WIND FARMS WITH BEST EFFICIENCY

Wind turbines belong at locations with good wind, that goes without saying. In order for the wind to be converted into a good electricity yield, wind turbine operators must take numerous factors into account. In the future, powerful computer models of wind flows could help to further improve the energy yield when planning and operating power plants. Such models are being developed by a research team at the Swiss Federal Institute of Technology in Lausanne (EPFL) headed by Prof. Fernando Porté-Agel. When planning wind farms, they help to position the wind turbines where the wind is strongest and interaction with other wind turbines is minimal.

A snapshot of a special kind: Due to special weather conditions, the wake of the wind turbines in a Danish offshore wind farm becomes visible through condensation. Photo: Vattenfall/Christian Steiness

A technical report about the results of a research project in the field of wind energy, which is financially supported by the Swiss Federal Office of Energy. The report has been published in the technical magazine ET Elektrotechnik (issue August 2020).

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2019 was an excellent wind year: The 37 Swiss wind power plants were able to report a record yield of 146 million kWh of electricity, which corresponds to the electricity requirements of around 50,000 four-person households. The wind yield was thus 20% higher than that generated by the same number of wind turbines in the previous year. This figure only highlights what people know from their everyday experience: The wind blows differently strong in different periods, so it is only logical that the production of wind turbines is also subject to considerable fluctuations.

This does not mean, however, that the production yield of wind power plants cannot be predicted at all. The electricity yield for a few days can be predicted on the basis of weather or wind forecasts and can also be estimated in the longer term. However, these yield forecasts for wind turbines are not sufficiently accurate. After all, wind is an extremely complex phenomenon, especially in uneven terrain. In addition to wind strength and direction, the location of a wind turbine influences its yield: hills, trees or buildings deflect the air flow and influence the wind speed and the extent of turbulence at different altitudes. In addition, changes in temperature on the ground and during the course of the day influence wind speed and turbulence.

Combining experiments with simulations

Scientists at the Ecole polytechnique fédérale de Lausanne (EPFL) aim to describe wind flows in the best possible way. In the Wind Engineering and Renewable Energy Laboratory (WiRE), they have set up a wind tunnel in which they study air flows under controlled conditions on miniaturised wind turbines and wind farms. They also carry out measurements on wind turbines in the field and develop computer simulations to realistically simulate wind flows.

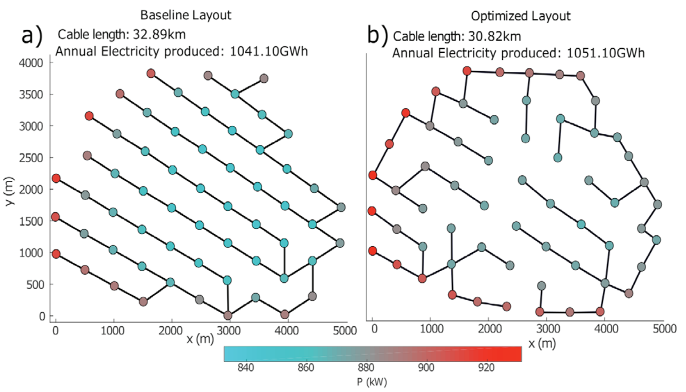
In a project supported by the SFOE, which was completed at the end of 2019, scientists led by Prof. Fernando Porté-Agel have been searching for the optimal design and operation of wind farms. Design in this context means the arrangement of the individual wind turbines within wind farms. The aim is not only to find the best position for the wind turbines in the landscape, the design process also takes into account the interactions between wind turbines. Although wind turbines are located several hundred meters apart, the wake flow behind the turbines is slowed down. This reduces the yield of the wind turbines behind them. In extreme cases, these losses can amount to up to 20% of annual production. In addition, turbulence is created in wind farms, which places mechanical stress on the rotors and causes them to age more quickly.

Fernando Porté-Agel is Director of the Laboratory of Wind Engineering and Renewable Energies (WiRE) at EPFL, whose central research facility is a wind tunnel. Photo: B. Vogel

Maximising the efficiency of wind farms

The Lausanne researchers want to prevent both negative effects as far as possible. To this end, they are creating computer models that describe the air flows around wind turbines more accurately than before. These predictions can be used to improve the design and operation of wind farms. "With our methods, we can not only improve the yield of wind farms, but also reduce their costs and thus increase their profitability by several percentage points. In today›s world, where climate change has become an urgent problem, our work can help accelerate the transition from fossil to renewable energies by making wind energy more competitive," says EPFL Professor Porté-Agel.

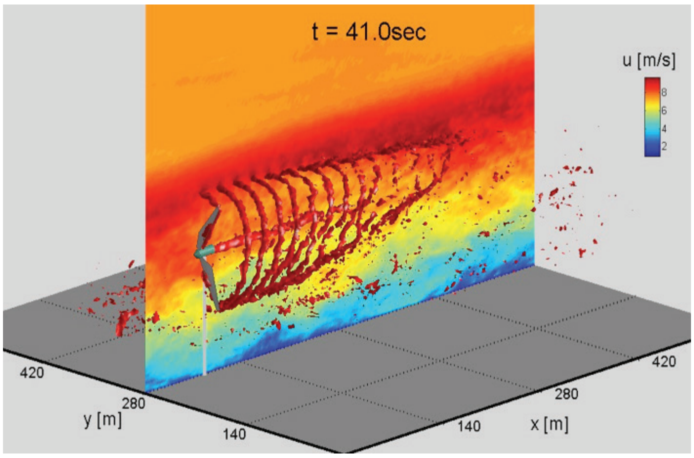
Simple computer models (known as ‚analytical models') are now available to model wind flows, as well as complex models such as Large Eddy Simulation (LES). The latter is more accurate, but requires more computing power. If you want



Example of a wind farm layout (dots = wind turbines; lines = cable connections): The improved arrangement of the wind turbines (right) was achieved with the analytical flow model of EPFL. The optimized layout improves the performance of the wind farm and at the same time reduces the length of the cable connections to access the wind turbines. Graph: WiRE

to model the behaviour of entire wind farms with LES, even supercomputers can only do this with lengthy computing operations.

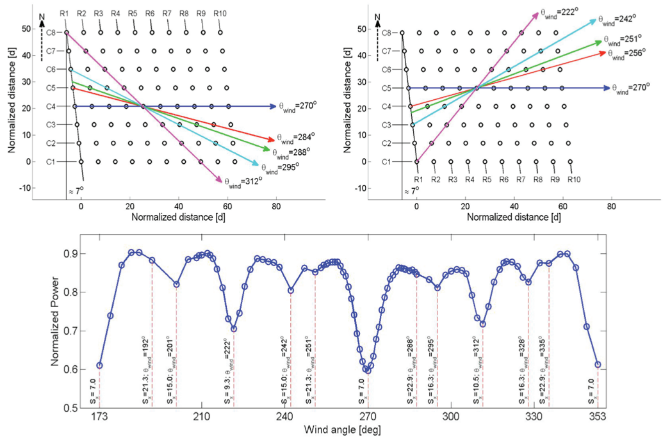
Scientists therefore resort to a trick: they use complex models and experiments to validate simple (‚analytical') models and improve their accuracy. "The new generation of analytical models deliver predictions of reasonable accuracy in a short time," says Porté-Agel. "Within the SFOE project, we have been able to improve both complex and simple models for wind turbines".



Large-Eddy-Simulation (LES) shows the three-dimensional vortex structure and the wind speed in the vertical plane of a wind turbine (concrete: a Vestas wind turbine with 112 m rotor diameter). Simulations of the LES type are particularly realistic in mapping turbulence. The simulations require very powerful computers. Simulation: WiRE

Targeted control of wake flow

If the models are to describe reality as accurately as possible, the scientists have to incorporate data from field measurements at existing wind turbines and from experiments in the wind tunnel, where the real conditions are reproduced on a scale of 1 to 1000. In the future, the models from the WiRE laboratory at EPFL should help to estimate the yields of wind turbines and wind farms more reliably than is currently possible. The models also provide important support during



The graph below illustrates the output of the wind farm shown above, consisting of eight times ten wind turbines, depending on the wind direction. A significant loss of power of around 30 percentage points occurs at an angle of attack of 270 degrees (frontal flow to the wind farm), which means that the wind turbines set back suffer a maximum loss of power. Such large power fluctuations are undesirable because they make the grid integration of wind farms more difficult. Graph: WiRE

OLIVE OIL MAKES THE WIND VISIBLE

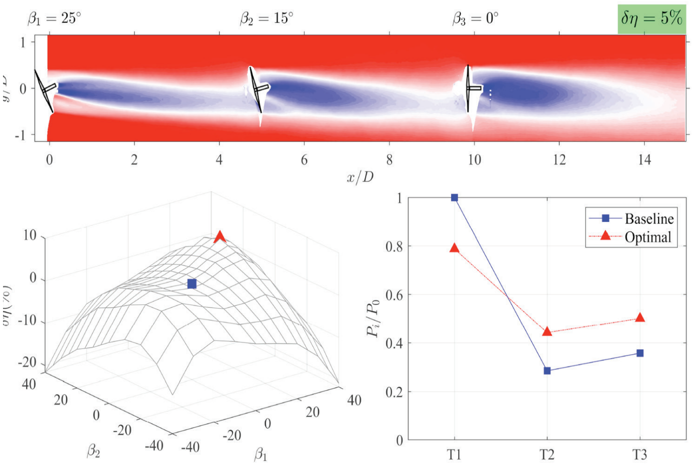
In the EPFL wind tunnel, a boundary layer of airflow with a thickness of 50 cm is generated over a 28-meter long test section. Here, wind turbines can be examined under different surface conditions. The turbulent boundary layer is a scaled-down replica of the wind conditions as they prevail on the surface of the Earth. In order to make the flow behaviour of the air visible, olive oil particles of one micrometer diameter are sprayed in the air. A laser makes the droplets glow so that they can be photographed by several cameras and followed along their path. This allows air currents to be measured with high resolution. Alternatively, bubbles filled with helium are used; they are larger than olive oil droplets and more suitable for three-dimensional flow measurements.

Thanks to its special design, the EPFL wind tunnel can simulate thermal effects that influence the performance of wind farms. In order to realistically reproduce the thermal effects of the atmosphere, the ground temperature can be controlled on the test section and 16 layers of air at different temperatures can be created in the wind tunnel. Part of the thermal control system are pipes, filled with liquids of different temperatures. To ensure that the thermal effects in the wind tunnel are similar to those in the lower atmosphere, the difference between the coolest and warmest air layer in the wind tunnel can be up to 120 degrees.

The measurements are carried out on wind turbines of about 20 cm in size, which are placed inside the wind tunnel. It is not enough to reconstruct a real wind turbine on a reduced scale in detail. Rather, the rotor of the small wind turbine must be specially designed so that it extracts the same percentage of energy from the wind as its big brother. BV

operation: they make it possible to develop innovative control systems for wind farms, which can be used to minimize the negative effects of wake flow such as power losses and fatigue load in wind farms. This supports maintenance and reduces costs.

A control strategy tested in the WiRE laboratory is called active yaw control: By actively turning the rotor out of the direction of the incoming wind, wind turbine operators can influence the wake (see text box p. 5). By cleverly controlling the rotors, the flow can be deflected in such a way that the negative influence on the downstream wind turbines is reduced. Wind tunnel experiments and computer simulations in the WiRE labs have shown that active yaw control can increase the yield of wind farms by up to 20% (based on the most unfavourable wind directions). The Lausanne research



Without yawing (tilting) of the front wind turbine, the wake flow would hit the rear wind turbine head-on and dampen its power production. The yaw of the front wind turbine can deflect the wake flow and control it in such a way that the power output of the rear wind turbine is increased. Experiments in the wind tunnel have shown that the power increase by means of active yaw control depends on the number of wind turbines. With a series of three turbines, the power output can be increased by 5%, whereas with five wind turbines an increase of 20% is possible (compared to a base scenario with an unfavourable arrangement of the wind turbines). Graph: WiRE

helps to develop the best control strategies for wind farms. In this way, the yield of wind power in wind farms can be further optimised.

- **Information** on the project can be obtained from Lionel Perret (lionel.perret[at]planair.ch), head of the SFOE Wind Energy Research Programme.

- Further **technical papers** on research, pilot, demonstration and lighthouse projects in the wind energy sector can be found at www.bfe.admin.ch/ec-wind.

210 SCENARIOS

The researchers have run through 210 scenarios in the EPFL wind laboratory to investigate how the yield of a wind farm varies when the yaw angles of the individual wind turbines are changed. Three strategies for controlling the yaw angle were of particular interest: If yaw control was applied only to the forwardmost turbine, which is the one the wind hits first, the efficiency of the wind farm in the most unfavorable wind direction could be increased by up to 4%. In the second strategy, the same yaw angle was applied to all turbines except the rearmost one. In this case, efficiency increases of up to 12% were achieved, not least due to the higher yields of the last turbine. The third strategy was to maximize efficiency by systematically adjusting the yaw angles. It was found that the efficiency can be increased most when the first wind turbine has a relatively large yaw angle, which tends to decrease for the turbines behind it and approaches zero for the last turbine.

In the ‚Journal of Renewable and Sustainable Energy' the scientists around Prof. Porté-Agel summarized their findings as follows: "In general, the most optimal yaw angle distributions tend to homogenize the power distribution within the wind farm by decreasing the first turbine power and increasing the power generated by downwind turbines." And: "The maximum achievable power enhancement via yaw angle control increases linearly with the number of turbine rows even though this increase is expected to reach an asymptotic value for large wind farms." BV

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Version: September 2020