Ειδικά κεφάλαια παραγωγής ενέργειας

Ενότητα 3: Wind Energy

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Τμήμα Μηχανολόγων Μηχανικών

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Χρηματοδότηση

- Το παρόν εκπαιδευτικό υλικό έχει αναπτυχθεί στα πλαίσια του εκπαιδευτικού έργου του διδάσκοντα.
- Το έργο «**Ανοικτά Ψηφιακά Μαθήματα στο Πανεπιστήμιο Δυτικής Μακεδονίας**» έχει χρηματοδοτήσει μόνο τη αναδιαμόρφωση του εκπαιδευτικού υλικού.
- Το έργο υλοποιείται στο πλαίσιο του Επιχειρησιακού Προγράμματος «Εκπαίδευση και Δια Βίου Μάθηση» και συγχρηματοδοτείται από την Ευρωπαϊκή Ένωση (Ευρωπαϊκό Κοινωνικό Ταμείο) και από εθνικούς πόρους.

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ΕΣΠΑ 2007-2013
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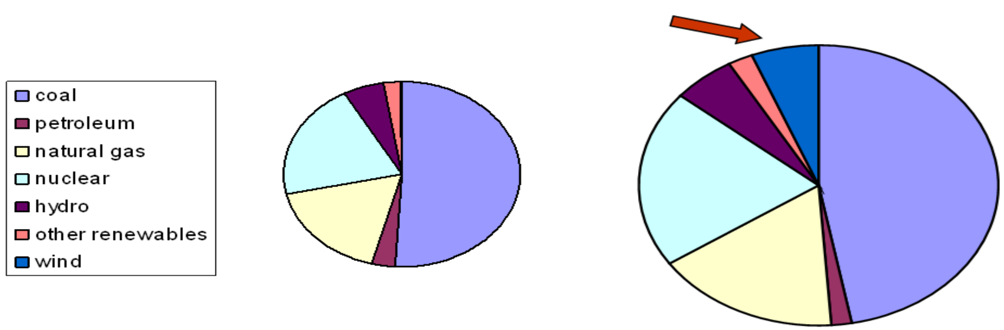
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

Wind Energy

Increasingly Significant Power Source

The global theoretical potential of wind power is currently estimated at 55 Gtoe, corresponding to **550%** of the global energy balance. The technical potential, i.e., the amount that is technologically feasible to be exploited, is estimated at **5 Gtoe or 50% of the global energy balance.**



Wind could generate 6% of US electricity by 2020.

Wind currently produces less than 1% of the US power.

Source: Energy Information Agency

Europe Wind Potential

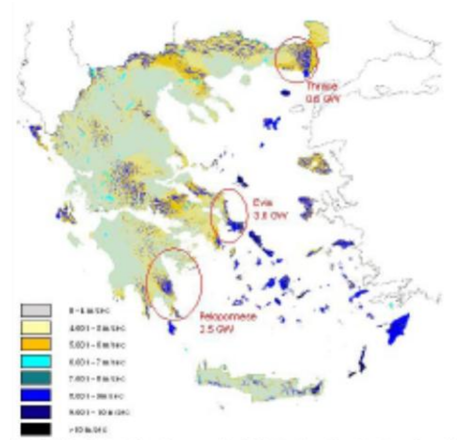
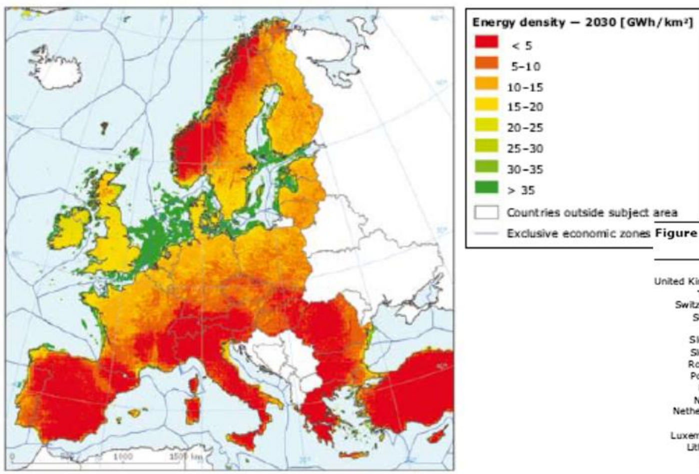


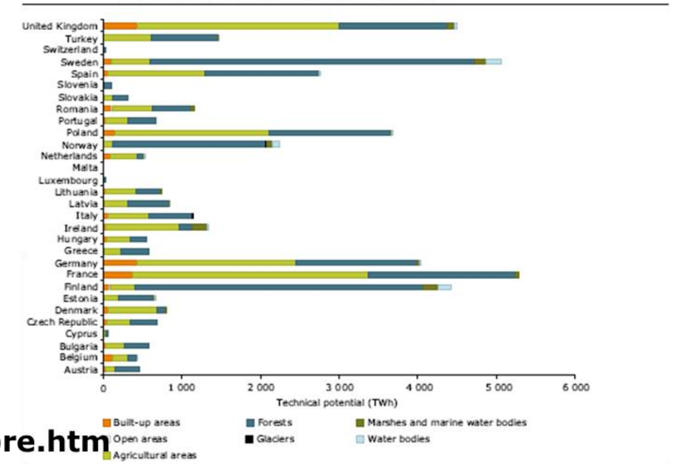
Fig. 1. Wind Potential and geographical distribution of applications for wind farms

Map 3.3 Distribution of wind energy density (GWh/km²) in Europe for 2030 (80 m hub height onshore, 120 m hub height offshore)



Source: EEA, 2008.

Figure 3.2 Unrestricted tech... estimated 80 m average wind speeds 2000–2005



www.cres.gr/kape/images/maps/img_pre.htm

Why Is Wind Energy So Popular?

- Wind is a clean/free energy source.
- Wind Farms are relatively cheap to build because of government incentives. The payback can be in the range of 2-4 years.
- The operating life of the wind turbine is +30 years.

Advantages of Wind Power

- Environmental (no emissions of harmful pollutants).
- Economic Development.
- Fuel Diversity & Conservation.
- Cost Stability to a utility's resource portfolio.
- Bring income and tax benefits to rural communities.

Environmental Benefits

- No air pollution.
- No greenhouse gasses.
- No depletion of natural sources (fossil fuels).
- No pollution through extraction and transportation (No hazardous wastes).
- There is no need for water.

One 750-kW wind turbine would displace:

- 3 million lbs of carbon dioxide per year.
- 14172 lbs of sulfur dioxide.
- 8688 lbs of nitrous oxides.

Economic Development Benefits

- **Expanding Wind Power development brings jobs to rural communities (providing steady income through lease or loyalty payments to farmers and other landowners).**
- **Reducing "hidden costs" resulting from air pollution and health care.**
- Each MW of wind power development provides 2.5-3 jobs years of employment.
- Wind plants can be a valuable source of property tax income for local authorities.

Fuel Diversity Benefits

- **Domestic and Inexhaustible energy source.**
- **Reduced supply risk.**
- Wind facilities consist of small generators that cannot be easily be damaged at the same time and easy to replace.
- If a wind facility is damaged, there is no secondary risk to the public, such as in the release of radioactivity, explosions, or the flooding of a dam.

Cost Stability Benefits

- With good wind resource estimates, the cost of the project is almost all in the up-front construction costs, and therefore constant over the life of the project.
- Flat-rate pricing:
  – hedge against fuel price volatility risk.
- Wind electricity is inflation-proof.

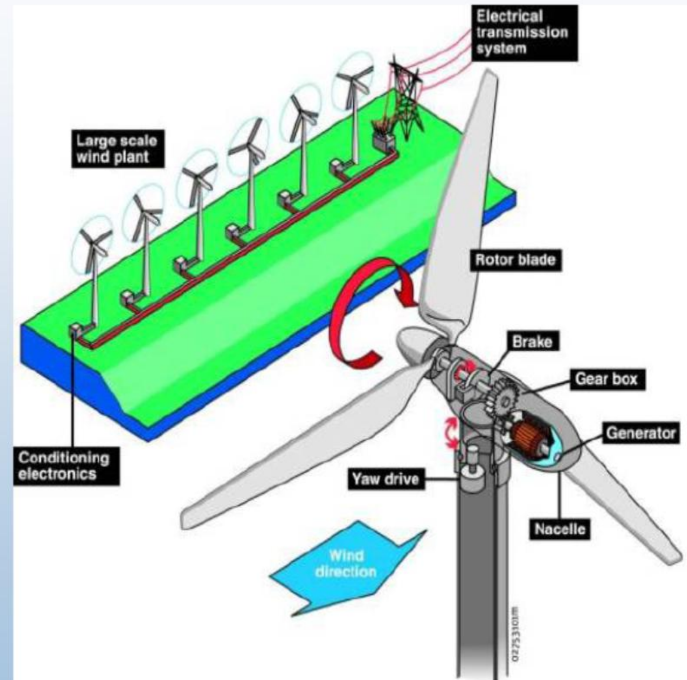
Introduction Of Wind Turbine

A wind turbine is a rotating machine which converts the kinetic energy in wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator, wind turbine, wind power unit (WPU), wind energy converter (WEC), or aero generator.

Wind Energy Technology

Wind Energy Technology

At it's simplest, the wind turns the turbine's blades, which spin a shaft connected to a generator that makes electricity. Large turbines can be grouped together to form a wind power plant, which feeds power to the electrical transmission system.



NREL National Renewable Energy Laboratory

Wind Velocity and Energy

- The kinetic energy of a mass of air, m, which moves with a certain velocity, V, equals to:

$$E = \frac{1}{2} m V^2 \ (J)$$

- The Power (energy per time):

$$P = \frac{1}{2} \dot{m} V^2 \ (W)$$

$$\dot{m} = \rho V A \ \left(\frac{kg}{s}\right)$$

Where

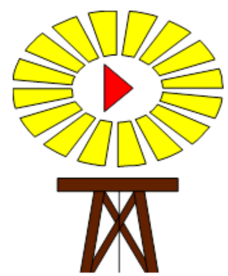
ρ= Air density (standard conditions ρ_o=1.225 kg/m^3).

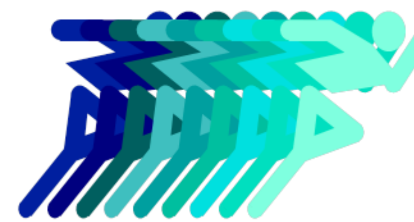
A= ($\pi D^2/4$) – Swept rotor area (D= 2xL).

Power in the Wind (W)

= 1/2 x air density x swept rotor area x (wind speed)^3

ρ | **A** | **V^3**





Density = P/(RxT)

P - pressure (Pa)
R - specific gas constant (287 J/kgK)
T - air temperature (K)

kg/m^3

Area = πr^2

m^2

Instantaneous Speed (not mean speed)

m/s

Specific Wind Power (W/m^2)

- The wind potential in a wind farm site is evaluated based on the specific power p:

$$p = \frac{1}{2}\rho V^3, p = \frac{P}{A}\left(\frac{W}{m^2}\right)$$

- From the whole power that is included in the wind, only a single fraction can be captured by the wings, P_o:

$$P_0 = \frac{1}{2}\dot{m}\left(V^2 - V_0{}^2\right)(W)$$

Where

V= Air velocity before the swept area.

V_o= Air velocity behind the swept area.

Mass flow rate through the wings

- The turbine is intercepting the air flow in the whole swept area although is usually consisting of 2-3 blades which cover the 5-10% of this area.
- The air velocity at this level equals to:

$$V_{ave} = \frac{V + V_0}{2} \left(\frac{m}{s}\right)$$

- Therefore the air mass flow rate through the wings is given by:

$$\dot{m} = \rho A \frac{V + V_0}{2} \left(\frac{Kg}{s}\right)$$

Rotor Efficiency

- The power acquired by the blades equals:

$$P_0 = \frac{1}{2}\rho A \frac{V + V_o}{2}(V^2 + V_0^2)(W)$$

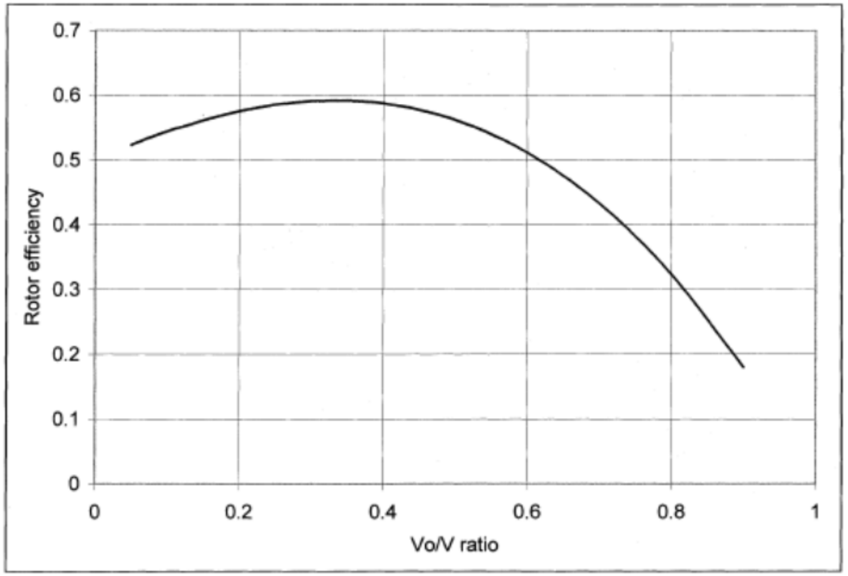
or

$$Po = \frac{1}{2}\rho \times A \times V^3 \times \frac{\left(1+\frac{Vo}{V}\right)\left(1-\left(\frac{Vo}{V}\right)^2\right)}{2} \quad [W]$$

- Rotor efficiency, C_p :

$$C_p = \frac{\left(1+\frac{Vo}{V}\right)\left[1-\left(\frac{Vo}{V}\right)^2\right]}{2}$$

Betz Limit or Efficiency



- Theoretical max. efficiency= 0.59 for $(V_o/V)=1/3$.
- The Betz limit denotes that the max. power that can be extracted from the wind it cannot be over 59% and this efficiency is only achieved when the air velocity behind the wind turbine equals to 1/3 of the air velocity before the turbine.

Actual Efficiency (1/2)

- In actual cases, the rotor efficiency reaches 50% and usually is ranged between 20-40 %.
- The power that is generated from a steam turbine:

$$P_o = C_p \times \frac{1}{2} \times \rho \times A \times V^3$$

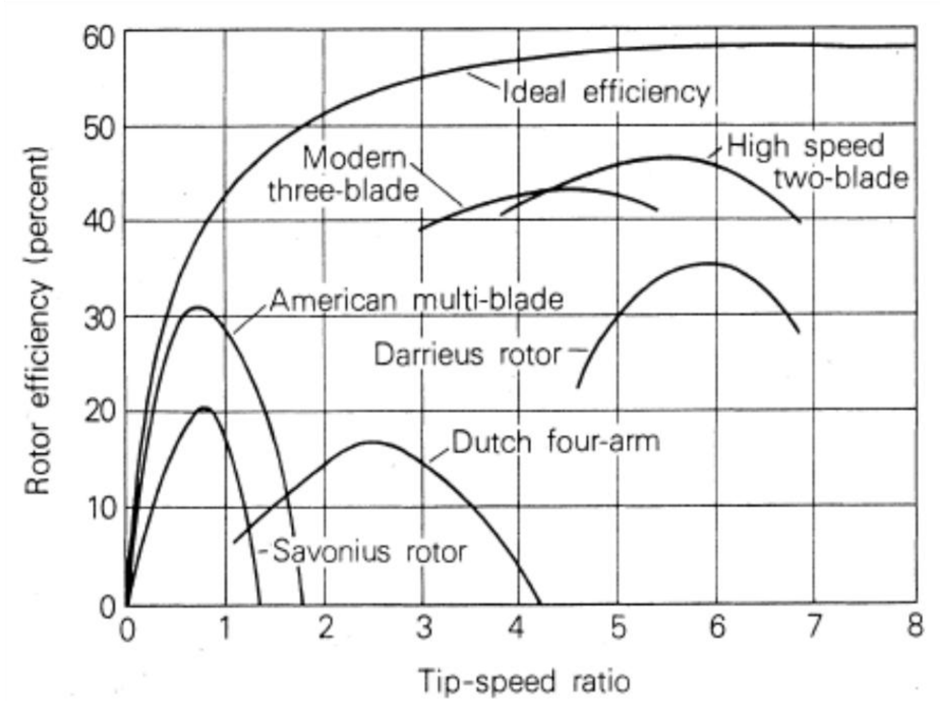
- The rotor efficiency coefficient is affected by its rotation velocity in relation to air velocity that hits the wind turbine.
- The tip-speed ratio (TSR) equals to:

$$TSR = \frac{V_{tip}}{V} = \frac{\omega R}{V}$$

where V_{TIP} is the velocity of the wing edge.

And ω is the angular rotation velocity.

Actual Efficiency (2/2)



Typical values of rotor efficiencies, as a function of the tip-speed ratio (TSR) for various turbine types

The effect of air density

- The power that is contained in the wind and the power that is achieved through the wind turbine is depending on the air density.

- The air density is related to temperature and pressure:

$$\rho = \frac{P}{RT} \left(\frac{Kg}{m^3}\right)$$

- Essentially, the density is not varied that much from temperature fluctuations, however it does change from pressure (altitude).

- The density is related to height, as follows:

$$\rho = \rho_0 - 1{,}194 * 10^{-4} * H \left(\frac{Kg}{m^3}\right)$$

Wind Energy Characteristics (1/2)

- Wind Speed:
  - Wind energy increases with the cube of the wind speed.
  - 10% increase in wind speed translates into 30% more electricity.
  - 2X the wind speed translates into 8X the electricity.

- Height:
  - Wind energy increases with height.
  - 2X the height translates into 10.4% more electricity.

Wind Energy Characteristics (2/2)

- Air density:
  - Wind energy increases proportionally with air density.
  - Humid climates have greater air density than dry climates.
  - Lower elevations have greater air density than higher elevations.
- Blade swept area:
  - Wind energy increases proportionally with swept area of the blades.
    - Blades are shaped like airplane wings.
  - 10% increase in swept diameter → 21% greater swept area.
  - Longest blades up to 413 feet in diameter.
    - Resulting in 600 foot total height.

Air velocity distribution (1/2)

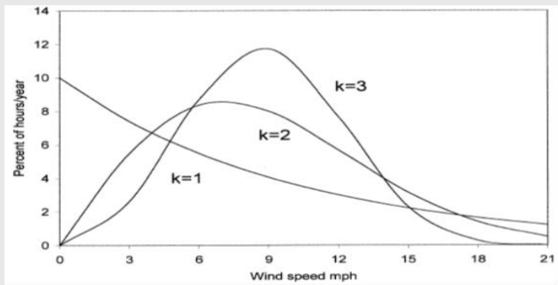
- Air velocity is always changed and its distribution is also changed from season to season.
- The variations of air velocity in one year are described from Weibull distribution:

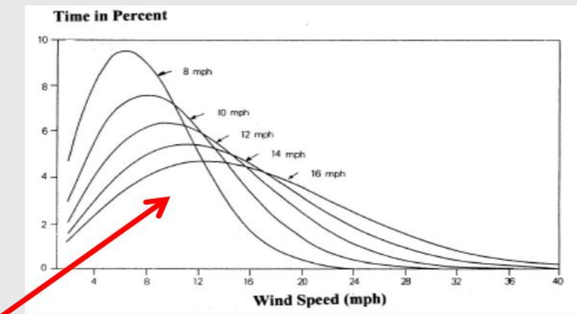
$$\boldsymbol{h}_i = \left(\frac{K}{C}\right)\left[\left(\frac{V_i}{C}\right)\right]^{K-1} - e^{-\left(\frac{V_i}{C}\right)^{K}}$$

where k is the dimensionless Weibull shape factor,
c is the Weibull scale factor (m/s), which is related with the mean air velocity, at each location,
h_i(%) is the probality the air velocity to be equal to V_i or the % frequency of $V_{i.}$

Air velocity distribution (2/2)

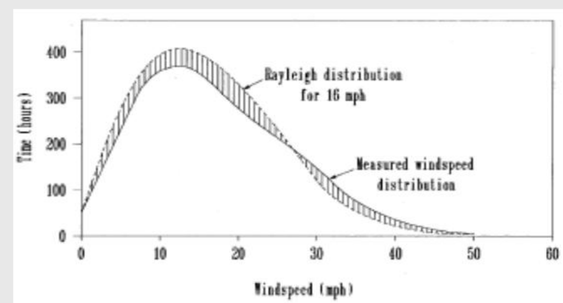
The actual air velocity distribution follows the Weibull distribution with k= 2 (Rayleigh distribution) and c= 5-25 m/s. At other c values is inefficient to exploit the wind potential.





- Rayleigh distribution:

$$hi = 2\lambda^2 V_i e^{-(\lambda v_i)^2} \ [\%]$$



λ= 1/c (s/m).

Annual air velocity distributions

- The most frequent value of distribution.
- Mean annual velocity $V_{ave} = \Sigma \boldsymbol{h}_i V_i \left(\frac{m}{s}\right)$ = 0.9 x c.
- Root mean cubic velocity, V_{rmc}

$$V_{rmc} = \sqrt[3]{\Sigma(\boldsymbol{h}_i) V_i^3}$$

- The V_{rmc} is a “tool” to calculate the specific wind potential.

$$\varepsilon = 365 * 24 * P_{rmc} \quad (Wh/m^2)$$

$$P_{rmc} = \frac{1}{2} \rho V_{RMC}^3 \left(\frac{W}{m^2}\right)$$

Exercise 1 (1/3)

In South Evia, a land of 16.000 acres have a mean annual wind velocity of 11,5 m/s. Considering that the wind velocity in these areas follows a Rayleigh distribution, draw the wind velocity and energy distributions and calculate the annual specific wind potential.

Exercise 1 (2/3)

- The Rayleigh distribution is the Weibull distribution for k= 2, where c= V_{ave}/0.9= 11.5/0.9= 12.8 m/s.
- For Rayleigh distribution for λ= 1/c= 0.078 s/m, the speed frequencies are the following.

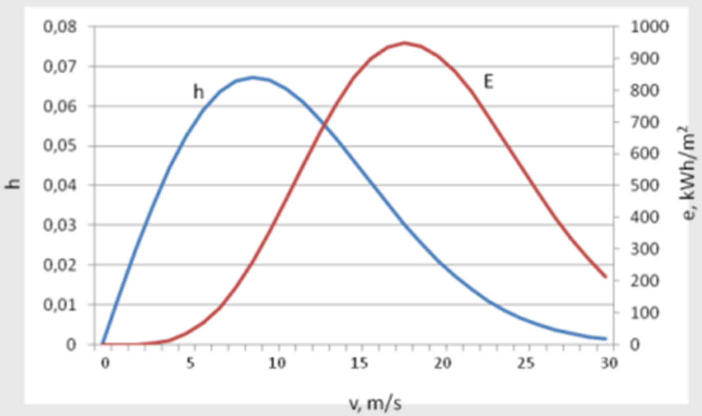
vi, m/s	hi	vi, m/s	hi	vi, m/s	hi
1	0,0122	11	0,0642	21	0,0173
2	0,0239	12	0,0609	22	0,0139
3	0,0348	13	0,0566	23	0,0110
4	0,0444	14	0,0516	24	0,0086
5	0,0526	15	0,0463	25	0,0067
6	0,0590	16	0,0409	26	0,0051
7	0,0635	17	0,0355	27	0,0038
8	0,0662	18	0,0303	28	0,0028
9	0,0671	19	0,0255	29	0,0021
10	0,0664	20	0,0211	30	0,0015

Exercise 1 (3/3)

The corresponding energy distribution is calculated from:

$e_i = (24 \times 365) \times h_i \times p_i = 8760 \times h_i \times (1/2 \times \rho \times V_i^3)$ kWh/m²/yr.

vi, m/s	ei kWh/m²/yr	vi, m/s	ei kWh/m²/yr	vi, m/s	ei kWh/m²/yr
1	0,1	11	458,6	21	858,2
2	1,0	12	564,2	22	794,3
3	5,0	13	666,8	23	720,3
4	15,3	14	760,1	24	640,4
5	35,2	15	838,7	25	558,5
6	68,3	16	898,0	26	478,1
7	116,9	17	935,0	27	401,9
8	181,9	18	948,4	28	331,9
9	262,6	19	938,6	29	269,3
10	356,2	20	907,5	30	214,9
					14.226



The mean annual specific wind energy potential equals to:

$V_{rmc} = (0.0122 \times 1^3 + 0.0239 \times 2^3 + \ldots + 0.0015 \times 30^3)^{1/3} = 13.8$ m/s.

Mean annual specific power: $p_{rmc} = ½ \times \rho \times V_{rmc}^3 = 1.62$ kW/m² .

Mean annual wind energy: $\varepsilon_{rmc} = p_{rmc} \times 24 \times 365 = 14226$ kWh/m² .

Exercise 2 (1/4)

Draw the velocity and energy distributions for the same areas of southern Evia and calculate the annual specific wind potential, if the wind velocities follow a Weibull distribution with a shape factor equal to k = 1,75 and 2,25.

Exercise 2 (2/4)

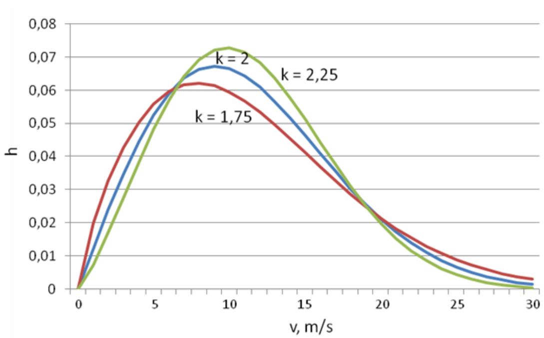
- For a Weibull distribution around k=2; c= V_{ave}/0.9= 11.5/0.9= 12.8 m/s.
- For a Weibull distribution for k= 1.75, the velocity and specific energy distributions are:

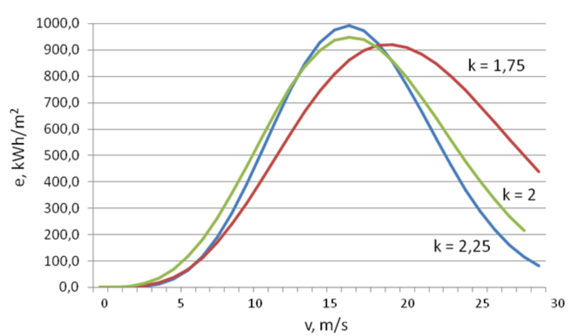
vi, m/s	hi	vi, m/s	hi	vi, m/s	hi	vi, m/s	ei	vi, m/s	ei	vi, m/s	ei
1	0,0200	11	0,0567	21	0,0183	1	0,1	11	405,0	21	909,2
2	0,0328	12	0,0533	22	0,0155	2	1,4	12	494,5	22	884,2
3	0,0427	13	0,0495	23	0,0130	3	6,2	13	583,5	23	847,3
4	0,0503	14	0,0454	24	0,0108	4	17,3	14	668,0	24	800,6
5	0,0558	15	0,0411	25	0,0089	5	37,4	15	744,3	25	746,4
6	0,0595	16	0,0368	26	0,0073	6	69,0	16	809,2	26	687,0
7	0,0615	17	0,0326	27	0,0059	7	113,2	17	860,5	27	624,7
8	0,0620	18	0,0287	28	0,0048	8	170,4	18	896,5	28	561,3
9	0,0613	19	0,0249	29	0,0038	9	239,6	19	916,4	29	498,6
10	0,0594	20	0,0214	30	0,0030	10	318,8	20	920,4	30	438,1
											15.269

Exercise 2 (3/4)

- For a Weibull distribution for k= 2.25, the velocity and specific energy distributions are:

vi, m/s	hi	vi, m/s	hi	vi, m/s	hi	vi, m/s	ei	vi, m/s	ei	vi, m/s	ei
1	0,007265	11	0,071512	21	0,015391	1	0,0	11	510,7	21	764,8
2	0,017071	12	0,068323	22	0,01164	2	0,7	12	633,5	22	665,0
3	0,027695	13	0,063623	23	0,008609	3	4,0	13	750,0	23	562,0
4	0,038318	14	0,0578	24	0,006227	4	13,2	14	851,0	24	461,9
5	0,048281	15	0,051263	25	0,004404	5	32,4	15	928,3	25	369,3
6	0,057027	16	0,04441	26	0,003046	6	66,1	16	976,0	26	287,3
7	0,064106	17	0,037594	27	0,00206	7	118,0	17	991,0	27	217,6
8	0,069197	18	0,031106	28	0,001363	8	190,1	18	973,3	28	160,5
9	0,072124	19	0,025161	29	0,000881	9	282,1	19	926,0	29	115,3
10	0,072857	20	0,0199	30	0,000557	10	390,9	20	854,2	30	80,7
											13.176





Exercise 2 (4/4)

- The root mean cubic velocity for the three different k values:

k = 1,75 v_{rmc} = 14,2 m/s

k = 2,00 v_{rmc} = 13,8 m/s

k = 2,25 v_{rmc} = 13,5 m/s

- Mean annual specific power:

k = 1,75 p_{rmc} = 1,74 kW/m^2

k = 2,00 p_{rmc} = 1,62 kW/m^2

k = 2,25 p_{rmc} = 1,50 kW/m^2

- Mean annual wind energy potential:

k = 1,75 ε_{rmc} = 15.269 kWh/m^2

k = 2,00 ε_{rmc} = 14.226 kWh/m^2

k = 2,25 ε_{rmc} = 13.176 kWh/m^2

Exercise 3 (1/6)

- Apart from the 16.000 acres of Example 1, in South Evia, there are also the following areas:
  - 26.000 acres with a mean annual wind velocity of 10,7 m/s.
  - 44.500 acres with a mean annual wind velocity of 9,8 m/s.
  - 69.500 acres with a mean annual wind velocity of 9,0 m/s.
- Considering that the wind velocity at these locations follows the Rayleigh distribution, design the velocity and and energy distributions. Calculate also the annual specific wind potential.

Exercise 3 (2/6)

The scale factors in the four cases are:

- mean annual wind velocity 11,5 m/s $c = V_{mean}/0,9 = 11,5/0,9 = 12,8$ m/s.
- mean annual wind velocity 10,7 m/s $c = V_{mean}/0,9 = 10,7/0,9 = 11,9$ m/s.
- mean annual wind velocity 9,8 m/s $c = V_{mean}/0,9 = 9,8/0,9 = 10,9$ m/s.
- mean annual wind velocity 9,0 m/s $c = V_{mean}/0,9 = 9,0/0,9 = 10,0$ m/s.
- The velocity and specific energy frequencies for a mean annual wind velocity of 10,7 m/s, are:

vi, m/s	hi	vi, m/s	hi	vi, m/s	hi	vi, m/s	ei	vi, m/s	Ei	vi, m/s	Ei
1	0,0140	11	0,0661	21	0,0131	1	0,1	11	472,2	21	652,0
2	0,0275	12	0,0613	22	0,0101	2	1,2	12	568,4	22	579,3
3	0,0398	13	0,0556	23	0,0077	3	5,8	13	655,9	23	503,4
4	0,0505	14	0,0495	24	0,0058	4	17,4	14	728,9	24	428,0
5	0,0593	15	0,0432	25	0,0042	5	39,8	15	782,3	25	356,3
6	0,0658	16	0,0370	26	0,0031	6	76,3	16	813,3	26	290,5
7	0,0700	17	0,0311	27	0,0022	7	128,9	17	820,7	27	232,2
8	0,0720	18	0,0257	28	0,0015	8	197,7	18	805,3	28	182,0
9	0,0718	19	0,0209	29	0,0011	9	280,8	19	769,4	29	139,9
10	0,0697	20	0,0167	30	0,0007	10	374,2	20	716,9	30	105,6

Exercise 3 (3/6)

- If the mean annual wind speed is equal to 9,8 m/s, then the velocity and specific energy frequencies are:

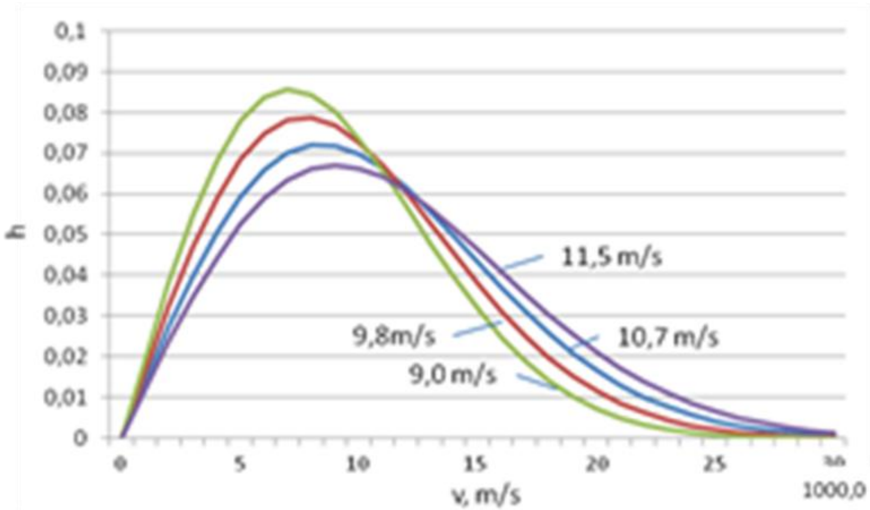
vi, m/s	hi	vi, m/s	hi	vi, m/s	hi	vi, m/s	ei	vi, m/s	ei	vi, m/s	ei
1	0,016726	11	0,066873	21	0,00859	1	0,1	11	477,6	21	426,8
2	0,032617	12	0,060089	22	0,006261	2	1,4	12	557,1	22	357,7
3	0,046905	13	0,052721	23	0,004479	3	6,8	13	621,5	23	292,4
4	0,058955	14	0,045214	24	0,003144	4	20,2	14	665,7	24	233,2
5	0,068306	15	0,037933	25	0,002166	5	45,8	15	686,9	25	181,6
6	0,074705	16	0,031153	26	0,001465	6	86,6	16	684,6	26	138,2
7	0,078106	17	0,025058	27	0,000973	7	143,7	17	660,6	27	102,8
8	0,078656	18	0,01975	28	0,000635	8	216,1	18	618,0	28	74,8
9	0,076668	19	0,015259	29	0,000406	9	299,9	19	561,6	29	53,2
10	0,072574	20	0,01156	30	0,000256	10	389,4	20	496,2	30	37,0

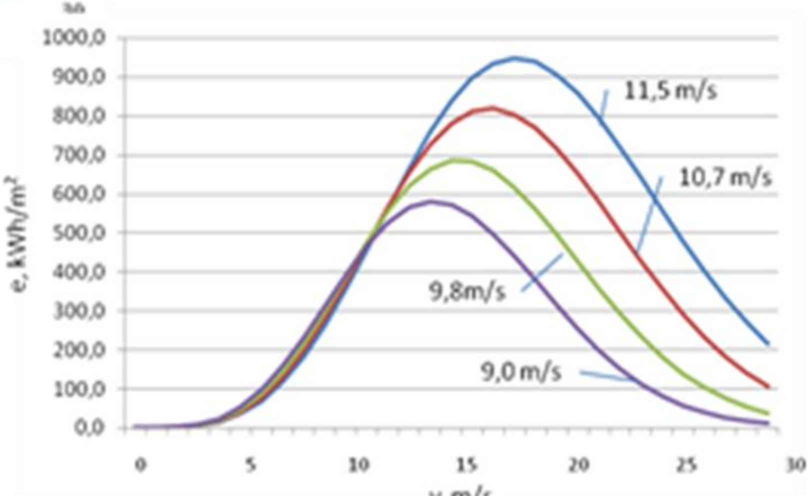
Exercise 3 (4/6)

- And for a mean annual wind velocity of 9,0 m/s, the velocity and specific energy frequencies are:

vi, m/s	hi	vi, m/s	hi	vi, m/s	hi	vi, m/s	ei	vi, m/s	ei	vi, m/s	ei
1	0,019801	11	0,065603	21	0,005105	1	0,1	11	468,5	21	253,7
2	0,038432	12	0,056863	22	0,003479	2	1,6	12	527,2	22	198,8
3	0,054836	13	0,047975	23	0,002319	3	7,9	13	565,5	23	151,4
4	0,068172	14	0,03944	24	0,001513	4	23,4	14	580,7	24	112,2
5	0,07788	15	0,03162	25	0,000965	5	52,2	15	572,6	25	80,9
6	0,083721	16	0,024738	26	0,000603	6	97,0	16	543,7	26	56,8
7	0,085768	17	0,018896	27	0,000368	7	157,8	17	498,1	27	38,9
8	0,084367	18	0,014099	28	0,00022	8	231,8	18	441,2	28	26,0
9	0,080074	19	0,01028	29	0,000129	9	313,2	19	378,3	29	16,9
10	0,073576	20	0,007326	30	0,000000	10	394,8	20	314,5	30	10,7

Exercise 3 (5/6)





Exercise 3 (6/6)

The corresponding root mean cubic velocities, are:

- Vmean = 11,5 m/s v_{rmc} = 13,8 m/s.
- Vmean =10,7 m/s v_{rmc} = 13,0 m/s.
- Vmean =9,8 m/s v_{rmc} = 11,9 m/s.
- Vmean =9,0 m/s v_{rmc} = 11,0 m/s.

Respectively the mean annual specific power is equal to:

- Vmean = 11,5 m/s p_{rmc} = 1,74 kW/m^2.
- Vmean =10,7 m/s p_{rmc} = 1,34 kW/m^2.
- Vmean =9,8 m/s p_{rmc} = 1,04 kW/m^2.
- Vmean =9,0 m/s p_{rmc} = 0,81 kW/m^2.

And the mean annual potential, are:

- Vmean = 11,5 m/s ε_{rmc} = 14.226 kWh/m^2.
- Vmean =10,7 m/s ε_{rmc} = 11.725 kWh/m^2.
- Vmean =9,8 m/s ε_{rmc} = 9.137 kWh/m^2.
- Vmean =9,0 m/s ε_{rmc} = 7.117 kWh/m^2.

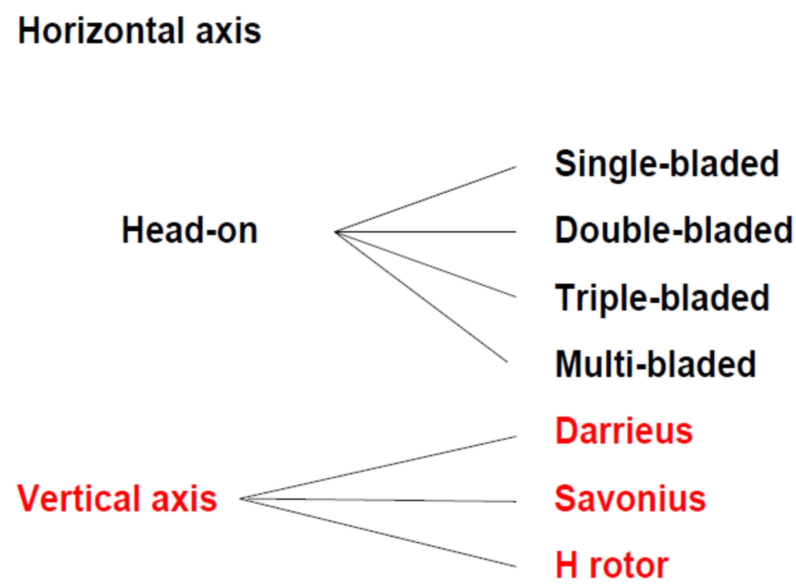
Fundamentals

Fundamentals

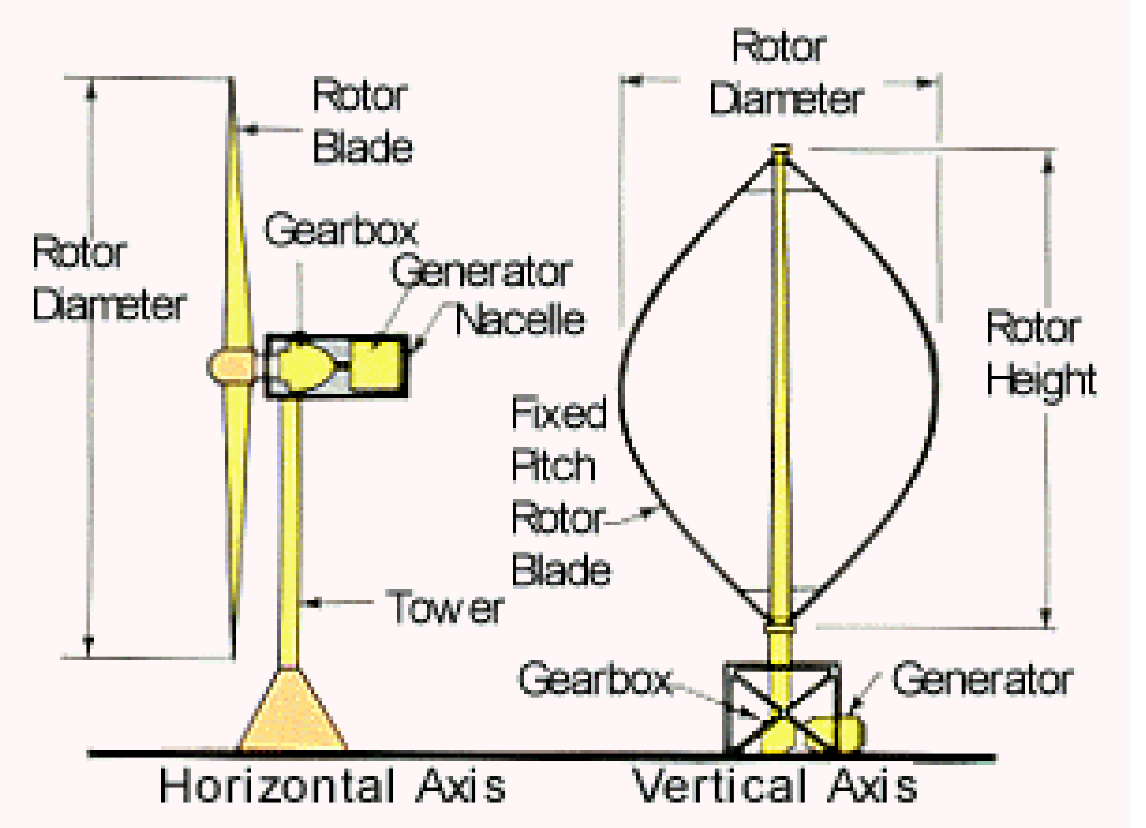
- Rotor
- Nacelle
- Tower

Wind Turbine Classification

- Wind turbines can be separated into two types based by the axis in which the turbine rotates.
- Turbines that rotate around a Horizontal axis are more common.
- Vertical-axis turbines are less frequently used.



Types of Wind Turbine



Wind Turbine Configurations

Wind Turbines Power for a House or City

Sizes and Applications

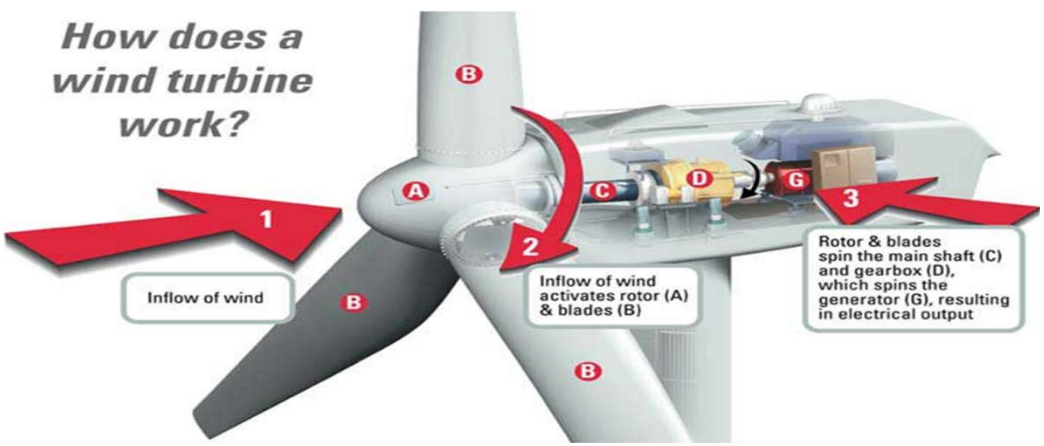
Small (≤10 kW)
- Homes
- Farms
- Remote Application

Intermediate
(10-250 kW)
- Village Power
- Hybrid Systems
- Distributed Power

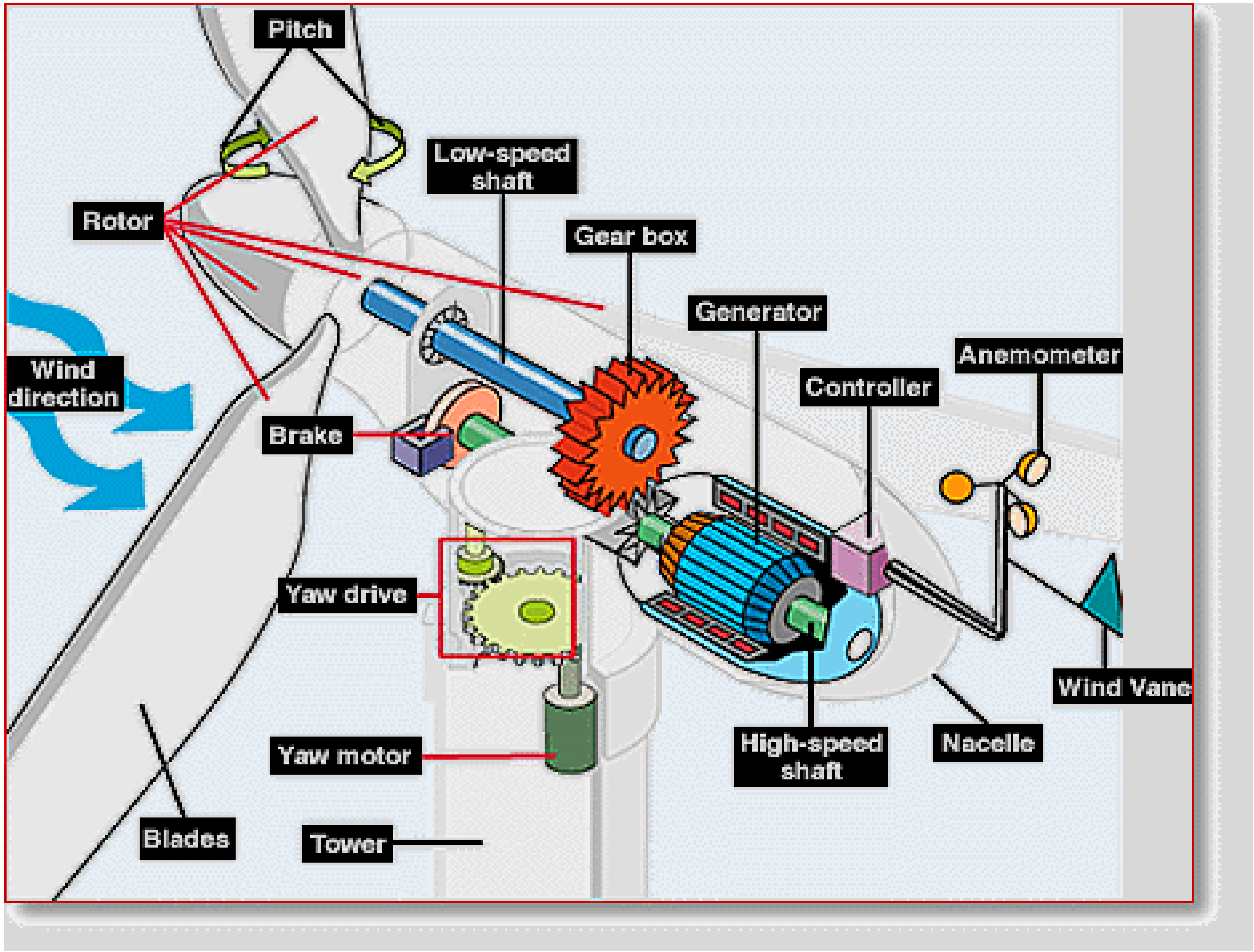
Large (660 kW - 2+MW)
- Central Station Wind Farms
- Distributed Power
- Community Wind

Generating Electricity

- To make electricity, the shaft of the turbine must be connected to an electrical generator. Through gearboxes, the generator converts the mechanical energy of the spinning turbine shaft into electricity.
- Generators are small enough that they can be housed under a light aerodynamically designed cover at the top of the pole or tower. Wires running down the tower carry electricity to the grid, batteries or other appliances, where it is stored, and/or used.



Components of Wind Turbine



Components of a Wind Turbine (1/3)

A wind turbine of horizontal axis consists of:

- The tower.
- The rotor, consisting of the hub and usually 2 or 3 blades.
- The chamber which contains the gearbox, the control system of the rotational speed, the brake and the electric generator.
- The orientation system of the chamber and the rotor, and,
- the corresponding power electronic systems.

Components of a Wind Turbine (2/3)

- The tower supports the chamber and the hub and its height serves for the capture of wind energy in the greatest possible distance from the ground, where the wind speed is increased.
- In wind turbines of small nominal power the height of the tower can be several times greater than the length of the blades.
- The main problem regarding the design of the tower is its resistance to the torque imposed by the wind and the vibration which arises from the rotation of the blades.
- Critical to the design of the whole setup is the avoidance of resonance phenomena, in the whole range of possible winds.

Components of a Wind Turbine (3/3)

- The blades are manufactured from epoxy synthetic materials of high strength and low specific weight, in order to withstand the developed torques and to minimize them.
- Especially the connection of the blades to the hub receives the highest mechanical stresses and is the most sensitive point of the whole construction.
- In order to hold these stresses below a threshold and to prevent the detachment of the blades, the speed of rotation is controlled by a mechanical brake, located inside the chamber.
- In cases of very strong winds, the rotation of the rotor is stopped and the plane of rotation of the blades, together with the whole chamber, rotates parallel to the wind direction.

Nominal Capacity of Wind Turbines

- The categorization of wind turbines is based on the maximum power that the generator can produce and the blade diameter, e.g. 300kW/30m.

- A second method to classify wind turbines in terms of their size, is the specific rated capacity (SRC), which is defined as:

$$SRC=\frac{\text{electrical motor capacity [kW]}}{\text{surface area swept by the blades [m}^2\text{]}}$$

e.g. a 300/30 wind turbine has a SRC= $300/(\pi \times 15^2)$= 0.42 kW/m^2 .

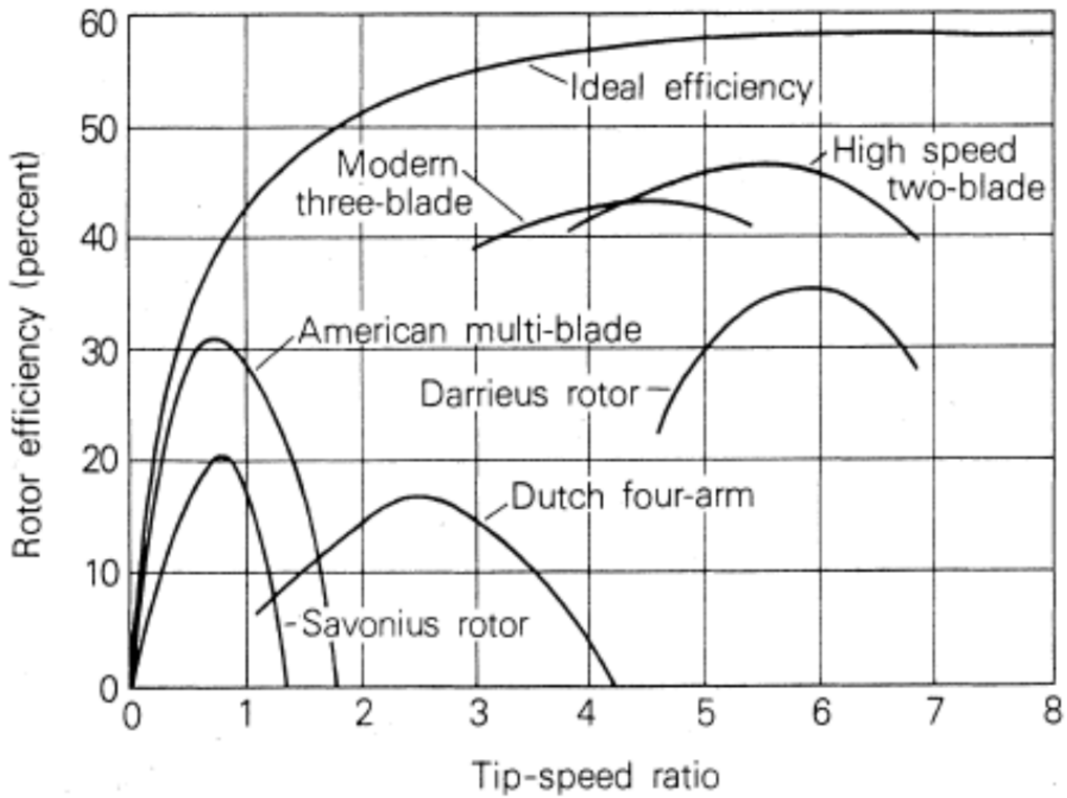
Operation at varied rotational speed

- For a given wind speed, the rotor efficiency C_p varies with the TSR ratio.

$$TSR = \frac{V_{tip}}{V} = \frac{\omega R}{V}$$

- In order to keep the wind turbine efficiency constant at its maximum value, the rotational speed of rotor has to be controlled at wind speed variations to optimize the TSR at values of maximum efficiency.
- Based on rotor rotational speed control, 4 different regions of wind speeds are determined:
- **1st region** is ranged from zero wind speed to the velocity that the rotor starts to rotate ($0 < Vi < V_s$). $P_{oi} = 0$ kW and $C_p = 0$.
- V_s is the start velocity and achieves values around 5 m/s.

Actual Efficiency



Typical values of rotor efficiencies, as a function of the tip-speed ratio (TSR) for various turbine types

Operation at varied rotational speed (1/2)

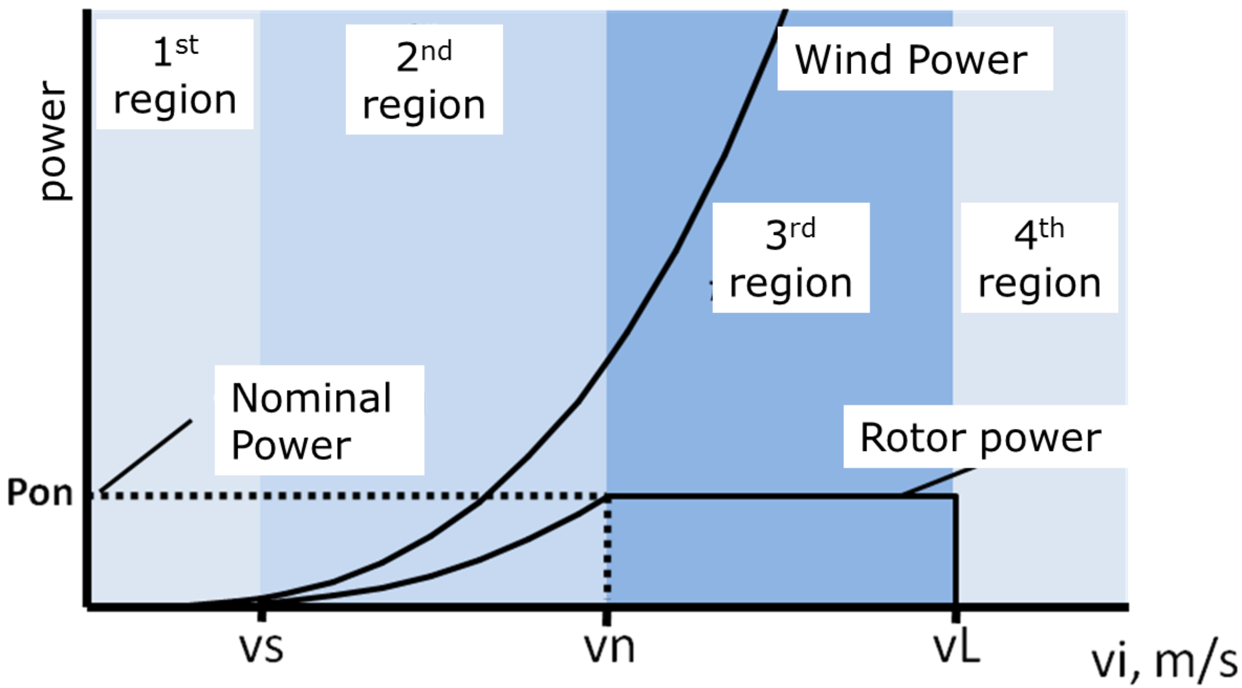
- **2nd region** is ranged between Vs and nominal velocity, V_n ($V_s < V_i < V_n$), where V_n achieves values around 15 m/s.
- In this region the wind turbine operates at constant C_p, equaled to the nominal efficiency ($C_p = C_{pn}$).
- In this velocity region, the rotational speed is linearly increased with wind velocity, keeping TSR at its optimum value where C_p is maximized.

  $P^*_{oi} = c_{pn} \times P_i$ (kW/m^2) the power that is achieved.
- **3rd region** is ranged from V_n to limit velocity, V_L, where the brake immobilizes the rotor and the nacelle turns accordingly in order to locate the blades in parallel to wind direction.
- In this region, the rotor is rotated at a constant speed, generating constant power (P^*_{oi}= const, P_{oi}= const).

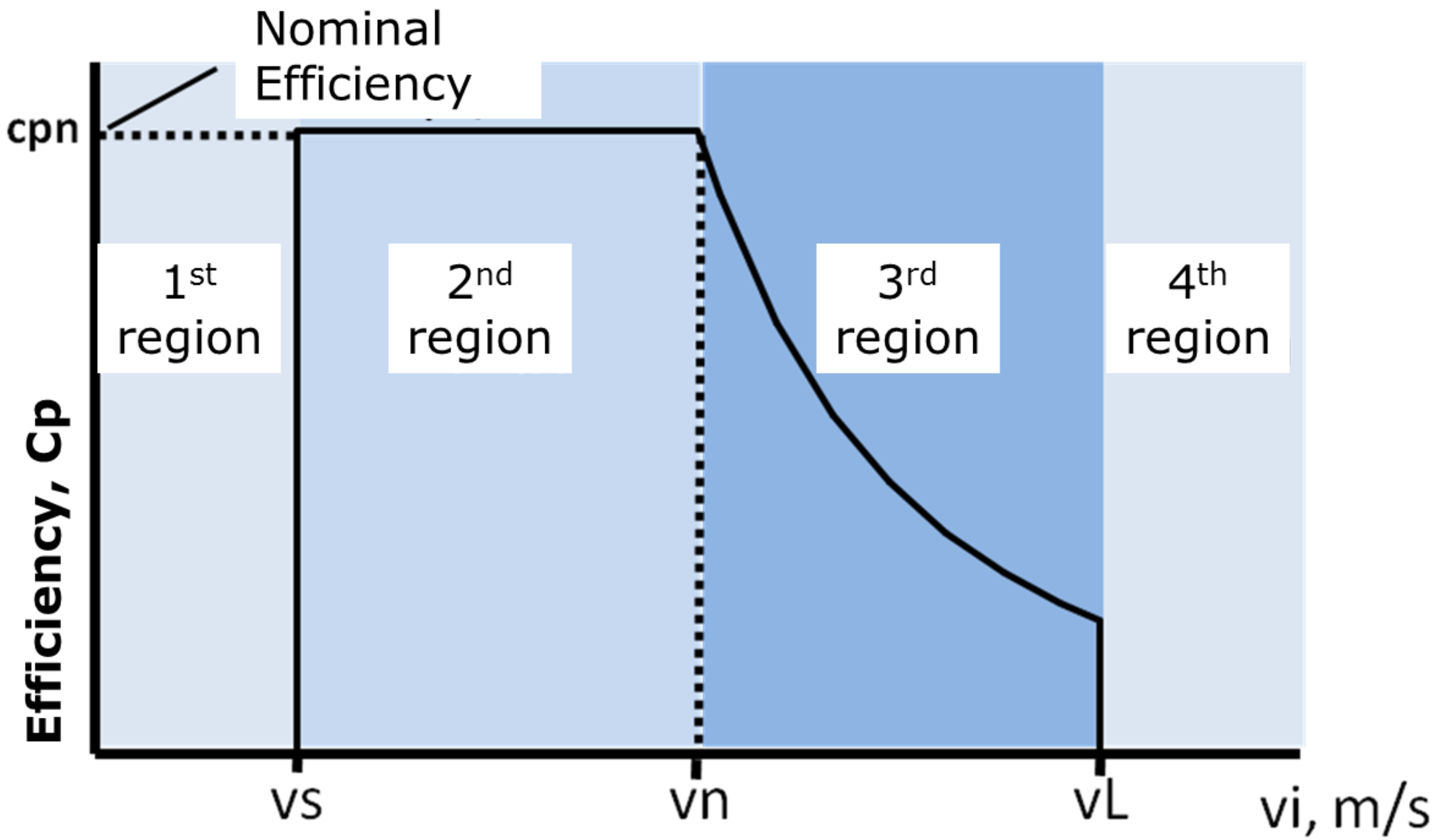
  $c_{pn} = 100 \times P^*_{oi}/P_i$ (%).

Operation at varied rotational speed (2/2)

- **4th region** contains velocities higher than V_L. The rotor is immobilized. At these too high wind velocities the wings have moved parallel to wind direction (P^*_{oi}= 0).



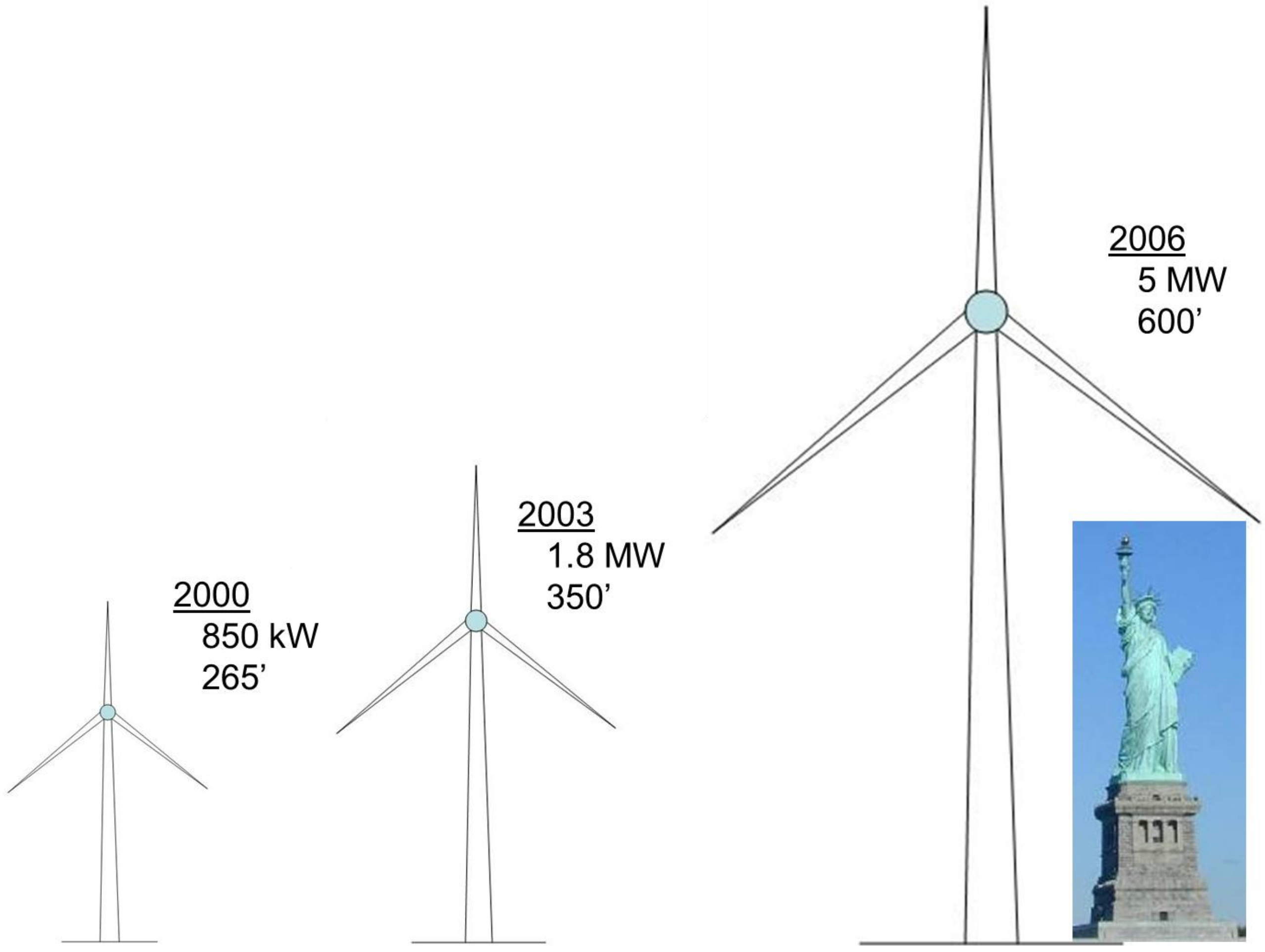
C_p vs Wind Velocity



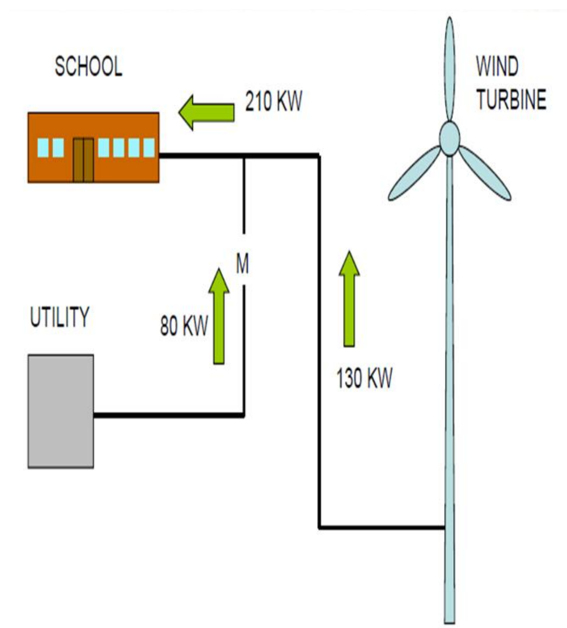
Turbines Constantly Improving

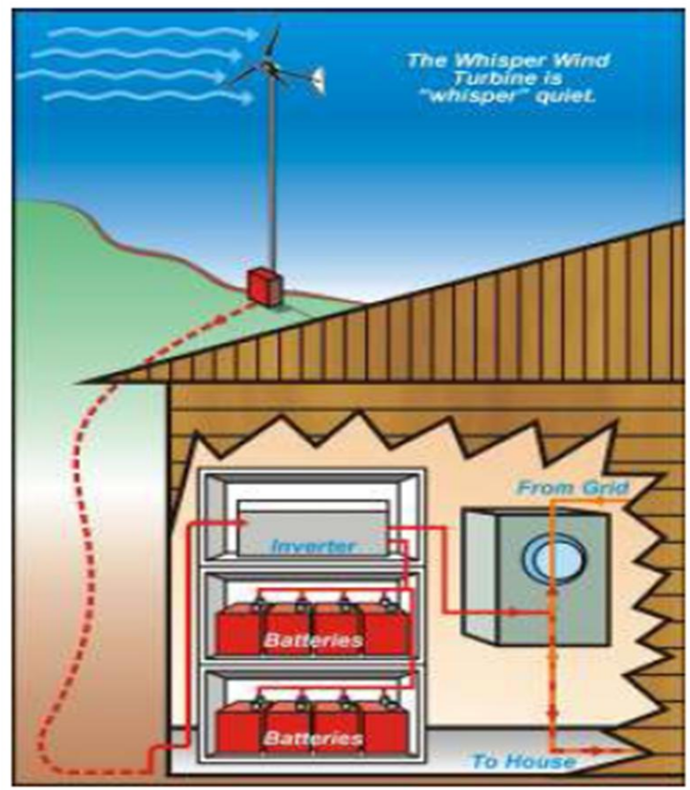
- Larger turbines produce exponentially more power, reducing unit cost.
- Specialized blade design.
- Power electronics improve turbine operations and maintenance.
- Computer modeling:
  - produces more efficient design.
- Manufacturing improvements.

Recent Capacity Enhancements

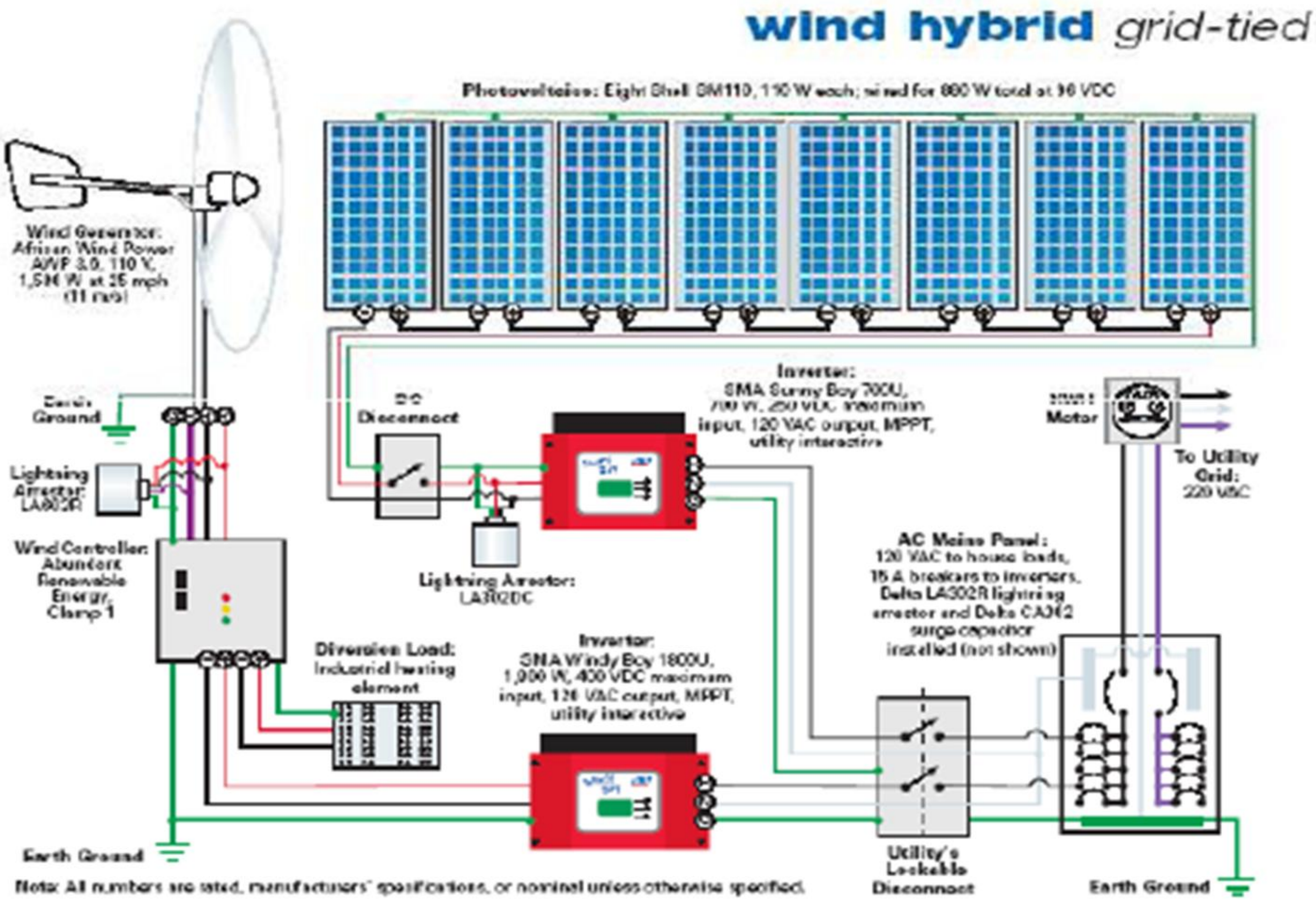


On-site
Generation to Offset Demand





Components of a Wind Turbine System



Wind Disadvantages

Market Barriers

- Siting:
  - Birds.
  - Noise (has been eliminated nowadays).
  - Aesthetics (local people are reluctant).
- Intermittent source of power.
- Transmission constraints – Connection to grid.
- Financing.

Wind Farm Development

Wind Farm Development (1/6)

- **Key parameters:**
  - – Wind resource.
  - – Zoning/Public Approval/Land Lease.
  - – Power purchase agreements.
  - – Connectivity to the grid.
  - – Financing.
  - – Tax incentives.

Wind Farm Development (2/6)

Wind resource:

– Absolutely vital to determine finances:
  - Wind is the fuel.
– Requires historical wind data:
  - Daily and hourly detail.
– Install meteorological towers:
  - Preferably at projected turbine hub height.
  - Multiple towers across proposed site.
– Multiyear data reduces financial risk.

Wind Farm Development (3/6)

Zoning/Public Approval/Land Lease:

- Obtain local and state governmental approvals:
  - Often includes Environmental Impact Studies:
    - Impact to wetlands, birds.
  - NIMBY component.
- Negotiate lease arrangements with farmers:
  - Annual payments per turbine or production based.

Wind Farm Development (4/6)

Power Purchase Agreements (PPA):

- Must have upfront financial commitment from utility.
- 15 to 20 year time frames.
- Utility agrees to purchase wind energy at a set rate:
  - e.g. Greece, 0.25 €/kWh for <50kW capacity.
  - For >50kW capacity 0.087€/kWh and 0.099€/kWh (islands).
- Financial stability/credit rating of utility important aspect of obtaining wind farm financing:
  - PPA only as good as the creditworthiness of the utility.
  - Utility goes bankrupt – you're in trouble.

Wind Farm Development (5/6)

- Connectivity to the grid:
  - Obtain approvals to tie to the grid:
    - Obtain from grid operators.
  - Power fluctuations stress the grid:
    - Especially when the grid is operating near max capacity.

Wind Farm Development (6/6)

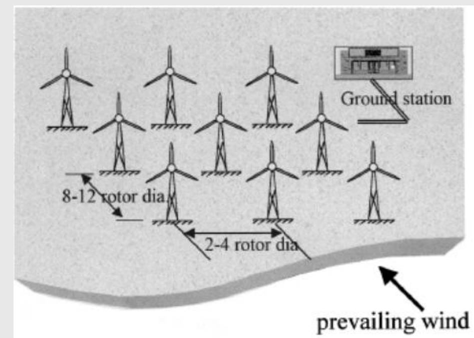
- Financing:
  - Once all components are settled…:
    - Wind resource.
    - Zoning/Public Approval/Land Lease.
    - Power Purchase Agreements (PPA).
    - Connectivity to the grid.
    - Turbine procurement.
    - Construction costs.
  - …Take the deal to get financed.

Sitting a Wind Farm

- Winds:
  - Minimum wind speed >7 m/s.
- Transmission:
  - Distance, voltage excess capacity.
- Permit approval:
  - Land-use compatibility.
  - Public acceptance.
  - Visual, noise, and bird impacts are biggest concern.
- Land area:
  - Economies of scale in construction.
  - Number of landowners.

Distance among wind turbines

- Wind turbines should be located at certain between them distances in order to maximize the “extraction” of power.
- Wind turbine distances are depending on:
  - Area morphology.
  - Wind speed.
  - Wind direction.
  - Turbine size.



- The optimum distances between the wind turbines are:
  - 8 to 12 X Wing diameter in the wind direction.
  - 2 to 4 X Wing diameter in the vertical direction of the wind.

Exercise 4 (1/6)

Calculate the nominal capacity and the energy produced during the year by a wind turbine (120 m height and 126 m diameter) located in the wind field of Example 1. If the ratio of the blade tip speed which maximizes the efficiency is 5.5, calculate the distribution of the angular velocity of the blade, in the range of wind velocities that the wind turbine operates.

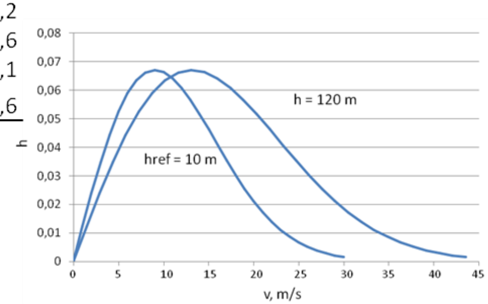
- ground roughness — $a = 0.15$.
- limit velocity — $v_l = 25$ m/s.
- start velocity — $v_s = 5$ m/s .
- nominal rotor efficiency — Cpn = 45 %.
- nominal velocity — $v_n = 15$ m/s .
- generator efficiency — nel = 85 %.

Exercise 4 (2/6)

For the estimation of the annual produced energy, the wind velocity distribution of Exercise 1 has to be reformed to the certain height of the wind turbine.

$$v_h = v\left(\frac{h}{h_{ref}}\right)^a \leftrightarrow v_h = v\left(\frac{120}{10}\right)^{0,15}$$

hi	vi, m/s	v_{hi}, m/s	hi	vi, m/s	v_{hi}, m/s	hi	vi, m/s	v_{hi}, m/s
0,0122	1	1,5	0,0642	11	16,0	0,0173	21	30,5
0,0239	2	2,9	0,0609	12	17,4	0,0139	22	31,9
0,0348	3	4,4	0,0566	13	18,9	0,0110	23	33,4
0,0444	4	5,8	0,0516	14	20,3	0,0086	24	34,8
0,0526	5	7,3	0,0463	15	21,8	0,0067	25	36,3
0,0590	6	8,7	0,0409	16	23,2	0,0051	26	37,7
0,0635	7	10,2	0,0355	17	24,7	0,0038	27	39,2
0,0662	8	11,6	0,0303	18	26,1	0,0028	28	40,6
0,0671	9	13,1	0,0255	19	27,6	0,0021	29	42,1
0,0664	10	14,5	0,0211	20	29,0	0,0015	30	43,6



Exercise 4 (3/6)

- Remember that a wind turbine starts to operate at V_s= 5 m/s and till V_n= 15 m/s the rotor efficiency is constant.
- For velocities higher than V_n and lower than V_l= 25 m/s, the wind turbine generates constant power.
  - ✓ V_{hi}, the wind velocity at the height of the wind turbine.
  - ✓ P_{hi}, the specific wind power per swept area, at the height of the WT.

$$P_{h_i} = \frac{1}{2}\rho V_{h_i}{}^3$$

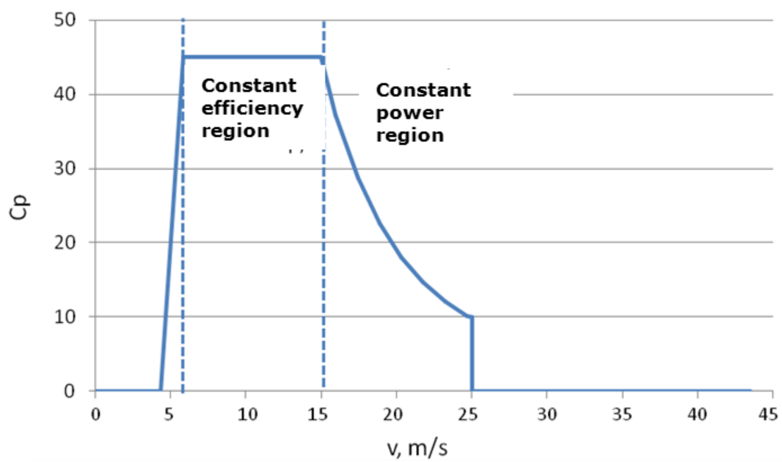
  - C_p, WT efficiency, which equals to C_{pn} for $V_s < V_i < V_n$.
  - The C_p for $V_n < V_i < V_L$ is calculated from P^*_{oi}/P_{hi}.
  - P^*_{oi}, specific rotor power= C_p x P_{hi}, which is constant between $V_n < V_i < V_L$.
  - P^*_{oi}= ½ x ρ x C_{pn} x V_n^3= ½ x 1.225 x 0.45 x 15^3= 0.93 kW/m^2.
  - P_{oi}, achieved rotor power= A x P^*_{oi}.
  - h_i, possibility for a V_{hi} wind velocity.
  - t_i, the hours of the year that the wind velocity equals to V_{hi} (h_i x 24 x 365).
  - E_{oi}, the energy that achieved by the rotor during all year at V_{hi} (t_i x P_{oi}).
  - E_{el}, the electrical energy produced by the WT (=n_{el} x E_{oi}).

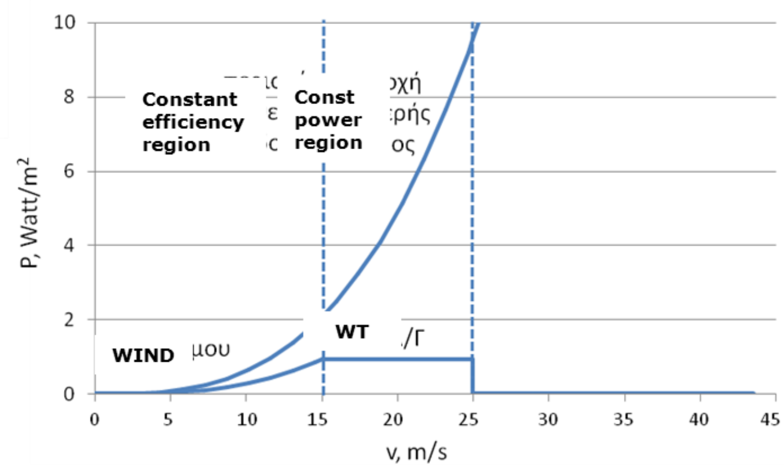
Exercise 4 (4/6)

v_{hi} m/s	Phi kW/m^2	Cp %	P*oi kW/m^2	A m^2	Poi MW	hi %	ti h	Eoi MWh	nel %	Eel MWh
0,0	0,0	0,0		12463		**0,000**	0			
1,5	0,0	0,0		12463		**0,012**	107			
2,9	0,0	0,0		12463		**0,024**	209			
4,4	0,1	0,0		12463		**0,035**	305			
5,8	0,1	45,0	0,05	12463	0,7	**0,044**	389	261,7	85	222,5
7,3	0,2	45,0	0,11	12463	1,3	**0,053**	460	604,7	85	514,0
8,7	0,4	45,0	0,18	12463	2,3	**0,059**	516	1172,3	85	996,4
10,2	0,6	45,0	0,29	12463	3,6	**0,064**	556	2005,6	85	1704,7
11,6	1,0	45,0	0,43	12463	5,4	**0,066**	580	3121,1	85	2652,9
13,1	1,4	45,0	0,61	12463	7,7	**0,067**	588	4505,0	85	3829,3
14,5	1,9	45,0	0,84	12463	10,5	**0,066**	582	6112,1	85	5195,3
16,0	2,5	37,3	0,93	12463	11,6	**0,064**	563	6520,1	85	5542,1
17,4	3,2	28,7	0,93	12463	11,6	**0,061**	533	6178,2	85	5251,5
18,9	4,1	22,6	0,93	12463	11,6	**0,057**	495	5742,9	85	4881,4
20,3	5,1	18,1	0,93	12463	11,6	**0,052**	452	5242,0	85	4455,7
21,8	6,3	14,7	0,93	12463	11,6	**0,046**	406	4702,4	85	3997,0
23,2	7,7	12,1	0,93	12463	11,6	**0,041**	358	4148,5	85	3526,2
24,7	9,2	10,1	0,93	12463	11,6	**0,035**	311	3601,1	85	3061,0
26,1	10,9	0,0		12463		**0,030**	266			
27,6	12,9	0,0		12463		**0,026**	223			
29,0	15,0	0,0		12463		**0,021**	185			
30,5	17,4	0,0		12463		**0,017**	151			
31,9	20,0	0,0		12463		**0,014**	122			
33,4	22,8	0,0		12463		**0,011**	97			
34,8	25,9	0,0		12463		**0,009**	76			
36,3	29,3	0,0		12463		**0,007**	58			
37,7	32,9	0,0		12463		**0,005**	44			
39,2	36,9	0,0		12463		**0,004**	33			
40,6	41,1	0,0		12463		**0,003**	25			
42,1	45,7	0,0		12463		**0,002**	18			
43,6	50,6	0,0		12463		**0,001**	13			
								53917,8		**45830,1**

Exercise 4 (5/6)

- C_p and wind and rotor power against wind speed variations.





Exercise 4 (6/6)

- The specific rated capacity, SRC, of the WT: SRC= Motor Capacity (kW)/Swept Area (m^2)= 12000/(π 63^2)= 0.96 kW/m^2.
- The nominal capacity of the motor is selected to be slightly higher compared to the power that will be produced at constant power conditions (**12000 kW** > 11600 kW).

The distribution of velocities are:

v_{hi}, m/s	V_{tip}, m/s	ω, rpm	v_{hi}, m/s	V_{tip}, m/s	ω, rpm
0,0			16,0	79,8	12,1
1,5			17,4	87,8	13,3
2,9			18,9	95,8	14,5
4,4			20,3	103,7	15,7
5,8	31,9	4,8	21,8	111,7	16,9
7,3	39,9	6,0	23,2	119,7	18,1
8,7	47,9	7,2	24,7	127,7	19,3
10,2	55,8	8,4	26,1	135,7	20,5
11,6	63,8	9,6	27,6		
13,1	71,8	10,8	29,0		

where V_{tip} is the velocity of wing end (= 5.5 x V_{hi}) and ω is the angular velocity of the wing = (60 s/min) x V_{tip} (2 x π x r).

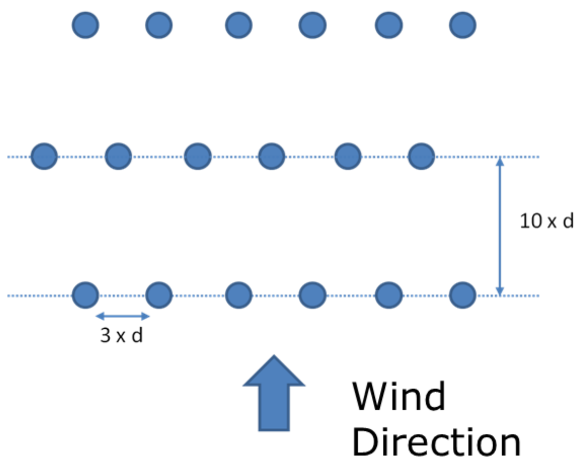
Exercise 5 (1/2)

- Estimate the number of turbines of Example 4 that can be sited in the location of Example 1 as well as the annual electricity generation of the wind farm.

Exercise 5 (2/2)

- The turbines are located as follows, where d= 126 m.
- The area that is needed for each W/T equals to:

E = 3 x d x 10 x d = 3 x 126 x 10 x 126 = 476.280 m^2 = 476,2 str



- Therefore in the 16000 str, 16000/476.2= 34 W/T will be located.
- The total electricity generation= 34 x 45830.1= 1558223 MWh.

Exercise 6 (1/5)

A private owner has available 10 acres (100 x 100 m) in a region where the average wind velocity is 11,5 m/s, in the southern Evia of Example 1. What is the expected annual electricity production, if the land is used for the installation of a wind farm. Assume that the wind direction that leads to the maximum power acquisition is perpendicular to the one side of the area.

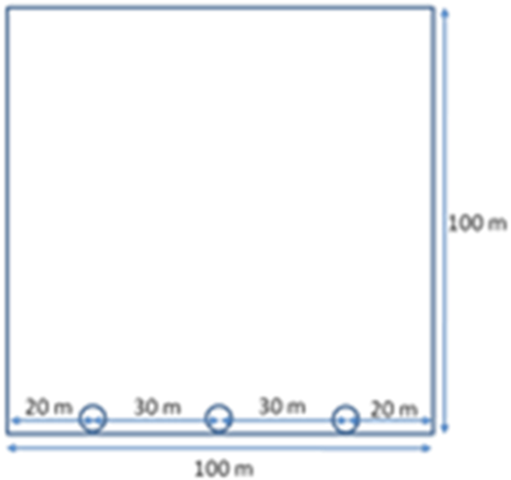
Given:

- ground roughness a = 0,15
- limit velocity v_l = 25 m/s
- start velocity v_s = 5 m/s
- nominal rotor efficiency Cpn = 45 %
- nominal velocity v_n = 15 m/s
- generator efficiency nel = 85 %
- turbine height 3 x blade diameter

Exercise 6 (2/5)

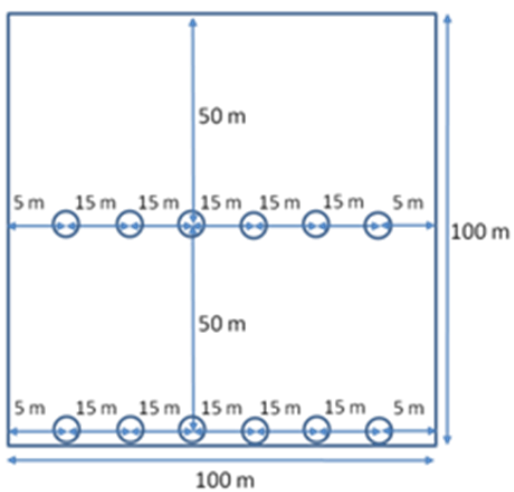
- One or more turbines should be placed at the front (windward) side of the field, that leads to maximum power extraction and should not affect the wind flow for a distance over 100 m downstream (behind turbine).
- Assuming that a turbine affects the wind flow behind it for a distance of 10 times the diameter of the blades, the maximum diameter should be, 10 m.
- Also the distance between the turbines in a direction perpendicular to the wind direction, that leads to the maximum power acquisition, is 3 times the diameter of the blades.

Exercise 6 (3/5)



The total area swept by the blades of the turbine is: $3 \times \pi \times 5^2 = 235{,}5\ m^2$

← This is the selected siting



A second alternative for turbine siting is the one shown in the figure and involves turbines with 5 m diameter blade in which the total area swept by the blades of the turbine is:

$12 \times \pi \times 2{,}5^2 = 235{,}5\ m^2$

Exercise 6 (4/5)

The height of the turbines is equal to:

Y = 3 x 10 m = 30 m

and the distribution of wind velocities should be converted to the height of turbines by the equation:

$$v_h = v\left(\frac{h}{h_{ref}}\right)^a \leftrightarrow v_h = v\left(\frac{30}{10}\right)^{0,15}$$

Exercise 6 (5/5)

hi	vi, m/s	v_{hi}, m/s	Hi	vi, m/s	v_{hi}, m/s	hi	vi, m/s	v_{hi}, m/s
0,0122	1	1,2	0,0642	11	13,0	0,0173	21	24,8
0,0239	2	2,4	0,0609	12	14,1	0,0139	22	25,9
0,0348	3	3,5	0,0566	13	15,3	0,0110	23	27,1
0,0444	4	4,7	0,0516	14	16,5	0,0086	24	28,3
0,0526	5	5,9	0,0463	15	17,7	0,0067	25	29,5
0,0590	6	7,1	0,0409	16	18,9	0,0051	26	30,7
0,0635	7	8,3	0,0355	17	20,0	0,0038	27	31,8
0,0662	8	9,4	0,0303	18	21,2	0,0028	28	33,0
0,0671	9	10,6	0,0255	19	22,4	0,0021	29	34,2
0,0664	10	11,8	0,0211	20	23,6	0,0015	30	35,4

The calculation of the annual energy production is:

v_{hi} m/s	Phi kW/m²	Cp %	P*oi kW/m²	A m²	Poi MW	hi %	ti h	Eoi MW h	nel %	Eel MWh
0,0	0,0	0,0	0,00	79	0,0	0,000	0	0,0	85	0
1,2	0,0	0,0	0,00	79	0,0	0,012	107	0,0	85	0
2,4	0,0	0,0	0,00	79	0,0	0,024	209	0,0	85	0
3,5	0,0	0,0	0,00	79	0,0	0,035	305	0,0	85	0
4,7	0,1	0,0	0,00	79	0,0	0,044	389	0,0	85	0,0
5,9	0,1	45,0	0,06	79	0,0	0,053	460	2,0	85	1,7
7,1	0,2	45,0	0,10	79	0,0	0,059	516	4,0	85	3,4
8,3	0,3	45,0	0,15	79	0,0	0,064	556	6,8	85	5,8
9,4	0,5	45,0	0,23	79	0,0	0,066	580	10,5	85	9,0
10,6	0,7	45,0	0,33	79	0,0	0,067	588	15,2	85	12,9
11,8	1,0	45,0	0,45	79	0,0	0,066	582	20,6	85	17,5
13,0	1,3	45,0	0,60	79	0,0	0,064	563	26,6	85	22,6
14,1	1,7	45,0	0,78	79	0,1	0,061	533	32,7	85	27,8
15,3	2,2	42,2	0,93	79	0,1	0,057	495	36,2	85	30,7
16,5	2,8	33,8	0,93	79	0,1	0,052	452	33,0	85	28,1
17,7	3,4	27,4	0,93	79	0,1	0,046	406	29,6	85	25,2
18,9	4,1	22,6	0,93	79	0,1	0,041	358	26,1	85	22,2
20,0	4,9	18,9	0,93	79	0,1	0,035	311	22,7	85	19,3
21,2	5,9	15,9	0,93	79	0,1	0,030	266	19,4	85	16,475 68
22,4	6,9	13,5	0,93	79	0,1	0,026	223	16,3	85	13,864 56
23,6	8,0	11,6	0,93	79	0,1	0,021	185	13,5	85	11,493 29
24,8	9,3	10,0	0,93	79	0,1	0,017	151	11,0	85	9,3880 6
25,9	10,7	0,0	0	79	0,0	0,014	122	0,0	85	0
27,1	12,2	0,0	0	79	0,0	0,011	97	0,0	85	0
28,3	13,9	0,0	0	79	0,0	0,009	76	0,0	85	0
29,5	15,7	0,0	0	79	0,0	0,007	58	0,0	85	0
30,7	17,6	0,0	0	79	0,0	0,005	44	0,0	85	0
31,8	19,8	0,0	0	79	0,0	0,004	33	0,0	85	0
33,0	22,0	0,0	0	79	0,0	0,003	25	0,0	85	0
34,2	24,5	0,0	0	79	0,0	0,002	18	0,0	85	0
35,4	27,1	0,0	0	79	0,0	0,001	13	0,0	85	0
								326, 3		277,3

Wind Economics

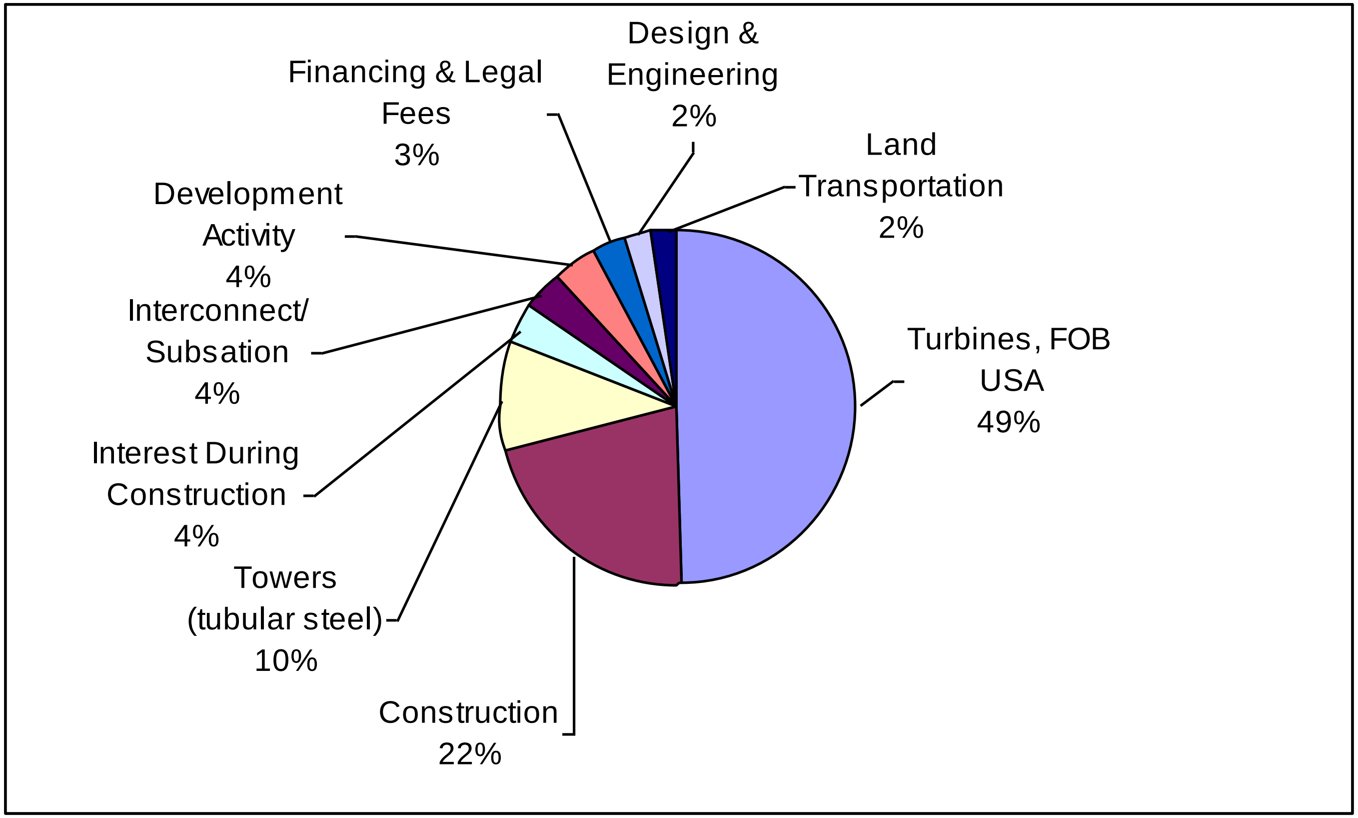
Wind Farm Design Economics

- Key Design Parameters:
  - Mean wind speed at hub height.
  - Capacity factor:
    - Start with 100% .
    - Subtract time when wind speed less than optimum.
    - Subtract time due to scheduled maintenance.
    - Subtract time due to unscheduled maintenance.
    - Subtract production losses:
      - Dirty blades, shut down due to high winds.
    - Typically 33% at a typical wind site.

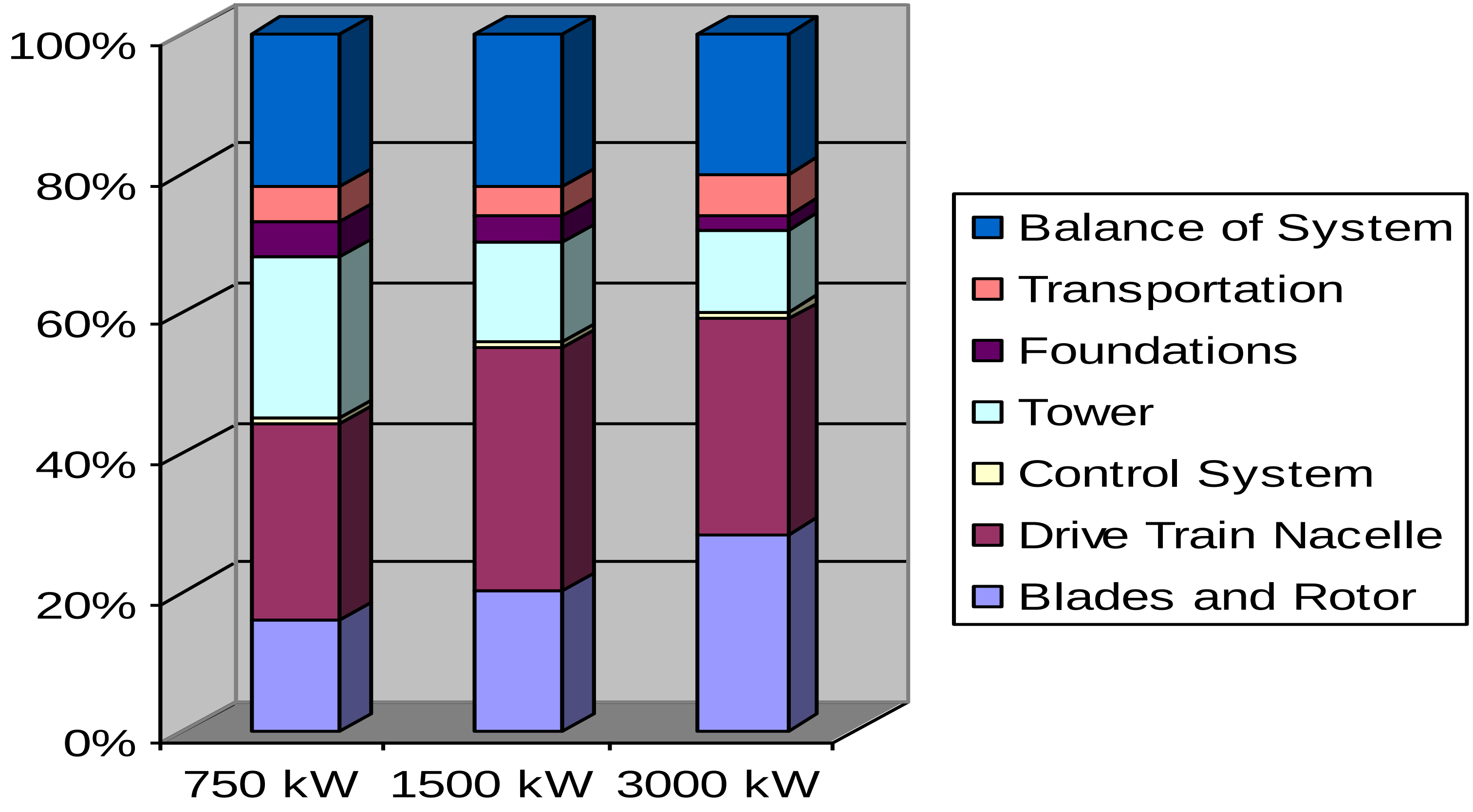
Wind Farm Financing

- Financing Terms:
  - Interest rate.
  - Loan term:
    - Up to 15 years.

Construction Cost Elements



Wind Farm Cost Components

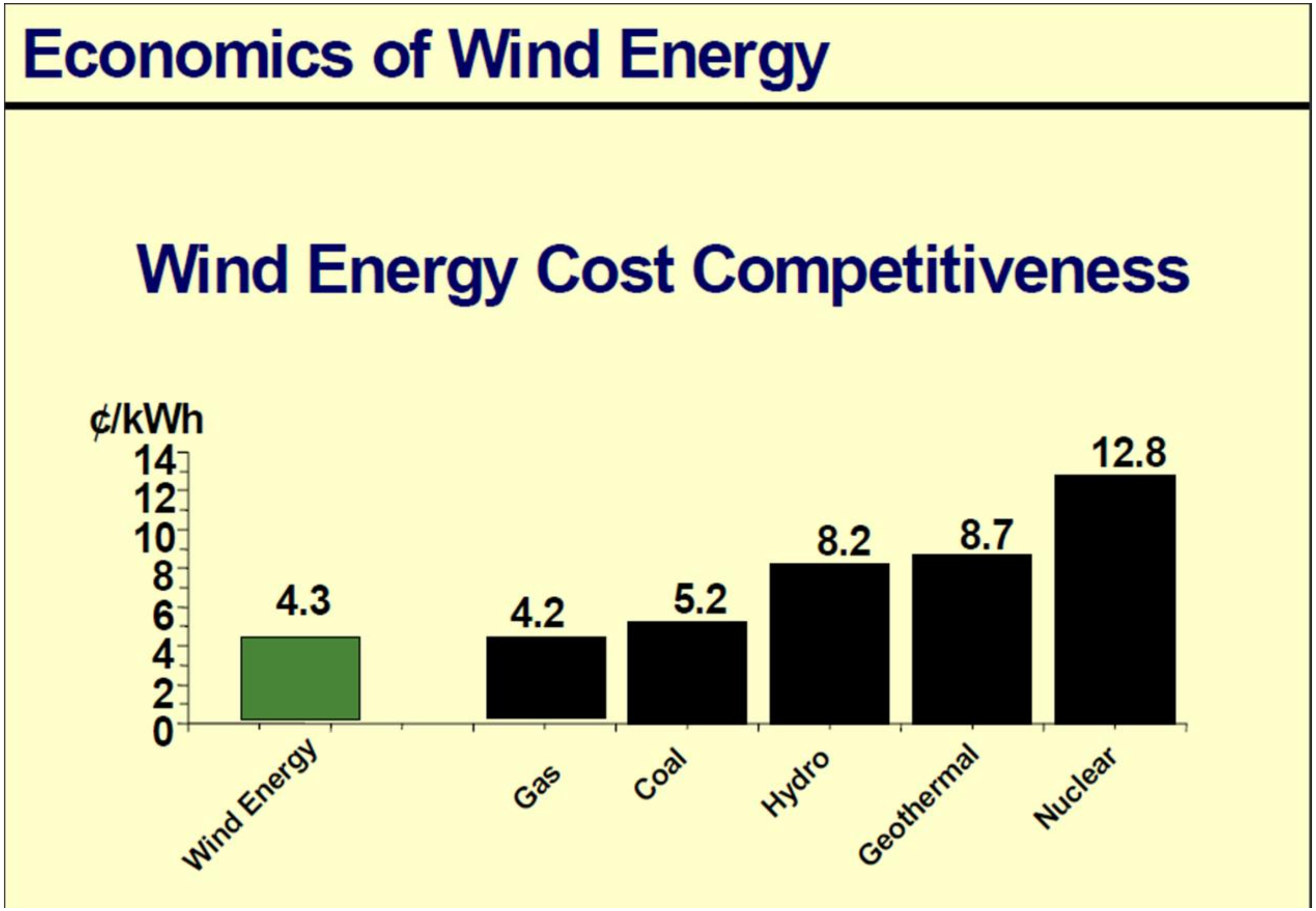


Cost of Energy Components

Cost (¢/kWh) = (Capital Recovery Cost + O&M) / kWh/year

- Capital Recovery = Debt and Equity Cost.
- O&M Cost = Turbine design, operating environment.
- kWh/year = Wind Resource.

Economics of Wind Energy



Improved Capacity Factor

- **Performance Improvements due to:**
  - Better sitting.
  - Larger turbines/energy capture.
  - Technology Advances.
  - Higher reliability.
- Capacity factors > 35% at good sites.

Wind Farm Economics (1/2)

- Key parameter:
  - Distance from grid interconnect:
    - ≈ $350,000/mile for overhead transmission lines.

Wind Farm Economics (2/2)

- The wind turbine cost is depending on its nominal capacity, P_n:

$$c_{WT} = \frac{870000}{621 + P_n^{2.05}} + 740 \quad [€/kW]$$

The cost of a W/T equals to $C_{WT} = c_{WT} \times P_n$ (€).

Taking into account all peripherals (per W/T) and the associated installation cost, the total specific cost of a W/T, is a calculated from: $c_{WT,tot} = c_{WT} \times 3.971 \times P_n^{-0.14}$ (€/kW), αnd the total cost $C_{WT,tot} = c_{WT,tot} \times P_n$ (€).

While the initial investment cost of a wind farm equals to:

$C = N \times C_{WT,tot}$ (€), N: number of W/T.

Exercise 7 (1/8) (a)

In the areas of southern Evia, wind farms are to be installed employing wind turbines of 2MW nominal power capacity:

- 1st category: 16.000 acres mean annual wind velocity 11,5 m/s.
- 2nd category: 26.000 acres mean annual wind velocity 10,7 m/s.
- 3rd category: 44.500 acres mean annual wind velocity 9,8 m/s.
- 4th category: 69.500 acres mean annual wind velocity 9,0 m/s .

Exercise 7 (1/8) (b)

Calculate:

the number of turbines to be sited, the annual electricity production from each category of land, the installation cost of wind farms in each category of land, the price for MWh electricity, from the wind farms of each category, in order for the initial investment to be paid off in 10 years. *Wind velocity in these areas follows Rayleigh distribution, given:*

- ground roughness $a = 0{,}15$.
- limit velocity $v_l = 25$ m/s.
- start velocity $v_s = 5$ m/s .
- nominal rotor efficiency Cpn = 45 %.
- nominal velocity $v_n = 15$ m/s .
- generator efficiency nel = 85 %.
- turbine height 100 m.

Exercise 7 (2/8)

The wind velocity distribution for a h= 100 m.

		1st	2nd	3rd	4th
vi, m/s	vhi, m/s	hi	hi	hi	hi
1	1,4	0,0122	0,0140	0,0167	0,0198
2	2,8	0,0239	0,0275	0,0326	0,0384
3	4,2	0,0348	0,0398	0,0469	0,0548
4	5,7	0,0444	0,0505	0,0590	0,0682
5	7,1	0,0526	0,0593	0,0683	0,0779
6	8,5	0,0590	0,0658	0,0747	0,0837
7	9,9	0,0635	0,0700	0,0781	0,0858
8	11,3	0,0662	0,0720	0,0787	0,0844
9	12,7	0,0671	0,0718	0,0767	0,0801
10	14,1	0,0664	0,0697	0,0726	0,0736
11	15,5	0,0642	0,0661	0,0669	0,0656
12	17,0	0,0609	0,0613	0,0601	0,0569
13	18,4	0,0566	0,0556	0,0527	0,0480
14	19,8	0,0516	0,0495	0,0452	0,0394
15	21,2	0,0463	0,0432	0,0379	0,0316
16	22,6	0,0409	0,0370	0,0312	0,0247
17	24,0	0,0355	0,0311	0,0251	0,0189
18	25,4	0,0303	0,0257	0,0198	0,0141
19	26,8	0,0255	0,0209	0,0153	0,0103
20	28,3	0,0211	0,0167	0,0116	0,0073
21	29,7	0,0173	0,0131	0,0086	0,0051
22	31,1	0,0139	0,0101	0,0063	0,0035
23	32,5	0,0110	0,0077	0,0045	0,0023
24	33,9	0,0086	0,0058	0,0031	0,0015
25	35,3	0,0067	0,0042	0,0022	0,0010
26	36,7	0,0051	0,0031	0,0015	0,0006
27	38,1	0,0038	0,0022	0,0010	0,0004
28	39,6	0,0028	0,0015	0,0006	0,0002
29	41,0	0,0021	0,0011	0,0004	0,0001
30	42,4	0,0015	0,0007	0,0003	0,0000

Exercise 7 (3/8)

vhi, m/s	Pi, kW/m2	Cp, %	P*oi, kW/m2	A,m2	Poi, MW
1,4	0,0	0,0	0,00	2151	0,0
2,8	0,0	0,0	0,00	2151	0,0
4,2	0,0	0,0	0,00	2151	0,0
5,7	0,1	45,0	0,05	2151	0,1
7,1	0,2	45,0	0,10	2151	0,2
8,5	0,4	45,0	0,17	2151	0,4
9,9	0,6	45,0	0,27	2151	0,6
11,3	0,9	45,0	0,40	2151	0,9
12,7	1,3	45,0	0,57	2151	1,2
14,1	1,7	45,0	0,78	2151	1,7
15,5	2,3	40,5	0,93	2151	2,0
17,0	3,0	31,2	0,93	2151	2,0
18,4	3,8	24,5	0,93	2151	2,0
19,8	4,7	19,6	0,93	2151	2,0
21,2	5,8	16,0	0,93	2151	2,0
22,6	7,1	13,2	0,93	2151	2,0
24,0	8,5	11,0	0,93	2151	2,0
25,4	10,1	0,0	0	2151	0,0
26,8	11,8	0,0	0	2151	0,0
28,3	13,8	0,0	0	2151	0,0
29,7	16,0	0,0	0	2151	0,0
31,1	18,4	0,0	0	2151	0,0
32,5	21,0	0,0	0	2151	0,0
33,9	23,9	0,0	0	2151	0,0
35,3	27,0	0,0	0	2151	0,0
36,7	30,3	0,0	0	2151	0,0
38,1	34,0	0,0	0	2151	0,0
39,6	37,9	0,0	0	2151	0,0
41,0	42,1	0,0	0	2151	0,0
42,4	46,6	0,0	0	2151	0,0

Exercise 7 (4/8)

- Calculation of wings diameter in order to obtain a 2MW nominal capacity in the designated areas.
- The wind speed values, V_{hi}, are independent of the area and only the frequency that a specific speed is observed is changing with the specific area.
- Each speed “transfer” a certain specific power and only a single fraction is captured by the W/T (P^{*}_{oi}) depending on Cp and the wind speed region (e.g., constant efficiency region or constant power region).
- The P^{*}_{oi} is multiplied with the swept area, A, which is calculated in order to obtain a nominal capacity, P_{oi} equal to 2 MW.
- $A = 2\ MW/0.93\ kW/m^2 = 2151\ m^2$.

Exercise 7 (5/8)

- Since A= 2151 m^2, then D:

$$D = \sqrt{\frac{4 \times A}{\pi}} = 52,3 \text{ m}$$

- The needed area for this specific W/T equals to:

$$(10 \times 52,3) \times (3 \times 52,3) = 82204 \text{ m}^2 = 82,2 \text{ str}$$

- Therefore the number of W/T that can be located in each region equals to:

1^{st} :	16.000 / 82,2 = 195
2^{nd} :	26.000 / 82,2 = 316
3^{rd} :	44.500 / 82,2 = 541
4^{th} :	69.500 / 82,2 = 845

Exercise 7 (6/8)

The energy that is going to be produced from each W/T:

		1st		2nd		3rd		4th	
vhi, m/s	Poi, MW	hi	Eel, MWh	hi	Eel, MWh	hi	Eel, MWh	hi	Eel, MWh
1,4	0,0	0,0122	0,0	0,014	0,0	0,0167	0,0	0,0198	0,0
2,8	0,0	0,0239	0,0	0,0275	0,0	0,0326	0,0	0,0384	0,0
4,2	0,0	0,0348	0,0	0,0398	0,0	0,0469	0,0	0,0548	0,0
5,7	0,1	0,0444	35,4	0,0505	40,2	0,0590	46,9	0,0682	54,3
7,1	0,2	0,0526	81,8	0,0593	92,2	0,0683	106,2	0,0779	121,1
8,5	0,4	0,059	158,6	0,0658	176,8	0,0747	200,8	0,0837	225,0
9,9	0,6	0,0635	271,0	0,07	298,7	0,0781	333,3	0,0858	366,0
11,3	0,9	0,0662	421,7	0,072	458,7	0,0787	501,1	0,0844	537,4
12,7	1,2	0,0671	608,6	0,0718	651,2	0,0767	695,4	0,0801	726,3
14,1	1,7	0,0664	826,1	0,0697	867,2	0,0726	902,9	0,0736	915,4
15,5	2,0	0,0642	956,1	0,0661	984,4	0,0669	995,9	0,0656	977,0
17,0	2,0	0,0609	907,1	0,0613	913,1	0,0601	895,0	0,0569	847,0
18,4	2,0	0,0566	843,1	0,0556	828,2	0,0527	785,3	0,0480	714,6
19,8	2,0	0,0516	768,6	0,0495	737,3	0,0452	673,5	0,0394	587,5
21,2	2,0	0,0463	689,6	0,0432	643,5	0,0379	565,0	0,0316	471,0
22,6	2,0	0,0409	609,2	0,037	551,1	0,0312	464,0	0,0247	368,5
24,0	2,0	0,0355	528,8	0,0311	463,2	0,0251	373,2	0,0189	281,5
25,4	0,0	0,0303	0,0	0,0257	0,0	0,0198	0,0	0,0141	0,0
26,8	0,0	0,0255	0,0	0,0209	0,0	0,0153	0,0	0,0103	0,0
28,3	0,0	0,0211	0,0	0,0167	0,0	0,0116	0,0	0,0073	0,0
29,7	0,0	0,0173	0,0	0,0131	0,0	0,0086	0,0	0,0051	0,0
31,1	0,0	0,0139	0,0	0,0101	0,0	0,0063	0,0	0,0035	0,0
32,5	0,0	0,011	0,0	0,0077	0,0	0,0045	0,0	0,0023	0,0
33,9	0,0	0,0086	0,0	0,0058	0,0	0,0031	0,0	0,0015	0,0
35,3	0,0	0,0067	0,0	0,0042	0,0	0,0022	0,0	0,0010	0,0
36,7	0,0	0,0051	0,0	0,0031	0,0	0,0015	0,0	0,0006	0,0
38,1	0,0	0,0038	0,0	0,0022	0,0	0,0010	0,0	0,0004	0,0
39,6	0,0	0,0028	0,0	0,0015	0,0	0,0006	0,0	0,0002	0,0
41,0	0,0	0,0021	0,0	0,0011	0,0	0,0004	0,0	0,0001	0,0
42,4	0,0	0,0015	0,0	0,0007	0,0	0,0003	0,0	0,0000	0,0
			7705,6		7705,8		7538,6		7192,5

Exercise 7 (7/8)

- Total annual electricity generation:

1^{st}:	7.705,6 MWh/yr/WT x 195 WT =	1.502,6 GWh/yr
2^{nd}:	7.705,8 MWh/yr/WT x 316 WT =	2.435,0 GWh/yr
3^{rd}:	7.538,6 MWh/yr/WT x 541 WT=	4.078,4 GWh/yr
4^{th}:	7.182,5 MWh/yr/WT x 845 WT =	6.077,6 GWh/yr
		14.093,7 GWh/yr

- The specific cost of a W/T:

$$c_{WT} = \frac{870000}{621 + 2000^{2,05}} + 740 = 740,4 \text{ €/kW}$$

The total specific cost:

$$c_{WT,tot} = 740,4 \times 3,971 \times 2.000^{-0,14} = 1.014,4 \text{ €/kW}$$

- Total cost:

$$C_{WT,tot} = 1.014,4 \times 2.000 = 2,03 \text{ M€}$$

Exercise 7 (8/8)

- Initial investment of the wind farm:

1st	C_{WT} = 195 x 2,03 = 396 M€
2nd	C_{WT} = 316 x 2,03 = 641 M€
3rd	C_{WT} = 541 x 2,03 = 1,10 G€
4th	C_{WT} = 845 x 2,03 = 1,72 G€
	3,85 G€

- Electricity cost to payback in 10 years:

1st	396 M€ / (1.502,6 GWh/yr x 10) GWh = 26,3 €
2nd	641 M€ / (2.435,0 GWh/yr x 10) GWh = 26,3 €
3rd	1,10 G€ / (4.078,4 GWh/yr x 10) GWh = 26,9 €
4th	1,72 G€ / (6.077,6 GWh/yr x 10) GWh = 28,2 €

Future Trends

Future Cost Reductions

- Financing Strategies.
- Manufacturing Economy of Scale.
- Better Sites and "Tuning" Turbines for Site Conditions.
- Technology Improvements.

The Future of Wind - Offshore

Wind Energy Storage (1/2)

- **Pumped hydroelectric:**
  - Georgetown facility – Completed 1967.
  - Two reservoirs separated by 1000 vertical feet.
  - Pump water uphill when wind energy production exceeds demand.
  - Flow water downhill through hydroelectric turbines when wind energy production is less than demand.
  - About 70 - 80% round trip efficiency.
  - Raises cost of wind energy by 25%.
  - Difficult to find, obtain government approval and build new facilities.

Wind Energy Storage (2/2)

- **Compressed Air Energy Storage:**
  - Using wind power to compress air in underground storage caverns.
    - Salt domes, empty natural gas reservoirs.
  - Costly, inefficient.
- **Hydrogen storage:**
  - Use wind power to electrolyze water into hydrogen.
  - Store hydrogen for use later in fuel cells.
  - 50% losses in energy from wind to hydrogen and hydrogen to electricity.
  - 25% round trip efficiency.
  - Raises cost of wind energy by 4 X.

Τέλος Ενότητας