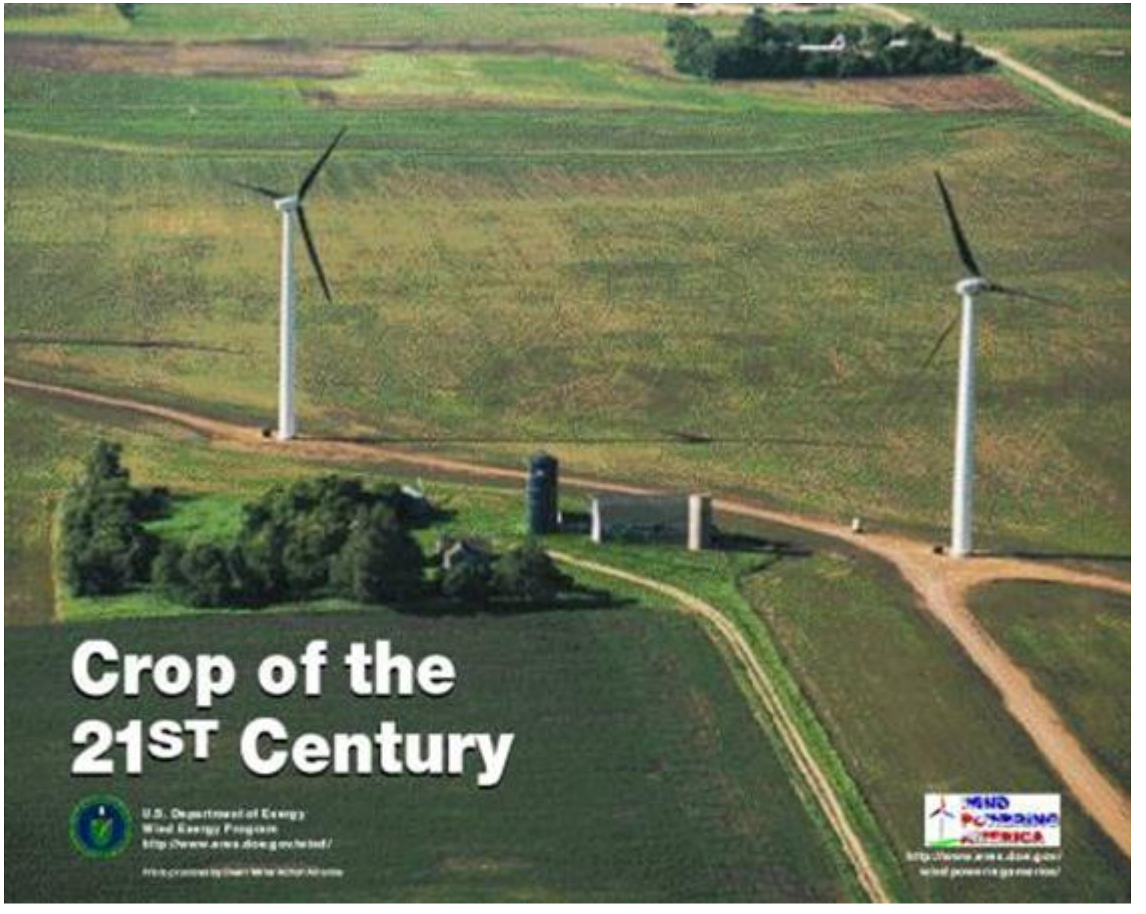
ELG4126 Wind Energy Technology



Major Source: Renewable and Efficient Electric Power Systems, by GM Masters, Wiely.

Introduction

- The world's first wind turbine used to generate electricity was built by a Dane, Poul la Cour, in 1891.
- In the United States the first wind-electric systems were built in the late 1890s; by the 1930s and 1940s, hundreds of thousands of small-capacity, wind electric systems were in use in rural areas not yet served by the electricity grid.
- In 1941 one of the largest wind-powered systems ever built went into operation at Grandpa's Knob in Vermont.
- Designed to produce 1250 kW from a 175-ft-diameter, two-bladed rotor system; the unit had withstood winds as high as 115 miles per hour before it catastrophically failed in 1945.

Wind Turbine at Grandpa’s Knob in Vermont

REUNION POWER

Evolution of Wind Energy

- Early wind turbines were used to grind grain into flour, hence the name "windmill." Therefore, calling a machine that pumps water or generates electricity a windmill is somewhat of a contradiction.
- **Question:** What is the difference between a Windmill and a Wind Turbine?
- Interest in wind systems declined as the utility grid expanded and became more reliable and electricity prices declined. The oil shocks of the 1970s, which heightened awareness of our energy problems, coupled with substantial financial and regulatory incentives for alternative energy systems, stimulated a renewal of interest in wind power.
- Within a decade or so, several manufacturers installed thousands of new wind turbines, mostly in California (USA), Germany, Spain, Denmark, The Netherlands, UK, India, Canada, etc.

Advantages of Wind Power

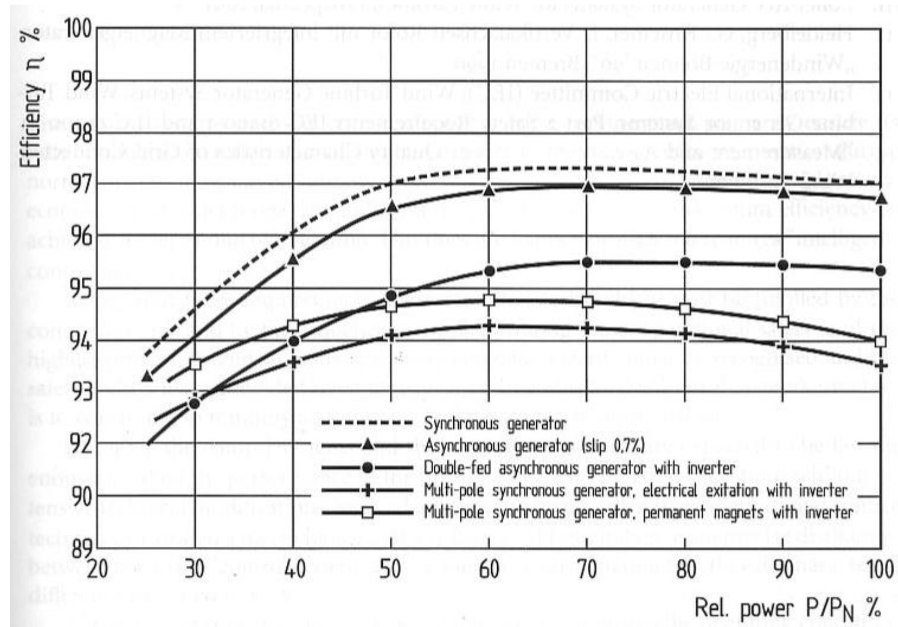
- After installation, the only cost is maintenance!
- Wind is renewable.
- Available everywhere to some extent.
- No pollution!
- Simple designs.
- Supply of wind energy cannot be controlled by anyone (no political maneuvering)!
- Wind farms make it profitable.

Disadvantages of Wind Power

- Expensive to set up, custom products.
- Wind speed varies a lot:
  - Hard to predict
  - Not steady, so unreliable
  - Accurate data absolutely necessary
- Environmental impact from manufacturing.
- Turbines can require large areas of land.

Generator Design Considerations

System	Typical speed range	Maximum efficiency of generator with inverter	Approx. cost ratio
Induction generator (squirrel-cage rotor)) – with static reactive-power compensation	 100 ± 0.5 %	0.965 0.955	100 %
Pole-changing two-speed induction generator	100 ± 0.5 % 66 ⅔ ± 0.5 %	0.965 0.945	110 %
Induction generator with oversynchronous cascade – with harmonic frequency filter and reactive-power compensation	100 + 30 %	0.95 0.935	150 %
Double-fed induction generator with static inverter (AC-DC-AC) – with harmonic frequency filter and reactive-power compensation	100 ± 50 %	0.955 0.94	160 %
Synchronous generator with static inverter (AC-DC-AC) – with harmonic frequency filter	100 ± 50 %	0.95 0.940	180 %
Direct-drive synchronous generator with static inverter (AC-DC-AC) and harmonics filter	100 ± 50 %	0.94	350 %
Direct-drive synchronous generator (permanent magnet excitation) and static inverter (AC-DC-AC) – with harmonics filter and reactive-power compensation	100 ± 50 %	0.96 0.94	450 %



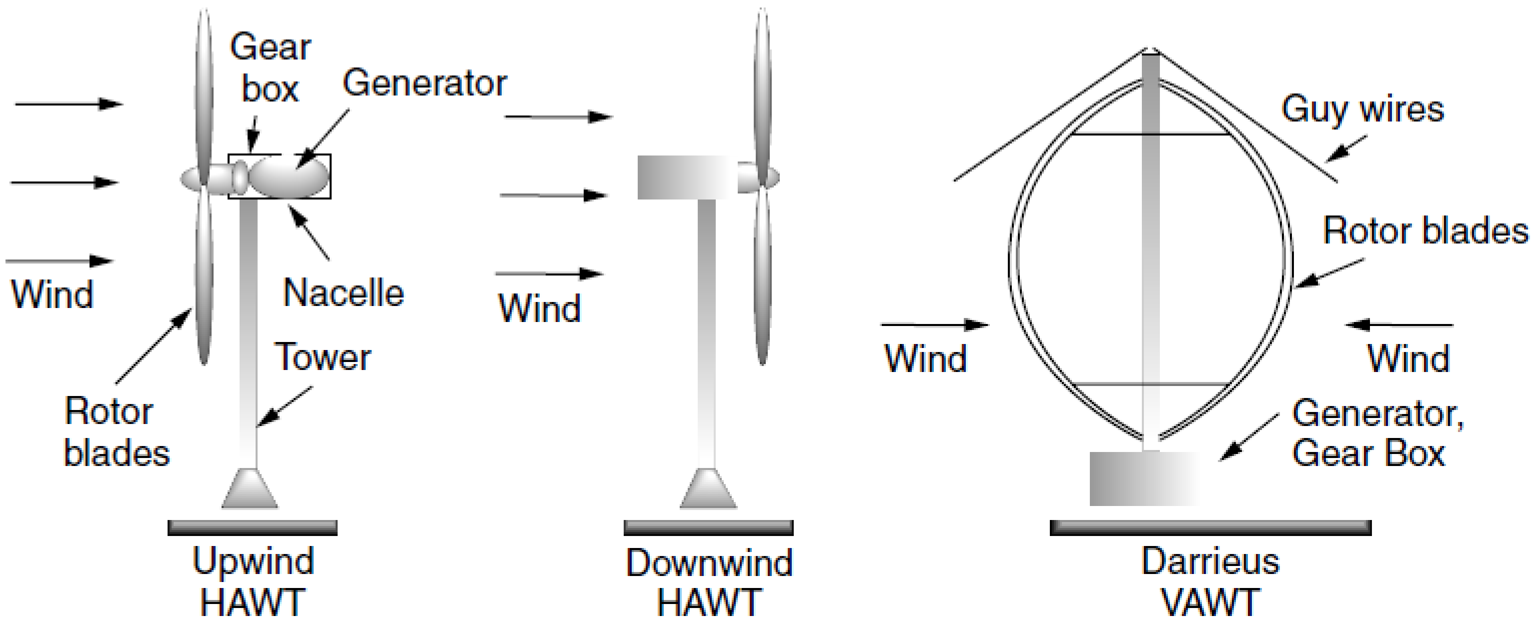
Other Factors:

- Weight
- Starting overcurrent
- Dynamic response behavior
- Speed range

Types of Wind Turbines

- **Terminology:** “Wind-driven generator,” “wind generator,” “wind turbine,” “wind-turbine generator” (WTG), and “wind energy conversion system” (WECS) all are in use. For our purposes, “wind turbine” will suffice even though often we will be talking about system components (towers, generators, etc.) that clearly are not part of a “turbine.”
- One way to classify wind turbines is in terms of the axis around which the turbine blades rotate. Most are horizontal axis wind turbines (HAWT), but there are some with blades that spin around a vertical axis (VAWT).
- The only vertical axis machine that has had any commercial success is the Darrieus rotor, named after its inventor the French engineer G. M. Darrieus, who first developed the turbines in the 1920s.

HAWT and VAWT



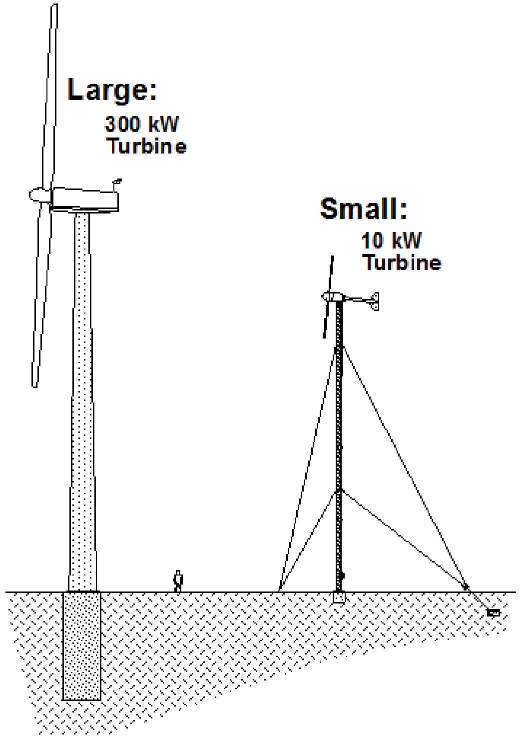
Large and Small Wind Turbines

Large Turbines (500-1500 kW):

Installed in “Wind farm” Arrays; Totaling 1 - 100 MW; Designed for Low Cost of energy; Requires 6 m/s (13 mph).

Small Turbines (0.3-100 kW):

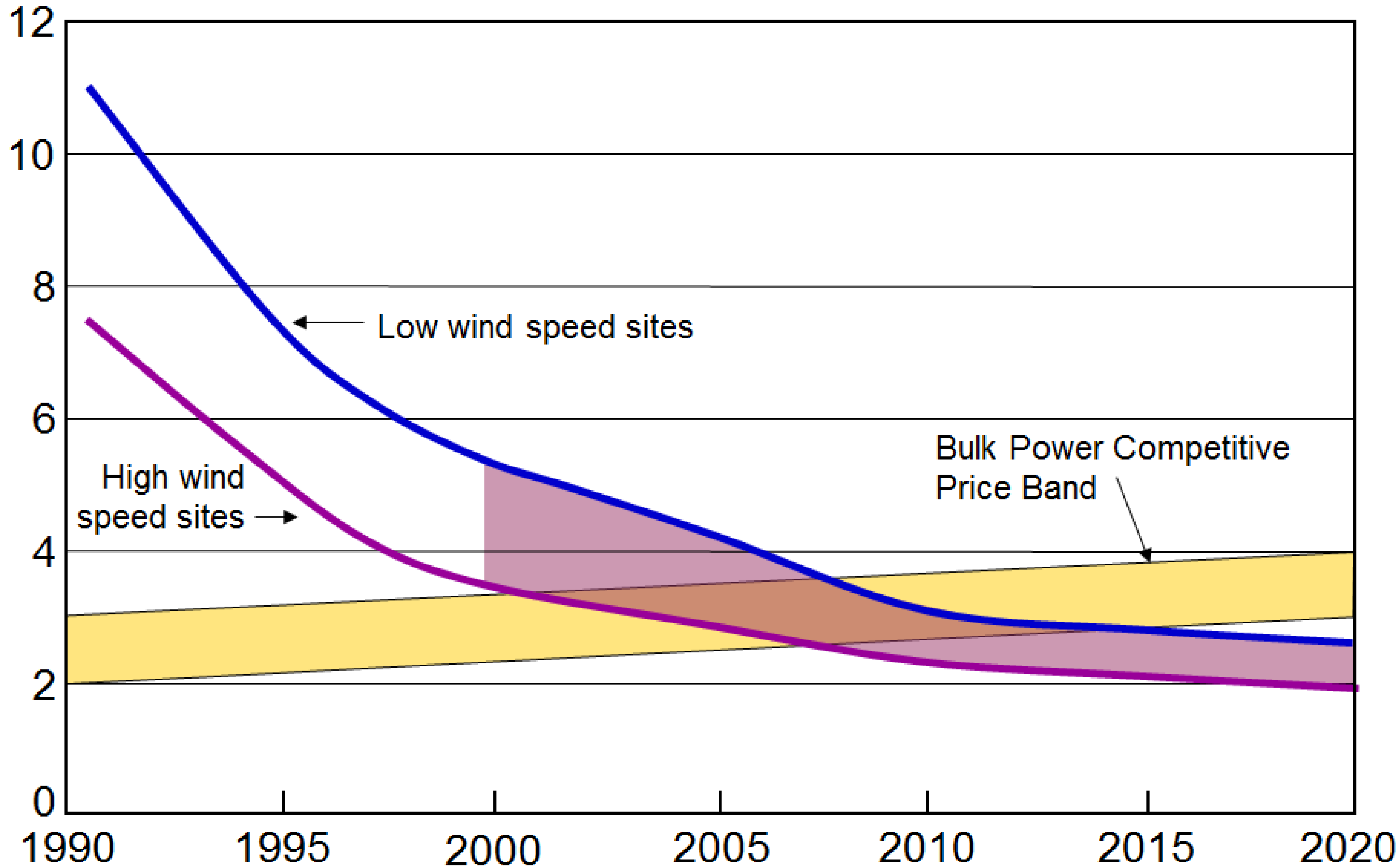
Installed in “Rural Residential” On-Grid and Off-Grid Applications; $2,500-5,000/kW; Designed for Reliability / Low Maintenance; Requires 4 m/s (9 mph).



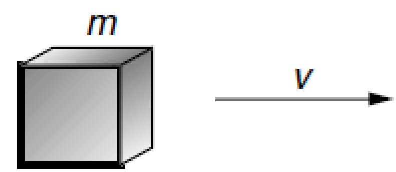
Technological Challenges

- Integrating unpredictable energy resources into existing power systems / grids.
- Accurate estimation of wind resources
  - Location, location, location!
- Not a commodity, a custom product.
- Scaling up, scaling down…
- Energy storage?
- Average wind speed of over 10 mph required
  - Ideal location: near constant flow of non-turbulent wind, minimal fluctuations & gusts
- Critically important to have accurate wind speed and direction data
  - Overestimating wind → massive loss of profit
- "Wind park effect" loss (as low as 2%)
- How far away is the grid?
  - Capital costs of any connection is substantial.

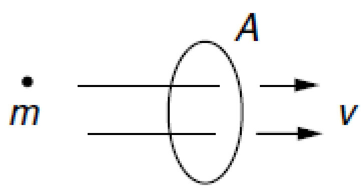
Wind Cost of Energy



Power in the Wind



$$\text{K.E.} = \frac{1}{2} m v^2$$



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2$$

The mass flow rate $\dot{m}$, through area A, is the product of air density ρ, speed v, and cross-sectional area A:

$$\left(\frac{\text{Mass passing through A}}{\text{Time}}\right) = \dot{m} = \rho A v$$

$$P_w = \tfrac{1}{2} \rho A v^3$$

Don't Use Average Windspeed. Compare the energy at 15°C, 1 atm pressure, contained in 1 m^2 of the following wind regimes:

a. 100 hours of 6-m/s winds (13.4 mph),
b. 50 hours at 3 m/s plus 50 hours at 9 m/s (i.e., an average windspeed of 6 m/s)

a. With steady 6 m/s winds, all we have to do is multiply power given by (6.4) times hours:

$$\text{Energy (6 m/s)} = \frac{1}{2}\rho A v^3 \Delta t = \frac{1}{2} \cdot 1.225\ \text{kg/m}^3 \cdot 1\ \text{m}^2 \cdot (6\ \text{m/s})^3 \cdot 100\ \text{h}$$
$$= 13{,}230\ \text{Wh}$$

b. With 50 h at 3 m/s

$$\text{Energy (3 m/s)} = \frac{1}{2} \cdot 1.225\ \text{kg/m}^3 \cdot 1\ \text{m}^2 \cdot (3\ \text{m/s})^3 \cdot 50\ \text{h} = 827\ \text{Wh}$$

And 50 h at 9 m/s contain

$$\text{Energy (9 m/s)} = \frac{1}{2} \cdot 1.225\ \text{kg/m}^3 \cdot 1\ \text{m}^2 \cdot (9\ \text{m/s})^3 \cdot 50\ \text{h} = 22{,}326\ \text{Wh}$$

for a total of $827 + 22{,}326 = 23{,}152$ Wh

Impact of Tower Height

- Since power in the wind is proportional to the cube of the wind speed, the economic impact of even modest increases in wind speed can be significant.
- One way to get the turbine into higher winds is to mount it on a taller tower. In the first few hundred meters above the ground, wind speed is greatly affected by the friction that the air experiences as it moves across the earth’s surface.
- Smooth surfaces, such as a calm sea, offer very little resistance, and the variation of speed with elevation is only modest. At the other extreme, surface winds are slowed considerably by high irregularities such as forests and buildings.

- One expression that may be used to characterize the impact of the roughness of the earth's surface on wind speed is the following:

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

where v is the wind speed at height H, v_0 is the wind speed at height H_0 (often a reference height of 10 m), and α is the friction coefficient.

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

Example **Increased Windpower with a Taller Tower.** An anemometer mounted at a height of 10 m above a surface with crops, hedges, and shrubs shows a windspeed of 5 m/s. Estimate the windspeed and the specific power in the wind at a height of 50 m. Assume 15°C and 1 atm of pressure.

Solution. From Table 6.3, the friction coefficient α for ground with hedges, and so on, is estimated to be 0.20. From the 15°C, 1-atm conditions, the air density is $\rho = 1.225\ \text{kg/m}^3$. Using (6.15), the windspeed at 50 m will be

$$v_{50} = 5 \cdot \left(\frac{50}{10}\right)^{0.20} = 6.9\ \text{m/s}$$

Specific power will be

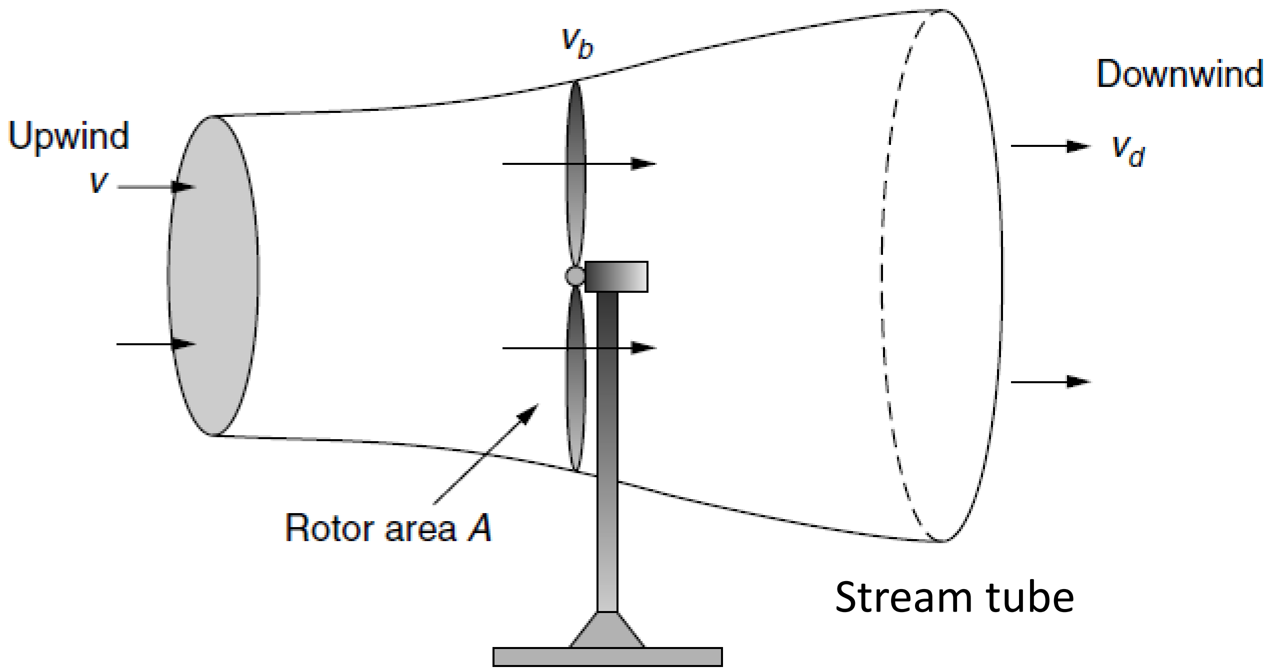
$$P_{50} = \tfrac{1}{2}\rho v^3 = 0.5 \times 1.225 \times 6.9^3 = 201\ \text{W/m}^2$$

That turns out to be more than two and one-half times as much power as the 76.5 W/m^2 available at 10 m.

Maximum Rotor Efficiency

- A number of energy technologies have certain fundamental constraints that restrict the maximum possible conversion efficiency from one form of energy to another.
- For heat engines, it is the Carnot efficiency that limits the maximum work that can be obtained from an engine working between a hot and a cold reservoir. For photovoltaics, we will see that it is the band gap of the material that limits the conversion efficiency from sunlight into electrical energy.
- For fuel cells, it is the Gibbs free energy that limits the energy conversion from chemical to electrical forms. And now, we will explore the constraint that limits the ability of a wind turbine to convert kinetic energy in the wind to mechanical power.

- The original derivation for the maximum power that a turbine can extract from the wind is credited to a German physicist, Albert Betz, who first formulated the relationship in 1919. The analysis begins by imagining what must happen to the wind as it passes through a wind turbine.
- **Question:** why can't the turbine extract all of the kinetic energy in the wind?



- In the figure, the upwind velocity of the undisturbed wind is v, the velocity of the wind through the plane of the rotor blades is v_b, and the downwind velocity is v_d . The mass flow rate of air within the stream tube is everywhere the same, call it $\dot{m}$. The power extracted by the blades P_b is equal to the difference in kinetic energy between the upwind and downwind air flows:

$$P_b = \tfrac{1}{2}\dot{m}(v^2 - v_d^2) \qquad \dot{m} = \rho A v_b$$

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

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

$$\text{Rotor efficiency} = C_P = \tfrac{1}{2}(1 + \lambda)(1 - \lambda^2)$$

- To find the maximum possible rotor efficiency, we simply take the derivative of the last equation with respect to λ and set it equal to zero:

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

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

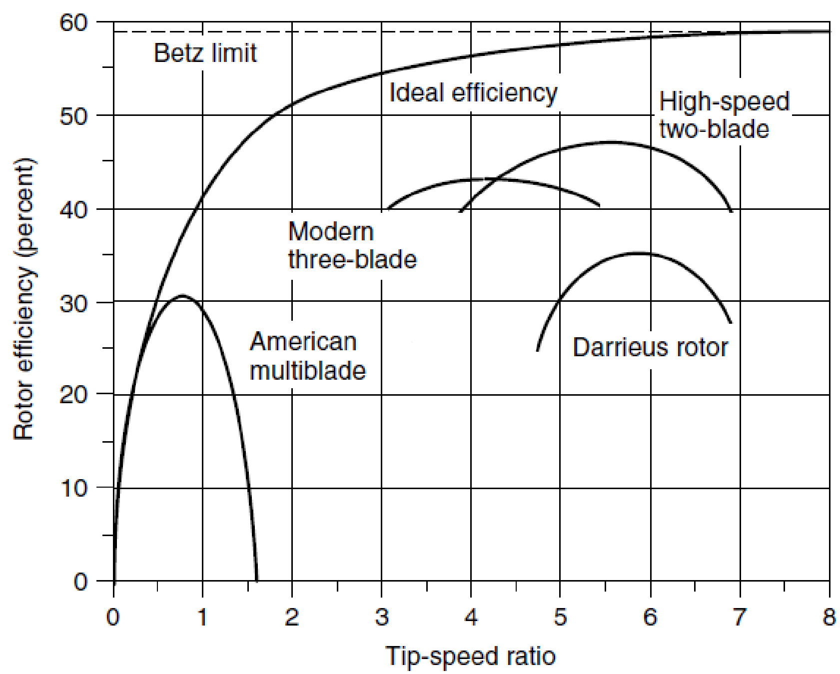
$$\lambda = \frac{v_d}{v} = \frac{1}{3}$$

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27} = 0.593 = 59.3\%$$

Tip Speed Ratio

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

where rpm is the rotor speed, revolutions per minute; D is the rotor diameter (m); and v is the wind speed (m/s) upwind of the turbine.



- **Example How Fast Does a Big Wind Turbine Turn?** 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,
- At what rpm does the rotor turn when it operates with a TSR of 4.0?

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

- What is the tip speed of the rotor?

$$\text{Tip speed} = \frac{26.7\ \text{rev/min} \times \pi 40\ \text{m/rev}}{60\ \text{s/ min}} = 55.9\ \text{m/s}$$

- If the generator needs to turn at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed?

$$\text{Gear ratio} = \frac{\text{Generator rpm}}{\text{Rotor rpm}} = \frac{1800}{26.7} = 67.4$$

- What is the efficiency of the complete wind turbine (blades, gear box, generator) under these conditions? Power in the wind is

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

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

Gearbox Design Decisions

Configuration:		mass t	rel. costs %
two stages: parallel	4490; 2585; 2500	70	180
two stages: parallel with torque splitting	3225; 2400; 2150	56	164
three stages: parallel	3580; 1800; 4290	77	192
two stages: one parallel one planetary	3750; 2585; 2800	41	169
three stages: two planetary one parallel	1250; 1025; 3200	17	110
three stages: planetary	1025; 2800	11	100

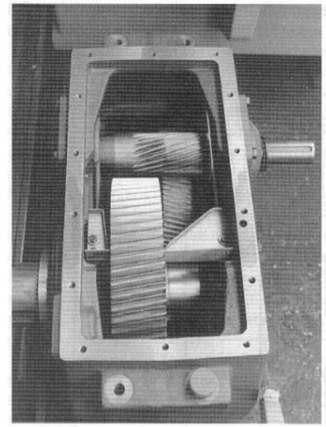


Figure 8.34. Two-stage parallel shaft gearbox for wind turbines of the 200 to 500 kW power class (Hansen)

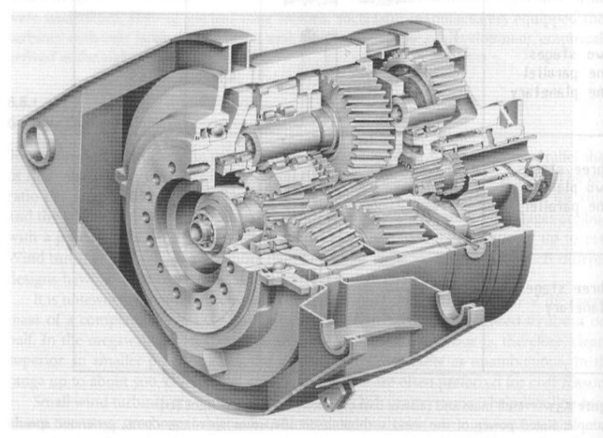
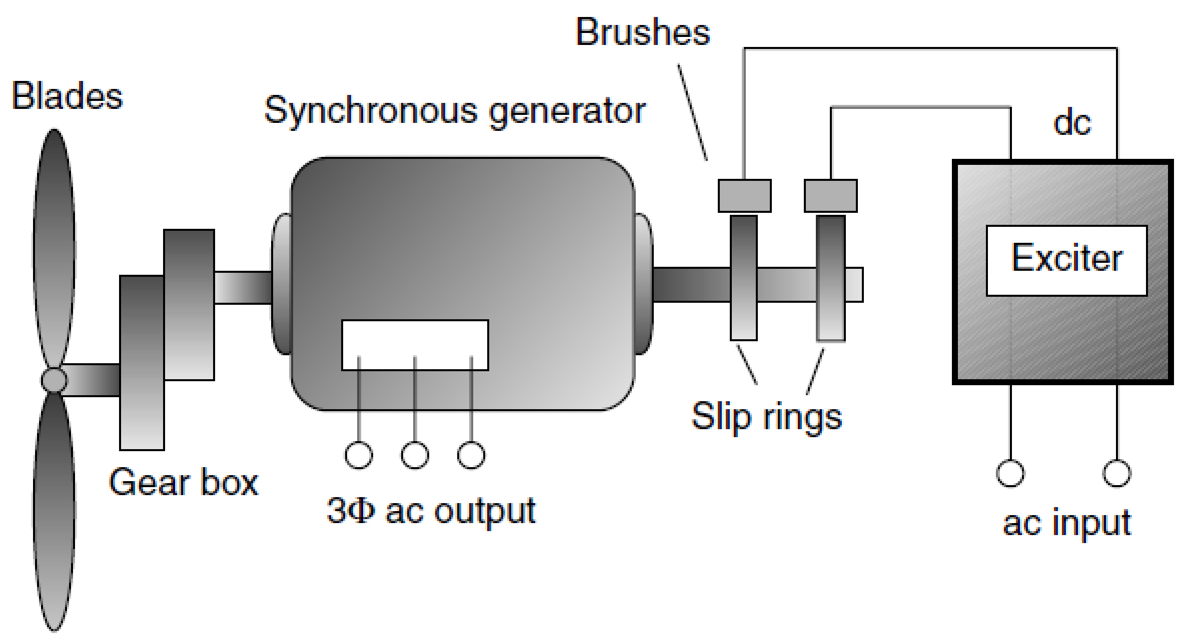


Figure 8.35. Three-stage planetary gearbox of the 2 to 3 MW power class (Thyssen)

Wind Turbine Generators

- **Synchronous Generators:** Synchronous generators are forced to spin at a precise rotational speed determined by the number of poles and the frequency needed for the power lines. Their magnetic fields are created on their rotors. While very small synchronous generators can create the needed magnetic field with a permanent magnet rotor, almost all wind turbines that use synchronous generators create the field by running direct current through windings around the rotor core.

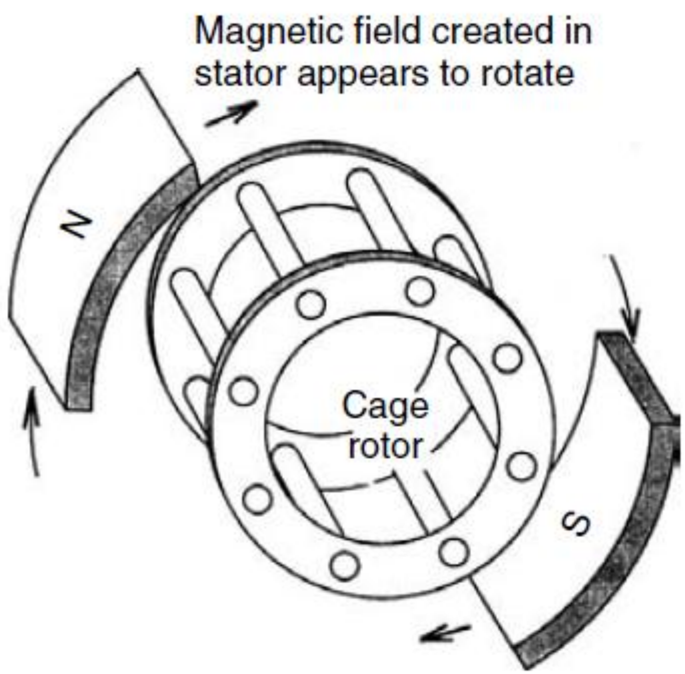


Induction Generator

- Most of the world's wind turbines use induction generators rather than the synchronous machines just described. In contrast to a synchronous generator (or motor), induction machines do not turn at a fixed speed, so they are often described as asynchronous generators.
- While induction generators are uncommon in power systems other than wind turbines, their counterpart, induction motors, are the most prevalent motors around—using almost one-third of all the electricity generated worldwide.
- As a motor, the rotor of the induction machine spins a little slower than the synchronous speed established by its field windings, and in its attempts to "catch up" it delivers power to its rotating shaft.
- As a generator, the turbine blades spin the rotor a little faster than the synchronous speed and energy is delivered into its stationary field windings.
- The main advantage of induction generators is that their rotors do not require the exciter, brushes, and slip rings that are needed by most synchronous generators. They do this by creating the necessary magnetic field in the stator rather than the rotor. This means that they are less complicated and less expensive and require less maintenance.

Induction Machines

- **The Squirrel Cage Rotor:** The rotor of many induction generators (and motors) consists of a number of copper or aluminum bars shorted together at their ends, forming a cage. The cage is then imbedded in an iron core consisting of thin (0.5 mm) insulated steel laminations. The laminations help control eddy current losses.

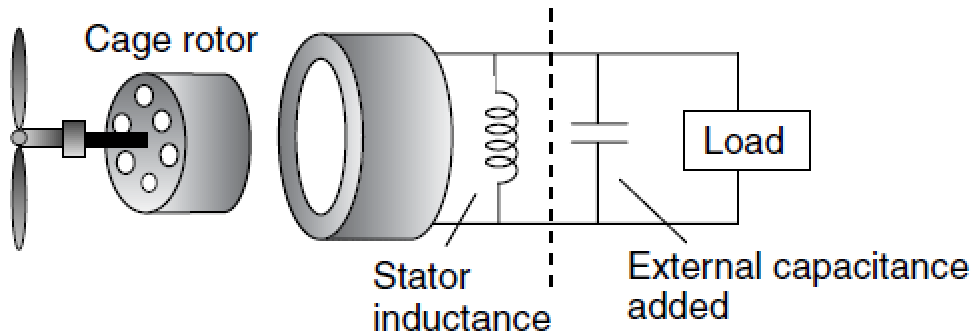


The Induction Machine as a Motor

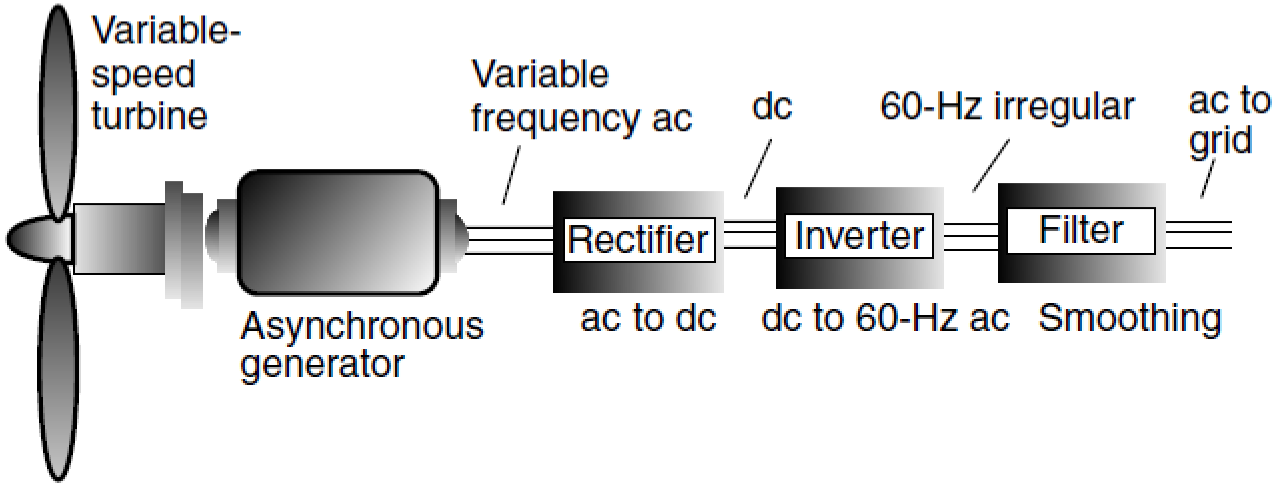
- The rotating magnetic field in the stator of the inductance machine causes the rotor to spin in the same direction. That is, the machine is a motor—an induction motor. Important: there are no electrical connections to the rotor; no slip rings or brushes are required.
- As the rotor approaches the synchronous speed of the rotating magnetic field, the relative motion between them gets smaller and smaller and less and less force is exerted on the rotor.
- If the rotor could move at the synchronous speed, there would be no relative motion, no current induced in the cage conductors, and no force developed to keep the rotor going.

The Induction Machine as a Generator

- When the stator is provided with three-phase excitation current and the shaft is connected to a wind turbine and gearbox, the machine will start operation by motoring up toward its synchronous speed. When the wind speed is sufficient to force the generator shaft to exceed synchronous speed, the induction machine automatically becomes a three-phase generator delivering electrical power back to its stator windings.



Indirect Grid Connection Systems

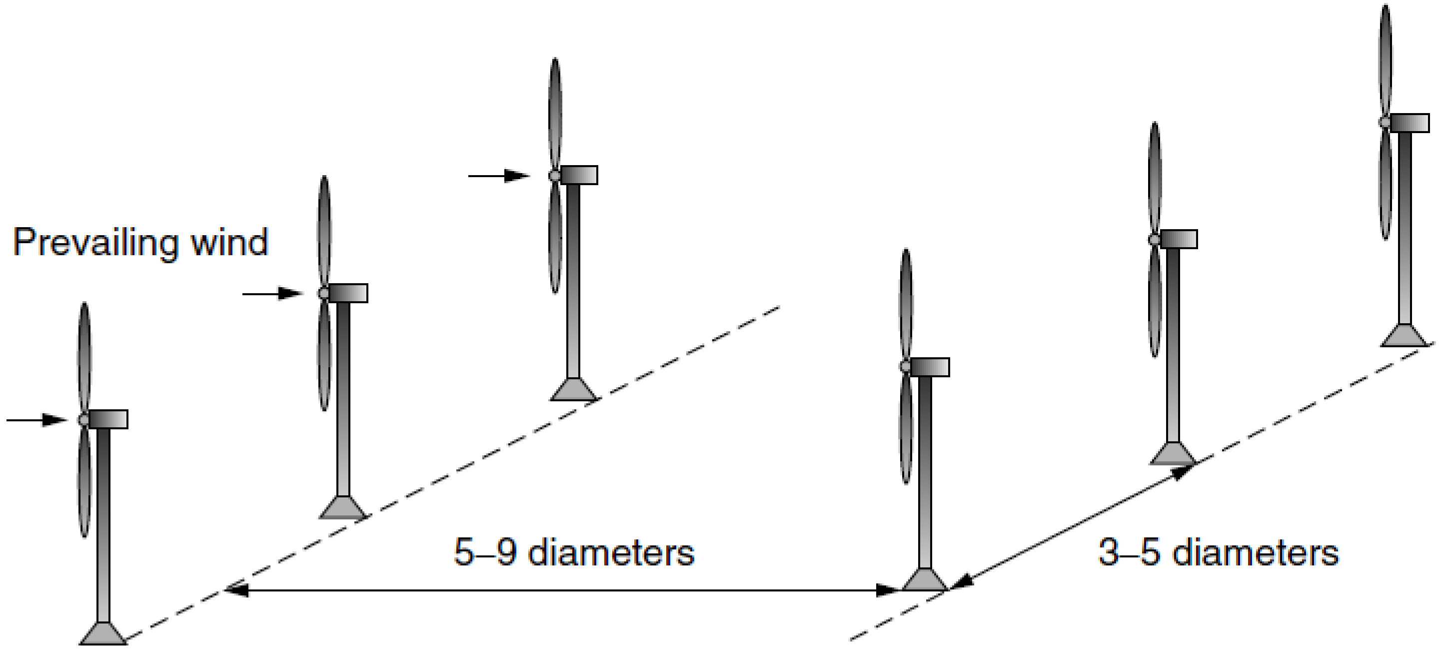


- Variable frequency AC from the generator is rectified and converted into dc using high power transistors. This DC is then sent to an inverter that converts it back to ac, but this time with a steady 50- or 60-Hz frequency. The raw output of an inverter is pretty choppy and needs to be filtered to smooth it.

Wind Power Classification

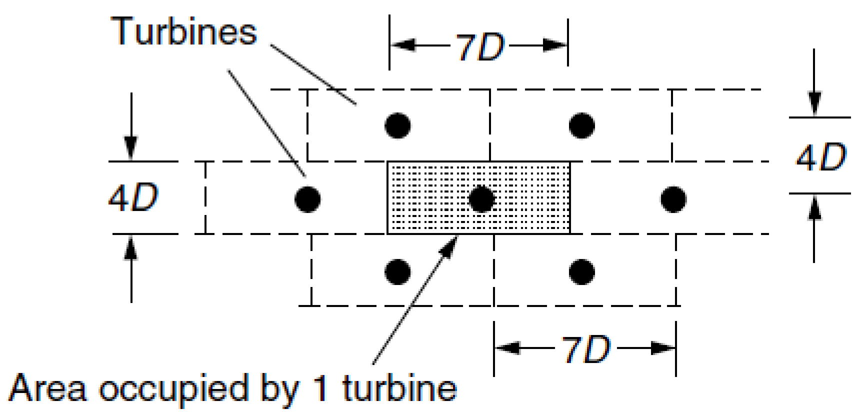
Wind Power Class	Avg Windspeed at 10 m (m/s)	Avg Windspeed at 10 m (mph)	Wind Power Density at 10 m (W/m^2)	Wind Power Density at 50 m (W/m^2)
1	0–4.4	0–9.8	0–100	0–200
2	4.4–5.1	9.8–11.4	100–150	200–300
3	5.1–5.6	11.4–12.5	150–200	300–400
4	5.6–6.0	12.5–13.4	200–250	400–500
5	6.0–6.4	13.4–14.3	250–300	500–600
6	6.4–7.0	14.3–15.7	300–400	600–800
7	7.0–9.5	15.7–21.5	400–1000	800–2000

Wind Farms



- **Example: Energy Potential for a Wind Farm.** Suppose that a wind farm has 4-rotor-diameter tower spacing along its rows, with 7-diameter spacing between rows (4*D* × 7*D*). 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).
  - b. Suppose that the owner of the wind turbines leases the land from a rancher for $100 per acre per year (about 10 times what a Texas rancher makes on cattle). What does the lease cost per kWh generated?



a. As the figure suggests, the land area occupied by one wind turbine is $4D \times 7D = 28D^2$, where D is the diameter of the rotor. The rotor area is $(\pi/4)D^2$. The energy produced per unit of land area is thus

$$\frac{\text{Energy}}{\text{Land area}} = \frac{1}{28D^2}\left(\frac{\text{Wind turbine}}{\text{m}^2 \text{ land}}\right) \cdot \frac{\pi}{4}D^2\left(\frac{\text{m}^2 \text{ rotor}}{\text{Wind turbine}}\right)$$
$$\times\, 400\left(\frac{\text{W}}{\text{m}^2 \text{ rotor}}\right) \times 0.30 \times 0.80 \times 8760\frac{\text{h}}{\text{yr}}$$
$$\frac{\text{Energy}}{\text{Land area}} = 23,588\frac{\text{W}\cdot\text{h}}{\text{m}^2\cdot\text{yr}} = 23.588\frac{\text{kWh}}{\text{m}^2\cdot\text{yr}}$$

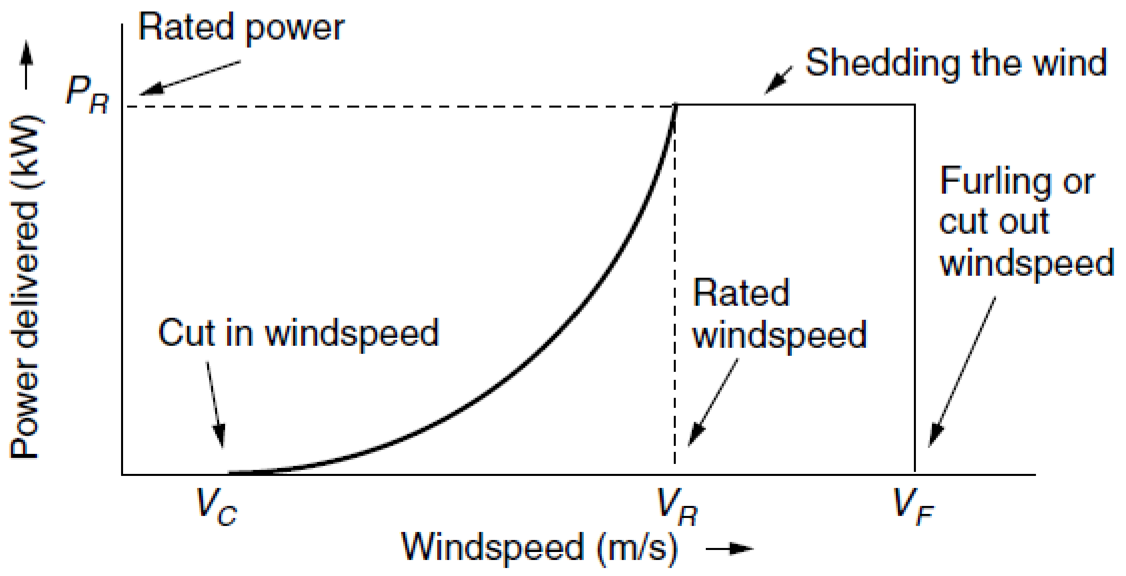
b. At 4047 m^2 per acre, the annual energy produced per acre is:

$$\frac{\text{Energy}}{\text{Land area}} = 23.588\frac{\text{kWh}}{\text{m}^2\cdot\text{yr}} \times \frac{4047 \text{ m}^2}{\text{acre}} = 95,461\frac{\text{kWh}}{\text{acre}\cdot\text{yr}}$$

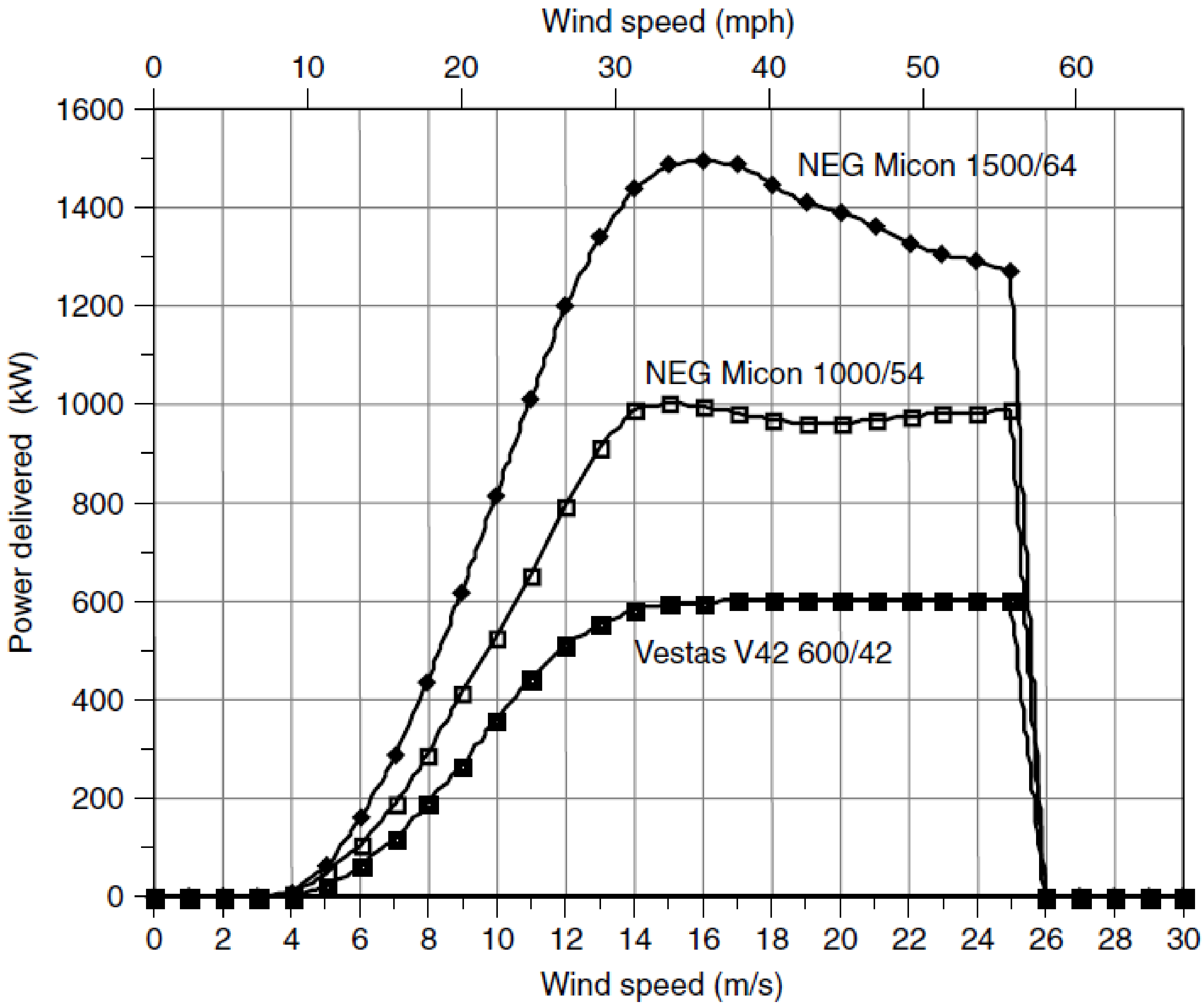
so, leasing the land costs the wind farmer:

$$\frac{\text{Land cost}}{\text{kWh}} = \frac{\$100}{\text{acre}\cdot\text{yr}} \times \frac{\text{acre}\cdot\text{yr}}{95,461 \text{ kWh}} = \$0.00105/\text{kWh} = 0.1\ ¢/\text{kWh}$$

Performance Calculations
Cut in and Cut out



Power Curves



Environmental and Social Concerns

- Pollution? Virtually none… What about construction?
- Birds? Studies have been published with contradictory results…
  - Negligible harm compared to other human activity
- Noise? Wind power noise is far less than most other human activity.
  - Does off-shore wind technology affect marine life?
- Aesthetics and safety?
  - Offshore wind farms can reduce aesthetics complaints.
  - Wind energy has an excellent safety record.