Wind energy, from the perspective of physics

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Windmill from the XIXᵉ century in northern Germany. Note the twisting of the rotor blades.

Electrical energy is one of the most valuable forms of energy, as it can be optimally transported and converted into other forms of energy with low losses.
Most future scenarios predict that electrical energy consumption will continue to grow significantly, and that the share of renewable energies, due to their abundance, will also increase.

This contribution focuses on wind power, discussing how it works and its contribution to the overall energy supply.

How do wind turbines work?

Wind energy is the energy contained in moving air. Its power density, i.e. the energy transported per unit of time across an area A perpendicular to the wind speed, is written as : $P_{wind} / A = 1/2\ \rho\ u^3$, where ρ is the air density and u is the wind speed. A typical wind speed of 12 m/s, often used as the design condition for a turbine, corresponds to a wind power of around 1 kW/m^2. By way of comparison, on a sunny day, the power density of solar energy incident on the ground is also of the order of 1 kW/m^2.

A "wind turbine" is a *wind energy converter* (WEC), whose output power P_{WEC} is related to P_{wind} by the relationship : $P_{CEV} = c(\lambda)P_{wind}$, where c(λ) indicates the efficiency of the conversion and depends on what is known as the blade tip-speed ratio: $\lambda = R\omega/\upsilon$.

In this expression, ω denotes the angular frequency of rotation of the rotor, and Rω the speed of the rotor tip.

To determine the maximum efficiency value c(λ), let's consider the case where a wind turbine converts 100% of the wind energy: the turbine would have the effect of a wall. The flow of new air masses - and therefore wind energy - would then not be possible: the flow would bypass the wind turbine and no further energy could be converted. An optimally functioning wind turbine must therefore have a certain permeability to the wind, which is controlled by the speed of rotation ω of the blades. By looking for the optimum, we can show that maximum energy yield is achieved when the wind is slowed down to 1/3 of its initial speed. This leads to a maximum efficiency of 59%, known as the Betz limit (more precisely, the Lanchester-Betz-Joukowsky limit [1]).

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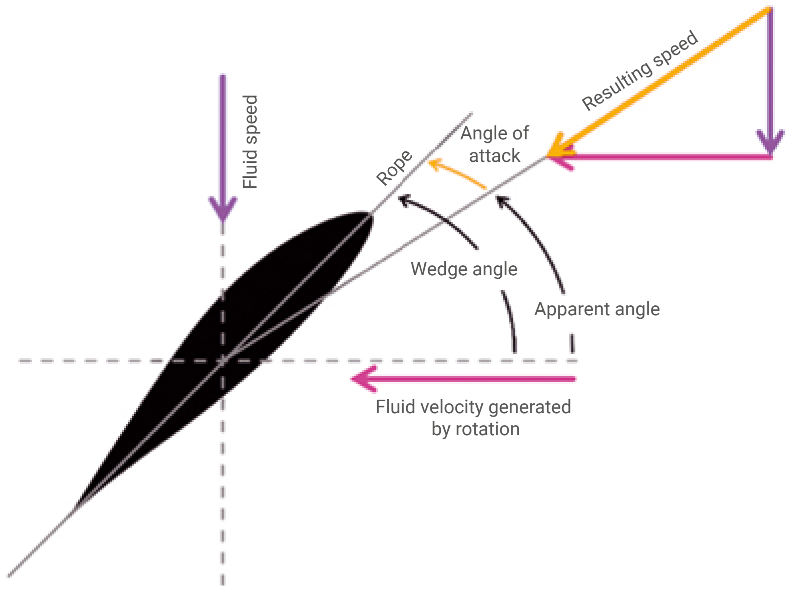

1. Diagram illustrating the flow geometry around a wind turbine blade profile.

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Modern turbines achieve c(λ) values of 50%, with a λ of around 7 for three-bladed wind turbines. From simple arguments, we can understand that:

- small wind turbines turn faster than large ones, since both types have roughly the same tip-speed ratio λ;
- two-bladed turbines have to turn faster than three- or four-bladed turbines, because they have to achieve the same degree of flow blockage;
- wider rotor blades lead to lower λ values than narrower blades.

Chord length and blade profile shape are other important aerodynamic variables for the conversion process. The diagram in Figure 1 provides an illustrated definition. For optimum energy conversion, the blade tip-speed ratio λ is fixed at its optimum. The wind input conditions vary along the blade: in the hub area, the wind comes from the front, but moving away from it as the radius r increases, its apparent direction varies more and more in the plane of rotation due to the intrinsic motion of a rotor blade segment (ωρ). As a result, the rotor blades are designed in a twisted manner (a principle that was also adopted in the old windmills of the 19th century, see photo p. 67). Optimising the power output for each radius leads to a longer chord length from the profile to the blade root and a more tapered shape at the tip .

The power of a wind turbine can therefore be controlled both by the frequency of rotation and by the position of the rotor blades in relation to the incoming flow, the latter method being known as "pitch control". Today's wind turbines have rotor blades of up to 110 m, covering an area of around 40 000 m^2, giving outputs of over 10 MW. This is the so-called rated power, which the turbine delivers at a rated wind speed of around 10 to 12 m/s. A rough estimate is that a turbine can produce around 0.5 kW per m^2 swept. Note that power varies as the cube of the speed u, so going from 10 to 12 m/s increases power by a factor of 1.7. In 2018, the typical output of onshore wind turbines was more than 3 MW and *offshore* wind turbines were close to 5 MW.

Researchers are working on concepts for 20 MW turbines, which require rotor blades over 100 m long. Their manufacture is a major challenge, raising fundamental questions about design and materials. As size increases, the whole structure can become unstable due to its own weight. Larger rotors become more flexible and the conversion process leads to more dynamic stresses. Similar difficulties were encountered in the development of the large wide-body aircraft, the A380 and the Dreamline, which led to a technological shift towards composite materials. It should be noted that the large wind turbines recently-envisaged have a wingspan greater than that of the new jumbo jets.

The dynamics of wind turbines

The blades of wind turbines operate at a height of 50 to 300 m above the ground, and are preferably installed in areas with strong winds. These conditions are similar to those to which an aircraft is exposed during a landing approach in strong winds. While passengers inside the aircraft clearly feel the turbulent jolts, seen from the outside, the aircraft glides calmly: this apparent "quiet glide" is only possible thanks to the use of the most modern control methods to master the effects of wind turbulence.

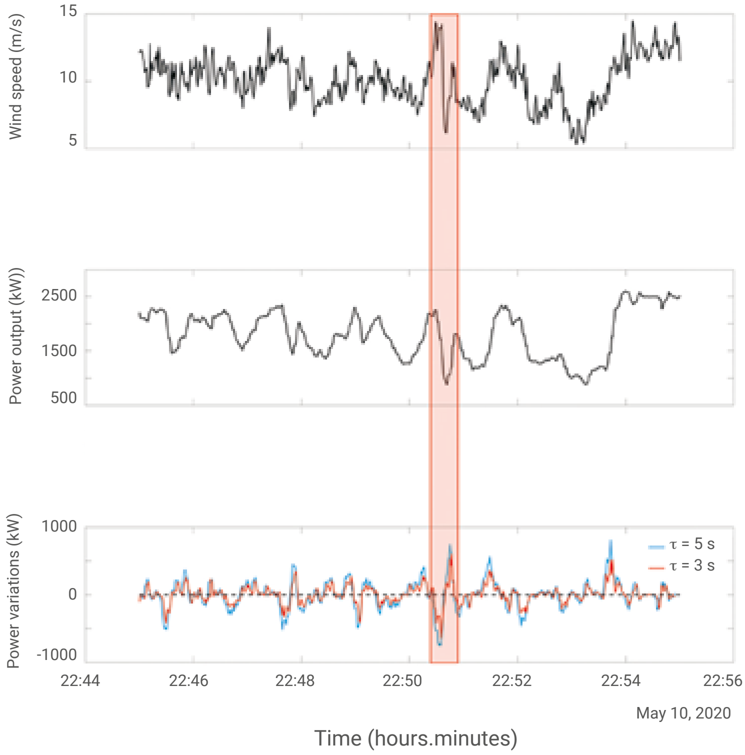
Wind turbines are very large machines exposed to extremely high load fluctuations. They are the largest turbulent flow machines ever built. The demands placed on wind turbines can be compared to the conditions that would apply to an aircraft enduring only landing approaches in strong winds. The load fluctuates even more than for a helicopter [2]...

It is generally assumed that the large rotor blades smooth out the turbulence, as there are no rapid changes in rotation speed. At first glance, therefore, it is surprising to find that wind turbulence affects the whole turbine down to a time scale of less than a second, as can be seen in the high-frequency part of the power output. Figure 2 shows a variation in measured power of more than 80% in a few seconds. However, in the wind energy sector, we generally only consider averages over ten minutes: this is clearly insufficient.

To understand these rapid fluctuations in power, we need to consider two aspects: firstly, the turbulence of the wind, which leads to large and rapid fluctuations in wind speed, and secondly, the speed with which wind turbines respond to these fluctuations [3].

What about the reaction of a wind turbine? From the point of view of fluid dynamics, we know that the time required for forces to develop on a rotor blade corresponds approximately to the time required for the air flow to pass over the blade once. From this we can deduce that the typical times taken for forces to develop on rotor blades with a chord profile of 1 to 5 m, for wind speeds of 10 m/s, are less than one second. For the very complex and not fully understood processes of turbulence generation and flow separation at the blade, even much smaller flow structures on the order of centimetres play an important role. Since the power is $P = T\omega$ (T is the torque, the product of the aerodynamic force and the radius), it is the rapid fluctuations in the force and therefore the torque that cause power fluctuations. The torque is transmitted very rapidly to the generator, which can react on a millisecond scale to build up a counter-torque, so that no effect on the speed of rotation is observed. Finally, the u^3 dependence of the power means that a 26% fluctuation in wind speed results in a factor of 2 on the power.

These considerations also show that, for the operation of a wind turbine, the energy resource, i.e. the atmospheric wind field, must be known down to a scale of the order of a metre or less, or down to a frequency scale of 10 Hz or more. The standards used in industry [4] only record the statistics of the ten minute averages of wind speeds and turbulence for various meteorological situations, which corresponds to the standard deviation of the wind speed around the ten-minute mean. Simplified universal properties, with Gaussian statistics, are used for fluctuations on smaller time scales. So-called extreme operating conditions caused by the wind are added to the Gaussian description for the design process. These extreme operating conditions include gusts, although to the best of our knowledge it is not known what a gust really is in a turbulent wind.



2. Time series of wind speed (top curve) and power output (middle curve) of a multi-megawatt wind turbine, measured in northern **Germany** (time scale in hours and minutes). A particularly rapid increase in wind speed and power output can be seen in the marked region. In the lower figure, we see the power variations for $\tau = 3$ s (red) and $\tau = 5$ s (blue). Power variations of more than 500 kW are observed, even for $\tau = 3$ s. The output power is almost constant at the highest wind speeds. This maximum power of 2 MW is given by the size of the generator used.

It is clear from the discussion so far that there is a need to know more about wind turbulence. In order to characterise it in more detail, it is common practice to describe fluctuations in terms of speed increments:

$u_\tau = u(t+\tau) - u(t)$, $u_r = u(x+r) - u(x)$.

The speed increments u_τ capture the temporal variability of the wind, resulting in temporal fluctuations in force as explained above. Spatial velocity increments u_r take into account the different locations on the rotor surface, resulting in, for example, abrupt variations in torque. The two increments can be converted into each other to a first approximation *via* the Taylor assumption of frozen turbulence and therefore have similar properties. For turbulent flows, it is known that increments on small scales (for small values of r and τ) exhibit increasing fluctuationstes and extreme values. In turbulence research, this property is known as the small-scale turbulence intermittency problem, and is statistically captured by the r-scale dependence of the general moments $<u_r^n>$, also known as structure functions.

Extreme events become more perceptible if we look directly at the probability distributions $P(u_r)$ or $P(u_\tau)$ and not at the higher order moments.

A remarkable property of turbulent flows is that the statistical distributions $P(u_r)$ and $P(u_\tau)$ develop larger and larger wings and thus deviate more and more from a Gaussian statistic, the smaller the scales r or τ become (fig. 3a). Comparison with a Gaussian statistic shows that large increments in the measured distributions have a probability several

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orders of magnitude higher. For the distribution in Fig. 4a, this means that the measured velocity increment of about 6.6 m/s in $\tau = 3$ s occurs in the free field 10^7 times more frequently than would be expected from a Gaussian distribution. As a result, the standard models used by industry allow us to expect such an event only after several tens of thousands of years, instead of a few days as measured! For a good functional description of these probabilities, readers are referred to the work of B. Castaing *et al.* [5].

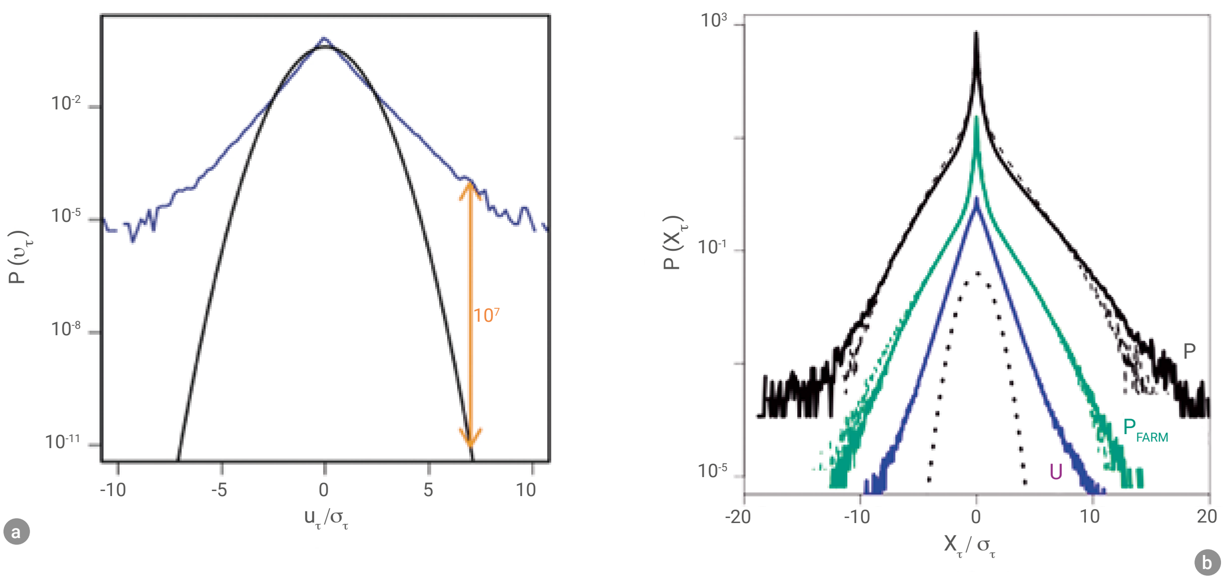
We can therefore conclude that the operating conditions of wind turbines are characterised by highly intermittent turbulent flows. These intermittencies, with their abnormal statistics and frequent extreme values, are reflected in fluctuations in the output power of turbines and even wind farms [3] (Fig. 3b).

It is therefore important to understand flow effects, load effects, control systems and grid integration as a function of turbulent statistics.

The fact that the consequences of turbulent intermittency are not taken into account in standard wind models does not mean that wind turbines do not operate efficiently. But a fairly large proportion of the costs of wind power is due to maintenance and repairs for "unexpected" failures, which seem to be linked to the intermittent structure of wind fluctuations [6].

This suggests that current turbines, which were designed without knowledge of actual operating conditions, and with insufficient estimation of safety factors, can be improved. Innovations should be based on a more accurate description of wind turbulence, including gusts. Another important aspect would be the aggregation of wind gusts or other special operating conditions, which would require the description of turbulence to be extended beyond two-point statistics, such as increments, to multi-point statistics. This requires new methods for which partially valid foundations already exist in nonlinear dynamics and statistical physics [7].

For more details on these fundamental issues, which are of great importance for the design and manufacture of wind turbines, we refer the interested reader to the authors' articles [3, 7].



3. Probability distributions.

a) In blue, measured probability distribution $P(u_\tau)$ of speed increments in semi-logarithmic representation, for $\tau = 3$ s; in black, corresponding Gaussian (parabolic) distribution. The 7σ event marked by an orange arrow corresponds to a change in wind speed of 6.6 m/s in 3 seconds. The abnormal probability statistic measured is a consequence of intermittent small-scale turbulence and determines the gusty character of the wind.

b) Probability distributions of wind speed and power increments for a single wind turbine (u) and a wind farm (FARM), here $\tau = 8$ s. The dashed curves are the results of stochastic modelling according to [3]. (The distributions are shifted vertically for clarity)

© Christian Steiness / Vattenfall (Horns Rev Offshore Wind Farm, Denmark).

4. ***Offshore*** **wind farm, where local weather conditions led to condensation revealing part of the turbines' wake.**

statistics, if a large amount of wind power is fed into the grid in a surrounding area of around 100 km [8].

Today, even if the European electricity grid is capable of operating with a high percentage of renewable energy, such as it was the case on 14 March 2021, with 25% renewable energy, and even in some countries with more than 50% wind power (see https://cutt.ly/windeurope_archive), the simplistic assumption that the turbulent energy production of individual systems averages out (i.e. follows the law of large numbers) is not true. Even fluctuations in wind power generation for the whole of Germany follow turbulent statistics, as shown by M. Anvari *et al* [9], and as is also the case for photovoltaics, which is even more intermittent. Clouds and their shading effects also reinforce turbulent structures.

More than a single wind turbine

In addition to the aerodynamic interaction between the fluid and the structure, there are other key issues to consider. First of all, there is the issue of mutual interactions within a wind farm, followed by the no less crucial issue of their integration into an electricity grid.

Since new wind turbines are almost exclusively installed in wind farms, the wind conditions in these farms take on great importance. The turbulent wake of one turbine strongly influences its neighbours (Fig. 4), so knowledge of turbulent interactions is of crucial importance.

However, despite extensive research, the wind conditions that are important in a wind farm are still far from well understood. This is partly due to the lack of high-quality measurement data: there are virtually no measuring masts equipped with high-resolution sensors in wind farms. At present, attempts are being made to use Lidar methods to measure the wind flow at different locations in a wind farm. Another approach is to use complex simulation methods to calculate this flow.

Interaction with the electricity grid, *via* generators and transformers, is a complex and topical issue that must also be considered in conjunction with the integration of photovoltaic solar energy. In the fourth part, the reader will find an article by G. Sapy (p. 135) specifically devoted to this crucial problem of the stability of electricity grids with a high proportion of intermittent renewable energy. In any case, fluctuations in wind and solar power are creating a new type of dynamic in the electricity grid. Weather maps show that atmospheric turbulence occurs hundreds of kilometres away. So there are many different aspects to grid integration. Currently, an effective solution for automatic control of grid frequency is provided by the inertia of rotating machines to smooth out fluctuations. This makes it possible to observe a variable frequency on a European scale at each electrical outlet, as shown in Figure 6 (see for example www.mainsfrequency.com/). It is probably because of this effective control that little is known about the actual statistics and their extreme values. By analysing these frequency data, we can see that the frequency increment for a time step of less than a second shows intermittent

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Power fluctuations caused by fluctuating renewable energies can lead to instabilities in the grid, which can result in a *blackout*. The typical properties of electricity networks are currently being studied intensively using coupled oscillator models (Kuramoto models) and certain network structures [10].

In this modelling issue, the multiscale aspects represent a major challenge. Already, in the numerical simulation of wind turbulence, the fundamental problem is that not all the relevant scales can be represented and that we need to rely on methods that enable bridges between scales to be established.

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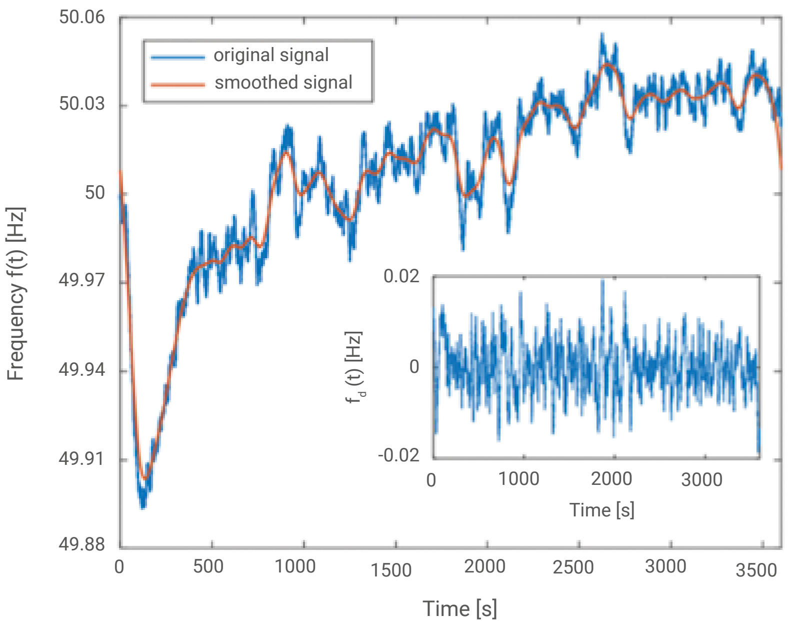
Conclusion

Although wind turbines have been built for centuries, there are still physical challenges to be overcome, as this contribution points out. Three main challenges must be stated here, a personal opinion of the authors:

1) Wind turbines, which are the largest turbulent flow machines in existence, have to manage operating conditions that are unknown in detail;
2) The construction of wind turbines must be carried out in the spirit of mass production (thousands of units), a novelty for such large machines;
3) the transition to a new energy system will involve wind power; but wind turbines, like any other electricity system, must be built by consensus with community participation .

Finally, for a much broader description of the challenges of wind energy research, we refer to the studies by G.A.M. Van Kuik *et al* [11] and P. Veers *et al* [12].



5. Example of the temporal evolution of the power grid frequency measured in Northern Germany over a period of one hour, with a resolution of 200 ms. Extracting the trend makes it possible to isolate the behaviour of the signal on small time scales. The initial peak observed is caused by a reaction to energy calls. The original frequency signal is shown in blue; the orange line is obtained after smoothing by weighted averaging over a sliding window of typical width 30 s. Inset: the signal obtained after subtracting the trend [8].

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