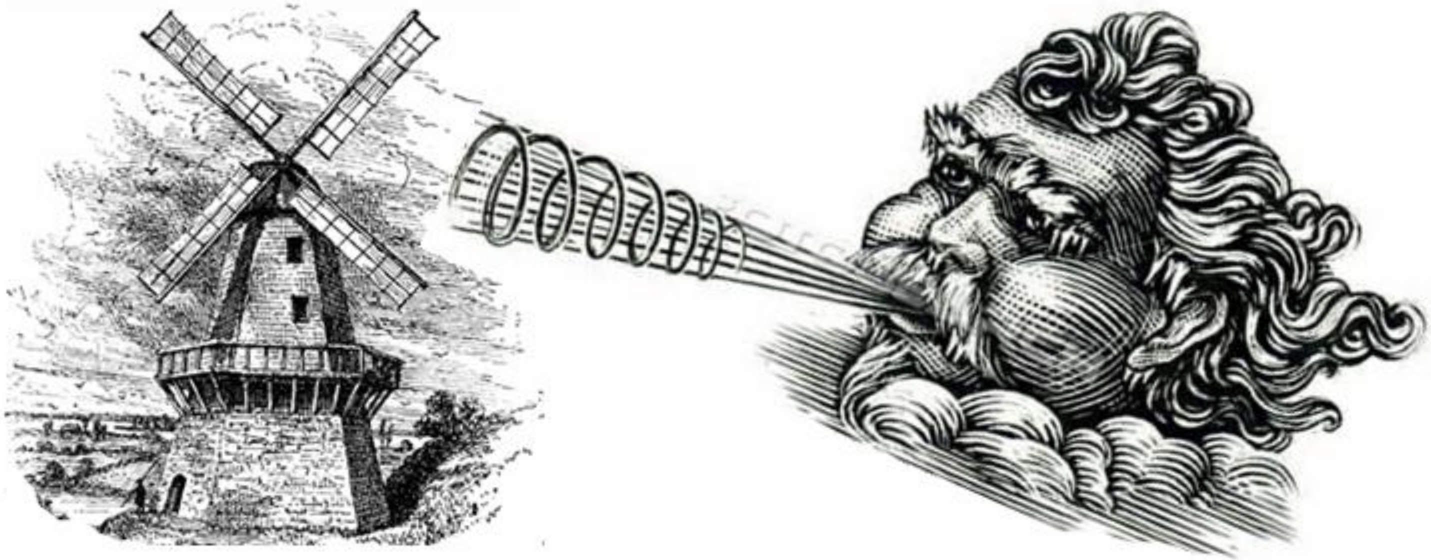
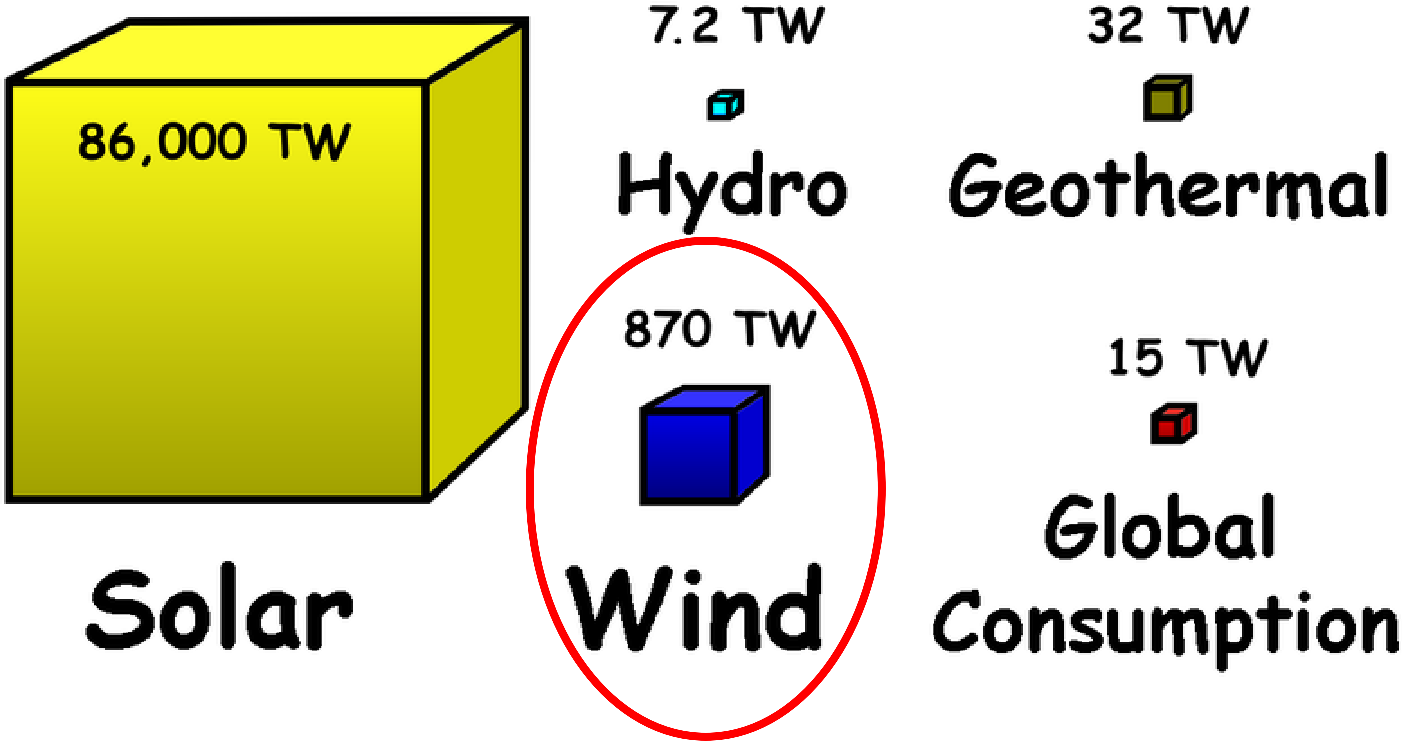
Wind



Power

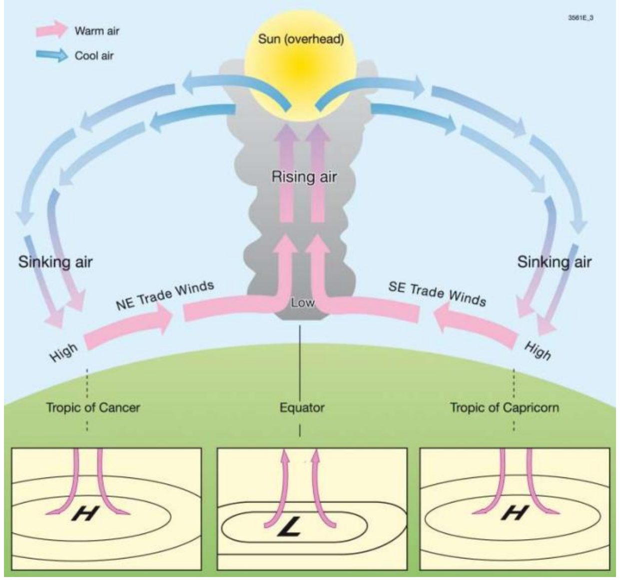
Wind – global resources:

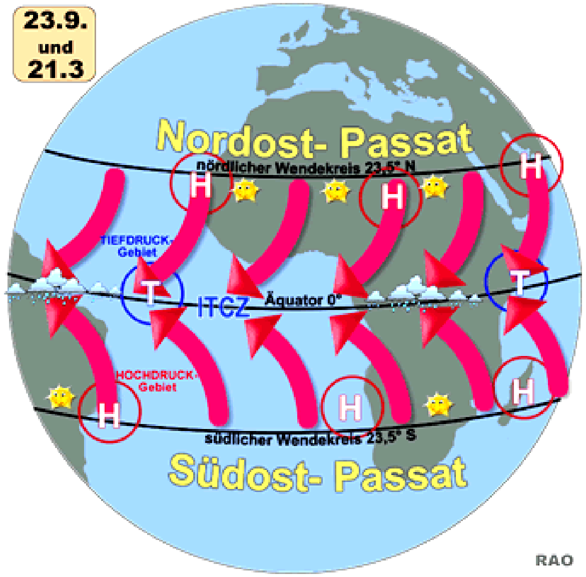


Almost 60 times more than current global energy consumption

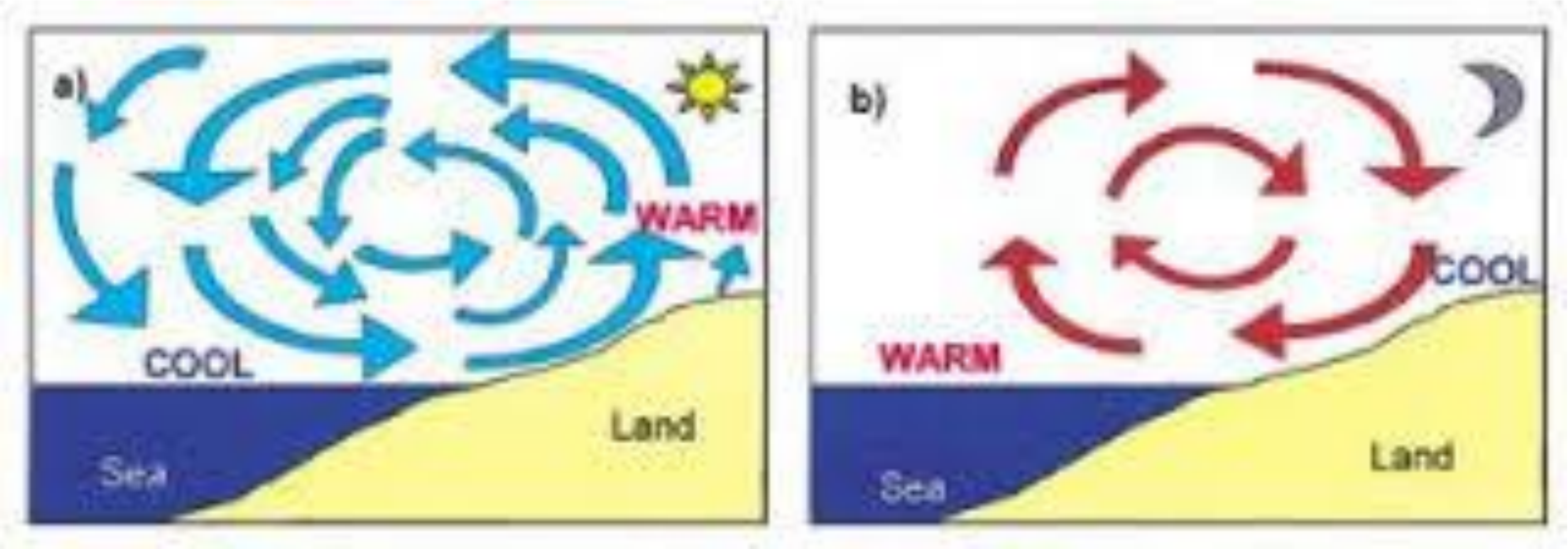
Wind power is nothing else than converted solar power (as is, e.g., hydropower, windpower, or power generated by burning biofuels). In general, wind is caused by the fact that different areas on the Earth surface get heated up at different rates by sunshine (or the rate of cooling after the sunset is different).

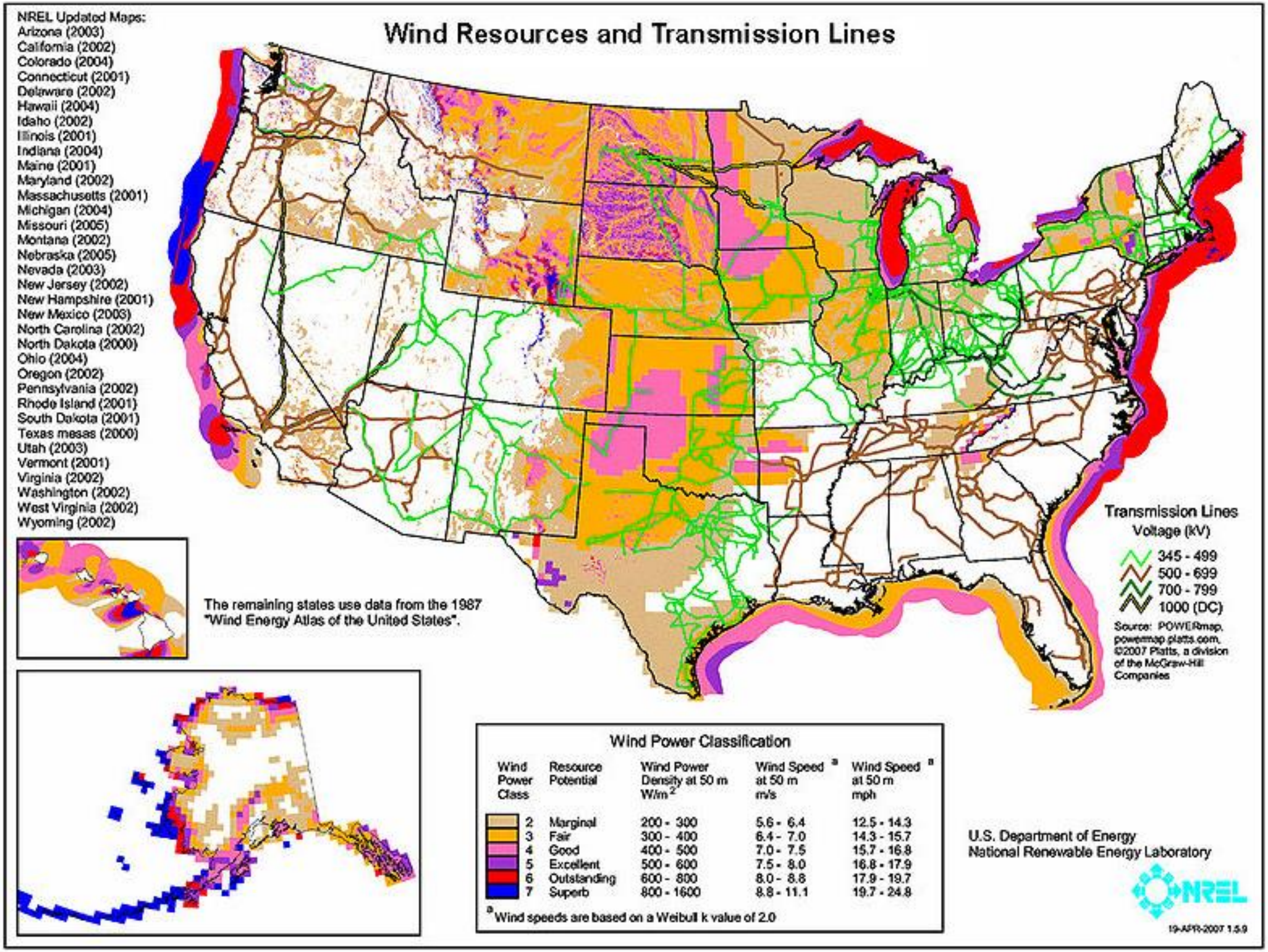
One well-known example is the passat, or “trade wind”, is caused by hot air rising in the vicinity of Equator, so that cooler air from latitudes more to the north and to the south blows in “to fill the void” created by the air “escaping up”.





Another instructive example are the mechanism producing breezes – the winds blowing at the ocean or lake shores, inshore after sunrise, or offshore at the sunset. The land warms up faster than the seawater at sunrise, so the air above the land rises up, and air from above the sea is blown in to "replace it". At sunset, the land cools down faster, so the mechanism is reversed.





Wind Resources and Transmission Lines

NREL Updated Maps:
Arizona (2003)
California (2002)
Colorado (2004)
Connecticut (2001)
Delaware (2002)
Hawaii (2004)
Idaho (2002)
Illinois (2001)
Indiana (2004)
Maine (2001)
Maryland (2002)
Massachusetts (2001)
Michigan (2004)
Missouri (2005)
Montana (2002)
Nebraska (2005)
Nevada (2003)
New Jersey (2002)
New Hampshire (2001)
New Mexico (2003)
North Carolina (2002)
North Dakota (2000)
Ohio (2004)
Oregon (2002)
Pennsylvania (2002)
Rhode Island (2001)
South Dakota (2001)
Texas mesas (2000)
Utah (2003)
Vermont (2001)
Virginia (2002)
Washington (2002)
West Virginia (2002)
Wyoming (2002)

The remaining states use data from the 1987 "Wind Energy Atlas of the United States".

Source: POWERmap, powermap.platts.com, ©2007 Platts, a division of the McGraw-Hill Companies

Wind Power Classification

Wind Power Class		Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
🟫	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
🟧	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
🟪	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
🟪	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
🟥	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
🟦	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory

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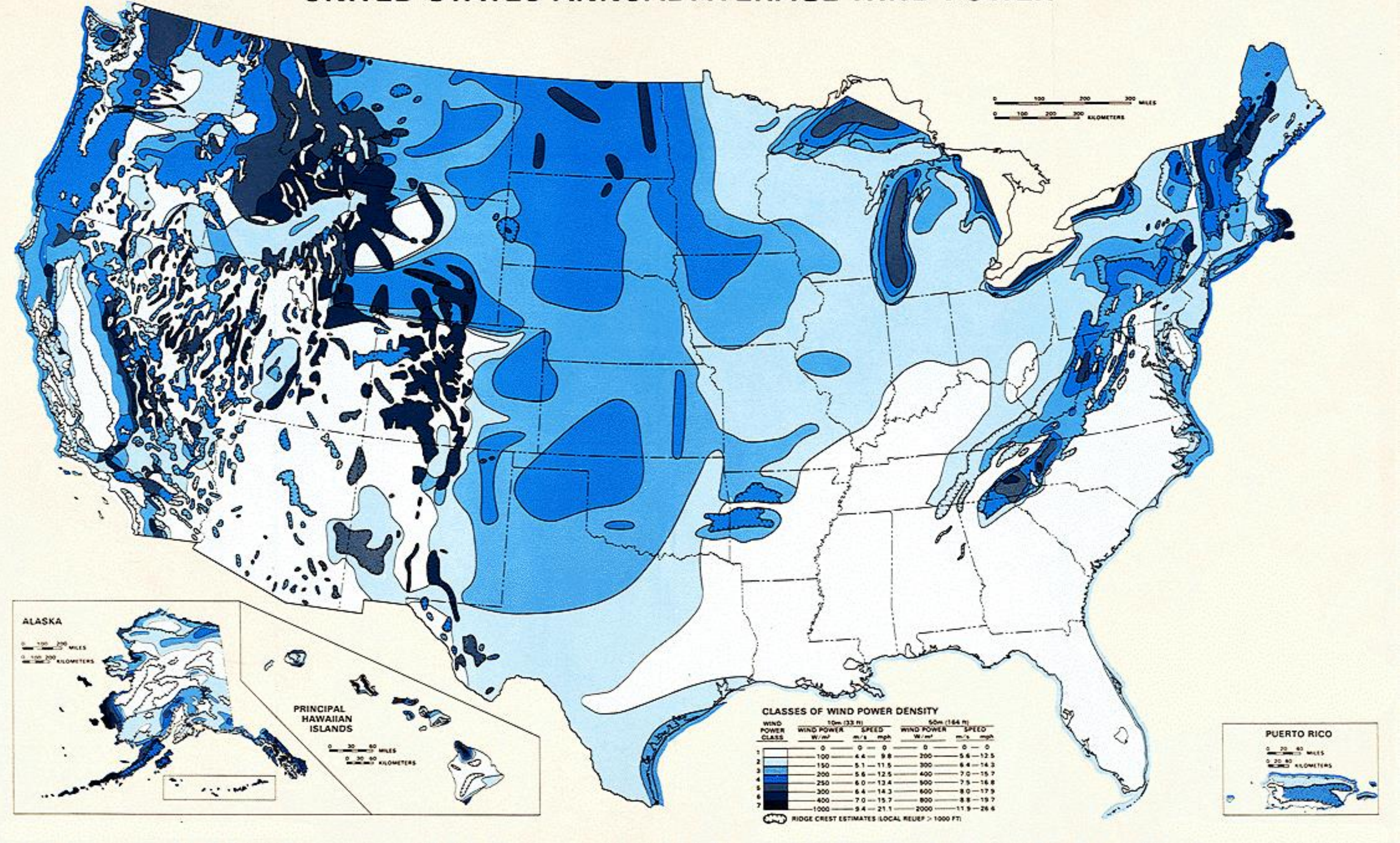
UNITED STATES ANNUAL AVERAGE WIND POWER



CLASSES OF WIND POWER DENSITY

WIND POWER CLASS	10m (33 ft) WIND POWER W/m²	10m (33 ft) SPEED m/s	10m (33 ft) SPEED mph	50m (164 ft) WIND POWER W/m²	50m (164 ft) SPEED m/s	50m (164 ft) SPEED mph
	0	0	0	0	0	0
1	100	4.4	9.8	200	5.6	12.5
2	150	5.1	11.5	300	6.4	14.3
3	200	5.6	12.5	400	7.0	15.7
4	250	6.0	13.4	500	7.5	16.8
5	300	6.4	14.3	600	8.0	17.9
6	400	7.0	15.7	800	8.8	19.7
7	1000	9.4	21.1	2000	11.9	26.6

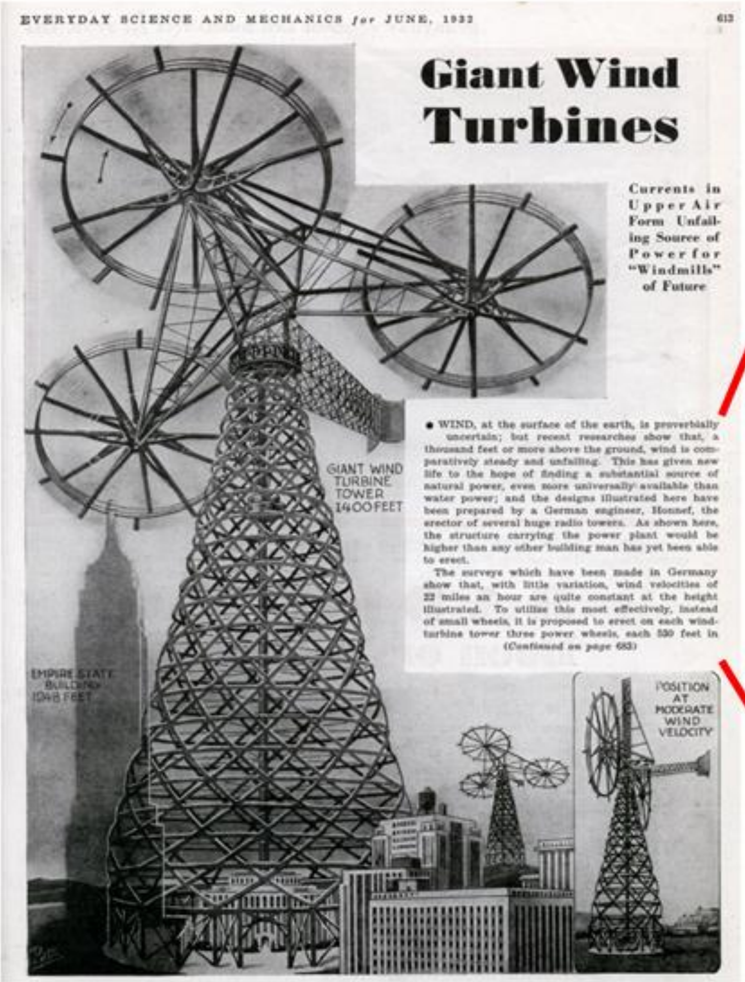
RIDGE CREST ESTIMATES (LOCAL RELIEF > 1000 FT)

Types of wind turbines

Classical Dutch windmill, used since the medieval age. In the XIX Century there were several thousand of them in the Netherlands, used primarily for water pumping.

Classical American multi-blade turbine. Widely used in rural areas upuntil the mid-1900s, for pumping water and generating household electricity. In the 1930s, there were ~6,000,000 of them in the US!

Today we need more powerful turbines, though! However, using wind energy at a gigantic scale is not a very new idea. Here is a clip from a 1932 issue of scientific magazine.



EVERYDAY SCIENCE AND MECHANICS *for* JUNE, 1932 613

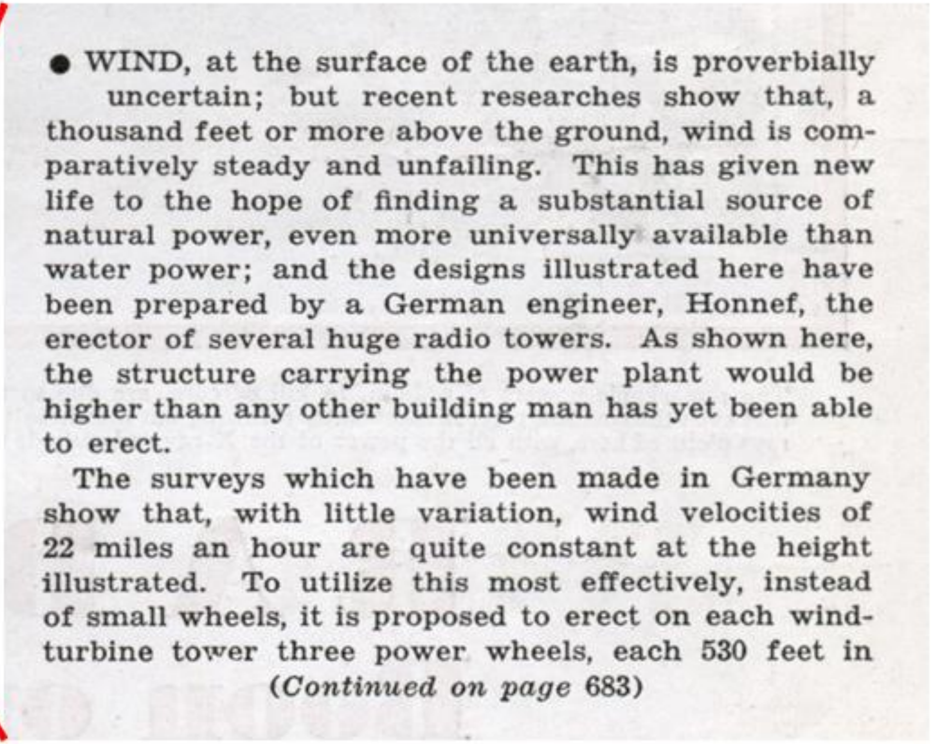
Giant Wind Turbines

Currents in Upper Air Form Unfailing Source of Power for "Windmills" of Future

● WIND, at the surface of the earth, is proverbially uncertain; but recent researches show that, a thousand feet or more above the ground, wind is comparatively steady and unfailing. This has given new life to the hope of finding a substantial source of natural power, even more universally available than water power; and the designs illustrated here have been prepared by a German engineer, Honnef, the erector of several huge radio towers. As shown here, the structure carrying the power plant would be higher than any other building man has yet been able to erect.

The surveys which have been made in Germany show that, with little variation, wind velocities of 22 miles an hour are quite constant at the height illustrated. To utilize this most effectively, instead of small wheels, it is proposed to erect on each wind-turbine tower three power wheels, each 530 feet in

(*Continued on page* 683)



● WIND, at the surface of the earth, is proverbially uncertain; but recent researches show that, a thousand feet or more above the ground, wind is comparatively steady and unfailing. This has given new life to the hope of finding a substantial source of natural power, even more universally available than water power; and the designs illustrated here have been prepared by a German engineer, Honnef, the erector of several huge radio towers. As shown here, the structure carrying the power plant would be higher than any other building man has yet been able to erect.

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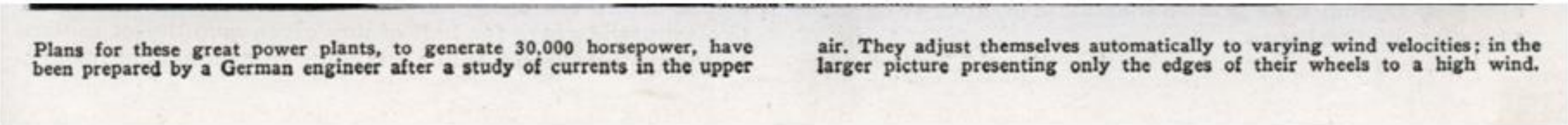
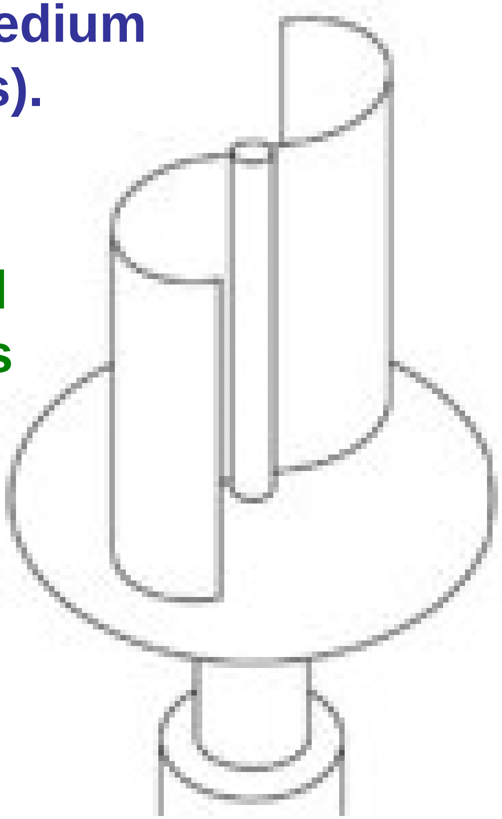


Plans for these great power plants, to generate 30,000 horsepower, have been prepared by a German engineer after a study of currents in the upper air. They adjust themselves automatically to varying wind velocities; in the larger picture presenting only the edges of their wheels to a high wind.

Modern Vertical-Axis Wind Turbines (low and medium power units).

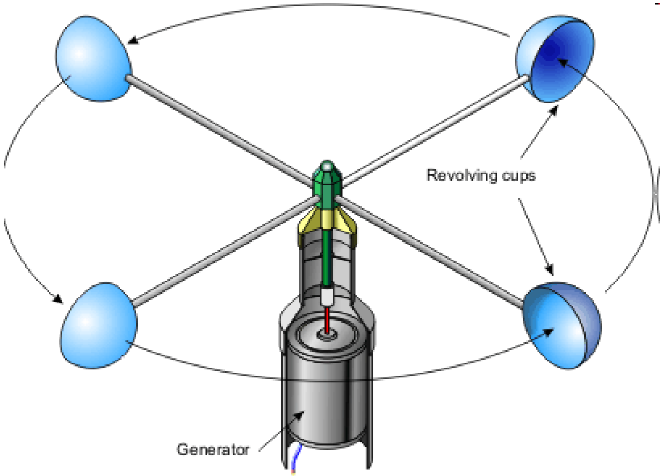
Classical Savonius vertical wind turbine



Darrieus Wind Turbine (right)

and

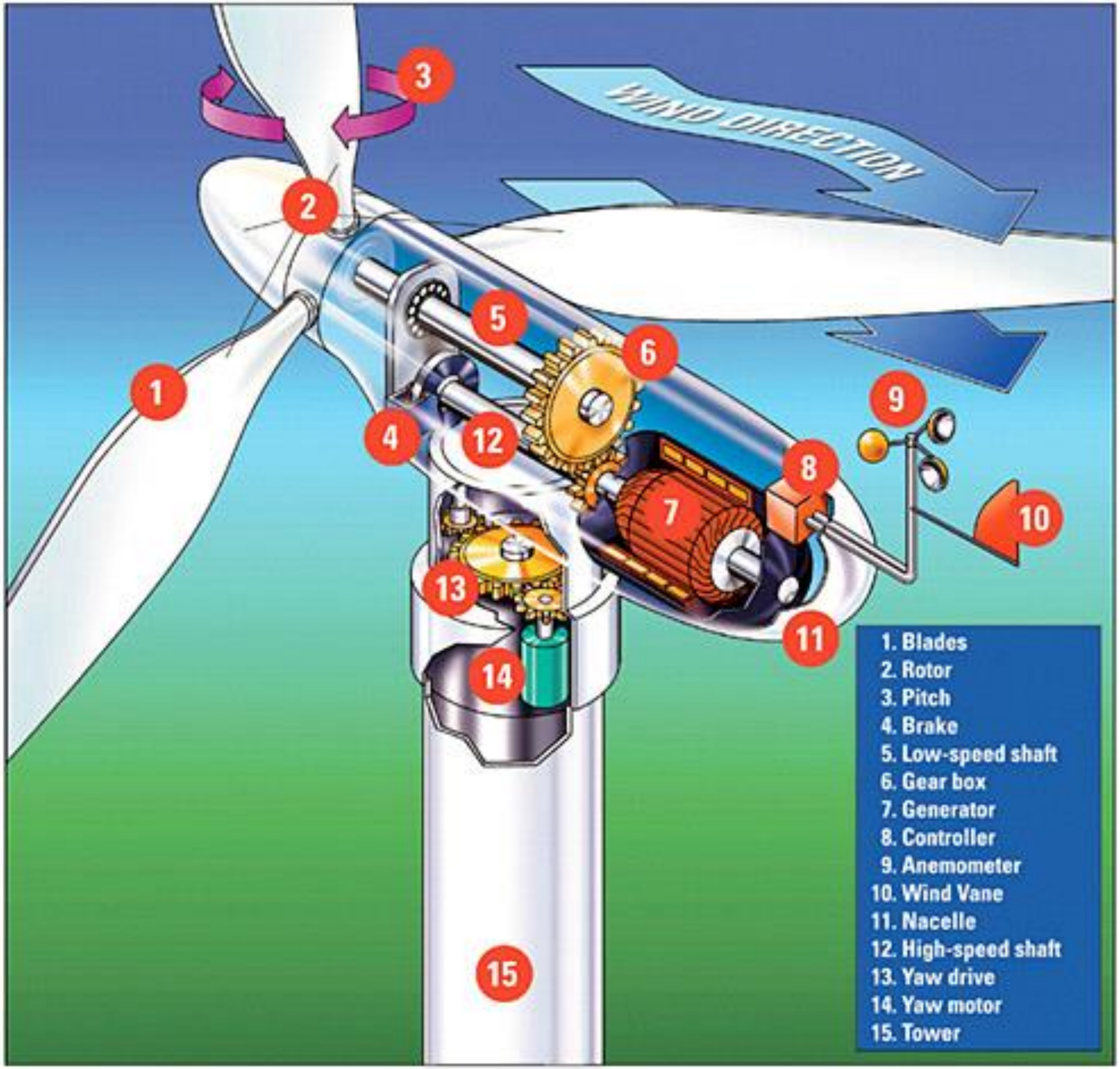
Helical Rotor wind turbine



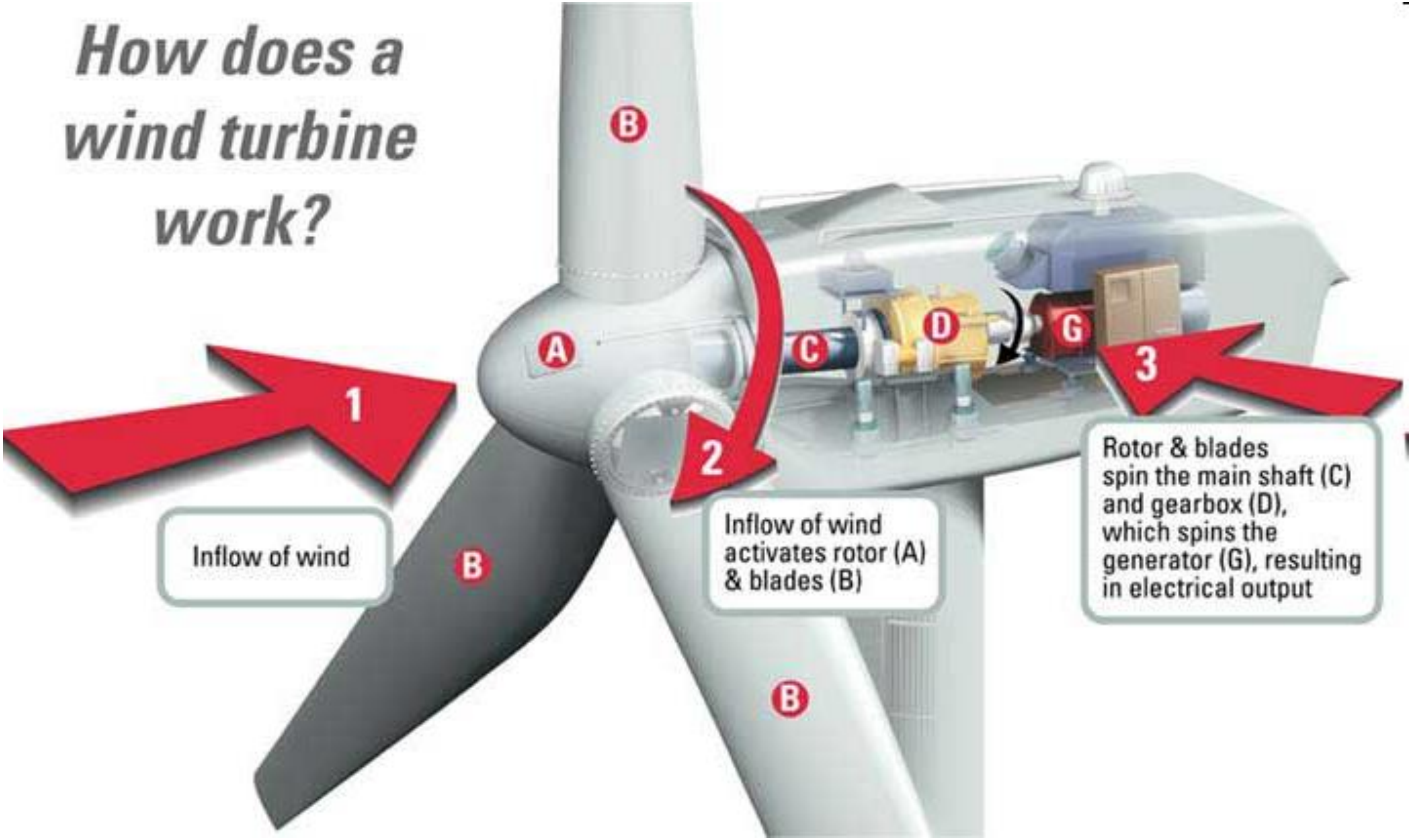
Anemometers (instruments for measuring the speed of wind have a similar design as the Savonius turbine

But the high-power generation is the kingdom of Horizontal-Axis Wind Turbines (HAWT)

The “anatomy” of a high-power HAWT



How does a wind turbine work?



Inflow of wind

Inflow of wind activates rotor (A) & blades (B)

Rotor & blades spin the main shaft (C) and gearbox (D), which spins the generator (G), resulting in electrical output

You can watch a good Youtube clip on how a wind turbine works -- please make a click here.

This short movie also explains very well the physics underlying the Betz Limit. It starts 4 minutes and 3 seconds after the beginning (if you skip the commercial at the beginning, of course – otherwise, it may be 14 minutes ☺).

World largest! 7+ MW

Diameter: 126 m (413 feet)
Where: in Germany

PHOTO GALLERY
of this monster:
Next two slides

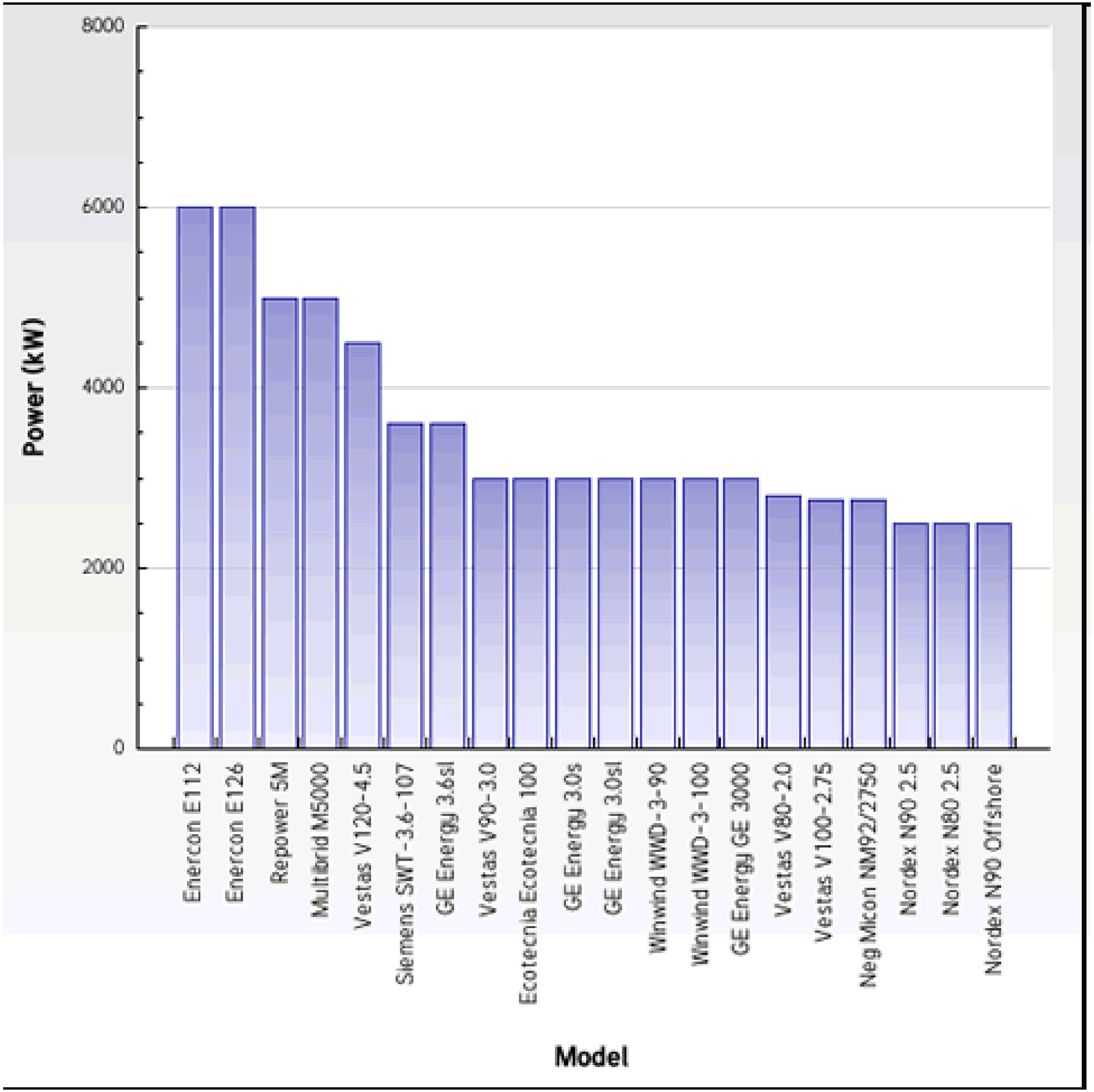
However, it's by no means the most powerful "wind machine" ever built! The legendary "Tea Clipper" *Cutty Sark* shown in the first slide, or other ships of that class (here is another legend, the *Sea Witch*) could drag up to 10,000 horse-power from the wind, i.e., ~ 7.5 MW . And

they had so much charm, while those modern wind turbines looking like "overgrown mobile scarecrows" only spoil the landscape.

One finished, another
one under construction

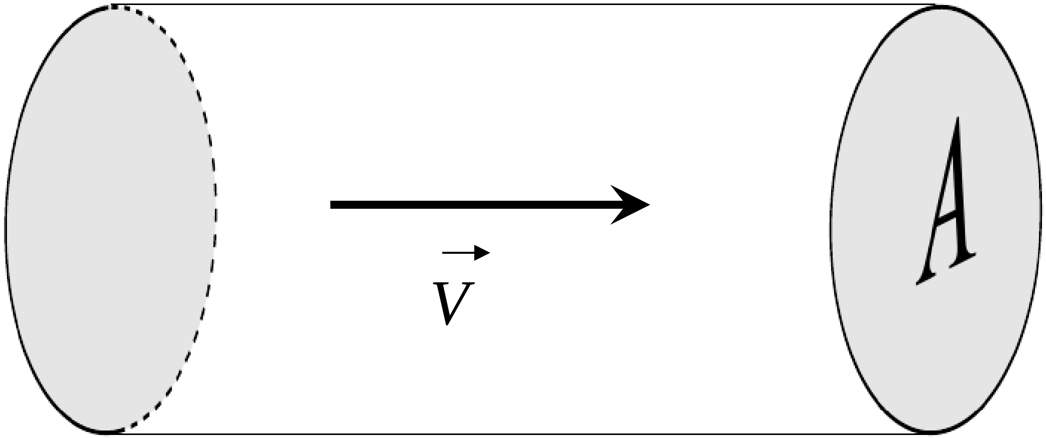
The head and the base

The largest world wind turbines



How much energy does the wind carry?

Consider an "imaginary cylinder" of cross section area A, with its axis parallel to the wind, and of length $L = V \cdot 1\,\mathrm{s}$ where V is the speed of the wind. Let ρ be the air density.

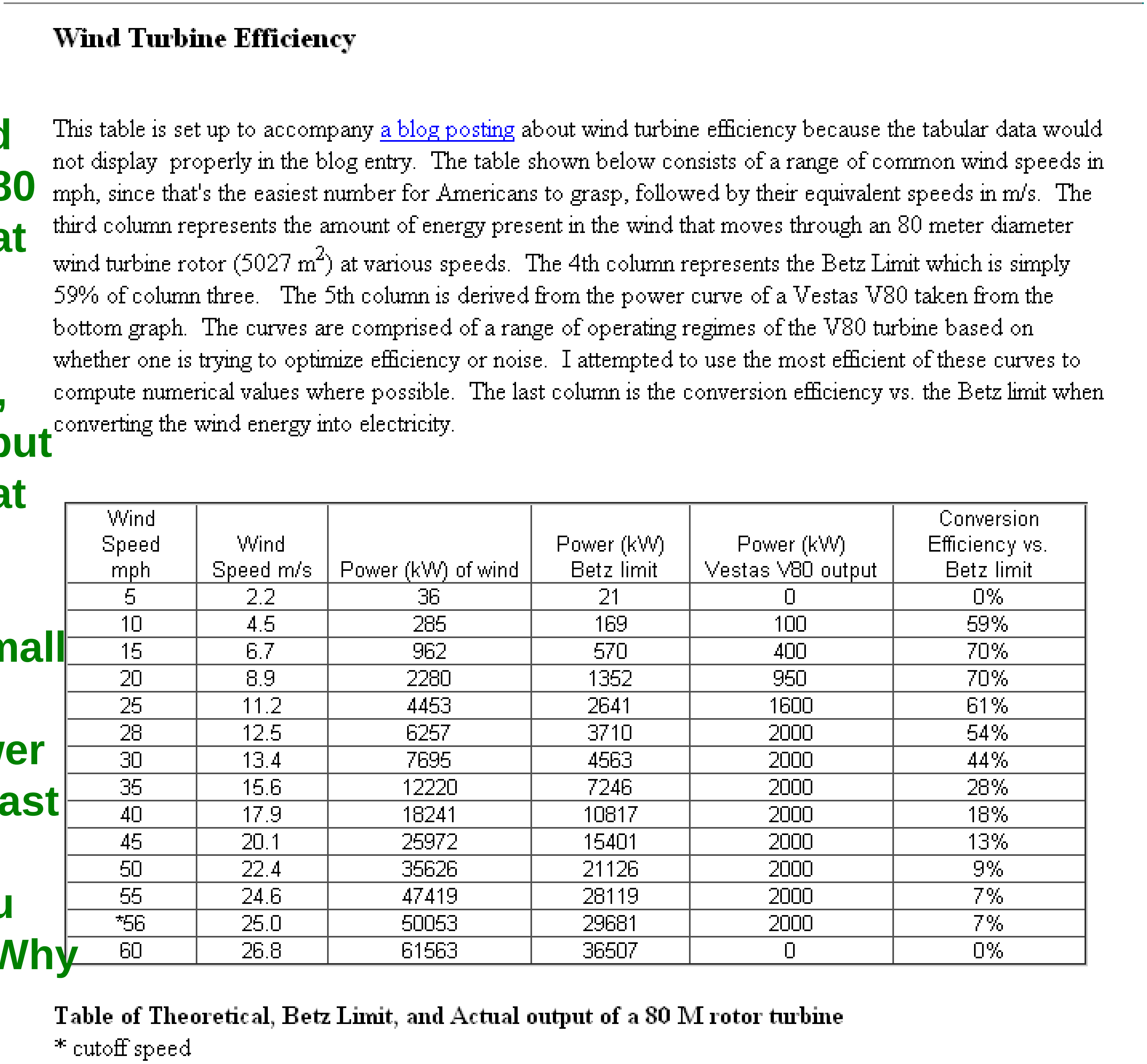


The mass of the air in the cylinder is $m = \rho \cdot A \cdot L = \rho \cdot A \cdot V \cdot 1\,\mathrm{s}$;

Its *kinetic* energy is: $K = \dfrac{mV^2}{2} = \dfrac{\rho \cdot A \cdot V^3}{2} \cdot 1\,\mathrm{s}$. This is the *total energy* that passes throught the area A in a single second. Accordingly, the power passing through this area is: $P(A) = \dfrac{\rho \cdot A \cdot V^3}{2}$, and the power per *unit area* is:

$$\boxed{P_{\mathrm{unit\,area}} = \frac{\rho \cdot V^3}{2}}$$

Power output vs. wind speed for a Vestas V80 turbine, used at many US wind farms (rotor diameter 80 m, maximum output 2 MW. Note that at high wind speeds it converts only a small fraction of the total wind power to electricity (last column in the table). Can you explain why? Why not all?



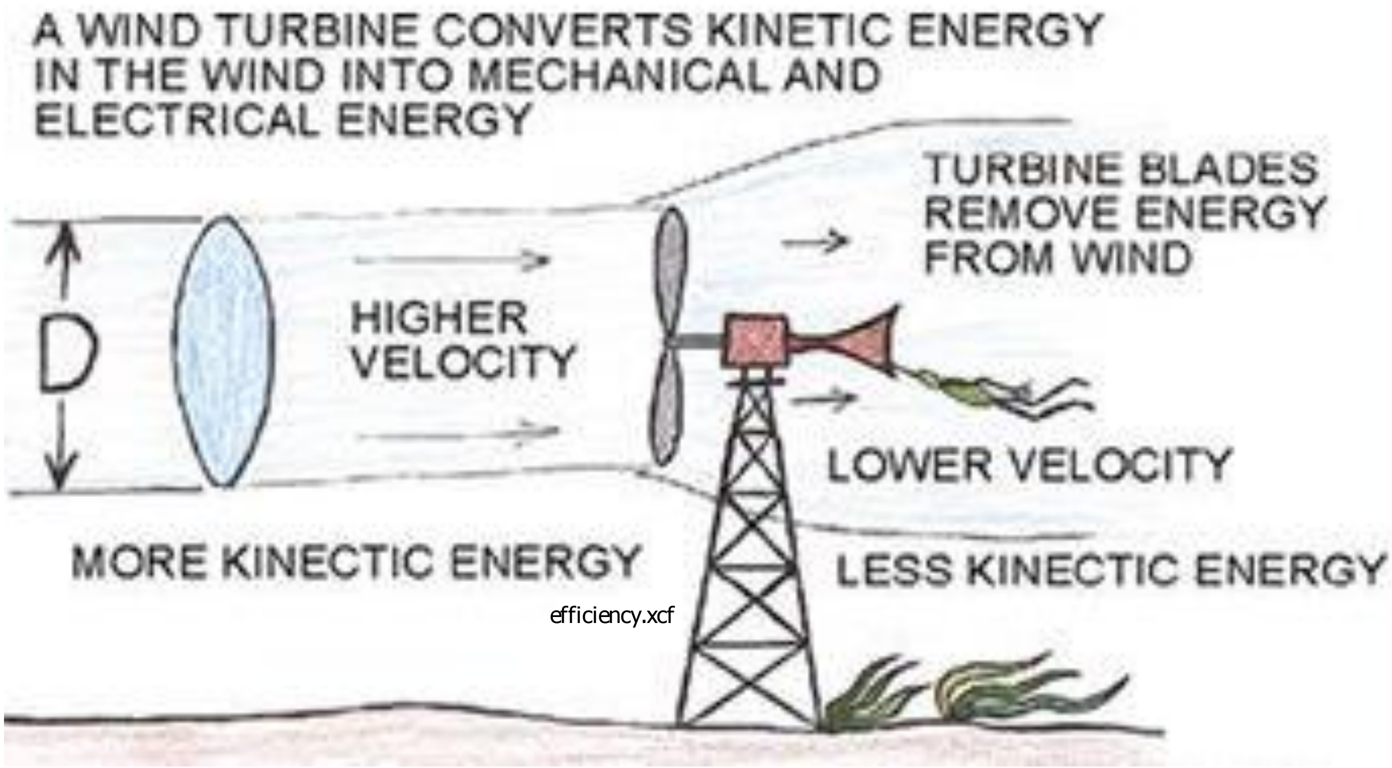
Wind Turbine Efficiency

This table is set up to accompany a blog posting about wind turbine efficiency because the tabular data would not display properly in the blog entry. The table shown below consists of a range of common wind speeds in mph, since that's the easiest number for Americans to grasp, followed by their equivalent speeds in m/s. The third column represents the amount of energy present in the wind that moves through an 80 meter diameter wind turbine rotor (5027 m^2) at various speeds. The 4th column represents the Betz Limit which is simply 59% of column three. The 5th column is derived from the power curve of a Vestas V80 taken from the bottom graph. The curves are comprised of a range of operating regimes of the V80 turbine based on whether one is trying to optimize efficiency or noise. I attempted to use the most efficient of these curves to compute numerical values where possible. The last column is the conversion efficiency vs. the Betz limit when converting the wind energy into electricity.

Wind Speed mph	Wind Speed m/s	Power (kW) of wind	Power (kW) Betz limit	Power (kW) Vestas V80 output	Conversion Efficiency vs. Betz limit
5	2.2	36	21	0	0%
10	4.5	285	169	100	59%
15	6.7	962	570	400	70%
20	8.9	2280	1352	950	70%
25	11.2	4453	2641	1600	61%
28	12.5	6257	3710	2000	54%
30	13.4	7695	4563	2000	44%
35	15.6	12220	7246	2000	28%
40	17.9	18241	10817	2000	18%
45	20.1	25972	15401	2000	13%
50	22.4	35626	21126	2000	9%
55	24.6	47419	28119	2000	7%
*56	25.0	50053	29681	2000	7%
60	26.8	61563	36507	0	0%

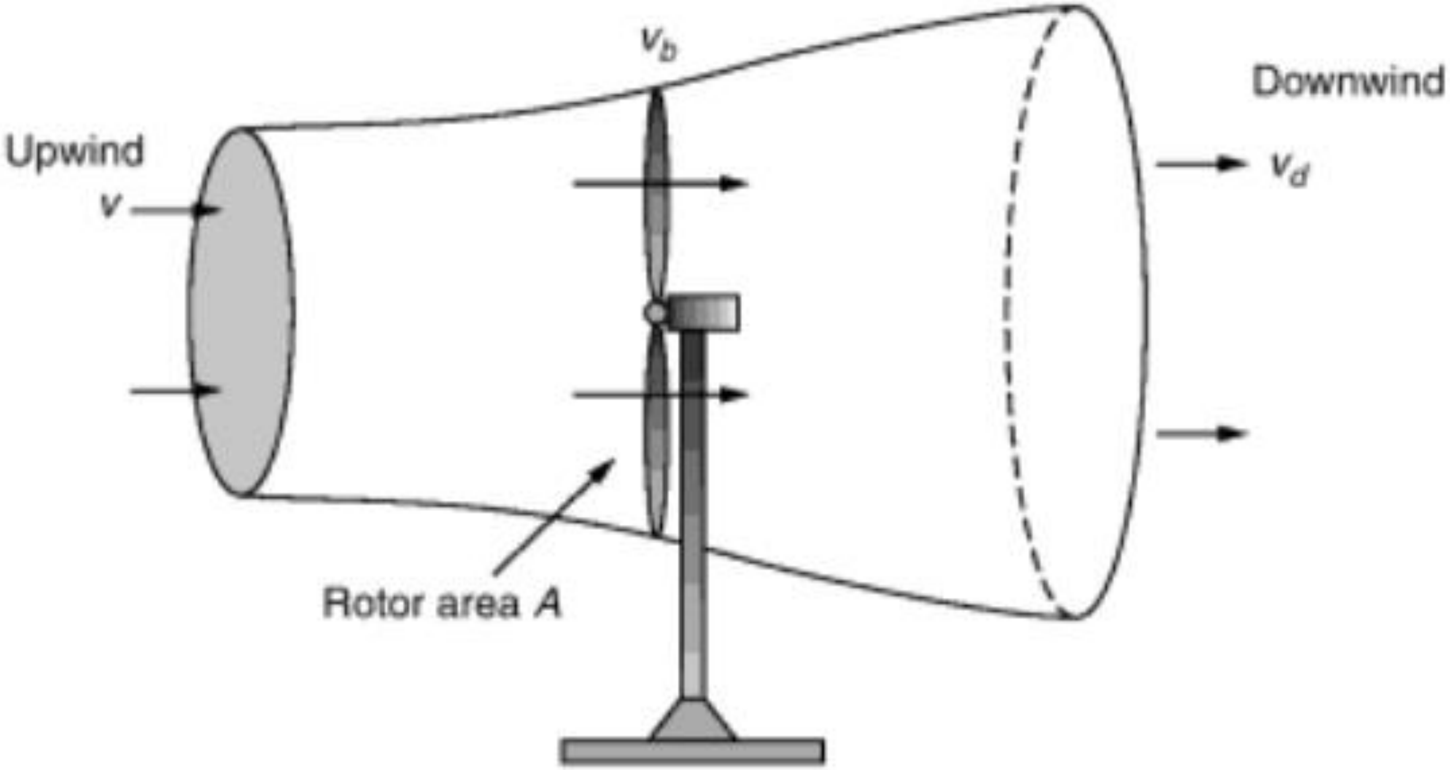
Table of Theoretical, Betz Limit, and Actual output of a 80 M rotor turbine

* cutoff speed

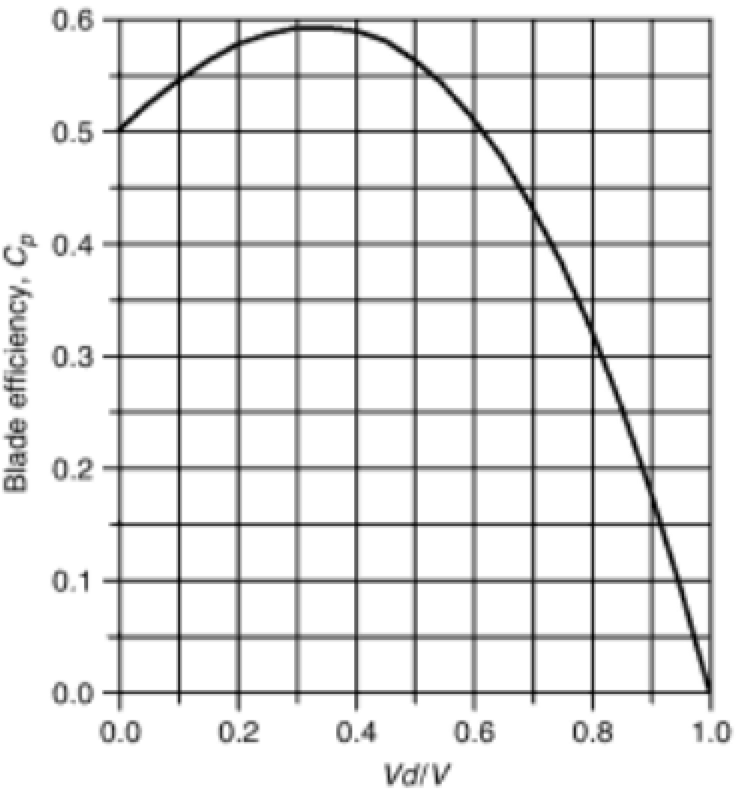


$$\text{POWER IN THE WIND} = \left(\text{DENSITY OF AIR}\right) \times \frac{\pi}{4} \times \left(\text{TURBINE BLADE DIAMETER}\right)^2 \times \left(\text{VELOCITY OF WIND}\right)^3 \times \left(\text{A CONSTANT}\right)$$

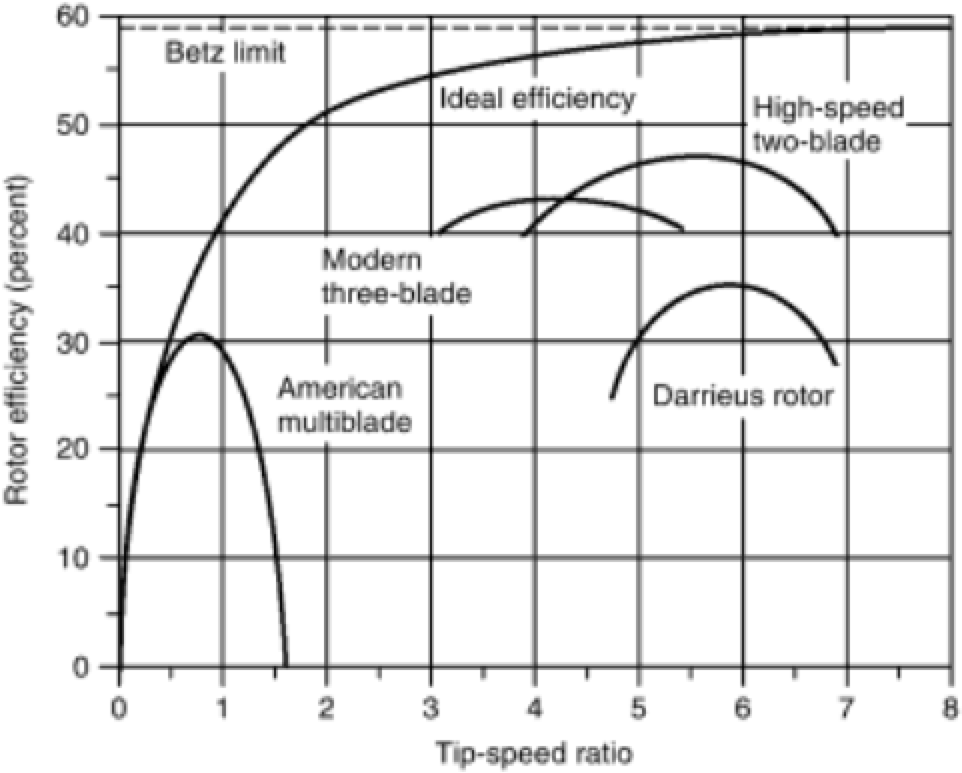
$$\text{POWER IN THE WIND} = d \times \frac{\pi}{4} \times D^2 \times V^3 \times C$$



The wind cannot pass *all* its kinetic energy to the rotor, because then the air velocity behind the rotor would be zero – but the “spent air” has to fly away! Otherwise, it would “accumulate” behind the rotor! It has to “get mixed” with the wind that passes by the turbine. The physics of this process is not simple, so we won’t discuss the details. The only important fact one should know is that the downwind-flying Air, after “doing its work”, still retains NO LESS THAN 41% of its Initial kinetic energy – in other words, it cannot transfer more that 59% of its energy to the rotor. It’s called the BETZ LIMIT.



The blade efficiency reaches Its maximum (the Betz limit) when the “downwind speed” (i.e., right behind the rotor is about 1/3 of the incoming air speed.



$$\text{"Tip speed"} = \frac{\text{Linear speed of the blade tip}}{\text{Wind speed}}$$

The efficiency of various rotor types vs. tip speed. You can see that modern Turbines perform quite well, they can Attain 70-80% of the maximum theoretical efficiency. The performance of the “American multi-blade” is not too impressive…

…but they have a high start-up torque, which is crucial…

…in water pumping. Besides, they are so cute, aren’t they?

Current usage of wind power in the US and globally

A highly interesting and thorough overview is presented in this Wikipedia article

Our plan is to open this site in class, and focus on a number of items presented – namely:

- Current global wind power installed, and forecasts for the next few years;
- The *Capacity Factor* -- it is very important to know what it is for realistic thinking of the "energy future" of the World. Wind power is a terrific thing, but too much enthusiasm and what I call "HURRAY—OPTIMISM" may lead to a loss of contact with reality.
- The wind power installed in the US and other leading "wind power consumers".
- The net annual energy output from wind turbines in those countries, and the % contribution of wind energy in their total energy balances.

Not yet the end! A few more slides will be added.

Continuation of the *Wind Power* PPT presentation

The picture that emerges from what we saw in the tables and graphs illustrating the quick progress in implementing wind power plants is quite rosy. Let us all follow the example of Denmark, where 20% of electrical power is generated at wind farms! Let's do the same in the US, let's go even further!

Well, optimism is OK, but too much optimism is never recommended. "Overblown" optimism often changes into a bitter disappointment, if it turns out that our expectations were not fully realistic. For the implementation of wind power In the US at a major scale many challenges need to be taken up, many technological problems need to be solved.

Let's take a closer look at some of those problems, using Denmark, the "wind power world leader as an example.

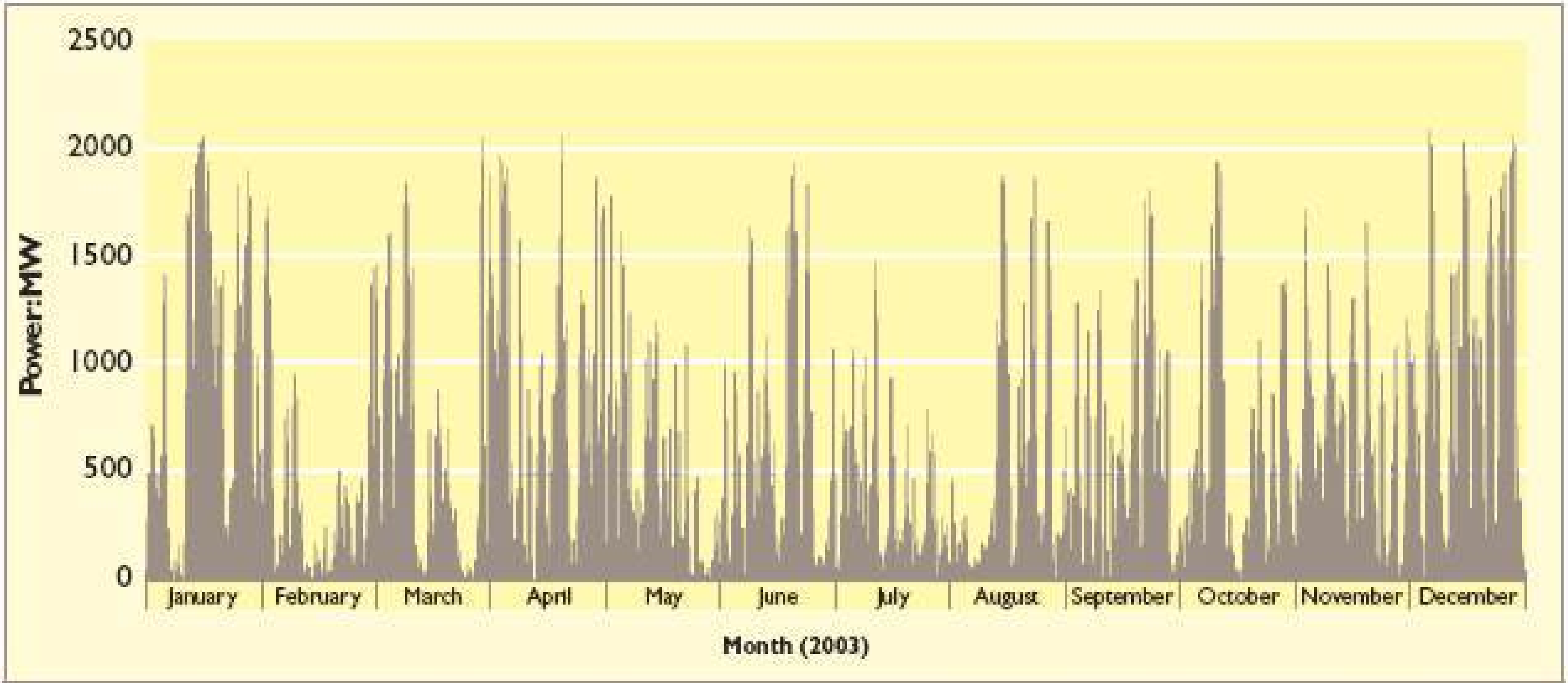


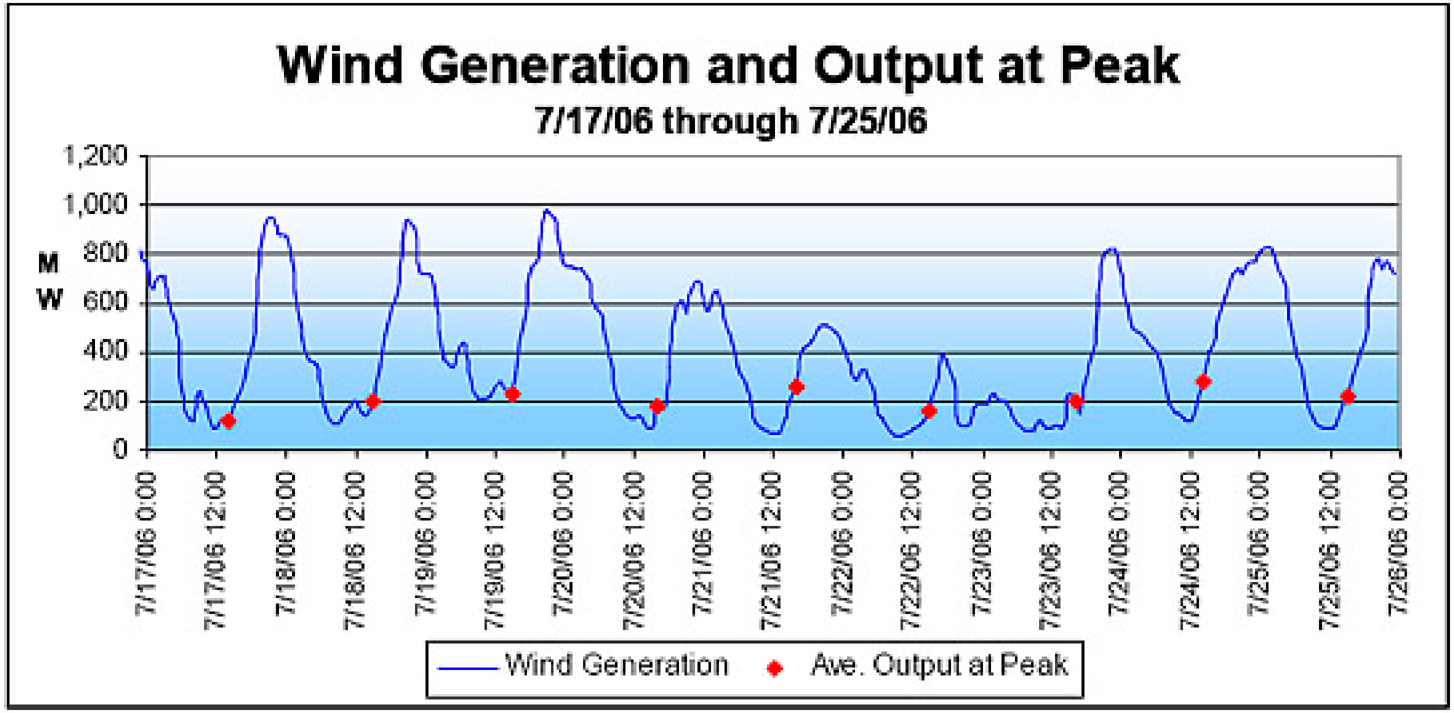
Fig. 8. Wind power production in west Denmark exceeded 2000 MW nine times during 2003

This graph illustrates the production of the wind-power electrical energy production in Denmark in the year 2003, day by day.
Not a very smooth curve, right?

How do the Danes cope with such enormous fluctuations? Well, they are a Scandinavian nation, and all Scandinavian countries (Denmark, Norway, Sweden, Finland and Island) feel like a family. Norway has vast resources of hydro-power. So, when the wind fades, they ask their Norwegian "cousins": "Please, send us promptly 1000 MW!" And current flows…

↓

However, we Americans don't have such a next-door neighbor with too much electricity… But the problems Are very much the same.



Here is the net power output from one large wind farm in California during an 8-day period in July 2006.

Another example – now from an American mid-western wind farm:

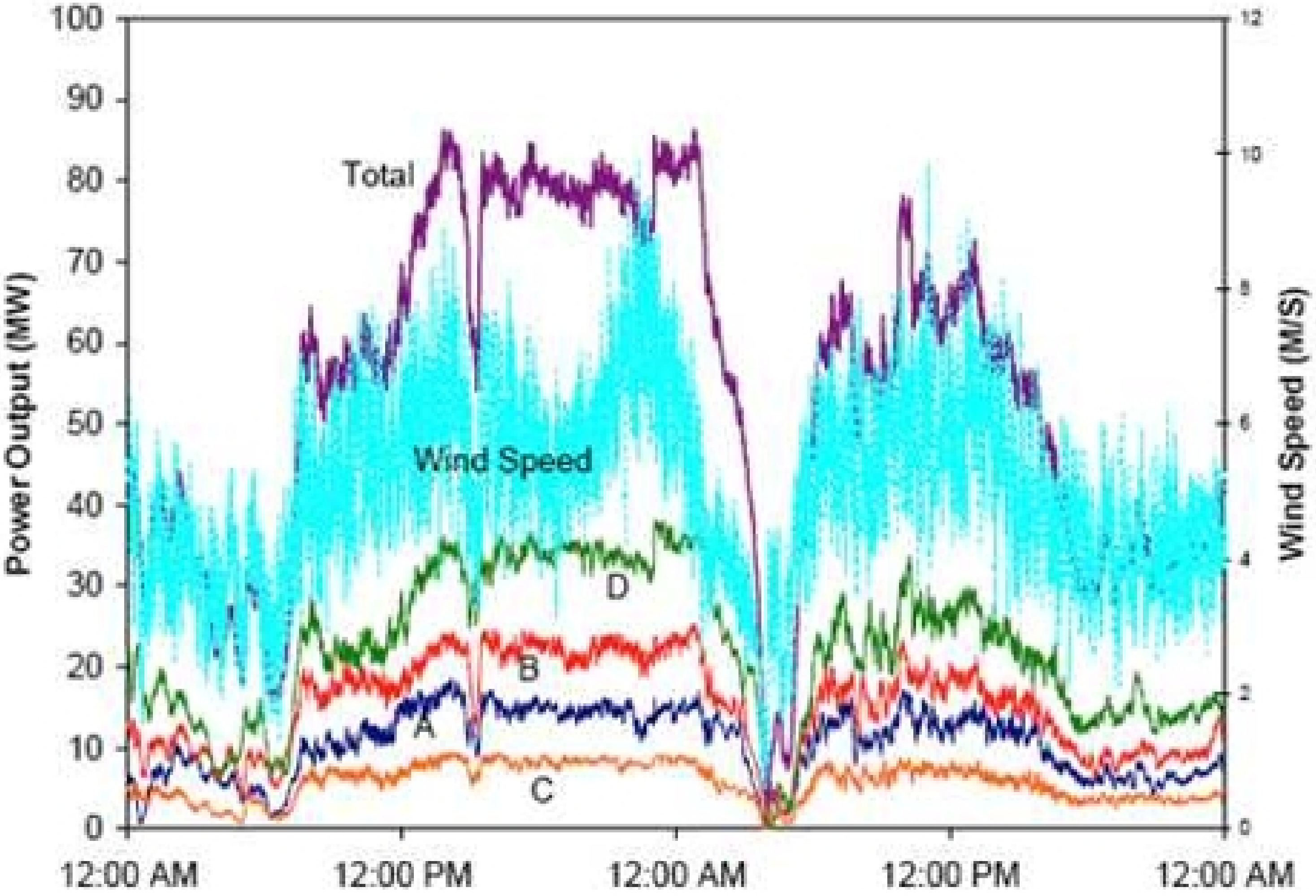


Fig. 8. Two days of output and wind speed from a four-section midwestern wind plant.

I believe that the above graphs clearly show where the problem is. The wind-power plants have to be "integrated" into the nation's power grid, that's obvious. But what to do if the wind stops blowing, what happens quite often, as the graphs show? The total power generated must be sufficient to satisfy the needs of all consumers! So, other facilities have to take over. But often They do not have enough extra capability, and then the problem may become really serious.

Experts in the field have coined a new term for that: a

DANCE PARTNER PROBLEM

Wind Power: the "DANCE PARTNER" picture

Think of such a situation: there is a dancing party. The gentleman dancing with the lady is a novice dancer – he is just taking the "Ballroom Dancing One" class at OSU (it might be Dr. Tom, he took that class in the last Winter term). In contrast, the lady is an experienced dancer.

What happens in such a situation? The gentleman all the time looses rhythm, makes wrong steps. The lady tries to correct his errors by gently pushing him, but it makes him even more confused.
The lady tries to keep the correct rhythm and footwork, but the partner's errors force her to make wrong steps, too. The result is that the gentleman often steps on the lady's toes. There is no harmony whatsoever in the motions of the two partners, and the dance is not a pleasant experience for any of them.

The above describes well the present “partnership” between the wind power sector, and the public utility grid.

It is not Dr. Tom who conceived that story. Actually, such a picture is painted in a recent article written by highly qualified experts in the field. This article was published in one of the latest issues of the SCIENCE magazine, one of the most prestigious American scientific journals. Here is a link to the PDF copy of the article: Please click!

You are strongly encouraged to read the article – if you don’t have enough time before our Friday class, please try to find 15 minutes during the weekend. The article is written in a very “pedagogical” style, and it gives a thorough diagnosis of the current situation – also, it tells what may happen in the future, if we continue to expand the wind power sector, doing little to make it a better “dance partner” for the already existing utility system.

Possible remedies:

- The gentleman should continue working on improving his dancing skills;
- If the lady wants to do more dancing with the gentleman in the future, and enjoy it, she should take a course for dancing instructors.

In fact, when Dr. Tom was taking the *Ballroom One* course, he used to be a horrible partner for the female classmates he danced with. But when he danced with the instructor, everything was going much smoother. Because she simply knew how to “control” an inexperienced partner!

So, the wind-power sector and the existing system should keep working on improving their partnership – and how it can be done? The answer is in the article: by making the grid “intelligent”!