LCP 4A: Wind Energy

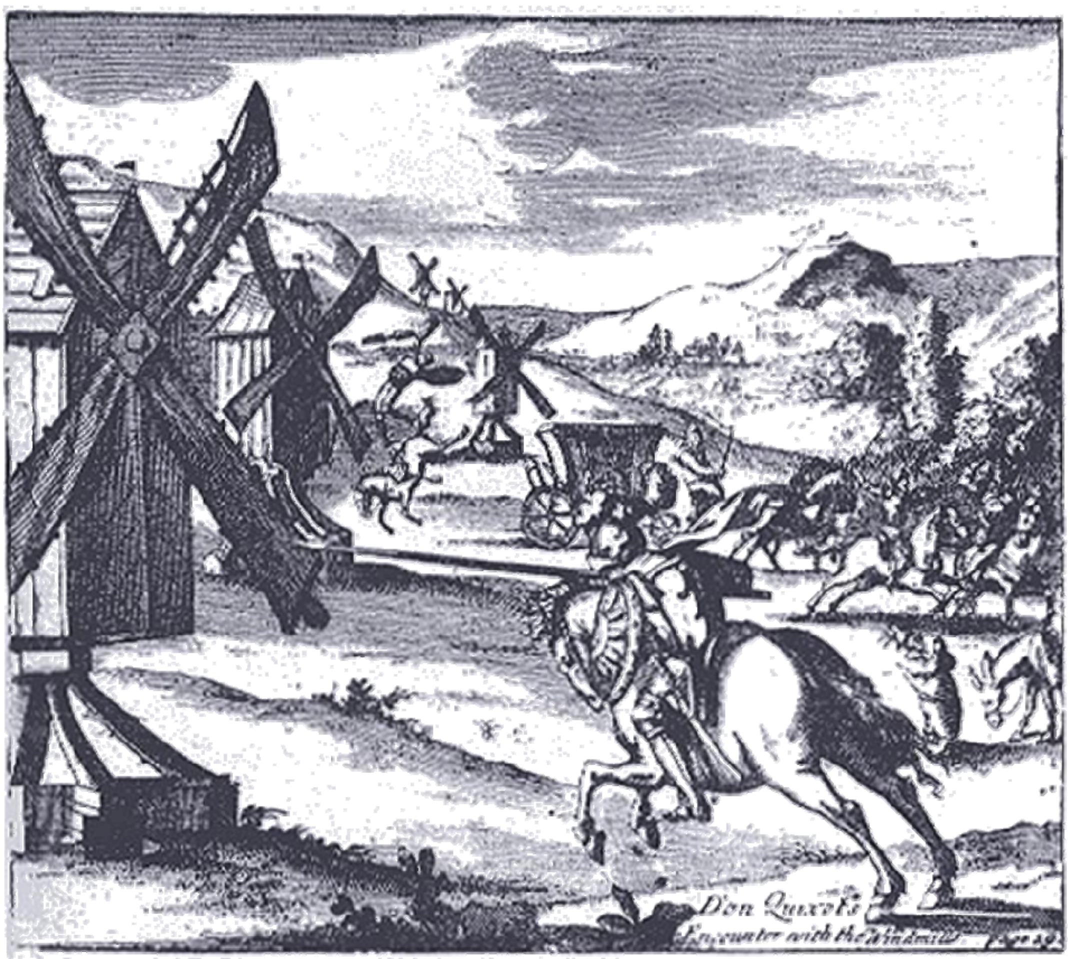


Fig. A: Don Quixote 17th-century Spanish tale about a madcap knight "chasing wind mills", by Miguel de Cervantes.

Fig. B: The sun sets behind a wind farm near Montezuma, Kansas. The farm's 170 turbines can generate enough electricity to power 40,000 households. AP/WWP Photo by Charlie Riedel

<u>IL 0</u> Source of figure B

a. 16th century (Europe) b. 19th century (US) c. Modern (US) Water Turbines

Fig. 1: Watermills and Water Turbines

a. 19th century (US) **b. Early 20th century (Dutch)** **c. Modern wind turbines (Danish)**

Fig. 2: Windmills and Wind Turbines

IL 1 *** History of watermills

IL 2 *** History of windmills

IL 3 *** History of watermills, good diagram of a modern hydroelectric plant

IL 4 **** A very comprehensive and detailed history of wind energy

THE MAIN IDEA

We hear a great deal about microrobots and nanotechnology but not very much about macrorobots. Good examples of macrorobots are radio telescopes, oil tankers, the International Space Station, and the revolving space station (RSS) that we will discuss later. These are all constructions beyond human scale. The macrorobots we will discuss here are the Giant Wind Turbines (GWT), recently established in Manitoba in St. Leon (63 turbines of 99 MW output) and then we will investigate the giant solar furnace (GSF) in Southern France. Each GWT in St. Leon as well as the GSF in Southern France, produce about 1 megawatts of power. The power of the GWT is used for producing electricity and that of the GSF is used mostly for chemical and physical experiments. The Louis Pyrenees solar furnace in France is still the largest in the world.

The GWT is truly a renewable energy production machine but the GSF is really only a giant research instrument. The study of the GWTs will be preceded by an investigation of the physics of a working water mill based on the technology of the late nineteenth century and a windmill of the type used in rural areas in the 1930’s. In LCP 4 B the study of the GSF will be introduced by the physics and construction of a solar cooker, followed by showing how can we can design solar collectors for household and design of robots on the human scale. We can also discuss the physics of voltaic cells and solar energy collection on the meso and macro scales (meso is between 10^{-7} and 10^{-9} m).

The first context in LCP 4A will be based on information and data given by Manitoba Hydro about the Wind Farm of St, Leon, completed in 2006. The second context (in LCP 4B) is based on a 1972 Time Magazine's Science section that described the world's largest solar furnace in sufficient technical detail to allow the setting for an investigation. The data, given in 1972, for the GSF is largely still valid today, but we will supplement it with data available on the Internet. The background information for the GWT is taken from the Internet and articles from journals like *The Physics Teacher* and *Physics Education*. A research article written by the author, "Solar Power for Northern Latitudes", published in the *The Physics Teacher* in 1978, will also be consulted.

Both contexts will involve a great deal of students' knowledge of physics and, with some guidance, can lead to the asking of a series of questions that in turn will suggest problems and experimentation we find in textbooks but will also go beyond the textbook. In summary, the questions generated by these two LCPs lead to the discussion of electricity, magnetism, mechanical energy, radiation, optics, wave motion, thermodynamics, solar energy, thermonuclear reactions, and BB radiation, and those generated by the GWT lead to a discussion of the physics of wind energy, electric power production, electric storage and electric circuits.

Wind is the world's fastest growing energy source with sustained world wide growth rates in excess of 30% annually. By the end of 2005, world-wide wind-generated capacity was almost 60,000 megawatts (MW). Canada has 683.5 MW of installed capacity (March 2006) and the Canadian market is growing by about 50% a year. Estimates suggest that wind generated electricity could represent over 3% of Canadian electricity demand by 2015 from about 1% currently. According to the Canadian Wind Energy Association, we have about 50,000 MW of developable wind resource - enough to supply about 20% of Canada's electricity supply. It is noteworthy that Denmark's electric power supply is largely based on wind energy, or about 3 0% of the rewired electric energy.

THE DESCRIPTION OF THE CONTEXT

A. The Giant Wind Turbine

There is evidence that wind energy was used to propel boats along the Nile River as early as 5000 B.C. Simple windmills were also used in China to pump water and grind grain. In the United States, millions of windmills were erected to pump water for farms and ranches as the American West was developed during the late 19th century. By 1910, many European countries were using wind turbine generators to produce electricity.

In Europe, windmills were developed in the Middle Ages. The earliest mills were probably grinding mills. They were mounted on city walls and could not be turned into the wind. The earliest known examples date from early 12th century Paris. Because fixed mills did not suffice for regions with changing wind directions, mill types that could be turned into the wind were developed. Soon wind mills became versatile in windy regions for all kinds of industry, most notably grain grinding mills, sawmills (late 16th century), threshing, and, "pumping mills" that were built by applying Archimedes' screw principle.

IL 5 *** Pictorial history of the water mill

IL 6 *** Elementary, but very comprehensive discussion of wind power.

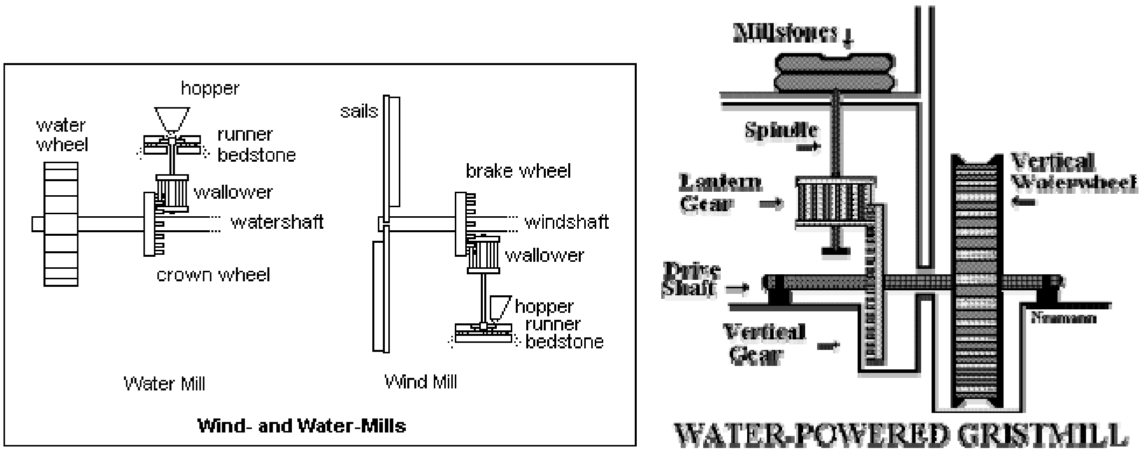


Fig. 3: Detail of Wind and Water Mills Gear System

With increasing environmental concern, and approaching limits to fossil fuel consumption, wind power has regained interest as a renewable energy source. The new generation of windmills produces electric power and is more generally referred to as wind turbines.

The development of the water-pumping windmill in the USA and Canada was the major factor in allowing the farming and ranching of vast areas of North America, which were otherwise devoid of readily accessible water. They contributed to the expansion of rail transport systems throughout the world, by pumping water from wells to supply the needs of the steam locomotives of the emerging railroads. They are still used today for the same purpose in some areas of the world where a connection to electric power lines is not a realistic option.

The multi-bladed wind turbine atop a lattice tower made of wood or steel was, for many years, a fixture of the landscape throughout rural America and Canada. These mills, made by a variety of manufacturers, featured a large number of blades so that they would turn slowly but with considerable torque in low winds and be self regulating in high winds. A tower-top gearbox and crankshaft converted the rotary motion into reciprocating strokes carried downward through a pole or rod to the pump cylinder below.

Windmills and related equipment are still manufactured and installed today on farms and ranches, usually in remote parts of the western United States and Canada where electric power is not readily available. The arrival of electricity in rural areas in the 1930s through the 1950s, contributed to the decline in the use of windmills. Today, however, increases in energy prices and the expense of replacing electric pumps has led to a corresponding increase in the repair, restoration and installation of new windmills.

The technology of using wind to generate electricity is the fastest-growing new source of electricity worldwide. Wind energy is produced by massive three-bladed wind turbines that sit atop tall towers and work like fans in reverse. Rather than using electricity to make wind, turbines use wind to make electricity. Since about 1980, research and testing has helped reduce the cost of wind energy from 80 cents (2007dollars) per kilowatt hour to between 4 and 6 cents per kilowatt hour today.

The wind industry has grown phenomenally in the past decade, thanks to supporting government policies researchers in collaboration with industry partners to develop innovative cost-reducing technologies, cultivate market growth, and identify new wind energy applications.

How to Extract Energy from the Wind

Wind energy is a form of solar energy. Sunlight falling on oceans and continents causes air to warm and then rise, which in turn generates surface winds. Wind turbines utilize these winds using large blades mounted on tall towers that house turbines. The wind spins the blades, rotating a generator that produces electricity.

A windmill is an engine powered by the wind to produce energy, often contained in a large building as in traditional post mills, smock mills and tower mills. The energy windmills produce can be used in many ways, traditionally for grinding grain or spices, pumping water, sawing wood or hammering seeds. Modern wind power machines are used for generating electricity and are more properly called wind turbines.

Wind turns the blades and the blades spin a shaft that is connected through a set of gears to drive an electrical generator. Large-scale turbines for utilities can generate from 750 kilowatts (a kilowatt is 1,000 watts) to 1.5 megawatts (a megawatt is 1 million watts). Homes, telecommunication stations, and water pumps use single small turbines of less than 100 kilowatts as an energy source, particularly in remote areas where there is no utility service.

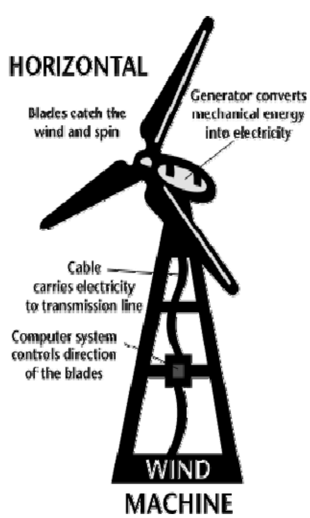


Fig. 4: a. Parts of a wind turbine b. A wind farm

Wind turbines are now placed in Wind Farms, where large groups of turbines are linked together to generate electricity for the utility grid. The electricity is sent through transmission and distribution lines to consumers.

How They Work

The simplest way to think about this is to imagine that a wind turbine works in exactly the opposite way to a fan. Instead of using electricity to make wind, like a fan, turbines use the wind to make electricity. Almost all wind turbines producing electricity consist of rotor blades which rotate around a horizontal hub. The hub is connected to a gearbox and generator, which are located inside the nacelle. The nacelle is the large part at the top of the tower where all the electrical components are located. Wind turbines start operating at wind speeds of 4 to 5 metres /second (around 15-18 km/h, or 10 miles/h) and reach maximum power output at around 15 meters/second (around 54 km/h, or 33 miles/h). At these very high wind speeds, i.e. gale force winds, wind turbines shut down. For more information, see the BWEA fact sheet, on wind energy technology, IL 6a.

IL6a ** BWEA fact sheet, on wind energy technology

Most wind turbines have three blades which face into the wind; the wind turns the blades round, this spins the shaft, which connects to a generator and this is where the electricity is made. A generator is a machine that produces electrical energy from mechanical energy, as opposed to an electric motor which does the opposite.

The blades are controlled to rotate at about 20 revolutions per minute at a constant speed. However, an increasing number of machines operate at variable speeds.

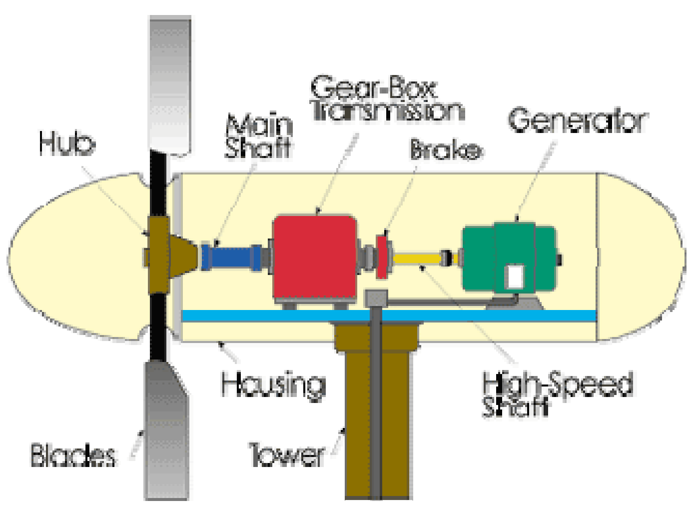


Fig. 5: Detail of a wind turbine. (See IL7 for explanations)

IL 7 **** (Wind energy manual, describing the energy transformations in detail; has a detailed picture of a wind turbine inside. This is the most detailed summary of wind power. Parts of this very long text are found in the Appendix.)

Safety

Wind Turbines have a designed working life of 20 to 25 years and require very little maintenance during this time. Wind Turbines are considered safe; there has been no recorded injury to a member of the general public anywhere in the world.

The Construction of GWTs

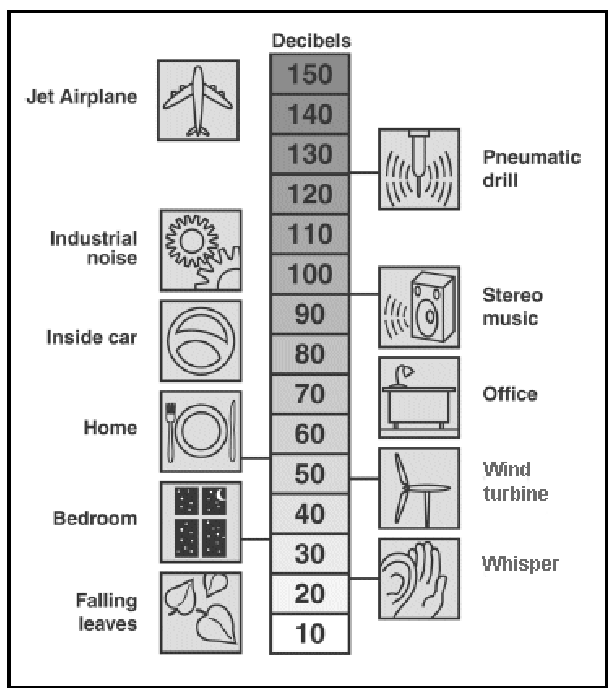
The Turbine consists of a large set of 3 blades which drive a generator via a large gearbox, this is installed in a nacelle which is mounted on a powered turntable at the top of a tall tower. When the wind speed increases above a certain speed, known as the *cut in speed*, which is typically about 3 to 4m/s. The Turbine will begin to generate electricity, and will continue to do so until the wind speed reaches the *cut out speed*, (about 25m/s) at this point the turbine will shut down, rotate out of the wind and wait for the wind speed to drop to a suitable value to allow the turbine to start again. The turbine will have an optimum operating wind speed at which maximum output will be achieved, which is typically about 13 to 16m/s. During operation the generator ensures that the blades maintain a constant rotational speed of about 20 revolutions per minute, which the gearbox then transforms into 1500 revolutions per minute. Higher wind loads acting on the blades result in increased power production but not a higher number of revolutions per minute.


Fig. 6: Construction of a GWT

<u>IL 8</u> **** Detailed physics of windpower. Should be considered a basic reference. Note: The text for this IL is in the Appendix.

Noise Level

Wind turbines are not noisy. A typical 1 megawatt (1,000,000 watts) Turbine, similar to the turbines installed at the wind farm in St. Leon, will produce about 45dB(A) or less at 300 meters. This noise level is about the same noise level you will hear sitting in your kitchen listening to your fridge. The average noise level in a typical home is 50dB. However this is only the noise produced by the Turbine, the natural wind rush noise is heard as well and this is normally about 40dB, so the end result at a typical *exclusion distance* of 300 to 400 meters where the turbines are almost inaudible. Some turbines produce up to 100dB but *this is measured at the gearbox at the top of the tower*. With the turbine running at its rated speed a normal conversation can be held at the base of the tower. This can be proven quite easily by visiting one of the existing Wind Farms and testing it for yourself.



Size of Wind Turbines

Wind turbines are big. The ones at St. Leon in Manitoba are between 50 meters (150 feet) and 80 meters (240 feet) tall. The rotor diameter (blade span) will be between 50 meters (150 feet) and 80 meters (240 feet).

Turbine towers are constructed from rolled steel plate and are normally about 4 to 5 meters (12 to 15 feet) diameter at the base and about 2 to 3 meters (6 to 9 feet) diameter at the top. Turbines are installed on concrete foundations that are buried well below ground level with a pedestal on which to mount the tower so the landholder can work the land right up to the base of the tower.

The towers are mostly tubular and made of steel, generally painted light grey. The blades are made of glass-fibre reinforced polyester or wood-epoxy. They are light grey because this is the colour which is found to be most inconspicuous under most lighting conditions. The finish is matt, to reduce reflected light. A wind turbine typically lasts around 20-25 years. During this time, as with a well made car, some parts may need replacing.

The very first of the mass-produced turbines celebrated its 20th birthday in May 2000. The Vestas 30kW machine has operated steadily throughout its lifetime, with none of the major components needing to be replaced.

Power Output and Efficiency of Wind Turbines

To obtain 10% of the electricity in the United Kingdom from the wind, for example, would require constructing around 12,000 MW of wind energy capacity. Depending on the size of the turbines, they would extend over 80,000 to 120,000 hectares (0.3% to 0.5% of the UK land area). Less than 1% of this (800 to 1,200 hectares) would be used for foundations and access roads, the other 99% could still b used for productive farming. For comparison, between 288,000 to 360,000 hectares (1.2-1.5% of the UK land area) is covered by roads and some 18.5 million hectares (77%) are used for agriculture.

The theoretical maximum energy which a wind turbine can extract from the wind blowing across it is just under 60%, known as the Betz limit, to be discussed later. However, the meaning of efficiency may be a redundant concept to apply to wind energy, where the fuel is “free”. The primary concern is not the efficiency for its own sake, but he improvement of productivity in order to bring the price of wind energy down.

IL 9 *** Calculation of wind power. A good explanation of the Betz limit.

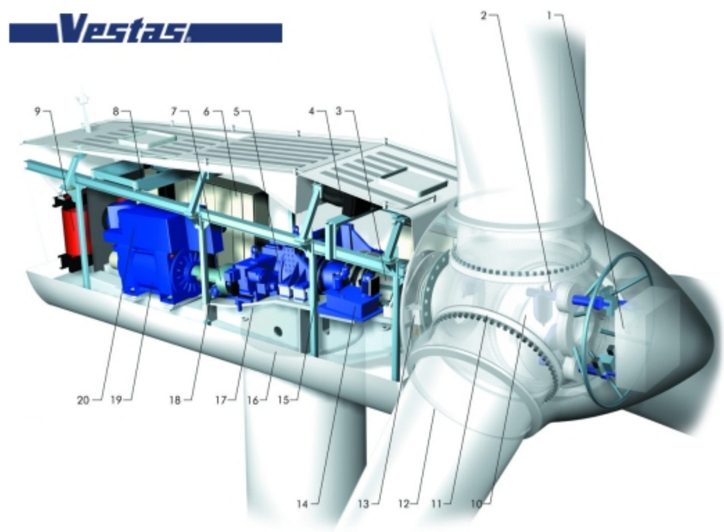


Fig. 7: The Vestas Turbine in Detail

Wind turbines consist of four main components—the rotor, transmission system, generator, and yaw and control systems—each of which is designed to work together to reliably convert the motion of the wind into electricity. These components are fixed onto or inside the nacelle, which is mounted on the tower. The nacelle rotates (or yaws) according to the wind direction.

Description of a Wind Farm

The most economical application of wind electric turbines is in groups of large machines (700 kW and up), called "wind power plants" or "Wind Farms." Wind plants can range in size from a few megawatts to hundreds of megawatts in capacity. Wind power plants are "modular," which means they consist of small individual modules (the turbines) and can easily be made larger or smaller as needed. Turbines can be added as electricity demand grows. A typical Wind Farm will use about 1% of the area where it is constructed, leaving the rest for normal farming or grazing practices.

Wind Turbines will generally be installed in small groups of 2 to 5 units connected to the existing utility grid, or in larger groups of 10 to 30 units with a "dedicated transmission line" to a suitable connection point at a nearby high voltage cable or switchyard. Wind farming is generally popular with farmers, because their land can continue to be used for growing crops or grazing livestock. Sheep, cows and horses are not disturbed by wind turbines. The wind is a diffuse form of energy, in common with many renewable sources. A typical wind farm of 20 turbines might extend over an area of 1 square kilometre, but only 1% of the land area would be used to house the turbines, electrical infrastructure and access roads; the remainder can be used for other purposes, such as farming or as natural habitat.

a. In the US

b. In Germany

c. On the prairies

d. In Spain

Fig. 8: Wind Farms

Global Wind Power Data

Thanks to recent research and development, global wind energy capacity has increased 10-fold in the last 10 years—from 3.5 gigawatts (a gigawatt is 1 billion watts) in 1994 to nearly 50 gigawatts by the end of 2004. In the United States, wind energy capacity tripled, from 1,600 megawatts in 1994 to more than 6,700 megawatts by the end of 2004—enough to serve more than 1.6 million households.

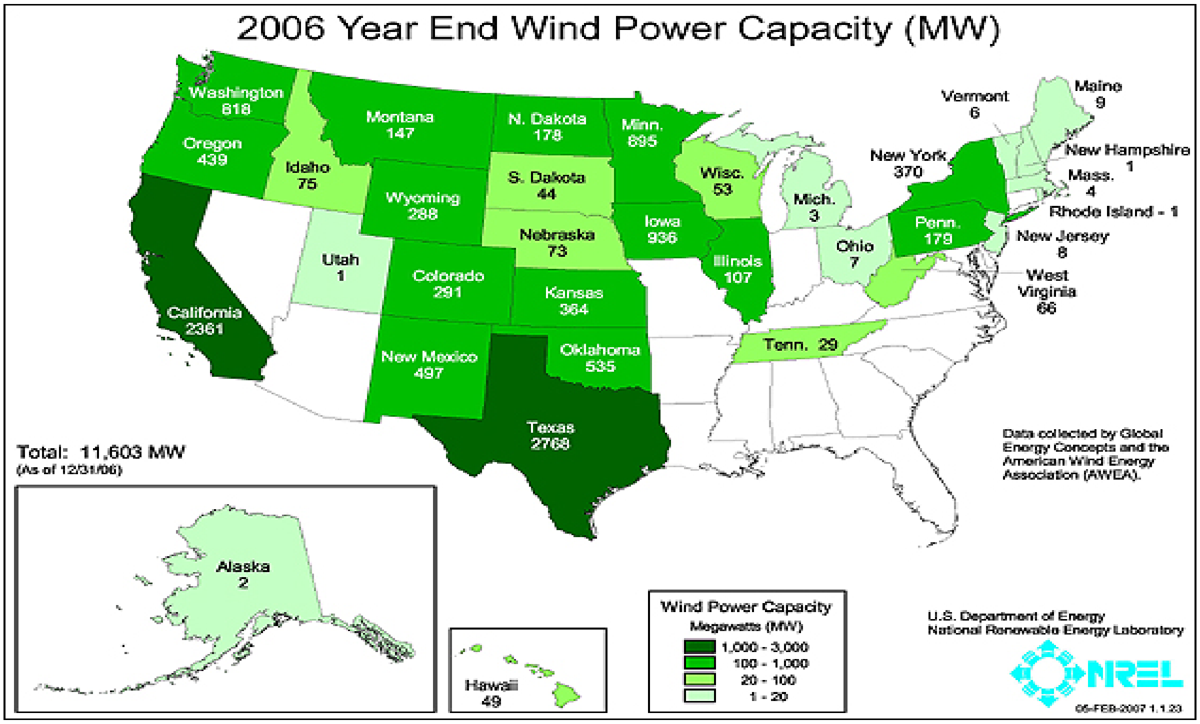


Fig. 9: Wind Power Distribution in the US

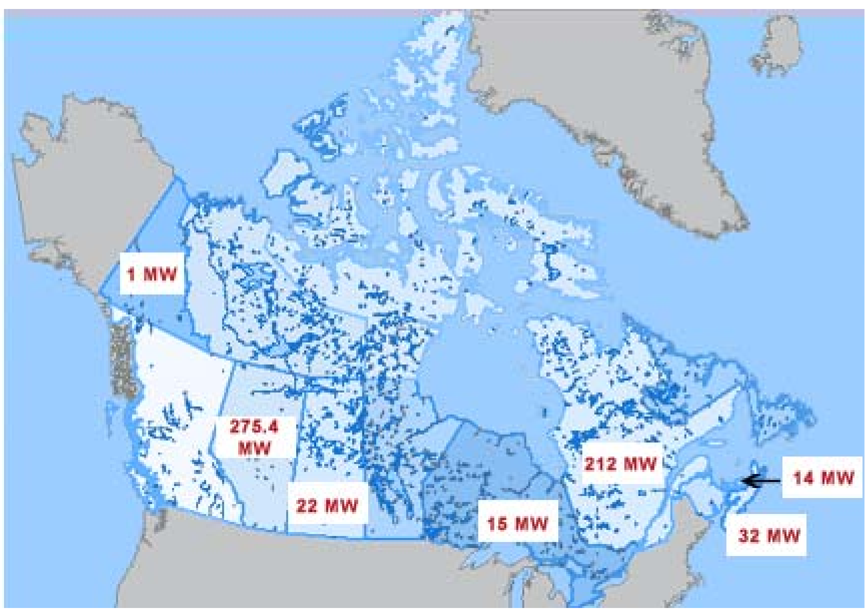


Fig. 10: Canadian Wind Power Distribution (2002)

Installed Windpower Capacity (MW)				
Rank	Nation	2005	2006	Latest
1	Germany	18,415	20,622	21,283
2	Spain	10,028	11,615	12,801
3	United States	9,149	11,603	12,634
4	India	4,430	6,270	7,231
5	Denmark (& Færoe Islands)	3,136	3,140	
6	China	1,260	2,604	2,956
7	Italy	1,718	2,123	
8	United Kingdom	1,332	1,963	2,191
9	Portugal	1,022	1,716	1,874
10	Canada	683	1,459	1,670

Fig. 11 Recent (2006) World Wind Power Distribution

IL 9a *** (The table above is taken from this IL)

Fig. 12: Global Wind Power Capacity (predicted)

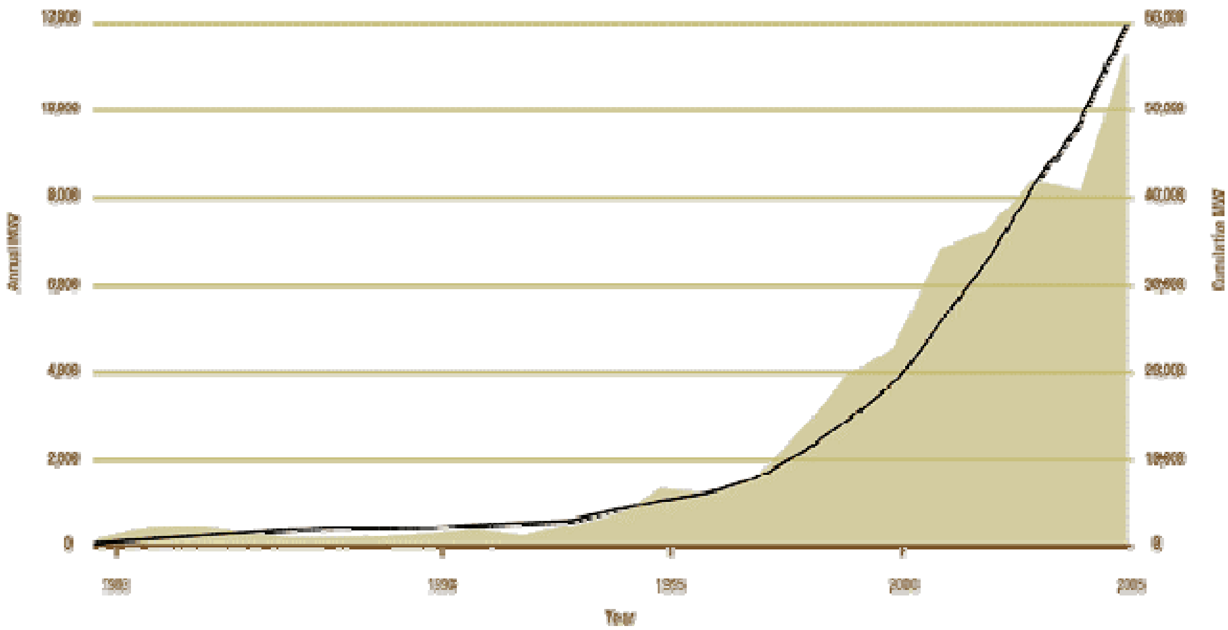


Fig. 13: Wind Power in the World (1983-2005)

Questions and Problems

1. a. Compare the two graphs in Fig. and Fig. that can be represented by an exponential function. Find the two exponential functions that can be expressed as:

   $\mathbf{y = ca^t}$, where **y** is the power output, **c** is a constant and **a** the number that is raised to the power of **t** (years). How do these functions compare?

   Hint: Call the first year (1997) year zero and find the value of c. Then take the power output for a subsequent year (say 2004) and find the value of a. Write out the equation.

   b. In the first graph predictions are made. Check these using your first equation.

   Discuss why it is difficult to predict the curve. What assumptions have been made to predict the power output for the future?

   c. Calculate the "doubling period" of the power growth for each.

3. Compare the *per capita* availability of wind power in Canada and the US. Comment.

Developing Cost-Reducing Technologies

Commercial wind energy is one of the most economical sources of new electricity available today. Compared with building new coal-fired generating stations or hydroelectric facilities, wind turbines can be set up quickly and economically. Modern wind-generating equipment is efficient, highly reliable, and environmentally sound.

Work conducted under DOE Wind Program projects from 1994 to 2004 produced innovative designs, larger turbines, and efficiencies that have led to dramatic cost reductions.

(See IL below). Although this drop in cost is impressive, electricity produced by wind energy is not yet fully competitive with that produced by fossil fuels. Researchers believe that further technology improvements will be needed to reduce the cost of electricity from wind another 30 percent for it to become fully competitive with conventional fuel-consuming electricity generation technologies.

IL 10 *** A clear presentation of wind energy in the US. Description of the DOE Wind Power program

One goal of the wind program is to further reduce the cost of utility-scale wind energy production to 3 cents per kilowatt hour at land-based, low-wind-speed sites and 5 cents per kilowatt hour for offshore (ocean) sites. A low-wind-speed site is one where the annual average wind speed measured 10 meters above the ground is about 6 m/s (21 kilometers per hour).

To accomplish this and other goals, two of DOE's main research laboratories, the National Renewable Energy Laboratory (NREL) in Colorado and Sandia National Laboratories in New Mexico, work with industry partners and university researchers nationwide to further advance wind energy technologies. Each laboratory has unique skills and capabilities to meet industry needs.

Large scale Wind Turbines can be installed for about $2.00 per watt or about two million dollars per megawatt. A typical large Wind Turbine will recover the energy used to manufacture and construct it (embodied energy) in 4 to 5 months of operation in a reasonable wind regime. It should be remembered that *a coal fired power station never recovers the energy used to construct and operate it as these power stations have a continuing requirement for very large amounts of energy to operate.*

Wind, as we all know, is neither constant nor consistent but society requires an electricity supply is, so base load power stations will always be required. What wind and other renewable energy sources can do is supplement these base load power stations and reduce the consumption of coal and therefore green house gas and aerosol emissions. Wind turbines have never caused an existing power station to close down, but it has meant that in countries like Denmark, Holland, Spain, Italy and Germany new coal fired power stations do not need to be built. Germany is one of the largest users of Wind Energy with 6113megawatts of Wind Turbines installed by 2005. This is assisting the German Government to close a number of its nuclear power stations. The Danish Government has gone further: it has determined that wind energy will provide 50% of the countries energy requirements by 2030; this means a 50% reduction in greenhouse emissions if this energy was obtained from coal power stations.

Capacity Factor

Capacity factor, sometimes called load factor, is the amount of time an energy production source is able to produce electricity. A coal power station will have a capacity factor of 65% to 85% that is, it will be able to produce output for 65% to 85% of the time, it will be out of action the rest of the time due to maintenance, labor strikes, breakdowns etc. A typical Wind Turbine will have a capacity factor of 25 to 40% depending on the available wind resource. For example, in Australia a Wind Farm will need a capacity factor of 32% or better to be viable.

Questions and Problems

1. In the St. Leon Wind Farm there are 63 1 MW wind turbines (see Fig.). It was mentioned earlier that large scale Wind Turbines can be installed for about $2.00 per watt or about two million dollars per megawatt. It is claimed that a typical large Wind Turbine will recover the energy used to manufacture and construct it (embodied energy) in 4 to 5 months of operation in a reasonable wind regime. Estimate the "profit" generated by the Wind Turbines if they run problem free for 10 years.
2. Compare the capacity factors of coal stations and Wind Turbines. List the advantages and disadvantages of these two sources of electric energy. What do you think must be the capacity factor of the St. Leon Wind Farm to make it "viable"? We will discuss the St. Leon Wind Farm in Manitoba later.

Pollution Due to Wind Energy

Energy in the wind spins large turbine blades which are connected to generators. Turbines are placed to use the best wind resources; hillsides, hilltops and open plains are the best locations. Pollution results only from the manufacture of materials and machinery and from the use of heavy equipment during the erection of towers.

Pros and Cons for Wind Power

One environmental concern about wind power is bird mortality. Turbine blades normally spin at high speeds and are difficult to see. Birds that drift into turbine blades are killed instantly in most cases and raptors such as the golden eagle (a federally protected species) are especially vulnerable. Proposed solutions to this problem include changing the tower design to eliminate beams used as perches, painting the turbine blades in colors and patterns to visually emphasize their presence, and reducing the populations of the raptors' prey by changing or removing vegetation. (Changing vegetation types and enhancing turbine visibility are mitigations aimed at reducing bird mortality, but these activities are likely to cause other problems.) Locally, researchers at UC Santa Cruz have chosen Altamont Pass as the subject of an investigation into the avian mortality issue.

The aesthetic effects of wind turbines are a special concern for people living close to wind farms, who have complained about the high visibility of turbines and the noise from the huge spinning blades.

The comparison of energy used in manufacture with the energy produced by a power station is known as the 'energy balance'. It can be expressed in terms of energy 'pay back' time, i.e., as the time needed to generate the equivalent amount of energy used in manufacturing the wind turbine or power station.

The average wind farm is expected to pay back the energy used in its manufacture within six to eight months, this compares favourably with coal or nuclear power stations, which take about six months to pay back the energy.

Finally, it should be emphasized that wind energy is one of the safest energy technologies. It is a matter of record that no member of the public has ever been injured during the normal operation of a wind turbine, with over 25 years operating experience and with more than 70,000 machines installed around the world. In summary then:

Summary of Pros and Cons for Wind Energy

Pros:

- There are no emissions.
- The energy available is abundant and renewable.
- Turbines can be set up without disturbing ecosystems.
- Existing technology makes the wind turbines affordable.

Cons:

- Wind is dependent on the availability of winds at a fairly constant speed of at least 10m/s (output is proportional to wind speed).
- Wind technology is not feasible for all locations (coastlines and high ridges are best).
- Wind energy is still considered too expensive.
- Sometimes the installation requires relatively heavy land use.
- The wind turbines are often considered unsightly and noisy.

The Future of Wind Power

One goal of the wind program is to further reduce the cost of utility-scale wind energy production to 3 cents per kilowatt hour at land-based, low-wind-speed sites and 5 cents per kilowatt hour for offshore (ocean) sites. A low-wind-speed site is one where the annual average wind speed measures 10 meters above the ground is about 6 m/s, or about 21 kilometers per hour.

THE PRESENTATION OF THE CONTEXT OF WIND ENERGY

The presentation of the contexts will be in three parts. In reparation for the discussion of wind turbines, we will first examine in detail the construction and physics of a small water mill that is still running today in Pioneer Village, located in Downsview, a few kilometers north of Toronto. The physics involved is very similar to the physics of wind turbines. This is Part One**.** In Part Two, the construction and the physics of a conventional wind mill that we still find in rural areas will be investigated. In Part Three, we will discuss the construction and physics of the giant wind turbines, using those at St. Leon wind turbine farm in south western Manitoba as an example.

PART ONE: Water Mills

Fig. 14: 19th century watermills

Water that flows from rivers and streams is a valuable and plentiful energy resource. People learned to use the power of running water to operate the small mills that were important to their families. Gristmills ground the grain the farmers grew. Sawmills cut their timber. Carding Mills combed the wool sheared from their sheep. Water powered machines cut nails, turned wood for furniture parts, cut shingles, and performed other useful tasks.

There are many types of wheels that harness the power of water. Each wheel is different and operates best in unique conditions. They vary in durability, cost, efficiency, and power output, among other things.

The overshot wheel is a much more efficient wheel than the undershot; it can harness over 85% of the potential energy in falling water. However, it is more difficult to build, requires careful site preparation, and will not operate in many locations.

Mounted vertically on a horizontal axle, it has angled troughs—also called buckets—mounted all around the rim. Water fills these buckets from above, making one side of the wheel heavy and causing it to turn as the water in the buckets falls. At the bottom the buckets are in an inverted position so that they spill out the used water, which flows gently away. While the water filling the buckets has a slight force upon the wheel, the overshot is primarily a gravity wheel in that it is the dead weight of water in the buckets that causes it to turn.

This large diameter wheel can generate a great deal of torque or twisting power. Because of its size it cannot turn very rapidly and therefore machinery that needs to run at higher speeds must use gears to increase the speed of rotation. But gears add cost, increase the requirement for maintenance, and take away some power.

The overshot wheel has the water channeled to the wheel at the top and slightly to one side in the direction of rotation. The water collects in the buckets on that side of the wheel, making it heavier than the other "empty" side. The weight turns the wheel, and the water flows out into the tail-water when the wheel rotates enough to invert the buckets. The overshot design uses almost all of the water flow for power (unless there is a leak) and does not require rapid flow. The overshot wheel is a far more powerful and efficient design, but because it requires constructing a dam and a pond it requires much more investment.

A Nineteenth Century Water Mill: Our First Example

The first waterwheel was invented and used about 100 B.C. in the Near East. This is the first historically recorded instance of a device that effectively converted gravitational potential energy to useful kinetic energy. By about 600 A.D. water-driven flour mills and saw mills were common in Europe, especially in France. Twenty years after the Norman conquest of Britain in 1066, about 5000 watermills were operating in 3000 British communities, and before the end of the fourteenth century, water power had been harnessed to grind flower, saw wood, tan leather, and grind pigments for paint.

By the seventeenth century watermills had a power output ranging from 2 to 12 kilowatts, the largest being the famous Versailles waterworks in France which is said to have had an astonishing power output of about 56 kilowatts. Water mills played an important part in setting the stage for the industrial revolution.

Fig. 15: Roblin's Mill, a watermill, at Black Creek Pioneer Village close to Toronto

Our first investigation of a representative power device of the pre-industrial era we have chosen Roblin's Mill, situated at Black Creek Village in Downsview, Ontario, just North of Toronto. The mill was constructed in the 1960s and is an authentic example of the last generation of water mills of the late nineteenth century, when the industrial revolution was in full swing. It is fully operational.

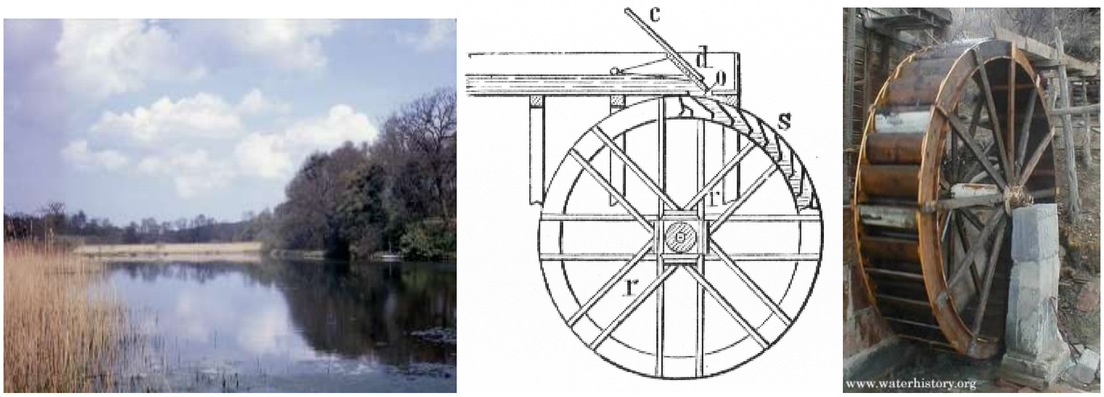


Fig. 16: Roblin's Mill

For a suitable site of a water mill, we must be able to build up an adequate "head" of water. This water must be carried over the top of the wheel so that the water falls beyond the wheel's center. As already mentioned, the overshot wheel turns because the weight of the water trapped in the buckets produces a torque or a turning effect. The water begins to fall out of the buckets they reach the bottom, thus wasting some energy, but we will neglect this effect.

A "rule of thumb" which allowed the estimate of the power output of a water mill of the size of Roblin's mill during the nineteenth century was given by "the following :"Twelve cubit feet of water should give one horsepower for every foot of fall." We will test this rule in our investigation.

<u>IL10</u> a *** An excellent review of history of water power. Download some of the pictures, especially photograph #3!

<u>IL11</u> *** A general description of water mills. Roblin's Mill is found here

Concepts, definitions and formulas you may need in answering the questions and solving the problems below.

1. Density of water: 1000 kg/m^3

<u>IL 12</u> *** Discussion of *density*, with examples

<u>IL13</u> *** Discussion of *density* with values for different materials and substances

2. <u>Circumference of a circle</u>: **$2\pi r$**

See IL19, for many examples of calculations using the formula above.

<u>IL14</u> ** Examples of calculations using $C = 2\pi r$.

3. <u>Work:</u>

Work is defined as *force times distance*, N.m, or Joules (J). If a force moves through a distance of 1 meter it produces 1 Joule of work

IL15 ** A visual presentation of the idea of work and energy, simple applets

IL16 ** Examples of calculating work

4. Gravitational potential energy:

The energy of a body in a gravitational field, calculated relative to its position

IL17 ** An advanced textbook presentation of gravitational potential energy, with an applet that allows you to calculate gravitational potential energy

5. Power:

The rate of doing work, or W / t (J/s)

IL18 *** A nicely animated discussion of power, with illustrations

6. Horsepower:

The rate of doing work at 746 J/s or 746 Watts.

The original definition goes back to the late 18th century: "You accomplish one horsepower if you can lift 550 pound of weight to a height of 1 foot in one second. You can show that in the SI system this is equivalent to 746 Joules per second (Watts).

IL19 ** History of the unit of horsepower

7. Angular speed (velocity):

One way to express this is by measuring *the number of times a wheel turns in one minute*, in rpm (revolutions per minute).

IL20 ** A detailed and advanced discussion of angular velocity

IL 21 *** An advanced discussion of the above

8. Torque:

Torque is the angular or rotational analogue of force, and is defined as *force times distance*, that is, the force applied (perpendicularly) to Newton/meters (N.m). Notice that the units are identical to defining work.

IL22 *** A discussion of torque

9. Newton's second law of motion:

As we have discussed in LCP 1 and LCP 2:

The law is stated by writing **F = ma,** where F is the unbalanced force given in Newtons (N), m the mass in kilograms (kg), and a is the acceleration produced by the force in meters per second per second (m/s/s, or m/s^2).

IL 23 *** An elementary but thorough discussion of Newton's second law

10. Efficiency:

Efficiency is defined as *the ratio between the amount of work you obtain to the amount of work you put into a system*, or $\mathbf{W_{in} / W_{out}}$. Machines of any kind have efficiencies ranging from low (about .1 to high, about .9) See the links below.

IL 24 **** A visually interesting presentation of the various forms of energy and the efficiency of energy transformations

IL 25 *** Efficiencies of various types of water mills, visually attractive

IL 26 *** Description of various energy transformations; very thorough and complete

Initial calculations (See Figs. 14, 15 and 16.)

1. Estimate the volume of the pond in cubic meters.
2. Call the lowest part of the wheel as your lowest gravitational potential level.
3. Estimate the total gravitational potential energy of the pond as a reservoir with respect to the water mill (Refer to Figure ??). Note: Estimate the center of mass of the water in the pond.
4. If you built a model of the mill such that all moving parts were reduced dimensionally to 1/10 of their original value, how would the power output be reduced? (Take a guess first, and then do your calculations. Refer to LCP3 where scaling was discussed).

See IL 13

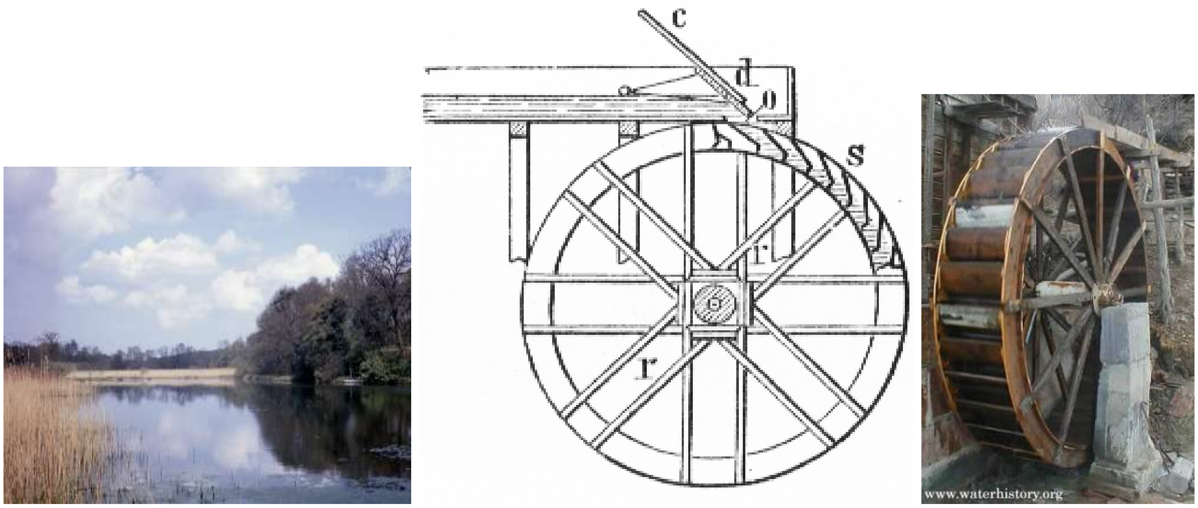


Fig. 17: Another Look the Water Wheel and the Mill Pond

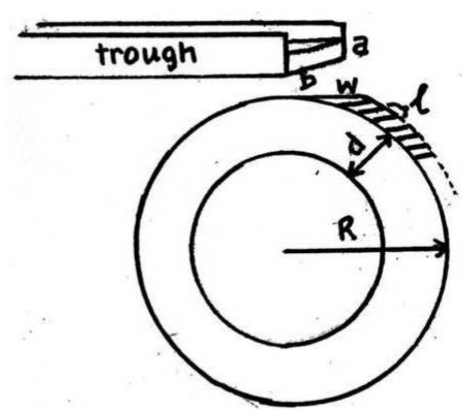
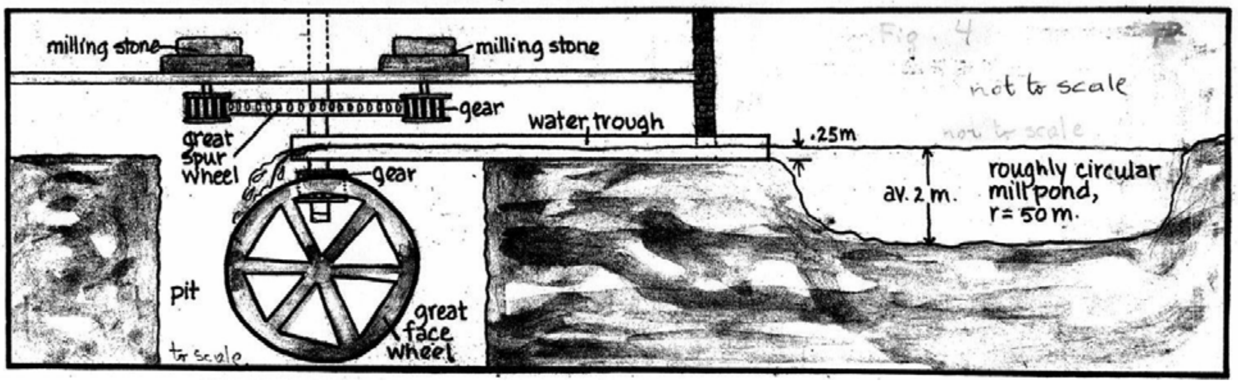


Fig. 18: Sketch of the Mill and Pond

The following are actual measurements made at the site of the mill by the author.

<u>Relevant Data</u>**:**

- **a** = depth of water in trough: 0.25 m.
- **b** = width of trough = 1.20 m.
- **l** = distance between buckets on rim: 0.26 m.
- **R** = Radius of wheel = 2.75 m.
- **d** = depth of bucket = 0.40 m.
- **t** = time for one revolution = 15 s.
- **w** = width of buckets = 1.2 m.



1. It is found that when the mill is in operation grinding flower, the speed of the mill is quite constant.
   a. Find the speed of a point on the rim of the wheel in meters per second.
   b. What is the angular speed of the wheel in revolutions per second?
   c. Find the rpm of the millstone from Fig.
2. Estimate the optimum speed of the water in the trough in meters per second and the water flow in liters per second, in order to just fill each bucket as the wheel turns at the given speed. See Fig.
3. Find the approximate mass of water each bucket can hold in kilograms and the corresponding weight in Newtons. See Fig.
4. Whenever we deal with rotation the concept of torque is required. The torque acting on the wheel, due to the force exerted by the water in each bucket as the wheel turns, varies from zero at the top to a maximum at 90 degrees (see Fig.). Find the torque in Newton-meters at points every 10 degrees and draw a graph of torque versus angle. Discuss the shape of the graph.

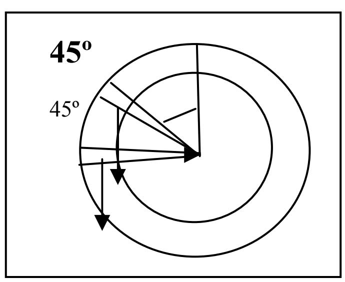


Fig. 19: Calculating the Torque on the Wheel

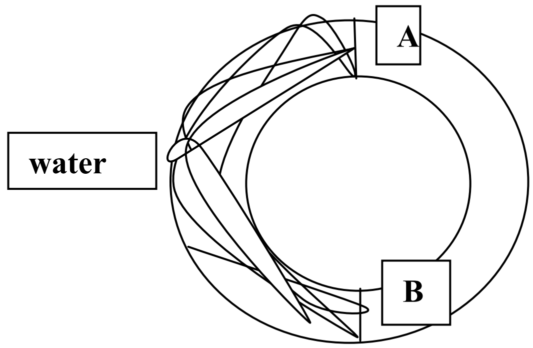


Fig. 20: The Total Amount of Water the Wheel Could Hold

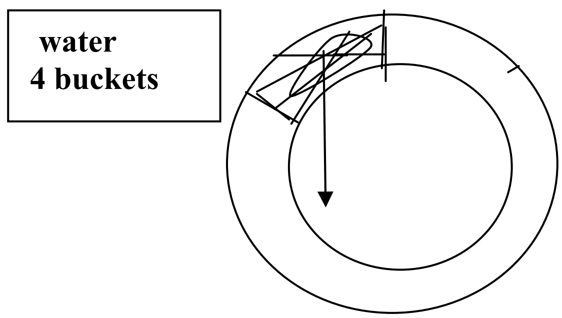


Fig. 21: Minimum Torque Required to Start the Water Wheel Moving

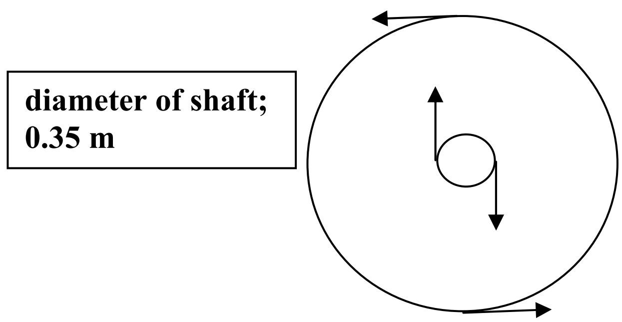


Fig. 22: The Torque Necessary to Overcome Frictional Effects

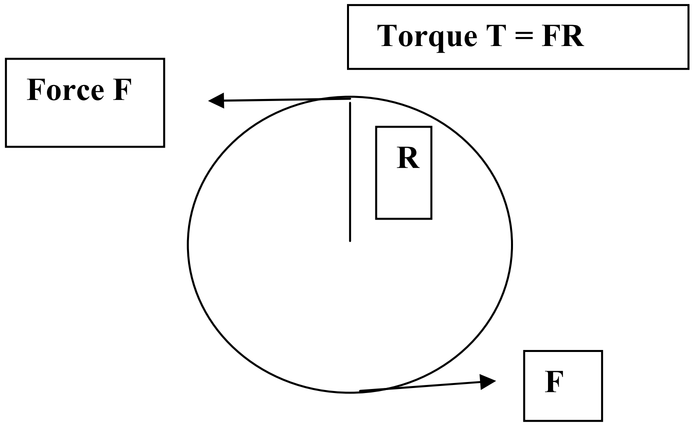


Fig. 23: The Torque Acting On the Water Wheel

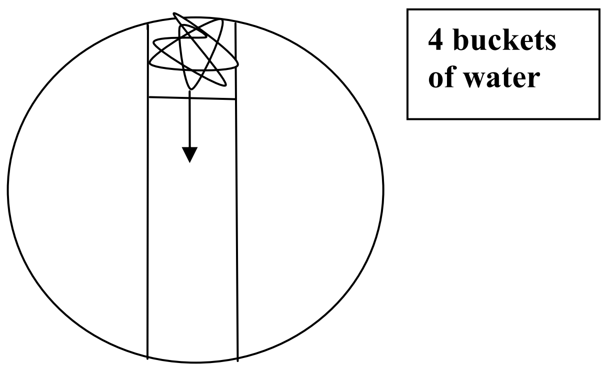


Fig. 24: The Gravitational Potential Energy of the Water

5. To find the power output of the mill we first determine the total amount of water the wheel can hold. For the sake of simplicity we will assume that no spilling will take place between points A and B. Find the total amount of water the wheel could ideally hold.
6. It is found that the wheel will not turn until four buckets are filled with water, as shown. Find the minimum torque necessary to start the wheel turning.
7. Assuming that all the frictional force resisting torque is in the main shaft, as shown, find this force.
8. Assuming that the friction produced by mechanical energy is converted into heat energy, how much heat energy do you loose through friction in ½ a revolution?

   Note: You can find the work loss in two ways:

   a. by applying the fact that the torque you found is continuing to act as shown, and
   b. by imagining the mass (weight) of water in 4 buckets to fall through a distance of the diameter.

Explain why the answers should be the same.

9. Calculate the maximum amount of useful work that the wheel can perform in one revolution.
10. We have now all the information needed to calculate the power output of the mill. What is the power output in horsepower? How good is the "rule of thumb" mentioned earlier?
11. Whenever we deal with energy transformations devices, the most important question is: What is the efficiency of the device? Find the efficiency of Roblin's mill from the data given.

More Advanced Problems

1 From the diagram in Fig. find the total potential energy of the pond as a reservoir with respect to the water mill

2. We saw that the torque varies with the angle. What "effective" torque at a constant value would result in the same power output as the varying torque?

3. If you could build a model such that all moving parts were reduced to 1/10 of their original value would the power output also be reduces to 1/10 of the original value? (See LCP 3 and reread the discussion on scaling).

More Internet Links about water mills:

IL 27 ** Details of mechanisms of water mill

IL 28 ** Source for many ILs for water mills

PART TWO

The Central Formulas for Calculating the Power and Efficiency of a Wind Mill or Turbine

You will notice that the British system of units is used predominantly in the specifications of wind mills and turbines from the US. So you must get used to working in both the British and SI system of units.

See Appendix for a full discussion of the derivation of the main formula for wind turbine power calculations given below. You can also find this discussion on **IL 38.**

The following are good sources for the discussion of the formulas presented.

IL 29 **** An excellent discussion of the power of a windmill

IL 30 **** The same as above

1. Power in the area swept by the wind turbine rotor:

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

where:

P = power in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)
ρ = air density (about 1.225 kg/m^3 at sea level, less higher up)
A = rotor swept area, exposed to the wind (m^2)
V = wind speed in meters/s (20 mph = 9 m/s) (mph/2.24 = m/s)

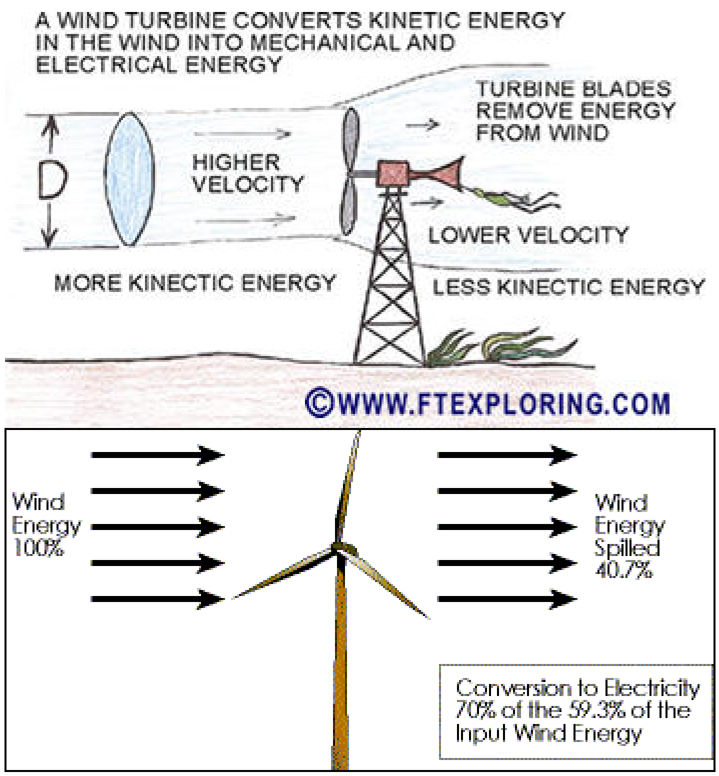


Fig. 25: The Production of Wind Power. See IL 38.

But this formula *yields the power in a free flowing stream of wind only*. Of course, it is impossible to extract all the power from the wind because some flow must be maintained through the rotor (otherwise a brick wall would be a 100% efficient wind power extractor). So, we need to include some additional terms to get a practical equation for a wind turbine. Study the derivation of the power formula carefully (IL38 and IL39).

Notice that the power is *directly proportional to the cube of the wind velocity*, *the square of the diamete*r and (area of the blades) and *the density of the air*. That means that if the diameter of the blades is doubled and the wind velocity doubled in the same place, the power goes up by a factor of 2^2 x 2^3, which is a factor of 4 x 8, or 32! The actual formula that one apply to a real windmill or wind turbine is a little more complicated, however.

The formula below shows how to calculate the power in the wind (not the power available to us because we can't get it all):

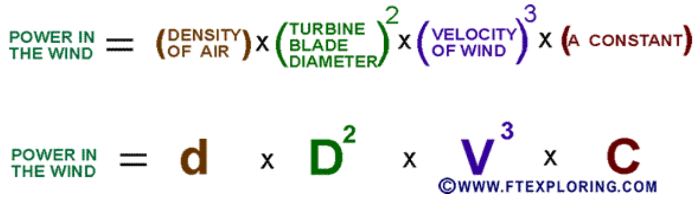


Fig. 26: The Central Formula for Calculating Wind Power. Taken from IL 38.

First, the efficiency of a wind turbine has a maximum value (the Betz limit) of about 60%, and secondly, the efficiency of the generator as well as the gearbox must be included.

An Elementary Derivation of the Wind Power Formula

We will first show why the power is proportional to the cube of the wind velocity, the density and the area of the blades, and then go further and derive the Betz limit.

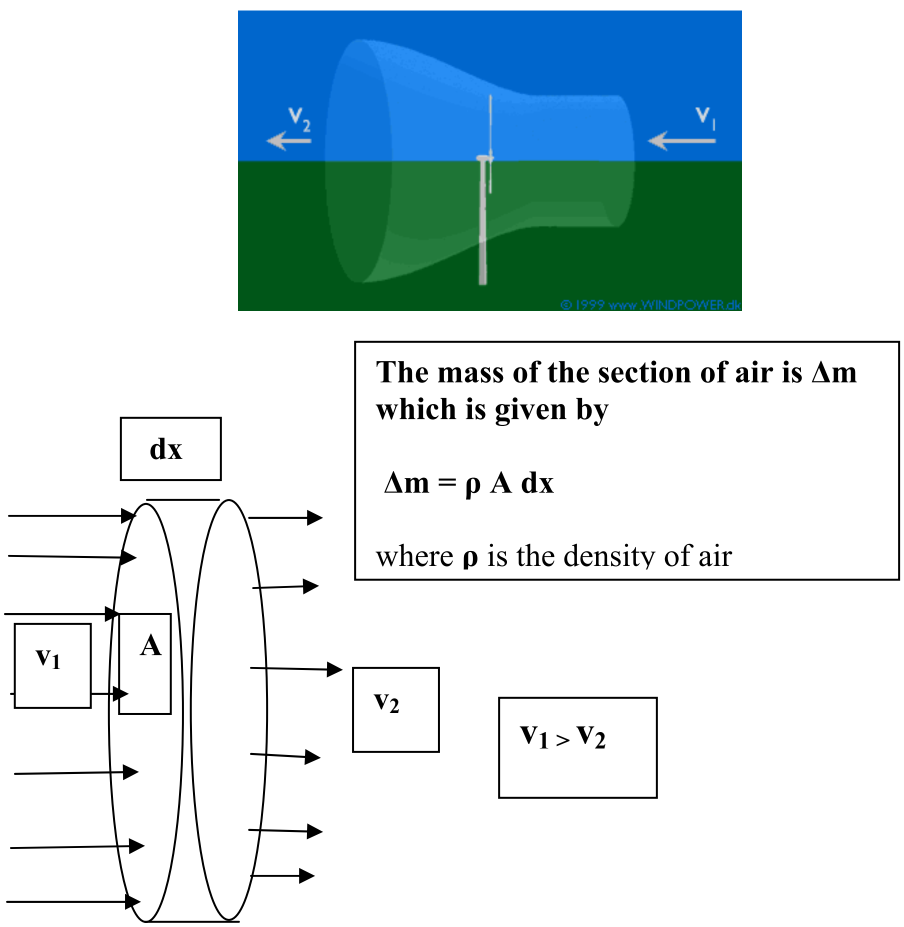


Fig. 27: Diagram on Which Calculations are Based

Air moves over the total area A of the rotating blades at velocity $\mathbf{v_1}$ and leaves with a lower velocity $\mathbf{v_2}$. First, we will look at the unrealistic case where $\mathbf{v_2}$ is small and negligible. This simplification will allow us to find the formula for the power of a wind mill or turbine that would be 100% efficient. Study Fig. above, as well as previous Fig.

The elemental mass **Δm** can be written as

$$\Delta m = \rho\ A\ \Delta x$$

We will assume that $\mathbf{v_2}$ is 0 and call $\mathbf{v_1}$ simply $\mathbf{v}$. Then the kinetic energy of the mass **Δm** will be: $\frac{1}{2}\ \Delta m\ v^2$

Since power P is defined as energy per unit time we can write:

$$P = E / \Delta t = E_k / \Delta t = \tfrac{1}{2}\ \Delta m\ v^2 / \Delta t$$

(E_k is kinetic energy)

Substituting $\Delta m = \rho\ A\ \Delta x$ into this equation we get:

$$P = \tfrac{1}{2}\ \rho\ A\ v^2\ \Delta x / \Delta t = \tfrac{1}{2}\ \rho\ A\ v^3$$

This simple analysis then gives us the formula for the case where the velocity leaving the blade area is zero.

However, if we tried to extract all the energy from the wind, the air would move away with the speed zero, i.e. the air could not leave the turbine. In that case we would not extract any energy at all, since all of the air would obviously also be prevented from entering the rotor of the turbine.

In the other extreme case, the wind could pass though our tube above without being hindered at all. In this case we would likewise not have extracted any energy from the wind.

We can therefore assume that there must be some way of braking the wind which is in between these two extremes, and is more efficient in converting the energy in the wind to useful mechanical energy. It was well known empirically (from experience) that an ideal wind turbine would slow down the wind by 2/3 of its original speed. To understand why, we have to use the fundamental physical law for the aerodynamics of wind turbines.

The Story of the Discovery of the Efficiency Formula

The German physicist Albert Betz published a book on wind power in 1926 (See IL) in which the formula for the efficiency of any wind turbine is described (he originally developed this formula for the German air force at the end of WWI in connection with the aerodynamics of airplane propellers). The following is roughly the proof that he gave:

The following was available to him:

1. The formula for the power of a windmill for the ideal case, the one we developed above: $\mathbf{P = ½ \rho A v^3}$
2. It was well known empirically (from experience) that an ideal wind turbine would slow down the wind by 2/3 of its original speed, that means that $\mathbf{v_2 = 1/3\ v}$.

IL 31 *** A very comprehensive discussion of Betz's law

IL 32 *** An outline of the proof of Betz's law

Betz argued like this: If the velocity of the air mass hitting the circular area of the blades is $\mathbf{v_1}$, and the velocity leaving the blades, $\mathbf{v_2}$, is about **1/3 of $\mathbf{v_1}$** then the average velocity for air moving through the blades must be given by

$$v_{av} = (v_1 + v_2) / 2$$

(Betz gave an argument why this is a plausible assumption. We will discuss this later).

Next, he wrote:

$$P = \Delta E_k / \Delta t = ½\ m\ (v_1^2 - v_2^2) / \Delta t = ½\ \rho\ A\ (v_1^2 - v_2^2)\ \Delta x / \Delta t$$

where $\mathbf{\Delta E_k}$ is the change in kinetic energy and $\mathbf{m = \rho\ A\ \Delta x}$

Notice that if we let $\mathbf{v_2 = 0}$ then $\mathbf{\Delta x / \Delta t}$ is equal to $\mathbf{v_1}$ and we have our original power formula

$$P = ½\ \rho\ A\ v_1^2\ \Delta x / \Delta t$$

where $\mathbf{\Delta x / \Delta t\ v_{av}}$ was first thought to be the $\mathbf{v_1}$ so that we have the idealized power equation.

Betz, however, argued that $\mathbf{\Delta x / \Delta t}$ is the average velocity $\mathbf{(v_1 + v_2) / 2}$ with which the mass **m** of air is moving through the blade area. Therefore, he argued, the power equation for the wind turbine becomes:

$$P = ½\ \rho\ A\ (v_1^2 - v_2^2)(\ (v_1 + v_2) / 2 = ¼\ \rho\ A\ (v_1^2 - v_2^2)(\ (v_1 + v_2)$$

Betz now compared this power output **P** with the power output $\mathbf{P_0}$ for the case when $\mathbf{v_2}$ is zero:

$$P_0 = ½\ \rho\ A\ v^3$$

And therefore $\mathbf{P / P_0 = (v_1^2 - v_2^2)(\ (v_1 + v_2) / v_1^3}$

After some algebraic manipulation we get:

$$P / P_0 = ½\ [\ \{1 - (v_2/v_1)^2\}\{(1 + (v_2/v_1)\}]$$

Substituting the empirical finding into the expression in the brackets that $\mathbf{v_2/v_1 = 1/3}$ we get:

$\mathbf{½\ \{1 - (1/3)^2\}\{(1 + (1/3)\} = 16/27}$. This can be written as 0.592, or about 60%.

This is a very important result that imposes a limit of about 60% on the most perfect windmill built under the most ideal conditions. See problems below for more details.

A graph below of v_2/v_1 and P / P_0 should be now discussed.

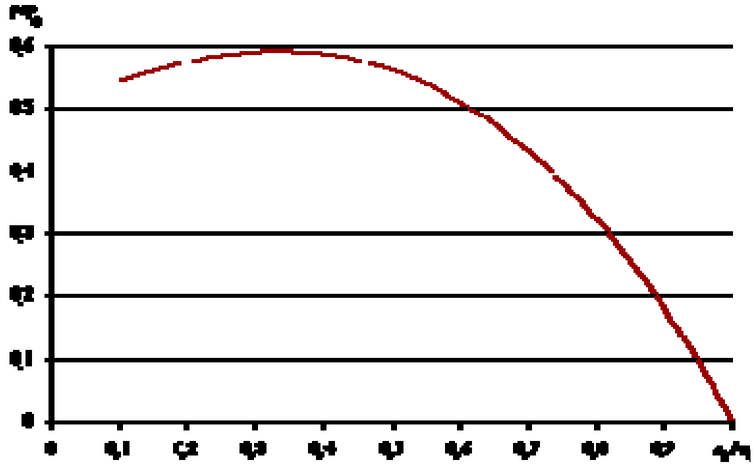


Fig. 28: A Graph of v_2/v_1 and P / P_0

We can see that the function reaches its maximum for $v_2/v_1 = 1/3$, and that the maximum value for the power extracted from the wind is 0.59 or 16/27 of the total power in the wind.

An Interesting Advanced Problem

The following is a speculation about how Albert Betz may have reasoned when he assumed that the mean velocity with which the air moves through the blades area can be represented by assuming that $v_{av} = (v_1 + v_2) / 2$

It was shown above that

$$P / P_0 = ½ (v_1^2 - v_2^2)((v_1 + v_2) / v_1^3$$

After some algebraic manipulation we get:

$$P / P_0 = [\{1 – (v_2/v_1)^2 \}\{(1 + (v_2/v_1)\}]$$

Suppose now we want to find the value of v_2/v_1 such that it is a maximum. To do that we simply

Write $P / P_0 = ½ [\{1 – R^2 \}\{(1 + R\}]$

where $R = v_2/v_1$

The value of R will be a maximum of we find the derivative $d (P / P_0) / dR$ and equate it to zero. You can do this and show that

$$d (P / P_0) / dR = ½ (1 + R - R^2 - R^3)$$

P / P_0 is a maximum when

$$3R^2 + 2R -1 = 0$$

Using simple factoring we get **$(3R - 1)(R + 1) = 0$**

it follows that **$R = 1/3$.**

That means that **$v_2/v_1 = 1/3$.**

This is result found when we assume that the average speed of the air rushing through the blade area is given by $v_{av} = (v_1 + v_2) / 2$ **.** This result is also firmly confirmed by empirical evidence.

A More Detailed Discussion of the Power Formula

The formula $P = ½ \rho A v^3$ then is the "ideal" representation of the power formula.

A more realistic way to write the formula would be:

$$P = ½ k \rho A v^3$$

Where the constant k is a proportionality constant that would automatically contain the Betz constant of 0.60. But there are other sources of efficiency constraints.

The Formula Used By Wind Turbine Designers

The following is the more realistic "engineering" version used to calculate the power output of "real" systems. Here we see that the constant k above actually contains several constants beyond Betz constant which generally written as C_p and is called "coefficient of performance.

Wind Turbine Power is written as

$$P = ½ \rho A V^3 C_p N_g N_b$$

where:

P = power in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)
ρ = air density (about 1.23 kg/m^3 at sea level, less higher up)
A = rotor swept area, exposed to the wind (m^2)
C_p = Coefficient of performance (.59 {Betz limit} is the maximum theoretically possible, and .35 for a good design).
V = wind speed in meters/s
N_g = generator efficiency (50% for car alternator, 80% or possibly more for a permanent magnet
Nb = gearbox/bearings efficiency (depends, could be as high as 95% if good)

Of course, we need not concern ourselves with all these engineering details. The formula,

$$P = ½ k \rho A v^3$$

given above, should be sufficient for most of the problems we will discuss. Remember, the constant **K** automatically contains C_p , which is really the Betts efficiency limit. We will use the formula above by illustrating its practical application.

More about the Efficiency of a Windmill or Wind Turbine

Study the discussion of efficiency in given in IL 38 and IL 39.

The power efficiency of the rotor is the fraction of the total power available which the blades are able to convert. The theoretical maximum is 0.59, as we have shown above.

At one extreme, a wind turbine could not extract 100% of the kinetic energy. To do this the blades would have to stop the wind completely, requiring all the swept area to be solid, like a disk. The wind would simply blow around the turbine, and the blades would not turn at all. At the other extreme, if there were no blades at all, then no kinetic energy would be extracted because the kinetic energy is $\frac{1}{2} m (v_1^2 - v_2^2)$.

Ideally we want a wind turbine that operates at a Cp as close to the Betz limit of 0.59 as possible, over a wide range of wind speeds. The power output is then approximately proportional to V^3, i.e. the cube of the wind speed. The power, however, has to be limited at high wind speeds in order to protect the mechanical and electrical components of the machine from overloading. This is done by somehow reducing the Cp as the wind speed increases. An ideal wind turbine operates at maximum Cp until the wind speed corresponds to the rated power, then, with increasing wind speed operates at a reducing Cp, so that the power output remains constant at its rated value.

Finally, in practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will (depending on the model) deliver between 10% and 30% of the original energy available in the wind. This will become clear when you solve the problems below.

A Detailed Discussion of Efficiency and How It Relates To Wind Speed and Power Output

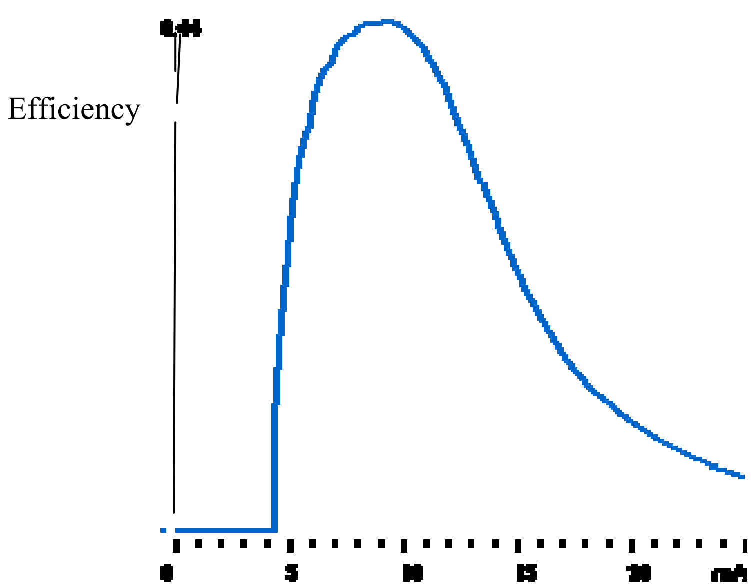


Fig. 29: Efficiency of Wind Turbines versus Air Speed

Very simply, we just divide the electrical power output by the wind energy input to measure how technically efficient a wind turbine is. In other words, we take the power curve, and divide it by the area of the rotor to get the power output per square meter of rotor area. For each wind speed, we then divide the result by the amount of power in the wind per square meter.

The graph shows a power coefficient curve for a typical Danish wind turbine. Although the average efficiency for these turbines is somewhat above 20 per cent, you can see that the efficiency varies very much with the wind speed.

As you can see, the mechanical efficiency of the turbine is largest (in this case 44 per cent) at a wind speed around some 9 m/s (32 km/h). This is a deliberate choice by the engineers who designed the turbine. At low wind speeds efficiency is not so important, because there is not much energy to harvest. At high wind speeds the turbine must waste any excess energy above what the generator was designed for. Efficiency therefore matters most in the region of wind speeds where most of the energy is to be found.

The Power Curve of a Wind Turbine

The power curve of a wind turbine is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds. (Compare this curve with the efficiency curve above).

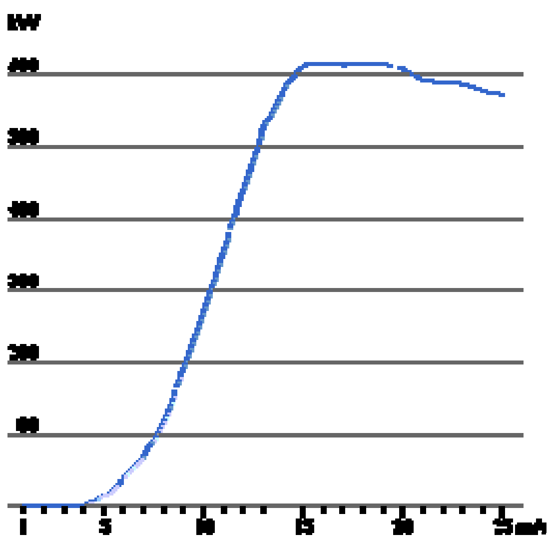


Fig. 30: Power Curve of a Wind Turbine

The graph shows a power curve for a typical Danish 600 kW wind turbine. Power curves are found by field measurements, where an anemometer is placed on a mast reasonably close to the wind turbine (not on the turbine itself or too close to it, since the turbine rotor may create turbulence, and make wind speed measurement unreliable).

If the wind speed is not fluctuating too rapidly, then one may use the wind speed measurements from the anemometer and read the electrical power output from the wind turbine and plot the two values together in a graph like the one to the left.

Later, we will see how the combination of the power curve and the efficiency curve allows us to make significant calculations for a wind turbine. Below are typical curves, taken from a problem we will discuss a little later.

IL 33 **** (An applet for a wind turbine).

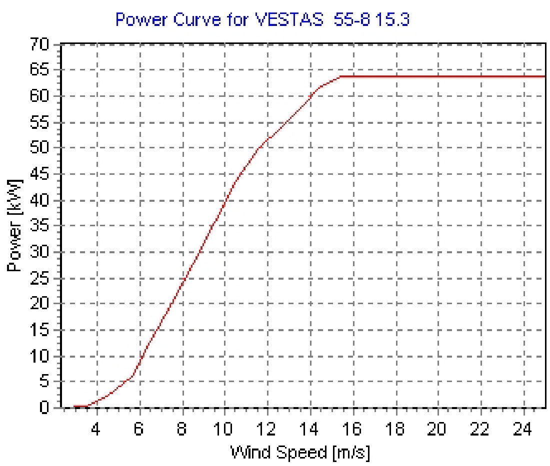


Fig. 31: A Typical Power / Wind Speed Curve for a Turbine

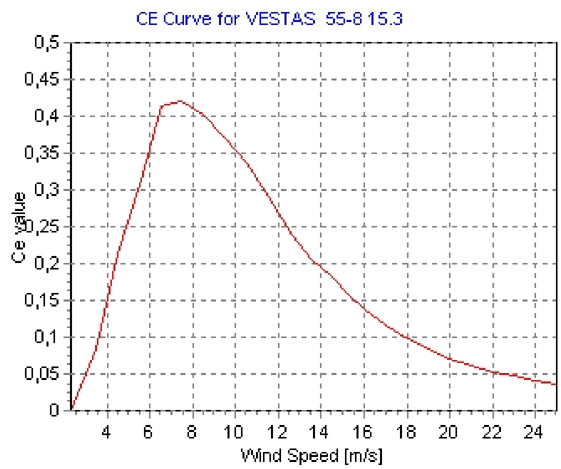


Fig. 32: A Typical Efficiency / Wind Speed Curve for a Turbine

IL 34 **38***** An excellent review of wind turbines, old and new; a range of wind generation applications; good discussion and many references

IL 35 **** A video about the early American windmills, shows the operation of a windmill. An excellent applet showing the pumping of water

IL 36 *** Windmill ranch, detailed description with good pictures

IL 37 ** Close-up picture of Fairbury windmill

IL 38 **** A more detailed physics discussion of wind water motion. The text of this IL is in the Appendix

IL 39 *** Calculating the power output of wind turbines in general. Wind power and wind power density calculation.

IL 40 *** The Fairbury windmill, Nebraska

IL 41 **** A comprehensive description of the physics of wind turbine

Problems and Questions

1. What is the “cut-in wind speed” and the “stop wind speed” for this turbine?
2. At what wind speed do you have maximum efficiency?
3. What percentage is the actual maximum efficiency of the maximum efficiency allowed by the Betz limit of 60%?
5. Why is it impossible to reach the Betz limit of about 60%? Discuss.
6. What would be the value of the power at 24 m/s wind speed if the efficiency remained at a maximum?
7. Why is the power output level between about 15 m/s and the ‘stop speed’ at about 24 m/s?
8. What would be the “ideal” wind speed for the turbine? Discuss.

Change of Wind Velocity with Height

The following is taken from IL61

IL 42

The approximate increase of speed with height for different surfaces can be calculated from the following equation:

$$\mathbf{v_2 = v_1 (h_2/h_1)^n}$$

where v_1 is the known (reference) wind speed at height h_1 above ground, v_2 is the speed at a second height h_2, and n is the exponent determining the wind change. Values for n are listed in the table below for different types of wind cover.

For example, for the wind turbines at St. Leon, n is about .16 and assume that the wind speed about 2 m above the ground is 5 m/s. Estimate the wind speed at the 80m level of the hub height of 80 m. Using the formula $\mathbf{v_2 = v_1 (h_2/h_1)^n}$ we get $5x\ (80/40)^{0.16} = 9.0$ m/s. If the ground speed at a height of 2 m doubles, then the speed at the hub will be 18 m/s. So generally we can write for this height

$$\mathbf{v_2 = v_1 \times 40^{0.16}} = 1.80 \times \mathbf{v_1}$$

ground cover	n
smooth surface ocean, sand	0.10
low grass or fallow ground	0.16
high grass or low row crops	0.18
tall row crops or low woods	0.20
high woods with many trees suburbs, small towns	0.30

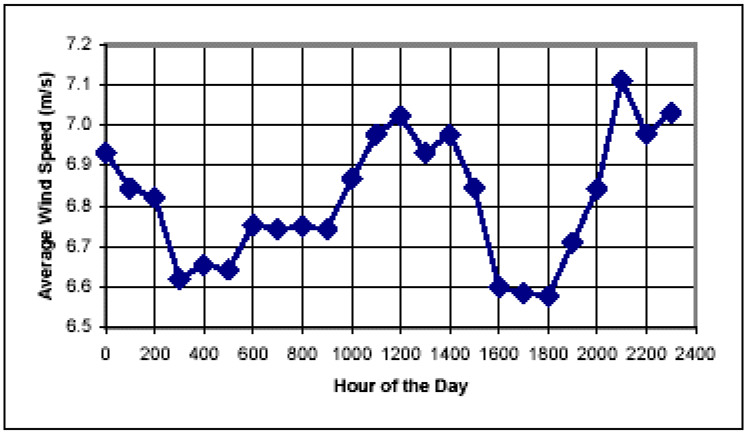


Fig. 33: Example of Wind Speed Distribution by Hour of the Day
Values shown are monthly averages of measurements made by anemometers.
(Source: US Department of Energy)

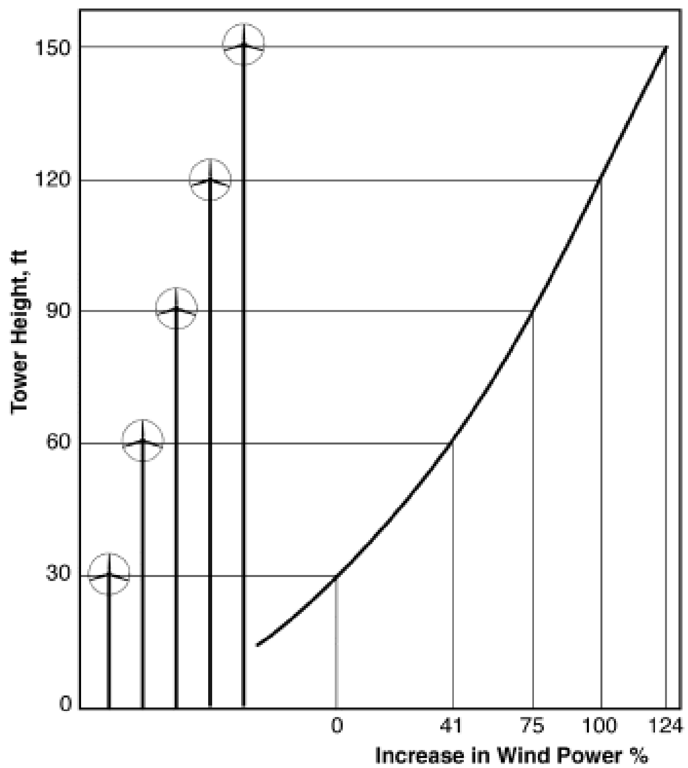


Fig. 34: The Relationship between Tower Height and Wind Power

Questions and problems

1. Find the wind velocity at the top of wind turbine with a height of 10m, 30m, and 80m placed in a field with low grass. The wind speed at a height of 2 meters is 5 m/s.

2. Find the efficiencies for these heights for this situation.
3. According to the graph in Fig. the wind speed increases only beyond a height of about 30 feet (about 10 m).
   a. At what height does the wind speed double?
   b. If the wind speed at 2 meters is 4 m/s at what height would you have maximum efficiency?
4. Find an equation for the graph of the type $\mathbf{v_2 = v_1 (h_2/h_1)^n}$ and comment.

Fig. 35: Restored Fairbury Windmill from IL48

Our Example of a Small Windmill

A famous and an excellent kind of windmill (often seen in Western movies) that can still be commonly seen, though less than formerly, is the American wind pump, simply called a "windmill" in the United States. It has an *annular sail*, which is very strong and durable, composed of many radial vanes. A tail vane keeps the sail faced into the wind. This vane is hinged so that it can be latched parallel to the sail when the mill is not intended to work. A cranked windshaft moves the vertical pump rod up and down to operate the pump in the well beneath it directly (See IL). The machinery is mounted at the top of a tower made from angle iron in the better machines, of wood in the lesser. This mill pumps water for cattle in isolated locations, and will work unattended, pumping whenever there is sufficient wind from any direction. Large mills of this type even provided locomotive water for the Union Pacific at certain locations where the installation of a steam engine was not warranted. There could be a device that folded the tail if the wind exceeded 30 mph, or even speed governors. One example of a small mill had a 6' wheel and a 19' redwood tower. Among manufacturers were the Fairbury Windmill Co. of Fairbury, Nebraska and the Chicago Aermotor Co. A Fairbury windmill with an 8' wheel and 33' tower, restored by Bill Alexander, is shown above.

Today, electricity has taken over most similar tasks once performed by the wind. Even the provision of small amounts of electricity for battery charging is now usually done with solar cells. However, windmills are made with geared heads for driving generators. Because of the variation in speed, the control of output voltage must be carefully considered.

A Simple Calculation Involving an Older Type Wind Mill

Here is a description of the windmill and the calculations to find the power output of the windmill, using the British system of units.

An 8' wheel has an area of 50.2 ft^2. The maximum operating wind velocity is 30 mph, or 44 fps, which gives an energy density of 2.25 ft-lb/ft^3. The total power available in the wind intercepted then is 4976 ft-lb/s or about 9 hp. At an efficiency of 50%, this means that a maximum of 4.5 hp is available. With an average wind of 15 mph or so, about 0.56 hp should be available, which can still pump a lot of water. The rapid variation of output with wind speed is one of the difficulties in applying wind power. Windmills are most useful for winds of Beaufort Force 4 to Force 6, or 15 to 30 mph. Over this range, their power varies by a factor of 8. Weaker winds will not provide sufficient power, while stronger winds may be damaging, and require that either the vanes be feathered or the wheel turned parallel to the wind.

Here are useful conversion figures:

1 mile = 5280 feet

1 mile = 1600 m

1 foot = 12 inches

1 inch= 2.54cm

1 m = 3.28 ft

1 km/h = 0.28 m/s

1 mile/h = 1.6 kmh

1 HP is equal to 550 ft pounds/s, or 746 J/s or Watts and the density of air is 1.3 kg/m^3 or 0.081 lb/ft^3.

We have to:

1. Change the units to the SI system.

2. Verify the calculations.

<u>Data for the windmill (converting to the SI system)</u>

Radius of wheel: 4 ft, or 1.22 m

Maximum operating wind velocity: 44 ft/s, or 13.4 m/s.

Average wind velocity: 15 ft/s, or 4.7 m/s

Density of air: 1.3 kg / m^3

Solution:

The maximum operating wind velocity is 30 mph, or 44 fps. Using the wind-power equation for the ideal case, and substituting values:

$$P = \frac{1}{2} K\rho AV^3$$

First, we will assume that K = 1 , then

$P = 0.5 \times 1.3 \times 4.7 \times (13.4)^3$

we get 7300 J/s or Watts

Most windmills, however, are no more than 35% efficient. That means that K= 035. Therefore the optimum power output of this windmill is about 1800 watts, or 1.8 kW. This can also be expressed as 1800 / 746 or 2.4 hp.

With an average wind of 15 mph (about 5 m/s) or so, we then have about ½ of a horse power available, which can still pump a lot of water. See problems below.

Problems for the Student

1. The formulas below are used by wind mill and wind turbine designers. Using you knowledge of the power equation verify the following comparison:

English units	**Metric units**
$w = 0.0052\, A\, v^3$	$w = 0.625\, A\, v^3$
where w is power in watts, and A is the cross-sectional area in square feet swept out by the wind turbine blades, and v is the wind speed in miles per hour.	where w is power in watts, and A is the cross-sectional area in square meters swept out by the wind turbine blades, and v is the wind speed in meters per second.

2. Using one of the above equations, calculate the power output of a wind turbine when the wind speed is 8 m/s, the diameter of the blades 100 m.

PART THREE: GIANT WIND TURBINES

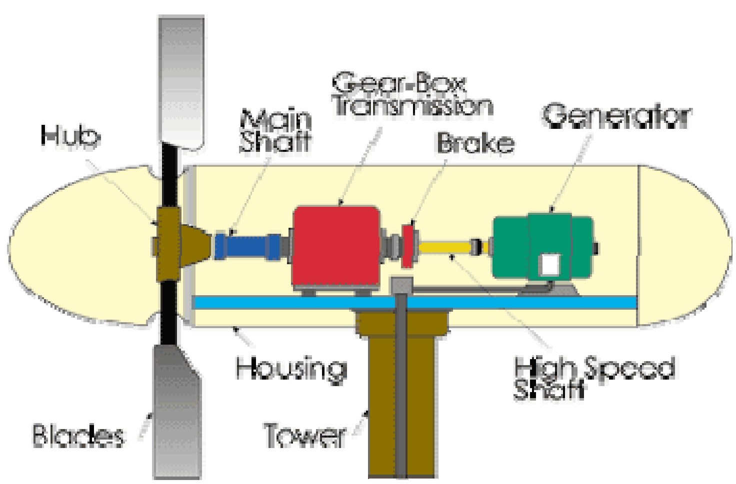


Fig. 36: Detail of a Wind Turbine. See IL 7 and the Appendix

Fig. 37: GE Wind Energy's 3.6 megawatt wind turbine
(One of the largest prototypes ever erected.
Larger wind turbines are more efficient and cost effective.)

Fig. 38: A 1 Megawatt Wind Turbine in St. Leon, Manitoba

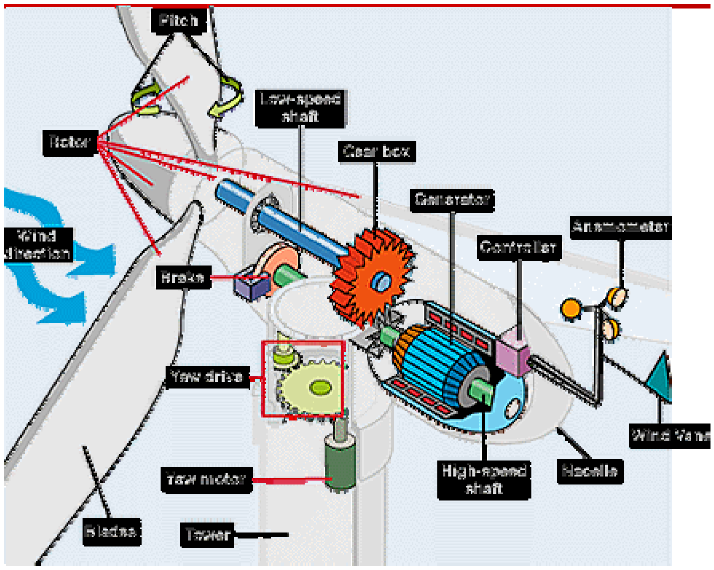


Fig. 39: Detail of a Giant Wind Turbine
(To see the description of each item,
click on IL 11, or see the Appendix.)

We will first look at the global perspective for wind energy, then at potential in Canada and finally the development in Manitoba. The information is taken from the Internet:

IL 43 *** An excellent link for detail of the construction of a wind turbine

IL 44 *** An example of a detailed calculation of wind power

Global Perspective

- The global wind industry increased by over 8,000 megawatts (MW) in 2003 and generating capacity is over 39,000 MW. Wind is the fastest growing source of electricity in the world, with growth averaging roughly 25 to 30 per cent over the past five years.
- Most of the installed capacity is in Germany, Spain and Denmark but North America is expected to witness significant growth.
- Canada has an installed base of about 600MW (2007) and has about 50,000 MW of developable wind resource —enough to supply 20 per cent of Canada's electricity supply.
- The U.S. nearly doubled its capacity in the last two years and currently (2005) has 6,374 MW installed capacity or about 16 per cent of the global capacity.
- Improvements in technology and larger turbines are driving costs down, allowing wind generation to penetrate new markets.

Why Wind in Manitoba?

Manitoba possesses a number of fundamentals that support large-scale wind farm development. These advantages include:

- Southwest Manitoba has a world-class wind regime that makes wind projects commercially viable and competitive with hydro generation.
- Virtually all of the province’s electricity is generated by water. A hydraulic system can store energy in reservoirs when the wind is blowing and release water to generate electricity when the wind is calm.
- Manitoba has accessible transmission so the power can be sent to markets when it is needed.
- The land and terrain in southwestern Manitoba lend themselves to large-scale wind farm development. Turbines complement the farming community because they only occupy a small footprint of land.
- Wind turbines provide landholders an additional source of income.
- Wind turbines also provide municipalities an additional source of revenue.
- Wind generated electricity provides diversity to our renewable energy mix.

The St. Leon wind turbine farm in Manitoba

<u>IL 45</u> ** Wind projects under construction

<u>IL 46</u> *** Best source of information about the St. Leon Wind Farm

Fig.40: Location of St. Leon Wind Farm. (From IL 54)

Improvements in technology have lowered the cost of wind generated power, so that today, wind power can compete with traditional sources of generation. Manitoba is particularly well positioned to capture a significant portion of wind generation. Initial testing has confirmed that Manitoba has a world class wind resource and accessible sites. Because wind is intermittent, it must be firmed and shaped. Manitoba Hydro has good firming and shaping capabilities. When the wind is blowing, water can be stored in reservoirs. When the wind is calm, water is released to generate power at the dam site ensuring that customers get firm power on demand. In addition, our wind regime is most productive in the winter months when our peak demand for power occurs. Manitoba has very good access to transmission lines so we can move the energy effectively and we have an enthusiastic rural population that embraces wind development.

The St. Leon Wind Energy Project site is located 150 kilometres southwest of the city of Winnipeg, near the town of St. Leon and within three kilometres of a 230-kilovolt Manitoba Hydro transmission line. This location benefits from exposure to prevailing winds at an average altitude of 490 m above sea level. The wind turbines are installed in open farm land used for growing wheat and canola.

Fig. 41: Cows feeding on St. Leon Wind Farm

<u>IL 47</u> **** An excellent PDF discussing the power equation of a wind turbine

<u>IL 48</u> **** An excellent discussion of energy and the savings for the environment

The 99-megawatt (MW) project, located in the rural municipalities of Lorne and Pembina near St. Leon, 150 kilometres southwest of Winnipeg, Manitoba, makes use of technology developed by Vestas Wind Systems. It resulted in the installation of 63 wind turbine generators over two phases and now generates enough power to serve approximately 35,000 homes, or the total energy needs of Portage La Prairie and Morden combined.

The Facility Site in St. Leon is comprised of 23,000 acres (7,284 hectares) of private land, access to which has been secured with land right-of-way agreements. St. Leon LP has entered into right-of-way agreements (collectively, the "Land Rights") with approximately fifty local landowners, using a single agreement template, providing for a minimum term of 40 years. Annual rent payable to the landowners is $0.62 per MWh from each turbine, subject to a minimum payment of $2,250 per wind turbine, with both amounts indexed to changes in the Canadian Consumer Price Index (using 2003 as the base year). Land without wind turbines is leased at a cost of $5 per acre, indexed by changes in the Canadian Consumer Price Index (using 2003 as the base year). In addition, St. Leon LP has agreed to reimburse landowners for crops damaged during the construction or operation of the wind turbines at the rate of 1.3 times the market value of the yield losses per acre of crops damaged (excluding permanent roads), calculated by multiplying the market price times the area average yield per acre, both as determined by Manitoba Crop Insurance Corporation, and taking into account the time of year in which the crop damage occurred.

CanWEA reports (as of January 2006) that Canada has approximately 682 MW of installed commercial wind power capacity. These installed wind turbines are expected to produce, on average, approximately 1,700 GWh of electricity per year which is enough to supply over 200,000 average Canadian homes. This clean source of electricity displaces coal-generated electricity, which in turn displaces the emission of roughly 1,500,000 tonnes of carbon dioxide into the atmosphere annually.

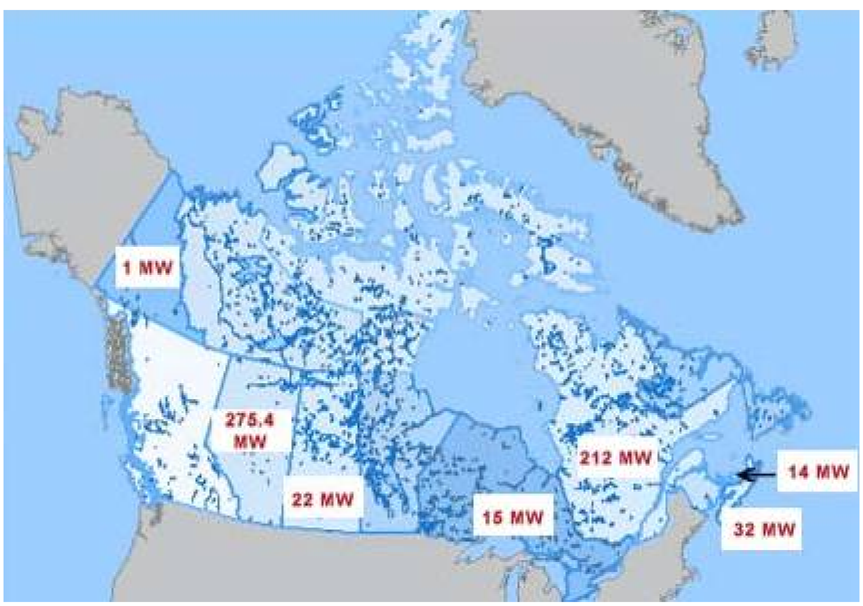


Fig. 42: Wind Power in Canada (2002)

This map outlines Canada's national installed capacity of wind resources, which provides assessment of the wind energy potential in Canada. Current information shows that Canada has a significant wind energy resource. For example Nunavut alone has enough wind resource to produce 40% of Canada's electricity needs. Besides wind resource, consider how much wind energy can be effectively integrated into Canada's electricity grid and at what cost. Based on the experience of other countries it is possible for Canada to achieve 20% of its electricity needs from wind energy; that would be 50,000 MW of wind energy capacity.

CanWEA reports (as of January 2006) that Canada has approximately 682 MW of installed commercial wind power capacity. These installed wind turbines are expected to produce, on average, approximately 1,700 GWh of electricity per year which is enough to supply over 200,000 average Canadian homes. This clean source of electricity displaces coal-generated electricity, which in turn displaces the emission of roughly 1,500,000 tonnes of carbon dioxide into the atmosphere annually.

The production of energy from wind power generating stations depends on wind fuel source that is naturally variable (which causes day-to-day variability of production from such a station). However, the use of long-term historical wind records and site-specific measurements allow preparation of a statistically predictable forecast for average monthly or annual energy production for a generating site. Expected annual production for a wind turbine is calculated as:

Annual Production (MWh) = Turbine Capacity (MW) x No. hours in one year (Hours) x Capacity Factor (percent)

"Turbine Capacity", measured in MW, is an indication of the energy production capability of a wind turbine. Current utility-scale land-based wind turbines have a capacity ranging from less than one MW to over three MW. Turbine Capacity multiplied by the number of hours in one year (8,760 hours) gives the maximum theoretical annual production of a wind turbine measured in megawatt hours.

Questions and Problems

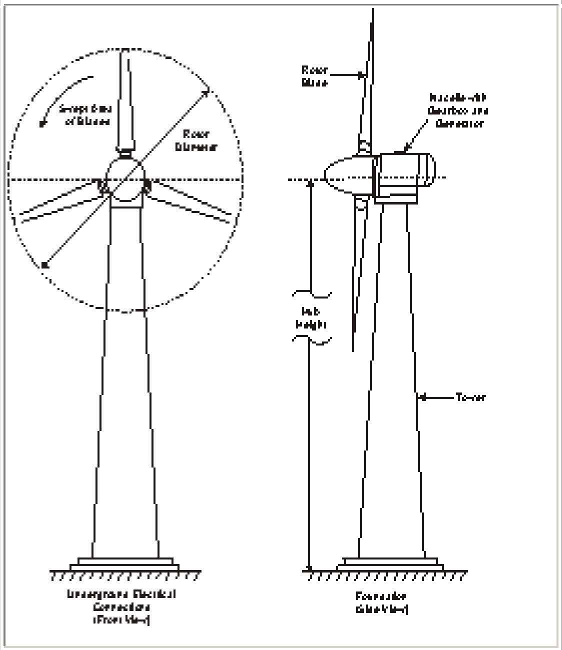
1. In 2007 (see graph of Fig.) there were about 74,000 MW of installed wind power in the world. In Canada we have (2007) nearly 1000 MW of wind power installed.
    a. What percentage is the Canadian wind power capacity?
    b. Assuming that it requires about 10 kW of power to provide electric energy to one average household, to how many houses could the Canadian wind power supply ongoing energy?
    c. Assuming that there are 3 people (on the average) in one household, approximately how many persons are supplied with electric energy in Canada?
    d. From this, estimate the percentage contribution of wind power in Canada.

IL 49 **** An excellent site that shows details of construction and electric transmission

Specifications of Modern Wind Turbines

Modern wind turbine generators are robust, sophisticated high-tech machines designed to convert the power of the wind into electricity. The following specifications are usually given:

Fig. 1: Wind Energy System Schematic



To understand the advances in wind farm technology, general knowledge of a wind turbine and its components is essential. Recent advances in component design in addition to site-specific optimization have been instrumental in improving energy output and reducing operation and maintenance costs. The text box that follows below provides a brief summary of the components in a wind turbine (see also Figure 1).

Physical Characteristics

During the past quarter century, extensive public- and private-sector efforts were made to optimize wind turbine design, including development of advanced rotor blade materials, design concepts, advanced turbine designs, and other wind energy conversion systems (WECS) components, such as towers.

Turbine Component	Function
Nacelle	Contains the key components of the wind turbine, including the gearbox, yaw system, and electrical generator.
Rotor blades	Captures the wind and transfers its power to the rotor hub.
Hub	Attaches the rotor to the low-speed shaft of the wind turbine.
Low speed shaft	Connects the rotor hub to the gearbox.
Gear box	Connects to the low-speed shaft and turns the high-speed shaft at a ratio several times (approximately 50 for a 600 kW turbine) faster than the low-speed shaft.
High-speed shaft with mechanical brake	Drives the electrical generator by rotating at approximately 1,500 revolutions per minute (RPM). The mechanical brake is used as backup to the aerodynamic brake, or when the turbine is being serviced.
Electric generator	Usually an induction generator or asynchronous generator with a maximum electric power of 500 to 1,500 kilowatts (kW) on a modern wind turbine.
Yaw mechanism	Turns the nacelle with the rotor into the wind using electrical or other motors.
Electronic controller	Continuously monitors the condition of the wind turbine. Controls pitch and yaw mechanisms. In case of any malfunction (e.g., overheating of the gearbox or the generator), it automatically stops the wind turbine and may also be designed to signal the turbine operator’s computer via a modem link.

Hydraulic system	Resets the aerodynamic brakes of the wind turbine. May also perform other functions.
Cooling system	Cools the electrical generator using an electric fan or liquid cooling system. In addition, the system may contain an oil cooling unit used to cool the oil in the gearbox.
Tower	Carries the nacelle and the rotor. Generally, it is advantageous to have a high tower, as wind speeds increase farther away from the ground.
Anemometer and wind vane	Measures the speed and the direction of the wind while sending signals to the controller to start or stop the turbine.

How Electricity Leaves the Turbine and Brings Us Power

A. Electricity and small wind turbines for the home

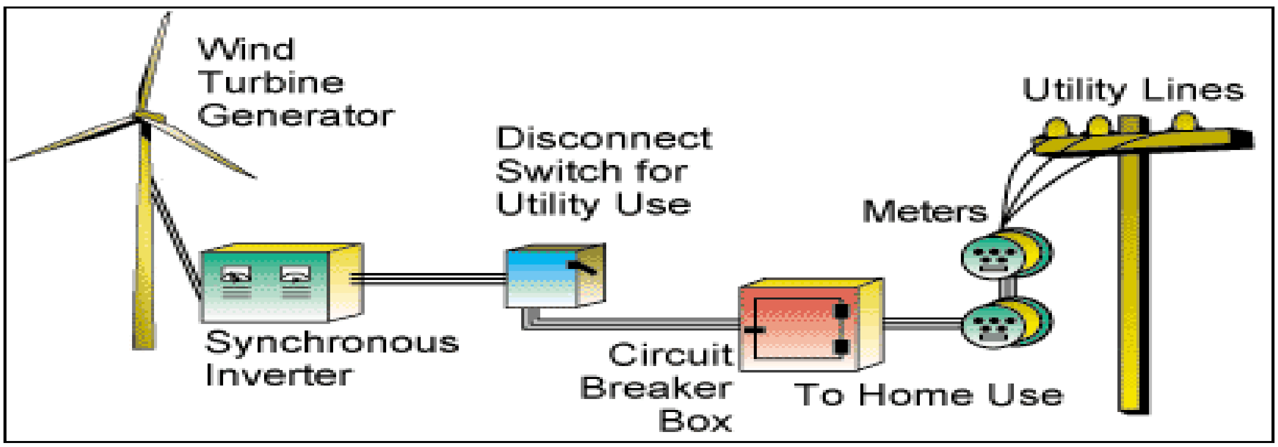
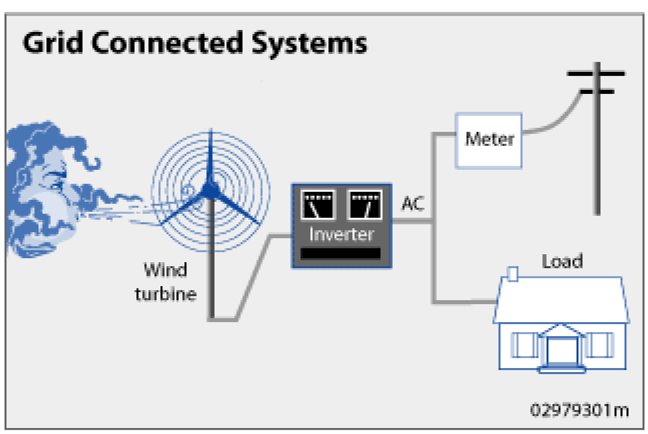


Fig. 43: Transmission of electricity for wind turbines (See IL10)



Fig, 44: Diagram of a Grid-Tied Wind Electric System
(Source: Phantom Electron Corp.)

An Advertisement for a Small Wind Turbine for a Home

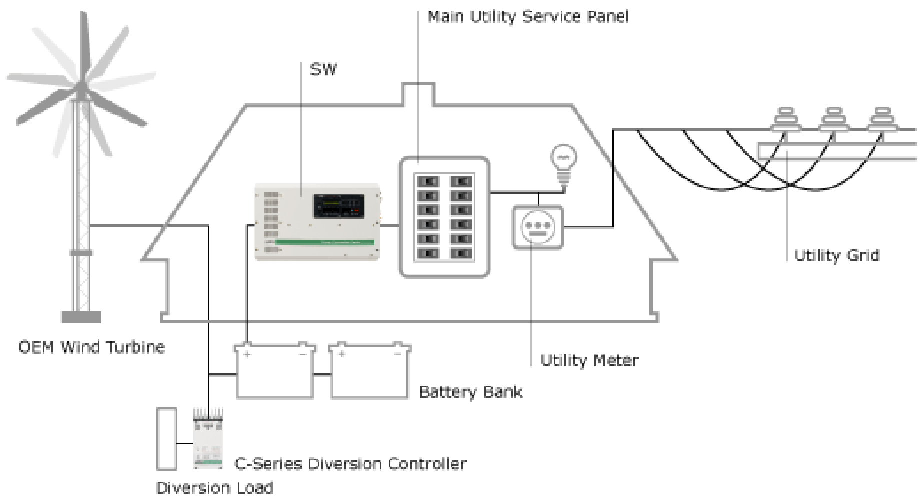


Fig. 45: A Small Wind Turbine Built for a Home

IL 50 *** (IL for the Fig. above and the advertisement below)

How it works: *When the wind blows, the grid-tie wind electric system will save you money by reducing your monthly electric bill, provide power to your home during blackouts, and help clean up the environment. The wind electric system consists of a Southwest Wind power Whisper H80 (1000 watt) or Whisper 175 (3000 watt) turbine fitted on a 24'-80' tower.*

Electricity is generated when the wind blows. The power then goes through a small battery bank into an inverter, and then into the house.

Skystream 3.7 *is a breakthrough in a new generation of RPA (Residential Power Appliances) that will change the energy landscape of how homes and small businesses receive electricity. Skystream is the first fully integrated system that produces energy for less than the average cost of electricity in the United Statesand it produces usable energy in exceptionally low winds.1*
Skystream *is available on towers ranging from 35 to 110 feet.2 Its universal inverter will deliver power compatible with any utility grid from 110-240 VAC.3 Skystreamwill efficiently and silently provide up to 100% of the energy needs for a home or small business. Any extra energy is fed into the grid spinning the meter backwards.*

Rated Capacity: *1.8 KW*
Rotor: *12 feet / 3.72 meters; 50 RPM*
Alternator: *Gearless, permanent magnet brushless*
Voltage Output: *240 VAC (Optional 277 VAC)*
Estimated Energy Production: *400 KWh per month at 12 MPH (5.4 m/s)*
Tower: *Towers from 35-110 feet are available; height is dependent by site.*

If your home or farm is connected to the power grid (Figure 8), on windier days you may be able to "sell" excess power generated by your wind turbine to your utility. Then, at other times when your turbine cannot generate all the power you need, you would buy power from the grid. This concept is called "net metering", or "net billing". Net metering is currently unavailable in most parts of Ontario (2003). Contact your local utility or Hydro for more information.

Even if net metering is unavailable, you might be able to reduce your power bills by using the electricity you generate using a grid-connected wind turbine. If you do this, then you would not have to buy as much electricity from your utility.

If you do connect your wind turbine to the grid, your utility will require a transfer switch between the wind turbine and the utility line as a well as a two-way meter to keep track of the energy you have stored in and taken from the power grid. It is very important that your wind generator meets certain standards and that it does not pose a risk to your utility's personnel or equipment. It is also important that the quality of power coming from your turbine adequately matches the electrical characteristics in your utility's power grid.

Small wind energy systems can be connected to the electricity distribution system. These are called grid-connected systems.

A grid-connected wind turbine can reduce your consumption of utility-supplied electricity for lighting, appliances, and electric heat. If the turbine cannot deliver the amount of energy you need, the utility makes up the difference. When the wind system produces more electricity than the household requires, the excess is sent or sold to the utility.

With this type of grid-connection, note that the wind turbine will operate only when the utility grid is available. During power outages, the wind turbine is required to shut down due to safety concerns.

While renewable energy systems are capable of powering houses and small businesses without any connection to the electricity grid, many people prefer the advantages that grid-connection offers. A grid-connected system allows you to power your home or small business with renewable energy during those periods (diurnal as well as seasonal) when the sun is shining, the water is running, or the wind is blowing. Any excess electricity you produce is fed back into the grid. When renewable resources are unavailable, electricity from the grid supplies your needs, thus eliminating the expense of electricity storage devices like batteries.

In addition, power providers (i.e. electric utilities) in most states now allow net metering, an arrangement where the excess electricity generated by grid-connected renewable energy systems "turns back" your electricity meter as it is fed back into the grid. Thus, if you use more electricity than your system feeds into the grid during a given month, you pay your power provider only for the difference between what you used and what you produced.

Your local system supplier or installer should know about and be able to help you meet the requirements from your community and power provider.

Questions and Problems

1. Use the power equation $\mathbf{P = \frac{1}{2} K\rho\, AV^3}$ to find the power output of the small wind turbine described above if the efficiency were 100%. Show that this is about 8500Watts.
2. The actual power output claimed is 1.8 KW. Show that this would mean that the small turbine is about 21% efficient. Comment.
3. The rotor turns around at 50 times every minute. How many times does it turn around each second?
4. The advertisement claims that estimated energy production per month at a wind speed of 5.4 m/s would be 400 KWH.

   a. What is the average energy consumption per day (30 day month).?

   b. Assume that the average energy consumption is for about 10 hours per day, what is the average energy consumption per hour?

   c. The company claims that the system is 'cost-effective' at 9 cents per KWH. How much would this electric energy consumption cost per month?

   d. Assuming that the electric energy taken from the grid would cost 15 cents per KWH, what is the yearly saving?
5. Manitobans enjoy one of the cheapest electric energy in the world, at about 7 cents per hour. As a Manitoban would you invest in this turbine? Even if you argued as a devoted environmentalist would, consider that the electric energy in Manitoba is based on a renewable hydro-electric source, taken from large dams.

Electricity Produced By Larger Wind Turbines

IL 51 ***

The following is based on the description of the Vestas V82-1.65 MW wind turbine: (See IL 51 above).

Electricity from each 1.65 MW wind turbine generator is fed through numerous 34.5-kilovolt power underground cables that come together at the wind farm substation near Rector Road. These cables channel the electricity via a step-up transformer and dedicated ten-mile power line into the New York electricity grid at the 230-kilovolt Niagara Mohawk Adirondack line, feeding power to towns and cities across New York's North Country and beyond. Sophisticated computer control systems run constantly to ensure that the machines are operating efficiently and safely. See Fig. 11 for more detail.

In wind plants or wind farms, groups of turbines are linked together to generate electricity for the utility grid. The electricity is sent through transmission and distribution lines to consumers. See the St Leon Wind Farm below as an example.

IL 52 ** Transmission lines

Design Choices in Generators and Grid Connection

Wind turbines may be designed with either synchronous or asynchronous generators, and with various forms of direct or indirect grid connection of the generator.

Direct grid connection mean that the generator is connected directly to the (usually 3-phase) alternating current grid.

Indirect grid connection means that the current from the turbine passes through a series of electric devices which adjust the current to match that of the grid. With an asynchronous generator this occurs automatically.

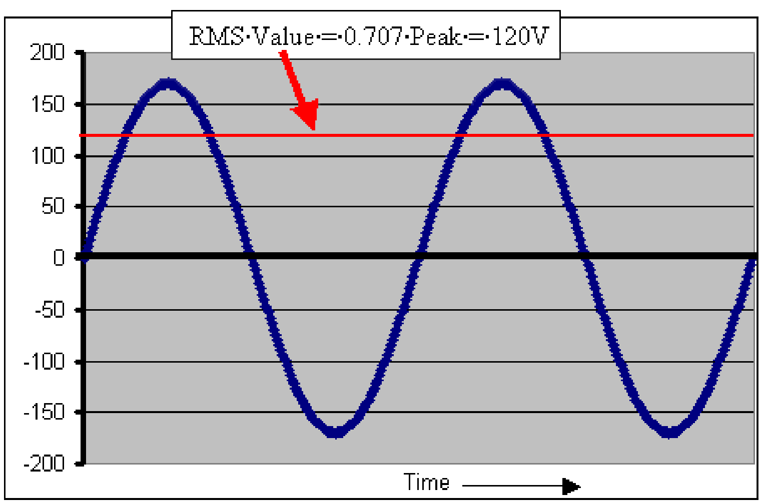
You might wonder why we us three phase systems when a single phase one might do. It is possible to use single phase motors for this. However, they require more capacitance, operate at lower efficiency, and are not easily excited. Three phase alternating current is also more efficiently converted to DC for battery systems.

IL 53 *** Excellent applet showing electric energy production and distribution for wind turbines

IL 54 **** Excellent applet showing electric production.

A Tutorial on Electricity

A. Root Mean Square (RMS) values of alternating currents



Most electrical appliances and equipment in the United States and Canada run on alternating current (AC) electricity, which is also referred to as single-phase, 120-volt AC service in homes, offices and some manufacturing facilities. If you could “look” at the electricity flow coming from a wall outlet in your home, you would see a sine wave (Figure) that oscillates between -170 volts and +170 volts. The rate of oscillation for the sine wave is 60 cycles per second and the AC term is used for the voltage, current and power.

The value of AC voltage is continually changing from zero up to the positive peak, through zero to the negative peak and back to zero again (Figure 1). For most of the time, the value of the voltage is less than the peak voltage and is not a good measure of its actual value. Instead we use the root mean square voltage (V_{RMS}) which is the square root of 2 , or 0.707 (about 71%) of the peak voltage (V_{peak}). The Root Mean Square (RMS) value is the effective value of a varying voltage or current. It is the equivalent of steady direct current (DC) constant value giving the same effect.

Electric Energy and Wind Energy

The sections below will help you learn about some of the issues involved in connecting a renewable energy system to the grid:

The wind turbine generator converts mechanical energy to electrical energy. Wind turbine generators are a bit unusual, compared to other generating units you ordinarily find attached to the electrical grid. One reason is that the generator has to work with a power source (the wind turbine rotor) which supplies very fluctuating mechanical power.

You should become familiar with the basics of electricity, electromagnetism, and in particular alternating current. If any of the expressions volt (V), phase, three phase, frequency, or Hertz (Hz) sound strange to you, you should take a look at the Reference Manual on Electricity, and read about alternating current , three phase alternating current , electromagnetism, and induction , before you proceed with the following:

Many available renewable energy technologies, such as photovoltaics (PV), produce direct current (DC) electricity. To run many standard AC appliances, the DC electricity must first be converted to AC electricity using inverters and related equipment. Note the RMS value of an AC sine wave is the equivalent DC power if you are using a resistive load like a toaster.

There are four basic elements to an inverter:

- Conversion—of constant DC power to oscillating AC power
- Frequency of the AC cycles—should be 60 cycles per second
- Voltage consistency—extent to which the RMS output voltage fluctuates

Generating Voltage (tension)

On large wind turbines (above 100-150 kW) the voltage (tension) generated by the turbine is usually 690 V three-phase alternating current (AC). The current is subsequently sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage to somewhere between 10,000 and 30,000 volts, depending on the standard in the local electrical grid.

Large manufacturers will supply both 50 Hz wind turbine models (for the electrical grids in most of the world) and 60 Hz models (for the electrical grid in Canada and America).

Cooling System

Generators need cooling while they work. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling, but a few manufacturers use water cooled generators. Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Generating Voltage (tension)

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Cooling System

Generators need cooling while they work. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling, but a few manufacturers use water cooled generators. Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Starting and Stopping the Generator

If you connected (or disconnected) a large wind turbine generator to the grid by flicking an ordinary switch, you would be quite likely to damage both the generator, the gearbox and the current in the grid in the neighbourhood.

You will learn how turbine designers deal with this challenge in the page on Power Quality Issues . See IL below.

IL 55 *** Detailed discussion of power quality.

The following are good sources of tutorials on basic electricity:

IL 56 *** Ohm’s law discussed.

IL 57 *** Power relationships discussed.

IL 58 *** A very comprehensive discussion of ammeters and voltmeters.

IL 59 **** An very good discussion of Ohm’s Law with an applet.

IL 60 *** A more detailed discussion of the physics of transformers)

IL 61 **** This is an excellent link for transformers, relevant to our discussion

IL 62 *** Generators pictorially explained.

IL 63 *** A short explanation of induction generators.

IL 64 *** An applet to show the workings of a generator.

IL 65 *** * An excellent discussion of transformers. See figures below.

IL 66 *** Resistivity and resistance explained.

More about Transformers

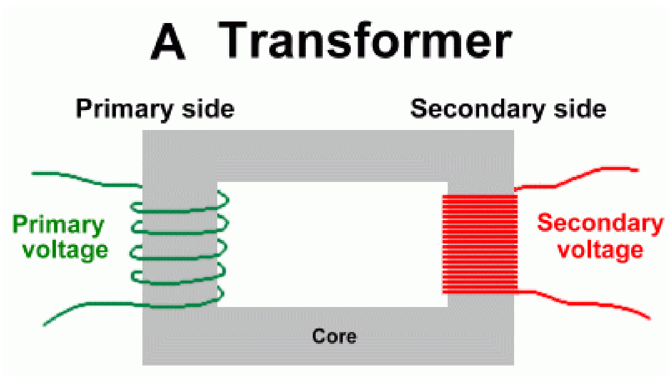


Fig. 46: Schematic of a Transformer

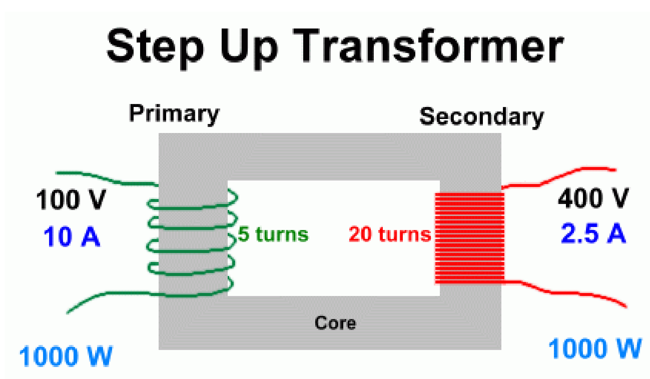


Fig. 47: A Schematic for a Step-up Transformer

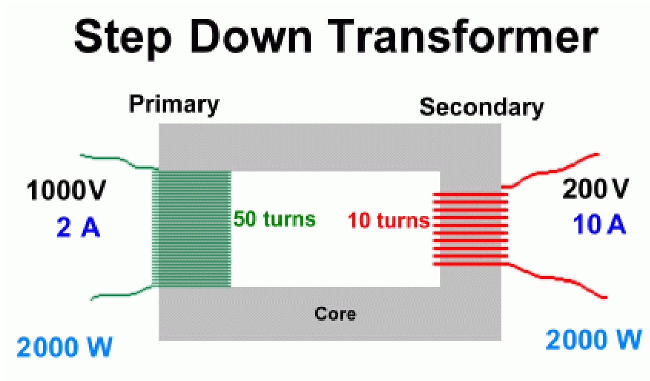


Fig. 48: A Schematic for a Step-down Transformer

IL 67 **** An excellent applet to show the workings of a 3 phase generator.

Fig. 49: A Typical Transformer Station Where the AC Voltage and Currents Are Changed

Questions and Problems

1. On large wind turbines the voltage (tension) generated by the turbine is usually 690 V three phase alternating current (AC). The current is subsequently sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage to somewhere between 10,000 and 30,000 volts, depending on the standard in the local electrical grid.

   Consider a 500 KW wind turbine, where the voltage is 690V. What should be the total current (AC) produced?

2. The voltage is to be increased to 30,000 V (AC), using a step-up transformer. How do the number of windings in the primary and secondary coil compare?

3. Calculate the current (AC) in the secondary coil.
4. The $I^2 R$ heat loss (see tutorial above) would be substantial the transformer were not used. Compare the heat loss (per unit length of conductor) for the current in the primary and the current in the secondary. Comment.

Wind Generators at St Leon Wind Farm: A Special Example

IL 68 **** Model wind competition at Red River College, November, 2007.

We can now apply the above concepts and ideas to a large Wind Farm for which we have sufficient detail and data.

The St. Leon installation is using induction generators and there is no AC/DC and DC/AC conversion. Energy losses will be just conduction losses, only about 3% to 4% .

The generator at each tower is rated 1808 kVA, 600 V, 1740 A. The voltage rating is between each pair of phase conductors. The current rating is for phase current, and it determines the size of conductors that will carry the current. St. Leon installation is using three 800 MCM[a] copper conductors in parallel per phase; that means there are 9 cables going from the generator at the top of the tower, to the transformer that is located at the foot of each tower. Each cable is approximately 1.25 inch in diameter. (One 800 MCM copper conductor is rated for around 500 A, depending on the allowable temperature rise.) See IL

The transformer is 600V/34.5kV, and it probably has a tertiary winding for 480V that is taken back to the tower to supply motors, computer equipment, etc. There are usually 6 transformers (with their accompanying generators) daisy-chained to one 34.5 kV transmission line that then goes to Manitoba Hydro switchyard where the power is again transformed to higher voltage (230 kV).

Also, there is the usual protection and control equipment between the generator and the Manitoba Hydro 34.5 kV/230kV transformer: switches, breakers, lightning arrestors, protective relays, control and communication equipment (called SCADA[b] when it is used on power systems), computers, etc.

The coils inside Hydro generators are arranged in such a way as to produce three separate pulses (or phases) of electricity. Three conductors lead away from a single generator, each carrying one of the three phases.

The phases are carefully balanced. At any one point in time an average taken across the three conductors would show equal numbers of electrons moving backwards and forwards. Electricity only flows in a circuit. The balancing of the three phases allows the part of the circuit from the user back to the generator to be completed along the same three lines used to transmit the electricity.

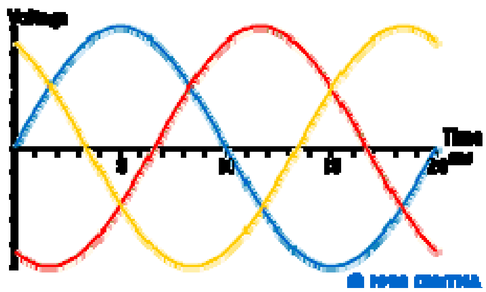
---

[a] MCM is thousand of circular mils (CM). 1 CM is the area of a circle of diameter of 0.001 inch. This is a unit specified by American Wire Gauge System.

More about 3-phase Generators

The power of alternating current (AC) fluctuates. For domestic use for e.g. light bulbs this is not a major problem, since the wire in the light bulb will stay warm for the brief interval while the power drops. Neon lights (and your computer screen) will blink, in fact, but faster than the human eye is able to perceive. For the operation of motors etc. it is useful, however, to have a current with constant power.

Voltage Variation for Three Phase Alternating Current



See IL

It is indeed possible to obtain constant power from an AC system by having three separate power lines with alternating current which run in parallel, and where the current phase is shifted one third of the cycle, i.e. the red curve above is running one third of a cycle behind the blue curve, and the yellow curve is running two thirds of a cycle behind the blue curve.

As we learned on the previous page, a full cycle lasts 20 milliseconds (ms) in a 50 Hz grid. Each of the three phases then lag behind the previous one by 20/3 = 6 2/3 ms.

Wherever you look along the horizontal axis in the graph above, you will find that the sum of the three voltages is always zero, and that the difference in voltage between any two phases fluctuates as an alternating current.

More Detail about Generators Used For Wind Turbines

IL 69 *** An excellent review and description of generators.

IL 70 *** Same as above.

IL 71 *** Good discussions and descriptions of generators.

IL 72 *** Generators explained**.**

Questions and Problems

For all problems we will us the power equation in this form:

$$\mathbf{P = \tfrac{1}{2}\, k\, \rho\, AV^3}$$

where k automatically contains the Betts limit of 60%.

1. Calculate the "ideal" power output of a St. Leon wind turbine that has a rotor diameter of 60 m, assuming a wind speed of 13m/s. Show that this would be about 2.6 MW.
2. Since the power output is about 1 MW, what is the overall efficiency of the wind turbine?
3. The generator at each tower is rated 1808 kVA, 600 V, 1740 A. That means that the voltage in the primary coil is 600V and the current is 1740A. Show that the electric power output is about 1 MW.
4. There are two sets of transformers. The first set transforms the power to 34.5 kV and the second to 230 kV. Calculate the current change for both cases.
5. Compare the I2 R loss for the three cases. Comment
6. The copper conductors have a diameter of 1.5 in, or 3.8 cm (See IL above on resistance and resistivity). The resistivity of copper is 1.72 x 10-8 Ohm-m, at 20º C . The formula for resistivity comes from the definition of resistance:

   R = ρ L / A, where **R** is the resistance in Ohms, **L** is the length of the conductor, **A** is the cross sectional area of the conductor, and **ρ** is the resistivity.

   Calculate the resistance of 1000 m of the copper conductor. Show that this is less than 1 Ohm for 1000m of wire. This is a very small resistance, so that the $\mathbf{I^2}$ **R** loss is very little,

More Examples of Wind Turbines

IL 73 **** A nice applet to show the power curve of a wind turbine.

Looking At an Example of a Small Wind Turbine

VESTAS 55

Company Manufacturer	**VESTAS**
Country of Origin	**DK**
Type/Varian	
Rated Power	**55 kW**
Small Generator	**7.5 kW**
Variable Speed	**2 generator**
Power control	**Stall**
Blade Type	**ØKÆR**
Rotor Diameter	**15.3 m**
Swept Area	**184 m^2**
Power per m2	**0.299 kW/m2**
Rpm at rated power	**50.4**
Nominal wind speed	**16 m/s**
Standard hub height(s)	**18 m**
Tower	**Lattice**

The above description of small wind turbine is taken from IL 74 below.

IL 74 ****

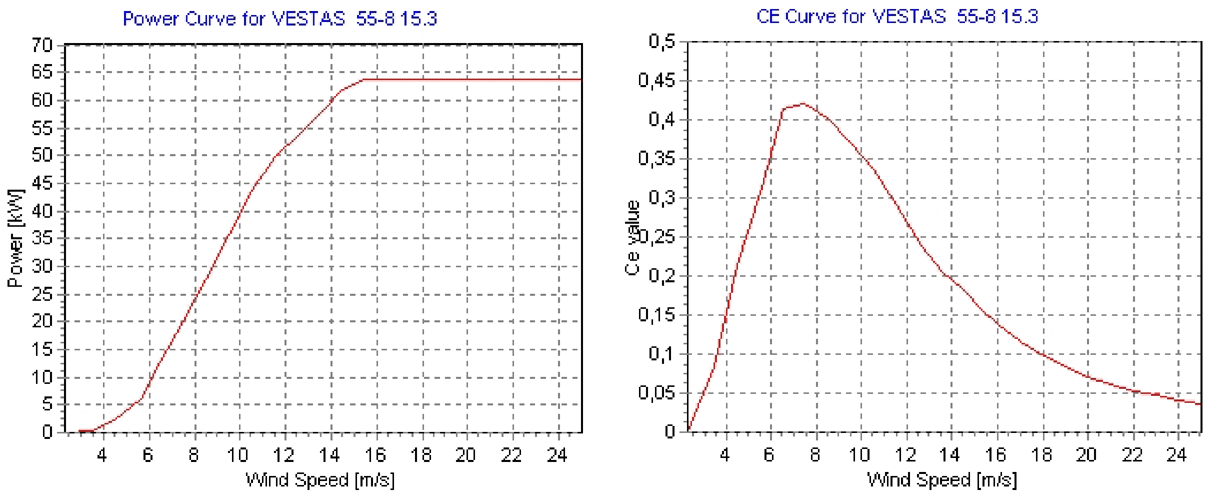


Fig. 50: Power and Efficiency Curves for the Vestas 55.

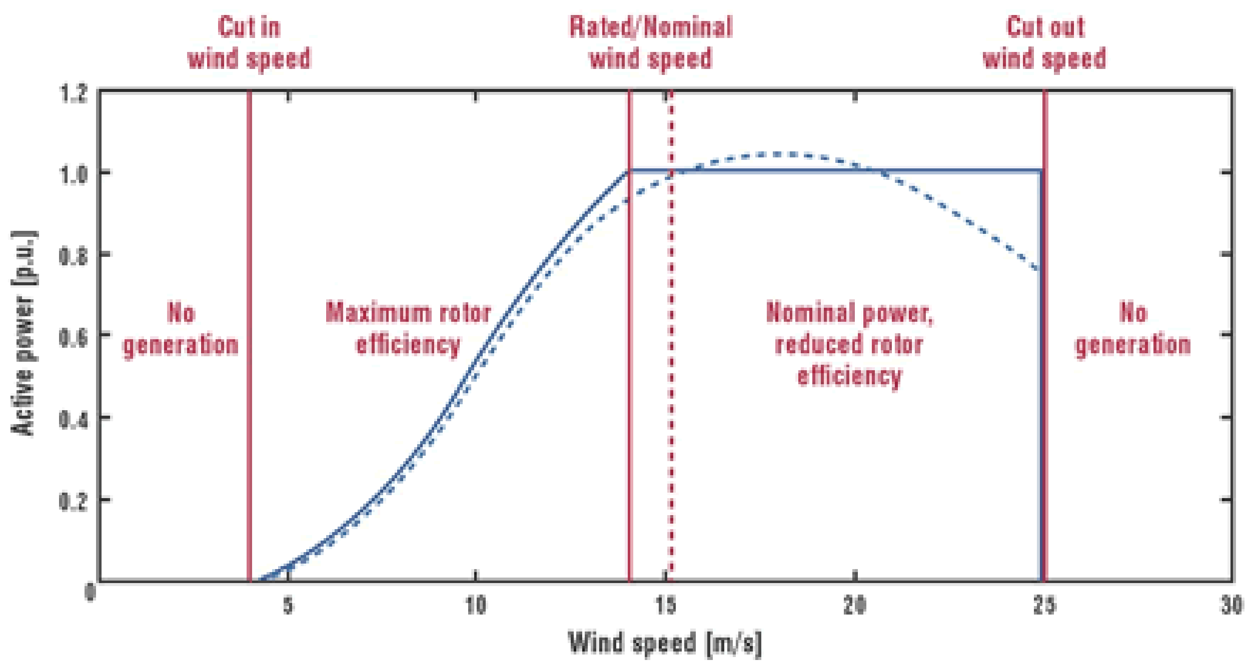


Fig. 51: Graphical Representation of Power Activity and Wind Speed for All Wind Turbines

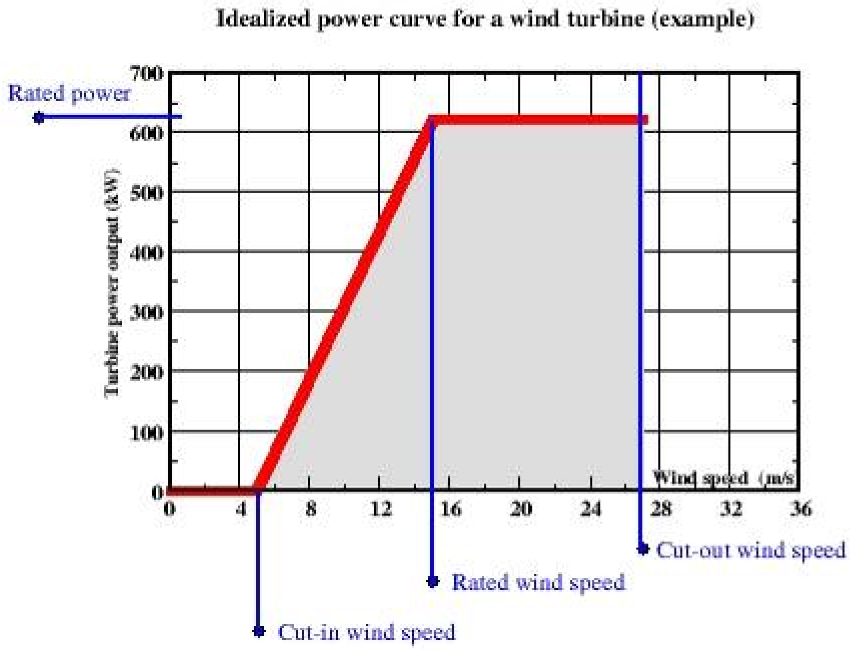


Fig. 52: Idealized Power Curve for a Wind Turbine

Questions and Problems Based On the 55 Kw Vestas Turbine

For all problems we will us the power equation in this form:

$$P = \frac{1}{2} k \rho AV^3$$

where k automatically contains the Betts limit of 60%.

1. Show that the area swept out by the blades is 184 m^2.
2. Calculate the maximum power *ideally* possible for the wind turbine. Use the nominal wind speed of 16 m/s Show that this power output would be about 450 kW.
3. The theoretical limit, however, would be about 60% of this value (Bett's law), or about 270 kw.
4. But the maximum power output (see graph), is only about 64 kW. Show that this is about 14% of the ideally possible and 23% of the theoretically possible power out put. Discuss.
5. Refer to the two graphs above. Pick a wind speed of 16 m/s and show that the total efficiency rating (this includes Bett's constant!) at this speed is indeed 0.14. Now confirm that the maximum power output (see graph) is about 64 kW. (Note that this efficiency rating automatically includes the Betts limit.)
6. It seems surprising that the power output stays at about 64 kW, although the efficiency drops dramatically. For example: When wind speed is 20 m/s, the power output is still about 64 kW, and the overall efficiency rating is 0.07. Show by calculation that the power output expected will be about 64 kW.

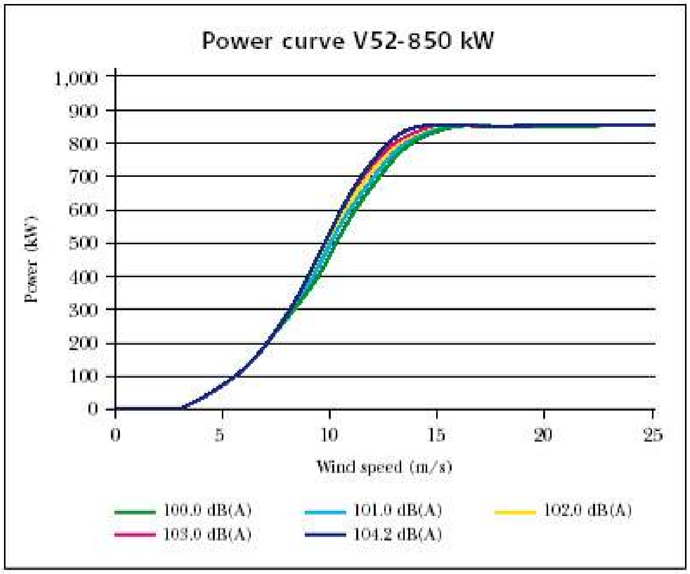
7. The highest efficiency is obtained occurs when the wind speed is about 7 m/s. The power output, according to the graph, is about 17 kW. Confirm this using the power equation.
8. Use the formula for finding wind speed at height h, $\mathbf{v_2 = v_1 (h_2/h_1)^n}$ to determine the speed of the wind at the hub level of 18 m for winds of 5, 10, and 15 m/s at the ground height of 2 m. Show that you can use the formula for this case in the form $\mathbf{v_2 = 1.42\ v_1}$
9. Verify the claim that the power per m2 is 0.299 kW / m^2.

   Having acquired some expertise in calculating power outputs for a small wind turbine, we will compare the size and performance of three Vestas wind turbines, of high power rating, 850 kW, 1.8 MW, and 3.0 MW.

Comparing Three Vestas Wind Turbines

	Vestas 850kW	**Vestas 1.8 MW**	**Vestas 3.0 MW**
Rotor diameter	52 m	80 m	90m
Swept area	2,124 m^2	5027 m^2	6363 m^2
Angular speed	26 rpm	16.rpm	16 rpm
Number of blades	3	3	3
Hub tower height	40-86m	60-78 m	80-105 m
Total height	66 m – 112 m	100 m – 118 m	125 – 150 m
Cut-in wind speed	4 m/s	4 m/s	4 m/s
Stop wind speed	25 m/s	25 m/s	25 m/s
Nominal wind speed	15 m/s	15 m/s	15 m/s
Generator nominal output	850 kW	1,800 kw	3.0 MW
Generator Voltage	690 V	690 V	1000 V
Weight (total)	290 metric tons	299 metric tons	300 metric tons

The rated, or nominal, wind speed is the speed at which the turbine produces power at its full capacity.



The figure above illustrates the power curves at different sound levels for the V52-850 kW turbine, which is equipped with OptiSpeed®.

Fig. 53: Vestas V850 Power Curve

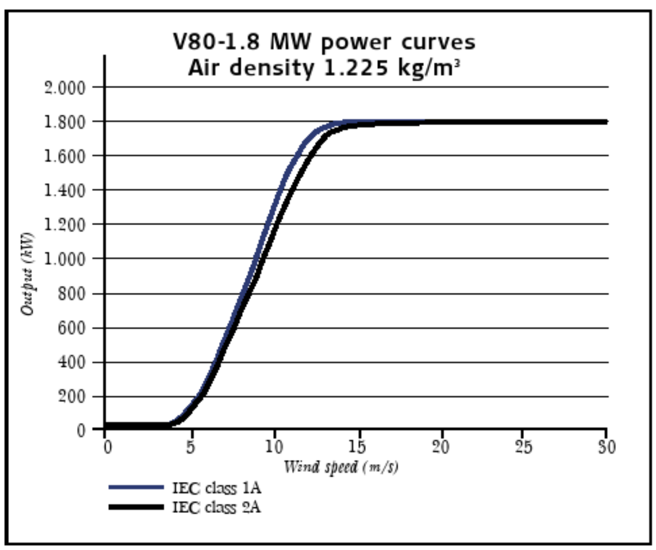


Fig. 54: Vestas 1.8 MW Power Curve

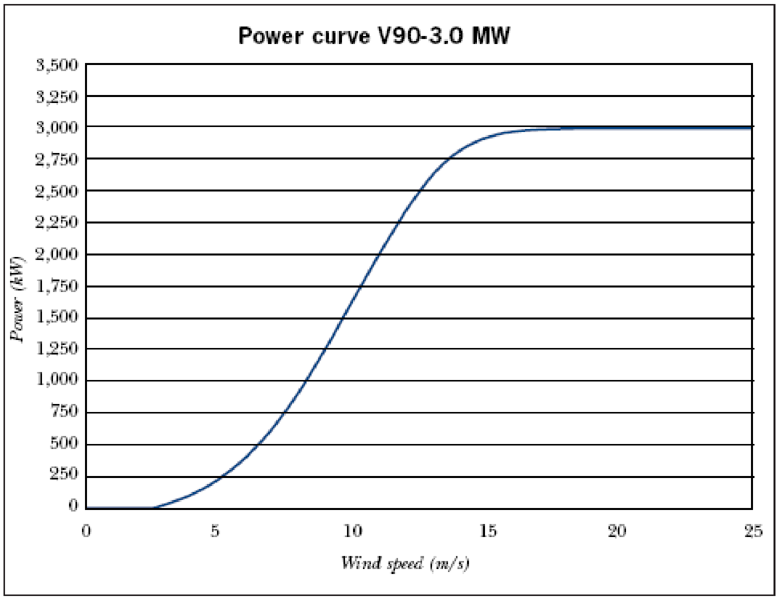


Fig. 55: Vestas 3.0 MW Power Curve

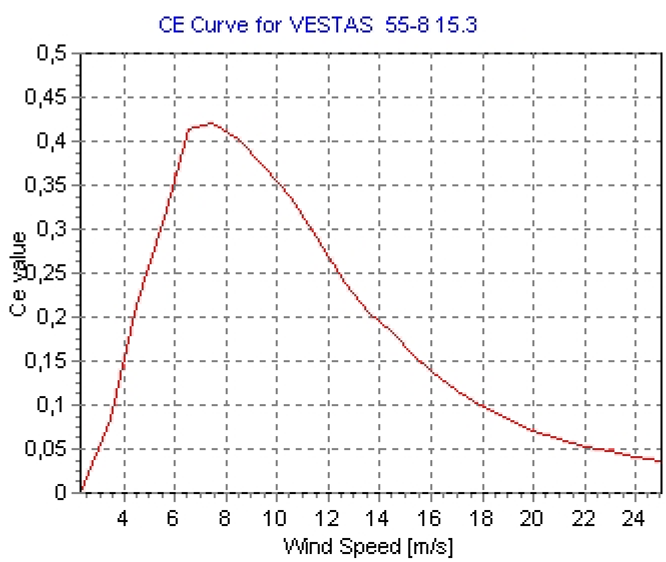


Fig. 56: General Efficiency Curve for the Above Wind Turbines

Questions and Problems

1. Notice that the following are the same for all three turbines: cut-in wind speed, stop wind speed, nominal wind speed, generator nominal output, and generator voltage. Can you explain why this is so?

2. The power curves for these three wind turbines are very similar. Discuss.
3. In LCP 3 we studied scaling. Let's apply the principles of scaling to the wind turbines. Compare the three wind turbines in terms of:

   a. Height and power output

   b. Total weight and power output.

   c. Swept area and power output.
4. Why, do you think, the efficiency curve above applies to all the wind turbines we have studied?

Fig. 57: Inside the Tower of A Wind Turbine

<u>IL 75</u>*** Wind turbine power calculator

Capital Costs for Various Electricity-Generating Technologies (2005)

Technology	Capital Costs per Installed kW
Gas/oil combined cycle	$445
Advanced gas/oil combined cycle	$576
Wind	$983
Coal	$1,092
Coal gasification cycle	$1,306
Waste and landfill gas combustion	$1,395
Geothermal	$1,708
Biomass	$1,732
Fuel cells	$2,041
Advanced nuclear	$2,188
Solar thermal	$2,946
Solar photovoltaic	$4,252

Source: Energy Information Administration, "Assumptions to the Annual Energy Outlook 2001" DOE/EIA0554 (2001), December 2000, Table 43, p. 69.

Wind farms in the US produce power at the average rate of about 1.2 watts per square meter (about 5000 watts per acre). In order to produce an average of 1000 MW—the power produced by any large conventional (coal, oil nuclear, gas) power plant would require about 833 square kilometers (300 square miles) of wind turbines. That's the area of a mile-wide swath of land extending from San Francisco to Los Angeles. Multiply that by about 30 and you have California's electricity.

Pollution Offset

The following are taken from various Internet sources and are presented for discussion.

Especially from:

IL 76 ***

1. Wind power is a renewable resource, which means using it will not deplete the earth's supply of fossil fuels. It also is a clean energy source, and operation does not produce carbon dioxide, sulfur dioxide, mercury, particulates, or any other type of air pollution, as do conventional fossil fuel power sources.
   Comment:
2. The American Wind Energy Association estimates that 1 MW of wind generation capacity is the equivalent of 1 square mile of new forest, in terms of offsetting or displacing carbon dioxide from conventional generating sources.
   Comment:

3. One typical (2MW) wind turbine in Australia can be expected to produce over 6000 megawatt hours of electricity each year. If this replaces coal-fired power, then the CO_2 released to the atmosphere will be reduced by 6000 tonnes each year, if it replaces oil or gas-fired power, CO_2 released each year is reduced by about 3000 tonnes.
Comment:

4. Wind power consumes no fuel for continuing operation, and has no emissions directly related to electricity production. Wind power stations, however, consume resources in manufacturing and construction, as do most other power production facilities. Wind power may also have an indirect effect on pollution at other production facilities, due to the need for reserve and regulation, and may affect the efficiency profile of plants used to balance demand and supply, particularly if those facilities use fossil fuel sources. Compared to other power sources, however, wind energy's direct emissions are low, and the materials used in construction (concrete, steel, fiberglass, generation components) and transportation are straightforward. Wind power's ability to reduce pollution and greenhouse gas emissions will depend on the amount of wind energy produced, and hence scalability, as well as the profile of other generating capacity.
Comment:

5. Electric power production is only part (about 39% in the USA[66]) of a country's energy use, so wind power's ability to mitigate the negative effects of energy use — as with any other clean source of electricity — is limited (except with a potential transition to electric or hydrogen vehicles). Wind power contributed less than 1% of the UK's national electricity supply[38] in 2004 and hence had negligible effects on CO2 emissions, which continued to rise in 2002 and 2003 (Department of Trade and Industry); the growth of installed wind capacity in the UK has been impressive (installed wind capacity doubled from 2002 to 2004, and again from end-2004 to mid-2006), but from low levels. Until wind energy achieves substantially greater scale worldwide, its ability to contribute will be limited.
Comment:

6. The energy return on investment (EROI) for wind energy is equal to the

cumulative electricity generated divided by the cumulative primary energy required to build and maintain a turbine.

The EROI for wind ranges from 5 to 35, with an average of around 18. This places wind energy in a favorable position relative to conventional power generation technologies in terms of EROI. Base-load coal-fired power generation has an EROI between 5 and 10:1. Nuclear power is probably no greater than 5:1. The EROI for hydropower probably exceeds 10, but in most places in the world the most favorable sites have been developed.[68]

When the EROEI of a resource is equal to or lower than 1, that energy source becomes an "energy sink", and can no longer be used as a primary source of energy.
Comment:

Ecological Footprint

Taken from IL below

Large-scale onshore and near-shore wind energy facilities (wind farms) can be controversial due to aesthetic reasons and impact on the local environment. Large-scale offshore wind farms are not visible from land and according to a comprehensive 8-year Danish Offshore Wind study on "Key Environmental Issues" have no discernible effect on aquatic species and no effect on migratory bird patterns or mortality rates. Modern wind farms make use of large towers with impressive blade spans, occupy large areas and may be considered unsightly at onshore and near-shore locations. They usually do not, however, interfere significantly with other uses, such as farming. The impact of onshore and near-shore wind farms on wildlife—particularly migratory birds and bats—is hotly debated, and studies with contradictory conclusions have been published.

Two preliminary conclusions for onshore and near-shore wind developments seem to be supported: first, the impact on wildlife is likely low compared to other forms of human and industrial activity; second, negative impacts on certain populations of sensitive species are possible, and efforts to mitigate these effects should be considered in the planning phase. According to recent estimates published in Nature, each wind turbine kills on average 0.03 birds per year, or one kill per thirty turbines [71]. However, the birds that are killed may on average be larger, so their populations affected more strongly by individual deaths. Aesthetic issues are important for onshore and near-shore locations in that the "visible footprint" may be extremely large compared to other sources of industrial power (which may be sited in industrially developed areas), and wind farms may be close to scenic or otherwise undeveloped areas. Offshore wind development locations remove the visual aesthetic issue by being at least 10 km from shore and in many cases much further away.

The ecological and environmental costs of wind plants are paid by those using the power produced, with no long-term effects on climate or local environment left for future generations.

More relevant ILs

IL 77 *** An applet showing the workings of an electric generato

An example of a Future Project

IL 78 **

A Special Problem: The World's Largest Wind Turbine

Fig. 58: World's Largest Wind Turbine

The German **RePower** turbines have a power output of **5 Megawatts** with a rotor blade diameter of 126 metres and a sweeping area of over 12,000 square metres. Maximum power output is achieved at around 50 kph (14 m/s), but a couple of MW are generated even in a fresh breeze. Rotors start turning at around 11 kph (3.1 m/s), and are automatically braked at 110 kph (31 n/s). Power control is achieved by **blade pitching** – i.e. turning the **rotor blades** individually in a very strong wind to prevent the whole structure from being damaged.

Each turbine weighs over 900 tonnes, including the 120 metre tall tower which has to be anchored in deep water. Each **turbine blade** is 61.5 metres long and weighs just under 18 tonnes. *LM Glasfiber*, the turbine blade manufacturer, managed to keep the weight down low, thus reducing the financial and environmental costs of building these large wind turbines.

These large wind turbine generators are ideally suited for the offshore environment, thanks to high and consistent wind speeds and minimal turbulence. According to historical measures of wind speeds at the Beatrice offshore location, it is expected that the turbines will run an impressive 96% of the time (8440 hours per year), and at **5MW** full power at 38% of the time.

IL 79 *** World's largest wind turbine

IL 80 *** A list of the world's largest wind turbines.

Problem Based on the Above

1. The world's largest wind turbine generator described above has a rotor blade diameter of 126 metres and so the rotors sweep an area of π x $(\text{diameter}/2)^2 = 12470\ m^2$! As this is an

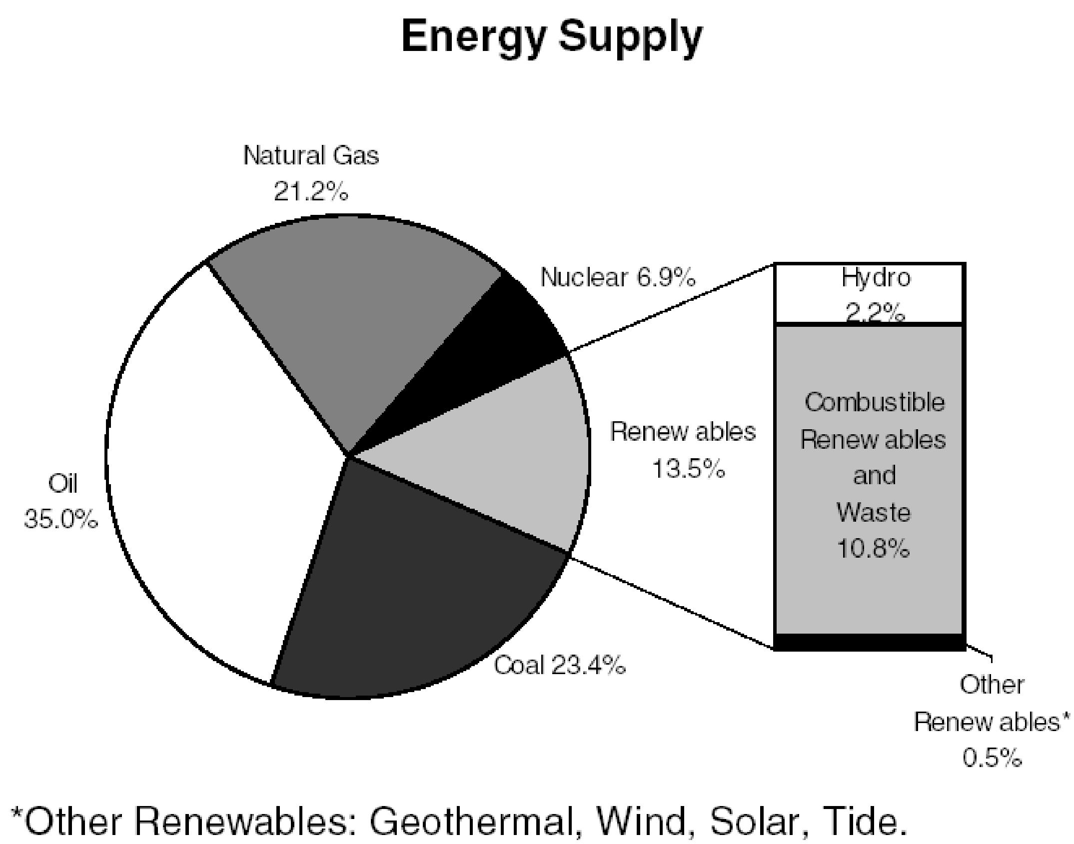
offshore wind turbine, we know it is situated at sea-level and so we know the air density is 1.23 kg/m^3. The turbine is rated at 5MW in 45 kph (14m/s) winds.

a. Show that the idealized power equation gives us a wind power of around 21,000,000 Watts.

b. Why is the power of the wind (21MW) so much larger than the rated power of the turbine generator (5MW)?

c. Show that the efficiency for this wind velocity is about 24%.

d. What is the total efficiency restrictions produced by effects other than the one imposed by Betz/s limit?



World Energy Production

Wind energy is growing fast (perhaps 30% per year), but is still at low levels (less than 0.1% of world energy production). The largest producers as of 2001 were Germany, Spain, United States and Denmark, in that order. Nevertheless, in absolute terms, wind energy now adds more capacity each year than does nuclear energy. It currently requires some subsidies or other incentives for deployment, but it is now close to market prices. In some regions, it may already compete favorably with traditional energy sources.

Fig. 59: Tiny Denmark plays an outsize role in wind power, generating 20% of its electricity from wind turbines like these at the Nysted wind farm, off the country's southern coast. The largest wind-energy installation in the world, it consists of 72 turbines and generates enough power for 110,000 households. (Oddly, the turbines were supplied by Germany's Siemens, not Denmark's Vestas Wind Systems, which is the world's largest producer of wind turbines.)

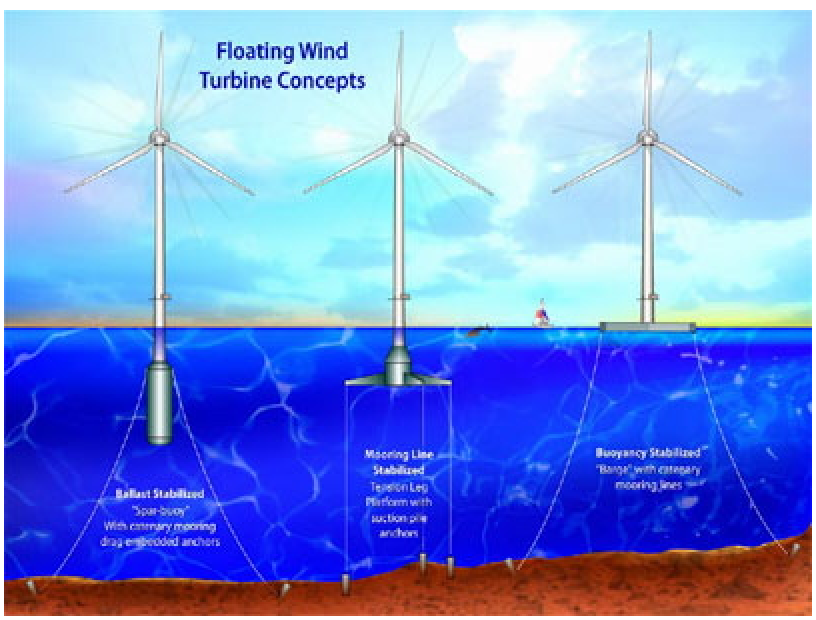


Fig. 60: Floating Wind Turbines

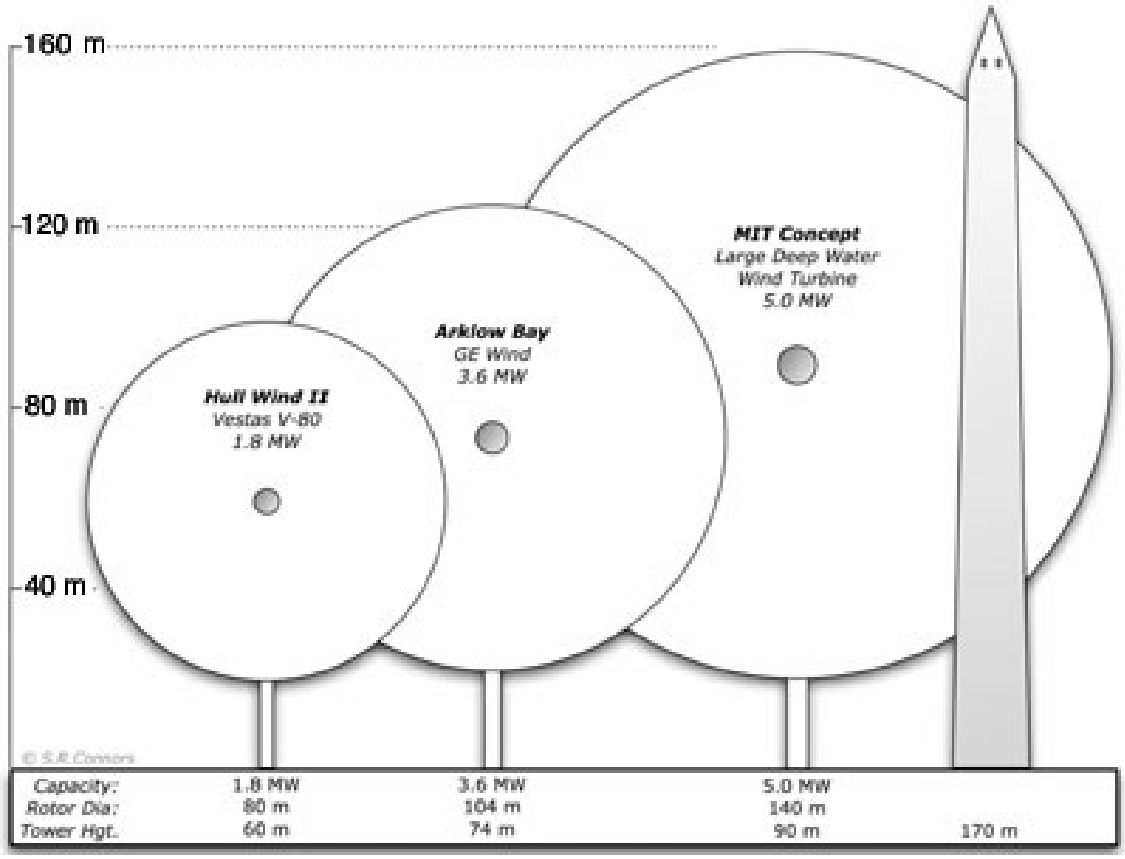


Fig. 61: This figure shows (from left to right) an onshore wind turbine, a conventional offshore unit, and the experimental unit used in MIT's concept for a deep-water floating turbine. In each case, the disk indicates the area swept by the turbine blades. The Washington Monument in Washington, D.C., appears for comparison.
Source: MIT

The text below is taken from:

IL 81 ****

Offshore wind turbines are an excellent source of power that could potentially serve hundreds of thousands of consumers. With solid potential for winds much of the time, these turbines have one drawback: No one wants to impede their beachfront property views with whirling wind turbines.

How about floating platforms hundreds of miles out to sea, where the winds are even stronger? That is where Paul D. Sclavounos comes in. The MIT professor of mechanical engineering and naval architecture spent decades designing and analyzing large floating structures for deep-sea oil and gas exploration. "Why can't we simply take those windmills and put them on floaters and move them farther offshore, where there's plenty of space and lots of wind?" he asked.

In 2004, he and his MIT colleagues teamed with wind-turbine experts from the National Renewable Energy Laboratory (NREL) to integrate a wind turbine with a floater. Their design *calls for a tension leg platform, a system in which long steel cables, or "tethers," connect the corners of the platform to a concrete-block or other mooring system on the ocean floor. The platform and turbine gain their support from buoyancy. "And you don't pay anything to be buoyant," Sclavounos said.*

The floater-mounted turbines could work in water depths ranging from 30 to 200 meters, Sclavounos said. In the Northeast, they could be 50 to 150 kilometers from shore. And the turbine atop each platform could be big, which is an economic advantage in the wind-farm business. The MIT-NREL design assumes a 5.0 megawatt (MW) experimental turbine now being developed by industry. (Onshore units are 1.5 MW; conventional offshore units are 3.6 MW.)

Ocean assembly of the floating turbines would be prohibitively expensive because of their size: The wind tower is 90 meters tall, the rotors about 140 meters in diameter. So the researchers designed them to put them together onshore and towed out to sea by a tugboat. To keep each platform stable, cylinders inside it gain ballast by using concrete and water. Once on site, the platform hooks up to previously installed tethers. They would pump out water from the cylinders until the entire assembly lifts up in the water, pulling the tethers taut.

The tethers allow the floating platforms to move from side to side but not up and down. Computer simulations show in hurricane conditions the floating platforms—each about 30 meters in diameter—would shift by one to two meters, and the bottom of the turbine blades would remain well above the peak of even the highest wave. Researchers are hoping to reduce the sideways motion still further by installing specially designed dampers similar to those used to steady the sway of skyscrapers during high winds and earthquakes.

Sclavounos estimated building and installing his floating support system should cost a third as much as constructing the type of truss tower now planned for deep-water installations. Installing the tethers, the electrical system, and the cable to the shore is standard procedure. Because of the strong offshore winds, the floating turbines should produce up to twice as much electricity per year (per installed megawatt) as wind turbines now in operation. And because the wind turbines do not permanently attach to the ocean floor, they are a movable asset. If a company with 400 wind turbines serving the Boston area needs more power for New York, it can unhook some of the floating turbines and tow them south.

Encouraged by positive responses from wind, electric power, and oil companies, Sclavounos said he hopes to install a half-scale prototype south of Cape Cod.

For related information, go to www.isa.org/environment.

Taken from IL

More Internet References for Wind Power

IL 82 *** Elementary discussion of wind power, one good diagram that could be downloaded - very comprehensive.

IL 83 *** Early history of water and windmills –to 1875

IL 84 ** Small wind turbines with detail for construction

IL 85 ** Summary of wind turbines

IL 86 ** build your own wind turbine

IL 87 ** St Leon Wind Farm details and global data for wind energ

IL 88 ** A small wind turbine offered on Amazon

IL 89 ** Wind-Solar combination home systems

IL 90 ** Electric generators