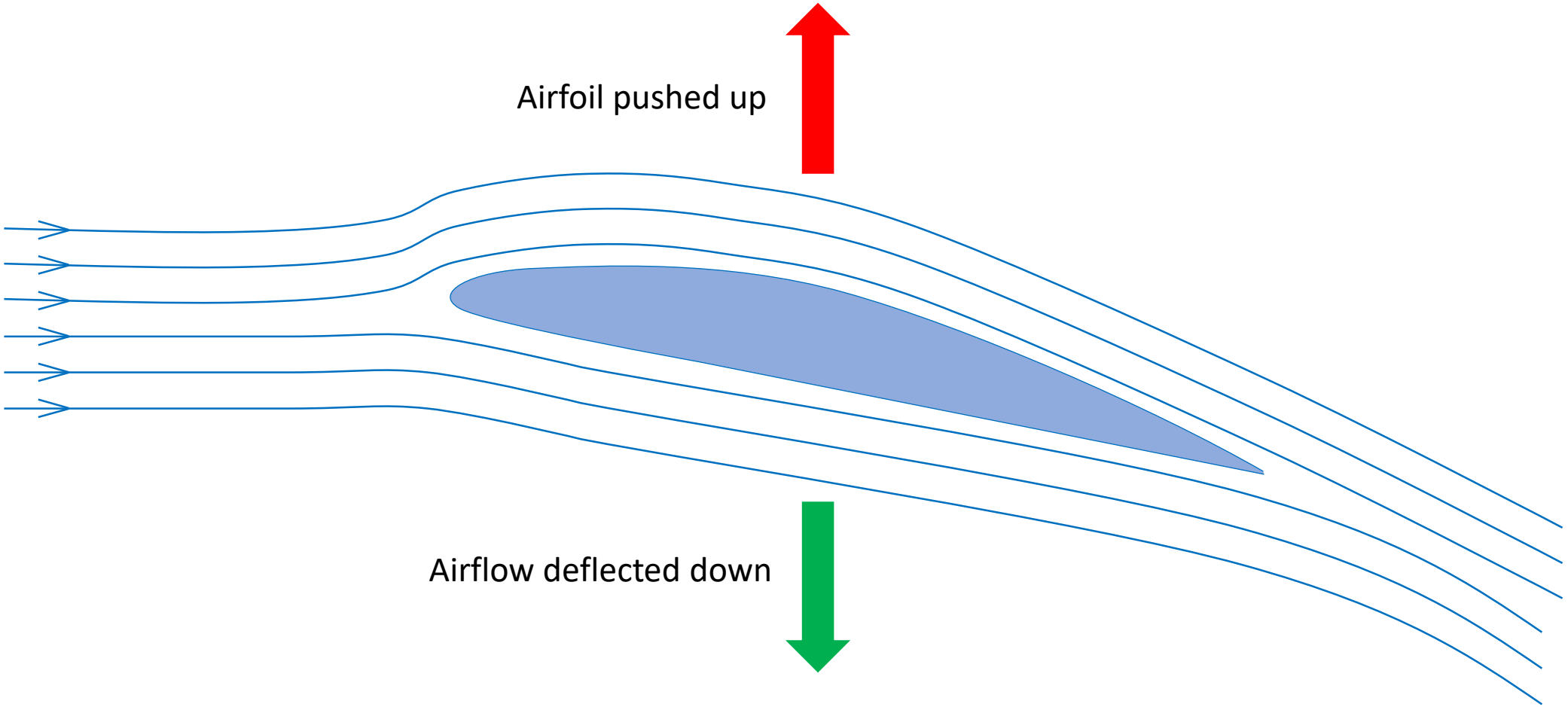


How much power can be captured?

- Capturing all of P_w is impossible
- $P_{blades} = C_p P_w$
- C_p: coefficient of performance
- $C_p < 0.593$ = Betz limit



Flow of air around an airfoil

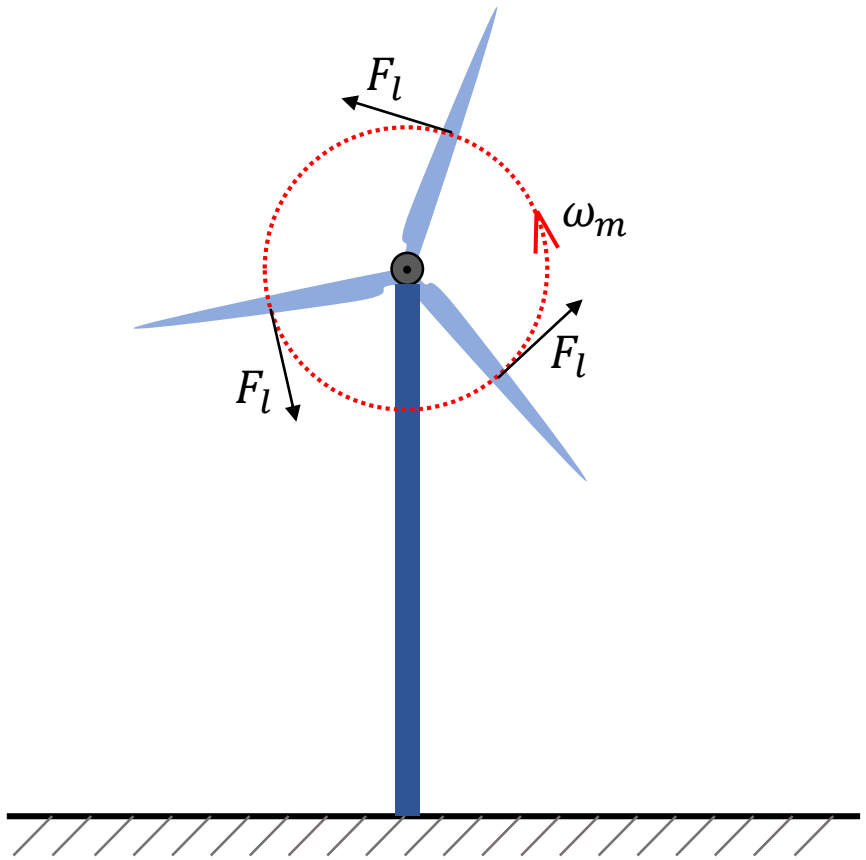


Lift force

- Airfoil deflects the airflow down
- Airfoil exerts a downward force on the air
- Newton’s third law: action – reaction
- Air exerts an upward force on the airfoil
- This lift force makes it possible for airplanes to fly

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Torque

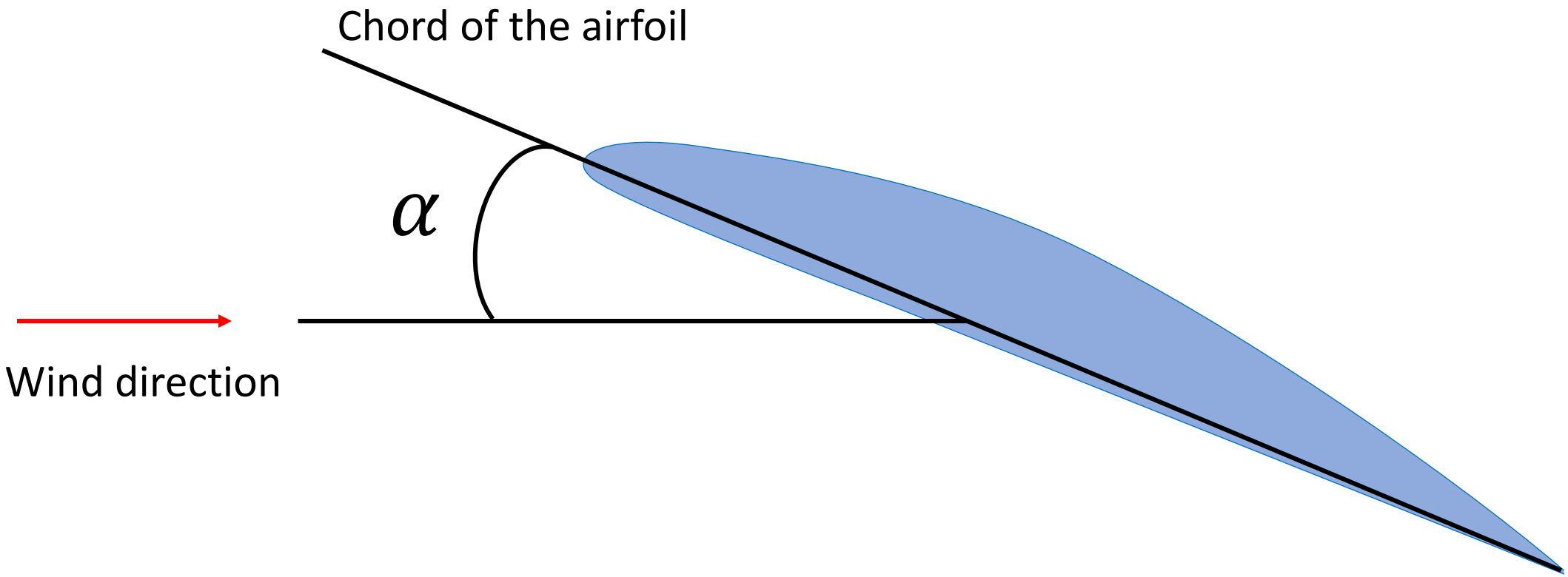


- Lift force F_l on each turbine blade
- Creates a torque T_m on the shaft of the turbine:

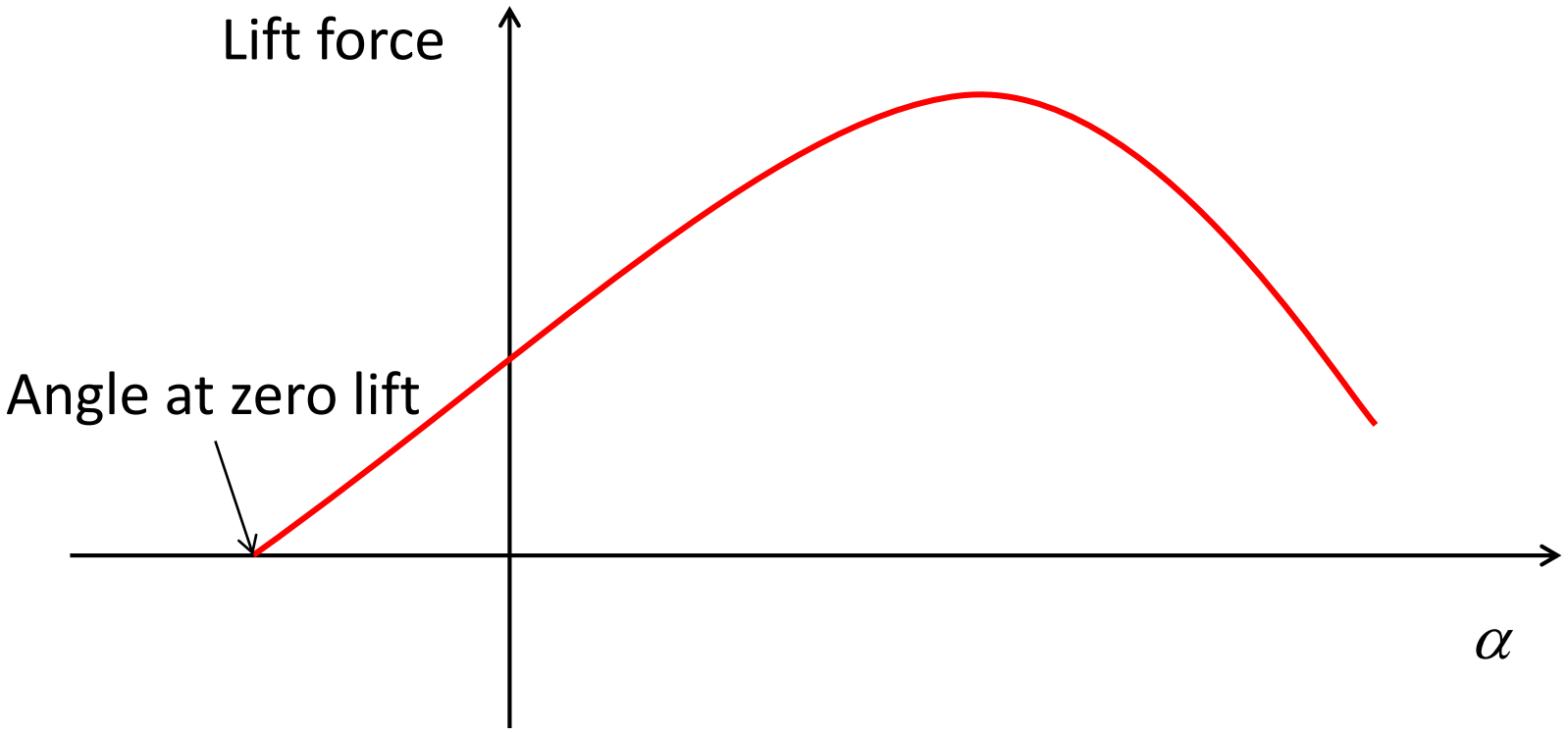
$$T_m = \frac{P_{blades}}{\omega_m}$$

- P_{blades}: wind power captured by the blades
- ω_m: Rotational speed of the turbine shaft

Angle of attack α

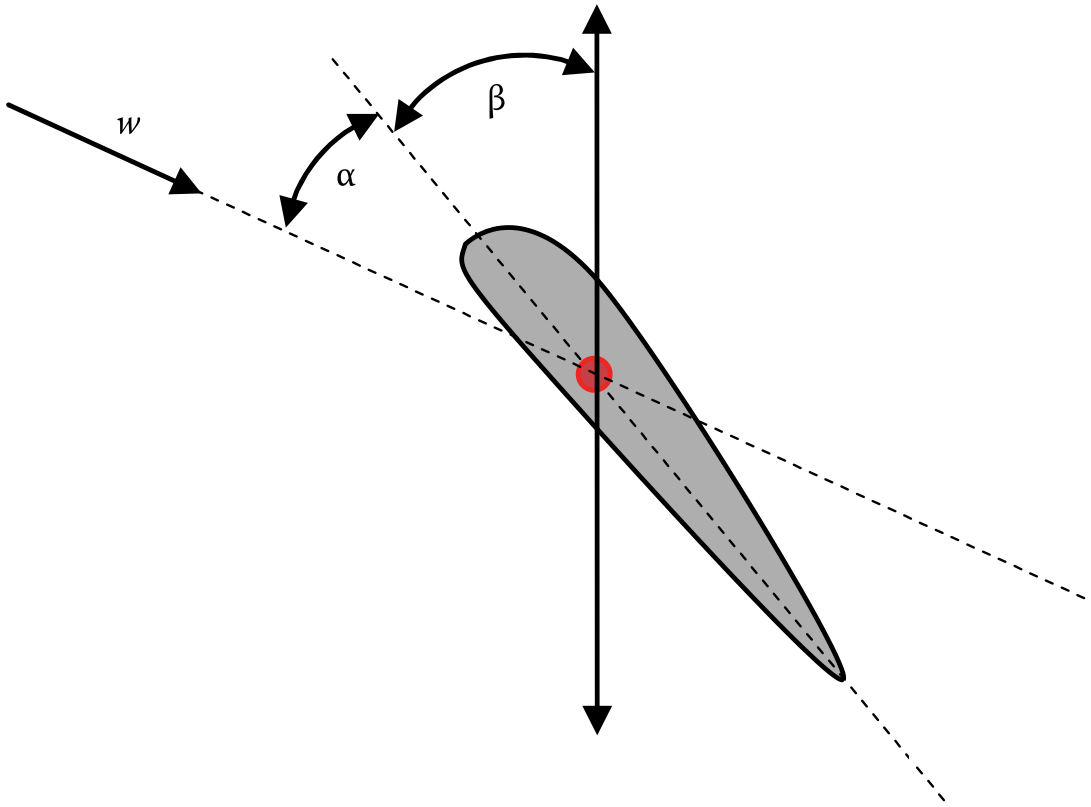


Lift force vs. angle of attack α



Pitch angle β

- Angle of attack α depends on the wind direction
- α is thus hard to measure
- Pitch angle β is the angle between the vertical and the chord
- We can control α by adjusting β



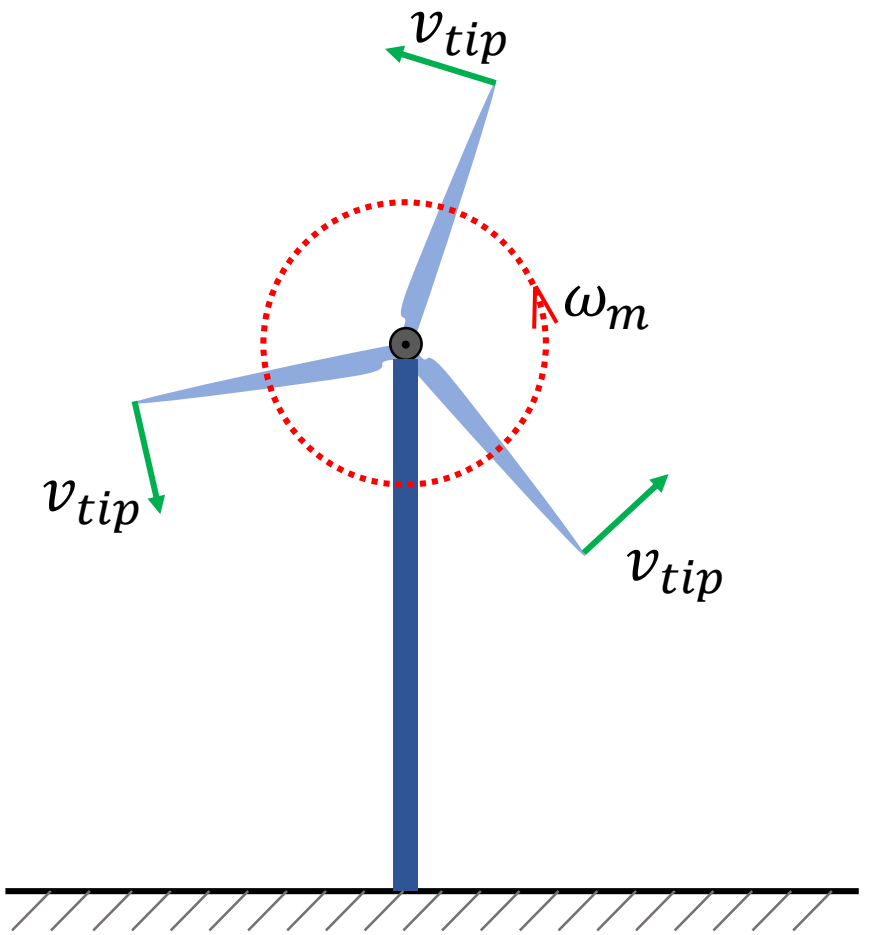
Controlling the pitch angle



- Pitch angle can be adjusted by rotating the blade where it connects to the shaft

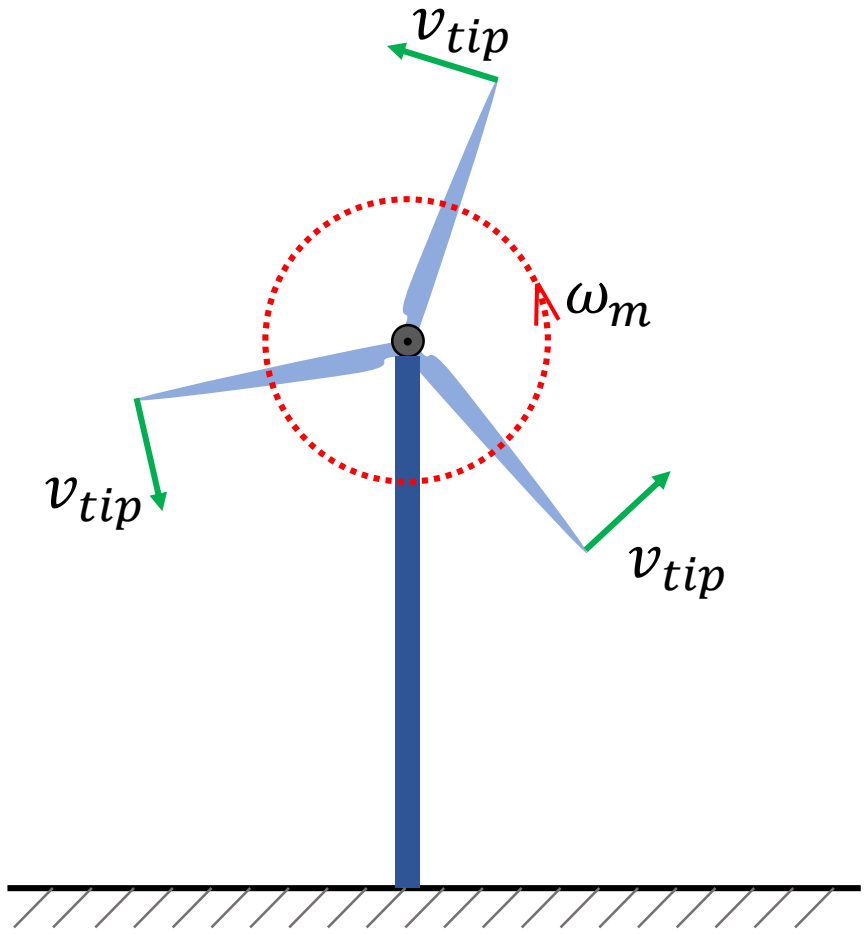
Tip speed ratio λ

- $\lambda = \frac{v_{tip}}{v} = \frac{\omega_m r}{v}$
  - v_{tip}: speed of the tip of the blade
  - v: wind speed
  - ω_m: rotational speed
  - r: length of the blades



Optimal tip speed ratio λ

- $\lambda = \frac{v_{tip}}{v}$
- λ too small:
  - → Too much wind passes through the turbine without being affected by the blades
- λ too large:
  - → Because blades follow each other too closely, turbulence does not have time to dissipate
  - → Lowers the coefficient of performance C_p

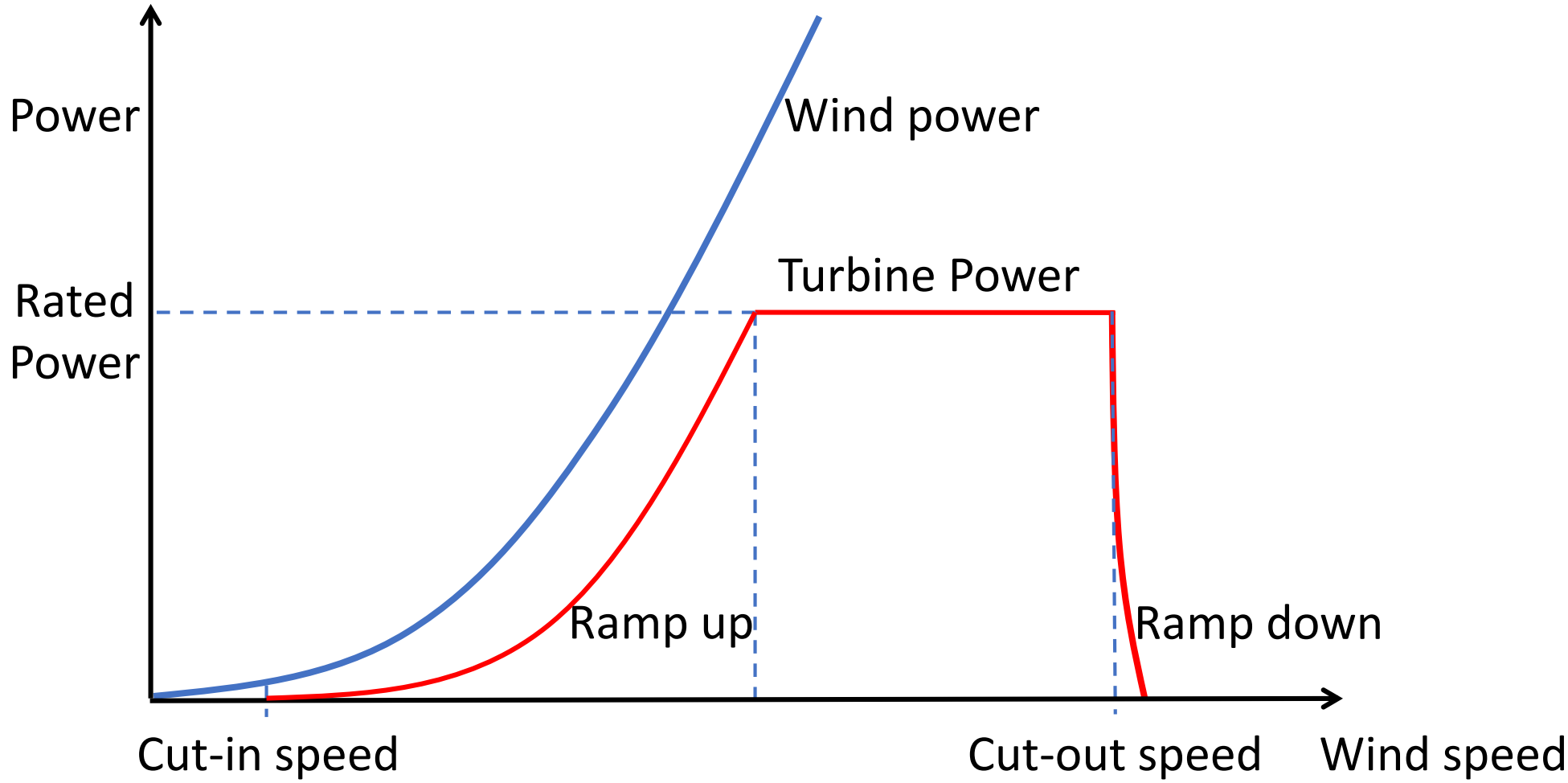


Controlling a wind turbine

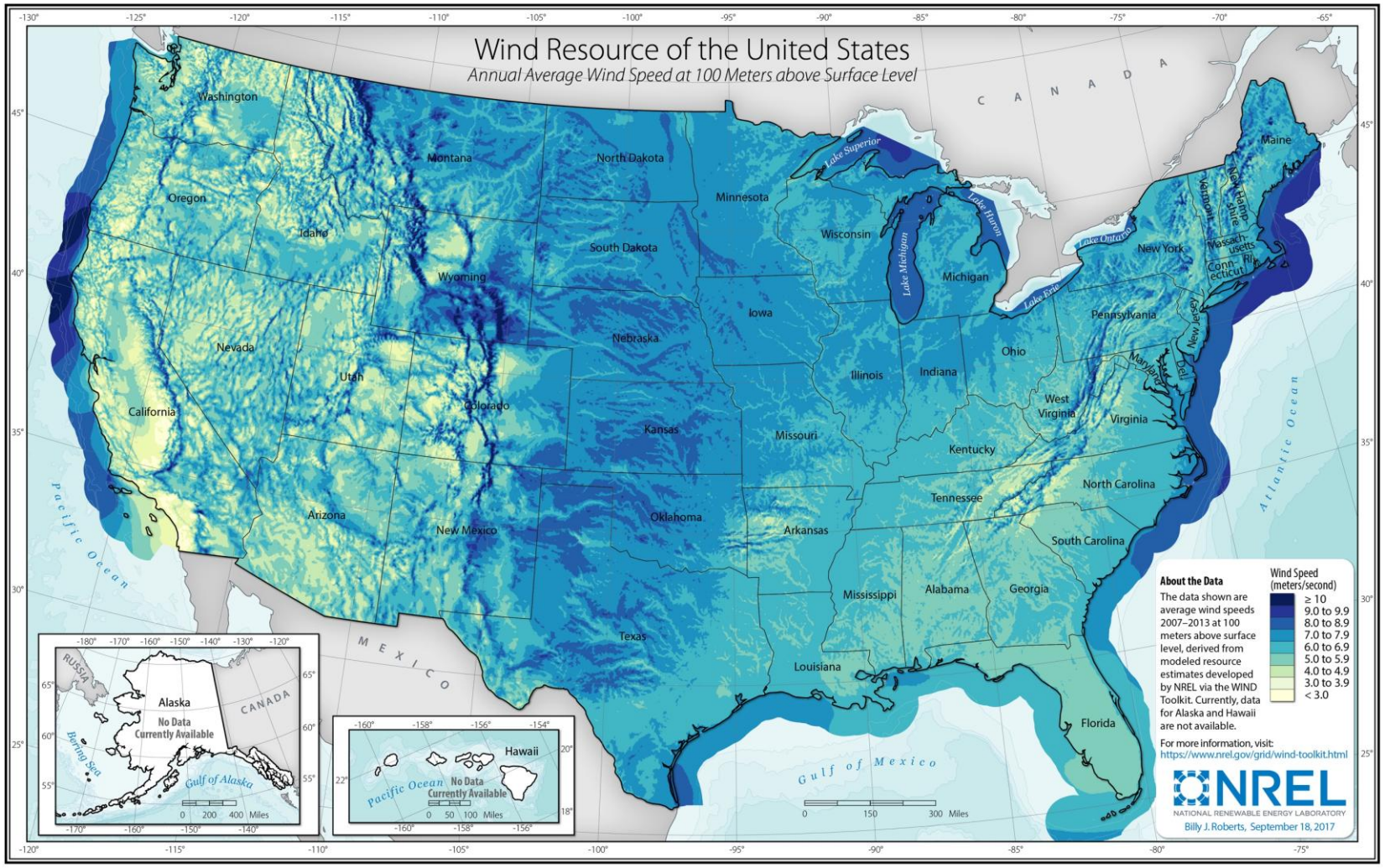
- Adjust pitch angle β and tip speed ratio λ
- Maximize extraction of wind power
- Avoid mechanical damage



Power vs. wind speed characteristic

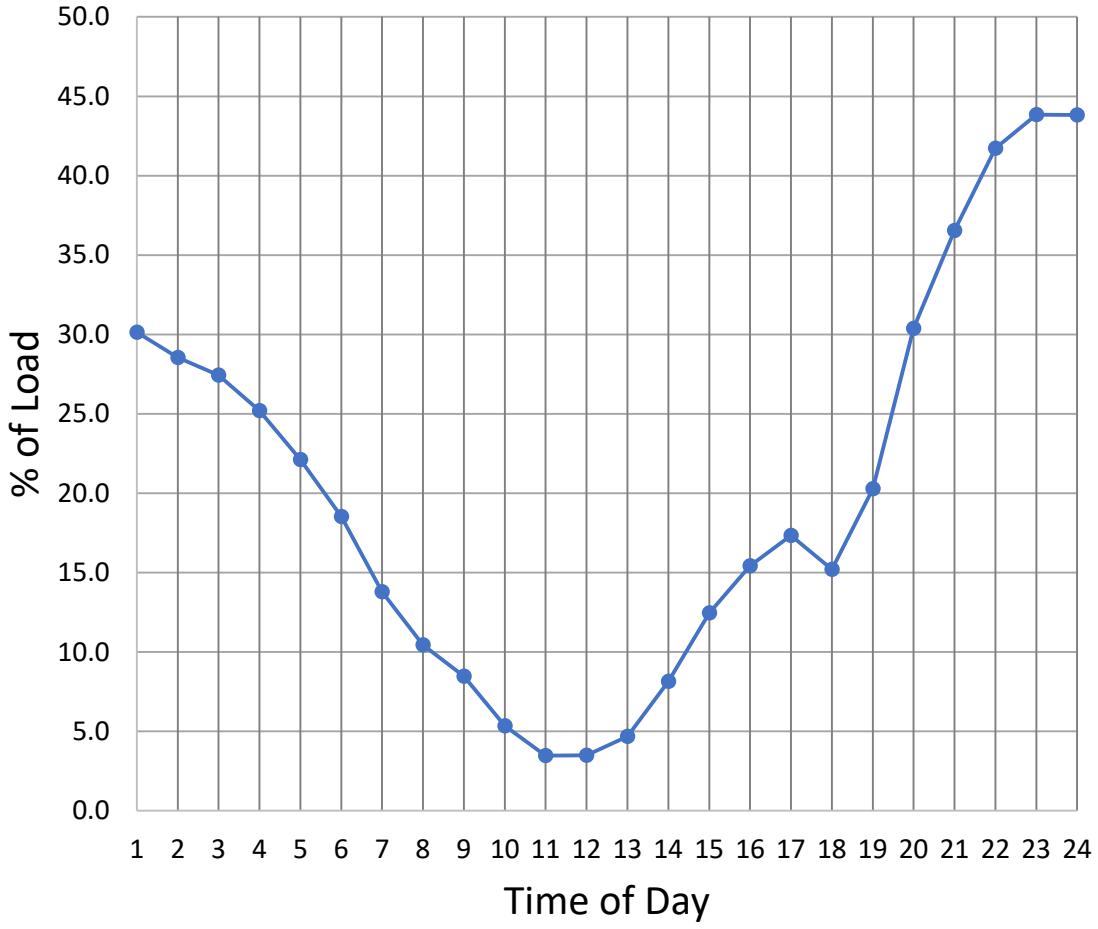


Wind resource of the United States.



Source: C. Draxl, B.M. Hodge, A. Clifton, and J. McCaa. 2015. *Overview and Meteorological Validation of the Wind Integration National Dataset Toolkit,* Technical Report, NREL/TP-5000-61740. Golden, CO: National Renewable Energy Laboratory.

Variability of wind generation

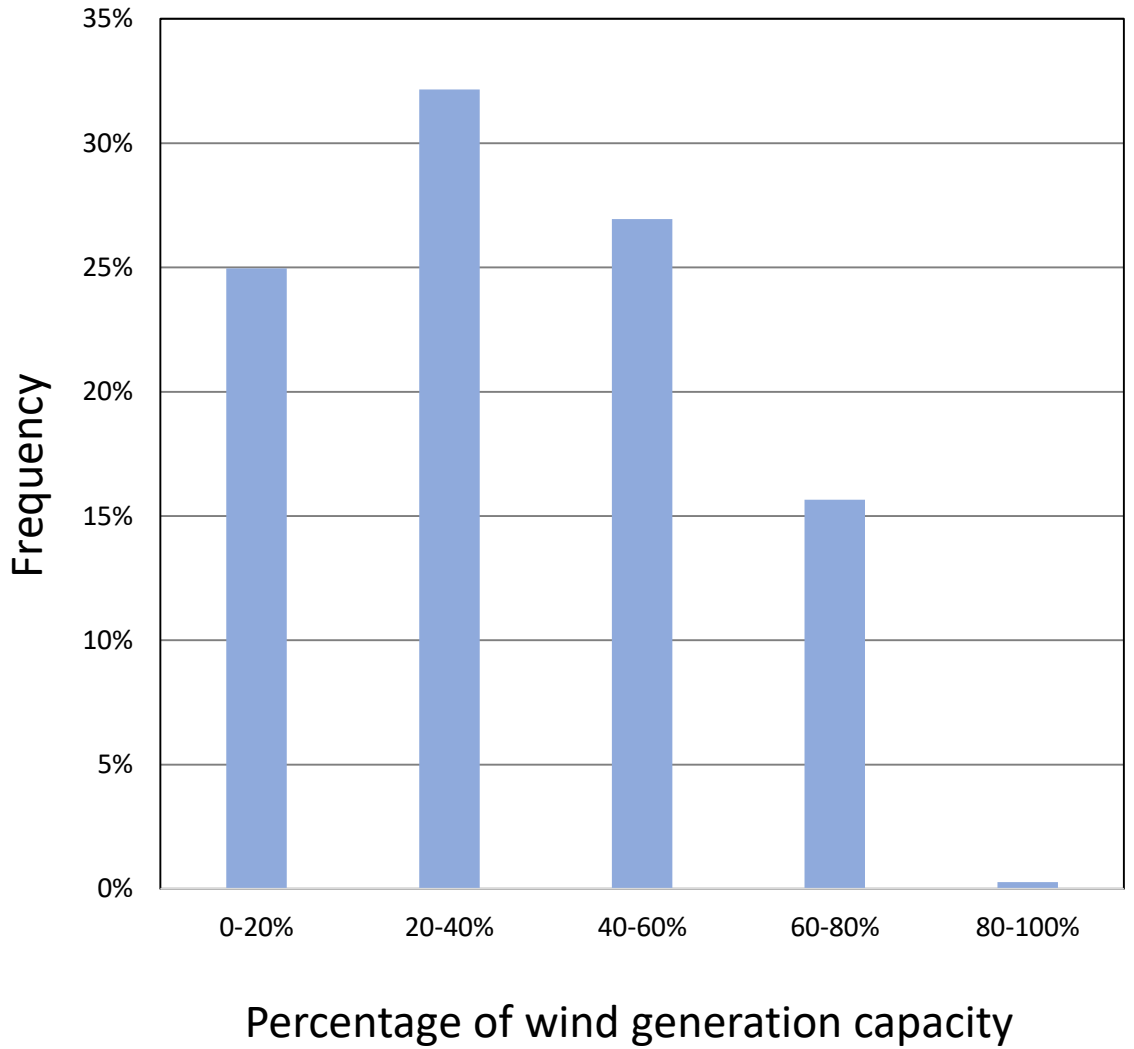


- Percentage of the aggregated load in the ERCOT system supplied by wind generation on November 16, 2018
- Rather extreme day
- Variability must be compensated by other sources

Source: http://www.ercot.com

Histogram of wind generation output

- Histogram of the wind generation output in the ERCOT system in 2018
- Overall wind generation capacity factor for 2018: 36.6%



Source: http://www.ercot.com

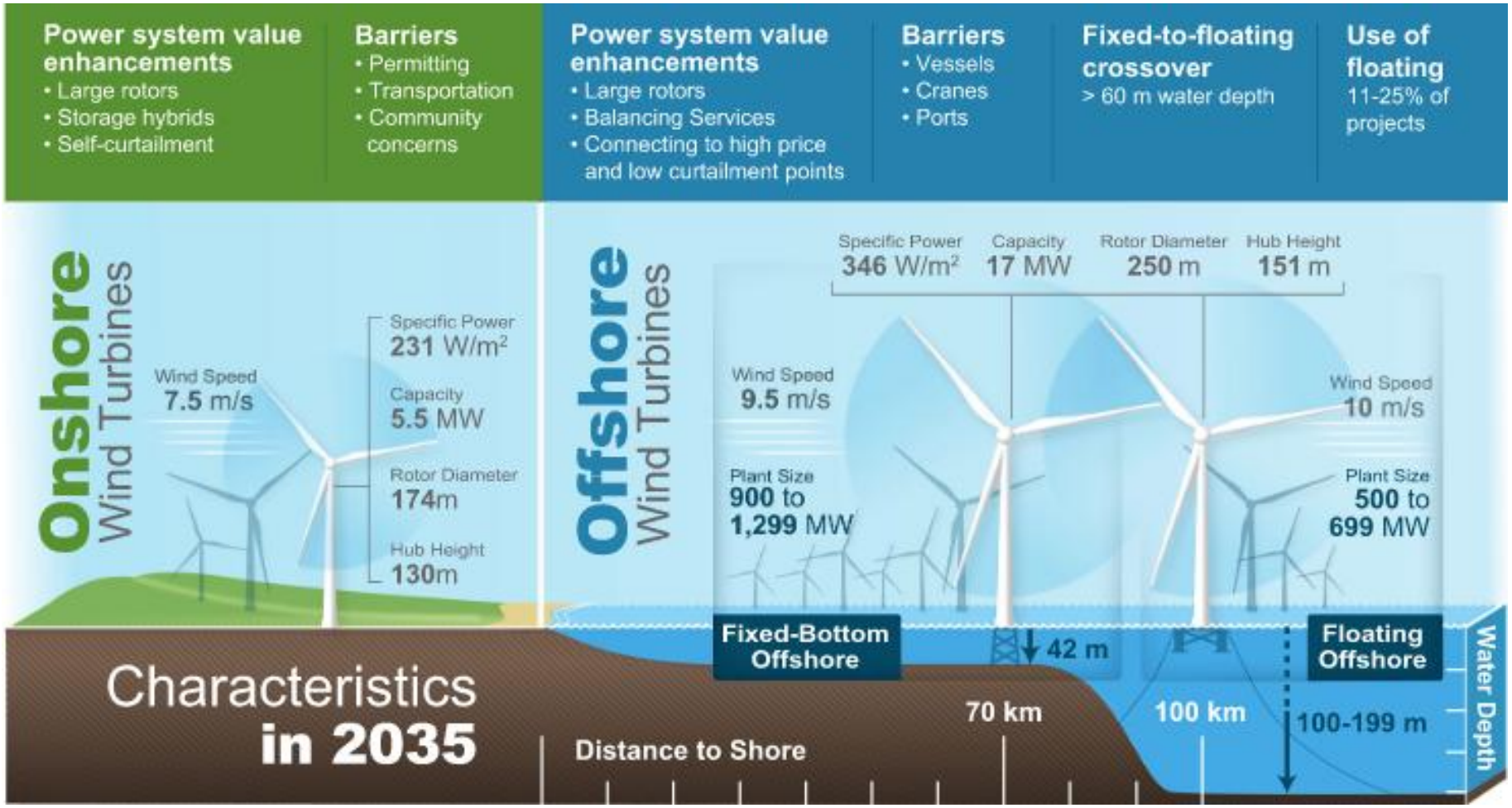
Offshore wind



Offshore wind



Offshore wind



Beiter et al., "Expert perspectives on the wind plant of the future", *Wind Energy*. 2022;1-16

Thermal generation



Heat engine

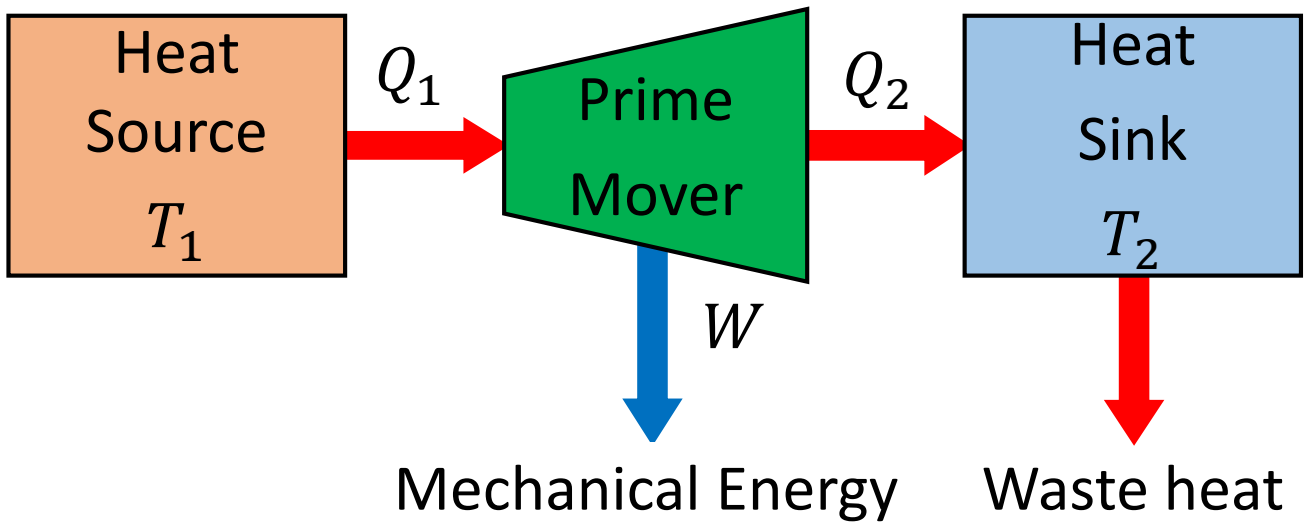
Q_1: Thermal energy to the prime mover

Q_2: Thermal energy wasted

W: Energy converted to mechanical form

T_1: Absolute temperature of the heat source

T_2: Absolute temperature of the heat sink



Carnot Efficiency

$$\eta_{Carnot} = \frac{W}{Q_1} = \frac{T_1 - T_2}{T_1}$$

Q_1: Thermal energy to the prime mover

Q_2: Thermal energy wasted

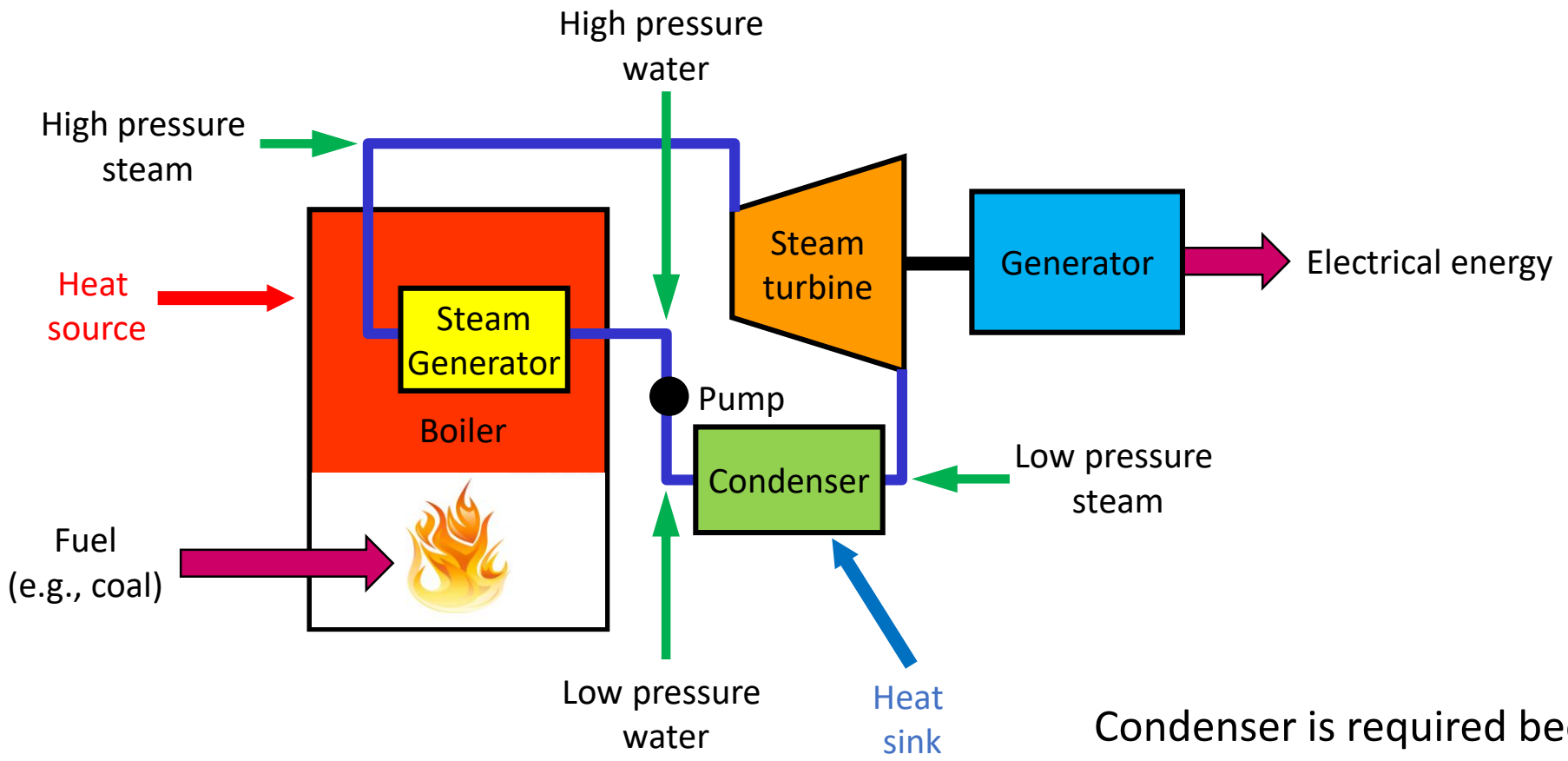
W: Energy converted to mechanical form

T_1: Absolute temperature of the heat source

T_2: Absolute temperature of the heat sink

- Maximum theoretical efficiency
- Practical efficiency much lower
- To increase efficiency:
  - Raise T_1
  - Lower T_2

Fossil-fueled steam plants



Condenser is required because pressuring steam requires much more energy than pressuring water

Example 3.1: Efficiency of a coal plant

In a sub-critical coal generating plant, the temperature of the steam as it leaves the boiler and enters the turbine is 565°C. The temperature of the water as it exits the condenser is 20°C.

The Carnot efficiency of this plant is:

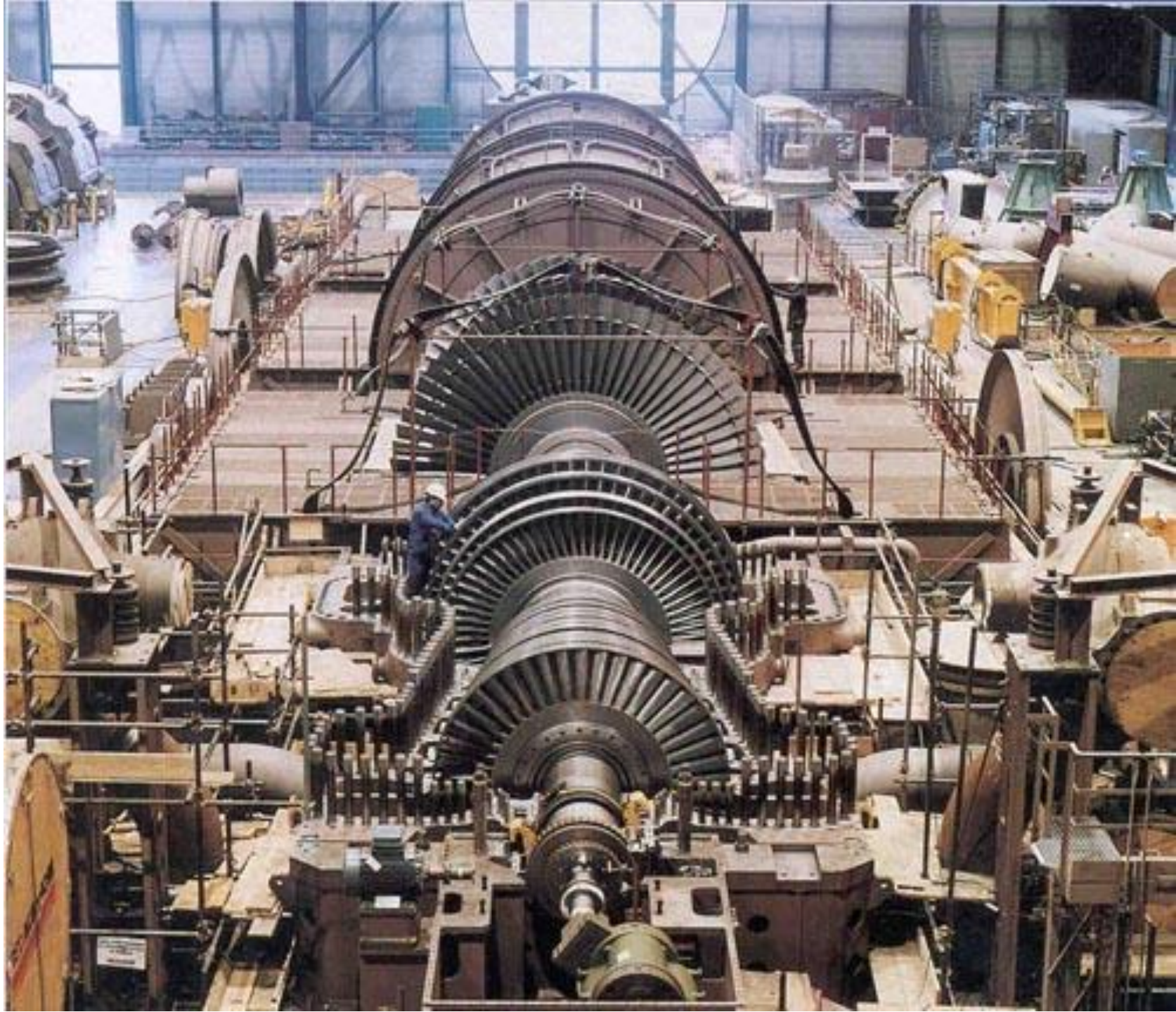
$$\eta_{Carnot} = \frac{T_1 - T_2}{T_1} = \frac{(565 + 273.15) - (20 + 273.15)}{(565 + 273.15)} = 65\%$$

- Practical efficiency of such a plant is typically around 39%.

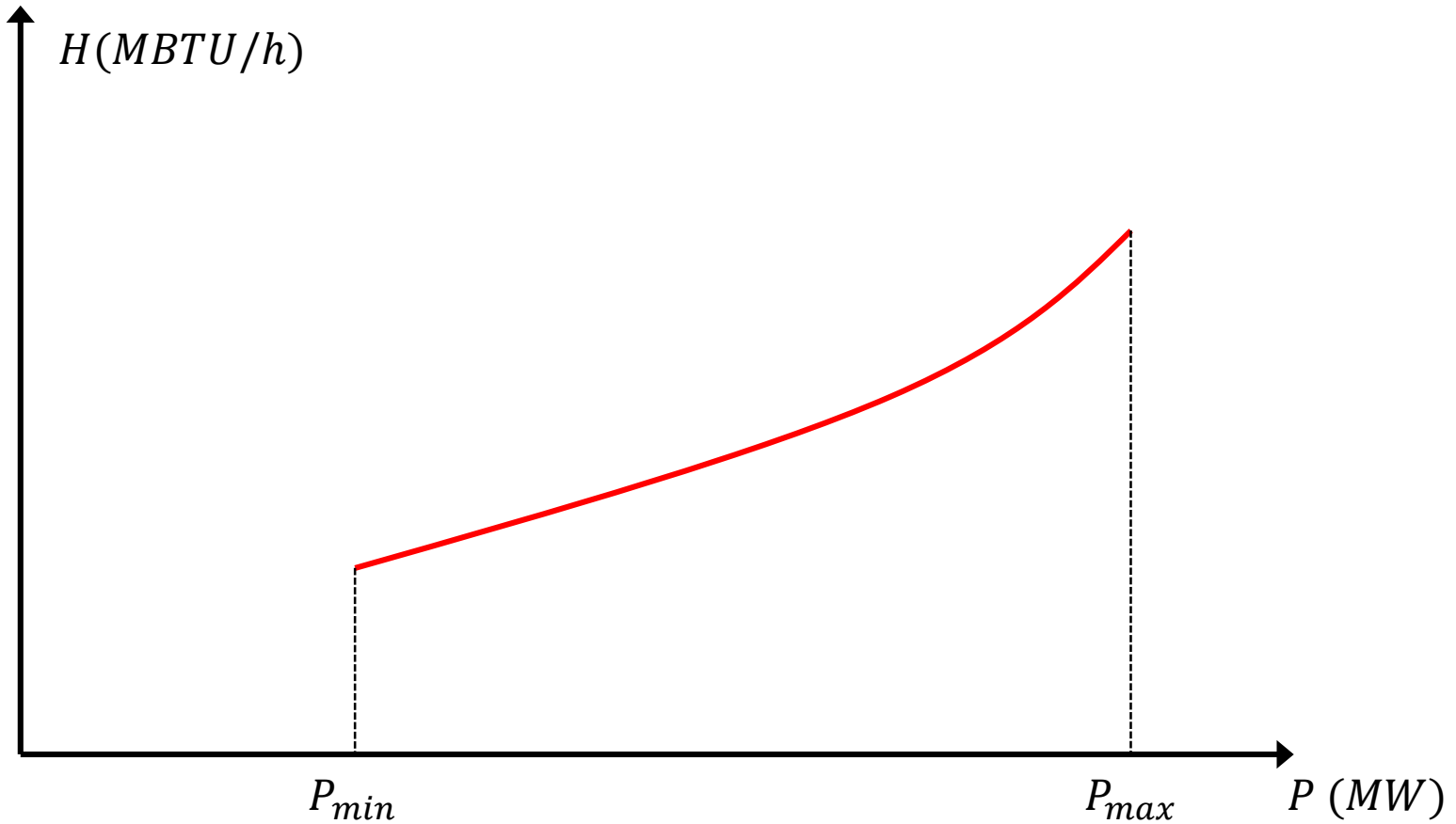
Coal power plant



Steam turbine



Input/output curve of a thermal power plant



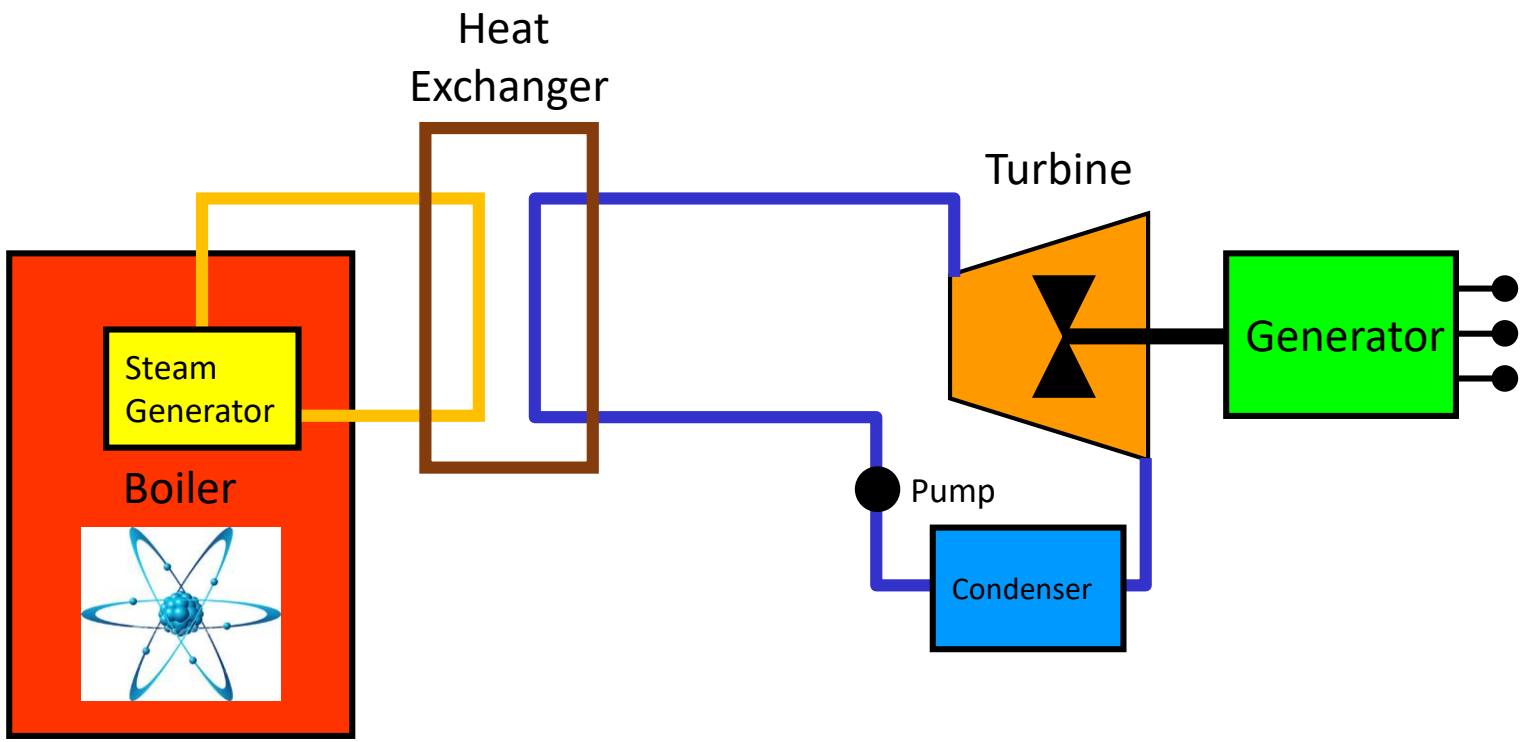
Example 3.2: Heat rate and CO_2 emissions

According to the United States Environmental Protection Agency, the average, annual operating heat rate of U.S. coal-fired power plants is approximately 10,400 BTU/kWh.

To generate a constant 500 MW, a power plant would therefore have to produce 5.2 10^9 BTU of heat every hour, which would require burning about 168,477 kg (371,429 pounds) of coal.

This plant would release 481,845 kg (1,062,360 pounds) of CO_2 each hour.

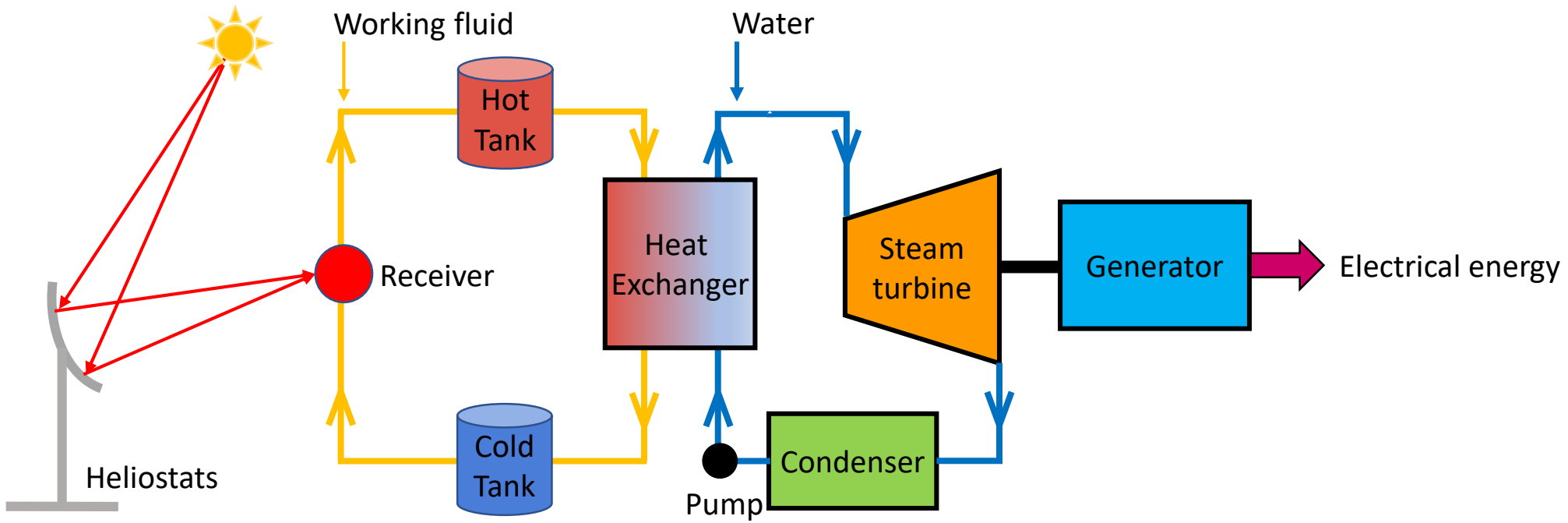
Nuclear power plants



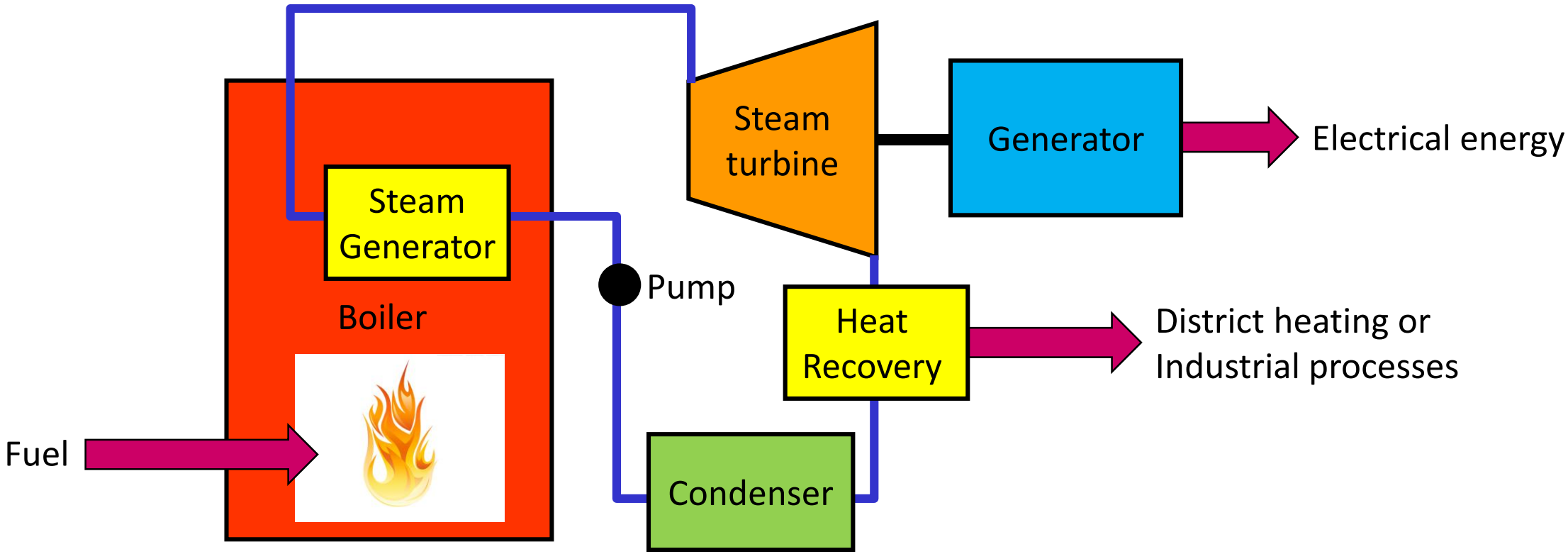
Nuclear power plant



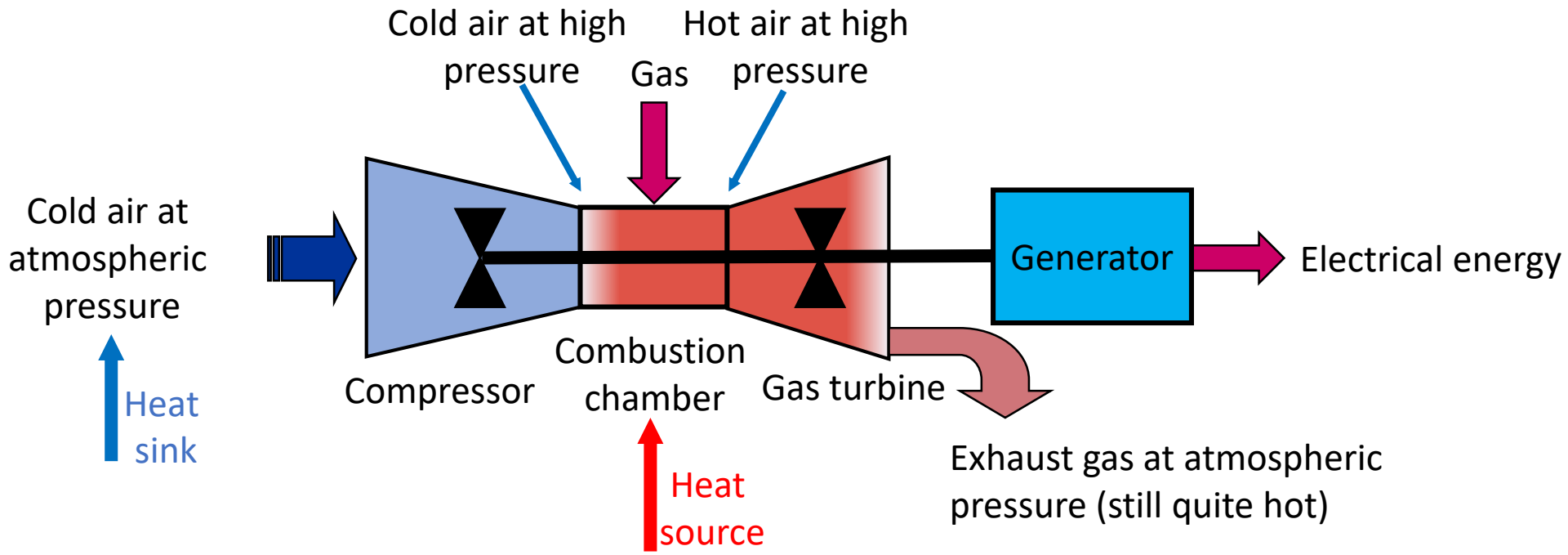
Concentrated solar plant



Combined heat and power plants - cogeneration

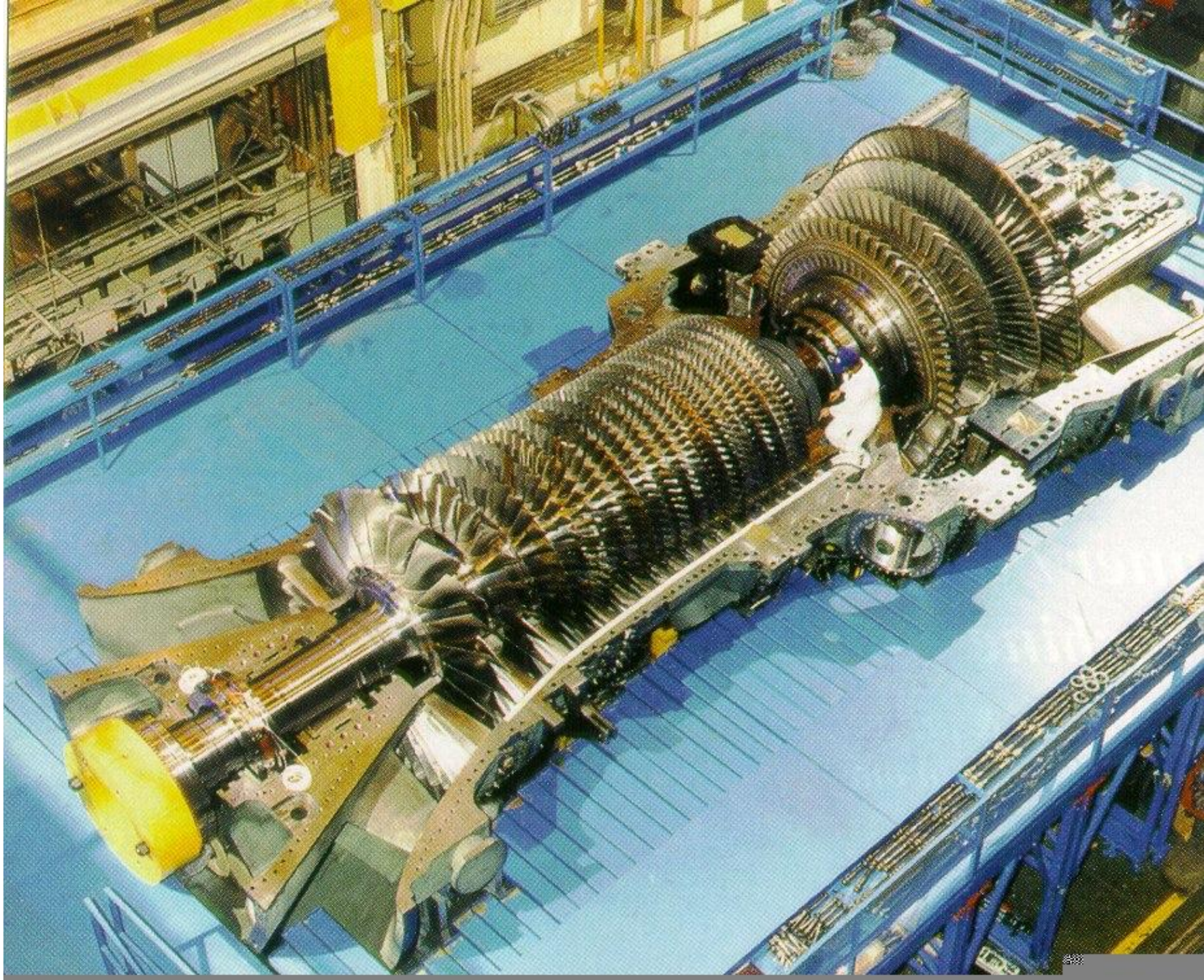


Open cycle gas turbine (OCGT)



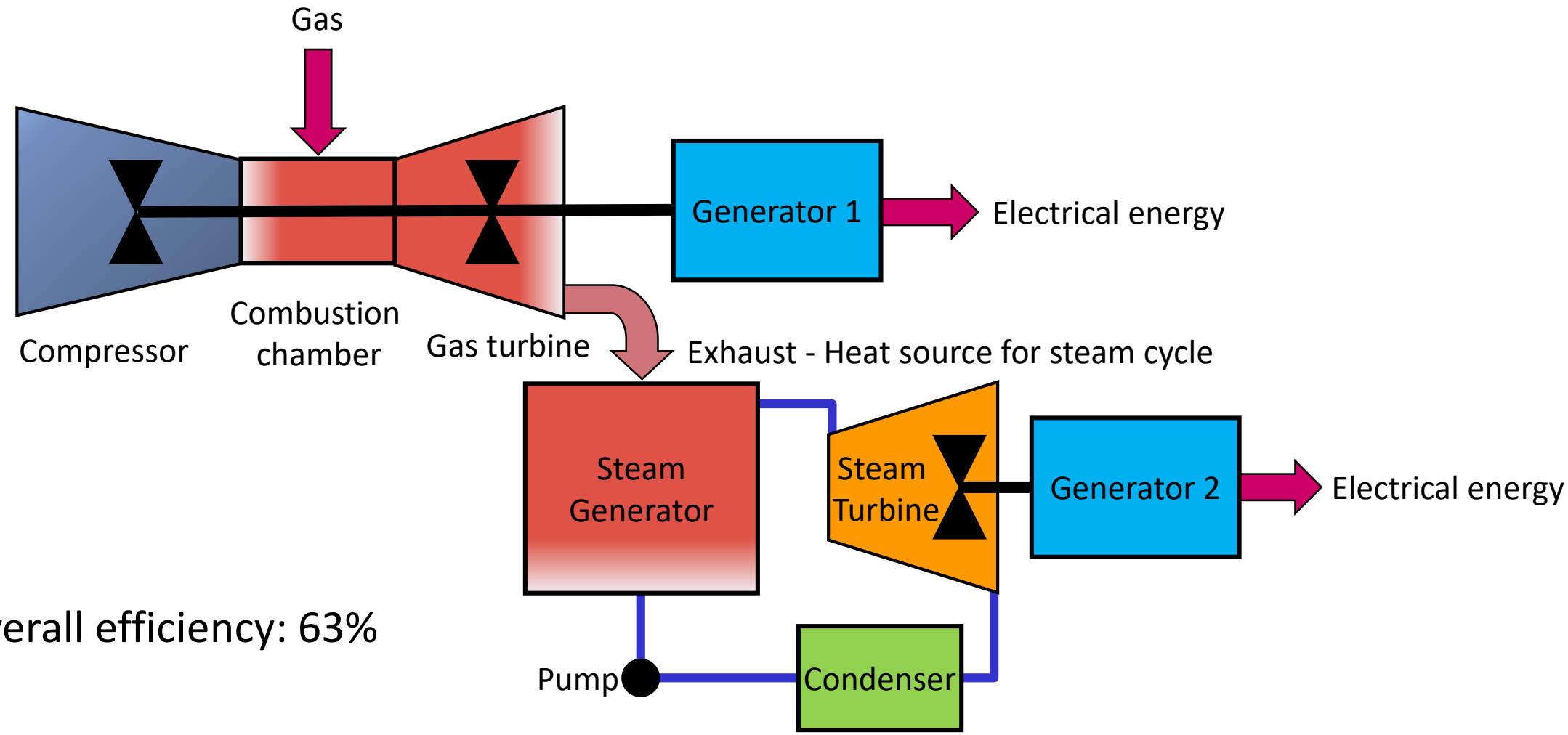
- Cheap to build
- Expensive to operate because inefficient
- Highly flexible (fast start, quick ramp up and down)

Gas turbine



Picture: General Electric

Combined cycle gas turbine (CCGT)



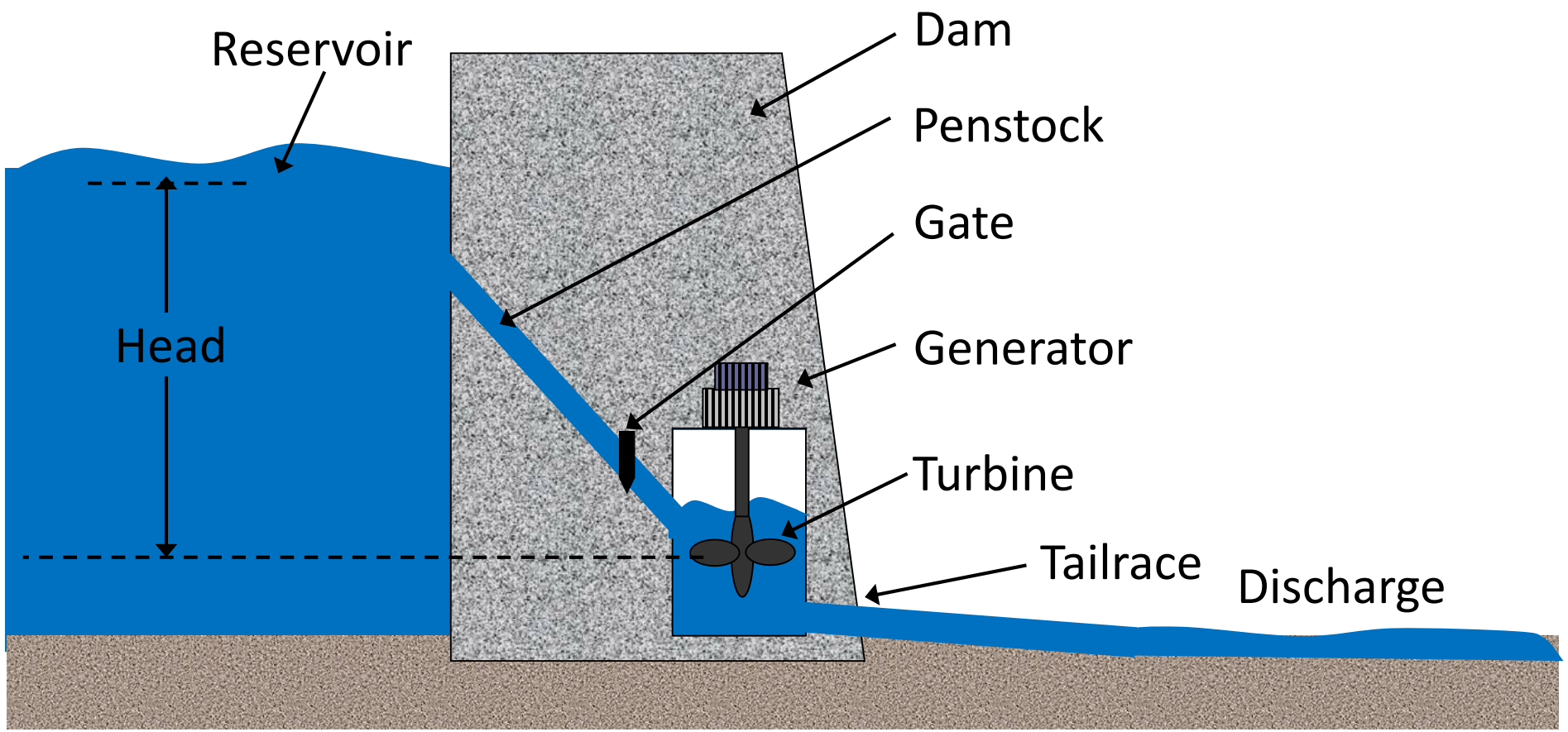
High overall efficiency: 63%

Hydroelectric generation

Grand Coulee Dam
Washington State, USA



Impoundment hydro plants



Grand Coulee Dam



Tailrace of Grand Coulee Dam



Turbine hall of Grand Coulee Dam



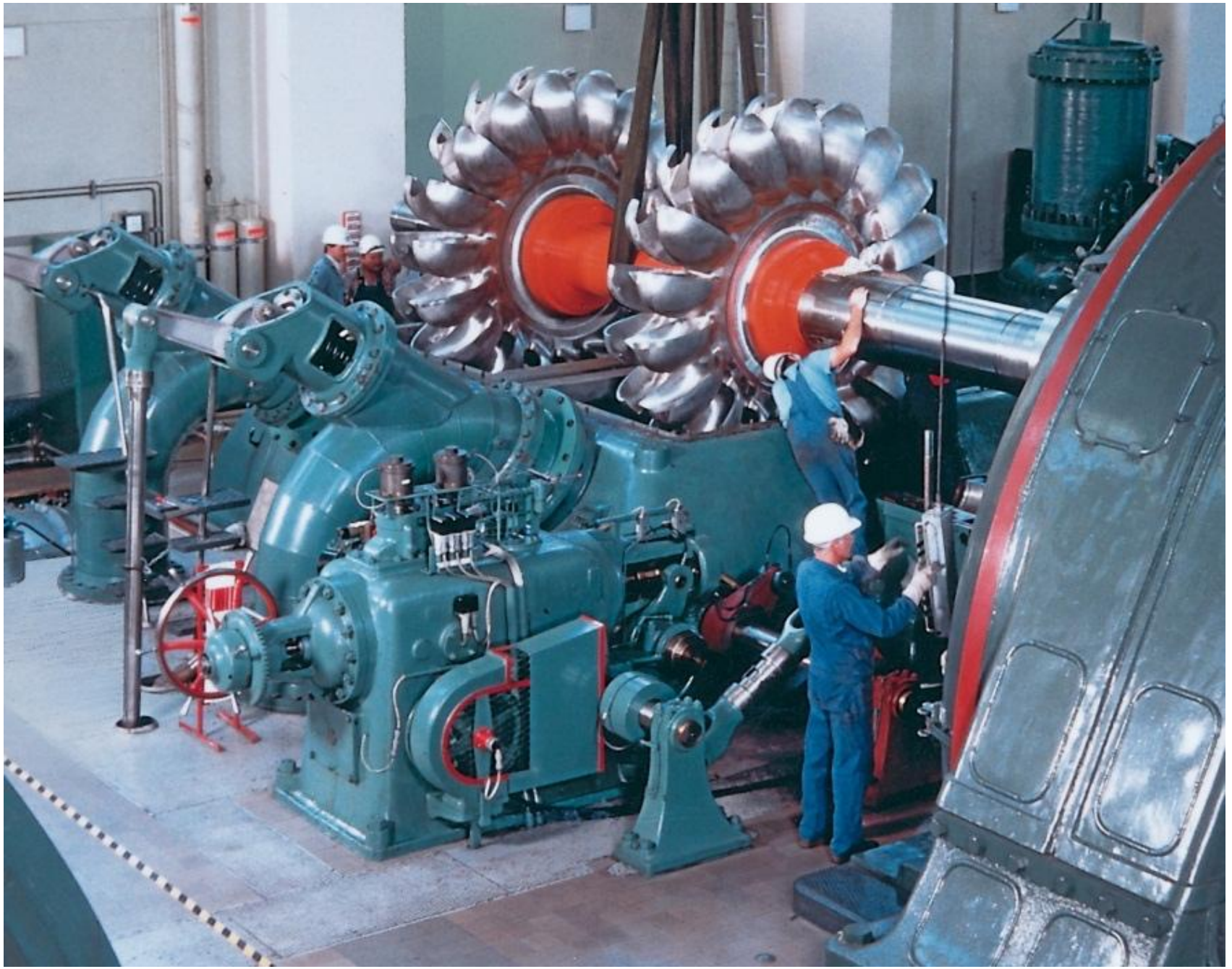
Francis turbine



Kaplan turbine



Pelton turbine



Three Gorges Dam on the Yangtze River



Itaipu Dam (Brazil & Paraguay)



Energy in an impoundment reservoir

- Potential energy per unit of volume of water:

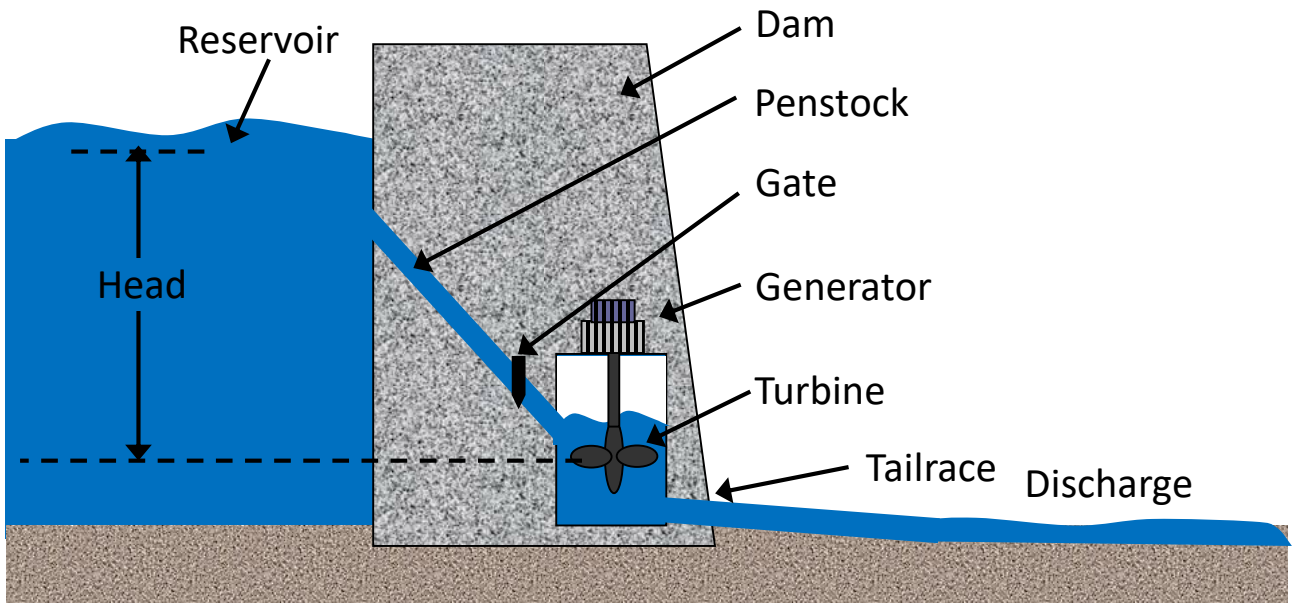
$$e = \rho_w g h$$

- ρ_w: specific mass of water (kg/m^3)
- g: acceleration of gravity (m/s^2)
- h: head (m)

- Total potential energy:

$$E = \rho_w g h V$$

- V: volume of the reservoir (m^3)



Example 3.3: Energy in a hydro reservoir

The reservoir behind the Grand Coulee dam in Washington State has a volume of 9,562,000 acre-ft (12 km^3). However, only 5,185,400 acre-ft (6 km^3) are considered “active” i.e., can be used for power generation. The hydraulic head is 116 m.

The useable potential energy in this reservoir is thus approximately:

$$E = 1000\frac{kg}{m^3} \times 9.81\frac{m}{s^2} \times 116m \times 6 \times 10^9 m^3 = 6.83 \times 10^{15} J = 1{,}897\ GWh$$

Approximately the amount of energy that the consumers of the city of Seattle use in 10 weeks.

Power from a hydro plant

- Power in the water:

$$P_w = \rho_w g h Q_w$$

- Q_w: Water flow rate (m^3/s)

- Power produced by the turbine:

$$P = \eta \rho_w g h Q_w$$

- η: turbine efficiency (~90%)

Controlling hydro power

- Hydro is highly flexible
  - Quick start
  - Fast ramp up and ramp down
- Turbine efficiency drops quickly when flow is off nominal
  - Install multiple small turbines
  - Operate each turbine at nominal flow or turn it off

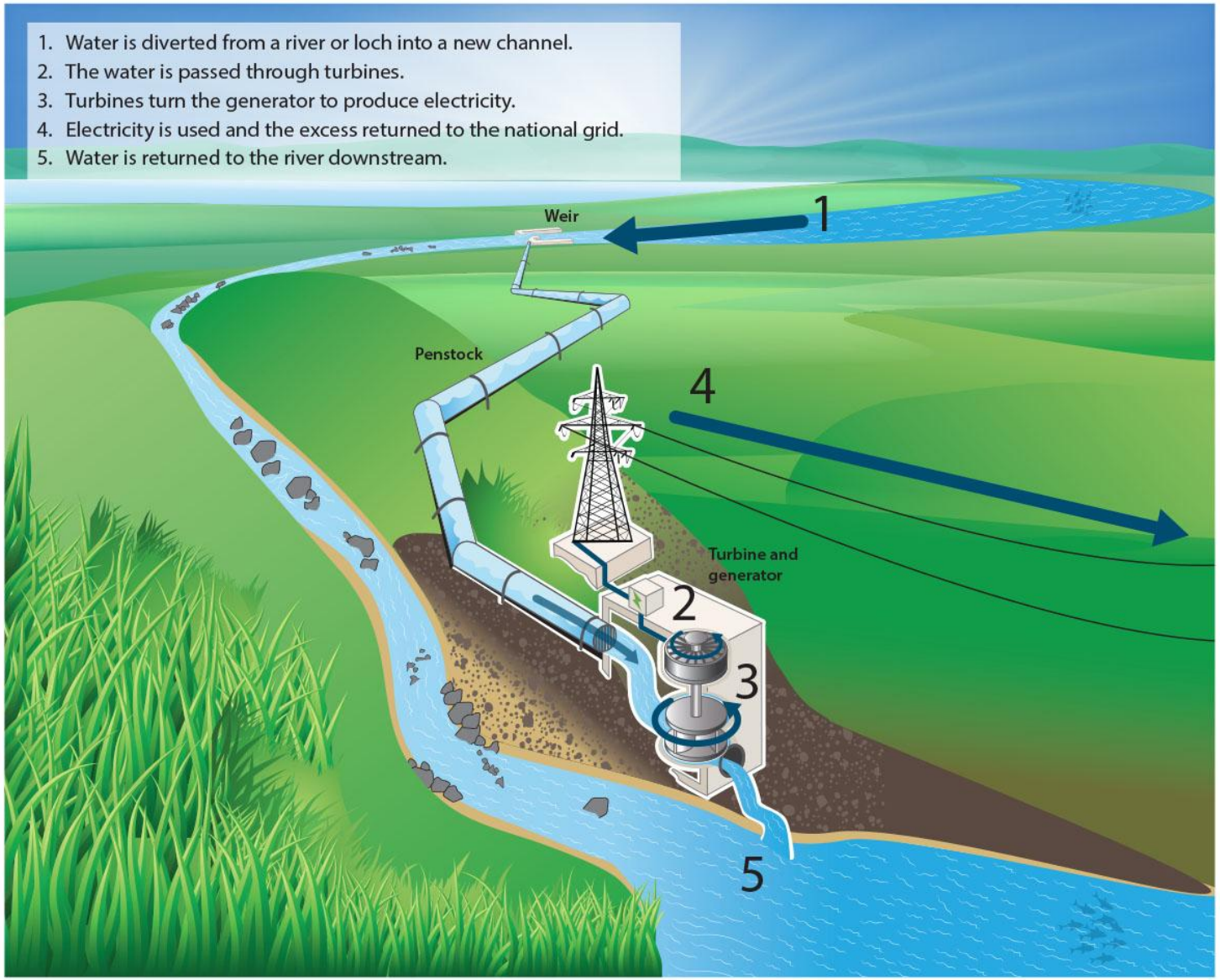
Columbia river system

- Operation of upstream dams affects the downstream dams
- Environmental constraints
  - Effect on fish population
- Interactions with other uses of water
  - Flood control
  - Irrigation
  - Transportation
  - Recreation
- Scheduling hydro production is a very complex problem



Diversion hydro plants

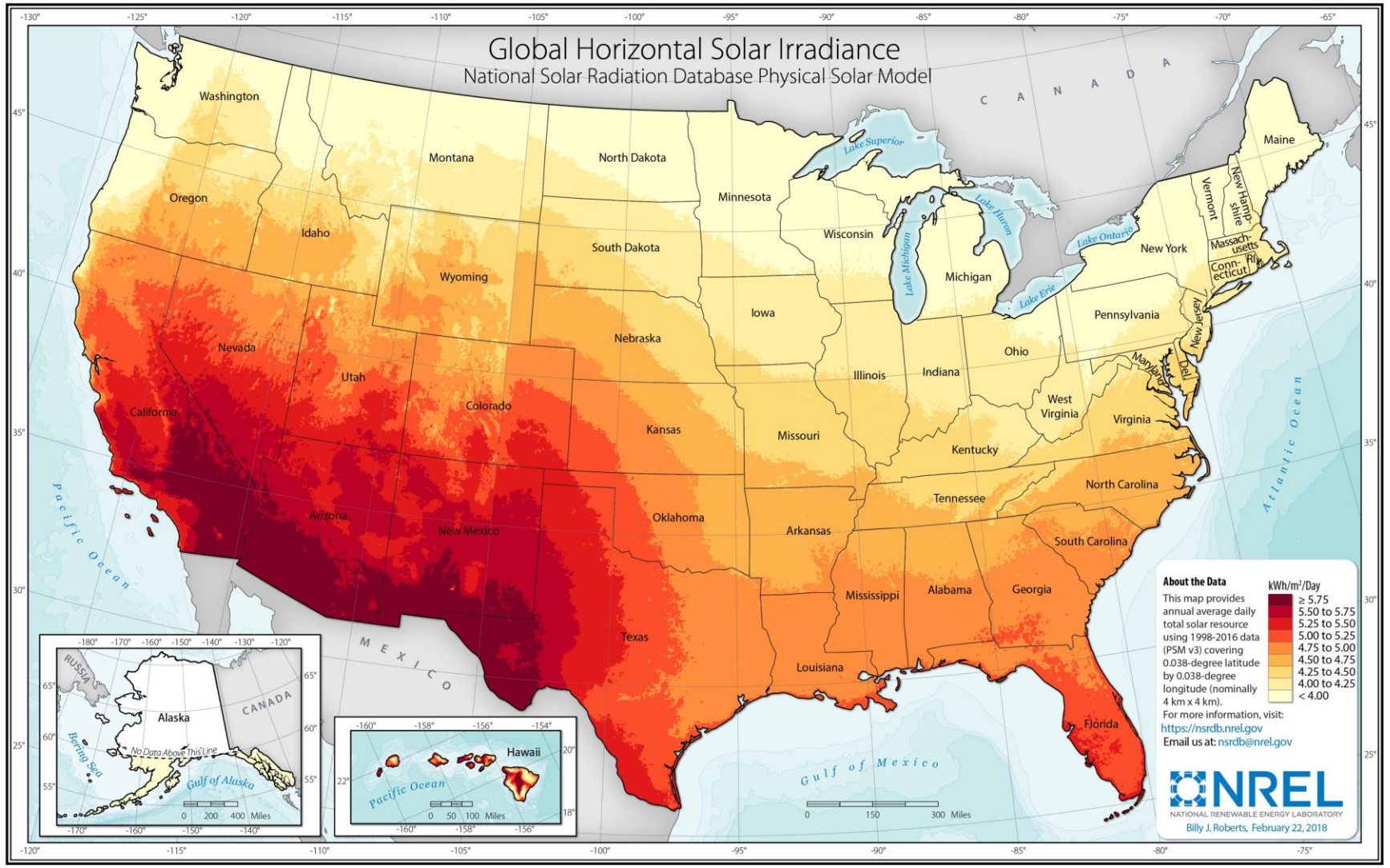
- “Run-of-the-river” hydro
- Power production depends on water flow in the river
- Much smaller environmental impact that impoundment hydro



Photovoltaic generation



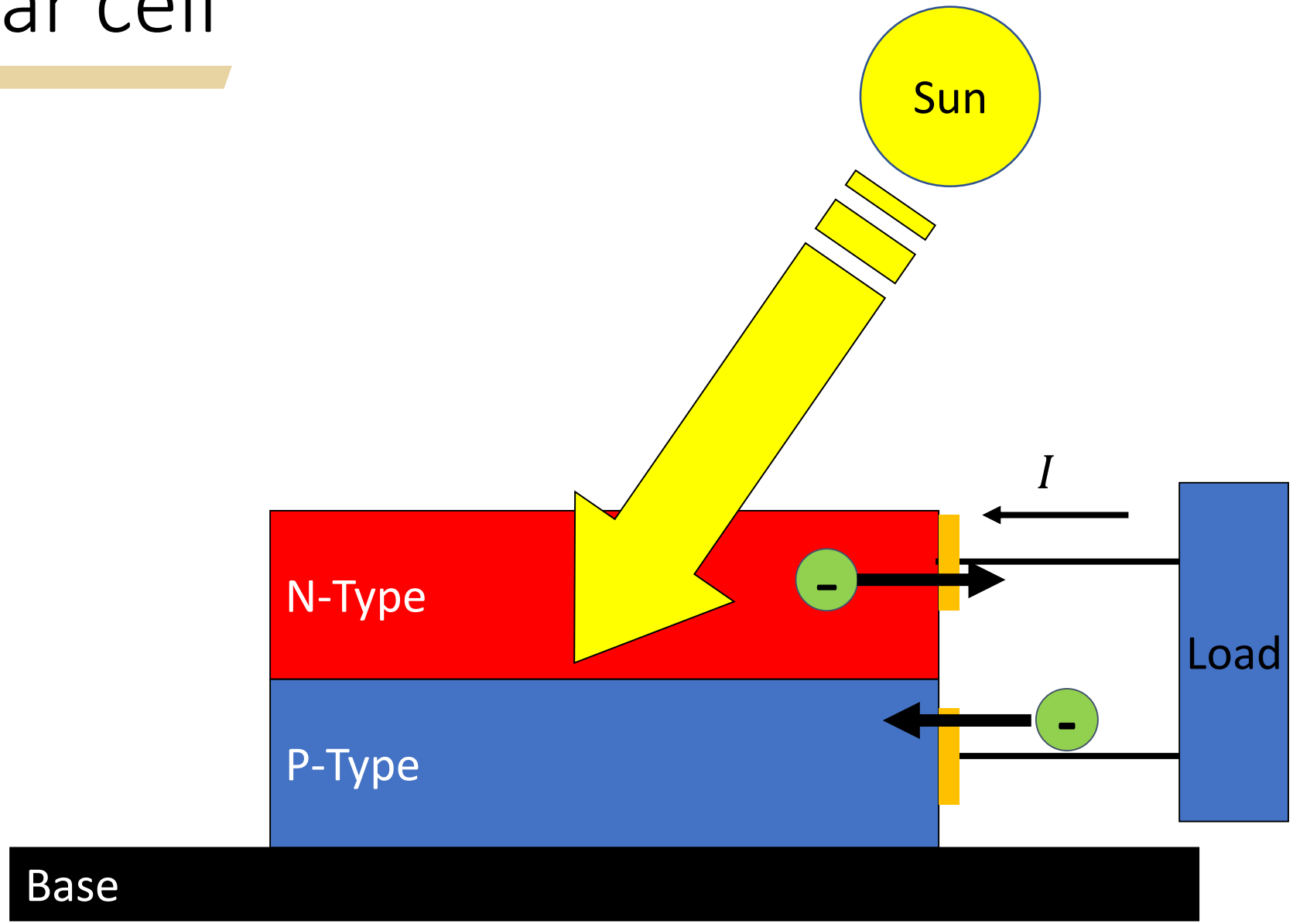
Solar resources in the United States



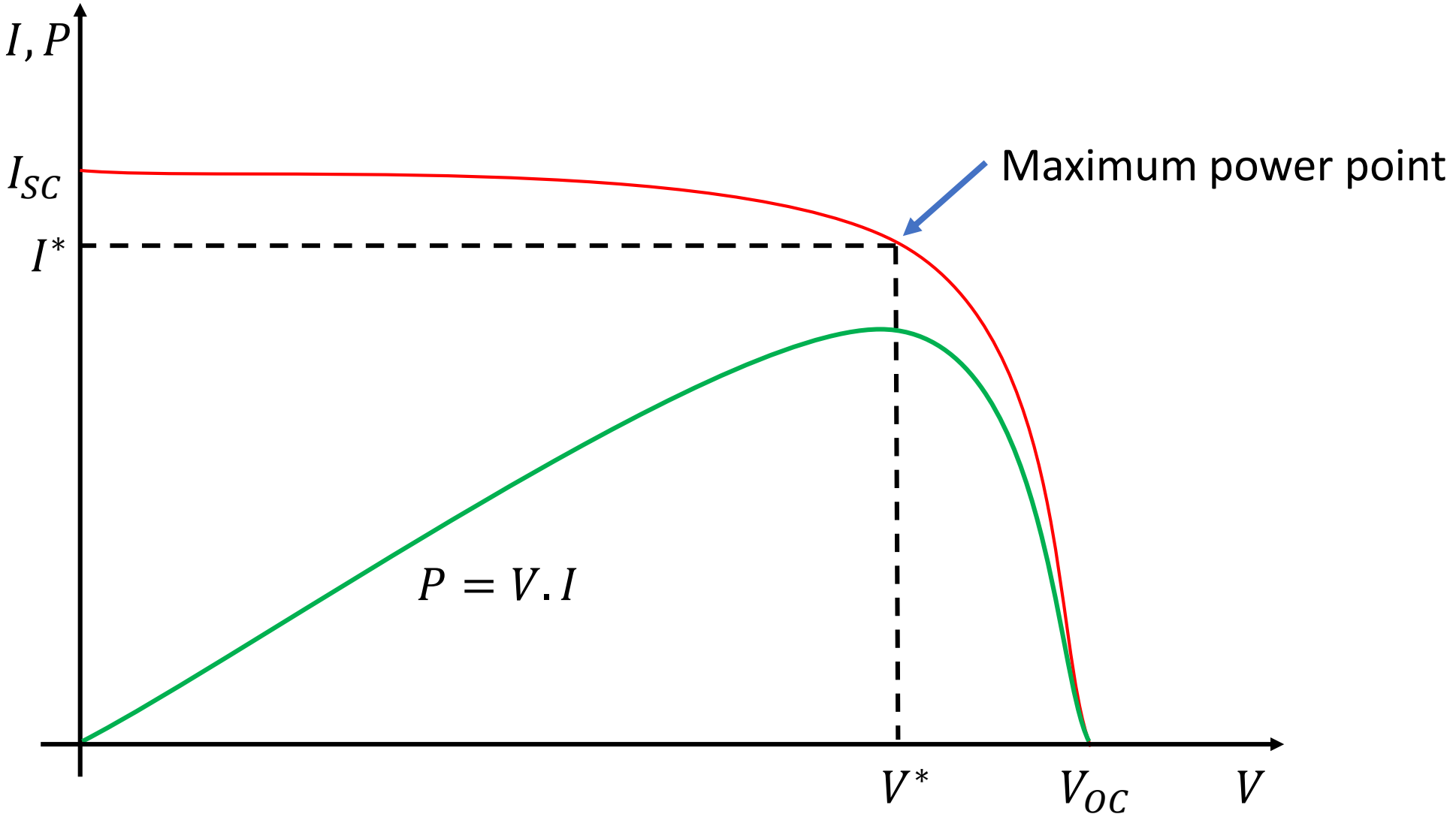
Global horizontal solar irradiance (W/m^2)

Source: Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. "The National Solar Radiation Data Base (NSRDB)." *Renewable and Sustainable Energy Reviews* 89 (June): 51-60.

Solar cell

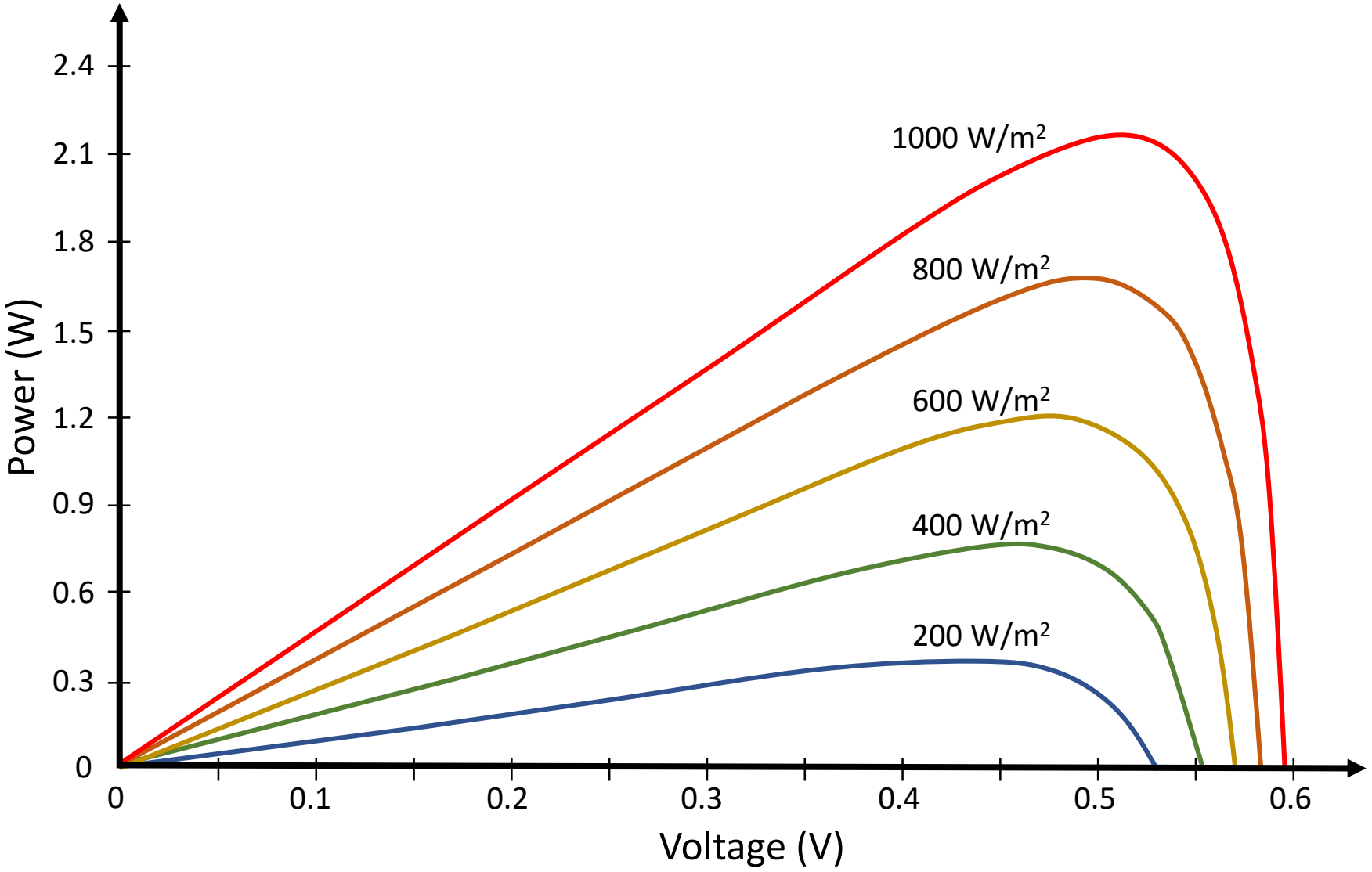


$I - V$ and $P - V$ characteristics of a solar cell

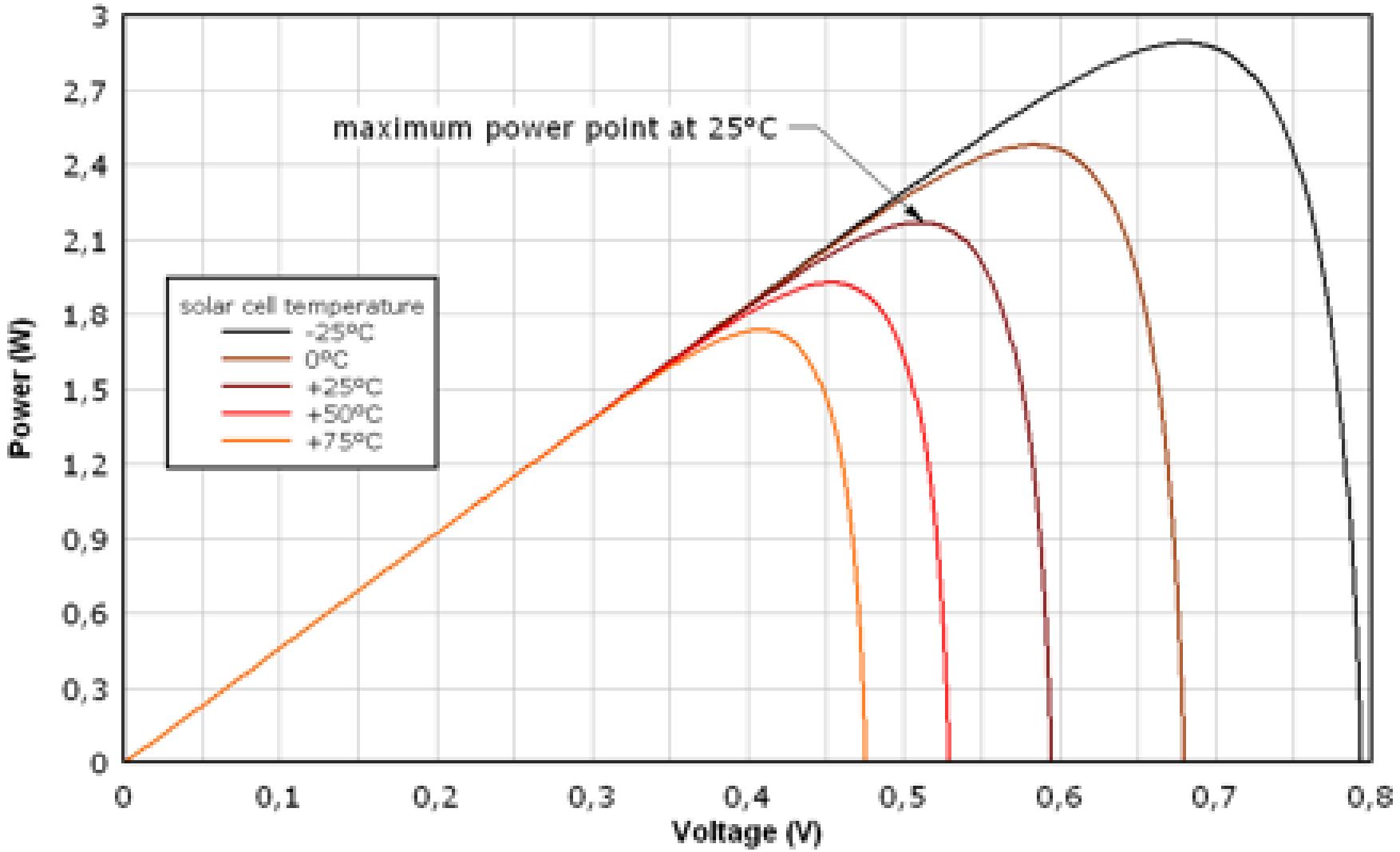


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Effect of irradiance on the $P - V$ characteristic



Effect of temperature on the $P - V$ characteristic



Source: https://www.pvresources.com/en/solarcells/solarcells.php

Maximizing solar generation

- Maximum power point depends on:
  - Irradiance
  - Temperature
- Operating at fixed voltage, fixed current or fixed resistance therefore does not maximize the efficiency of the cell.
- Must adjust the voltage to track the maximum power point
  - See chapter on power electronics energy conversion

- Each solar cell produces at best a small voltage and current
  - Connect cells in series to increase the voltage
  - Connect cells in parallel to increase the current

Example 3.4: PV array

A small PV array consists of two parallel columns of four panels connected in series. Each of these panels comprises 4 rows of 9 cells connected in series. Each cell produces a maximum of 2.5W at 0.5V. Calculate the voltage, current and power rating of this array.

The voltage in each row of a panel is $9 \times 0.5 = 4.5V$.
The maximum power produced by each panel is $36 \times 2.5 = 90W$.
The current produced by each panel is then: $I_{panel} = \frac{90}{4.5} = 20A$.
Since each column of the array consists of four panels in series, the voltage rating of the array is:
$V_{array} = V_{panel} \times 4 = 18V$.
Since there are two columns in parallel, the current rating of the array is:

$$I_{array} = I_{panel} \times 2 = 40A$$

Finally, the power rating is given by:

$$P_{array} = V_{array} \times I_{array} = 18 \times 40 = 720W$$

Solar tracking

- Concept: rotate the solar panel to maximize irradiance
- Horizontal axis rotation to track solar elevation
- Vertical axis rotation to track solar azimuth
- ~50% of utility-scale solar installations use single-axis tracking
- A few utility-scale solar installations use two-axis tracking
- Remainder and most residential solar installations do not use tracking
- Efficiency gain must be weighed against higher cost

Vertical axis tracking



Source: Vinaykumar8687 through Wikimedia

Horizontal axis tracking

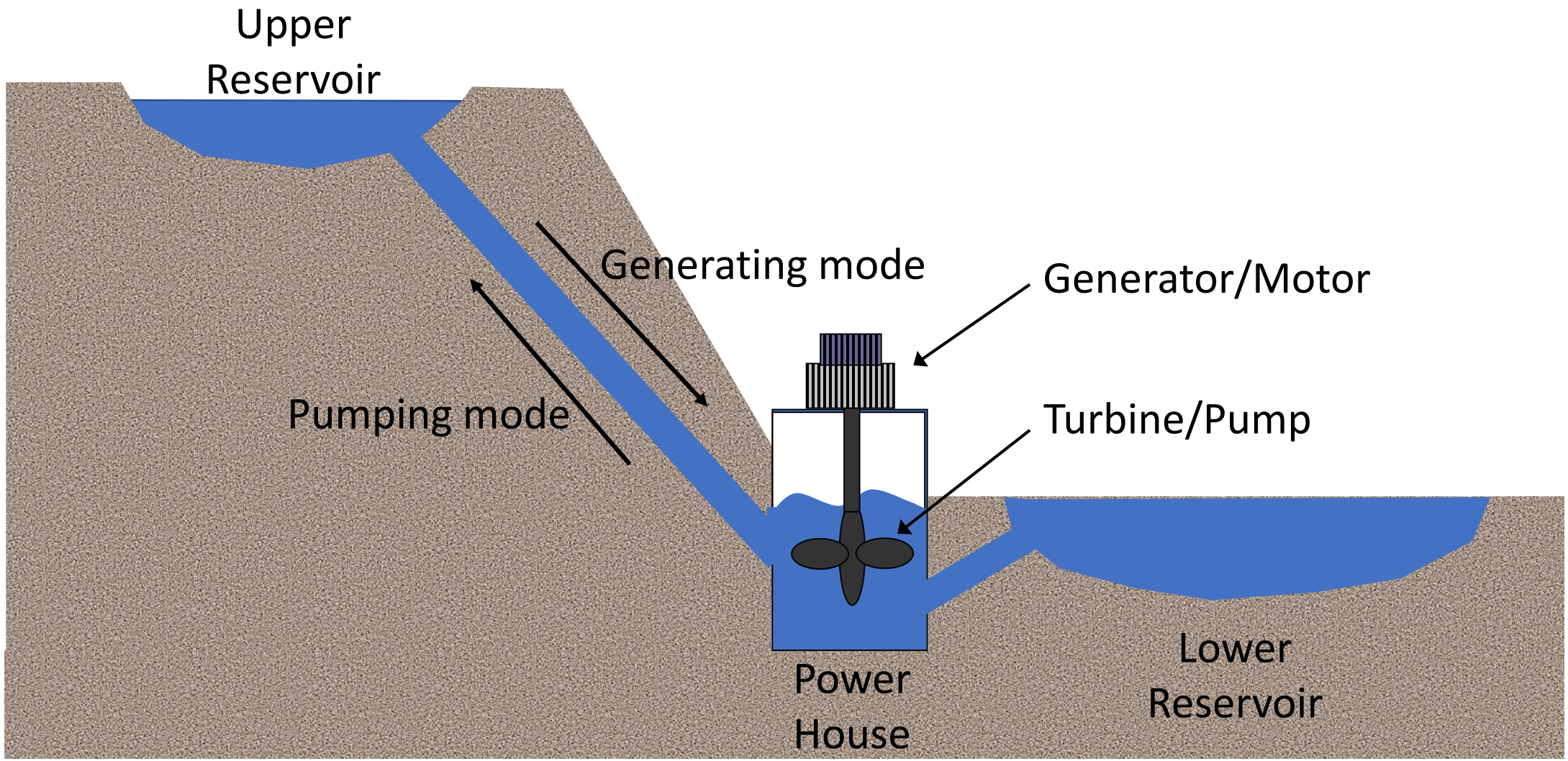


Source: Vinaykumar8687 through Wikimedia

Energy storage



Pumped hydro plant



Pumped hydro plant

- Large power ratings: 100’s to 1000’s of MW
- Typically stores enough water to discharge at full MW capacity for 6-8 hours
- Typical roundtrip efficiency 70-80%
- Construction cost is large

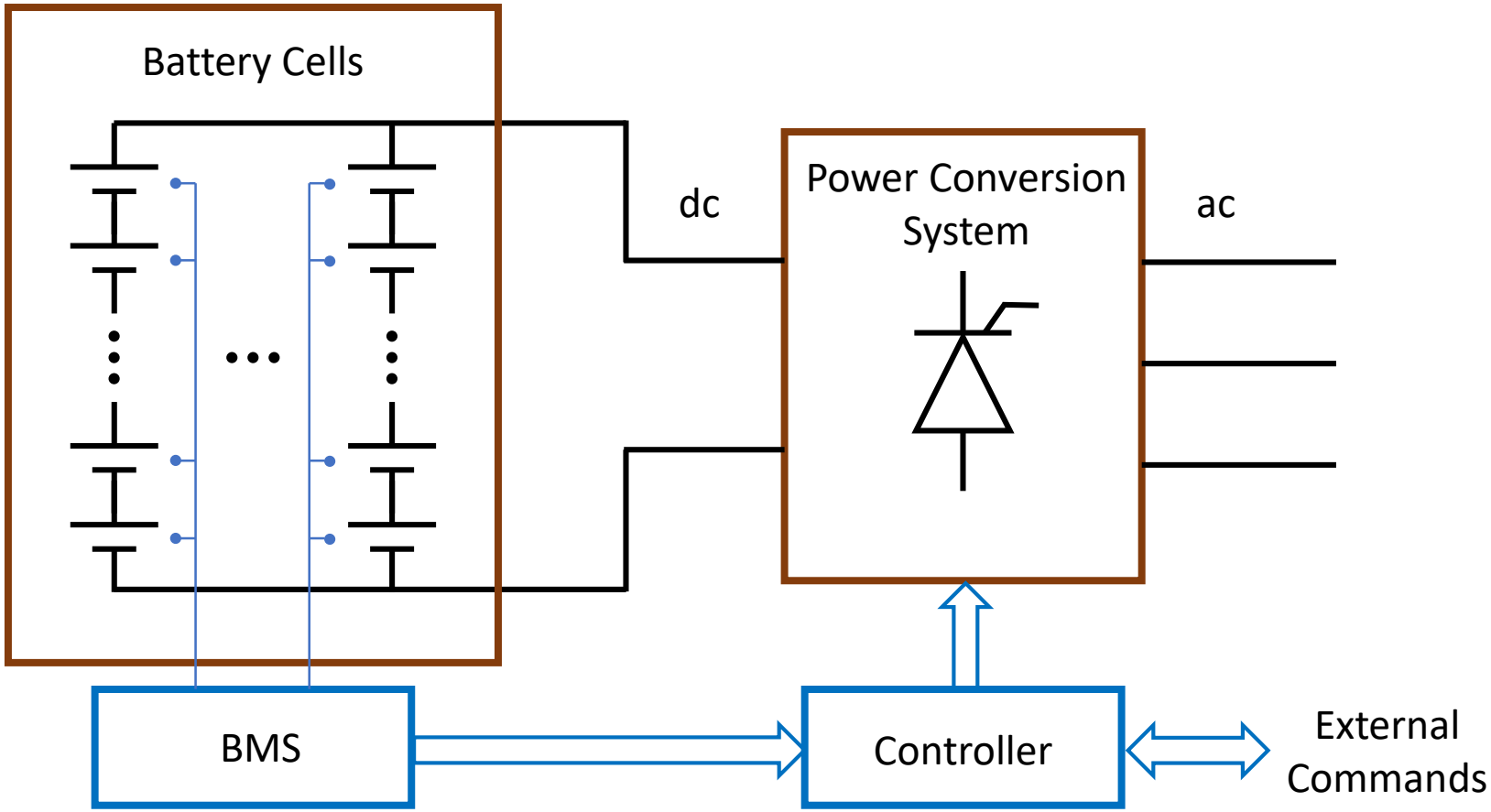
Rocky Mountain Hydroelectric Plant (Georgia)



Hohenwarte II in Thuringia, Germany



Battery energy storage systems (BESS)



Battery energy storage systems

- Battery cells arranged in series and parallel
  - Achieve suitable current and voltage ratings
- Bidirectional power electronics converter
- Battery management system (BMS)
  - Monitors currents, voltages, temperatures of the battery cells
  - Balance loading during charging and discharging
  - Maintain safe operating condition

BESS characteristics

- Energy rating (MWh)
- Power rating (MW)
- Roundtrip efficiency (~80% typically)
- State of Charge (SoC): percentage of energy rating available
- Battery degradation
  - Typically, 75% of energy capacity remains after 10 years
- C-rate
  - C = 1 means that a fully charged battery is discharged in one hour
  - Faster charge/discharge rates reduce the battery life

Example 3.5: Battery energy storage system

The BESS of Snohomish PUD's Arlington microgrid is rated at 1MW, 1.38 MWh.

The cells are arranged in 11 parallel racks of 9 modules in series.

The voltage on the dc side varies between 1,126 V and 1,461 V depending on whether the battery is charging or discharging.

The voltage on the ac side is 630 V.

It is housed in a $23.3' \times 8' \times 9.6'$ container that weighs 55,000 pounds.

Other energy storage technologies

- Flywheels rotating at up to 100,000 rpm
- Compressed air combined with gas turbines
- Use surplus renewable energy to electrolyze water and produce “green hydrogen”.
  - Burning this hydrogen to generate electricity is not economically viable due to low thermodynamic efficiency.

Applications of energy storage

- Arbitrage – “Buy low – Sell high”
  - Charge when renewable energy is abundant, and demand is low
  - Discharge when demand is high and renewable energy is scarce
  - Requires a large price difference to compensate for losses
- Frequency regulation
  - Compensate for small fluctuations in load and generation
- Reserve services
  - Compensate for a sudden loss of generation
- Peaking generation
  - Provide power during periods of high demand

Choosing a generation technology



Factors affecting the choice of technology

- Local availability of primary energy
  - Hydro, fossil fuel, nuclear, wind, solar
- Self-reliance vs. imports
- Mandates for use of renewable sources
- Economic considerations
  - Profitability

A simple profitability calculation model

- Simplifying assumptions:
  - Consider a single year
  - Ignore uncertainties

- Profit Γ :

$$\Gamma = \pi E - C$$

  - π: sale price of electrical energy
  - E: amount of energy produced by the plant in one year
  - C: Cost of ownership of the plant
    - Annuitized investment cost + operating cost

Cost of ownership

$$C = \underbrace{c_{capacity}P}_{\text{Annuitized investment cost}} + \underbrace{c_{energy}E}_{\text{Operating cost}}$$

- P: capacity of the plant (MW)
- $c_{capacity}$ in \$/MW
- c_{energy} in \$/MWh

$$E = 8760 \times C_f P = C_h P$$

- C_f: Expected capacity factor of the plant

Breakeven price

$$\Gamma = \pi\, C_h P - c_{capacity} P - c_{energy} C_h P$$

Profit per MW of installed capacity (ignoring economies of scale):

$$\frac{\Gamma}{P} = \left(\pi - c_{energy}\right) C_h - c_{capacity}$$

Energy price at which the plant breaks even:

$$\pi = c_{energy} + \frac{c_{capacity}}{C_h}$$

Competitiveness

$$\pi = c_{energy} + \frac{c_{capacity}}{C_h}$$

To be competitive, a technology with a high investment cost must have:

- A low operating cost
- A large capacity factor

Example 3.6: Breakeven energy prices

	c_{energy} ($/MWh)	$c_{capacity}$ ($/MW)	C_f	C_h (h)	π ($/MWh)
Wind farm	0	140000	40%	3504.0	39.95
CCGT	26.5	88200	87%	7621.2	38.07

Levelized cost of energy (LCOE)

- Combines more rigorously operating and investment costs

$$LCOE = \frac{\sum_{t=0}^{N} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \text{ (\$/MWh)}$$

- N: expected life of the plant (years)
- I_t: expected investment cost in year t (\$)
- I_t: expected maintenance cost in year t (\$)
- F_t: expected fuel cost in year t (\$)
- E_t: expected energy production in year t (MWh)
- $(1+r)^t$: discount factor to reflect the time value of money

LCOE estimates

Plant type	Capacity factor (%)	LCOE ($/MWh)
Ultra-supercritical coal	85	76.44
CCGT	87	38.07
OCGT	30	66.62
Advanced nuclear	90	74.88
Geothermal	90	35.43
Biomass	83	94.83
Wind, onshore	40	39.95
Wind, offshore	44	122.25
Solar photovoltaic	29	33.12
Hydroelectric	59	52.79

US EIA estimates of the unweighted LCOE for new generation resources entering service in 2025 (2019 dollars)
(Source: www.eia.gov/aeo/pdf/electricity_generation.pdf)