RENEWABLE ENERGY (MCE 536)

INTRODUCTION

By 2050, the demand for energy could double or even triple, as the global population rises and developing countries expand their economies. All life on Earth depends on energy and the cycling of carbon. Energy is essential for economic and social development but also poses an environmental challenge. We must explore all aspects of energy production and consumption including energy efficiency, clean energy, global carbon cycle, carbon sources and sinks, and biomass, as well as their relationship to climate and natural resource issues. Knowledge of energy has allowed humans to nourish in numbers unimaginable to our ancestors. The world's dependence on fossil fuels began approximately two hundred years ago. Are we running out of oil? No, but we are certainly running out of the affordable oil that has powered the world economy since the 1950s. We know how to recover fossil fuels and harvest their energy for operating power plants, planes, trains, and automobiles that result in modifying the carbon cycle and additional greenhouse gas emissions. This has resulted in the debate on availability of fossil energy resources, peak oil era and timing for the anticipated end of the fossil fuel era, and price and environmental impact versus various renewable resources and use, carbon footprint, emission and control including cap and trade and emergence of "green power."

Our current consumption has largely relied on oil for mobile applications and coal, natural gas, and nuclear or water power for stationary applications. In order to address the energy issues in a comprehensive manner, it is vital to consider the complexity of energy. Any energy resource - including oil, coal, wind, biomass, and so on- is an element of a complex supply chain and must be considered in the entirety as a system from production through consumption. All of the elements of the system are interrelated and interdependent. Oil, for example, requires consideration for interlinking of all of the elements including exploration, drilling, production, water, transportation, refining, refinery products and byproducts, waste, environmental impact, distribution, consumption/application and finally emissions. Inefficiencies in any part of the system will impact the overall system, and disruption in any one of these elements would cause major interruption in consumption. As we have experienced in the past, interrupted exploration will result in disruption in production, restricted refining and distribution, and consumption shortages; therefore, any proposed energy solution requires careful evaluation and as such, may be one of the key barriers to implement the proposed use of hydrogen as a mobile fuel.

Even though an admirable level of effort has gone into improving the efficiency of fuel sources for delivery of energy, we are faced with severe challenges on many fronts. This includes population growth, emerging economies, new and expanded usage, and limited natural resources. All energy solutions include some level of risk, including technology snafus, changes in market demand, economic drivers, and others. This is particularly true when proposing energy solutions involving implementation of untested alternative energy technologies.

There are concerns that emissions from fossil fuels will lead to climate change with possible disastrous consequences. Over the past five decades, the world's collective greenhouse gas emissions have increased significantly even as efficiency has increased, resulting in extending energy benefits to more of the population. Many propose that we improve the efficiency of energy use and conserve resources to lessen green house gas emissions and avoid a climate catastrophe. Using fossil fuels more efficiently has not reduced overall greenhouse gas emissions due to various reasons, and it is unlikely that such initiatives will have a perceptible effect on atmospheric greenhouse gas content. While there is a debatable correlation between energy use and greenhouse gas emissions, there are effective means to produce energy, even from fossil fuels, while controlling emissions. There are also emerging technologies and engineered alternatives that will actually manage the makeup of the atmosphere but will require significant understanding and careful use of energy.

We need to step back and reconsider our role and knowledge of energy use. The traditional approach of micromanagement of greenhouse gas emissions is not feasible or functional over a long period of time. More assertive methods to influence the carbon cycle are needed and will be emerging in the coming years. Modifications to the cycle means we must look at all options in managing atmospheric greenhouse gases, including various ways to produce, consume, and deal with energy. We need to be willing to face reality and search in earnest for alternative energy solutions. There appear to be technologies that could assist; however, they may not all be viable. The proposed solutions must not be in terms of a "quick approach," but a more comprehensive, long-term (10, 25, and 50 plus years) approach that is science based and utilizes aggressive research and development. The proposed solutions must be capable of being retrofitted into our existing energy chain. In the meantime, we must continually seek to increase the efficiency of converting energy into heat and power.

When an energy engineer[1] thinks of access to energy or energy systems, whether as a professional responsible for the function of some aspect of the system, or as an individual consumer of energy, a wide range of applications come to mind. These application include electricity for lighting or electronics, natural gas for space heating and industrial uses, and petroleum products such as gasoline or diesel for transportation. Access to energy in the industrialized countries of Asia, Europe, and North America is so pervasive that consumption of energy in some form is almost constant in all aspects of modern life—at home, at work, or while moving from place to place. In the urban areas of industrializing and less-developed countries, not all citizens have access to energy, but all live in close proximity to the local power lines and motorized vehicles that are part of t system. Even in the rural areas of these countries, people may not be aware of mode energy systems on an everyday basis, but may come into occasional contact with t through access to food shipments or the use of rural bus services. Indeed, there are very few human beings who live in complete isolation from this system.

If it is true that use of energy is omnipresent in modern life, then it is also true that both individuals and institutions (governments, private corporations, universities, schools, and the like) *depend* on reliable access to energy in all its forms. Without accessibility, the technologies that deliver modern amenities including comfortable indoor temperature, safe food products, high-speed transportation, *and so* on, would quickly cease to function. Even the poorest persons in the less-developed countries may rely on occasion for their survival on shipments of food aid that could not be moved effectively without mechanized transportation.

One of the best ways to define sustainable development is through long-term, affordable availability of resources including energy. There are many potential constraints to sustainable development. Foremost is the competition for water use in energy production, manufacturing, farming, and others versus a shortage of fresh water for consumption and development. Sustainable development is also dependent on the earth's limited amount of soil, and in the not Hence, possible solutions must be comprehensive and based on integrating our energy use with nature's management of carbon, water, and life on Earth as represented by the carbon and hydro-geological cycles. Obviously the challenges presented by the need to control atmospheric green house gases are enormous and require "out of the box" thinking, innovative approach, imagination and bold engineering initiatives in order to achieve sustainable development. We will need to ingeniously exploit even more energy and integrate its use with control of atmospheric greenhouse gases. The continued development and application of energy is essential to the development of human society in a sustainable manner through the coming centuries. All alternative energy technologies are not equal and have risks and drawbacks. When evaluating our energy options, we must consider all aspects including performance against known criteria, basic economics and benefits, efficiency, processing and utilization requirements, infrastructure requirements, subsidies and credits, waste and ecosystem, as well as unintended consequences such as impacts to natural resources and the environment. Additionally, we must include the overall changes and the emerging energy picture based on current and future efforts to modify fossil fuels and evaluate the energy return for the investment of funds and other natural resources such as water.

Also for an energy resources to be reliable, it must first of all, deliver the service that the consumer expects. Secondly, it must be available in the quantity desired, when the consumer wishes to consume it (whether this electricity from a wall outlet or gasoline dispensed from a filling station). Lastly, the resource must be available at a price that is economically affordable.

The above qualities define the reliability of the energy resource, for which the consumer will experience adverse consequences if not met—immediately, should the energy system or device stops functioning correctly, or within a short period of time, if the price of the resource is unaffordable. Longer term, there is another criterion for the energy resource that must be met, and one for which society as a whole suffers negative consequences, even if the individual user does not experience consequences directly from her or his actions and choices: environmental sustainability. At the beginning of the twenty-first century, this dimension of energy use and energy systems is increasingly important. Practices that may have placed negligible stress on the planet 100 or 150 years ago, simply because so few people had access to them, are no longer acceptable today, when billions of human beings already have access to these practices or are on the verge of achieving sufficient wealth to have access to them. Thus the need to deliver energy in a way that is both *reliable,* and *sustainable* places before humanity a challenge that is both substantial and complex, and one that will require the talent and •(forts of engineers as well as research scientists, business managers, government administrators, policy analysts, and so on, for many years, if not decades, to come.

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Classification of Energy

Renewable and Non-Renewable Energy

Renewable energy is energy obtained from sources that are essentially inexhaustible. Examples of renewable resources include wind power, solar power, biomass or bio-energy, geothermal energy, hydroelectric power etc. The most important feature of renewable energy is that it can be harnessed without the release of harmful pollutants.

Non-renewable energy is the conventional fossil fuels such as coal, liquid fuel (Petroleum) natural gas, nuclear etc. which are likely to deplete with time.

Solar energy technologies can be loosely divided into two categories: solar thermal systems and solar electric or photovoltaic (PV) systems.

In wind energy, turbine is being used to produce power by converting the force of the wind (kinetic energy) acting on the rotor blades (rotational energy) into torque (turning force or mechanical energy).

Biomass or Bioenergy is a general term that covers energy derived from a wide variety of material of plant or animal origin. Strictly, this includes fossil fuels but, generally, the term is used to mean renewable energy sources such as wood and wood residues, agricultural crops and residues, animal fats, and animal and human wastes, all of which can yield useful fuels either directly or after some form of conversion.

Hydropower is the extraction of energy from falling water (from a higher to a lower altitude) when it is made to pass through an energy conversion device, such as a water turbine or a water wheel.

Geothermal is energy available as heat emitted from within the earth, usually in the form of hot water or steam. Geothermal heat has two sources: the original heat produced from the formation of the earth by gravitational collapse and the heat produced by the radioactive decay of various isotopes.

1.0 WIND ENERGY

This is electrical energy obtained from harnessing the wind with windmills or wind turbines. Wind energy has been in use for thousands of years to propel boats and ships and to provide rotary windmill power for lifting water and grinding grain. The traditional windmills were mostly made of locally available materials like bamboo, wood planks or combination of these. The windmill as source of mechanical power may be considered as an appropriate technology for rural applications. The available technology for harnessing wind in the World is not yet optimum in terms of cost, reliability, safety, convenience etc. Wind energy can be harnessed from either horizontal or vertical axis type of rotors which are relatively simple in design and construction. Only about 48% of the energy conversion has been possible from such designs and overall efficiency of the system does not exceed 35%.

Before the Industrial Revolution, wind was a major source of power for; water, grinding grain, and long-distance transportation (sailing ships). Even I the peak use of farm windmills in the United States was in the 1930s and 1940s when there were over 6 million, these windmills are still being manufactured and used in the United States and around the world . The advantages and disadvantages of wind energy are similar to most other renewable energy resources: It is renewable (non-depleting) and ubiquitous (located in] regions of the world) and does not require water for the generation of electricity, disadvantages are that it is variable and a low-density source, which then 1 into high initial costs. In general, windy areas are distant from load centers, means that transmission is a problem for large-scale installation of wind farms. The rapid growth of wind power has been due to wind farms with 158,500MW installed by the end of 2009; in addition, there are around 1,000 MW from other applications.

As of 2009, over 70 countries had installed wind power as most countries are seeking renewable energy sources and have wind power as part of their national planning. Therefore, countries have wind resource maps, and others are in the process of determining their wind power potential, which also includes offshore areas.

During the 1930s, small wind systems (100 W to 1 kW) with batteries were installed in rural areas; however, these units were displaced with power from the electric grid through rural electric cooperatives. After the first oil crisis in 1973, there was a resurgence of interest in systems of this size, with the sale of refurbished units and manufacture of new units. Also as a response to the oil crisis, governments and utilities , were interested in the development of large wind turbines as power plants for the grid. Then, starting in 1980s the market was driven by distributed wind in Denmark and wind farm market in California, which led to the significant wind industry today.

Estimation of available wind energy depends on an understanding of the frequency and duration of different wind speeds, which can be measured empirically or modeled using statistical functions. Knowledge of the available wind speeds can be converted to a projection of the average annual output from a specific turbine using a "power curve" for that turbine. The function of the turbine can be modeled with either a simple theoretical model known as an "actuator disc" or a more sophisticated "strip theory" model that takes into account the shape of the wind turbine blades. Both analytic solutions to blade design and approximate solutions that analyze performance at a finite number of points along the blade are presented. Lastly, the economics of both small- and large-scale wind systems are considered, in terms of their ability to repay investment through sales of electricity or displacement of electricity purchases from the grid.

Use of wind energy for human purposes entails the conversion of the kinetic energy that is present intermittently in the wind into mechanical energy, usually in the form of rotation of a shaft. From there, the energy can be applied to mechanical work or further converted to electricity using a generator. As in solar resource , the amount of energy available in the wind around the planet at any one moment in time is vast. However, much of it is too far from the earth's surface to be accessible using currently available technology, and the energy that is accessible requires investment in a conversion device, such as a windmill or wind turbine. Furthermore, no location is continuously windy, and the power (i.e., rate of energy flow) in the wind is highly variable, requiring provision both for alternative energy supplies during times of little or no wind, and means of protecting the wind energy conversion device from damage in times of extremely high wind.

While the use of wind energy for mechanical applications such as grinding grain dates back many centuries, the use of wind power for the generation of electricity, which is the focus of this chapter (specifically at a utility scale as opposed to residential scale), dates back to the end of the nineteenth century. Early machines were based on windmill designs for water pumping, and produced limited output. Throughout the twentieth century, the design of the small-scale wind turbine evolved toward fewer blades, lighter weight, and faster rotational speeds. Although some attempts were made at utility-scale wind devices in the mid-twentieth century, these efforts did not bear fruit, so that through the 1930s and 1940s, wind turbines were developed on the scale of tens of kilowatts, especially for rural locations, prior to national electrification efforts. As of the 1960s, the only commercially available devices capable of generating electricity were sized for powering households or farms, especially in remote locations that were not easily reached by the electric grid.

The evolution of the modern utility scale wind turbine began with experimental devices in the 1970s that tested many possible design variables: horizontal or vertical axis; one, two, or three blades; or blades upwind or downwind of the tower. By the early 1980s, turbines began entering the U.S. market for grid electricity, especially in California, and the total installed capacity of these devices in the United States grew from a negligible amount in 1980 to approximately 2500 MW in the year 2000. Thereafter the U.S. market entered an accelerated growth phase, reaching some 9100 MW by the end of 2005 and 40,300 MW by the end of 2010.

World use of wind energy has been growing rapidly as well in recent years. In 2002, there were 32,400 MW of large-scale wind power in use by utilities around the world; by 2005, this figure had reached 59,100 MW, and by 2010, it had reached 195,000 MW. Global leaders in terms of share of the 2010 total installed capacity include China (22%), United States (21%), Germany (14%), Spain (11%), and India (7%) . Note that statistics on total installed capacity should be seen in context. In the year 2009, installed capacity of fossil fuel powered plants in the United States alone totaled 772,000 MW.

The success of the large-scale wind turbine emerged from advances involving several engineering disciplines. First, an improved understanding of the fluid dynamics of wind moving past the device enabled improved design of the turbine blade. Second, improved materials allowed for the fabrication of large turbines that were both light and strong enough to perform robustly and efficiently, and also increasing the maximum *swept area* (i.e., circular area formed by the rotational span of the turbine blades) of the device, which helped to reduce the cost per kWh.

Wind Resource

The primary difference between wind and solar power is that power in the wind increases as the cube of the wind speed:

$$P/A = 0.5 * p * v^3, \text{ W/m} \quad \cdots\cdots\cdots\cdots \quad (1)$$

Where p is the air density, and v is the wind speed. The power/area is also referred to as wind power density. The air density depends on the temperature and barometric pressure, so wind power will decrease with elevation, around 10% per 1,000 m. The average wind speed is only an indication of wind power potential, and the use of the average wind speed will underestimate the actual wind power. A wind speed histogram or frequency distribution is needed to estimate the wind power/area. For siting of wind farms , data are needed at heights of 50 m and probably at hub heights. Since wind speeds vary by hour, day, season, and even years, 2 to 3 yr of data are needed to have a decent estimate of the wind power potential at a specific site. Wind speed data for wind resource assessment are generally sampled at 1 Hz and averaged over 10min (sometimes 1 hr). From these wind speed histograms (bin width of 1 m), the wind power/area is determined.

Wind Shear

Wind shear is the change in wind speed with height, and the wind speed at higher heights can be estimated from a known wind speed. Different formulas are available, but most use a power law.

$$\frac{v}{v_0} = (\frac{H}{H_0})^{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where v is the estimated wind speed at height *H,* v_0 is the known wind speed at height H_0 and α is the wind shear exponent. The wind shear exponent is determined from measurements; in the past, a value of 1/7 (0.14) was used I'm stable atmospheric conditions. Also, this value meant that the power/area doubled from 10 to 50 m, a convenient value since the world meteorological standard for measurement of wind speed was a height of 10 m.

In many continental areas, the wind shear exponent is larger than 0.14, and the wind shear also depends on the time of day , with a change in the pattern from day to night at a height around 40 m. This means that wind farms will be producing more power at night when the load of the utility is lower, a problem for the value of the energy sold by the wind farm. There is more power in the wind at 40 m and higher heights than determined by data taken at a height of 10 m . The pattern of the data at 50 m for Washburn (not shown on graph) was similar to the 50-m data at White Deer; however, there was some difference between the two sites. Both sites were in the plains, around 40 km apart. This shows that wind power is fairly site specific. Wind data for wind farms has to be taken at heights of at least 40 m to 50 m as at these heights and above the wind pattern will be same, and the wind speeds at higher heights at the same site can be estimated using equation 2. There are some locations, such as mountain passes, where there is little wind shear so taller towers for wind turbines would not be needed.

Wind Turbines

Wind turbines are classified according to the interaction of the blades with the wind, orientation of the rotor axis with respect to the ground and to the tower (upwind, downwind), and innovative or unusual types of machines. The interaction of the blades with the wind is by drag, lift, or a combination of the two.

For a drag device, the wind pushes against the blade or sail, forcing the rotor to turn on its axis, and drag devices are inherently limited in efficiency since the speed of the device or blades cannot be greater than the wind speed. The maximum theoretical efficiency is 15%. Another major problem is that drag devices have a lot of material in the blades. Although a number of different drag devices have been built, there are essentially no commercial (economically viable) drag devices in production for the generation of electricity.

Most lift devices use airfoils for blades (Figure below), similar to propellers or airplane wings; however, other concepts are Magnus (rotating cylinders) and Savonius wind turbines . A Savonius rotor is not strictly a drag device, but it has the same characteristic of large blade area to intercept area. This means more material and problems with the force of the wind on the rotor at high wind speeds, even if the rotor is not turning. An advantage of the Savonius wind turbine is the ease of construction. Using lift, the blades can move faster than the wind and are more efficient in terms of aerodynamics and use of material, a ratio of around 100 to 1 compared to a drag device. The tip speed ratio is the speed of the tip of the blade divided by the wind speed, and lift devices typically have tip speed ratios around seven. There have even been one-bladed wind turbines, which saves on material; however, most modern wind turbines have two or three blades. The power coefficient is the power out or power produced by the wind turbine divided by the power in the wind. A power curve shows the power produced as a function of wind speed (Figure 3). Because there is a large scatter in the measured power versus wind speed, the method of bins (usually 1 m/s bin width suffices) is used.

Wind turbines are further classified by the orientation of the rotor axis with respect to the ground: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT).The rotors on HAWTs need to be kept perpendicular to the wind, and yaw is the relation of the unit about the tower axis. For upwind units, yaw is by a tail for small wind turbines and a motor on large wind turbines; for downwind units, yaw may be by coning (passive yaw) or a motor.

YAWTs have the advantage of accepting the wind from any direction. Two examples of VAWTs are the Darrieus and giromill. The Darrieus shape is similar to the curve of a moving jump rope; however, the Darrieus is not self-starting as the blades have to be moving faster than the wind to generate power. The giromill can have articulated blades that change angle, so it can be self starting. Another advantage of VAWTs is that the speed increaser and generator can be at ground level. A disadvantage is that taller towers are a problem for VAWTs, especially for units of wind farm size. Today, there are no commercial, large-scale VAWTs for wind farms, although there are a number of development projects and new companies for small VAWTs. Some companies claim they can scale to megawatt size for wind farms.

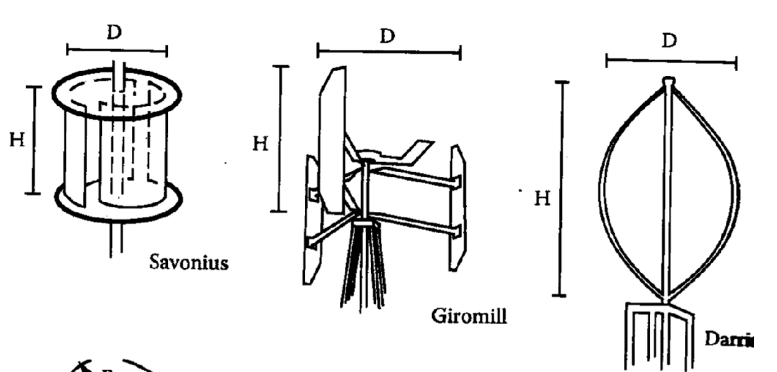
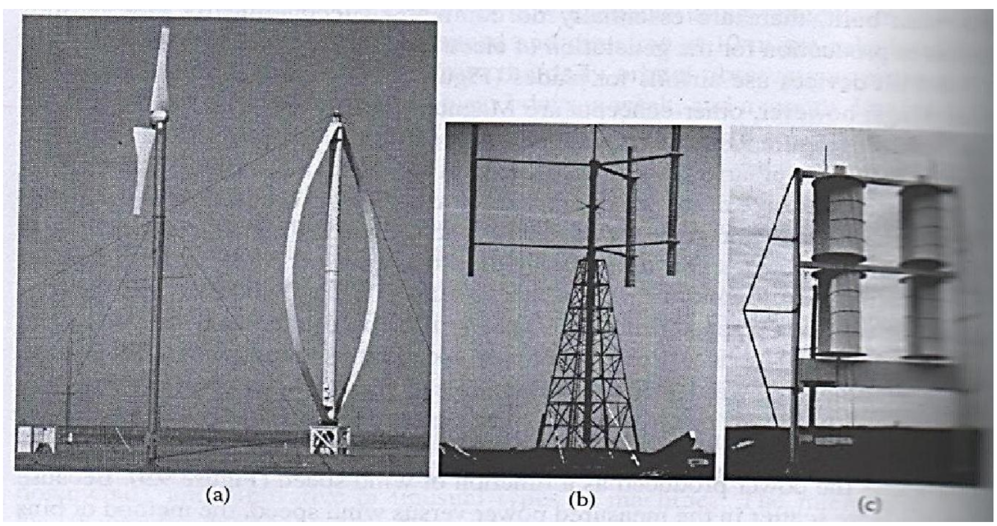


Diagram of different rotors for horizontal and vertical axis wind turbines.

The total system consists of the wind turbine and the load, which is also called a wind energy conversion system ("WECS). A typical large wind turbine consists of the rotor (blades aid hub), speed increaser (gearbox), conversion system, controls, and the tower (Figure 4). The most common configuration for large wind turbines is three blades, full-span pitch control (motors in hub), upwind with yaw motor, speed increaser (gearbox), and doubly fed induction generator (allows a wider range of revolutions per minute for better aerodynamic efficiency). The nacelle is the covering or enclosure of the speed increaser and generator.



Examples of different wind turbines, a) HAWT (b) Giromill (c) Savonius

The output of the wind turbine, rotational kinetic energy, can be converted to mechanical, electrical, or thermal energy. Generally, it is electrical energy. The generators can be synchronous or induction connected directly to the grid or a variable-frequency alternator (permanent magnet alternator) or direct current generator connected indirectly to the grid through an inverter.

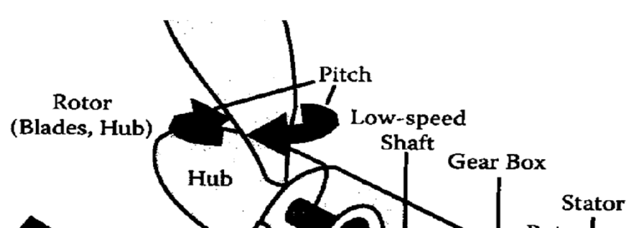
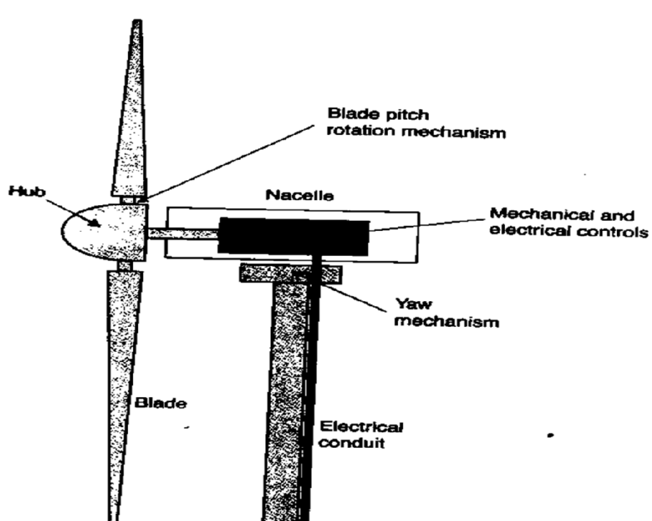


Figure 4. Diagram of main components of large wind turbine.

Components of a Turbine

The horizontal axis wind turbine (HAWT) system consists of blades attached to a central hub to form a rotor that rotates when force is exerted upon them by the wind. The hub is in turn attached to a driveshaft that transmits rotational energy to the interior of the *nacelle,* a central enclosure that sits atop the turbine tower and is rotated by a "yaw mechanism" on a vertical axis to face the wind from any direction. Here "yaw" is defined as the angular orientation of the nacelle and rotor around its vertical axis. The nacelle contains the bearing for the driveshaft, the transmission, generator, mechanical brake, and gears and drives to change both the orientation of the nacelle and the pitch of the turbine blades. Because it is difficult to access the nacelle, controls and monitors are installed inside the base of the tower, when possible. Major components of the turbine system are shown in below.



Main parts of a utility-scale wind turbine

Darrieus wind turbine

"Eggbeater" turbines, or Darrieus turbines, were named after the French inventor, Georges Darrieus. They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source, or an additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

Giromill

A subtype of Darrieus turbine with straight, as opposed to curved, blades. The cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting . The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V, or curved blades may be used.

Savonius wind turbine

These are drag-type devices with two (or more) scoops that are used in anemometers, *Flettner* vents (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops.

Using Wind Data to Evaluate a Potential Location

The viability of wind energy at a given site depends on having sufficient wind speed available at the height at which you intend to install the turbine. Long-term data gathering of wind speed data at many sites over multiyear periods shows that once the average and variance of the wind speed are known, these values are fairly consistent from year to year, varying no more than 10% in either direction in most locations.

There are two levels of detail at which to measure wind speed. The first approach is to measure the average wind speed with a limited number of readings, or to obtain such a measure from a *statistical wind map* that uses wind data from nearby locations and information about terrain and prevailing winds to estimate the average wind speed.

The other approach is to measure the wind continuously at the site throughout the year (or through multiple years), and assign each of the 8760 h in the year to a wind speed "bin" based on the average speed for that hour. Naturally, the latter approach costs more and takes longer to record, but allows the analyst to more accurately predict how well the turbine will perform.

In this section, we will start with a data set based on detailed wind measurement and then compare the results with others based on use of the average wind speed for the same site. The detailed wind data set for a hypothetical site (see Table 1) is based on continuous wind data gathering for an entire year. Note that the table is formatted as shown for reasons of brevity and simplicity; in the wind industry, bins are often broken down in 0.5 m/s increments and centered on half or whole m/s average speeds, for example, a bin might be created between 0.75 and 1.25 m/s, with a 1 m/s average speed. For this site, the winds range between 0 and 14 m/s, except for 2 h/year where they exceed this value. The wind speed distribution is typical of a flat area with no obstructions close to the turbine, and would be characterized as "fair" in terms of its potential for wind power development . In other words, a private entity such as a household or small business might be able to develop the resource, since they would then avoid *paying* grid charges to bring electricity in, but the average wind speed is not high enough to compete with the best sites for *wind farms* (i.e., facilities with multiple large turbines, sometimes also called *wind parks).*

For comparison, the site used by the utilities at Fenner, New York, near Syracuse, New York, in the United States, averages 7.7 m/s (17 mph) year round at the turbine hub height of 65 m. The data are divided up into "bins," where the number of hours per year that the wind speed is in the given bin is shown in the table (e.g., for bin 1,80 h/year of no wind, and the like). The hours per year can be translated into a percentage by dividing the number of hours in the bin by 8760 h total per year. The last column gives the average wind speed for the bin. Taking a weighted average of the bin average wind speed gives the following:

$$U_{average} = \sum_{i=1}^{n} p_i \; U_{i\,average} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Here $U_{average}$ = average speed for the site, p_i = percentage of year that wind speed is in bin /', and $U_{i\ average}$ = average speed for the bin i. The calculation gives $U_{avm\ e}$ = 5.57 m/s for the year, as shown. Note that the 2 h for bin 16 are not included in the average speed calculation since the bin average speed is unknown.

Wind Data Distributed by Bins for Hypothetical Site (Average wind speed 5.57m/s or 12.2mph)

Bin	Wind Speed		hours/year	Frequency (pct)	Bin Avg. Speed (m/s)
	Mln. (m/s)	Max. (m/s)			
1	0	0	80	0.9%	0
2	0	1	204	2.3%	0.5

3	1	2	496	5.7%	1.5
4	2	3	806	9.2%	2.5
5	3	4	1211	13.8%	3.5
6	4	5	1254	14.3%	4.5
7	5	6	1246	14.2%	5.5
8	6	7	1027	11.7%	6.5
9	7	8	709	8.1%	7.5
10	8	9	549	6.3%	8.5
11	9	10	443	5.1%	9.5
12	10	11	328	3.7%	10.5
13	11	| 12	221	2.5%	11.5
14	12	13	124	1.4%	12.5
15	13	14	60	0.7%	13.5
16	**14**	**1 No upper bound**	**2**	**0.02%**	—

Using Statistical Distributions to Approximate Available Energy

The distribution of wind speeds in Table provides *a* solid basis for calculating available energy at this site. However, suppose we only knew $U_{average}$ =5 57 m/s, and did not have the hourly bin data for the year.

Observations have shown that in many locations, if the average wind speed is known, the probability of the wind speed being in a given range can be predicted using the *Weibull* or *Rayleigh* distributions from probability and statistics, the Rayleigh being a special case of the Weibull. The probability density function (PDF) for the Weibull distribution has the following form:

$$f(x) = \frac{k}{\sigma}\left(\frac{x}{\sigma}\right)^{\boldsymbol{k-1}} \exp[-(x/p)^k], \text{ for } x \geq 0 \text{ ....} (4)$$

f(x) = 0, f x < 0

where *k* and *a* are shape and scale parameters, respectively, and .x is the independent variable for which the PDF is to be evaluated. Integrating from 0 to x gives the cumulative distribution function (CDF) as follows:

$$F(x) = 1 - \exp[-(x/p)^k], \text{ for } x \geq 0 \quad \text{...} (5)$$

If we set the shape factor to *k = 2, we* arrive at the particular instance of the Weibull called the Rayleigh function, which has the following PDF:

$$f(x) = 2x.\ \frac{\exp[-x/p)^2)]}{\sigma^2} \text{ for } x \geq 0 \quad \text{..................................} (6)$$

The CDF for the Rayleigh is then

F(x) = 0, for x <

$$F(x) = 1 - \exp[-(x/\sigma)^2], \text{ for } x \geq 0 \text{ ....} (7)$$

For analysis of the distribution of wind speed, it is convenient to rewrite the CDF in Eq. in terms of *a* given wind speed U and the average wind speed *U*average. From probability and statistics it is known that the expected value of a Rayleigh function is $\bar{x}=\sigma.(\pi/4)^{1/2}$. Substituting $U_{average}$ for $\bar{x}$ and rearranging to find the scale factor in terms of known values gives:

$$\sigma = U\text{average}.(\pi/4)^{1/2} \qquad \ldots\ldots(8)$$

Substituting Eq. (6) into Eq. (5) and simplifying gives

$$F(U) = 1\text{-}\exp[-(\frac{U}{U_{average(4/\pi)^{1/2}}})^2]$$

$$= 1\text{-}\exp[-(\frac{1}{4/\pi})(\frac{U}{U_{average}})^2]$$

$$= 1\text{-}\exp[(-\frac{\pi}{4}(\frac{U}{U_{average}})^2)] \qquad \ldots\ldots \quad (9)$$

The CDF is used to calculate the probability that the wind speed will be at or below a given value *U,* givena known value of $U_{average}$

$$p(\text{wind speed}<U) = 1 - \exp[(-\pi/4)(U/U_{average})^2] \qquad \ldots\ldots(10)$$

So, for example, substituting the value U= 4 m/s into Eq. (4), the probability with $U_{average}$ = 5.57 m/s that the wind speed is less than or equal to this value is 32%. The application of the Rayleigh distribution to working with wind speed bins is illustrated in Example 1.

Example 1 Using the Rayleigh distribution and $U_{average}$ = 5.57 m/s, calculate the probability that the wind is in bin 6.

Solution The probability that the wind is in the bin is the difference between the probability of wind at the maximum value for the bin, and the probability of the minimum value. Bin 6 is between 4 and 5 m/s. From Eq. (8) above

$P(wind\ speed \leq 4) = 1 - \exp[(-\pi/4)(4/5.57)^2] = 0.33 = 33\%$

$Pfwind\ speed \leq 5) = 1 - \exp[(-\pi 4)(5/5.57)^2] = 0.469 = 46.9\%$

Therefore, the bin probability is 46.9% - 33.3% = 13.6%. This is the value obtained using the Rayleigh distribution; the observed value is 1254 h/8760 h/year = 14.3%.

To show how well the estimate using the Rayleigh distribution fits the above data, we can plot them next to each other, as shown below. From visual inspection, the Rayleigh estimated curve fits the observed data fairly well. Note that the estimating technique must be used with caution: although it happened to fit this data set well, there is no guarantee that for another location, the fit might not be quite poor, for example, in a case where the observed distribution has more than one peak. In order to understand the impact of using an estimated versus observed distribution for wind speed, we will calculate the estimate of energy available in th wind using both methods. For a given wind speed and swept area of a turbine A, the power P in watts available in the wind is calculated as follows

$$P = 0.5\rho U^3 A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Comparison of observed and Rayleigh estimated probabilities of wind speeds in a given bin for wind speeds up to 14m/s . Here p is the density of air in kg/m^3, which often has values on the order of 1 kg/m^3, depending on elevation above sea level and current weather conditions. From Eq. (9), the amount of energy available in the wind grows with the cube of the wind speed, so there is much more energy available in the wind at high wind speeds. For example, per unit of swept area, at $U_{average}$ and ρ= 1.15 kg/m^3, the available power density is 99 W/m^2, but it the upper range of the bins at 14 m/s, the power density is 1578 W/m^2. Variation in air density plays a significant role as well: values as low as 0.9 and as high as 1.3 kg/m^3 are observed, depending on the site. With air density at the low end of this range, P_i is reduced by 31% compared to the high value, all other things being equal.

Based on the actual bin data, we can calculate the annual energy available at the site by calculating the power available in kW in each bin, based on the bin average speed, and multiplying by the number of hours per year to obtain energy in kWh. Example 2 tests the accuracy of the Rayleigh function compared to the observed data.

Example 2. Suppose a wind analyst calculates the wind energy available at the site given in Table 1, knowing only wind speed U tor the site and using a Rayleigh function to calculate probabilities for the given wind bins. By what percent will the estimated energy differ from the value obtained if the bin data are known? Use an air density value of p = 1.15 kg/m^3.

Solution Using Eq. (9) to calculate the power available in each bin and the percentage of the year in each bin to calculate the number of hours, it is possible to generate a table of observed and estimated energy values by bin. We will use bin 6, for which we calculated statistical probability in Example 1, as an example. The average speed in this bin is 4.5 m/s; therefore, the average power available is P = $(0.5)(1.15)(4.5)^3 = 52.4$ W/m^2

According to the Rayleigh estimate, the wind is in the bin for (0.136)(8760h/year) = 1191 h/year. Therefore, the values of the observed and estimated output in the bin are, respectively

$$E_{observed} = (1254\,\frac{h}{year})(52.4\frac{W}{m^2}) = 65.7\ \text{kWh/m}$$

$$E_{estimated} = (1191\,\frac{h}{year})(52.4\frac{W}{m^2}) = 62.4\ \text{kWh/m}^2$$

Repeating this process for each bin gives the following results

Bin	Power Density (W/m^2)	Annual Output	
		Observed (kWh/m^2)	Estimated (kWh/m*)
1	0.00	0.0	0.0
2	0.07	0.0	0.0
3	1.94	1.0	1.2
4	8.98	7.2	8.5
5	24.65	29.9	27.9
6	52.40	65.7	62.4
7	95.67	119.2	108.2
8	157.91	162.2	155.9
9	242.58	172.0	194.2
10	353.12	193.9	214.1
11	492.99	218.4	212.2
12	665.63	218.3	191.2
13	874.50	193.3	158.0
14	! 1123.05	139.3	120.5
15	1414.72	84.9	85.1
Total		1605.1	1539.3

From the observed data, this value is 1605 kWh/m^2, while for the Rayleigh estimate, the value is 1539 kWh/m^2, excluding any wind above bin 15. So the Rayleigh underestimates the energy available at the site by a factor of 4.1%.

PERFORMANCE

In the final analysis, performance of wind turbines is reduced to energy production and the value or cost of that energy in comparison to other sources of energy. The annual energy production (AEP) can be estimated by the following methods:

Generator size (rated power)

Rotor area and wind map value Manufacturer's curve of energy versus annual average wind speed. The generator size method is a rough approximation as wind turbines with the same size rotors (same area) can have different size generators, but it is a fairly good first approximation.

AEP = OF * OS * 8,760, kWh/yr or in MWh/yr ……………………… (12)

where AEP is the annual energy production, CF is the capacity factor, GS is the rated power of tile wind turbine, and 8,760 is the number of hours in a year. The CF is the average power divided by the rated power. The average power is generally calculated by knowing the energy production divided by the hours in that time period (usually a year or can be calculated for a month or a quarter). For example, if the AEP is 4,500 MWh for a wind turbine rated at 1.5 MW, then the average power = energy/hours = 4,500/8.760=0.5 MW, and the CF would be 0.5 M W/1.5 MW = 0.33 = 33%, So, the CF is like an average efficiency.

CFs depend on the rated power versus rotor area as wind turbine models can have different size generators for the same size rotor or the same size generators for different size rotors for better performance in different wind regimes. For wind farms, CFs range from 30% to 45% for class 3 wind regimes to class 5 wind regimes.

Example 3

Estimate the AEP for a 2-MW wind turbine in a class 4 wind regime. Since class 4 is a good wind regime, $Cf = 40\% = 0.40$.

Use Equation 10.

AEP = 0.4 x 2 MW x 8,760 h = 7,000 MWh/yr

Availability is the time the wind turbine is available to operate, whether the wind is or is not blowing. The availability of wind turbines is now in the range of 95-98%. Availability is also an indication of quality or reliability of the wind turbine. So. the AEP in the example is reduced to 6,650 MWh/yr for an availability of 95%. If the wind turbine is located at higher elevations, then there is also a reduction for change in density (air pressure component) of around 10% for every 1,000 m of elevation.

Since the most important *factors* are the rotor area and the wind regime, the AEP can be estimated from

AEP = CF x Ar x W_M x 8.76, kWh/yr ………………………….. (13)

where Ar is the area of the rotor *(m^2);* W_H is the value of power/area for that location from the wind map (W/m[a]); and 8.76 h/yr converts watts to kilowatts,

Example 4

For a wind turbine with rotor diameter of 60 m in a region with 450 W/m[J], Assume the CF is 0.40.

Rotor area = πr^2 = 3.14 x 30 x 30 = 2,826 m^2

AEP = 0.40 x 2,826 x 450 x 8.76 = 4,450 MWh/yr

If the availability is 95%, then the AEP = 4,200 MWh/yr,

The manufacturer may provide a curve of AEP versus annual average wind speed , where AEP is calculated from the power curve for that wind turbine and a wind speed histogram calculated from average wind speed using a Rayleigh distribution .

The best estimate of AEP is the calculated value from measured wind speed data and the power curve of a wind turbine (from measured data). The calculated AEP is just the multiplication of the power curve value times the number of hours for each bin (Table), If the availability is 95% and there is a 10% decrease due to elevation, then the calculated energy production would be around 2,600 MWh/yr.