Wind Turbine Design Optimization

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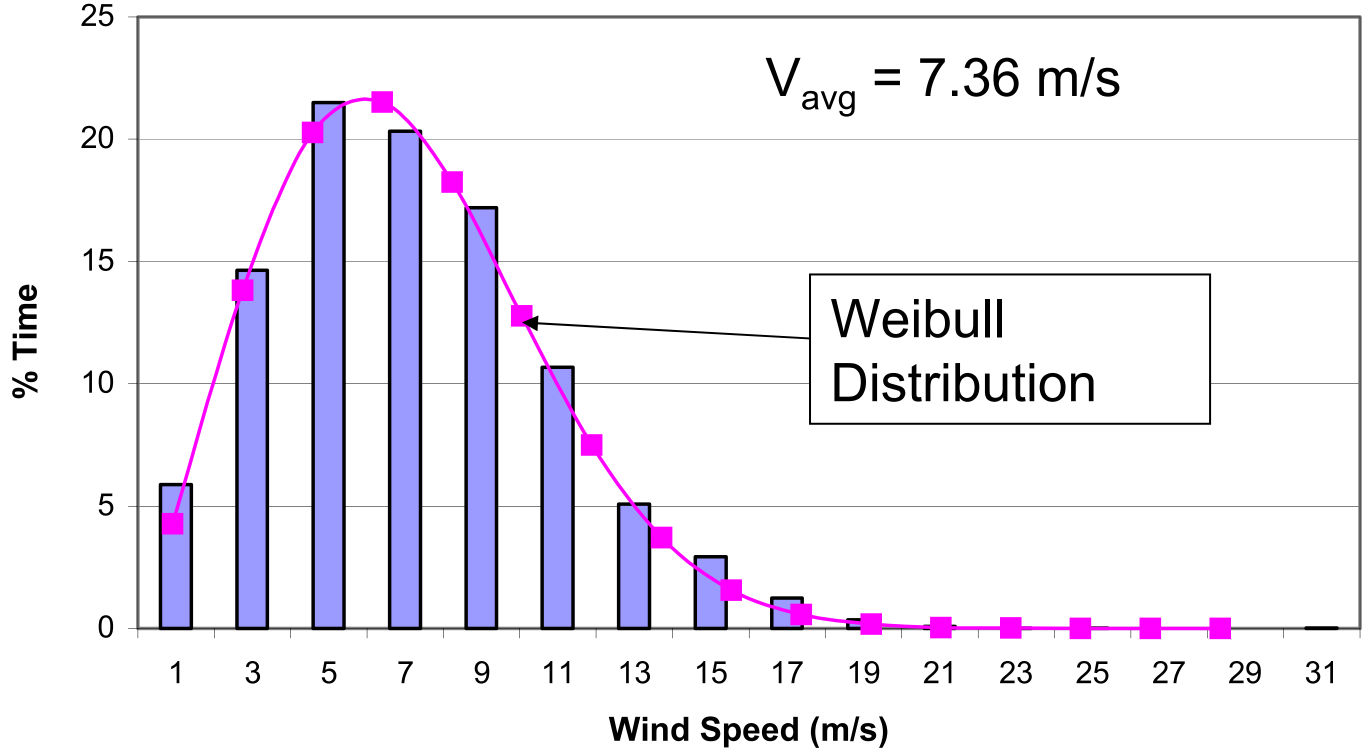
Objective

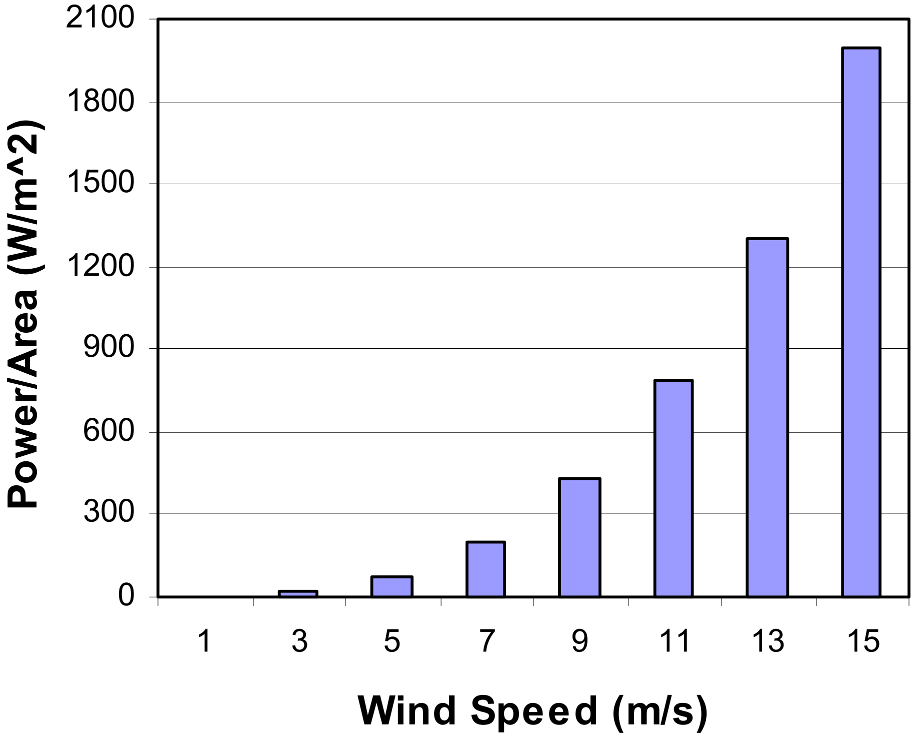
To determine the optimal site specific wind turbine design, which is the design that results in the lowest cost of energy at that particular site. There are many decisions that have to made in designing a modern wind turbine. The optimal wind turbine design for one location is not necessarily the optimal design for another location because the wind speed distribution may vary between locations. In addition, the turbine with the highest efficiency is not necessarily the optimal turbine. It is possible for a less efficient wind turbine to have a lower cost of energy.

The Wind Resource



- The figure above shows a typical wind speed distribution, which can be modeled by a Weibull curve. The distribution will vary from site to site.
- The optimum wind turbine design is dependent on the wind speed distribution of the specific site.

Wind Power Density



$$\dot{W} = \tfrac{1}{2}\dot{m}V^2$$
$$= \tfrac{1}{2}\left(\rho A V\right)V^2$$
$$= \tfrac{1}{2}\rho A V^3$$

where:

$\dot{W}$ = Power

$\dot{m}$ = mass flow rate

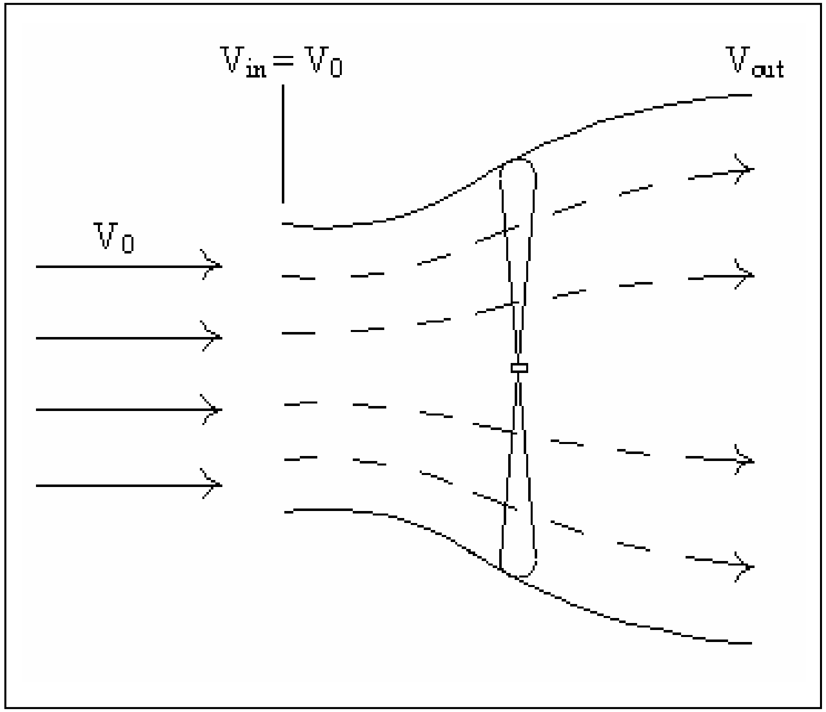
V = Wind Velocity

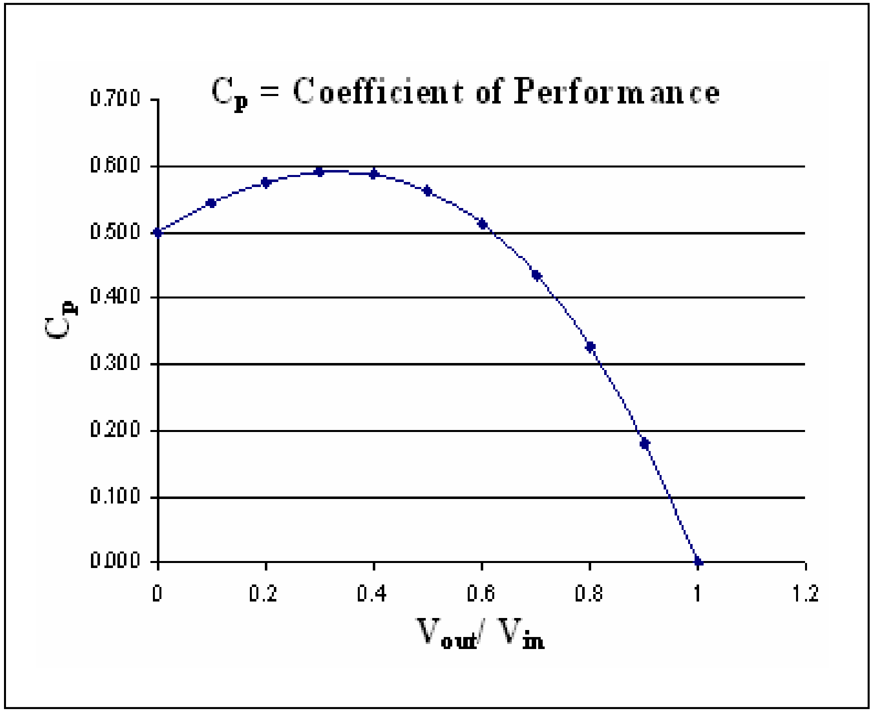
A = Rotor Swept Area

ρ = Air Density

- The power increases with the cube of the wind velocity.
- It is not possible to capture 100% of the wind power.
- The Betz limit dictates that at most 59% of the wind power can be captured

Betz Limit - C_p = 59%



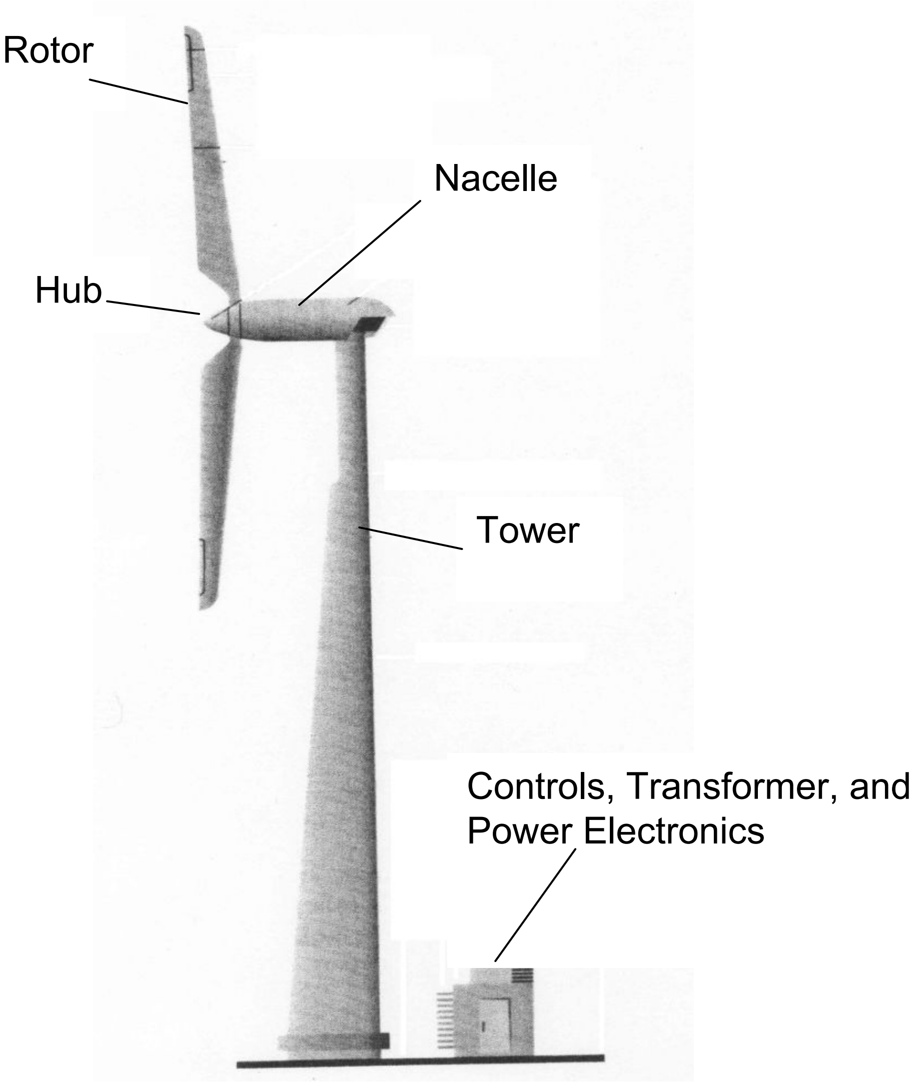


$$\dot{W} = \frac{1}{2}\rho A V_0^{\,3} C_p$$

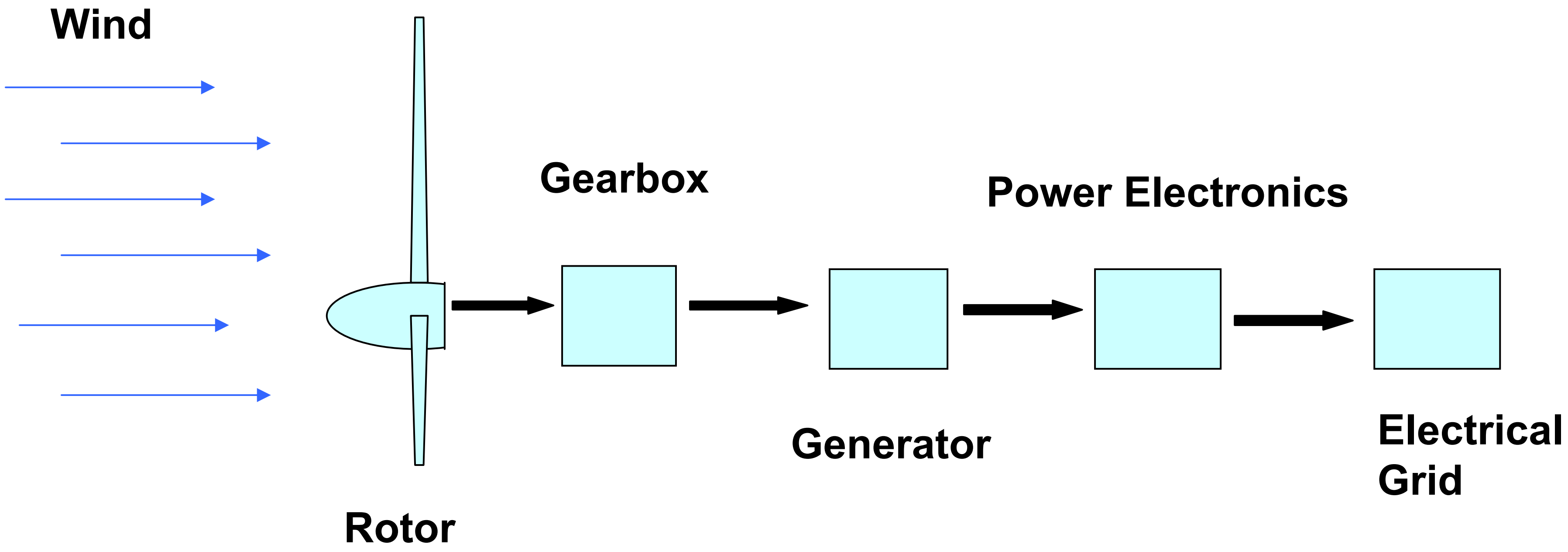
$$C_p = \frac{\left(1+\frac{V_{out}}{V_{in}}\right)\left[1-\left(\frac{V_{out}}{V_{in}}\right)^2\right]}{2}$$

The Wind Turbine

- The figure to the right shows the general parts of a wind turbine.
- The rotor of modern wind turbines typically have three blades.
- The nacelle yaws or rotates on the tower to keep the turbine faced into the wind.
- The nacelle houses the gear box and generator.



Power Transfer from Wind to Grid



- Power is transferred from the wind to the rotor then passed through the gearbox, generator, and power electronics until it finally reaches the gird.
- Each stage of the power transfer has a certain efficiency. Therefore, each power transfer stage presents an opportunity to reduce the cost of energy from a wind turbine.

Wind Turbine Design Options

The following is a list of some important design variables for a wind turbine.

- Rotor diameter

  A larger rotor captures more energy but cost more.
- Generator capacity

  A larger generator can capture more energy at higher wind speeds but also costs more. The rotor diameter and generator capacity must match one another. The optimal match is dependant on the site’s wind conditions
- Hub height

  Wind speeds increase with hub height but so does the tower cost.
- Rotor blade design

  The blades have a slight twist which can be optimized to capture the maximum amount of wind power.

Wind Turbine Design Options Cont'd

- Power control - active pitch or passive stall

  An active pitch control system allows the pitch to be continuously optimized for maximum power. Active pitch control also can be used to prevent the generator from being overpowered by stalling the blades. With passive stall, the blades are bolted in place. The blades are designed to stall at high wind speeds to prevent the generator from being overpowered. Most turbines today come with active pitch control.

- Generator type - synchronous or asynchronous

  A synchronous generator which is connected to the grid will run at a fixed speed. If the torque going to the generator is increased, the magnetic forces of the generator will resist an increase in speed. As a result, a gust of wind will cause large stresses on the wind turbines drive train.

  An asynchronous generator allows for a limited amount of slip or variation in generator RPM. The amount of slip can be changed by adjusting the resistance in the rotor windings. Therefore, the rotor RPM can increase a limited amount with a gust of wind, which reduces drive train wear and tear.

Wind Turbine Design Options Cont'd

- Pole changing, two speed generator

  If a grid connected generator can change the number of poles it uses, it can change its synchronous RPM. Therefore, the turbine will have two generators in one. Of course pole changing increases the generator cost.

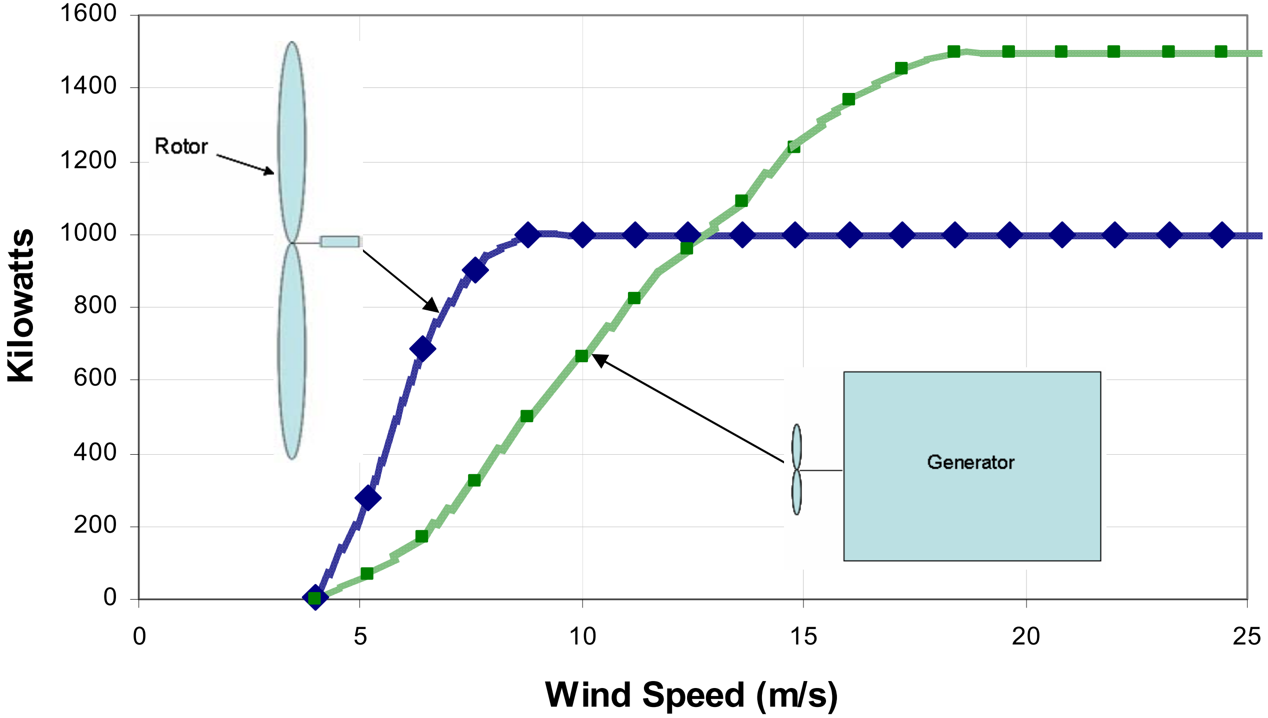
- Fixed speed or variable speed

  If a turbine is connected directly to the grid, the rotor and generator must turn at a fixed speed in order to produce power at 60 Hz. If the turbine is connected to the grid indirectly, the rotor and generator can rotate at variable speeds. Allowing the rotor to rotate at various speeds results in a more efficient capture of wind energy and less stress on the turbine drive train due to wind gusts. However, the power from a variable speed system must be rectified. The additional power electronics increase cost and do not have a 100% efficiency.

- Fixed rotor RPM's (for fixed speed wind turbine)

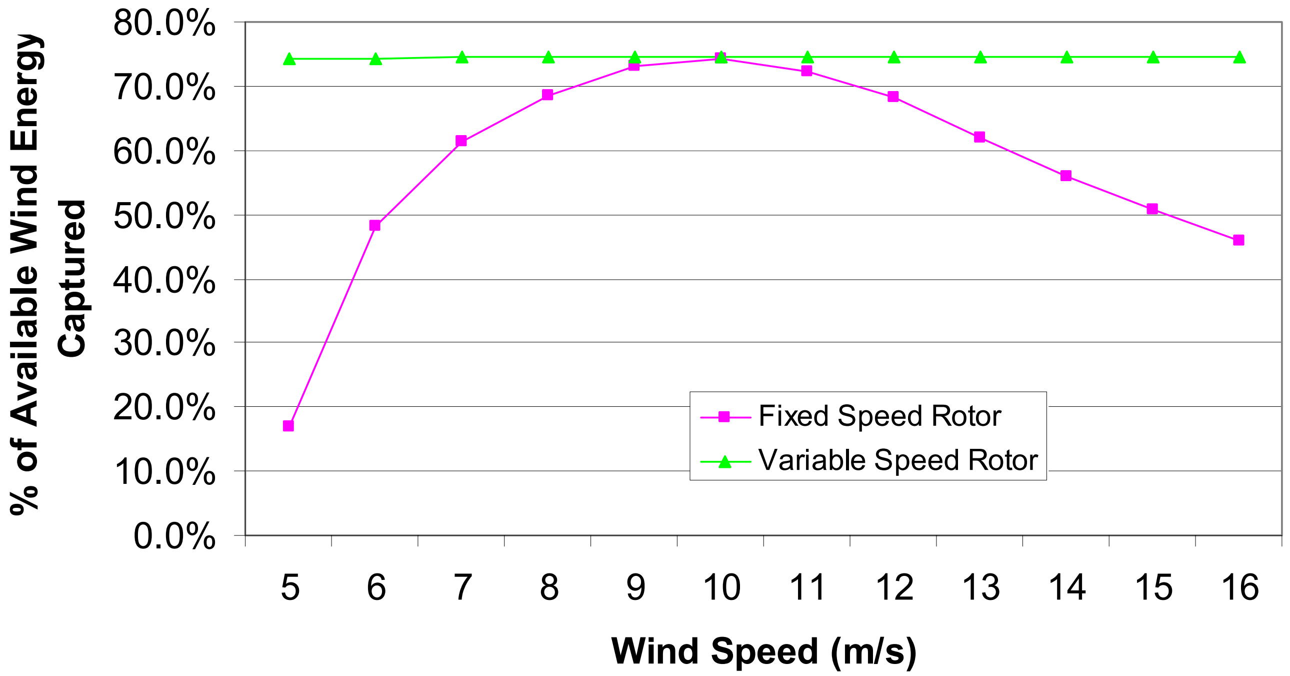
  For a fixed speed turbine there will be an optimum rotor RPM which is dependent on the site's wind distribution.

What is the Best Rotor-to-Generator Ratio for a Given Wind Resource?



- A large rotor-to-generator ratio captures more energy at low wind speeds
- A small rotor-to-generator ratio captures more energy at high wind speeds
- The ratio must be optimized for the site specific wind speed distribution

Fixed Speed Vs Variable Speed Rotor



- The figure above compares the percentage of available wind power (Betz's Limit already accounted for) that a fixed speed rotor and variable speed rotor can capture at each wind speed.
- The variable speed captures more energy at almost all wind speeds. However, the power electronics needed for a variable speed system are costly and take away some of the efficiency gains. Whether the variable speed system is worth the extra cost depends on the sites wind speed distribution.

Wind Turbine Design Optimization Model

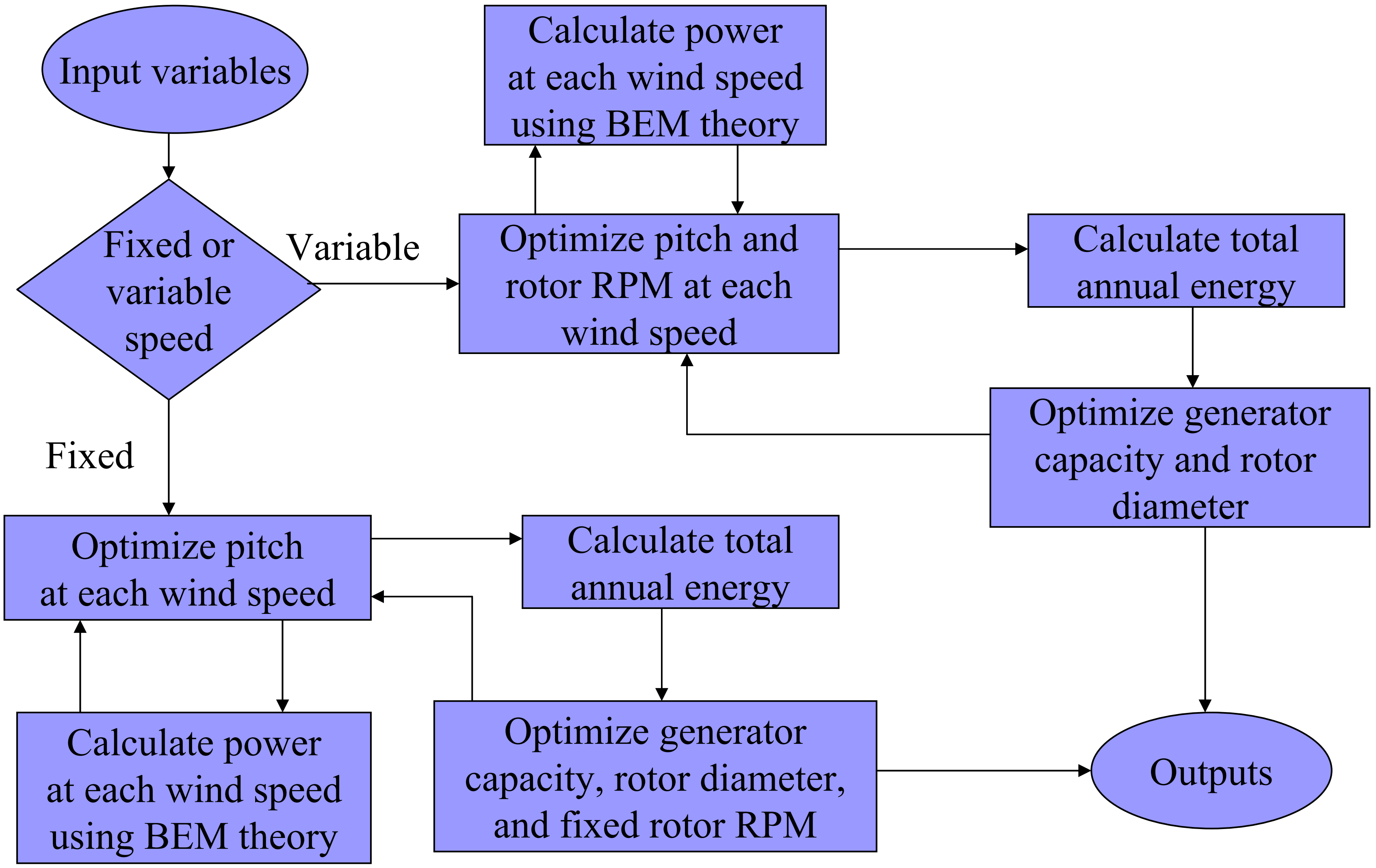
Inputs

- Average wind speed
- Weibull parameter
- Capital investment
- Fixed or variable speed
- Blade coefficients of lift and drag at each wind speed
- Gearbox efficiency
- Generator efficiency
- Power electronics efficiency
- Price of electricity

Outputs

- Optimal rotor diameter
- Optimal generator capacity
- Optimal RPM for fixed speed design
- Optimal blade pitch at each wind speed
- Torque on gearbox at each wind speed
- Power produced at each wind speed
- Maximum total annual energy produced

Wind Turbine Design Optimization Model



Input variables

Fixed or variable speed

Variable

Calculate power at each wind speed using BEM theory

Optimize pitch and rotor RPM at each wind speed

Calculate total annual energy

Optimize generator capacity and rotor diameter

Fixed

Optimize pitch at each wind speed

Calculate total annual energy

Calculate power at each wind speed using BEM theory

Optimize generator capacity, rotor diameter, and fixed rotor RPM

Outputs

Wind Turbine Design Optimization Model

Blade Element Momentum Theory

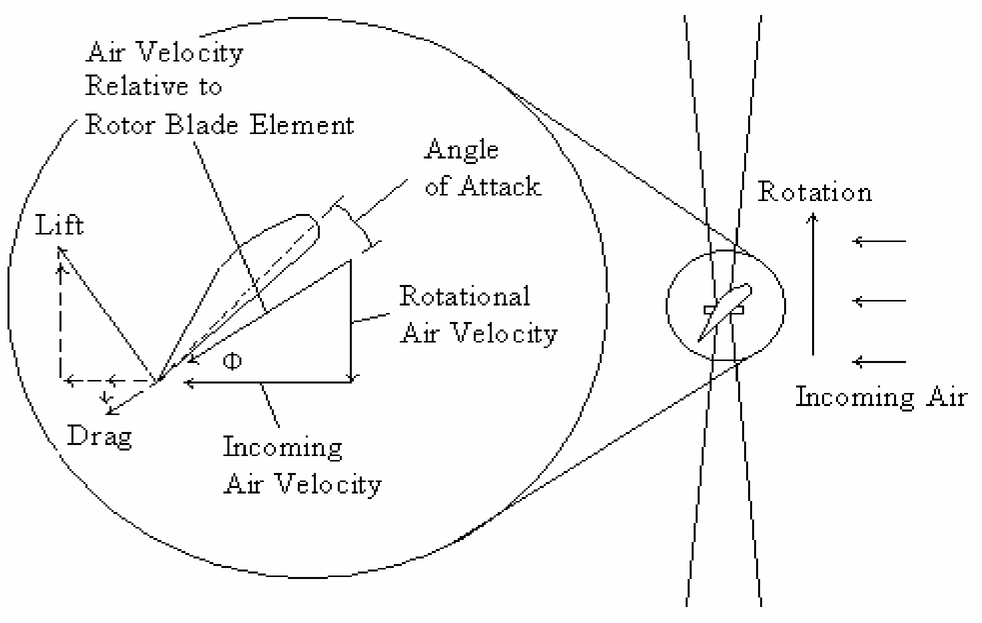
The amount of power a rotor extracts from the wind can be calculated with blade element momentum theory. The power is calculated from the rotor angular velocity and torque, which are found by solving system of nonlinear equations. These equations are derived from two different approaches to calculating power. The first approach determines the power from lift and drag on the rotor blades. The second approach determines power from a momentum balance. The system of nonlinear equations must be solved iteratively with an equation solver.

Optimization Techniques

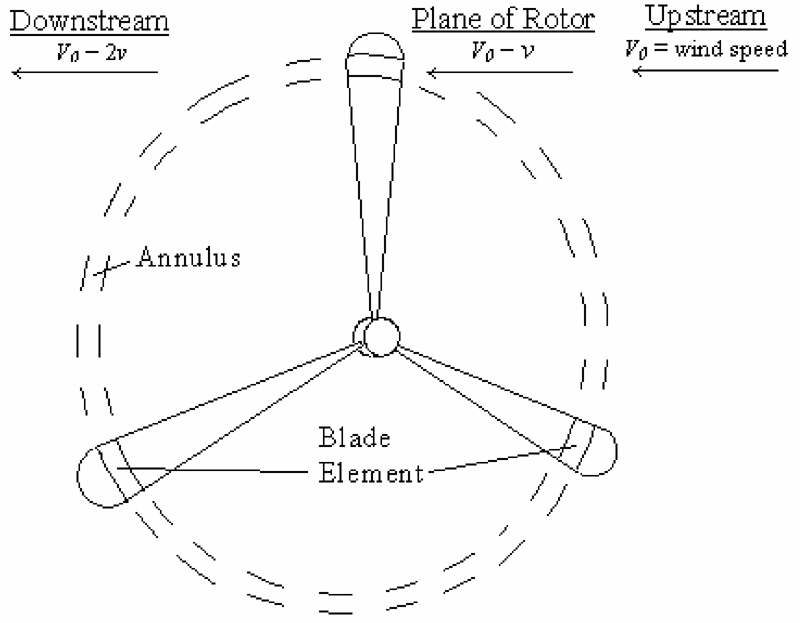
Because there are an infinite combination of possible designs optimization techniques are used to reduce the amount of calculation time needed to determine the optimal wind turbine design. This model uses the golden section method and the simplex method.

Blade Element Momentum (BEM) Theory

Torque & Thrust by Lift & Drag



Torque & Thrust by Momentum Balance



$$\lambda_{1,i} = C_{L,i}\cos\phi_i + C_{D,i}\sin\phi_i \qquad \lambda_{2,i} = C_{L,i}\sin\phi_i - C_{D,i}\cos\phi_i$$

$$\dot{m}_i = \rho A_i (V_0 - v_i) = \rho\left(2\pi R_i \cdot r_i\right)\left(V_0 - v_i\right)$$

$$T_i = \lambda_{1,i}\frac{1}{2}\rho V_i^2 c_i \cdot r_i$$

$$Q_i = \lambda_{2,i}\frac{1}{2}\rho V_i^2 c_i \cdot r_i \cdot R_i$$

$$T_i = \dot{m}_i \cdot 2v_i$$

$$Q_i = \dot{m}_i \cdot 2u_i \cdot R_i$$