Renewable Energy & Hydroelectric Works

8th semester, School of Civil Engineering

2nd semester, Master's Programme "Water Resources Science & Technology"

Introduction to energy engineering and renewable energy

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Course outline

- **Hydropower**
  - Layout and key components of hydropower systems (penstocks, hydro turbines)
  - Small hydropower plants (in-stream, run-off-river)
  - Hydroelectric reservoirs
- **Renewable energy**
  - Wind and solar energy
  - Energy storage (emphasis to pumped storage)
  - Hybrid renewable energy systems
  - Water-energy-food-land nexus
- **Generic tools**
  - Simulation and optimization models
  - Technical-financial analysis

Home assignments (non-mandatory, groups of up to three students)

- Design of small hydroelectric plant
- Simulation and optimization of hydroelectric reservoir operation policy
- Planning of hybrid renewable energy system across a non-interconnected island

To begin with…

- **Energy:** ability to do work or cause change
- **Work**: energy transferred to or from an object via the application of force along a displacement
- Equivalent definitions:
  - amount of energy produced or consumed by a body during a change in its kinetic state
  - energy transferred from one body to another or transformed from one form to another
- **Power**: rate at which energy is transferred or transformed with respect to time.

$$P = \frac{dE}{dt} \approx \frac{\Delta E}{\Delta t}$$

- **Units (SI):**
  - Force: 1 N = 1 kg × 1 m/s^2
  - Energy (or work): 1 J = 1 N × 1 m
  - Power: 1 W = 1 J/s
  - Conversion of J to Wh (kJ → kWh, MJ → MWh, GJ → GWh): division by 3600 (s/h)

Energy sources

- **Fossil fuels (also referred to as conventional sources):**
  - Solid (coal, in various forms, e.g., lignite)
  - Liquids (petroleum and its by-products)
  - Gases (natural gas, in various forms)
  - Nuclear (mainly uranium)
- **Renewable energy sources (RES):**
  - Solar (dominant technology: photovoltaic, PV)
  - Aeolic (wind)
  - Hydraulic (dominant technology: hydropower)
  - Biomass (similar process with fossil fuels)
  - Geothermal
  - Marine (waves, tides, currents)

Remarks

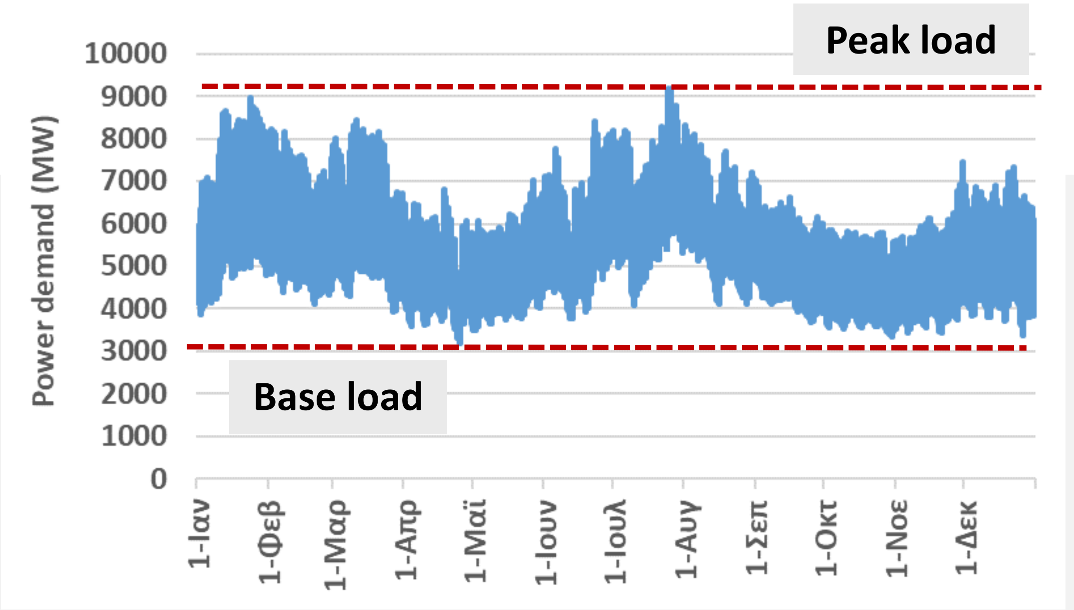
- The term *renewable* refers to the time scale of re-creation of the energy source. On the geological scale, fossil fuels may also be considered as renewables.
- Parent energy:
  - Fossil fuels, biomass → thermochemical
  - Geotherm, solar heat → thermic
  - Wind, water → kinetic (fluid motion)
  - Solar PV → photon
  - Water → hydrodynamic → hydraulic
- In practice, RES are exclusively used to produce **electricity**.

Principles of electricity

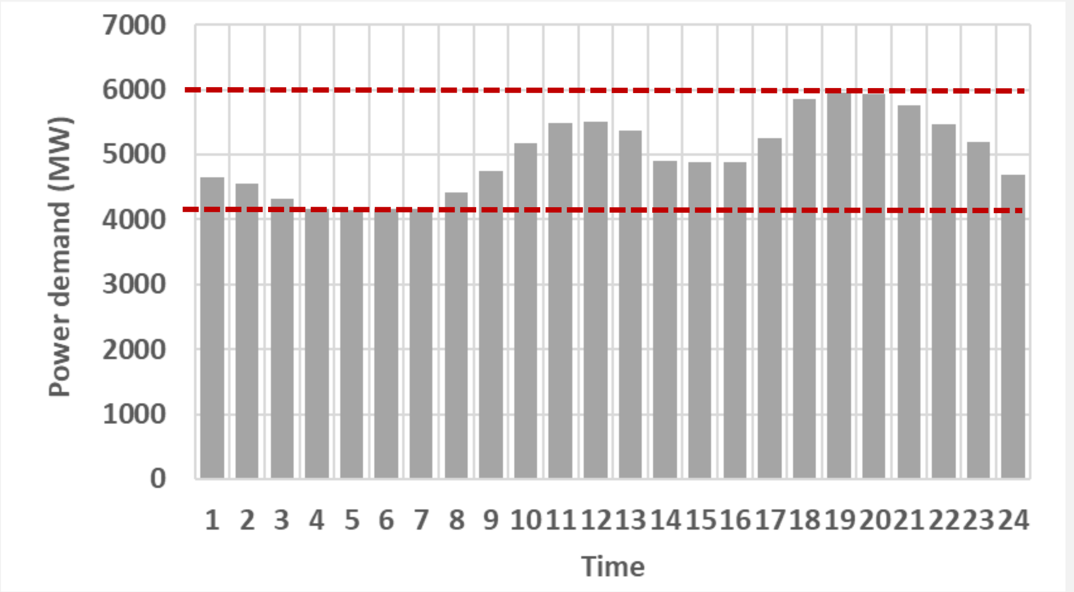
- **Advantages of electricity**:
  - Easily transferrable through transmission lines;
  - Easily convertible into other forms of energy (heat, radiation, mechanical energy, chemical energy).
- **Major disadvantage**: Inability to store electricity, except on very small scales → synchronization of production and consumption (the grid can absorb deviations of the order of 1-2%)
- **Energy mix**: Set of electricity generation units that utilize different sources, integrated within an interconnected management, transmission and distribution system.
- Key **strategic issues** in energy mix configuration:
  - Variability of energy demand, across all time scales
  - Flexibility to adapt to changing loads
  - Grid limitations (transmission, distribution)
  - System security and reliability
  - Energy policy – geopolitics (self-sufficiency, inter-state agreements)

Operational issues of electricity mix

- **Annual energy demand** → minimum requirement in total energy production by the energy mix
- **Peak load demand** → minimum requirement in total installed capacity of the energy mix, to be supplied with very high reliability (in contrast to stochasticity of RES)
- **Lower load demand** → minimum power requirement to be continuously supplied by base units
- Practical handling of **energy mix configuration**:
  - Oversizing, so that the total installed power clearly exceeds the corresponding maximum load;
  - Spatial dispersion of power sources (safety, smoothing of hydroclimatic variability, in case of RES);
  - Connections with neighboring countries (cf. EU electricity interconnection target).



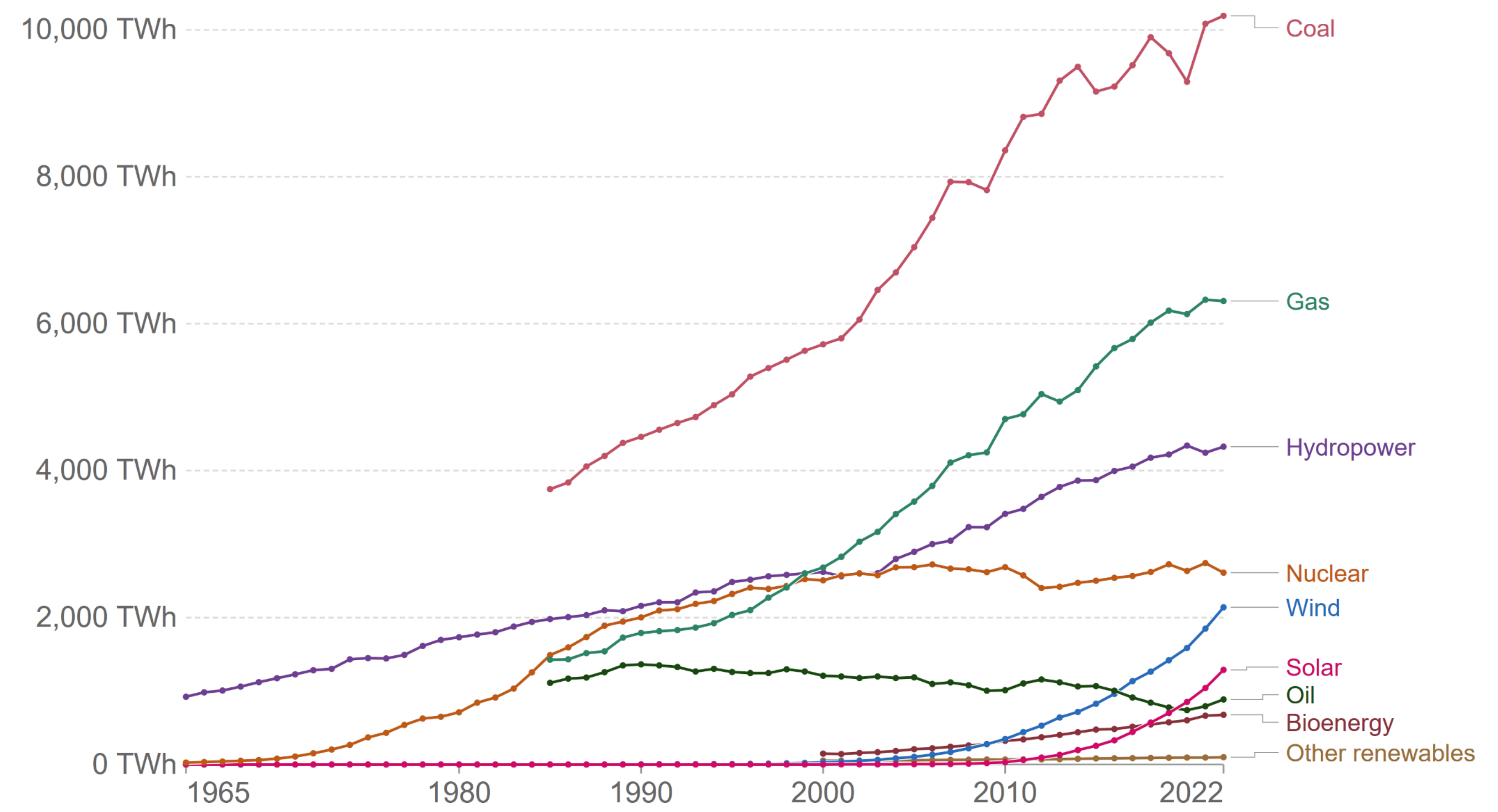
Hourly power demand in Greece in year 2022



Hourly power demand on 1/1/2022

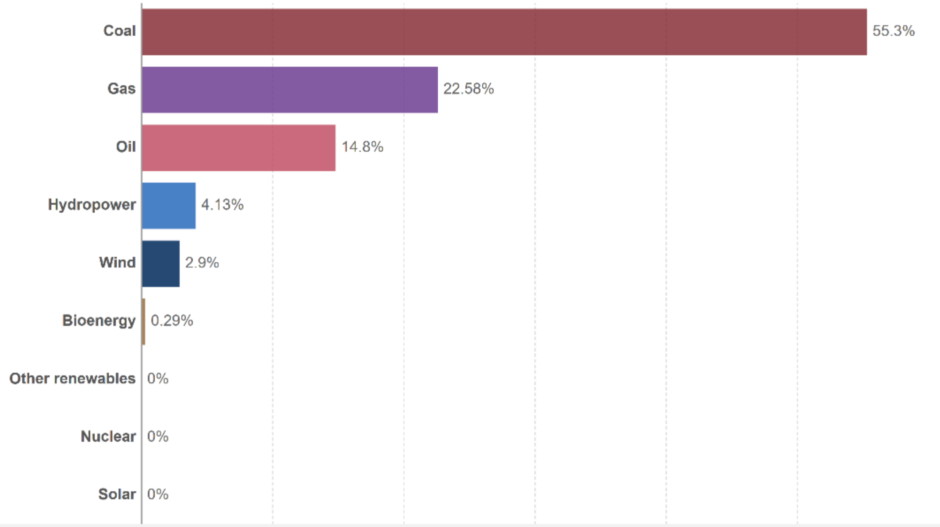
Some statistics

Evolution of electricity production over the globe (1965-2023)

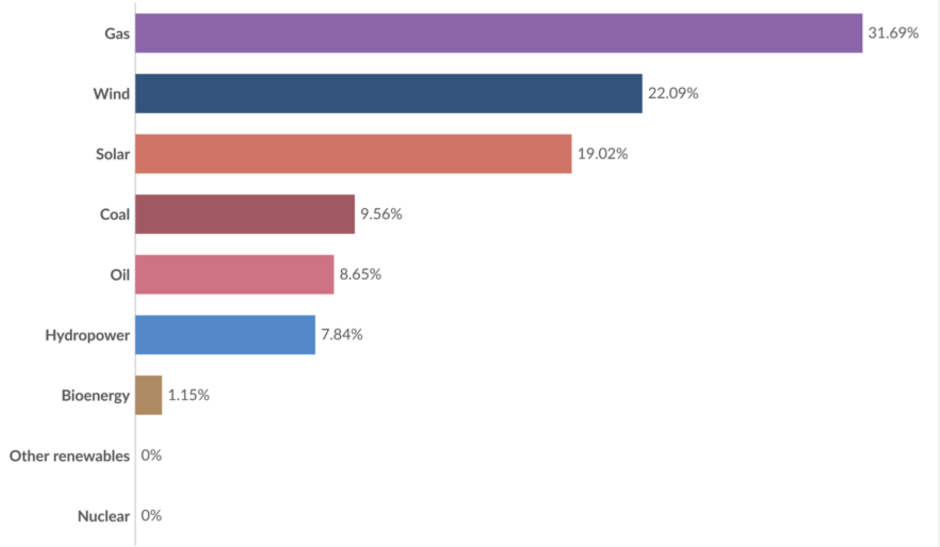


Data source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy
Note: 'Other renewables' includes waste, geothermal and wave and tidal energy.
OurWorldInData.org/energy | CC BY

Share of electricity production by source, Greece, 2007



Share of electricity production by source, Greece, 2023



Data source: Ember (2024); Energy Institute - Statistical Review of World Energy (2024) OurWorldInData.org/energy | CC BY

Recent status in Greece (year 2023)

- Total capacity: 23.2 GW (21.5 GW in 2022)
- Total annual demand: 49.5 TWh (50.7 TWh in 2022)
- Min load: 3.37 GW (17/4/2023 21:00)
- Max load: 10.39 GW (26/7/2023 15:00)
- Load record: 10.72 GW (5/8/2021 15:00)

	Capacity (MW)
Photovoltaics (P/V)	7 088
Natural gas	4 935
Wind	5 226
Large hydropower (reservoirs, >15 MW)	3 171
Lignite (to be abandoned until 2030)	2 061
Small hydropower plants (<15 MW)	281
Combined (electricity-heat cogeneration)	256
Biomass	131
Total	**23 149**

	Generation (GWh)	Percentage
Lignite	4 513	9.1%
Natural gas	14 631	29.6%
Large hydropower (reservoirs, > 15 MW)	4 047	8.2%
Other sources	16	0.0%
Sum of conventional sources	**23 207**	**46.9%**
Photovoltaics	1 055	2.1%
Wind	9 689	19.6%
Small hydropower plants	125	0.3%
Combined (electricity-heat cogeneration)	965	1.9%
Direct supply to the grid (mainly house PVs	9 527	19.3%
Crete connection	11	0.0%
Biogas	2	0.0%
Sum of renewables	**21 362**	**43.2%**
Imports	8 152	
Exports	-3 240	
Interconnection balance	**4 912**	**9.9%**
Total	**49 481**	

Generic scheme of power conversion processes (1)

- For given input power, P_0, driving an energy conversion system, the output power, P, is:

$$P = \eta \, P_0$$

  where η is a dimensionless factor called (total) **efficiency** (by definition, $\eta < 1$).

- The input power is a function of the form:

$$P_0 = P_0(x, \boldsymbol{\lambda})$$

  where x is the flow rate of the medium/material used for power generation and $\boldsymbol{\lambda}$ are physical properties of the generation medium and the geometrical characteristics of the conversion system (e.g., wind density and wind turbine diameter); in the generic case, x is a **stochastic process**.

- Usually, the function $P_0(x, \boldsymbol{\lambda})$ can be determined analytically (theoretical power).
- The flux x, and hence the theoretical power can be:
  - **Controlled, as result of storage** (e.g., rate of fuel mass imported into a thermoelectric unit, water discharge conveyed from a reservoir to a hydropower station)
  - **Uncontrolled** (e.g., river flow, wind, sun, waves), driven by varying hydrometeorological processes.

Generic scheme of power conversion processes (2)

- Efficiency is function of flux x, and characteristic properties, $\boldsymbol{\mu}$, of the conversion system, i.e. $\eta = \eta(x, \boldsymbol{\mu})$; it is also subject to atmospheric and other external drivers (random processes), as well as to ageing effects.
- The **total efficiency** is the product of individual efficiency values that refer to different components of the power transformation system, to express the associated energy losses.
- In contrast to theoretical power, the function $\eta(x, \boldsymbol{\mu})$ cannot be determined analytically; in fact, each power machine has its own efficiency function, expressed by nomographs that are provided by the manufacturer, based on laboratory results (the conversion is also directly given in terms of **power curve**).
- In several systems, a minimum flux x_{min} is required to produce power, while all have an upper output limit, P_{max}, called **nominal power**, which is characteristic property of the power system, thus:

$$P = \begin{cases} 0 & x < x_{min} \\ \eta(x)\, P_0(x) & x_{min} \le x < x_{max} \\ P_{max} & x_{max} \le x < x_s \\ 0 & x \ge x_s \end{cases}$$

x_s: cut-out value of input flux (applicable for some cases), above which the power machine stops for safety reasons

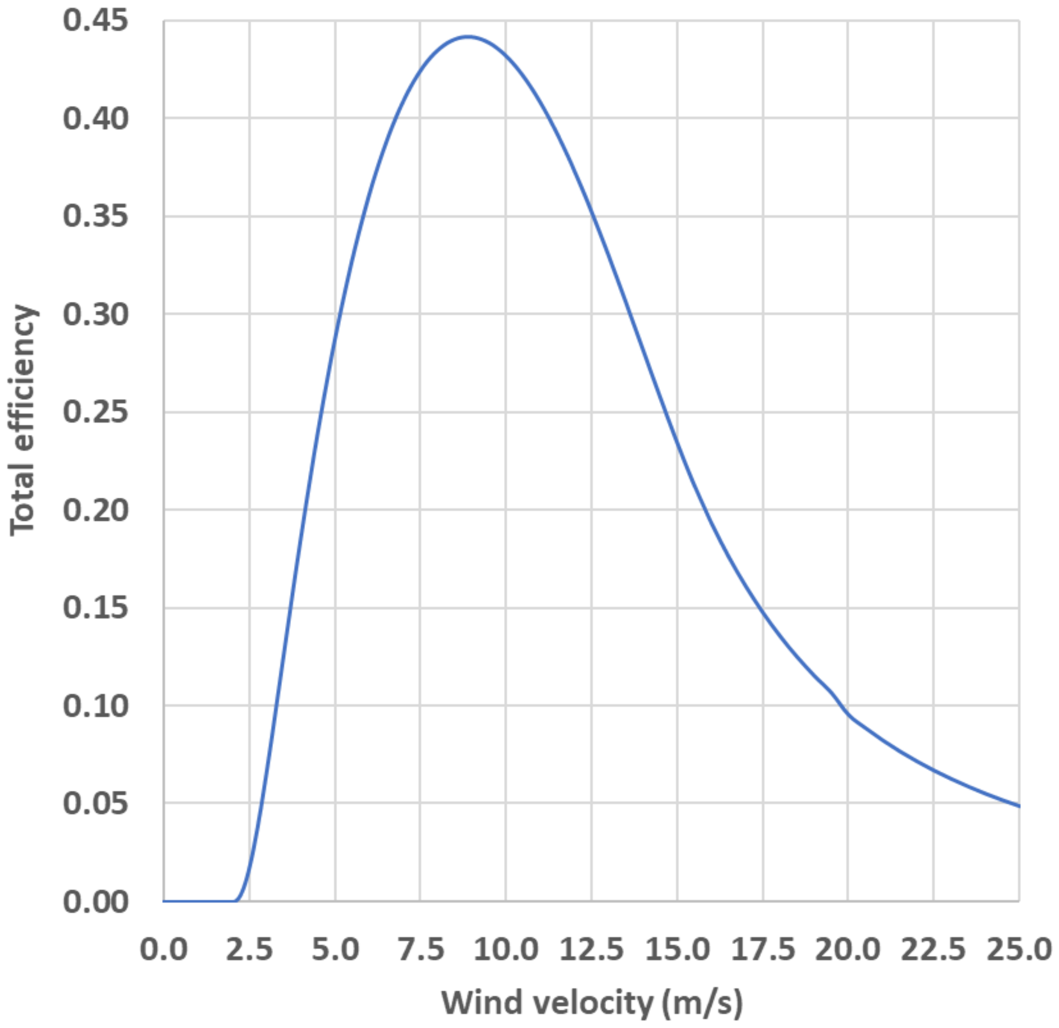
Example: Wind turbine

- Theoretical (input) power:

$$P_0 = \frac{1}{8}\,\rho_\alpha\,\pi\,D^2\,V^3$$

where ρ_α is the air density (**physical property** of the driving process, 1.225 kg/m^3, under standard pressure and temperature conditions, i.e., 1 atm and 15^{o}C), D is the diameter of the blade (**geometrical property** of the machine) and V is the wind speed (**flux**).

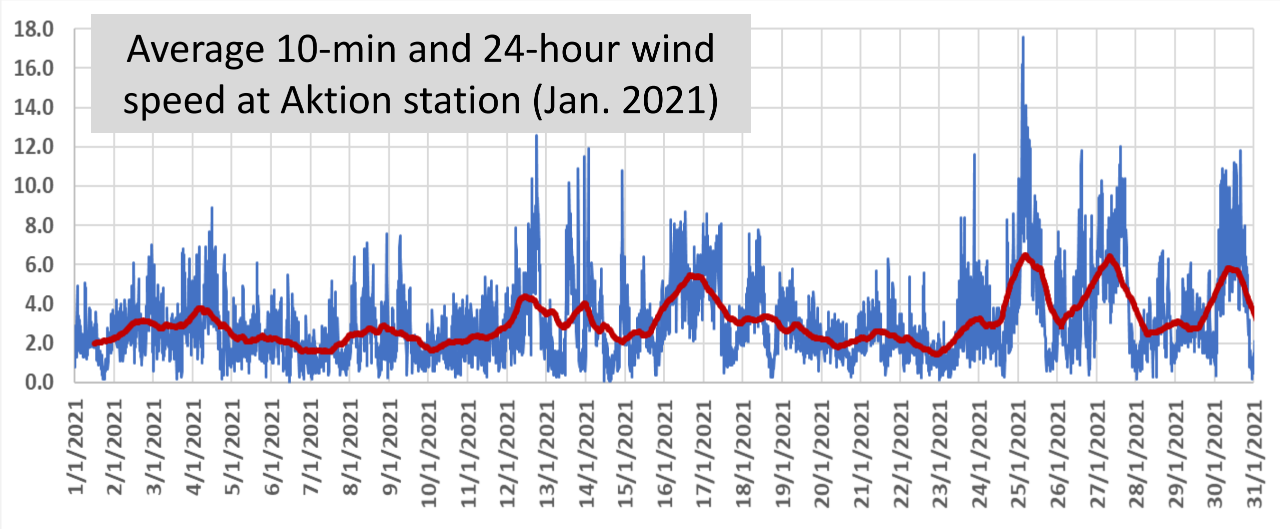
- The total efficiency is given by a nomograph (specific for each commercial turbine model).
- Typical values of V_{min}, V_{max} and V_s are 2.5, 12.0 and 25.0 m/s, respectively.
- Theoretically maximum efficiency: 16/27 = 0.593 (Berz limit, refers to an ideal turbine).

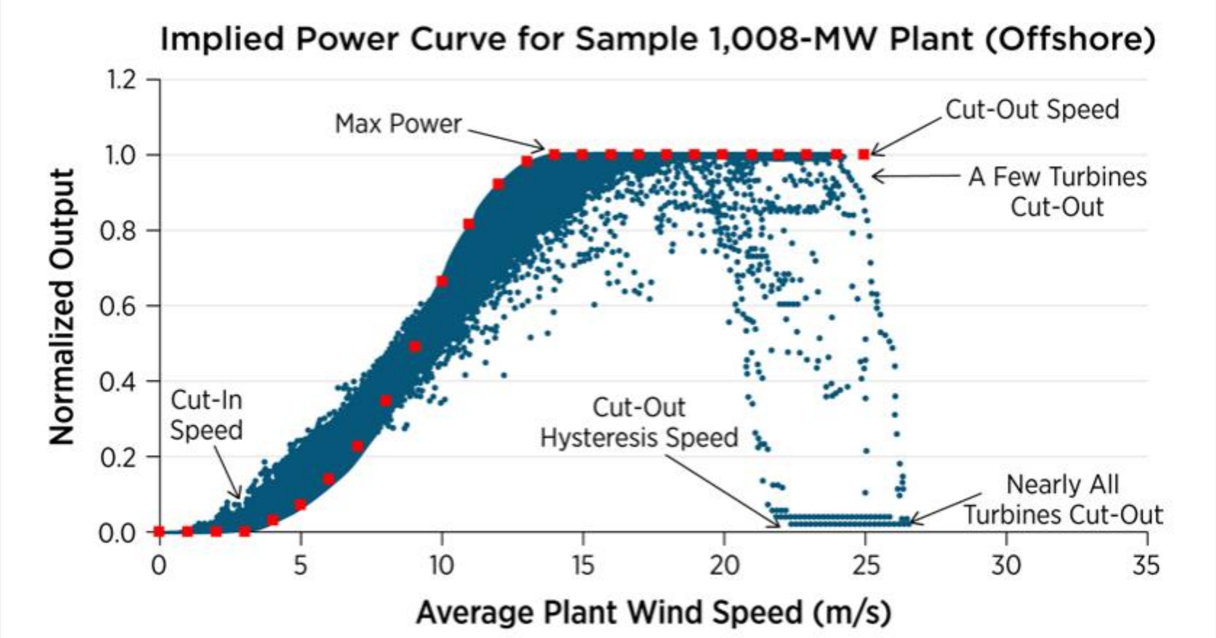


Source: https://en.wind-turbine-models.com/ turbines/135-enercon-e-66-18.70 (reconstructed, through the given power curve)

Real-world power production by RES under uncertainty

- Input processes (flux, x) are inherently uncertain (river flow, wind velocity, solar radiation);
- Conversion model (expressed in terms of “ideal” efficiency or power curve) is uncertain due to:
  - deviations between the actual performance of the power machine in the field and its prototype;
  - drop of efficiency due to deterioration, damage and ageing of equipment over time;
  - complex dependence of efficiency to in situ conditions.
- Maintenance, grid, and market restrictions result to deviations of theoretical vs. actual power production.





Assessment tools: Capacity factor

- **Definition**: Ratio of actual electricity production, E, to the theoretically maximum that can be produced by a project (or system of projects) of total nominal power P_{max} during a given time interval, T:

$$CF = \frac{E}{P_{max}\,T} = \frac{\int_0^T P(t)\,dt}{P_{max}\,T}$$

- Usually, CF is referred to the annual scale, for which the theoretical maximum energy production is equal to the maximum (nominal) power of the system during the hours of the year ($T = 8760$ h).
- In case of **non-controllable** power sources that are driven by randomly-varying atmospheric conditions (e.g., wind, solar, small hydro), CF can be regarded as a macroscopic **financial assessment** metric, since it contrasts the output power (benefits by energy selling) with the installed power (investment costs).
- Typical "good" values for Greece: solar parks 20%, wind parks 40%, small hydropower plants 30%
- For **controllable** sources (including large hydropower), CF reflects the **operation policy** (generation of base or peak energy, maintenance schedule). For instance, the total capacity of Greece's large hydropower works is 3.17 GW, while the annual electricity production in 2023 was 4.05 TWh, which yields $CF = 14.4\%$ (almost all plants are used for peak power production, but this may also be attributed to low inflows).

Assessment tools: Power-duration curve

- The curve is obtained by sorting a time series of **energy production** values (also expressed in terms of mean power production or capacity factor, over a specific time scale) in descending order and assigning an **empirical exceedance probability** to each value. If n is the size of data, the probability of exceeding the sorted value at position i is estimated by the Weibull plotting position, $p_i = i / (n+1)$.