

The Power Grid's Got Rhythm

New forms and sources of energy need new power lines as well. In the future, a larger number of small, distributed wind and solar installations in place of a smaller number of large power plants are projected to supply Germany with energy. At the **Max Planck Institute for Dynamics and Self-Organization**, the Network Dynamics Group headed by **Marc Timme** is investigating how the high-voltage grid will respond to this and how it can be optimized.

TEXT **TIM SCHRÖDER**

Wind turbines in the German state of Schleswig Holstein already produce almost half of the power consumed there. If the proportion especially of distributed regenerative power stations grows, the transmission grid must adapt as well.



Many people abruptly became aware of just how delicate a large power grid can be when the lights went out around 10 p.m. on November 4, 2006. The outage didn't affect just televisions and light bulbs – it also took streetcars offline, even in distant Austria. All of this happened even though just one single power transmission line in northern Germany had been shut down – the 380-kV Conneforde high-voltage line over the Ems River.

A huge new transoceanic liner was on its way from the shipyard in Papenburg to the North Sea; a ship so tall that it came dangerously close to the overhead transmission line. The power was turned off as a precaution – with fatal consequences: pressing the off switch turned half of Europe upside down because the grid operators hadn't properly coordinated how to compensate for the loss. In the end, distant regions in Germany, France, Belgium, Italy, Austria and Spain were without power for several hours.

Power grids are incredibly complex and aren't completely understood, even today. Of course, there are a lot of safety features that normally prevent power outages. Still, the example of the Conneforde line shows that it sometimes takes just one misunderstanding for the world to come to a standstill. The power grid will become even more complex in the future, with the expansion of renewable energy. New wind parks and solar parks are developing and need their own lines connected to the European integrated network. For the North Sea alone, there are hundreds of wind power installations planned, which are set to deliver 20 gigawatts of power – as much as 12 nuclear power plants. Critics are afraid that the massive expansion could weaken the power grid.

To understand these concerns, it helps to take a look at the physical foundations of our power system. The European integrated network operates

Second try. On November 7, 2006, the "Norwegian Pearl" (right) was towed from the shipyard at Papenburg along the Ems River to the North Sea after a first attempt a few days before was aborted: it had led to a power outage in broad areas of Europe because a transmission line over the river had been turned off as a precautionary measure. The grid operator has since raised the towers of the route (below).



with alternating current. This current pulsates in phase with the rhythm of power station generators. Electromagnets as tall as houses, yet just like those in a bicycle generator, rotate inside a copper winding. The current changes its sign 100 times per second: 50 times plus and 50 times minus, which makes a frequency of 50 hertz. All power station generators and large electric motors in Central and Western Europe rotate in close coordination with this frequency so that they operate synchronously.

MANY SMALL POWER PLANTS TO REPLACE A FEW LARGE ONES

Before power plants go online, their operators carefully adjust the generator frequency to match the 50-hertz grid frequency. If one power plant goes down, other power plants have to do

its job and are ramped up. However, since that takes some time, their generators initially slow down in order to keep the power level up. As a result, the grid frequency falls slightly. If one line goes down, other lines must take over its load – and must themselves not be permitted to collapse, causing a blackout. In addition, the frequency in various regions of the network can drift apart due to a line breakdown. If the frequency varies too strongly, the network gets out of synchronization. Uncontrolled fluctuations and short circuits are the result. To prevent this, the system executes an emergency shutdown when it detects a frequency disparity; a power outage occurs.

Controlling the supply of power is thus a difficult process, but it has been worked out pretty well in the current German transmission grid – with the exception of the case of the Con-



eforde line. But will it work just as well in the power grid of the future?

The power grid today is oriented toward large, centralized coal- or gas-fired plants and nuclear power plants that supply primarily the surrounding regions with power. If more and more solar and wind installations are connected to this network, critics worry that it could become less stable. Their skepticism is not unfounded. After all, the power provided by wind turbines and photovoltaic installations fluctuates with the weather. But what the skeptics hardly noticed until now is that the network architecture will also change completely. The large power plants that serve primarily their immediate vicinity will be gone, replaced by many smaller, distributed power producers.

It could be more difficult to synchronize the frequency of their power outputs than to bring a few large play-

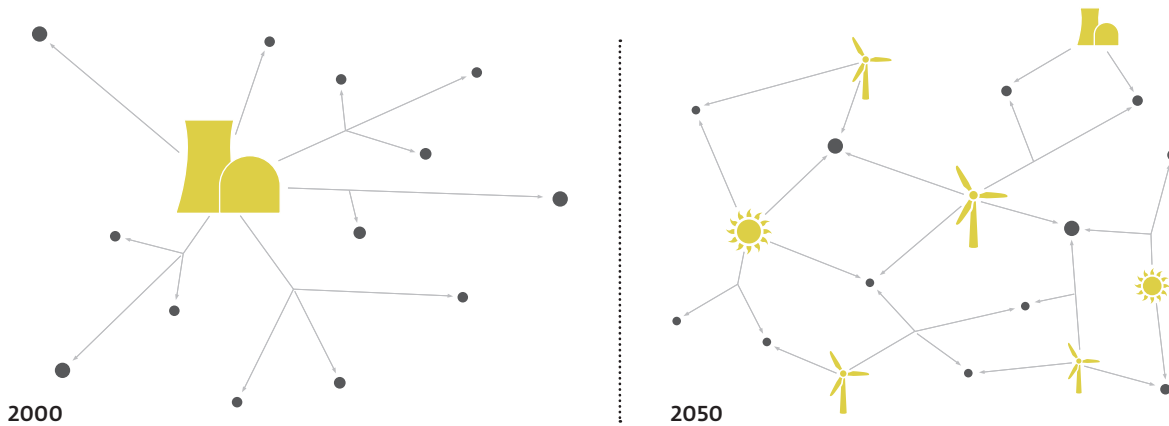
ers into a common cadence – the same way a cellist and pianist achieve a common rhythm more easily than a large orchestra. Large power plants will continue to come online, of course, but some of these will be powerful wind parks in northern Germany, whose power is also intended for use in the south of the country.

A DISTRIBUTED NETWORK IS MORE STABLE

A distributed network like this might not deliver power as reliably as we are accustomed to. That was at least a possibility that mathematicians and physicists from the Network Dynamics Group at the Max Planck Institute for Dynamics and Self-Organization in Göttingen began to consider. They are investigating how the new network structure and the fluctuating available

power will affect the stability of the electricity supply. Recommendations follow from this about how to make the network more robust for the transition to new energy sources.

The scientists working with Marc Timme began with the question of whether a power grid made up of decentralized power plants is more frequently threatened with power outages. This study of distributed networks also lays the groundwork for the working group to subsequently investigate how fluctuating power output affects the network. They established from their calculations that network instability wouldn't be as bad as one might imagine. Quite the contrary: the researchers compared various power grids with one another, from classic grids in which large nuclear or coal-fired power plants predominate, to those with many small-scale power plants. Their



Energy turnaround as a network problem: At present, large centralized power plants supply primarily their local area. In the future, small-scale distributed wind and solar installations will increasingly be taking over supplying power. This will result in a new network architecture that can be more stable and suffer fewer outages than today's structure – contrary to what many fear.

conclusion: a power grid is likelier to become more stable with the addition of smaller facilities.

Marc Timme and his co-workers thus filled a knowledge gap. For one, there were mathematical models for large power grids, though only abstract ones thus far. However, these models didn't include the dynamics of alternating current and the 50-hertz oscillations. They considered only the current flows, namely the transport of electrical energy. For another, although there were studies that took many of the processes into detailed account, they permitted predictions only for small networks with a few power stations and energy consumers. Statements about the larger whole were hardly possible with these models. It still isn't clear even today how the addition of renewable energy will affect the stability of large power grids.

In a novel theoretical study, the Network Dynamics Group connected more than 100 virtual power plants in a group and made mathematical predictions for this network. As a result, the scientists now better understand how robust such a structure is with regard to perturbations, like the failure of a large power station. The working group especially wants to find out how the addition of many new small-scale power plants, such as wind parks and solar installations, influences the dynamics of the network.

"When you tackle an analysis like this, you first have to use a simulation model to clarify certain basic ques-

tions," says Timme. For instance, in a network with a constant power supply and no line failures, can there be normal, stable distribution of power one moment, and a power failure the next? Say, when the power consumption fluctuates? Or even more subtle: when too many consumers demand power for equipment like electric motors whose alternating voltage isn't precisely synchronized with the power grid? And if this leads to a power failure, to what extent will this co-existence of stable and unstable conditions be influenced by the overall structure of the network – that is, by the capacity and location of the power stations, as well as the architecture of the transmission line system?

MINI POWER STATIONS LOAD DOWN INDIVIDUAL LINES LESS

To answer these questions, the team first did the calculations for the simplest conceivable network: the connection between one power station and one consumer. "Both stable and unstable states can actually be created, even here. Situations can arise in which the capacity of a power line is suddenly no longer sufficient, even if the power rating is the same," says Dirk Witthaut, a scientist in Timme's working group. Sometimes oscillations in the supply and demand for voltage that don't run completely parallel to each other are enough to cause a collapse of the connection. As it was shown, it is possible to use sample networks like this to es-

tablish under what conditions even large networks can become unstable.

These investigations still haven't answered the question of how stable a branched network with distributed mini power plants would actually be. "Strictly speaking, mathematicians differentiate between two terms – robustness and stability," says Timme. To test stability, researchers begin with a network having fixed connections and defined characteristics, for example a fixed number of power plants and constant power consumption.

Mathematicians test the extent to which this system remains stable when external disruptions occur – if, say, an aluminum factory that eats up power is suddenly shut down. Robustness, in contrast, provides information about how the system copes with spontaneous internal changes such as a power line outage – or the shutting down of a transmission line. Timme's working group investigated both attributes.

Here, too, the scientists first had to simplify. The team designed power grids in which power plants steadily produce power and consumers constantly absorb power. What is new is that Timme takes into account the frequency within highly branched networks, the oscillation of alternating current, and the dreaded frequency drift in various areas of the network. As an example, the researchers chose a power grid of the size of Great Britain and dominated by large power plants. One by one, they replaced individual major power plants with several small-

Large power stations will be built in the era of renewable energy as well, primarily wind parks in the North and Baltic Seas. Twelve offshore wind turbines from alpha ventus (top) located 45 kilometers (27 miles) north of Borkum have been producing 60 megawatts of power since 2009. Their power initially arrives on the coast at Wilhelmshaven through a 60-km underwater cable (center) as thick as an arm, laid with a special ship (bottom). In the future, wind parks like this will increasingly supply power to southern Germany, for which the grid architecture will need to be adapted.



scale installations. Then they sent power through the lines – sometimes more, sometimes less.

In the process, the scientists observed that a network with many small, distributed power plants remains synchronized just as well as the network that is still distributing power throughout Germany at present. And it even remains more stable. “In the distributed branched network, individual lines are loaded less,” says Witthaut. That makes sense, since the power in a network like this can search out alternative routes to the consumer when the output of the power plants is increased. If there is only one main line, it quickly becomes overloaded. As a consequence, a distributed network is fundamentally more capable.

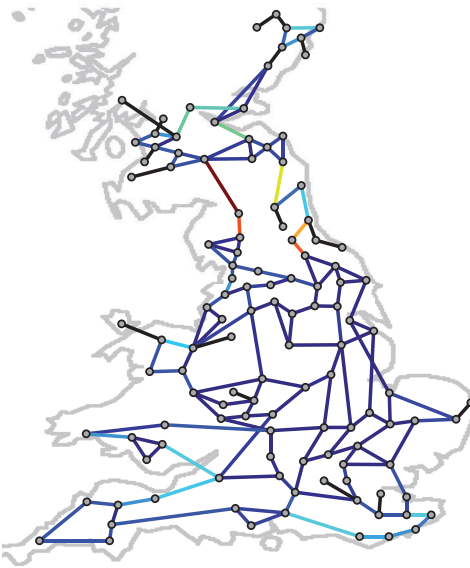
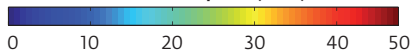
Of course the researchers didn’t do the calculations for just one power grid. They repeatedly varied the number of power plants using a random number generator, along with their positions and the interweaving of the power line routes. In this way, they showed that their assertions are valid not for just one power grid, but for all possible networks.

The calculations for robustness worked out just as clearly. The Göttingen-based researchers tested this by capping the individual power lines mathematically. As it turned out, there are considerably more critical power lines in a power grid where major power stations predominate – irreplaceable power cables that the stability of the entire network depends on. If these fail, a black out à la Ems can hardly be prevented. Their model showed that



How robust is the grid? Researchers in Göttingen used the British power grid as an example to calculate what happens when individual lines go down. If one of the blue connections is interrupted, a power outage over the entire grid is improbable. For the dark red routes, the probability of a total collapse is almost 50 percent.

Probability of a power outage if a connection is disrupted (in %)



the main lines between England and Scotland are especially critical. As the number of distributed mini power stations rises, the number of these critical lines falls significantly. "The distributed power grid of the future will be both more stable and more robust in the event of damage," says Timme.

NEW ROUTES CAN IMPAIR THE FLOW OF POWER

Up to now, no research group had been able to make such strong assertions. Danish scientists had investigated relatively simple networks – rings in which power stations and consumers were strung like pearls in a necklace. "However, these investigations didn't take into account the network effects that result if you join many of these rings with one another," says Timme. The England model does this thoroughly. In addition, the Max Planck researchers take into account the "non-linear dynamics" – the oscillation of the current.

Marc Timme and his colleagues carried the analysis of the power grid even further and found evidence of an effect that was previously unknown in the world of power generation: Braess' paradox. At the end of the 1960s, mathematician Dietrich Braess discovered that new traffic routes didn't necessarily improve traffic flow, but rather, to the contrary, can cause more congestion. This occurred when drivers were

able to follow alternative routes between A and B prior to the construction of the supposed shortcut. Bottlenecks along these stretches aren't so heavily loaded that they slow the traffic flow.

The new road now shortens the travel distance, so that all drivers suddenly take the same route. However, if the supposed shortcut connects the bottlenecks with one another in a disadvantageous way, and all drivers must now pass through these narrow spots, the traffic becomes congested there. The bottom line is that the drivers then have longer travel times than before the construction of the new road. For this reason, road planners, too, would do well to take Braess' paradox into account for new projects.

Dirk Witthaut and Marc Timme have now discovered that this paradoxical situation can also arise in power grids. "The paradox wasn't an issue with the old power grid because the power lines from major power stations primarily branched out radially in many directions," explains Witthaut. "In a modern, highly branched, distributed network with hundreds of circuits and connections, it becomes highly relevant."

In the power grid, in contrast, the oscillations are the main reason the paradox can arise. Alternating current can be imagined as a smoothly fluctuating sine wave. The phase of this wave can be different at various points in the

network – the voltages at these points may all oscillate with the same frequency, but rather than being in phase, they are shifted in relation to each other instead. In the present-day grid, this isn't necessarily noticeable, as the individual regions within it are largely centrally supplied. If the voltage of a power station in northern Germany oscillates slightly shifted in relation to the voltage of one in the south, it makes no difference because both supply primarily their respective regions and they hardly sense one another.

But the following situation can be a problem: In the power grid, numerous rings can be identified in which several nodes are connected with one another. If the phase of the alternating current from one station to the next is only slightly shifted in such a ring, that isn't a problem. All that matters is that this phase shift meets certain mathematical conditions in each circuit.

If a new direct line is now laid between two non-adjacent nodes in a ring, this supplementary connection should actually facilitate the current flow. However, it results in the creation of two additional rings in which the conditions for the phase shift must also be satisfied. But that doesn't always happen.

HOW DOES THE NETWORK DEAL WITH FLUCTUATING POWER?

"In physics, this phenomenon is known as frustration," explains Marc Timme. "The system is frustrated because it can't satisfy all of the conditions simultaneously." This leads to Braess' paradox: since the current now prefers to flow over the new shortcut, it essentially obstructs the rest of the network. Current flow is thus worse throughout the network than it was in the original power line system without the new route that is actually intended to improve the flow.



Marc Timme (left) and Dirk Witthaut develop mathematical methods to analyze the stability and robustness of the power grid with distributed power stations and a fluctuating power supply.

Dirk Witthaut illustrates Braess' paradox in the power grid with an image: "Instead of phase shift, imagine three people at a table, where each person has one domino piece inscribed with a one and a six. They won't succeed in placing the three dominoes in a circle so that every 'one' touches another 'one.' It just doesn't work."

The team carried out calculations for power grids according to Braess and demonstrated for the first time that the paradox also applies to these oscillating systems – and that even though it was originally formulated for traffic flow, a simple linear system. The conclusions of the working group are striking: approximately 5 percent of all newly connected links in the power grids that were investigated proved to be disadvantageous. They make the entire network less stable. "Braess' paradox really has to be kept in mind for future expansion of power grids to include an increasing portion of renewable energy sources," says Marc Timme. It could also be important when high-capacity routes connect the wind parks in the North and Baltic Seas to consumers in the south.

Thus far, Timme and his colleagues still haven't taken short-term fluctuations of wind and solar power production into account in their calculations. They want to do this now in coopera-

tion with researchers at Siemens in Munich and the Institute for Information Technology (OFFIS) at the University of Oldenburg. Yet the insights obtained so far already have a practical application – Marc Timme is certain of that: "Our

results already provide an important principle for guiding the operation of future networks, because the basic research we've already completed forms the foundation for operating a real network with fluctuations." ◀

TO THE POINT

- If power is soon increasingly obtained from regenerative energy sources, the architecture of the high-voltage grid will change: small-scale distributed power plants will replace large nuclear power plants that supply primarily their immediate vicinity. In addition, large wind parks in northern Germany will come online and must supply the south as well.
- Distributed expansion of the network will make the energy supply more stable because individual lines won't be as heavily loaded.
- New lines can destabilize the electricity supply if they connect points in the network where the relative phase of their voltage swings is shifted too much and the voltage swings are too far out of cadence. This disrupts the connection, which also affects other parts of the network.

GLOSSARY

Braess' paradox: If new connections are made in a traffic network or power grid, these can reduce the flow of traffic or the transport of power if parts of the network are joined with one another whose characteristics when connected directly lead to mutual obstruction.

Phase shift: This describes the relative state of two fluctuations to each other and whether the oscillations reach their maximum or minimum values at the same moment or slightly shifted in relation to one another.

Robustness: Indicates how the network responds to internal perturbations, for example the collapse of an important high-voltage line.

Stability: Indicates how well the power grid can cope with external perturbations, say when a large consumer taps into the voltage.