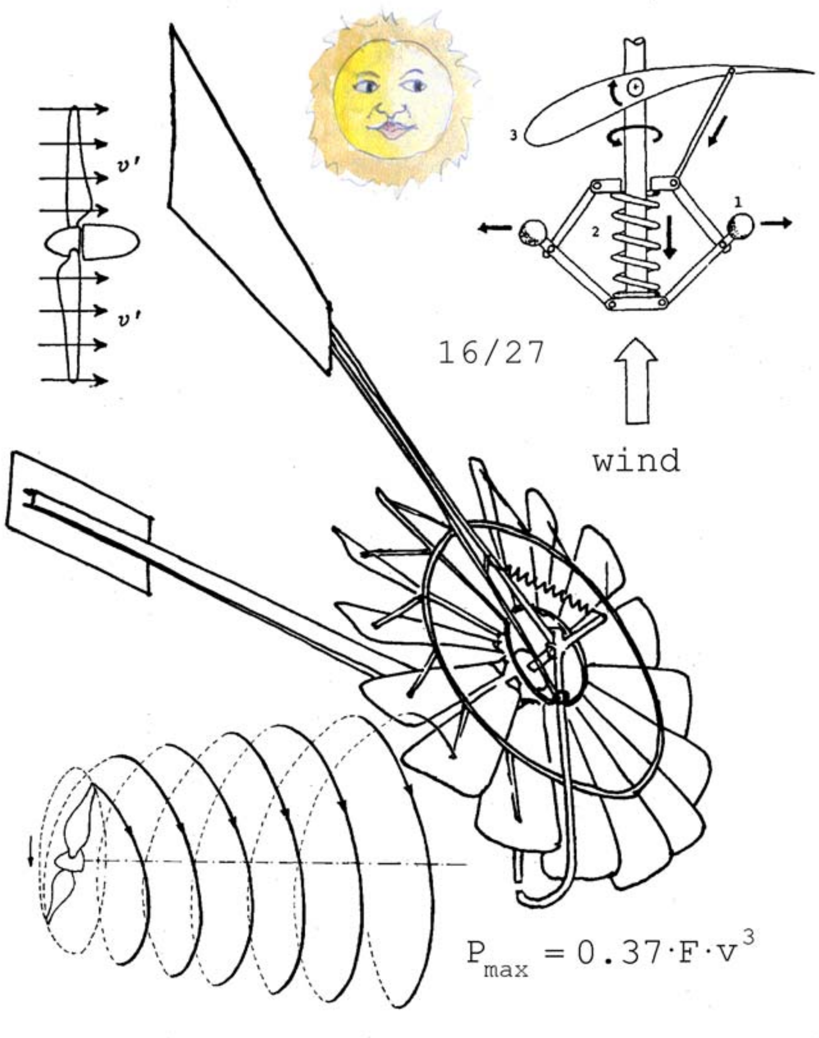
Notions of wind energy for the complete idiot

by Manuel Franquesa Voneschen



This manual has been translated from Spanish with the help of Google Translate and the author's brain.
 The author is in Facebook.

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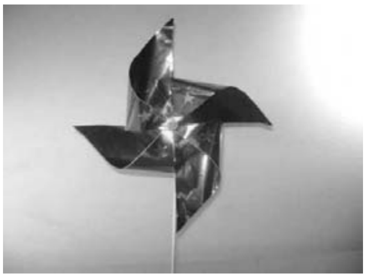
Note

Despite my passion for wind energy, for many reasons I am not fond of building huge wind farms.
Let me tell you one of these reasons:
A modern car has an average rated power of 100 kW. According to the "father" of thermodynamics - Sadi Carnot (1796 - 1832) -, a combustion engine can convert into mechanical energy only 1/3 of the energy content of the fuel, while 2/3 of this energy gets "lost" as heat, so the amount of fuel needed by the engine of a 100 kW-car could generate theoretically a net power of 300 kW. But even so, a windmill with a rated power of 100 kW requires a diameter of over 25 meters, and this rated power will only be avaiable for a relatively short period per year (depending on the site), because the wind blows the way it wants.
So, to "save" the fossil energy consumed by 1000 moving cars it takes a huge amount of windmills of this size. And if we add the energy required to build them, very soon we will reach the story of the milkmaid.

Prologue

Today, "windmills" are rather called “wind turbines” or “wind generators”, because they are not "milling" grain, but producing electricity.

Allmost everyone has played with a windmill as a child. These toys, sold in parks and fairs, are called pinwheels. Do you remember?



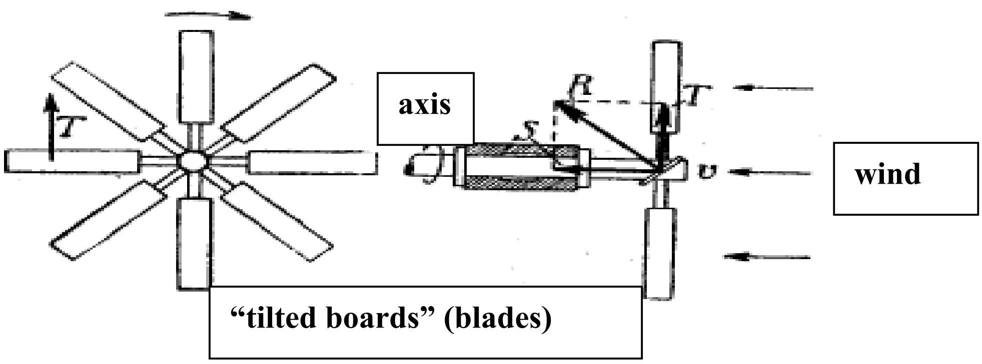
When there was no wind the wheel did not turn, but if we started to run the blades started spinning. It's like when you go on a bike: although there is no wind, you "feel" the wind in your face. Because in fact it’s the same if you're standing and the wind is blowing on your face or if there is no wind, but you are moving and therefore "cutting" the still air.

What is it that moves the blades of a windmill?

When you put a wooden board towards the wind, you'll notice that the board exerts a force against you. If the board and the wind speed are big enough, this force will be able to make you fall. And if you tilt the board to one side, you will notice that it wants to "escape" to the opposite side. Because now there are two forces on scene: one that pushes you back and another that pushes your arms to the side.

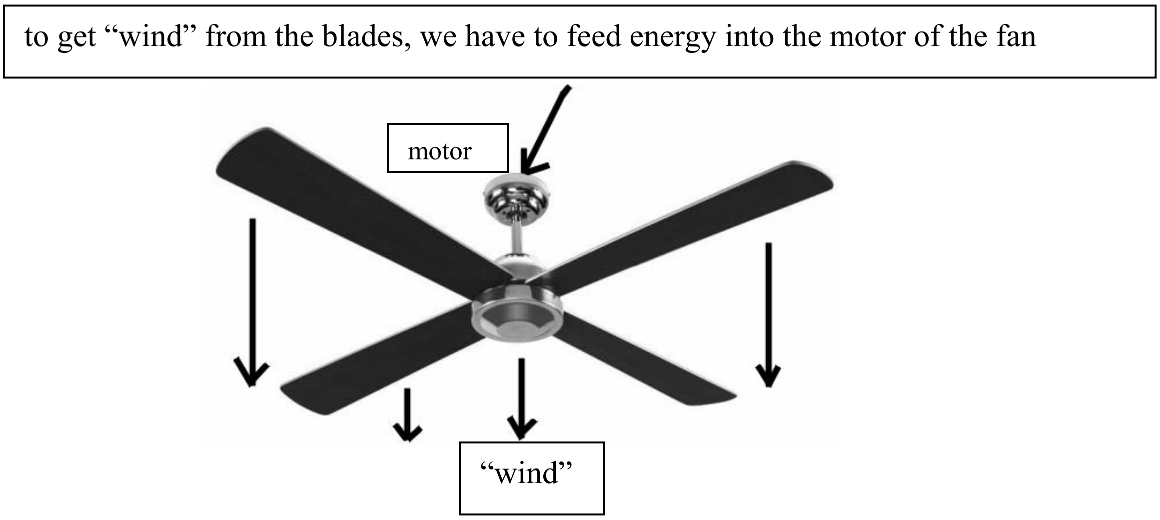
The blades of a windmill are **always** tilted with respect to the wind direction. As they have several such tilted "boards" (blades) attached to a common bearing (the axis of the windmill), there is nothing that can stop them from moving to one side and, therefore, begin to rotate around the bearing. Like a carousel.

In the next picture you can see the force "T" acting on the blades, forcing them to rotate around the axis of the windmill. "S" is the force that pushes the blades backwards.

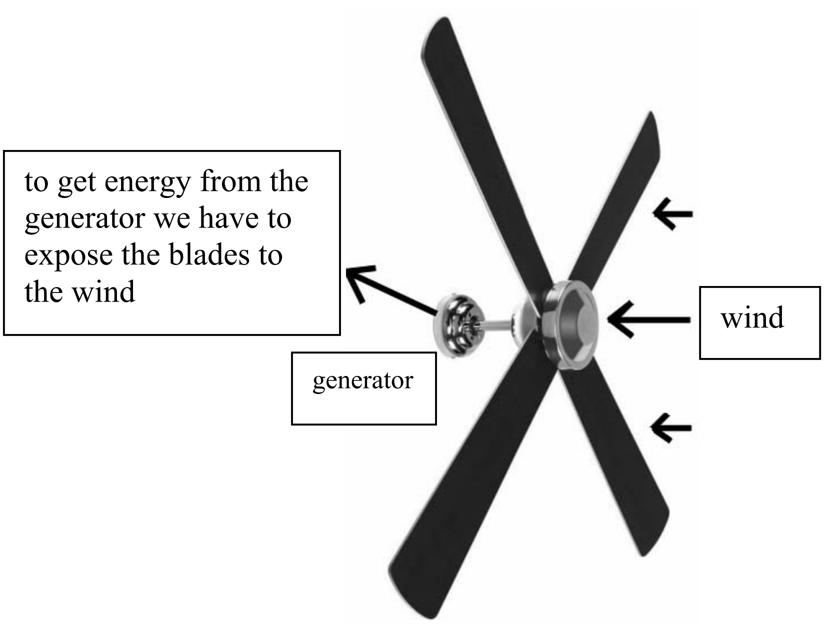


By the way, a fan that cools us with air during hot weather is also a windmill, but an "inverted" one. Instead of generating electricity with wind it generates wind with electricity. If we connect the motor of the to the current, the motor will make rotate the blades and they will produce the air we feel in the face. If we turn the fan 90 degrees, in principle we could use it to generate energy.

Ceiling fan → produces "wind":



If we turn the fan 90 degrees and put it into the wind → we (could) get energy:



Unfortunately, in real life this is not so easy, because electric motors that run on AC voltage can not be simply used as generators. Only DC motors (dynamos) can be used indiscriminately as motor or generator.

Some words about the difference between power and energy

A little further down I will present you a mathematical formula with which you can approximately calculate the power of a windmill knowing the diameter of its rotor ("propeller") and the wind speed.

This formula is a child of German scientist Albert Betz, who in 1926 published the first book in history about the theory of windmills. Even today he's still considered "the father" of wind energy.

Note:
If you want to read a copy of Betz's book, here is a link:
http://www.amics21.com/laveritat/albert_betz_wind_energie.pdf
I have also translated most of it into Spanish:
http://www.amics21.com/laveritat/betz_energia_eolica.pdf

But before proceeding, let's dedicate a few minutes to the concepts of "**power**" and "**energy**".

The **power** of a machine, appliance, motorcycle, car, stove, lamp, etc.. tells us the "potential" energy that this object would be able to provide us **when we plug it in (electricity) or move with it (fuel)**. Its unit is the **watt**, abbreviated as "**W**", after the British physicist James Watt (1736 - 1819).

If for example you buy a bulb of 60 W (watts) in a store, obviously the bulb will not provide you any energy as long it remains in a shelf of the store or in a drawer at your house. But if you plug it in, the bulb will produce energy as light and especially as heat (dont tuch the bulb!, we were told when we were kids). The same goes for a car: the owner can brag that his four whell drive car has a rated power of 250 kW. But if he has no money for fuel his car will not move an inch!

Energy is what the machine, appliance, motorcycle, car, bulb, etc. gives us in a palpable way (movement of a vehicle, heat from a heater, air from a fan, light from a bulb) **while plugged in or running**. We instinctively feel that the longer the object in question is plugged in or running, the more energy we will get, usually in exchange for money (for example: you have to go to a gas station and pay a lot of money for the *power* of gasoline or pay the electrical energy you consume at home).

The following formula is as simple as important. Its says that **energy (E) is equal to the power (P) of the object in question multiplied by the time (t) during which this object is plugged in or running:**

$$\mathbf{E = P \cdot t}$$

The unit of electrical energy (usually to be paid) is the **kWh (kilowatt hour).**

For this reason, when your electricity bill arrives, you have to pay for the amount of kWh consumed at home, that is, you pay for the power **P** of all household appliances **that have been plugged in during t hours**, including the computer that you never turn off.

Example: Suppose the price of electricity is 0.25 euros (25 cents) per kWh. How much will it cost you having an electrical heater of 1000 watts power plugged in 24 hours a day?

Energy consumed by the heater:

E_{heater} = 1000 watts x 24 hours = 24000 watt-hours = 24 kilowatt-hours (kWh)

In money:

Rule of three: "If 1 kWh costs 0.25 euros, how much I will have to pay for the 24 kWh “burned” by my little heater?

Solution: 24 kWh multiplied by 0.25 euros / kWh = 6 euros a day (= 180 euros per month).

How much energy can we get from the wind?

The above mentioned Mr. Betz found that the maximum power that a windmill could (theoretically) deliver can be calculated using the following formula:

$$\mathbf{P_{theoretical} = 0{,}29 \cdot D^2 \cdot v^3}$$

In words: **The maximum power that a windmill could have if the world was perfect is equal to 0.29 multiplied by the square of its rotor diameter multiplied by the cube of the wind speed.**

This formula tells us something very important: **the power of windmill increases with the cube of wind speed**. If for example the wind speed doubles, the power of the windmill will be eight times higher. To double the wind speed means introducing in the above formula 2 times v instead of v:

$$P_{theoretical\ at\ double\ wind\ speed} = 0{,}29 \cdot D^2 \cdot (2 \cdot v)^3$$

$$= 0{,}29 \cdot D^2 \cdot 2^3 \cdot v^3 = \mathbf{8} \cdot 0{,}29 \cdot D^2 \cdot v^3 = \mathbf{8} \cdot P_{theoretical}$$

The factor **8** means that the power has increased 8 times.

It is therefore important to install windmills at sites with good winds, but knowing that a strong wind can destroy your windmill in a few seconds, and its parts flying around can be very dangerous for people and animals and/or the roof of your home.

What is important in this formula - as in all formulas of physics - is to enter the values in the correct physical units.

If for $\mathbf{P_{theoretical}}$ we want to obtain **watts (W)**, for the diameter of the windmill rotor we will have to use **meters (m)** and for the wind speed **meters per second (m/s).**

As modern motorized humans, we are used to indicate the speed in kilometers per hour (km/h).

Refreshing exercise: **How can I convert kilometers per hour into meters per second?**

One hour has 60 minutes and one minute has 60 seconds. Therefore, one hour has 60 times 60 = 3600 seconds. And a kilometer has 1000 meters.

Example: If a windless day I circulate with my bike at a speed of 40 km/h. What wind speed in meters per second (m/s) will I feel on my face?

40 km = 40000 meters
1 h = 3600 seconds

If we divide 40000 meters by 3600 seconds, we will get the speed in meters per second:

40000 : 3600 = **11.11 m/s**

In general, to convert a speed given in kilometers per hour (km/h) into meters per second (m/s), you can use this simple formula:

m/s = 0.278 x km/h

Example: How many m/s equals 75 km/h?
Solution: 0.278 x 75 = **20.85 m/s**

Now we can go to an example of calculating wind power and wind energy:

Suppose in a windless day we place (securely attached!) a small windmill of 50 cm in diameter on the roof of a car and circulate along a deserted road (not to endanger pedestrians if the windmill is released and becomes a **rotating guillotine**) at a speed of 40 km/h. What is the theoretical maximum power that this windmill could have?

Let's go to Mr. Betz's formula:

Diameter of the windmill in meters: D = **0.5 m**
Car speed = wind speed = 40 km/h = (see above) = **11.11 m/s**

$$\mathbf{P_{theoretical} = 0.29 \cdot 0.5^2 \cdot 11.11^3 = 0.29 \cdot 0.5 \cdot 0.5 \cdot 11.11 \cdot 11.11 \cdot 11.11 = 99.42\ W}$$

If we drove continuously for 10 hours at that speed (40 km/h) with the windmill on the roof of the car, the theoretical energy we could produce with our small windmill would be:

$$\mathbf{E_{theoretical} = 99.42\ W \cdot 10\ h = 994.2\ Wh}$$

= (almost) 1 kWh or 25 cents savings (see above).

Note: If you take into account the actual price is gasoline, this experiment is not highly recommended!

However, in practice we will never achieve this power (or get this energy), because all machines in this world (including us) have **losses**.

As we already said, any combustion engine (car, motorcycle, tractor, plane, ship etc.) can convert into net energy (which we need to work and/or move) only approx. **one third of the energy of the fuel**. Two thirds of the fuel-energy (that you pay) get "lost" as heat. If for one liter of gasoline you pay 1.50 euros, 1 euro will fade away as heat, which you have to deliver to the environment because you can not take it home to heat the bed or to make fried eggs with french potatoes.

To describe these losses that any machine, device or human being has, in physics we use the concept of **efficiency,** obtained by dividing **what you have to put in order to get what you want**.

For example, when someone sells you a machine with an efficiency of 50%, this means that this machine will deliver half the amount of energy you had to feed into it.

Returning to wind energy: a windmill rarely will have an efficiency higher than 50% [1]. In order to not overestimate the maximum power, we will divide the formula of Mr. Betz by two (50% efficiency):

$$\mathbf{P_{maximum} \approx 0.15 \cdot D^2 \cdot v^3}$$

Of course, a “primitive” windmill will have much less then that.

Example:

The wind turbines used in the controversial "wind farms" are huge. Its propellers have diameters up to 100 meters or even more. Let’s calculate the maximum power that one of these giants could have when the wind blows at a speed of 10 m/s (= 36 km/h, see above):

Suppose that one of these super windmills has a diameter of 50 meters → **D** = 50 m

Applying the formula above:

$\mathbf{P_{maximum} = 0.15 \cdot 50^2 \cdot 10^3 = 0.15 \cdot 50 \cdot 50 \cdot 10 \cdot 10 \cdot 10 = 375000\ W}$
= 375 kW (1 kW = 1000 W).

Sounds good, but the trouble is that the wind will not blow at this speed all the time. This is the main drawback of wind as an energy source: wind is more or less **random**, ie, the wind is very capricious. It does not blow when **we** want.

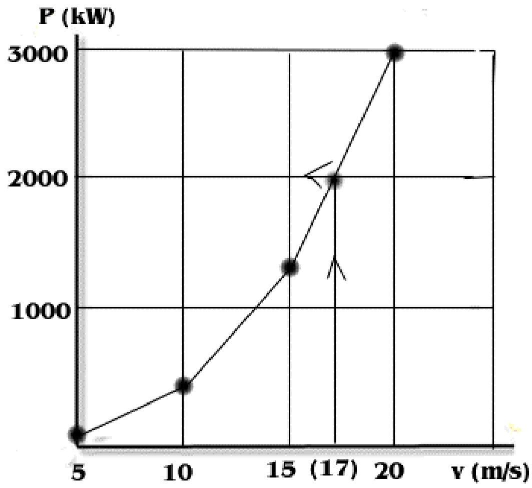
[1] Modern high-tech wind generators can reach efficiencies up to 70%

Let's now calculate a curve with which we can immediately read the power of the windmill in this example for any wind speed. To calculate such a curve it is best to use a table like this one:

Diameter of the windmill **D = 50 m**

Wind speed in metres per second (m/s)	**Wind speed in kilometers per hour (km/h)**	**Power of the windmill in watts (W)** **Remember:** $P_{max} = 0.15 \cdot D^2 \cdot v^3$	**Power of the windmill in kilowatts (kW)** **Remember:** **1 kW = 1000 W**
5	18	46875	**46.875**
10	36	375000	**375.0**
15	54	1265625	**1265.625**
20	72	3000000	**3000.0**

If we plot the calculated points in a coordinate axis system and join them by lines, we will get the so-called **power curve of the windmill**:



If for example we want to know the power of the windmill in our example at a wind speed of 17 m/s, instead of calculating this power with the formula we just have to find the point on the curve corresponding to this wind speed (17 m/s) → about 2000 kW (follow the arrows).

Let's now try to answer another question asked by many people interested in wind energy:

With how many revolutions per minute turns the rotor of a windmill?

The **rotational speed** (revolutions per minute or - abbreviated - **rpm**) of a windmill is not as easy to calculate as its power, because it depends on two factors that can not be seen with the naked eye in a windmill: **the width and the pitch of the blades**. But it also depends on something very important: **the energy delivered by the windmill at the moment we want to know its rotational speed**. It's like when you climb a hill with a motorbike: the motor runs slower, because it has to carry uphill both the weight of the bike and your body. By the way, lifting a stone is the same: you can raise a little pebbel in a second, but if it is a heavy rock you will be forced to do it very slowly. It's law of life. So, if suddently someone is consuming most of the energy delivered by the windmill, its rotor will slow down.

However, it is possible to calculate an approximate value for the rotational speed: In **modern** windmills, which generally have three relatively narrow blades, **the value of rotational speed in revolutions per minute oscilates between 130 to 170 times the wind speed (v) in meters per second divided by the propeller diameter (D) in meters**.

If we call **n** the speed of rotation, we can write this expression as a formula:

$n = (130 \ldots 170) \cdot v/D$ (rpm)

For a rough estimate, we can use the mean value of both limits (150), ie

$$\mathbf{n = 150 \cdot v / D} \quad \textbf{(rpm)}$$

Remember: to get the rotational speed in revolutions per minute (rpm) you have to enter the wind speed in meters per second (m/s) and the diameter of the windmill in meters (m)!

Suppose a small modern windmill of 2 meters in diameter next to your house. Let's calculate its estimated rotational speed for different wind speeds. Again we will use a table:

Diameter of the windmill **D = 2 m**

Wind speed in metres per second (m/s)	**Wind speed in kilometers per hour (km/h)**	**Factor v/D**	**Rotational speed of the windmill in revolutions per minute (rpm)** **Remember: n = 150 · v / D**
5	18	2.5	**375**
10	36	5.0	**750**
15	54	7.5	**1125**
20	72	10.0	**1500**

At a wind speed of 54 kilometers per hour (= 15 m/s), its rotational speed is 1125 rpm (see table). At this rotational speed, the propeller of your windmill will make a hell of a noise, because the tips of the blades have a **very high velocity!**
Let's calculate that velocity with a bit of elementary mathematics (the only ones you need to properly manage any honest business):

During each turn of the propeller, in one minute the tips of the blades have to cover the circumference of a circle of 2 meters in diameter.

The calculation of the circumference of a circle was already known by the Egyptians and Chinese more than seven thousand years ago: it is equal to the diameter of the circle multiplied by the divine number "pi", written with the Greek letter **π**:

Length of circumference = $\pi \cdot D$

As we all (should) know, the approximate value of **π is 3.14**

Our windmill has a diameter of 2 meters, therefore the length of its circumference is equal to 3.14 multiplied by 2 meters = **6.28 meters**.

Rule of Three: If in a minute the tips of the blades have to travel 1125 times the 6.28 meters in circumference, what is their speed in meters per second?

Solution: one minute has 60 seconds, so we have to divide 1125 · 6.28 meters = 7065 meters by 60 seconds (= 1 minute) and we will get 117.75 meters per second, **or 423.90 km/h!!!**

or **423.90 km/h! → Noise! → Danger!**

Note: This high speed of the blade tips makes a lot of noise in modern wind farms and is **extremely dangerous to the birds**.

The speed of the blade tips does not depend on the size of the mindmill, but on the width and the pitch angle of its blades or type of windmill (“slow” or “fast”, see below).

For modern windmills with few (usually 3), thin blades, the tip speed of the blades can be estimated with this simple formula (v = wind speed):

$$v_{tip} \approx 8 \cdot v$$

Distinction between slow and fast windmills

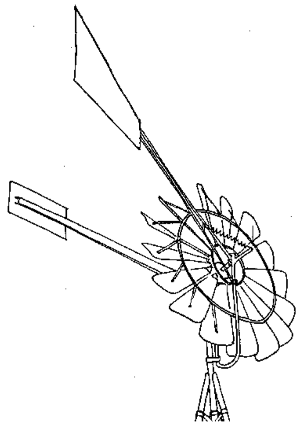
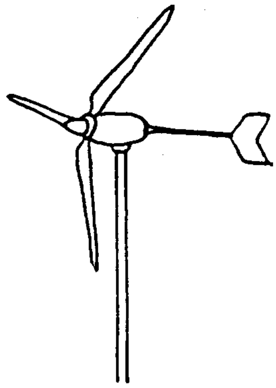
In the field of wind energy we distinguish between “slow” and “fast” windmills. This distinction is not absolute, but relative. It simply means that if we have two windmills of identical diameter, under the same wind speed the one we call "fast" can turn up to 10 or even more times faster than the "slow" windmill.
Remember: Small windmills turns much faster then big ones.

These two types of windmills can be distinguished at first sight: the slow ones have many (up to 20 or more) large blades, which are quite tilted with respect to wind direction (“pitch angle” up to 35°). The fast ones have few narrow blades (usually 3), with a small pitch angle (down to 3° or even less).

In addition to spin more slowly, for some aerodynamic reasons the **slow windmills have a lower efficiency than fast ones** (up to 30 to 40% less), **but they have the advantage to start rotating at relatively low wind speeds**.

Typical slow windmills can still be seen in the countryside, which once upon the time they were mainly used to pump water for crops or livestock. Typical modern windmills (wind generators) are the ones we can see in modern wind farms, which usually have three relatively slender blades.

The following table allows you to quickly estimate the maximum power and the optimum rotational speed of these two types of windmills:

	Slow windmills	**Fast windmills**
Distinction at first sight		
Properties	Many, large blades with a large pitch angle	Few, narrow blades with a small pitch angle
Maximum power* [W]	$\mathbf{P_{max} \approx 0.15 \cdot D^2 \cdot v^3}$	$\mathbf{P_{max} \approx 0.20 \cdot D^2 \cdot v^3}$
Optimal rotational speed* [rpm]	$\mathbf{n_{opt} \approx 20 \cdot v/D}$	$\mathbf{n_{opt} \approx 150 \cdot v/D}$
Speed of the blade tips	$\mathbf{v_{tip} \approx v}$	$\mathbf{v_{tip} \approx 8 \cdot v}$

*) Remember that to get the power in watts [W] and the rotational speed in revolutions per minute [rpm], in the formula you have to enter the windmill diameter (D) in meters and the wind speed (v) in meters per second [m/s].

How much energy can I produce with a windmill in one year?

The old Greeks postulated that the wind was the breath of Gaia, our planet.
Its energy can only be calculated statistically, because you never know for sure when and how much wind you will have tomorrow. If at a specific site we measure the intensity and the direction of the wind, even for years, the most we can get is some probability that next year the wind will display similar behavior. These statistics of the wind are called **wind climate**.
However, many places have their more or less steady windy season. These seasonal winds have beautiful names: *Abroholos, Blizzard, Cape Doctor, Dzhani, Elephanta, Föhn, Galerna, Haboob, Iseran, Jasna Bura, Kapalilua, Liberator, Mistral, Nowaki, Pampero, Scirocco, Tramontana, Varatraza, Witch, Xlokk, Yama Oroshi, Zefiro*, to name just a few.

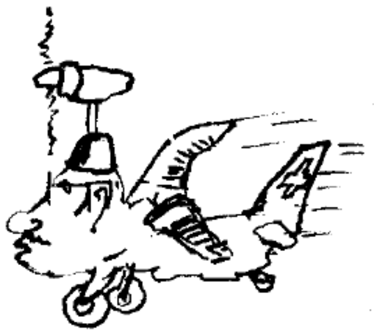
If we know the **average annual wind speed of a particular site**, with the following table we can **roughly estimate the annual energy produced by a wind turbine** with a rated power $\mathbf{P_r}$ [kW], the percentage of time during which the windmill will deliver its rated power P_r and the percentage of time during which the windmill will not produce any energy.

Average annual windspeed of the site [m/s]	5	6	7	8	9
Produced annual energy $\mathbf{E_{annual}}$ **[kWh]**	**1100·P_r**	**1850·P_r**	**2600·P_r**	**3350·P_r**	**4050·P_r**
Percentage of time during which the windmill will deliver its rated power **[%]**	**15**	**24**	**33**	**42**	**50**
Percentage of time with no energy production **[%]**	**60**	**50**	**40**	**30**	**20**

*) To obtain the annual energy in kWh, the rated power of the windmill has to be introduced in **kW**
Note: These values are valid for a modern high tech wind generator. For a "home made" windmill you should count with about 30% less of this annual energy production.

Example:
How much energy can we produce in one year with a windmill of 2 meters in diameter with a nominal power of 600 W at a site with an average annual wind speed of 6 m/s?

Solution: P_r = 600 W = 0.6 kW.
For an average annual wind speed of 6 m/s, the table delivers:
$\mathbf{E_{annual}}$ = 1850·P_r = 1850·0,6 = **1110 kWh/year**



The author as seen by Fra Noël

Conclusions

I guess it's time to leave you alone to think a little about all this.

If you ever live in the countryside – with no electricity, but with many hens - remember that with a little windmill and a few solar panels you could cover your basic energy needs, provided these need are not accompanied by the worst of all human sins: **greed**.

And if I have been able to arouse your interest in physics, I warmly recommend you to follow on youtube one of the lectures of Professor **Walter Lewin**, a wise man who has managed to arouse interest in the physical sciences of many thousands of people around the world.

And if someday you want to get "hands-on", remember this old Chinese proverb:

"What I hear, I forget;
What I see (read), I remember;
What I do, I understand"

I wish you good winds, good health and a a lot of humor!

Manuel Franquesa Voneschen

Castelldefels, spring 2012

Links

Some years ago I published some practical manuals to build a homemade windmill. Here are the links:

http://www.amics21.com/laveritat/savonius_generator_english.pdf
http://www.amics21.com/laveritat/wind_generator_manual.pdf
http://www.amics21.com/laveritat/introduction_darrieus_wind_turbines.pdf

This humble manual is also available in Spanish:
www.amics21.com/laveritat/nociones_de_energia_eolica.pdf