**CATs**

COHERENT APPLICATION
THREADS

Mechanical
Engineering

BOSTON UNIVERSITY

# WIND TURBINES

## Introduction

Wind turbines are systems that harness the kinetic energy of the wind for useful power.  Wind flows over the rotor of a wind turbine, causing it to rotate on a shaft.  The resulting shaft power can be used for mechanical work, like pumping water, or to turn a generator to produce electrical power.

Wind turbines span a wide range of sizes, from small rooftop turbines generating less than 100 kilowatts up to large commercial wind turbines in the megawatt power range, many of which operate in large clusters called wind farms (like the one in the picture above).

This introductory module  will cover several basic concepts, and will serve as a foundation for future examination of the detailed engineering aspects of wind power.  Text highlighted in green indicate **Looking Forward** markers that show concepts that will be covered in courses later in the ME curriculum.  Mouse over the text for more details.

## Some basic facts

- Total worldwide installed capacity of wind turbines in 2008:  121 gigawatts (1 giggawatt = 1 billion Watts).  This represents about 1% of total power generation from all sources.
- Country with highest wind energy use:  US with 29 gigawatts (or 2.9% of US total).  This can power nearly 800,000 households and replace close to 30 million barrels of oil per year.
- States  with largest wind turbine generating capacity:   Texas (8.4 gigawatts), Iowa (3.0 gigawatts), and California (2.8 gigawatts) account for almost one half of the US total wind capacity.  See map for all states.
- Monetary worth of wind turbine market: $47.5 billion worldwide and $7.9 billion in the US.
- World's largest wind turbine:  Enercon E-126 generates 6 MW (1 MW= 1 million watts), with a rotor diameter of over 400 ft.
- World's largest windfarm:  Horse Hollow Energy Center, spread over 47,000 acres in Nolan and Tayler counties in Texas , has 421 wind turbines generating 735 MW of electricity.

## Links

An Illustrated History of Wind Power.  From ancient times to modern wind farms with plenty of pictures.
Guided Tour on Wind Energy.  A thorough discussion of the concepts and issues associated with wind power and wind turbines by the Danish Wind Industry Association.
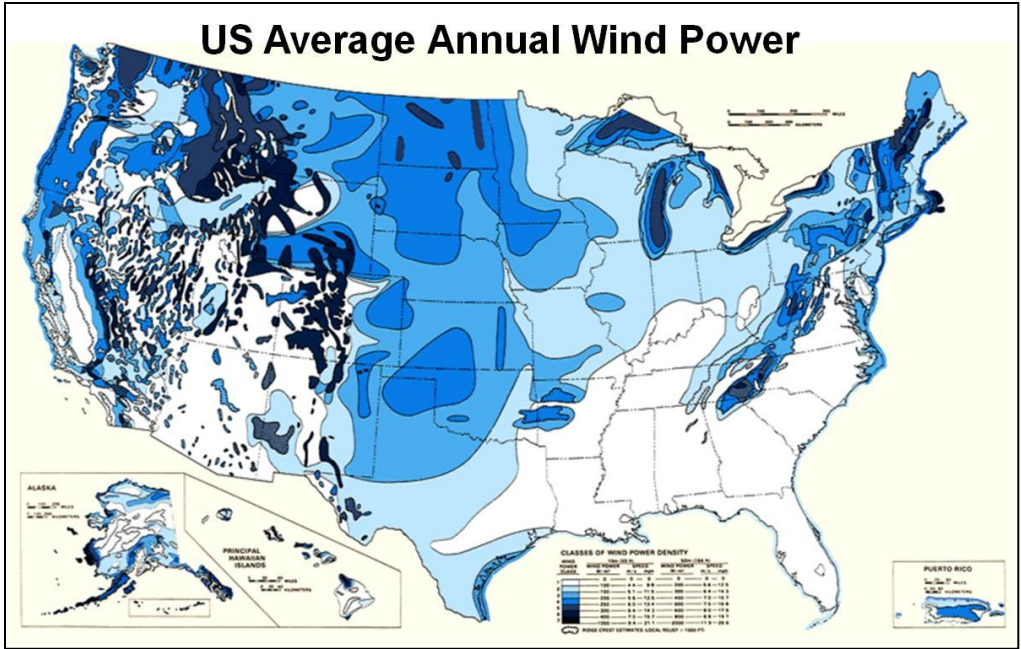American Wind Energy Association.  A very extensive site from the industry group that promotes wind energy.
Alternative Energy News.  Basic concepts, as well as the latest developments.
Department of Energy (DOE).  Basic concepts and descriptions of DOE funded initiatives.
Vestas Wind Turbines.  This Danish company is the  largest wind turbine manufacturer in the world, with 39,000 turbines installed representing 20% market share.
GE Wind Turbines.  The second largest wind turbine manufacturer with 18% market share.

**CATs**

**C**OHERENT **A**PPLICATION **T**HREAD**S**

Mechanical
Engineering

**BOSTON
UNIVERSITY**

## US Average Annual Wind Power



# WIND TURBINES

## Introduction

## Wind as an Energy Resource

### How much power is in the wind?

The power available in the wind, **P**, can be found from the following equation:

$$P = \tfrac{1}{2}A\rho V^3$$

where $\rho$ is the density of the air, **A** is the capture area, and **V** is the wind speed.

Wind speed increases with height above the ground, because of the earth's boundary layer. This effect is modeled using a power law relation

$$V_z = V_{10}(z/10)^\alpha$$

where $V_z$ is the wind speed at some height **z** (in meters), $V_{10}$ is the wind speed at 10 meters (the height often used for meteorological reporting of wind speed), and $\alpha$ is the power law exponent or index. $\alpha$ varies over a wide range, 0.1 to 0.6 depending on atmospheric conditions and the terrain near the wind turbine, but a value of 0.2 is common for wind turbine analysis.

For the example shown in Figure 2, the wind speed at 10 meter height is 15 m/s wind speed. At 20 meter height, the wind speed is 17.2 m/s and there is 0.94 MW of power available in the wind, for a 300 $m^2$ capture area. (1 MW= 1 million Watts). At 60 meters, the wind speed is about 25 % higher, but the power is almost doubled at 1.8 MW.

Not all of this power can be captured by a wind turbine, due to physical limits (e.g., Betz limit) as well as inefficiencies in the rotor, generator and gearboxes (See Wind Turbine Performance ).
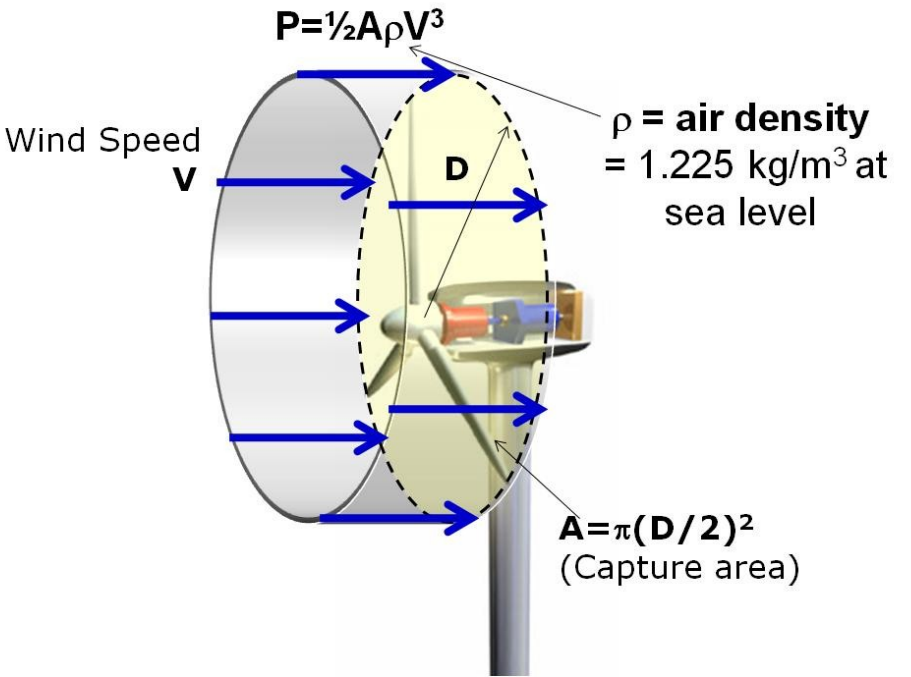
### Figure 1: Power Available from the Wind



### Figure 2: Wind Speed, Power & Height
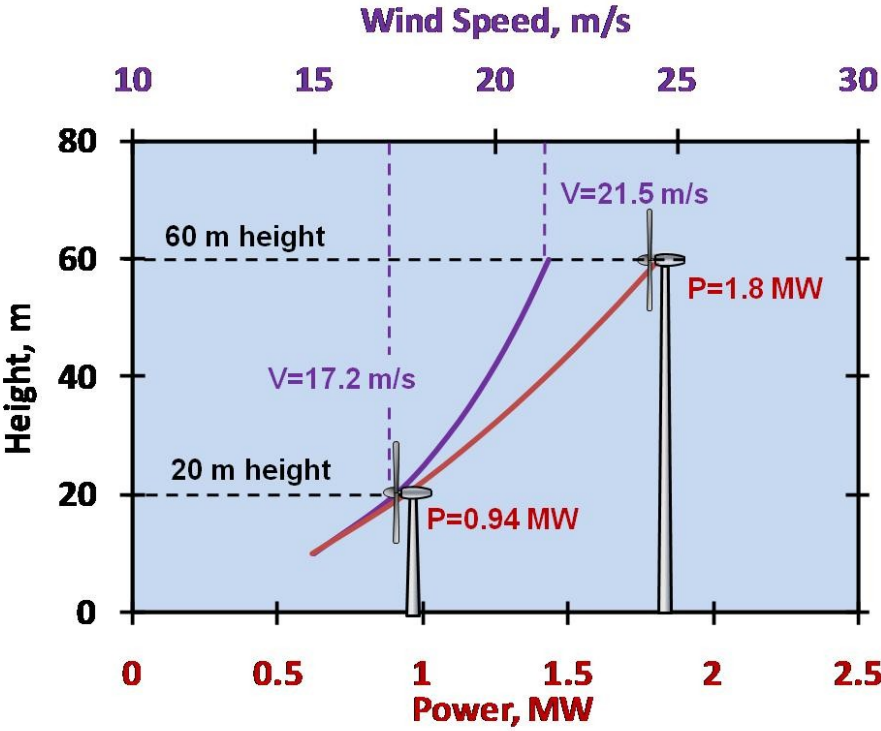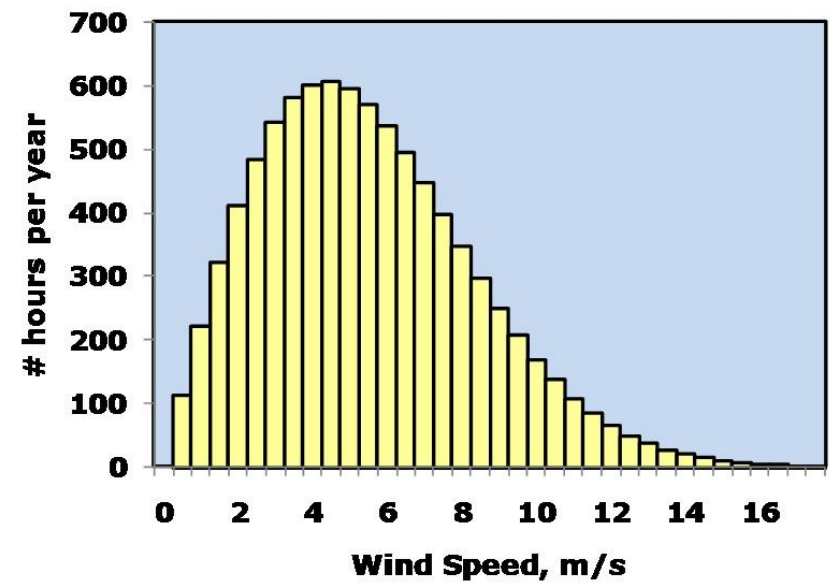### (300 m² capture area)
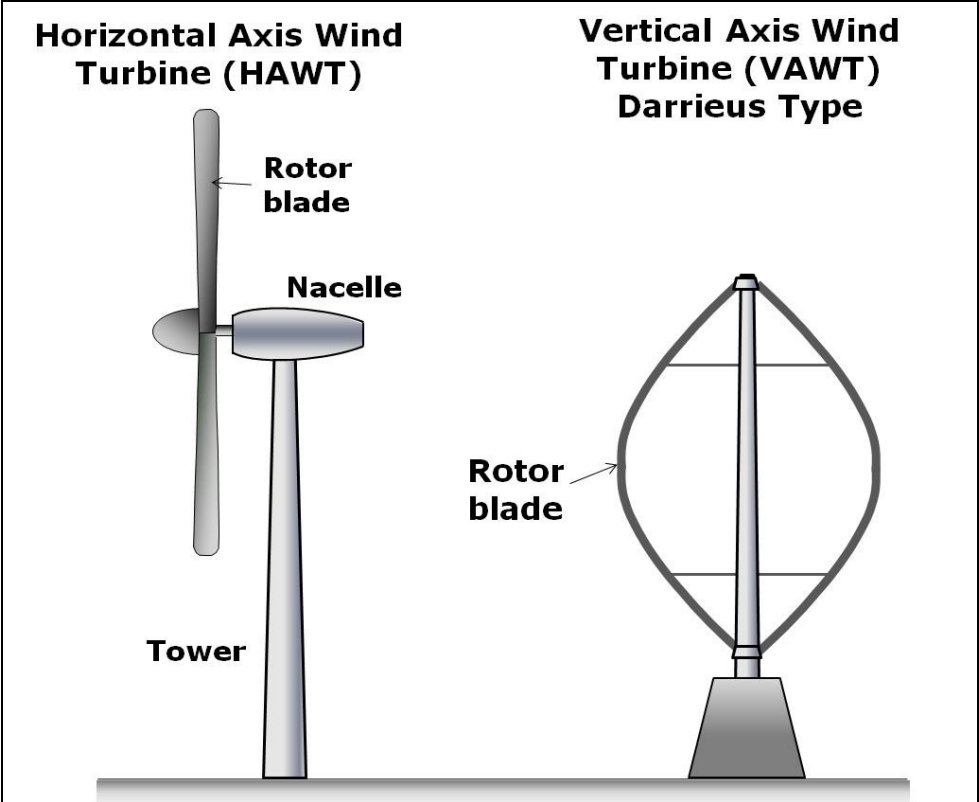


### Figure 3  Annual Wind Speed Distribution



This plot shows the expected number of hours per year that the wind speed will be at a certain value (+/- 0.25 m/s), for a site with a mean annual wind speed of 5.5 m/s (Boston area). For example, the winds speed will be between 3.75 m/s and 4.25 m/s for 600 hours per year. The data is based on a Weibull distribution.

### Wild is the Wind

Variability is a major problem associated with wind power. If the wind is too weak, very little power is generated. But, if its too strong, the large forces exerted may cause structural damage, so many turbines shut down in high winds. The variations in wind speed are often modeled statistically using a Weibull curve (see Figure 3). In essence, for a given annual average wind speed, the **Weibull curve** provides an estimate of how many hours per year the wind will be within a range of values.

In addition to day-to-day variability, winds are rarely steady. Instead, they are almost always gusting. This turbulence leads to two problems: (1) the electrical power output of the generator will constantly vary, requiring proper conditioning; and (2) the continually changing forces on the blades results in fatigue loading that is the main factor in how long a blade can be run before needing replacement.

**Horizontal Axis Wind Turbine (HAWT)**

Rotor blade

Nacelle

Tower

**Vertical Axis Wind Turbine (VAWT) Darrieus Type**

Rotor blade

# WIND TURBINES

## Introduction

### Types of Wind Turbines

Although there are many different wind turbine designs, they are broadly grouped in two categories based on the orientation of the axis of rotation:  Horizontal Axis Wind Turbines, or HAWTS, the most common type of wind turbine, and Vertical Axis Wind Turbines, or VAWTS.

## HAWTS

Modern HAWTs usually feature rotors that resemble aircraft propellers, which operate on similar aerodynamic principles, i.e., the air flow over the airfoil shaped blades creates a lifting force that turns the rotor. The nacelle of a HAWT houses a gearbox and generator.  HAWTS can be placed on towers to take advantage of higher winds farther from the ground.

The capture area of a HAWT, the area over which the sweeping blades can  "capture" the wind, is given by

$$A=\pi(D/2)^2$$

where **D** is the rotor diameter.  However, this capture area must face directly into the wind, to maximize power generation, so HAWTS require a means for alignment (yawing mechanism) so that the entire nacelle can rotate into the wind. On smaller wind turbines (like the Lokata shown in Figure 1), a tail vane provides a "passive" yaw control.  In large, grid-connected turbines, yaw control is active, with wind direction sensors and motors that rotate the nacelle.

### Figure 1: Horizontal Axis Wind Turbines (HAWT)

3 bladed wind turbine by Vestas, a Danish company that makes large wind turbines, from 0.85 MW to 3 MW.

Lokota, a small 900 W wind turbine made by Aeromag, a Chinese company.

## Vertical Axis Wind Turbine (VAWT)

**Darrieus** wind turbine with classic tropsokein or egg-beater shaped rotor. This one features a 30 meter high rotor.

The 5 bladed **H-type or Gyromill** wind turbine is a variation of the Darrieus-type wind turbine.

A **Savonius** wind turbine mounted on a roof in Finland.

## VAWTS

There are two main types of VAWTs,  the Savnoius and the Darrieus.  The Savnoius operates like a water wheel using drag forces, while the Darrieus uses blades similar to those used on HAWTS.   VAWTs typically operate closer to the ground, which has the advantage of allowing placement of heavy equipment, like the generator and gearbox, near ground level rather than in the nacelle.  However, winds are lower near ground level, so for the same wind and capture area, less power will be produced.

Another advantage of a VAWT over the HAWT is that it doesn't require a yaw mechanism, since it can harness wind from any direction.   This advantage is outweighed by many other disadvantages, including:  time varying power output due to variation of power during a single rotation of the blade, the need for guy wires to support the tower and the fact that Darrieus VAWTS are not self starting like HAWTS.

## Flow Field Around Airfoil with Pressure Field (colors) and Aerodynamic Forces



| Low pressure | -1.5 -1.0 -0.5 0.0 0.5 1.0 | High pressure |

# WIND TURBINES

## Introduction

### Lift and Drag

Airflow over any surface creates two types of **aerodynamic forces**— drag forces, in the direction of the airflow, and lift forces, perpendicular to the airflow.  Either or both of these can be used to generate the forces needed to rotate  the blades of a wind turbine.  Click here for a simple way to demonstrate lift and drag using a piece of paper.

### Drag-based wind turbine

In drag-based wind turbines, the force of the wind pushes against a surface, like an open sail.  In fact, the earliest wind turbines, dating back to ancient Persia, used this approach.  The Savonius rotor is a simple drag-based windmill that you can make at home (Figure 1).  It works because the drag of the open, or concave, face of the cylinder is greater than the drag on the closed or convex section.

## Figure 1: Drag-based Wind Turbine Concept
(Savonius Rotor)
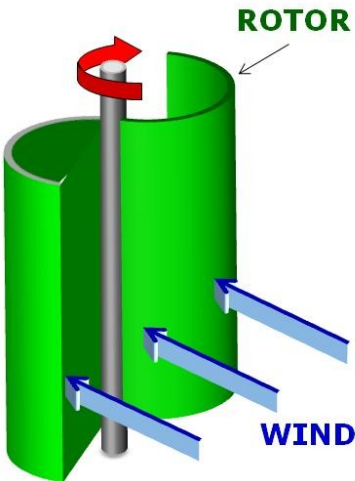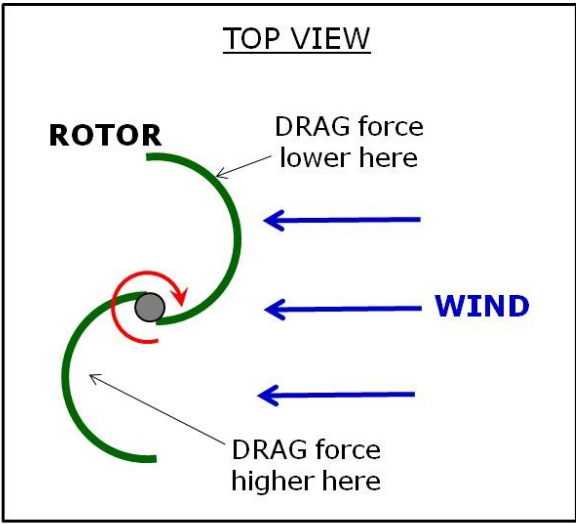


Rotation created by difference in DRAG forces on the convex and concave surfaces of the rotot

## Figure 2: Lift-based Wind Turbine Concept



Differential pressure caused by flow over airfoil shaped body leads to net LIFT force
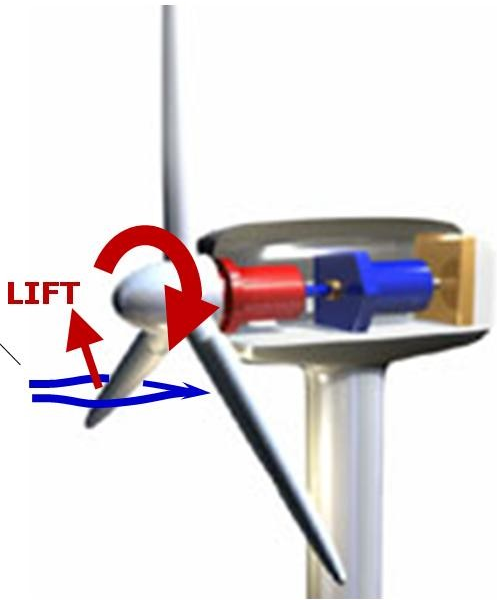
### Lift-based Wind Turbines

More energy can be extracted from wind using lift rather than drag, but this requires specially shaped airfoil surfaces, like those used on airplane wings (Figure 2).   The airfoil shape is designed to create a differential pressure between the upper and lower surfaces, leading to a net force in the direction perpendicular to the wind direction.  Rotors of this type must be carefully oriented (the orientation is referred to as the rotor pitch), to maintain their ability to harness the power of the wind as wind speed changes.

**CATs**

**C**OHERENT **A**PPLICATION **T**HREADS

Mechanical
Engineering

**BOSTON
UNIVERSITY**

## Components of a Horizontal Axis Wind Turbine



# WIND TURBINES

## 1. Introduction

### Wind Turbine Components



The picture above shows the various components of a Horizontal Axis Wind Turbine (HAWT).  The three most important parts are the rotor, the gear box, and the generator.

### Rotor– HAWTS

In order to produce lift, an airfoil shape must be oriented so that its rounded leading edge is facing approximately into the airflow direction.  But, the airflow direction for a wind turbine is actually a **vector sum of the wind itself and the relative wind** caused by the rotation of the blade through the air. (If you flap your arms up and down, you can feel the relative wind on your hands).   This effect is described using the tip-speed-ratio (TSR):

**TSR=$\Omega$R/V**

where $\Omega$ is the angular velocity of the rotor, **R** is the distance between the axis of rotation and the tip of the blade, and **V** is the wind speed.

Since the speed of a rotating blade varies from the center to the tip, the angle with which the airflow encounters the airfoil varies along the blade (see Figure 1).  To account for this, the rotor blades must be twisted.

For any tip speed ratio, an optimum blade twist can be found that maximizes the power generated.  But, as the wind speed changes, the twist is no longer optimum.   There are several ways to deal with this, including variable pitch operation (rotating the entire blade along its axis as the wind speed varies) or variable rotation speeds.

### Rotor– VAWTS

The unique egg-beater shape of a Darrieus VAWT is called a troposkein shape. Troposkein, Greek for turning rope, is the shape that a rotating rope would create. Since a rope can only support tension forces, a wind turbine with this shape will have only **tension forces** when in operation, and thus can be made lighter than a comparable rotor for a HAWT.  However, a true troposkein shape is hard to manufacture—one reason that new VAWT designs have concentrated on the H-type rotor configuration.

### Figure 1: Why Turbine Blades are Twisted

The blade experiences a relative wind velocity that is a vector sum of the **actual wind speed (V)** and the speed caused by the rotation of the rotor ($\Omega$r where $\Omega$ is the rotational speed and **r** is the distance from the rotation axis)



### Generator and Gear Box

The generator converts the power from the rotating rotor shaft to electrical power, which can be used on site, or be sent into the electrical grid (the system that interconnects power plants, electrical distribution networks, and electrical power users).  Generators are used in all electrical power plants, including coal and oil-fired plants.  A generator can be thought of as an electric motor run in reverse; in fact, many motors can also be used as generators.   Typical generators operate with a rotation speed of 1000 to 3600 revolutions per minute (rpm). These speeds are far too fast for a wind turbine for several reasons, including excessive stress and turbulence at high speeds and the fact the tip speed is limited by the speed of sound (340.3 m/s) due to both excessive drag and noise caused by shock wave formation.  The **gear box** solves the problem, by converting the low speed rotation of the wind turbine rotor (typically less than 100 rpm) to the high rpm needed by the generator.

**CATs**

**C**OHERENT **A**PPLICATION
**T**HREAD**S**

Mechanical
Engineering

**BOSTON**
**UNIVERSITY**

**Vestas V82 Wind Turbine**
**Used in Example**

Diameter: 82 m
Swept Area: 5,281 m$^2$
Tower Height: 78 m
Rated Power: 1.65 kW

# WIND TURBINES

## Introduction

## Performance

### Coefficient of Performance

Recall that the power available in the wind can be expressed as

$$P = \tfrac{1}{2}A\rho V^3$$

where $\rho$ is the density of the air, **A** is the capture area, and **V** is the wind speed.

The power actually captured by the wind turbine rotor, $P_R$, is some fraction of the available power, defined by the coefficient of performance, $C_p$, which is essentially a type of power conversion efficiency:

$$C_p = P_R/P$$

**Figure 1: Coefficient of Power vs Tip Speed Ratio for Different Wind Turbines**



The maximum theoretical value of the coefficient of performance is 0.593, a value determined by a fluid mechanics constraint known as the **Betz limit**. Actual coefficients of performance are less than this limit due to various aerodynamic and mechanical losses. For a given turbine design, $C_p$ is a function of tip speed ratio (**TSR**). As shown in the curves in Figure 1, there is a tip speed ratio for which the power capture is a maximum. Comparisons of the various wind turbine types in Figure 1 shows how inefficient the drag-based Savonius turbine is compared to the lift-based turbines. The Darrieus turbines and the HAWT have similar values of the maximum coefficient of performance, but the HAWT can operate at much higher tips speed ratios (faster rotation speeds or lower wind speeds).

### Power Curve

The electrical power output from the generator is less than the power captured by the rotor, due to losses in both the gear train and generator:

$$P_T = C_p \eta_g \eta_b (\tfrac{1}{2}A\rho V^3)$$

where $\eta_g$ and $\eta_b$ are efficiencies (power output over power input) for the generator and the gearbox. Gearbox efficiencies are typically 90-95%, while generator efficiencies range from 50% (for a car alternator) to better than 80% for a high quality, grid-connected model.

**Figure 2 Power Curve for Vestas V82**



The power curve for a wind turbine shows this net power output as a function of wind speed. As shown in Figure 2 (for an 82 m diameter wind turbine), these curves feature three key wind speeds:
1. <u>Cut in wind speed</u>: This is the wind speed at which the wind turbine will start generating power— typical cut-in wind speeds are 3 to 5 m/s.
2. <u>Nominal wind speed</u>: This is the lowest speed at which the wind turbine reaches its nominal power output. Above this speed, higher power outputs are possible, but the rotor is controlled to maintain a constant power to limit loads and stresses on the blades.
3. <u>Cut-out wind speed</u>: This is the highest wind speed which the turbine will operate at. Above this speed, the turbine is stopped to prevent damage to the blades.

### Annual Energy Generation and Capacity Factor

The power curve combined with the annual wind speed distribution can be used to estimate how much energy a wind turbine could generate in typical year. Specifically, the power at each wind speed is multiplied by the number of hours per year that the wind blows at that speed to estimate how much energy is generated at each wind speed (red curve in Figure 3). This is then summed to get the annual energy generated. For the Vestas V82 example shown, a 1.7 MW turbine operating in Boston, 3,800 MWh are generated each year. This is enough energy to power approximately 350 homes.

The capacity factor of a wind turbine is the total annual energy generated divided by the energy that could be generated if it were running continuously at rated capacity 24 hrs a day for 365 days a year. For the V82 example, the capacity factor is found from:

**3,800 MWh/(1.7 MW*8760 hr) = 25%**.

This value is on the low end of the typical range of 25 to 40%, mainly because Boston is not a as windy as the locations typically chosen for wind farms.
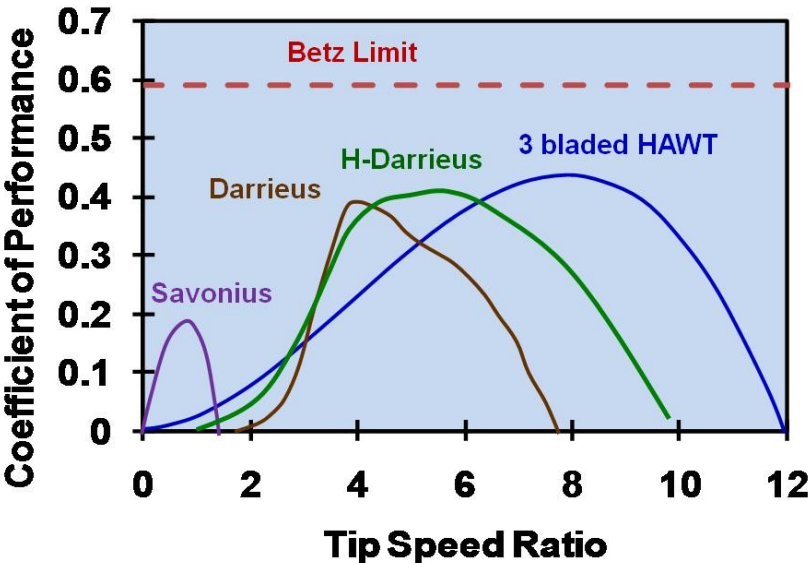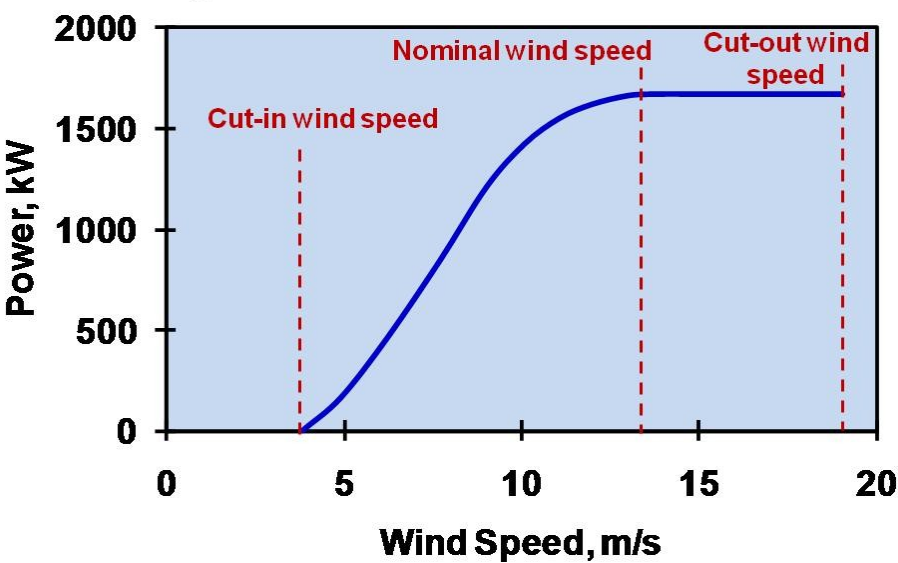
**Figure 3: Estimating Annual Energy Generated**



Total Annual Energy Generated = 3,800 MWh (MegaWatt Hours)

**CATs**

COHERENT APPLICATION
THREADS

Mechanical
Engineering

**BOSTON UNIVERSITY**
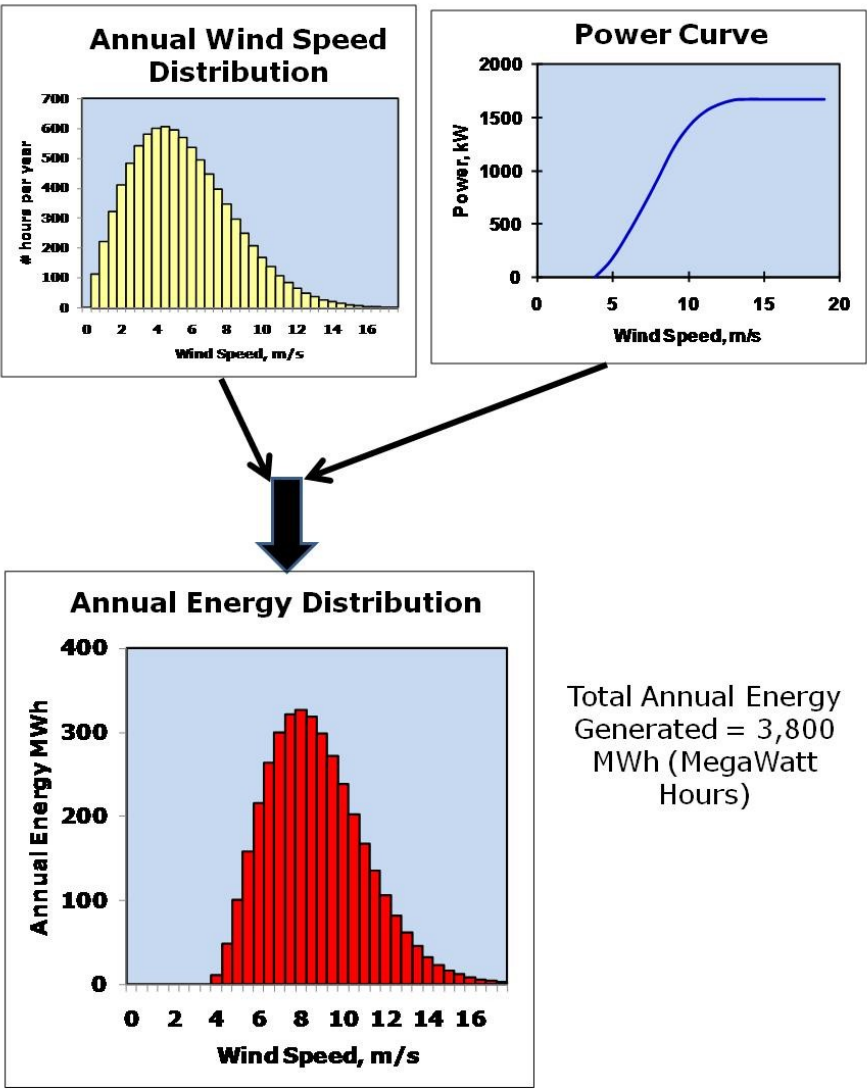
# WIND TURBINES

## Introduction

## Technical and Social issues

### Environmental/Social Issues

Wind energy is a renewable resource, emits no pollutants or green house gases during operation, and does not require fuel so there is no mining or drilling needed as is the case for coal, oil or natural gas power plants. Sounds like an environmentalists dream. Yet many of the social barriers to widespread wind power utilization are environmental, some of which invoke strong emotional opposition by residents near proposed wind farms.

- Visual impacts:  Medium and large wind turbines sit atop towers 100 ft high with rotors that can be hundreds of feet in diameter. Wind farms near residential areas have met strong opposition from local residents who argue that large clusters of large wind turbines are a blight on the landscape and ultimately decrease property values.
- Noise:  In general, the noise levels from large, modern wind turbines are relatively low, consisting primarily of a low pitch rhythmic "whooshing" sound. Most complaints from residents close to wind farms occur at night when there is little other ambient noise— during the day, other noises tend to dominate. (See this video comparing wind turbine noise to other typical ambient noise sources).  "Wind-farm syndrome" is a term used to describe a variety of health maladies caused by inaudible "infrasound," but the scientific backing for this is minimal.
- Wildlife:  The large, rotating blades of a rotor pose a hazard for birds, as evidenced by the increased mortality rates of large birds of prey near the Altamont Pass wind farm in California.  A Spanish study estimated that a single wind turbine kills, on average, 10 birds per year.  However, comparisons with other manmade hazards reveal that wind turbines represent a minor hazard.  small fraction of birds  with other manmade haxof the number of birds killed by wind turbines compared to other man0made hazards.
- Land Use:  Because wind power is not a concentrated form of energy (like oil or coal), it requires large amounts of land, typically 10 to 30 acres per turbine.  For example,  DOE estimated that 142,000 1.5 MW turbines would be required to generate 20% of the nations electricity needs; at 20 acres per turbine, almost 3 billion acres of land are needed.  However, most of the land associated with wind farms is "empty space," and could be available for other used, such as agriculture.

### Technical  Issues

Despite the maturity of modern wind technologies, two key technical issues must be addressed before it can find widespread use:

- Variability:  Unlike coal or oil power plants, wind turbines don't power continuously due to the variability of the wind.  During periods of low winds, the turbines may be idle, and as a result, there is continuing debate over whether wind power can really reduce the need for conventional power plants (often called "capacity credit").  In addition, the wind is rarely steady, leading to short-term variability and "noisy" power output.
- Grid connectivity:  The best wind resources tend to be far from the transmission lines needed to connect the wind turbines to the grid.  The variability of the power from wind also presents challenges for the current electrical grid system, which was designed for the relatively uniform and predictable power generated from conventional oil and coal power plants

CATs

COHERENT APPLICATION
THREADS

Mechanical
Engineering

BOSTON
UNIVERSITY

# Lift and Drag Force Demonstration

What you need:

1 piece of paper
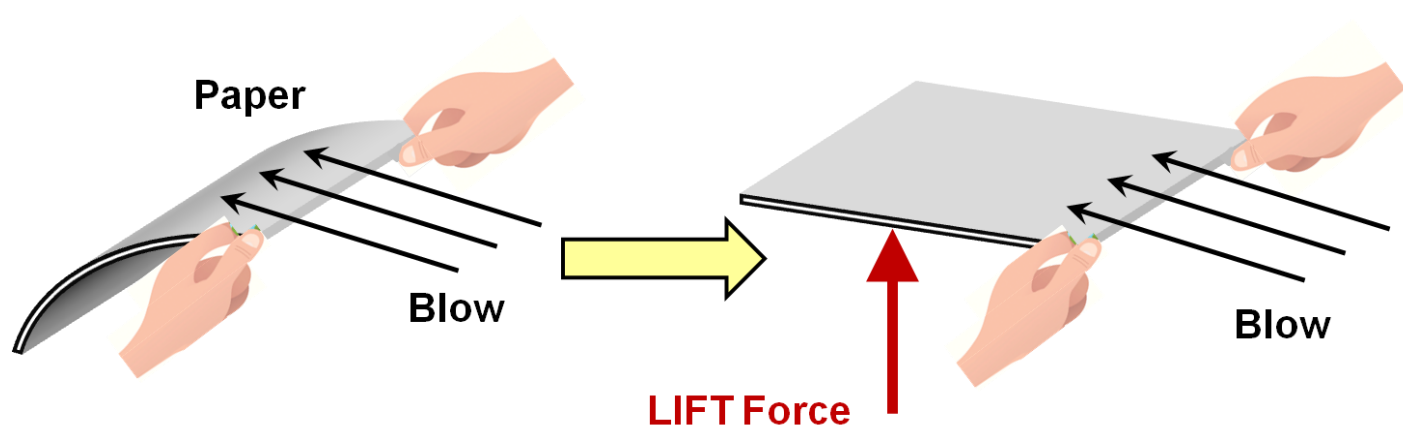A set of good lungs

## Drag Force

- Hold a piece of paper by the top edges, as shown in left side of the figure below.
- Blow directly at the paper.
- The bottom of the paper should flip up as shown.
- This is the type of force used on drag-based wind turbines like the Savonius rotor.

**Paper**  **Blow**  **Blow**  **DRAG Force**
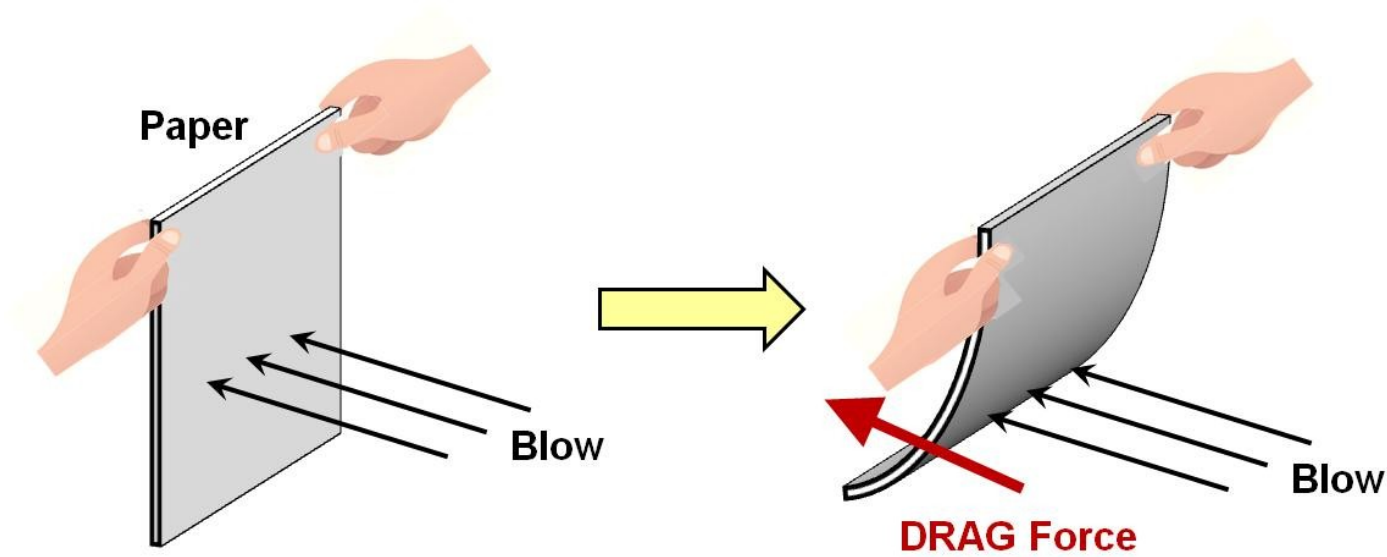
## Lift Force

- Hold a piece of paper by the edges, as shown in left side of the figure below.  The edge that you're holding should be parallel to the ground, while the unsupported edge should be hanging down.
- Blow directly above the edge of the paper that you're holding.
- The paper should lift.  The higher velocity on the top creates a reduced pressure (Bernoulli's effect).
- This is the type of force used on lift based wind turbines.

**Paper**  **Blow**  **Blow**  **LIFT Force**

HOME          RETURN