Q.1 What are the components in a HAWT type wind turbine system?Describe the function of each component.
Blade pitch system: control power output and portect the turbine in strong wind by adjusting the blade's angle of attack
Yaw system: Adjust the direction of the wind rotor to face the wind
Gearbox: Increase rotational speed,converting low-speed rotation to a speed suitable for the generator
Generator: Convert mechanical energy into electrical energy

Q.2 Why are wind turbine rotor blades twisted towards the end?
For a constant rotational speed,the speed of the rotor along the blade is proportional to the distance from the hub.
The nearer to the tip (further from the hub),the stronger the apparent wind is.
Blade must be twisted to keep the angles right to maximize the lift-to-drag force ratio

Q.3 What is the specific power in wind at a location with wind speed of 5m/s?Determine the theoretical maximum power output of a 40-m diameter wind turbine generator at this location.Assume density of air to be 1.225Kg/m3.

① $P_w = \frac{1}{2}\rho V^3 = \frac{1}{2} \times 1.225 \times 5^3 = 76.56W$

② $P_w = \frac{1}{2}\rho A V^3 = \frac{1}{2} \times 1.225 \times \frac{\pi}{4}(40)^2 \times 5^3 = 96211.28W$

$P_w = \frac{1}{2}\rho A V^3$

specific power = Power per meter² (power density) (Watts/m²)

HAWT: $A = \frac{\pi}{4}D^2$

VAWT: $A = \frac{2}{3}D \cdot H$

$\rho = \frac{P}{RT} = 1.225\ K_T K_A$ → 15°C

Q.4 The wind speed in a city area is 5 m/s at a height of 10m.The location has a friction coefficient of 0.4.What is the specific power at a height of 50m?Assume density of air to be 1.225Kg/m3.

$\left(\frac{V}{V_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha} \Rightarrow \frac{V}{5} = \left(\frac{50}{10}\right)^{0.4} \Rightarrow V = 9.52\ m/s$

$P_w = \frac{1}{2}\rho V^3 = 528.47W$

$\left(\frac{V}{V_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$ ← friction coefficient

$\left(\frac{P}{P_0}\right) = \left(\frac{\frac{1}{2}\rho A V^3}{\frac{1}{2}\rho A V_0^3}\right) = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$

Terrain Characteristics	Friction Coefficient α
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

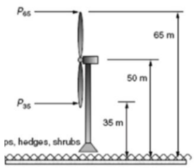
Q.5 At tip-speed-ratio of 5,what is the rpm of the wind turbine rotor with a diameter of 40m,if the wind speed is 10m/s?

tip speed ratio $= \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{rpm \times \pi D}{60V}$

$\frac{rpm \times \pi \times 40}{60 \times 10} = 5$

$rpm = \frac{75}{\pi} = 23.87$

Example : A wind turbine with a 30-m rotor diameter is mounted with its hub at 50 m above a ground surface that is characterized by shrubs and hedges.Estimate the ratio of specific power in the wind at the highest point that a rotor blade tip reaches to the lowest point that it falls to.



The ratio of velocities:

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha}$$

$$\left(\frac{v_{65}}{v_{35}}\right) = \left(\frac{65}{35}\right)^{0.2} = 1.13$$

Since power density varies as cube of the velocity,

$$\left(\frac{P_{65}}{P_{35}}\right) = \left(\left(\frac{65}{35}\right)^{0.2}\right)^3 = \left(\frac{65}{35}\right)^{0.2\times 3} = 1.45$$

Q.6 Explain how the rotor blades in a wind turbine get the required thrust to rotate.
Air moving over top of airfoil has more distance to travel ->Air pressure on top is lower than under airfoil→Lift"is created

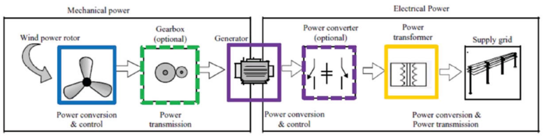
Q.7 What are the various methods used for varying the wind turbine rotor speed based on wind speed?

- Adjust angle of attack at the turbine blades

Electrical parts: Generator, Power converts
Mechanical parts: Gear box, Yaw control, Turbine blade

- Stall or pitch control

Main Components of Wind Energy Conversion Systems (WECS)



Power extracted by the rotor at low rotational speed, typically at 10-15 rpm.	Gearbox is used to increase rotational speed to a higher rpm to generate 50/60Hz electricity.	Generators and power converters are the main components to make sure that WECS produce high quality voltage supplies.	Transformers are used to step-up the voltage to connect the generator to the grid.

Q.8 Draw the complete block diagram of the wind energy conversion system to convert wind energy to electricity for the grid.Briefly explain the function of each block

Q.9 Using appropriate equations,explain why it is economical to increase the size of the wind turbine rotor.
The larger the diameter of its blades,the more power it is capable of extracting from the wind.Doubling the diameter increases the power available by a factor of 4. The cost of a turbine increases roughly in proportion to blade diameter,but power is proportional to diameter squared,so bigger machines have proven to be more cost effective.

$$\begin{cases} P_w = \frac{1}{2}\rho A V^3 \\ A = \frac{\pi}{4}D^2 \end{cases}$$

Q.10 Explain the cause of rotor stress in large wind turbines.

As seen in the previous example, the blade at the top of its rotation can experience much higher wind speeds than at the bottom of its rotation. This results in flexing of the blade.

It can also:

- Increase noise.
- Contribute to blade fatigue, which can lead to blade failure.

Q.11 From first principle,derive Betz's Law for retrieving maximum energy from wind using a wind turbine.

2

Rotor Efficiency

Define Rotor efficiency as,

$$C_P = \frac{1}{2}(1+\lambda)(1-\lambda^2)$$

Fundamental relationship for power delivered by the rotor,

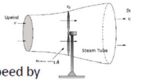
$$\boxed{P_b = \frac{1}{2}\rho A v^3 \cdot C_p}$$

1

Power Extracted

Assume that the velocity of wind v_b is just the average of the upwind and downwind speed,

$$P_b = \frac{1}{2}\rho A \left(\frac{v + v_d}{2}\right)(v^2 - v_d^2)$$



Denote the ratio between upwind and downwind speed by

$$\lambda = \left(\frac{v_d}{v}\right)$$

Substitute v_d, then we have,

$$P_b = \frac{1}{2}\rho A \left(\frac{v + \lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$= \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in the wind}} \cdot \boxed{\underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}}}$$

3

Maximum Rotor Efficiency

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$

$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$

$$= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

The blade efficiency will be maximum if it slows the wind to one-third of the upwind speed. $\lambda = \frac{v_d}{v} = \frac{1}{3}$

$$\text{Efficiency} = \frac{1}{2}(1+\lambda)(1-\lambda^2) = \frac{16}{27} \doteq 59.3\%$$

Q.12 What is the tip seed ratio (TSR) of wind turbine? How does TSR affect the rotor efficiency of a wind turbine?

- For a given wind speed, the rotor efficiency depends on the speed of rotation of the blades.
- TSR is the speed at rotor tip divided by the wind speed.

$$\frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

D: diameter (m)
v: wind speed (m/s)

– If TSR is high, it means that the blade spins too fast, and that the blade will experience turbulent wind.

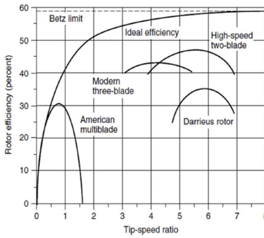
– If TSR is low, it means that the blade spins too slowly, and it can r efficiently capture wind energy.

The optimal TSR gives the maximum efficiency that a turbine can extract wind energy.

- For a given wind speed, rotor efficiency is a function of the rate at which a rotor turns.

– If Rotor turns too slow letting too much wind to pass
  => efficiency drops.

– If Rotor turns too fast causing turbulence
  =>efficiency drops.



Q.13 Describe the various types of wind turbine generators based on type of speed control used.

WTGs Classification by Speed Control

Wind turbine generators can be divided into 5 types.

1. Type 1: Fixed speed (1-2% variation)
2. Type 2: Limited variable speed (10% variation)
3. Type 3: Variable speed with partial power electronic conversion (30% variation)
4. Type 4: Variable speed with full power electronic conversion (full variation)
5. Type 5: Variable speed with mechanical torque converter to control synchronous speed (full variation)

Example

A 40-m, three-bladed wind turbine produces 600 kW at a wind speed of 14 m/s. Air density is the standard 1.225 kg/m3. Under these conditions,

a. At what rpm does the rotor turn when it operates with a TSR of 4.0?
b. What is the tip speed of the rotor?
c. If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?
d. What is the efficiency of the complete wind turbine (blades, gear box, generator) under these conditions?

(a) $$\text{Tip-Speed-Ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

$$\text{rpm} = \frac{\text{TSR} \times 60\ v}{\pi D}$$

$$= \frac{4 \times 60\ \text{s/min} \times 14\ \text{m/s}}{40\pi\ \text{m/rev}} = 26.7\ \text{rev/min}$$

(b) The tip of each blade is moving at

$$\text{Tip speed} = \frac{26.7\ \text{rev/min} \times \pi 40\ \text{m/rev}}{60\ \text{s/ min}}$$

$$= 55.9\ \text{m/s}$$

(c) $$\text{Gear ratio} = \frac{\text{Generator rpm}}{\text{Rotor rpm}}$$

$$= \frac{1800}{26.7} = 67.4$$

(d)

The power in the wind is:

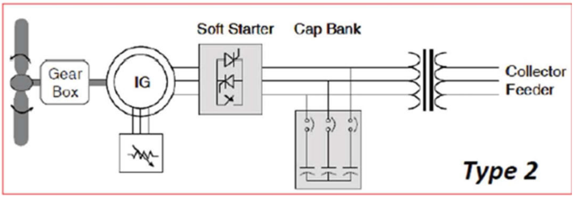
$$P_w = \frac{1}{2}\rho A v_w^3 = \frac{1}{2} \times 1.225 \times \frac{\pi}{4} \times 40^2 \times 14^3 = 2112\ kW$$

Out of the generator is given as $600\ kW$.

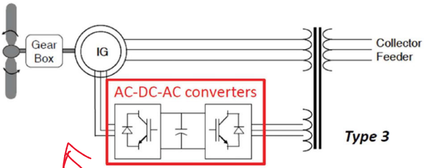
$$\text{Overall efficiency} = \frac{600\ kw}{2112\ kW} = 0.284 = 28.4\%$$

Q.14 Using block diagram, describe the various types of variable speed wind turbine generator systems with electrical control on generator side.

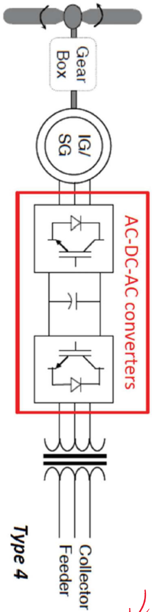
Type 2: Variable Speed Systems



Type 3: Doubly Fed Induction Generator(DFIG)



Type 4: Indirect Grid Connection



Q.15 Using block diagram, explain the operation of wind turbine system with a doubly fed induction generator (DFIG).

Instead of variable resistors in Type 2, this Type 3 design adds AC-DC-AC converters to the rotor circuit.

Rotor frequency is decoupled from grid frequency.

The machine can still be synchronized with the grid while the wind speed varies.

Allows the turbine to rotate at its optimal speed.

AC output from generator frequency is different and decoupled from grid frequency.

AC-DC-AC converter is used to connect the AC output to the grid.

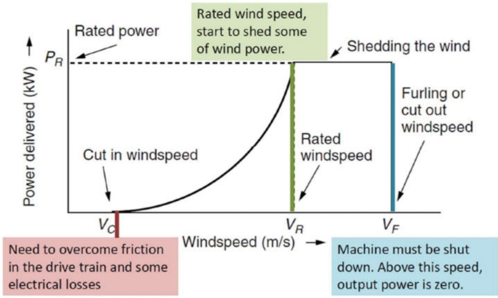
Full control and flexibility in the design and operation of wind turbine.

The ratings of power electronics are higher than Type 3.

Q.16 Using block diagram, explain the operation of variable turbine speed, type 4 wind turbine system with a Synchronous generator.

Q.17 Draw the ideal power delivered vs wind speed curve for a wind turbine generator. Clearly explain the operation at different wind speed.

Ideal Power Curve



Q.18 What is meant by wind shedding? Explain the various methods for shedding wind power?

Wind shedding refers to the intentional reduction of power output to protect the turbine during high winds. Methods include:

Pitch-controlled turbines

– Active control by reducing ‘angle of attack’ Stall-controlled turbines.

– Passive control using pure aerodynamic design.

Active stall control.

– Induce stall for large wind turbine by increasing ‘angle of attack’.

Passive yaw control

– Small kW size turbine, causing axis of turbine to move off the wind.

Average Wind Speed calculation

$$v_{avg} = \frac{\text{Miles of wind}}{\text{Total hours}} = \frac{3\text{ h}\cdot 0\text{ mile/hr} + 3\text{ h}\cdot 5\text{ mile/h} + 4\text{ h}\cdot 10\text{ mile/h}}{3+3+4\text{ h}}$$

$$v_{avg} = \left(\frac{3\text{ h}}{10\text{ h}}\right)\times 0\text{ mph} + \left(\frac{3\text{ h}}{10\text{ h}}\right)\times 5\text{ mph} + \left(\frac{4\text{ h}}{10\text{ h}}\right)\times 10\text{ mph} = 5.5\text{ mph}$$

A more general expression for the above two equations would be:

Probability that the speed is v_i!!

$$v_{avg} = \frac{\sum_i [v_i\cdot(\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i\cdot \boxed{\text{fraction of hours @ } v_i}]$$

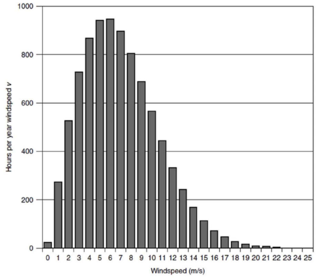
$$(v^3)_{avg} = \frac{\sum_i [v_i^3\cdot(\text{hours @ } v_i)]}{\sum \text{hours}} = \sum_i [v_i^3\cdot(\text{fraction of hours @ } v_i)]$$

$$(v^3)_{avg} = \sum_i [v_i^3\cdot \text{probability}(v = v_i)]$$

Example

Using the data given below, find the average windspeed and the average power in the wind (W/m^2). Assume air density = 1.225 kg/m^3.

v (m/s)	Hrs/yr
0	24
1	276
2	527
3	729
4	869
5	941
6	946
7	896
8	805
9	690
10	565
11	444
12	335
13	243
14	170
15	114
16	74
17	46
18	28
19	16
20	9
21	5
22	3
23	1
24	1
25	0
Total hrs	8,760



Solution

The average windspeed is

$$v_{avg} = \sum_i [v_i\cdot(\text{Fraction of hours @ } v_i)] = 7.0\text{ m/s}$$

The average value of v^3 is

$$(v^3)_{avg} = \sum_i [v_i^3\cdot(\text{Fraction of hours @ } v_i)] = 653.24$$

The average power in the wind is

$$P_{avg} = \tfrac{1}{2}\rho(v^3)_{avg} = 0.5\times 1.225\times 653.24 = 400\text{ W/m}^2$$

If we had miscalculated average power in the wind using the 7 m/s *average* windspeed, we would have found:

$$\boxed{\begin{aligned} P_{average}(\text{WRONG}) &= \tfrac{1}{2}\rho(v_{avg})^3 \\ &= 0.5\times 1.225\times 7.0^3 = 210\text{ W/m}^2\end{aligned}}$$

Q.19 The table below gives the measurement of wind speed during one day. Calculate the total energy generated for the day using a 40-m diameter rotor wind turbine generator with rotor efficiency of 40% and generator efficiency of 85%. The cut-in speed is 3 m/s and cut-out speed is 9 m/s. Assume there is no wind shedding.

$D = 40$ m

$\rho = 1.225$ kg/m^3

$A = \frac{\pi}{4}D^2 = 400\pi$ m^2

	Wind speed (m/s)	Number of hours recorded during the day
<3	1	5
	2	3
calculation	4 i=1	4
	7 2	6
	8 3	4
>9	10	2

$P_w = \frac{1}{2}\rho A v^3$ $\quad P_{w1} = 49.26$ kW $\quad P_{w2} = 264$ kW $\quad P_{w3} = 394.08$ kW

$P_{out} = P_w\cdot 0.4\cdot 0.85$ $\quad P_{out1} = 16.75$ kW $\quad P_{out2} = 89.76$ kW $\quad P_{out3} = 133.99$ kW

$E = P_{out}\cdot \text{hours}$ $\quad E_{all} = \Sigma E_i = 1141.51$ kWh

Q15

A wind turbine system with a DFIG mainly includes a wind turbine, a gearbox, a DFIG, and a control system. The wind turbine converts wind energy into mechanical rotation. The gearbox adjusts the speed. The DFIG has its stator directly connected to the grid and its rotor connected to the grid via a power converter. The control system monitors parameters like wind speed and rotor speed, and sends signals to the power converter to adjust the rotor excitation for optimal operation.

Rayleigh PDF: Average Wind Speed

From $f(v) = \frac{2v}{c^2}\exp\left[-\left(\frac{v}{c}\right)^2\right]$

$$\bar{v} = \int_0^\infty v\cdot f(v)\,dv = \int_0^\infty \frac{2v^2}{c^2}\exp\left[-\left(\frac{v}{c}\right)^2\right]$$

$$= \frac{\sqrt{\pi}}{2}c \cong 0.886c$$

Substituting in equation for standard integrals

Or, we can write: $c = \frac{2}{\sqrt{\pi}}\bar{v} \cong 1.128\,\bar{v}$

The Rayleigh probability density function can be written as follows in terms of average wind speed.

$$\boxed{f(v) = \frac{\pi}{2}\frac{v}{\bar{v}^2}\exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right]}$$

Rayleigh PDF: Average Power

Coupling average windspeed with the assumption that the wind speed distribution follows Rayleigh statistics enables us to find the average power in the wind.

$$P_{avg} = \tfrac{1}{2}\rho A(v^3)_{avg}$$

$$(v^3)_{avg} = \int_0^\infty v^3\cdot f(v)dv$$

$$= \int_0^\infty v^3\cdot\frac{2v}{c^2}\exp\left[-\left(\frac{v}{c}\right)^2\right]dv = \frac{3}{4}c^3\sqrt{\pi}$$

Substitute $c = \frac{2}{\sqrt{\pi}}\bar{v}$ ➡ $(v^3)_{avg} = \frac{3}{4}\sqrt{\pi}\left(\frac{2\bar{v}}{\sqrt{\pi}}\right)^3$

$$= \frac{6}{\pi}\bar{v}^3 = 1.91\,\bar{v}^3$$

$$\boxed{\bar{P} = \frac{6}{\pi}\cdot\frac{1}{2}\rho A\bar{v}^3}$$

Example

Estimate the average power in the wind at a height of 50 m when the wind speed at 10 m averages 6 m/s.

Assume Rayleigh statistics;

Standard friction coefficient $\alpha = \frac{1}{7}$;

Standard air density $\rho = 1.225\frac{kg}{m^3}$.

Solution

We first adjust the winds at 10 m to those expected at 50 m

$$\bar{v}_{50} = \bar{v}_{10}\left(\frac{H_{50}}{H_{10}}\right)^\alpha = 6\cdot\left(\frac{50}{10}\right)^{1/7} = 7.55\text{ m/s}$$

the average wind power density would be

$$\bar{P}_{50} = \frac{6}{\pi}\cdot\frac{1}{2}\rho\bar{v}^3$$

$$= \frac{6}{\pi}\cdot\frac{1}{2}\cdot 1.225\cdot(7.55)^3 = 504\text{ W/m}^2$$

Overall Efficiency

Average power in the wind (W/m²) → Power extracted from the wind (W/m²), depending turbine blade (rotor) efficiency → Electrical power output (W/m²), depending on the gearbox and generator efficiency

$P_{wind} = \frac{1}{2}\rho A \omega^3$ $\quad P_{blade} = \frac{1}{2}\rho A \omega^3 \cdot C_p$

(Assume $C_p = 0.45$)

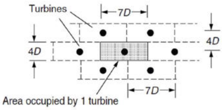
(Assume gearbox and generator efficiency has combined efficiency of 2/3)

$$\text{Overall efficiency} = \frac{P_{electrical}}{P_{wind}} = 0.45 \times \frac{2}{3} = 0.3 = 30\%$$

Example

Suppose that a wind farm has 4-rotor-diameter tower spacing along its rows, with 7-diameter spacing between rows (4D × 7D).

Assume 30% wind turbine efficiency and an array efficiency of 80%.



Find the annual energy production per unit of land area in an area with 400-W/m2 winds at hub height (the edge of 50 m, Class 4 winds).

$$\frac{Energy}{Land\ area} = \frac{Power\ density\ of\ wind\ turbine \times swept\ area\ of\ rotor \times turbine\ efficiency \times array\ efficiency}{land\ area\ for\ one\ turbine} \times hours$$

Solution

The land area occupied by one turbine is $4D \times 7D = 28D^2$.

The rotor area $\frac{\pi}{4}D^2$.

The yearly energy produced by one turbine =

$$= Wind\ power\ density \times rotor\ area \times turbine\ efficiency \times array\ efficiency \times hours\ per\ year$$

$$= 400 \times \frac{\pi}{4}D^2 \times 0.3 \times 0.8 \times 8760 = 660153.6D^2$$

$$\frac{Energy}{Land\ Area} = \frac{660153.6D^2}{28D^2} = 23.58\ kWh/m^2$$

Example

Suppose that a NEG Micon 60-m diameter wind turbine having a rated power of 1000 kW is installed at a site having Rayleigh wind statistics with an average wind speed of 7m/s at the hub height. The generator output for various wind speeds are given on the right.

a) Find the annual energy generated.
b) From the result, find the overall average efficiency of this turbine in these winds.
c) Find the productivity in terms of kWh/yr delivered per m² of swept area.

	Manufacturer:	NEG Micon
	Rated Power (kW):	1000
	Diameter (m):	60
Avg. Windspeed		
v (m/s)	v(mph)	kW
0	0	0
1	2.2	0
2	4.5	0
3	6.7	0
4	8.9	33
5	11.2	86
6	13.4	150
7	15.7	248
8	17.9	385
9	20.1	535
10	22.4	670
11	24.6	780
12	26.8	864
13	29.1	924
14	31.3	964
15	33.6	989
16	35.8	1000
17	38.0	998
18	40.3	987
19	42.5	968
20	44.7	944
21	47.0	917
22	49.2	889
23	51.5	863
24	53.7	840
25	55.9	822
26	58.2	0

Solution

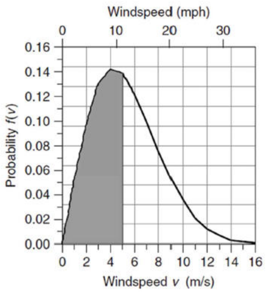
Assumption: Rayleigh wind statistics with average wind speed of 7 m/s at hub height.

Step 1: Find the probability of each wind speed. How???

Step 2: Find the energy produced at each wind speed.

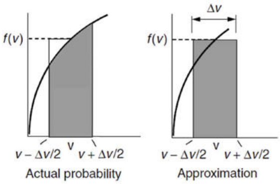
Step 3: Annual energy generated = summation of energy produced at each wind speed

Probability Approximation



$$f(v) = \frac{\pi v}{2\overline{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right]$$

We can discretize a continuous PDF and say that the probability that the wind blows at v is just f(v).



$$\text{Area} = \int_{v-\Delta v/2}^{v+\Delta v/2} f(v)\,dv \approx f(v)\Delta v$$

at 6 m/s the NEG Micon 1000/60 generates 150 kW

the Rayleigh p.d.f. at 6 m/s in a regime with 7-m/s average windspeed is

$$f(v) = \frac{\pi v}{2\overline{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right]$$

$$= \frac{\pi \cdot 6}{2 \cdot 7^2} \exp\left[-\frac{\pi}{4}\left(\frac{6}{7}\right)^2\right] = 0.10801$$

In a year with 8760 h, our estimate of the hours the wind blows at 6 m/s is

$$\text{Hours @6 m/s} = 8760\ \text{h/yr} \times 0.10801 = 946\ \text{h/yr}$$

So the energy delivered by 6-m/s winds is

$$\text{Energy (@6 m/s)} = 150\ \text{kW} \times 946\ \text{h/yr}$$

$$= 141,929\ \text{kWh/yr}$$

Do this for all speeds and add them up!

The overall average efficiency of this turbine

Windspeed (m/s)	Power (kW)	Probability $f(v)$	Hrs/yr at v	Energy (kWh/yr)
0	0	0.000	0	0
1	0	0.032	276	0
2	0	0.060	527	0
3	0	0.083	729	0
4	33	0.099	869	28,683
5	86	0.107	941	80,885
6	150	0.108	946	141,929
7	248	0.102	896	222,271
8	385	0.092	805	310,076
9	535	0.079	690	369,126
10	670	0.065	565	378,785
11	780	0.051	444	346,435
12	864	0.038	335	289,551
13	924	0.028	243	224,707
14	964	0.019	170	163,779
15	989	0.013	114	113,101
16	1000	0.008	74	74,218
17	998	0.005	46	46,371
18	987	0.003	28	27,709
19	968	0.002	16	15,853
20	944	0.001	9	8,709
21	917	0.001	5	4,604
22	889	0.000	3	2,347
23	863	0.000	1	1,158
24	840	0.000	1	554
25	822	0.000	0	257
26	0	0.000	0	0
			Total:	2,851,109

average power in the wind for a 60-m rotor diameter

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A\overline{v}^3$$

$$= \frac{6}{\pi} \times 0.5 \times 1.225 \times \frac{\pi}{4}(60)^2 \times (7)^3$$

$$= 1.134 \times 10^6\ \text{W} = 1134\ \text{kW}$$

In a year with 8760 h, the energy in the wind is

$$\text{Energy in wind} = 8760\ \text{h/yr} \times 1134\ \text{kW}$$

$$= 9.938 \times 10^6\ \text{kWh}$$

$$\text{Average efficiency} = \frac{2.85 \times 10^6\ \text{kWh/yr}}{9.938 \times 10^6\ \text{kWh/yr}}$$

$$= 0.29 = 29\%$$

Annual Energy Production: Capacity Factor Method

Capacity factor is a measure of the fraction of actual energy delivered to the rated energy output in one year.

$$\text{CF} = \frac{\text{Actual energy delivered}}{\text{Rated power} \times 8760}$$

$$\text{Annual energy (kWh/yr)} = P_R\ \text{(kW)} \times 8760\ \text{(h/yr)} \times \text{CF}$$

where P_R is the rated power (kW) and CF is the capacity factor

$$\text{CF} = \frac{\text{Actual energy delivered}}{P_R \times 8760}$$

another way to express it is

$$\text{CF} = \frac{\text{Actual energy delivered/8760 h/yr}}{P_R} = \frac{\text{Average power}}{\text{Rated power}}$$

- Dimensionless quantity between 0 and 1.
- CF is meant for calculating 'actual energy delivered' given that we know the rated power.

$$CF = 0.087\,\overline{V} - \frac{P_R}{D^2}$$

Estimate of energy delivered from a turbine of diameter D:

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\text{kW}) \left\{ 0.087\overline{V}(\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2} \right\}$$