## The history of wind power:

Wind power has been used for thousands of years. Here are some key events in the history of wind power:

**Ancient Civilizations (500-1500 AD)**

1. Persia (modern-day Iran): The first windmills were developed around 500-900 AD to pump water and grind grain.

2. China: Windmills were used (960-1279 AD) for water pumping and milling.

3. Europe: Windmills were introduced in the 12th century.

**Medieval Period (1500-1800 AD)**

1. Netherlands: The Dutch developed advanced windmills with vertical axes, used for drainage and milling.

2. England: Windmills were used for grinding grain and pumping water.

**Industrial Revolution (1800-1900 AD)**

1. Wind-powered machinery: Windmills were used to power machinery, such as sawmills and textile mills.

2. First wind turbines: The first wind turbines were developed in Scotland in the 1880s.

**Modern Era (1900-present)**

1. Wind farms: The first wind farm was established in Denmark in 1957.

2. Commercial wind turbines: Modern commercial wind turbines were developed in the 1970s and 1980s.

3. Renewable energy growth: Wind power has become a significant contributor to renewable energy globally, with over 700 GW of installed capacity.

Wind power has come a long way, from ancient windmills to modern, high-tech turbines. As technology continues to evolve, wind power will remain a vital component of our transition to renewable energy.

**INDIAN AND GLOBAL STATISTICS OF WIND POWER**

**Global Wind Power Statistics**

- Total Installed Capacity: Over 1,051 gigawatts (GW) as of 2023, with 120 GW added in 2023 alone, representing a 12.9% growth.

- Global Electricity Generation: Wind power generates around 10% of global electricity.

The top markets for wind power are:

- China: Added 75 GW of new capacity in 2023, accounting for two-thirds of the global market

- United States: Ranks second in terms of total capacity

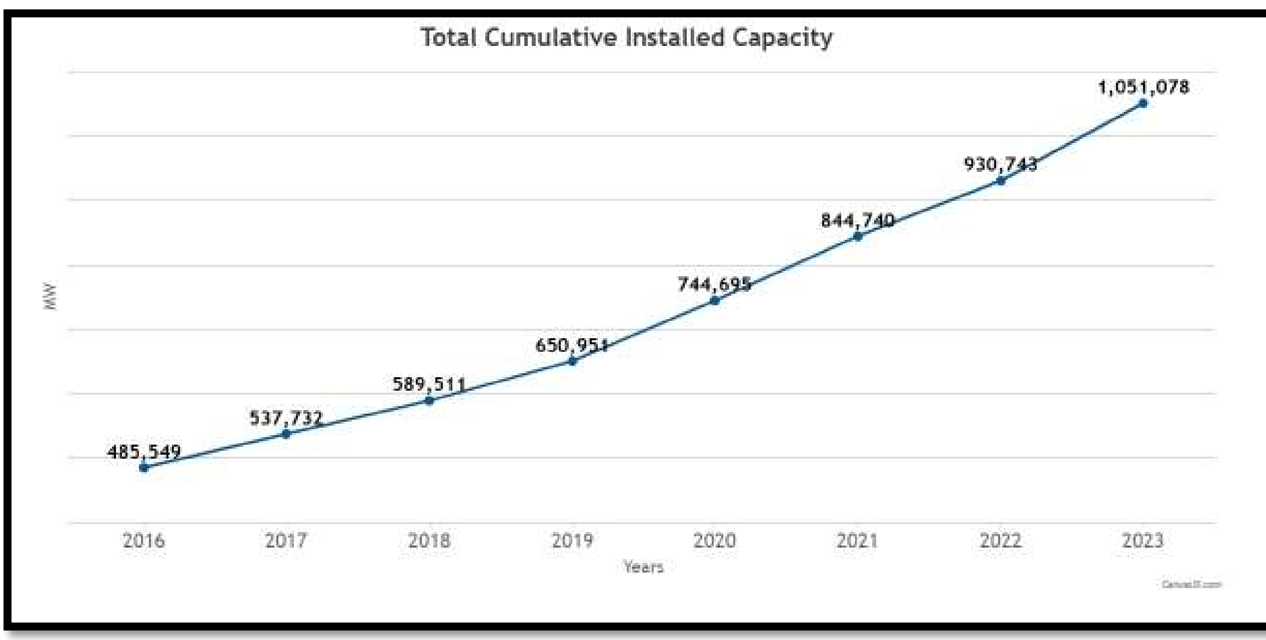
- Germany: A leading market in Europe

- India: Expected to remain fourth in terms of overall capacity in the coming years

Growth Prospects

The wind industry is expected to continue growing rapidly, with predictions of Tripling capacity by 2030: Reaching 1,210 GW of installed capacity.

A graph shown below is plotted between years (2016-2023) and MW of cumulative wind capacity. From the graph it is clear that in the year 2016, cumulative wind capacity was 485549 MW which became 537732 MW in 2017 and so on. In the year 2023 it reached 1051078 MW.



**Indian Wind Power Statistics**

- Total Installed Capacity: 47.36 GW as of September 2024, making India the fourth-largest wind power market globally .

- Growth Rate: India's wind power capacity is expected to grow significantly, with an estimated 21.2 GW of new installations by 2027.

- State-wise Distribution: Wind power capacity is mainly concentrated in the southern, western, and northwestern states of India .

**State-wise Distribution**

The top five states with the highest installed wind power capacity are:

- Gujarat: 12,209.18 MW

- Tamil Nadu: 11,042.44 MW

- Karnataka: 6,564.36 MW

- Maharashtra: 5,214.28 MW

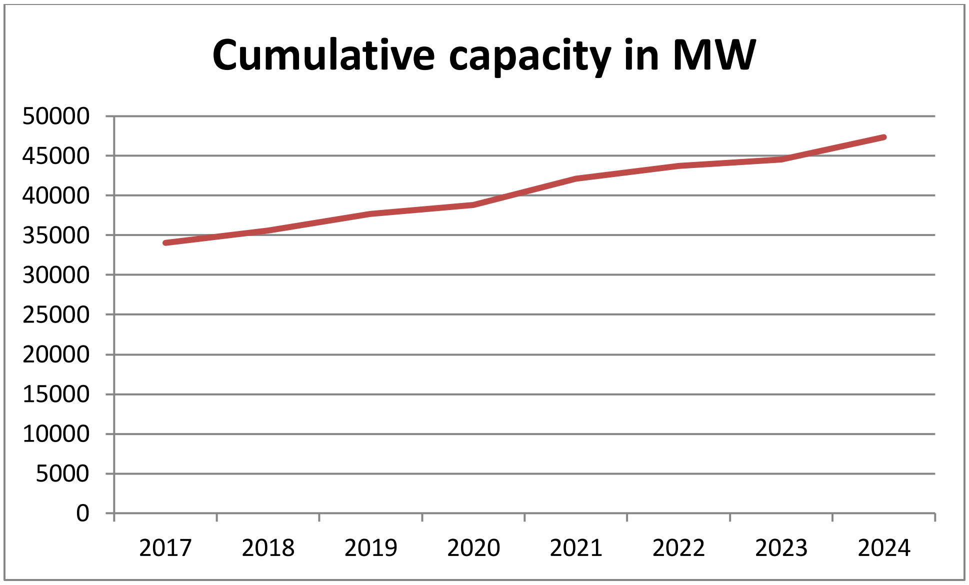
- Rajasthan: 5,195.82 MW

Growth Prospects

India aims to increase its wind power capacity to 60,000 MW by 2027, with a focus on offshore wind farms and hybrid renewable energy projects .

Table and a graph below shows the data of **Cumulative wind capacity in MW for years 2017 to 2024.**

| Year | Cumulative capacity in MW |
| --- | --- |
| 2017 | 34,046 |
| 2018 | 35,626 |
| 2019 | 37,669 |
| 2020 | 38,785 |
| 2021 | 42,149 |
| 2022 | 43,773 |
| 2023 | 44,560 |
| 2024 | 47,360 |


Cumulative capacity in MW
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
2017
2018
2019
2020
2021
2022
2023
2024

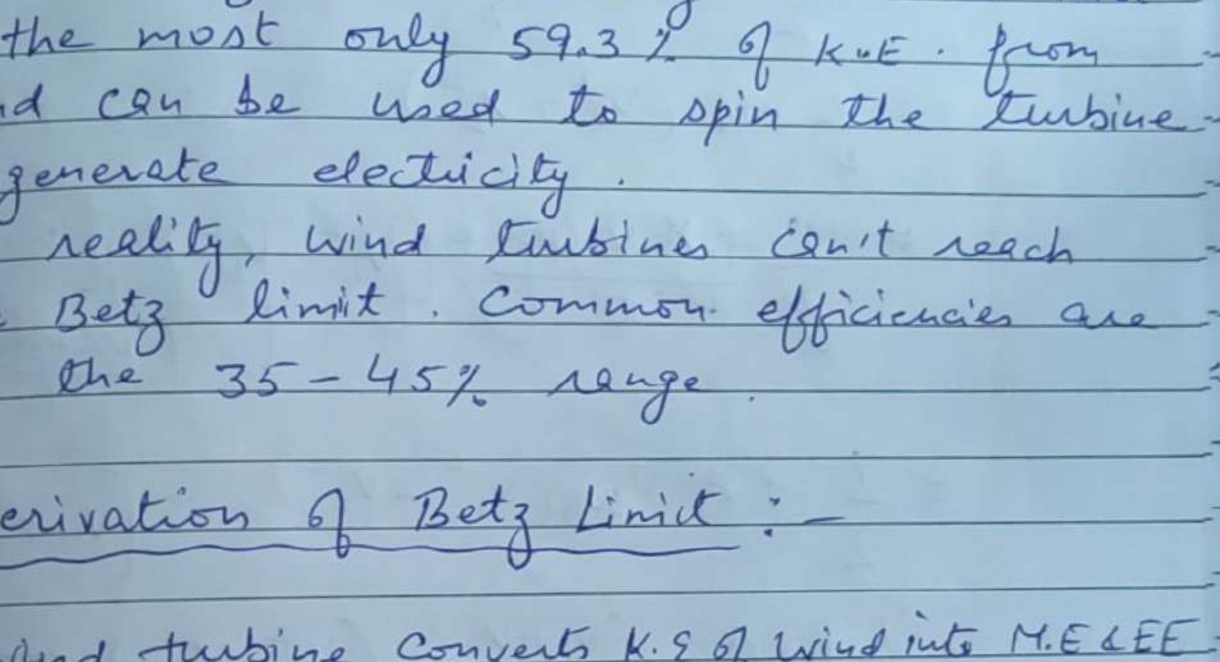
# Betz Limit

Betz limit is the theoretical maximum efficiency of a wind turbine, which is about 59.3%. It is also known as Betz's law.

- Betz's limit was given by German Physicist Albert Betz in 1919. Betz concluded that at the most only 59.3% of K.E. from wind can be used to spin the turbine & generate electricity.
- In reality, wind turbines can't reach the Betz limit. Common efficiencies are in the 35-45% range.

## Derivation of Betz Limit :-

A wind turbine converts K.E of wind into M.E & EE




Let $V_1 \rightarrow$ Inlet velocity of wind

$V_2$ – velocity of wind at outlet $(V_1 > V_2)$

classmate
Date
Page

Let output power be $P_0$ (Mech Energy produced by wind turbine)

$P_0$ = Change in kinetic energy before striking & after striking blades of turbine

$= P_1 - P_2$

$= \frac{1}{2} \dot{m}_a V_1^2 - \frac{1}{2} \dot{m}_a V_2^2$

$= \frac{1}{2} \dot{m}_a (V_1^2 - V_2^2) \qquad (\dot{m}_a = \rho A V_{wb})$

$\cancel{= \frac{1}{2} \rho \times \frac{Volume}{t} (V_1^2 - V_2^2)} \quad \cancel{[m = \rho \times Volume]}$

$\cancel{\left[\frac{Volume}{t} = Discharge\right]}$

$= \frac{1}{2} \rho A V_{wb} (V_1^2 - V_2^2) \qquad \left[V_w = \frac{V_1 + V_2}{2}\right]$

$= \frac{1}{2} \rho \times A \times \left(\frac{V_1 + V_2}{2}\right)(V_1^2 - V_2^2) \quad — (1)$

$= \frac{1}{4} \rho \times A \times V_1^3 - V_1 V_2^2 + V_1^2 V_2 - V_2^3$

$= \frac{1}{4} \rho A \times V_1^3 - V_2^3 + V_1^2 V_2 - V_1 V_2^2$

$\frac{\partial P_0}{d V_2} = 0$ For maximum power output

$\Rightarrow \frac{\partial P_0}{\partial V_2} = -3V_2^2 + V_1^2 - 2V_1 V_2 = 0 \quad — (2)$

behavior during grid ...
experiences in the world. Hybrid and isolated ...

classmate

Date ____

Page ____

from eqn 2 :—

Either

$V_1 = V_2$

or $\boxed{V_2 = \frac{V_1}{3}}$ — 3

So eqn 3 gives the condition for maximum power that is final velocity $(V_2)$ is one third of initial velocity $(V_1)$.

] — Calculation of maximum power output $P_{max}$

Put condition $V_2 = V_1/3$ in eqn 1 :—

$$\Rightarrow P_{max} = \frac{1}{2}\rho A\left[\frac{V_1 + \left(\frac{V_1}{3}\right)}{2}\right]\left[V_1^2 - \left(\frac{V_1}{3}\right)^2\right]$$

$$= \frac{1}{4}\rho A\left(\frac{3V_1 + V_1}{3}\right)\left(\frac{9V_1^2 - V_1^2}{9}\right)$$

$$= \frac{1}{4\times 27}\times\rho\times A(4V_1)(8V_1^2)$$

$$\Rightarrow \boxed{P_{max} = \frac{8}{27}\rho\times A\times V_1^3} \quad — 4$$

— Calculation of max. efficiency $\eta_{max}$

Let $P_i$ = K.E in the wind p.u time

$$= \frac{1}{2} \frac{m_a}{t} \times V_1^2$$

$$= \frac{1}{2} \dot{m}_a \times V_1^2 = \frac{1}{2}(\rho A V_1) \times V_1^2$$

$$P_i = \frac{1}{2} \rho \times A \times V_1^3 \quad \text{—— (5)}$$

$$\eta_{max} = \frac{\text{Maximum Output Power}}{\text{Input Power}}$$

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

Put $P_{max}$ & $P_i$ from (4) & (5) :—

$$\Rightarrow \eta_{max} = \frac{\frac{8}{27} \times \rho \times A \times V_1^3}{\frac{1}{2} \rho \times A \times V_1^3}$$

$$= \frac{16}{27} = 0.59 = 59\%$$

Thus max efficiency is 59 % & this 59% is known as Betz Limit.

## Tip Speed Ratio (TSR)

The tip speed ratio of a wind turbine is defined as ratio of speed of blade at its tip to the speed of wind.

i.e $$\lambda = \frac{R\omega}{V_w} = \frac{2\pi N \cdot R}{V_w}$$

Where $\lambda$ → TSR
$R$ → Radius of swept area (m)
$N$ → Rotational speed in Rev. per second.
$V_w$ → Wind velocity (m/s)

- Rotors with high solidity ratio have low TSRs & vice versa. The value of TSR can be as high as 9.
- The value of TSR depends upon no. of blades in wind turbine rotor.
- The fewer the no. of blades, faster the wind turbine rotor needs to turn to extract maximum power from the wind.
- A 2-bladed rotor has an optimum TSR of around 6, 3-bladed rotor

around 5 & a four-bladed rotor around 3.

- Highly efficient aerofoil rotor blade design can increase these values by as much as 25 - 30 %, increasing the speed at which the rotor turns & therefore generating more power.
- A well designed typical 3-bladed rotor would have a TSR of around 6 to 7.
- If the TSR is too low & rotor blades are poorly designed, then wind turbine will tend to slow down or stall.
- If the TSR is too high, the turbine will spin very fast through turbulent air.
- Therefor power will not be optimally extracted from the wind & wind turbine will be highly stressed & there will be risk of structural failure.

Therefore TSR plays a very important role in wind turbines.

# Power regulation

- Power curve of a typical wind turbine is shown in Fig. 4.9. The turbine starts generating power as the wind speeds crosses its cut-in velocity of 3.5 m/s. The power increases with the wind speed upto the rated wind velocity of 15 m/s, at which it generates its rated power of 250 kW. Between the rated velocity and cut-out velocity (25 m/s), the system generates the same rated power of 250 kW, irrespective of the increase in wind velocity. At wind velocities higher than the cut-off limit, the turbine is not allowed to produce any power due to safety reasons.

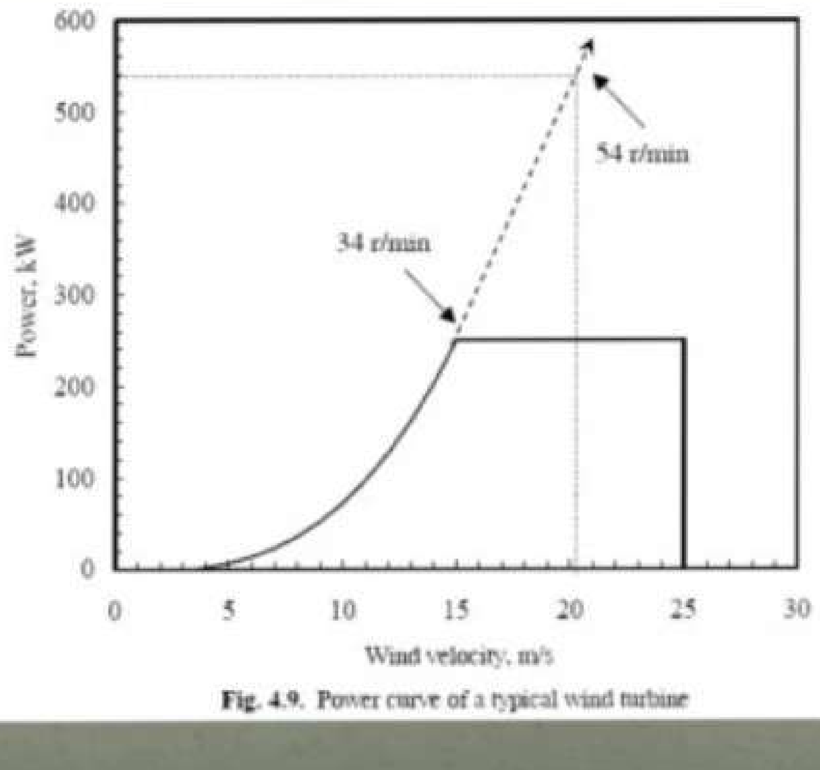



**Fig. 4.9.** Power curve of a typical wind turbine

- Power generated by the turbine is regulated to its rated level between the rated and cut-out wind speeds. If not regulated, the power would have been increased with wind speed as indicated by the dotted lines as in the figure. In the above example, we can see that the power corresponding to 20 m/s is more than twice the rated power of the system. However, if we want to harness the power at its full capacity even at this high velocity, the turbine has to be designed to accommodate higher levels of power. This means that, the system would require stronger transmission and bigger generator. On the other hand, probability for such high wind velocities is very low in most of the wind regimes. Hence, it is not logical to over design the system to accommodate the extra power available for a very short span of time.

## Aerodynamic Power Control: Passive Stall, Active Stall, and Pitch Control

- The aerodynamics of wind turbines are very similar to that of airplanes. The blade rotates in the wind because the air flowing along the surface that is not facing the wind moves faster than that on the surface against the wind. This creates a lift force to pull the blade to rotate.
- The angle of attack of the blade plays a critical role in determining the amount of force and torque generated by the turbine. Therefore, it is an effective means to control the amount of captured power.
- There are three aerodynamic methods to control the capture of power for large wind turbines: passive stall, active stall, and pitch control.

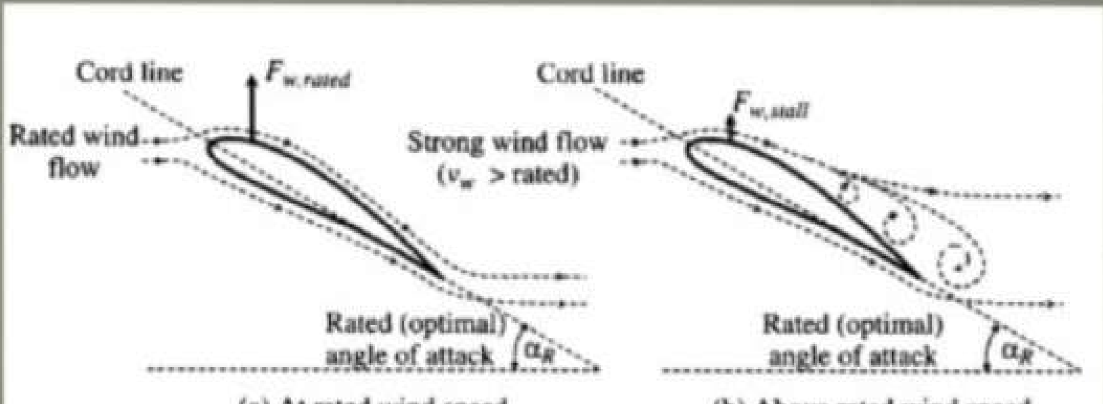


## Passive-Stall Control

- In passive-stall-controlled wind turbines, the blade is fixed onto the rotor hub at an optimal (rated) angle of attack. When the wind speed is below or at the rated value, the turbine blades with the rated angle of attack can capture the maximum possible power from the wind. With the wind speed exceeding the rated value, the strong wind can cause turbulence on the surface of the blade not facing the wind. As a result, the lifting force will be reduced and eventually disappear with the increase of the wind speed, slowing down the turbine rotational speed. This phenomenon is called stall. The stall phenomenon is undesirable for airplanes, but it provides an effective means to limit the power capture to prevent turbine damage.

# Passive-Stall Control

- The operating principle of the passive-stall control is illustrated in the next figure, where the lift force produced by higher than rated wind, which is the stall lifting force $F_{w\text{-}stall}$, is lower than the rated force $F_{w\text{-}rated}$.



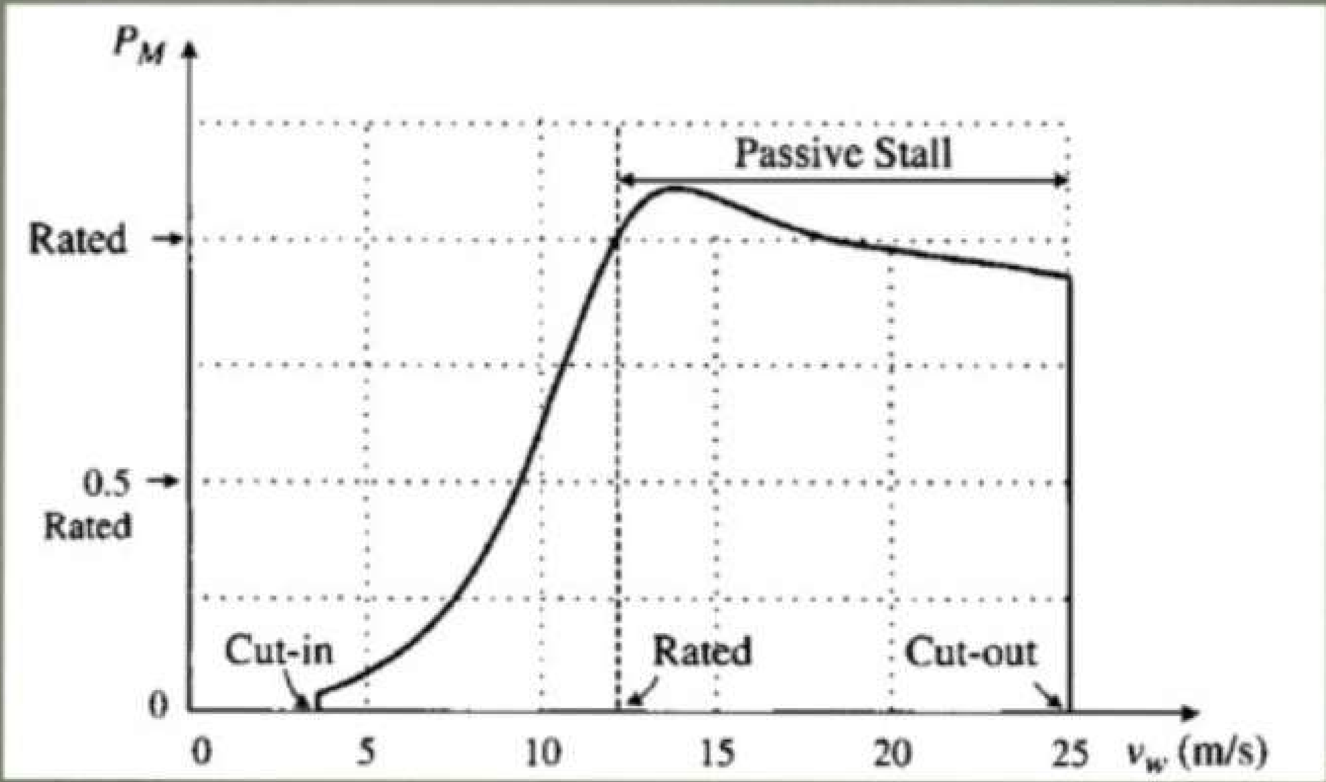

(a) At rated wind speed (b) Above rated wind speed



# Passive-Stall Control

- The blade profile is aerodynamically designed to ensure that stall occurs only when the wind speed exceeds the rated value.
- To ensure that the blade stall occurs gradually rather than abruptly, the blades for large wind turbines are usually twisted along the longitudinal axis by a couple of degrees.
- The passive-stall-controlled wind turbines do not need complex pitch mechanisms, but the blades require a complex aerodynamic design. The passive stall may not be able to keep the captured power $P_M$ at a constant value. It may exceed the rated power at some wind speeds, which is not a desirable feature.

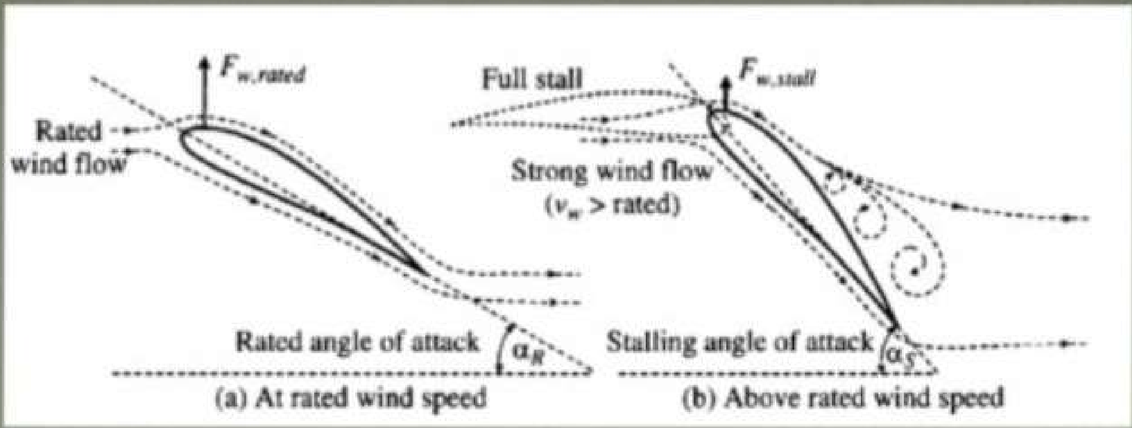
# Passive-Stall Control






# Active-Stall Control

- In active-stall turbines, the stall phenomenon can be induced not only by higher wind speeds, but also by increasing the angle of attack of the blade. Thus, active-stall wind turbines have adjustable blades with a pitch control mechanism. When the wind speed exceeds the rated value, the blades are controlled to turn more into the wind, leading to the reduction of captured power. The captured power can, therefore, be maintained at the rated value by adjusting the blade angle of attack.
- A qualitative example of the active-stall principle is illustrated in the next figure.

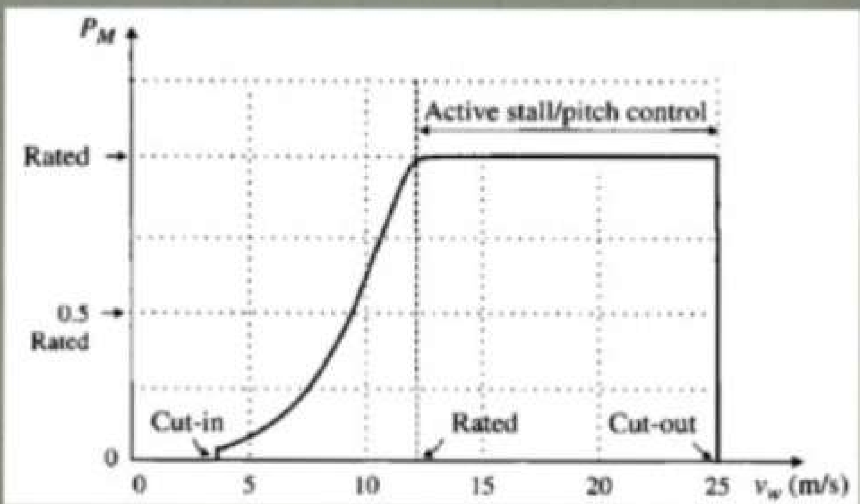



- When the blade is turned completely into the wind, as shown in the dashed blade, the blade loses all interaction with the wind and causes the rotor to stop. This operating condition can be used above the cut-out wind speed to stop the turbine and protect it from damage.



# Active-Stall Control

- With active-stall control, it is possible to maintain the rated power above the rated wind speed, as can be appreciated in the next figure. Active-stall controlled large megawatt wind turbines are commercially available.

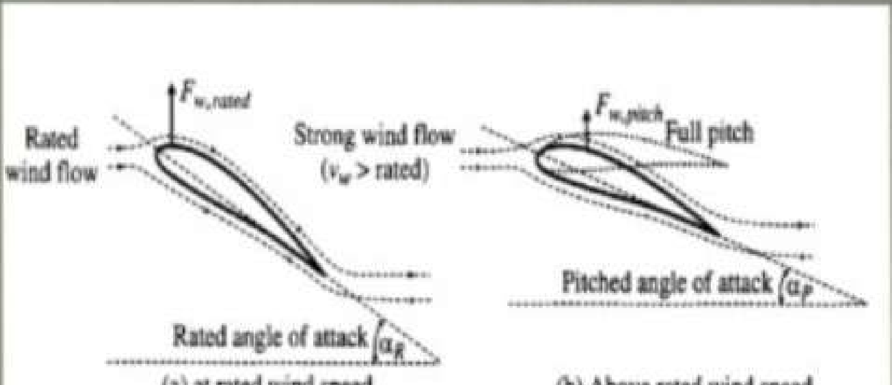


# Pitch Control

- Similar to the active-stall control, pitch-controlled wind turbines have adjustable blades on the rotor hub. When the wind speed exceeds the rated value, the pitch controller will reduce the angle of attack, turning the blades (pitching) gradually out of the wind. The pressure difference in front and on the back of the blade is reduced, leading to a reduction in the lifting force on the blade. The operating principle of the pitch control is illustrated in the next figure. When the wind is below or at the rated speed, the blade angle of attack is kept at its rated (optimal) value $\alpha_R$. With higher than the rated wind, the angle of attack of the blade is reduced, causing a reduction in lift force, $F_{w\text{-}pitch}$.



# Pitch Control




(a) at rated wind speed (b) Above rated wind speed

When the blade is fully pitched, the blade angle of attack is aligned with the wind, as shown by the dashed blade in the figure, and no lift force will be produced. The turbine will stop rotating and then be locked by the mechanical brake for protection.

# Active-Stall Control versus Pitch Control

- Both pitch and active-stall controls are based on rotating actions on the blade, but the pitch control turns the blade out of the wind, leading to a reduction in lift force, whereas the active-stall control turns the blades into the wind, causing turbulences that reduce the lift force.

classmate
Date
Page

# Wind Physics

Wind physics is the study of behaviour of air in motion, including forces that drive wind.

Types of Winds :-

- Local winds :- Uneven heating & cooling of ground surfaces & water bodies in day & night
- Planetary winds :- Caused by rotation of earth about its axis & temperature difference at equator & polar region. Warm air moves from tropical region to polar & cold air moves from pole to tropical region

Working Principle :-

If $V_w \rightarrow$ Wind velocity
$A_b \rightarrow$ Blade area
$\dot{m}_a \rightarrow$ Mass flow rate of air
$\rho_a \rightarrow$ Density of air

Then Kinetic energy $K.E = \frac{1}{2} m_a \times V_w^2$

& $\frac{d(K.E)}{dt} =$ Power $= \frac{1}{2} \frac{m_a}{t} . V_w^2$

$(Power)_{avail} = \frac{1}{2} \dot{m}_a \times V_w^2 =$ Available Power

$$\dot{m}_a = \rho_a \times A_b \times V_w$$

$$\Rightarrow \boxed{(\text{Power})_{\text{available}} = \frac{1}{2} \rho_a A_b \times V_w^3} \quad (1)$$

Equation (1) gives the power available in wind. But Maximum shaft Power is 59.3% of available power of wind.

Applications of Wind Physics :-

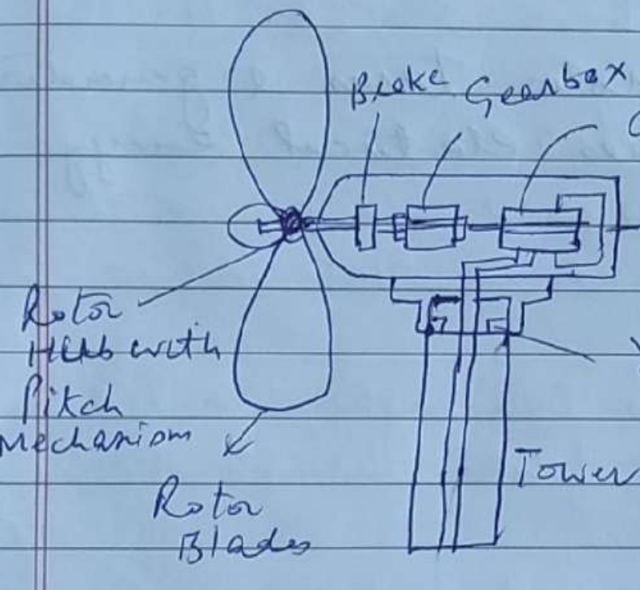
- Weather Forecasting :- Understanding wind patterns help predicting weather conditions.
- Wind Energy :- Harnessing the K.E. of wind to generate electricity using wind turbines
- Climate studies :- Wind patterns play a important role in global climate distribution.

classmate
Date
Page

## Wind energy Conversion system (WECS)

A system that converts wind's K.E to electrical energy. It is made up of several interconnected components like Wind turbines & generators.

### Construction & Working :-




⟸ Fig 1

Fig. 1 shows the construction of wind energy conversion system. Figure shows various components like Wind turbine, Generator, gearbox, brake, yaw control mechanism, pitch control mechanism, electric controls & Tower etc.

The Core of the WECS is wind turbine

plications, Narosa Publications 200[illegible]

Where K.E of Wind is converted into ~~Electrical~~ Mechanical energy.

Working :-

- Wind blows over turbine blades, causing them to turn.
- The blades are connected to a rotor that spins.
- The spinning rotor turns a generator which produces electrical energy.