Understanding the wind

Every year, Germany produces more energy using wind turbines. This development poses many challenges – from selecting the right materials to ensuring the stability of electrical grids. The conversion of atmospheric kinetic energy into electricity begins with the wind, a constantly fluctuating energy source. At the University of Oldenburg's ForWind Centre for Wind Energy Research, scientists are working intensively to gain a better understanding of the continuously changing air flow

The rotor blades in wind farms turn majestically and seemingly at a constant speed in the airflow – here in a wind park near Emden. But the installation's output can double or halve within seconds.

The eternal wanderer, the dragon with a thousand tails, the swirling dancer: the dynamic nature and power of the wind has inspired many pretty metaphors over time. But what makes atmospheric air flow so fascinating to poets is an on-going problem for physicists and meteorologists: the motion of air in the first 200 metres above the ground is so variable that it is virtually impossible to predict it using equations, approximations and model calculations.

"The physics of wind as an energy source still hasn't been adequately researched," says Prof. Dr. Joachim Peinke, a turbulence researcher at the University of Oldenburg's ForWind Center for Wind Energy Research. Although equations that describe the behaviour of the atmosphere's air flow exist, even the world's most high-performance computers can't solve them accurately. The turbulent boundary layer close to the ground is simply too chaotic: wind speeds vary not just over days, months and years, but within minutes and seconds. A gentle breeze can be followed by a sudden squall which then subsides as quickly as it came. Some air vortexes are as large as continents, others as small as a mosquito. Obstacles such as mountains, forests and buildings change air flow in unpredictable ways.

This volatility poses a major challenge for the green energy transition. In 2018 wind was the second most important resource in the German power mix after lignite, providing 20 percent of the country's electricity. But it is far more difficult to plan electricity generation from wind energy than from fossil fuels. "In the quest to make optimum use of wind as an energy source we face various constraints" says Peinke.

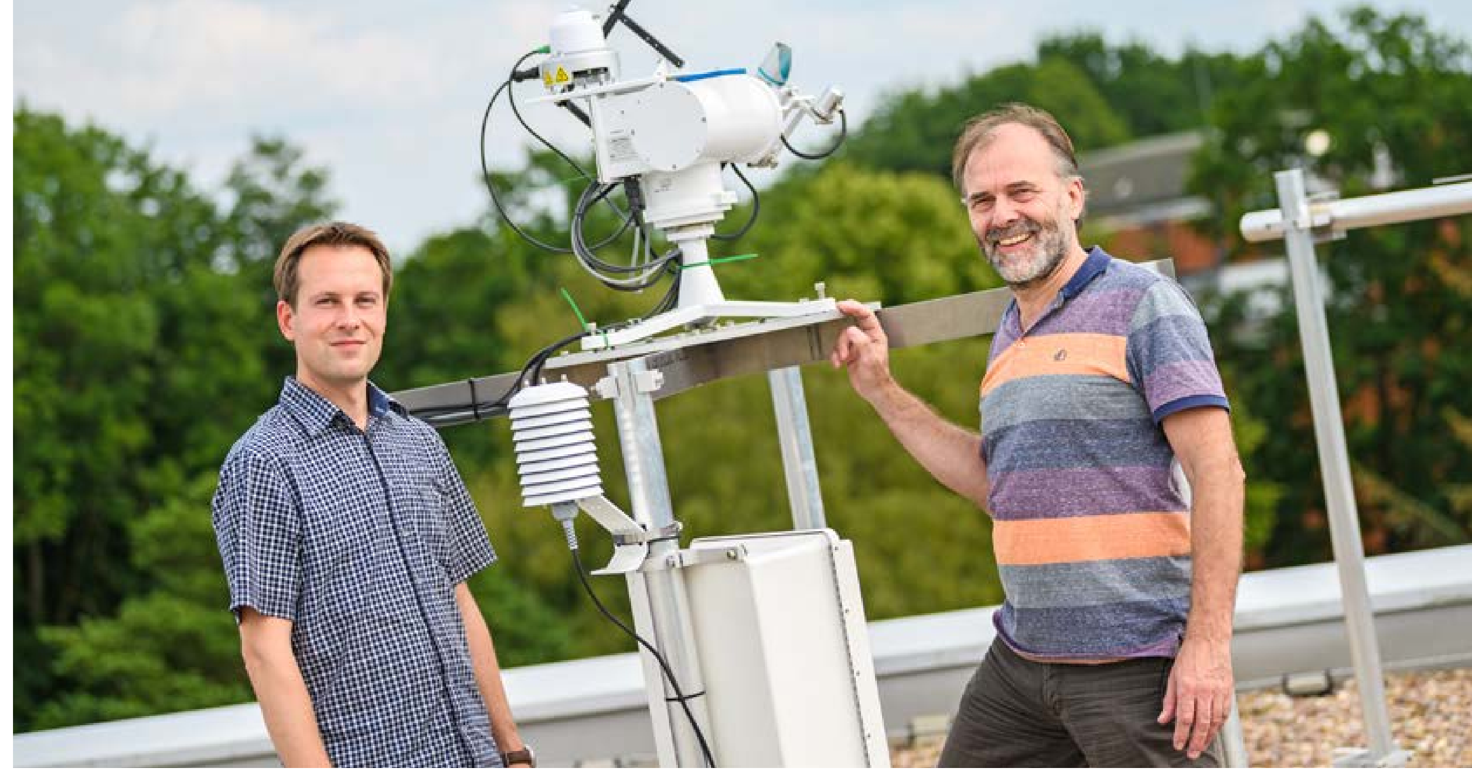
The scientists at ForWind are working to improve their knowledge of the wind in order to make wind-based electricity generation more reliable and plannable. Peinke, a renowned turbulence researcher, is among these scientists. He and his research group Turbulence, Wind Energy and Stochastic (TWIST) are trying to decipher the properties of the wind using complex mathematical methods. In addition, a team of energy meteorologists led by Dr. Detlev Heinemann measures and predicts wind flow at wind farms and across larger areas.

An atlas for wind power

Wind resource assessment plays a key role in the planning of wind farms. Until now project developers have had to rely on data from the 1980s that produced viable results only for flattish terrain like northern Germany. In the kind of hilly or mountainous terrain where a growing number of new wind farms are now being built this model has failed. This means that until now there has been no way to reliably predict the energy yield of wind farms located outside flat terrain. Again and again, wind farm operators have ended up in financial difficulties due to planning errors. "If you make a rough calculation of the yields and the average wind speed differs from the estimate by just 0.2 metres per second, it can cost a large wind farm with 50 turbines up to five million euros – per year!" Heinemann explains.

Since June 2019, however, planners have had access to better data: the New European Wind Atlas (NEWA) now provides accurate information on wind strength at any location within the European Union as well as the North and Baltic Seas in the last thirty years. Heinemann and his colleague Dr. Björn Witha were key participants in this international project, which had a budget of approximately 13 million euros. "Our goal was to provide detailed, long-term data about the wind climate across Europe," says Witha.

Joachim Peinke (here in front of the active grid in the large wind tunnel of ForWind) uses statistical methodology to research the qualities of the wind.



Energy meteorologists Björn Witha (l.) and Detlev Heinemann characterise the wind using weather research methodologies.

Launched in 2015 and led by the Technical University of Denmark in Roskilde, around thirty institutions from eight countries participated in the mammoth project. The objective was to create a virtual grid with a three-kilometre grid spacing that spanned the entire continent, and to generate complete time-series wind datasets for the last 30 years at each node. Users would, for example, be able to call up data on the average wind speed, maximum wind speed or temperature for any given day – for heights between ten and 500 metres above ground and 30-minute intervals. For an even tighter network with a grid spacing of 50 metres, the goal was to provide at least statistical data on variables such as the frequency of specific wind speeds and directions.

The researchers had to make all these calculations on their own. They did this using a computer model commonly used for weather forecasting into which they fed the relevant weather data to determine the values at the nodes. "We couldn't just press a button and start calculating; we had to do extensive preparatory work," says Witha, who was largely responsible for designing and coordinating the tests. The team tested different versions of the model to determine the optimum configuration. The researchers also examined how the selection of different physical parameters affected the results and compared the results with measurements made during four measurement campaigns conducted specifically for the project at several test sites.

Most of the preparatory model calculations were performed on the University of Oldenburg's high-performance computing cluster, which has specifically been made available for wind energy research. For the simulations which ultimately provided the data for the Wind Atlas, the team resorted to the even greater computing capacity of the Mare Nostrum supercomputer at the University of Barcelona. Even so, the calculations took more than half a year – a standard PC would have needed around 1,600 years to complete this task.

The Wind Atlas's new website now offers free access to interactive maps, time-series and wind-speed statistics, and other relevant parameters for wind power. "The scope and resolution of NEWA are unique," Witha says. After publication the data quickly started generating a lot of attention, he adds. There are many interesting things to discover – for example that the wind blows less in cities like Oldenburg than in the surrounding area, that the Brocken in the Harz mountain range is the windiest location on the German mainland, and that there is almost no wind at all in the Po Valley in northern Italy. Consulting engineers can use the website to gather all the data they need to plan a wind farm. And government authorities, farmers and water sports enthusiasts also benefit from the information it provides.

Information for farmers and authorities

As well as large-scale flow patterns and long-term average values, small-scale air turbulences also play an important role for wind power. "Wind structures of just one metre in size determine which local forces act on a wind turbine," turbulence researcher Peinke explains. An airplane taking off in a heavy storm encounters the turbulent layer of air close to the ground only during take-off and landing, while for the rest of the flight wind currents will generally be calm. "But for wind turbines, turbulence is a permanent state," says the researcher. This places tough demands on materials – especially as wind turbines have grown dramatically in recent decades. Whereas back in the 1980s rotor blades were typically just seven to eight metres long, today they are around eighty metres long, surpassing the wingspan of an A380 aircraft. To keep weight down, many components are designed to function at the limits of their capacity. "If rotors were still made out of metal, as they were in the 1980s, they would break under their own weight," says Peinke.

Manufacturers use turbulence models to calculate the forces a turbine must withstand. But small-scale turbulences in particular are difficult to predict. "There are so many local fluctuations in the wind that surprises are not rare," says Peinke. To learn more about the mysteries of turbulence he and his colleagues use complex mathematical methods to study, for example, how best to characterize small-scale fluctuations, or whether properties exist that are common to all turbulent flows. Here they look into questions such as how much small-scale turbulences depend on the structure of the large-scale flow from which they emerge, or whether details such as the duration or stability of a wind gust depend on environmental conditions.

Peinke's research group also carries out experiments in the ForWind Research Center's purpose-built, 30-metre wind tunnel. Inside the tunnel a one-of-a-kind grid with almost a thousand movable, diamond-shaped aluminium blades creates natural wind fields, including large and small turbulences. "The great thing about the wind tunnel is that, unlike in nature, we can repeat certain turbulence patterns to see what impact they have on model systems," explains Dr. Michael Hölling, a colleague of Peinke who is responsible for the wind tunnel.

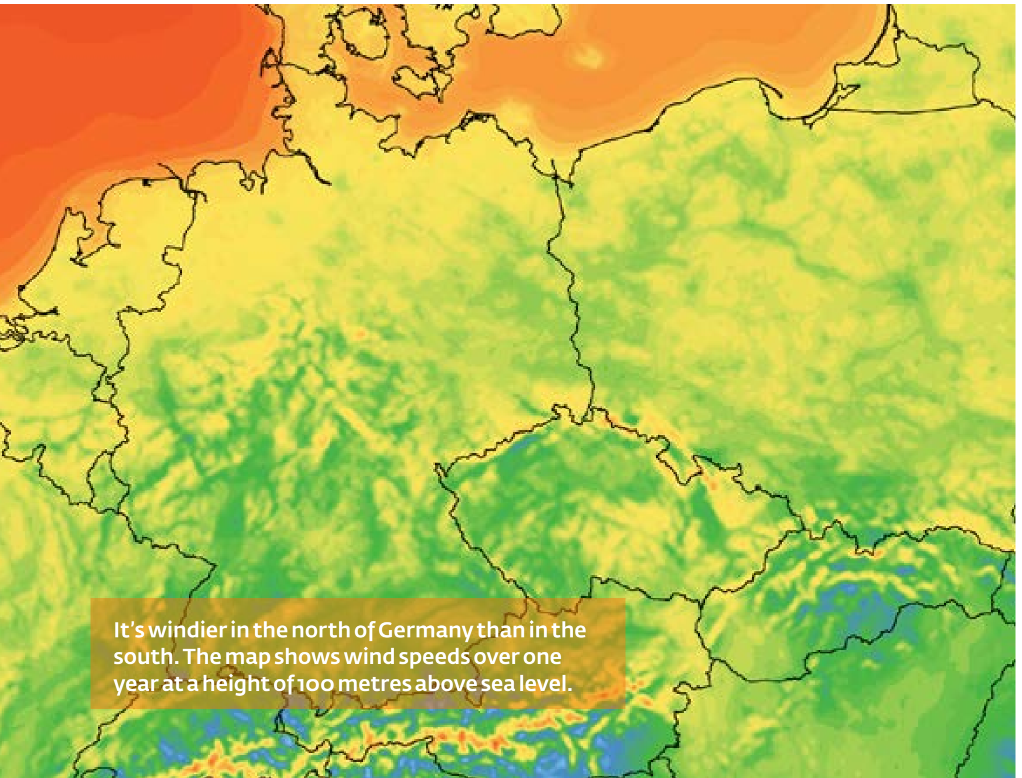
Statistics offers another possibility for analysing the properties of flow patterns. Peinke and his research group study physical parameters such as turbulence intensity in air flows and wind speed distribution in order to deduce general rules. In a scientific publication from 2012, the team demonstrated that a special statistical principle applies for wind gusts: extreme fluctuations in wind speed occur far more frequently than the statistics currently used by industry suggest, meaning that in some cases the frequency of extreme events is drastically underestimated. "An extreme event that – according to the Gaussian statistics applied to date should only occur once every 1,250 years – actually occurs once every hour," Peinke explains. The scientists were also able to establish that this property of the wind, known as intermittency, is present at all stages of the process of converting wind energy into electricity, from the forces acting on the turbine to the electricity generation process. By comparing measurement data the team established that all these variables fluctuate just as much as wind speeds do. "For example the amount of power generated by a wind turbine can increase or decrease by fifty percent within seconds," Peinke explains.

Fluctuations in the power grid

Gusts of wind and whirlwinds that occur locally without affecting all the turbines in a wind farm or a larger area still have an impact on the power grid as a whole – and in particular on the grid frequency, as a team led by Peinke and his PhD student Hauke Hähne demonstrated in a paper published in 2018 in the science journal Europhysics Letters. The researchers studied the oscillations of the AC voltage in the regional power grid over a period of four-and-a-half months. "The mains frequency indicates the current ratio of electricity production to consumption, and is thus a stability parameter," explains Peinke. If several megawatts of wind power are suddenly fed into the grid without consumption rising at the same time, the frequency changes. If it deviates too much from the desired value - 50 hertz, or 50 oscillations per second - within a few seconds a control mechanism intervenes to ensure that the power grid remains stable. Minor fluctuations are automatically compensated for by rotational inertia in large power stations.

To find out how gusts of wind and other turbulences affect this interaction, the team made 10,000 measurements per second of the frequency, allowing the researchers to record fluctuations on very small timescales. Their analysis showed that the phenomenon of intermittency is also present in the grid frequency: its fluctuations obey a statistical law similar to that which governs wind speed distribution, with relatively large fluctuations occurring far more frequently than expected. The researchers also discovered that the more wind energy was fed into the grid within a given period, the more frequently strong fluctuations in frequency occurred. "This suggests that the fluctuations in wind power caused the fluctuations in frequency," says Peinke. The documented frequency fluctuations were so small that they didn't pose a threat to the power grid. But in the future, if the proportion of renewable energies in electricity generation increases, the fluctuations could increase. The observed probability distribution can help scientists to correctly identify risks and develop control strategies, Peinke explains. "It's essential to have a precise knowledge of the fluctuations in order to be able to correctly assess the probability of large, potentially critical fluctuations."

Solar energy is even more disruptive for the power grid than wind energy: "On days when the sky is alternately cloudless and cloudy, solar power systems switch on and off repeatedly within very short periods," says Peinke. Such episodes are particularly likely to destabilise smaller subnetworks, which are expected to multiply as the energy transition advances. In 2017, a team of ForWind turbulence research and energy meteorology scientists working in collaboration with electrical engineers from the Clausthal University of Technology published a study in the science journal Solar Energy. It provides a mathematical description of the erratic nature of solar energy. In their paper the researchers present a method for deriving parameters directly from a measured time series that describe the stochastic – i.e. random – properties of solar power. Network operators could potentially use these parameters to develop an algorithm to filter out and suppress dramatic fluctuations. Batteries, capacitors and inverters with just a few percent of the installed capacity can be used to stabilise microgrids, including those running on a high proportion of renewable energies, Peinke points out.



It's windier in the north of Germany than in the south. The map shows wind speeds over one year at a height of 100 metres above sea level.

Word is now spreading in the wind energy sector that the complex challenges of wind energy can be tackled using statistics and turbulence research. Peinke is currently preparing a project for monitoring the condition of wind turbines using statistical data analysis. "We want to develop a kind of wind turbine doctor," says Dr. Matthias Wächter, who runs the project. Each wind turbine contains hundreds of sensors that monitor numerous parameters, from the oil level of the generator to the bending moment of the rotors. "Because the turbines wobble constantly, the data is very noisy and so far hardly anyone has been able to do anything with it," explains Peinke. He and his team now want to work with computer scientists to evaluate and analyse these mountains of data using big data technologies. They aim to extract information from the noise such as whether everything is running smoothly or whether certain components of a system, for instance the motors, are showing signs of fatigue and need replacing.

Particularly in the case of offshore turbines, which are difficult to access, it would be useful to be able to better plan maintenance work so that it can be carried out when the wind is low. "The costs for outages and maintenance work account for a significant proportion of wind energy costs," stresses Peinke. "To reduce these costs, it will be necessary not only to increase the efficiency of wind turbines, but to understand them better - so that they can operate maintenance-free even in turbulent times." (uk)