Wind 101

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Wind Turbines

- Horizontal Axis, HAWT (all large power turbines are this type)
  - Upwind
  - Downwind

- Vertical Axis, VAWT
  - Good for low wind and turbulent wind (near ground)
- Lift (more efficient that drag type)
- Drag

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

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  - Upwind
  - Downwind

Wind Direction

Wind Direction

World's Largest Turbines

- Enercon E-126
  - Rotor diameter of 126 m (413 ft)
  - Rated at 6 MW, but produces 7+ MW

- Clipper (off-shore)
  - Rotor diameter of 150 m (492 ft)
  - Hub Height is 328 ft
  - Rated at 7.5 MW

- Clipper 2.5 MW
  - Hub height 80 m (262 ft)
  - Rotor diameter 99 m (295 ft)
  - 4 PM generators in one nacelle

    - 3.28 ft/m

- Vestas 1.65 MW turbines at Ainsworth wind farm
  - Class 5 wind site (avg. wind speed is 19.5 mph)
  - 36 turbines in farm
  - Hub height is 230 feet
  - Rotor diameter is 269 feet
  - Project cost was about $1,355/kW

Small Wind Turbine

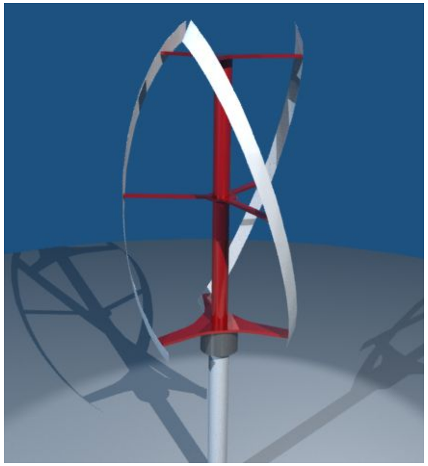
- Bergey Excel 10 kW
  - Hub height 18-43 m (59-140 ft)
  - Rotor diameter 7 m (23 ft)

- 2.4 kW Skystream Southwest Wind Power
  - Hub height is 45-60 ft.
  - Rotor diameter is 12 ft.
  - Installation cost is about $7 to $8.50 per Watt

VAWT

- 30 m Darrieus

- Helical Twist



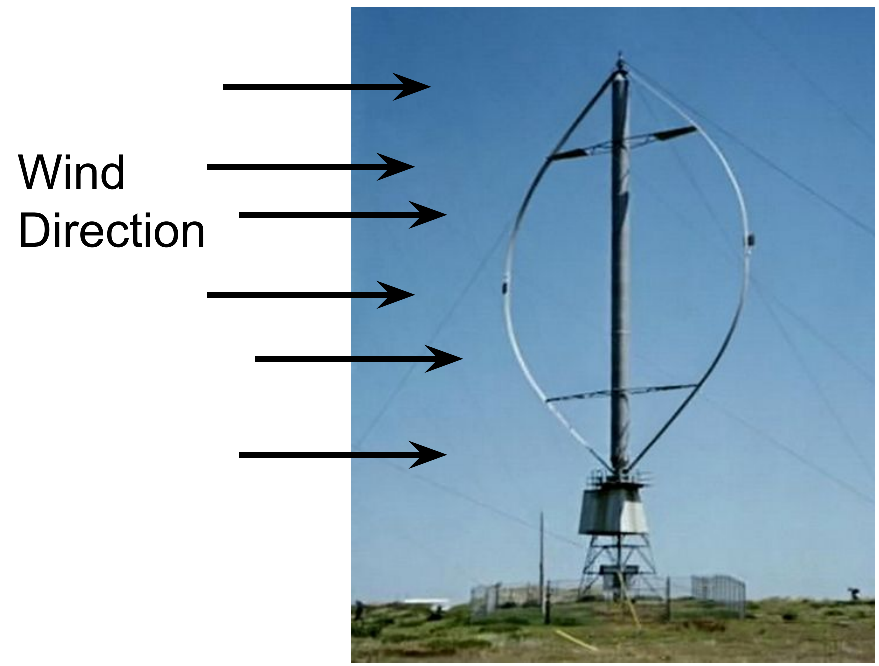
VAWT are designed to

operate near the ground where the wind power is lower

and

produce drag on the trailing blades as they rotate through the wind.

Turbine Types



- Vertical Axis, VAWT
  - Good for low wind and turbulent wind (near ground)

Vertical axis turbines

- PacWind Seahawk, 500 W
  Drag type

- PacWind Delta I, 2 kW
  - Lift type

- Darius turbine, few 10’s kW

Wind-Turbine Physics

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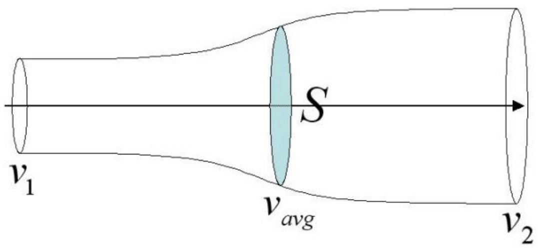
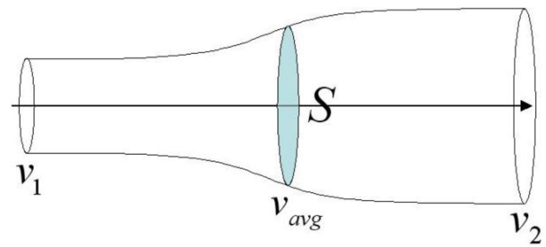
$(P_w = ½\, \rho A v^3)$



Wind-Turbine Physics

- Power available in the wind is proportional to the
  - Air Density, ρ
  - **Swept Area of the Rotor, *A***
  - ***Cube of the Air Velocity, (v x v x v)***

  $(P_w = \frac{1}{2} \rho A v^3)$



- **Betz Limit** – theoretical maximum power that can be extracted from the wind is 0.59 or 59%

Swept Area

- Swept area is the area that the blades of a wind turbine intersect with the wind. NOTE: Swept Area is NOT the surface area of the blades!
  - A HAWT with one or more blades has them moving in a circular motion so the swept area, *A*, is a circle with a radius, *R*, equal to the blade length, *L*, plus the rotor hub radius. Since the blades are typically much longer than the hub, the blade length is often used to estimate the swept area radius.
    - Therefore, the swept area for this type of blade arrangement is $A = \pi R^2 \approx \pi L^2$

Physics Continued

- **Tip Speed Ratio**, λ, is the ratio of the blade-tip speed (linear velocity) to wind speed.

  $\lambda = \Omega R/v$

  - Ω is the angular velocity of the rotor
  - R is the radius of the rotor
  - v is the wind velocity
- The **Power** Coefficient, C_p, is a **maximum** (approaches Betz Limit) when the **Tip Speed Ratio is in the range of 7.5 to 10.**

Ω is the angular velocity of the rotor tip in units of radians/second

Note: A 50 m blade moving at 15 rpm has its tip moving at about 175 mph!

Physics Continued

- In **Drag-type turbines**, Power transfer from the wind **maximizes at about 8.1 %**
  - ***Compare to the Betz Limit of 59% for Lift devices***

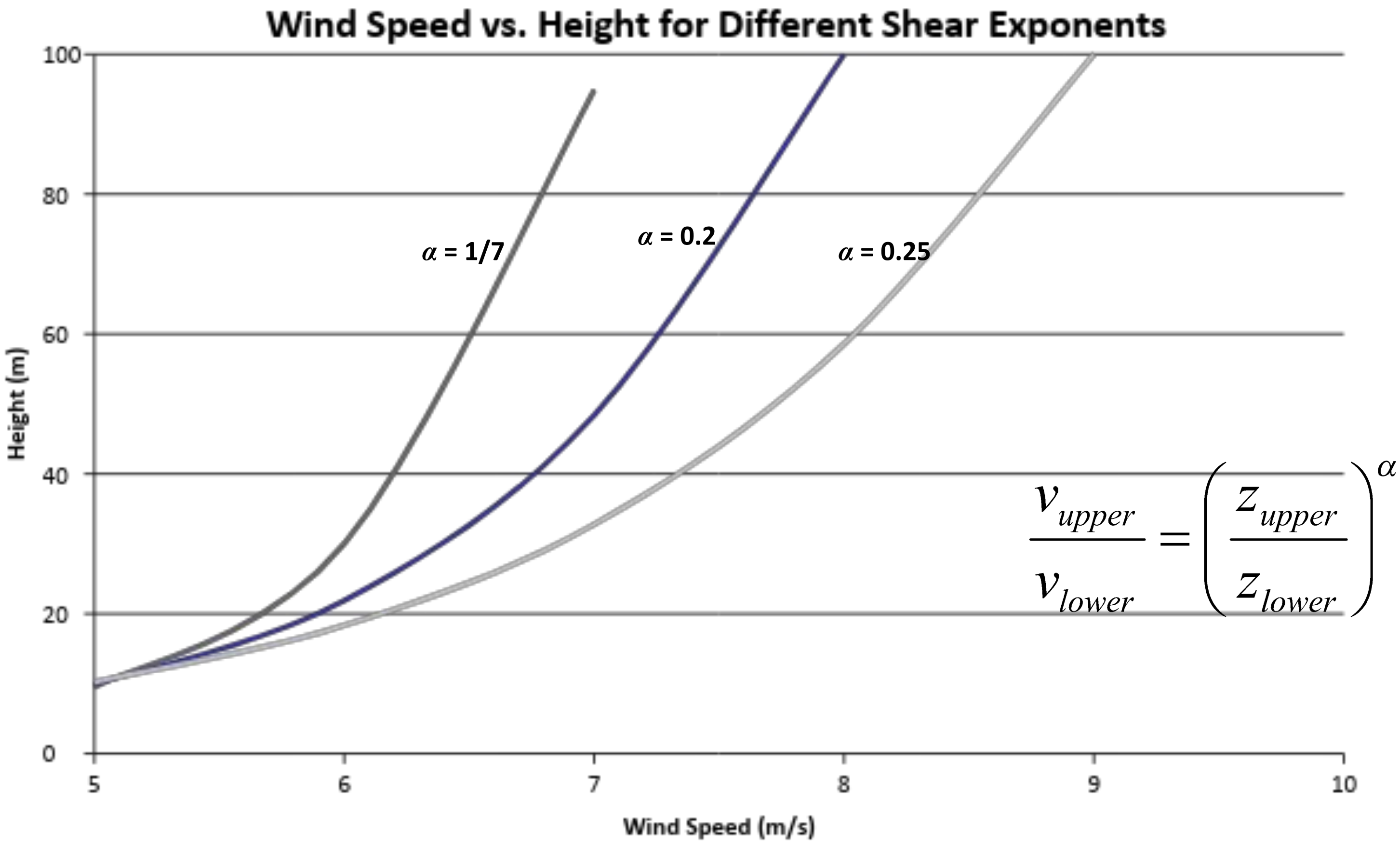
Wind and Height

- Generally, the wind velocity is on average a larger value as you move above the ground.
  - This should be intuitive as the ground interferes less with the wind so the air is undisturbed and free to flow better as we get higher.
  - Therefore, placing a turbine as high as possible above the ground will provide better performance on average.

Wind and Height

- The variation of wind velocity with respect to height is termed ***Shear***.
- Empirical* relationships for the wind shear are typically made using ratios of heights and associated velocities.

* Empirical means an equation based on measurements, not an equation derived from fundamental physics.



Annual average shear exponents can vary from 1/7 to 0.25, causing considerable uncertainty in vertical extrapolations of wind resource.

Wind Turbine Average Output Power

- One quick measure of turbine performance is to assume an ideal turbine where the power transferred from the wind is 0.591 (Betz Limit),
- an efficiency of $\eta = 1$,
- and a idealized distribution of wind speeds (Rayleigh) .

$$P_{Turbineavg} = \rho\ (2D/3)^2 (v_{avg})^3$$

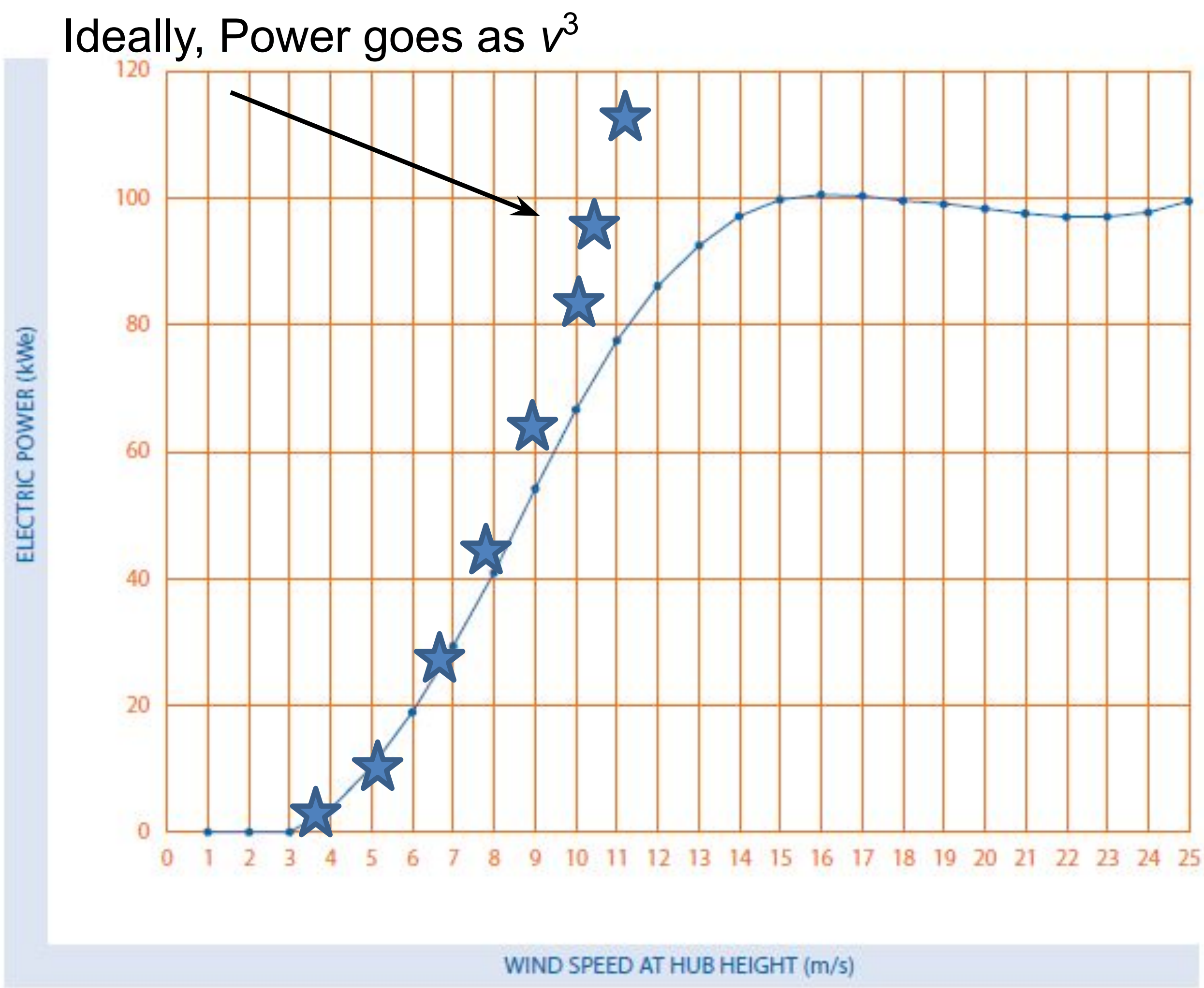
ρ is air density, D is rotor diameter, v_{avg} is average wind speed

POWER CURVE: 21-METER ROT0R

Standard Density (1.225 kg/m^3)

WIND SPEED (m/s)	POWER (kWe)
1	0
2	0
3	0
4	3.7
5	10.5
6	19.0
7	29.4
8	41.0
9	54.3
10	66.8
11	77.7
12	86.4
13	92.8
14	97.3
15	100.0
16	100.8
17	100.6
18	99.8
19	99.4
20	98.6
21	97.8
22	97.3
23	97.3
24	98.0
25	99.7

Why does the Power Curve Peak and then Lay Over?



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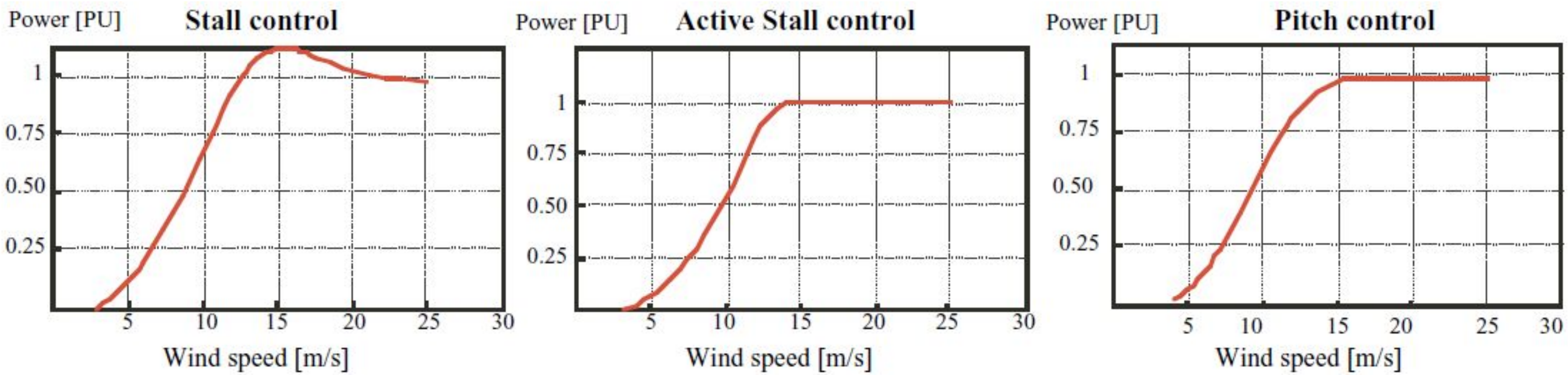
Must Control Power Coupled into Turbine or this Happens

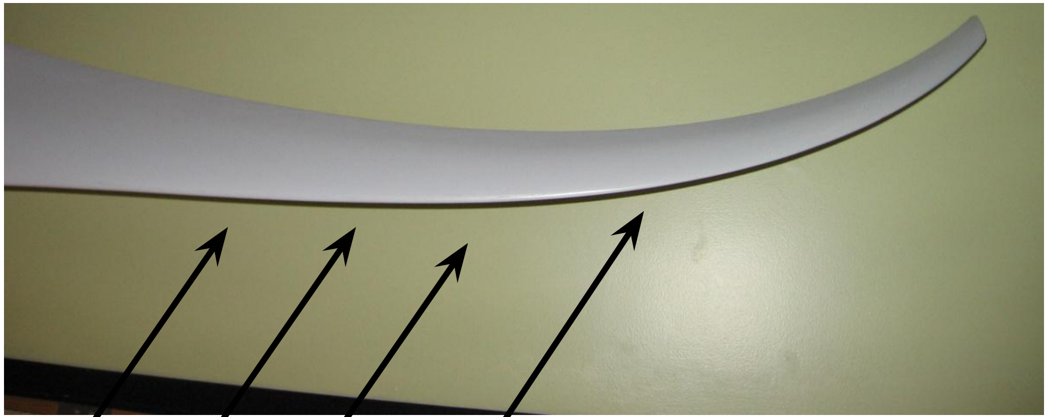
Blade positioning is actively or passively controlled to limit the power output from the turbine.

- Power curve can be made smooth by active control (active stall or pitch for large turbines)
- Passive Stall control has an overshoot depending on blade design (small turbines)



Pitch and Yaw

- Pitch refers to the relative angle of the turbine blades to the incoming wind direction.



Apparent Wind Direction

Yaw is the direction of rotation of the turbine nacelle and rotor assembly as it pivots around the tower to move into or out of the wind.

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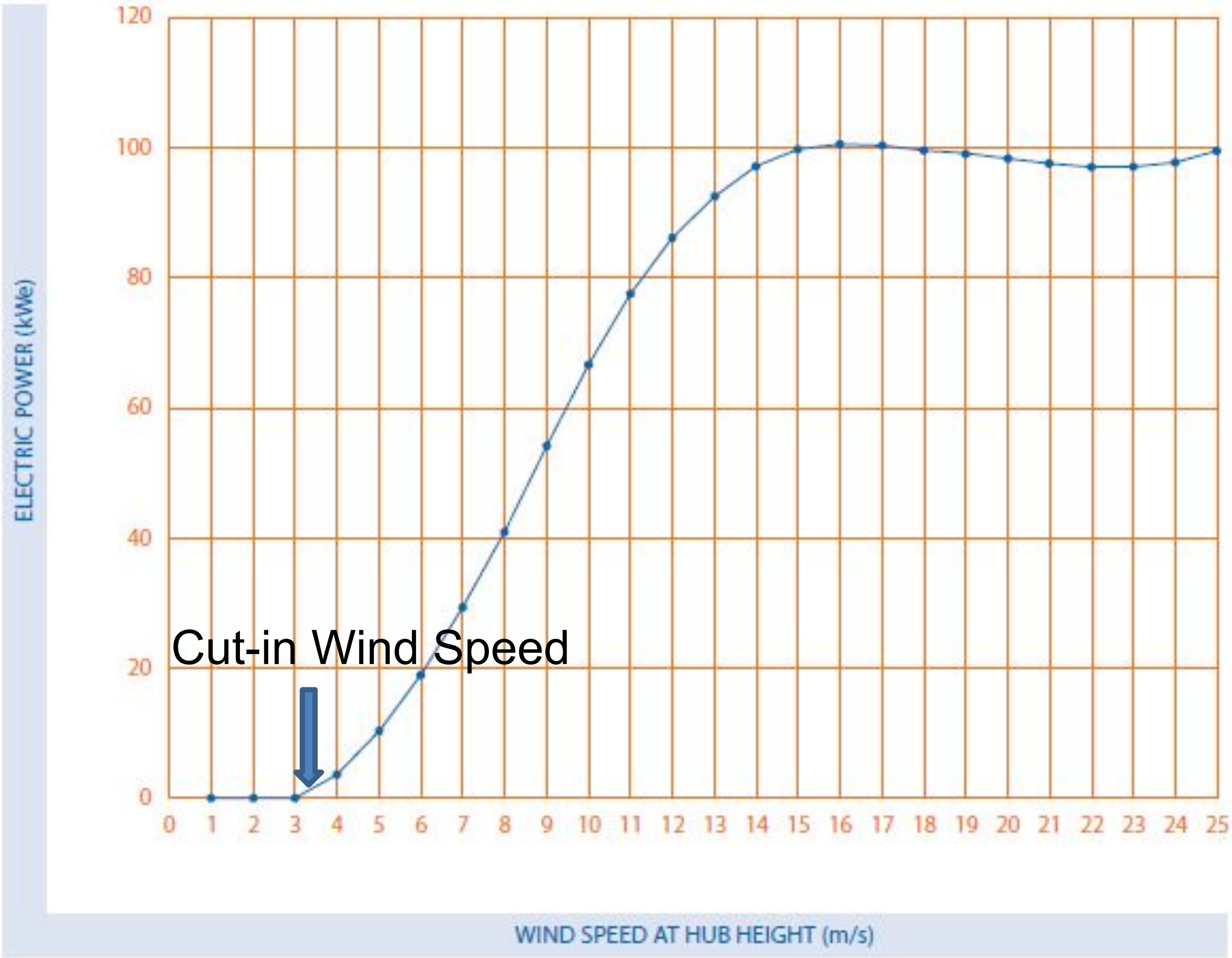

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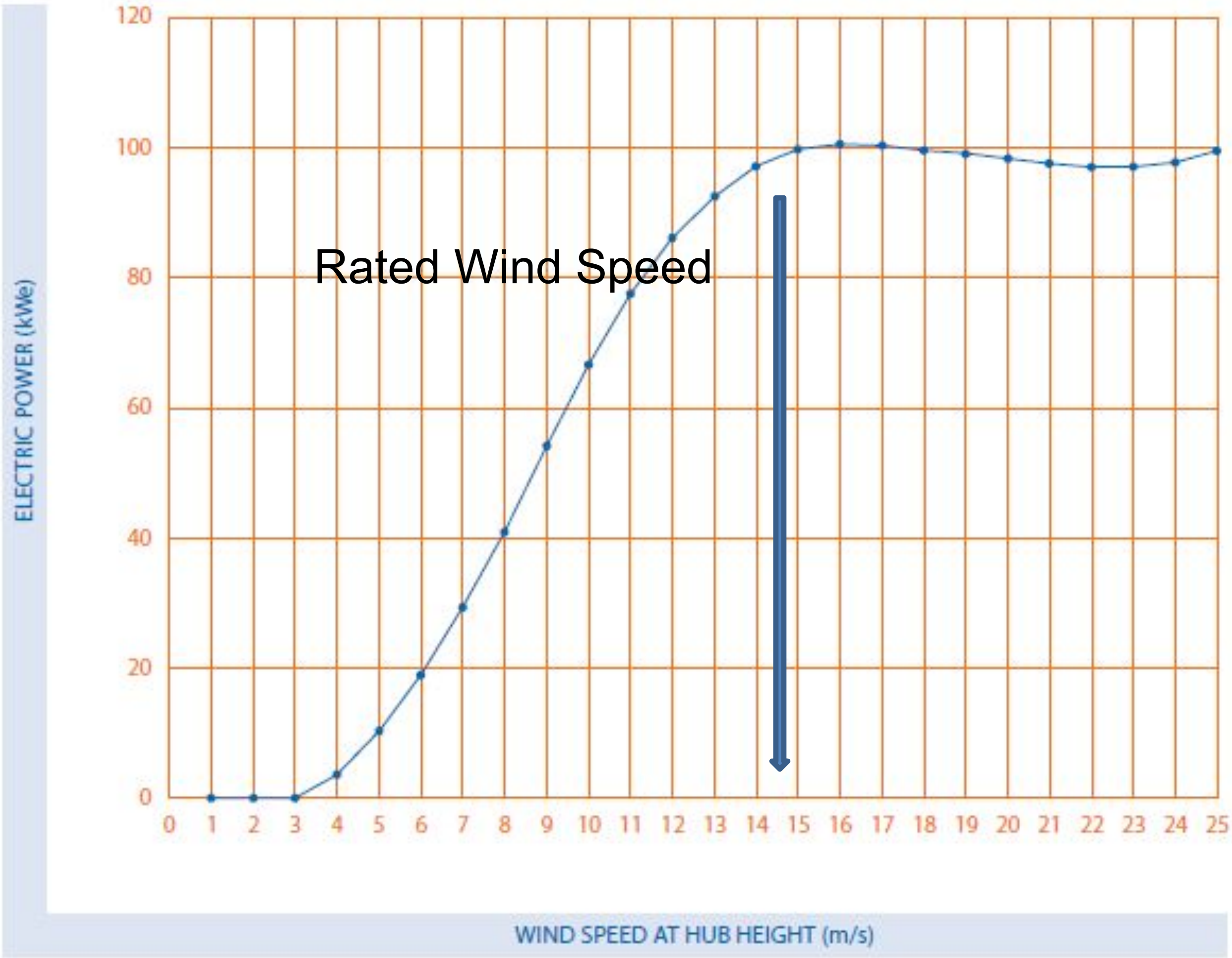

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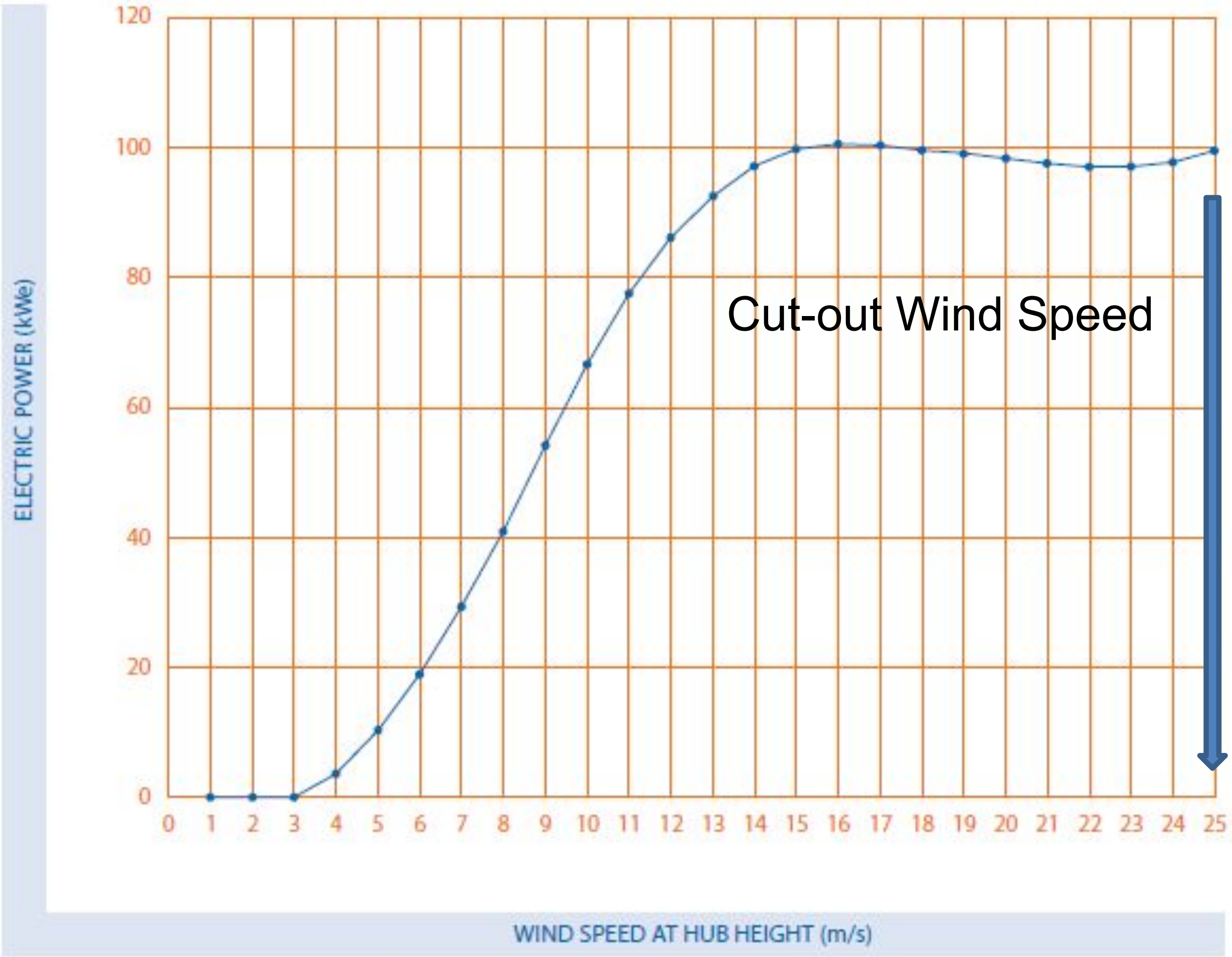

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Northwind 100

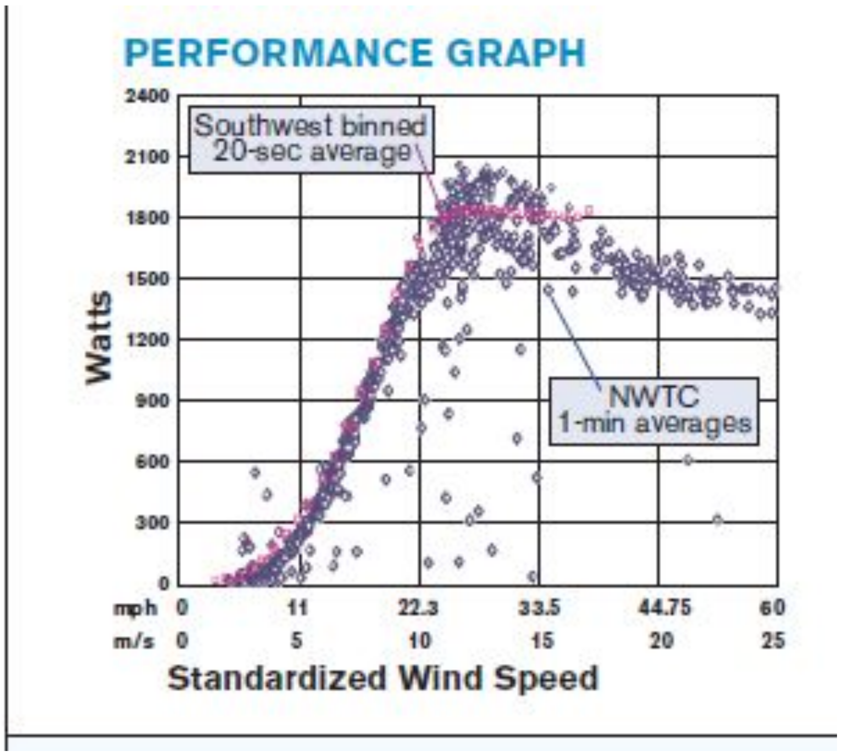
GENERAL CONFIGURATION	DESCRIPTION
Model	Northwind 100
Design Class	IEC IIA (air density 1.225 kg/m³, average annual wind below 8.5 m/s, 50-yr peak gust below 59.5 m/s)
Design Life	20 Years
Hub Height	37 m (121 ft)
Tower Type	Tubular steel monopole
Orientation	Upwind
Rotor Diameter	21 m (69 ft)
Power Regulation	Variable Speed, Stall Control

PERFORMANCE	DESCRIPTION (standard conditions: air density of 1.225 kg/m³, equivalent to 15°C (59°F) at sea level)
Rated Electrical Power	100 kW, 3 Phase, 480 VAC, 60 Hz
Rated Wind Speed	14.5 m/s (32.4 mph)
Maximum Rotation Speed	59 rpm
Cut-In Wind Speed	3.5 m/s (7.8 mph)
Cut-Out Wind Speed	25 m/s (56 mph)
Survival Wind Speed	59.5 m/s (133 mph)

WEIGHT	DESCRIPTION
Rotor (21-meter)	1,400 kg (3,100 lbs)
Nacelle (standard)	5,800 kg (13,000 lbs)
Tower (37-meter)	13,800 kg (30,000 lbs)

DRIVE TRAIN	DESCRIPTION
Gearbox Type	No Gearbox (Direct Drive)
Generator Type	Permanent magnet, passively cooled

Real Turbines with Measured Performance



Technical Specifications

Model	Skystream 3.7
Rated Capacity	1.8 kW rated 2.4 kW peak
Weight	170 lbs. / 77 kg
Rotor Diameter	12 feet / 3.72 meters
Swept Area	115.7 ft^2 / 10.87 m^2
Type	Downwind rotor with stall regulation control
Direction of Rotation	Clockwise looking upwind
Blade Material	Fiberglass reinforced composite
Number of Blades	3
Rated Speed	50 - 325 rpm
Tip Speed	66 - 213 f/s / 9.7 - 63 m/s
Alternator	Slotless permanent magnet brushless
Yaw Control	Passive
Grid Feeding	Southwest Windpower inverter 120/240 VAC 50-60/Hz
Braking System	Electronic stall regulation w/redundant relay switch control
Cut-in Wind Speed	8 mph / 3.5 m/s
Rated Wind Speed	20 mph / 9 m/s
User Control	Wireless 2 way interface remote system
Survival Wind Speed	140 mph / 63 m/s
Warranty	5 Year Limited Warranty

1. Based on a 12 mph (5.4 m/s) wind and utility energy cost of $.09/kWh
2. Taller towers are available
3. 120V will be available in the 4th quarter of 2006
4. Assuming the Skystream 3.7 is producing more energy than the load is consuming

MADE IN THE USA

TECHNICAL DATA FOR V90-1.8 MV

Power regulation	pitch regulated with variable speed

Operating data

Rated power	1,800 kW
Cut-in wind speed	4 m/s
Rated wind speed	12 m/s
Cut-out wind speed	25 m/s
Wind Class	IEC IIA
Operating temperature	standard range -20°C to 40°C low temperature option -30°C to 40°C

Sound power

(10 m above ground, hub height 80 m, standard air density 1,225 kg/m3)

4 m/s	95.6 dB(A)
5 m/s	99.4 dB(A)
6 m/s	102.3 dB(A)
7 m/s	103.1 dB(A)
> 8 m/s	103.5 dB(A)

Rotor

Rotor diameter	90 m
Swept area	6,362 m²
Nominal revolutions	14.5 rpm
Operational interval	9.3 - 16.6 rpm
Air brake	full blade feathering with 3 pitch cylinders

Tower

Type	tubular steel tower
Hub heights	80 m and 95 m

Generator

Type	6-pole asynchronous with variable speed
Nominal output	1,800 kW
Operational data	60 Hz 690 V

Gearbox

Type	3-stage planetary/helical

Main dimensions

Blade

Length	44 m
Max. chord	3.5 m
Weight	6,700 kg

Nacelle

Height for transport	4 m
Height installed (including CoolerTop)	5.4 m
Length	10.4 m
Width	3.4 m
Weight	70 metric tonnes

Hub

Max diameter	3.3 m
Max. width	4 m
Length	4.2 m
Weight	18 metric tonnes

Tower

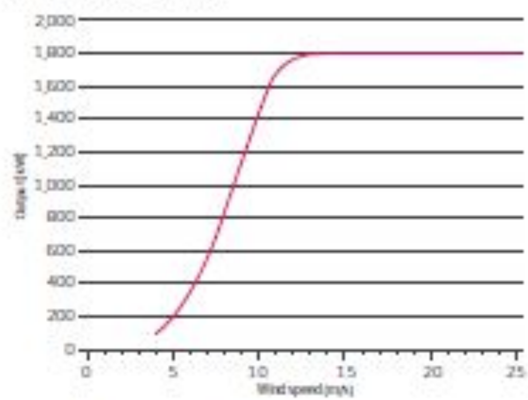
80 m

Weight	155 metric tonnes

95 m

Weight	205 metric tonnes

Power curve V90-1.8 MW



Noise reduced sound power modes are available.

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- **Measure the Wind Resource!**

- **Turbine Power Curve and Real Performance Data!**