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GERMANY'S ENERGY GAMBLE

An ambitious plan to slash greenhouse-gas emissions must clear some high technical and economic hurdles.

BY QUIRIN SCHIERMEIER

In an industrial warehouse on the outskirts of Stuttgart, the sooty past is shaking hands with Germany's green-energy future. In one corner sits a relic destined for a museum: a cast-iron engine as big as a bus, which was used until the early 1970s to compress coal gas for lighting, cooking and heating. Nearby, a gleaming network of stainless-steel tanks uses electricity to create methane out of water and carbon dioxide.

This power-to-gas (P2G) pilot plant is the largest of its kind in the world, and the research behind it could help to propel Germany to the front of the race for cleaner energy. Developers of the €3.5-million (US$4.5-million) project say that the P2G technology is an ideal way to cope with the unreliable nature of solar and wind power. During sunny or breezy days, excess electricity can be used to make methane, which can be stored and then burned to generate power when the winds fail or the days turn dark.

The quest to develop P2G storage is part of Germany's ambitious *Energiewende*, or energy transition, a long-term plan to clean up the country's energy systems. Enshrined in law, the scheme aims to slash CO_2 emissions by replacing fossil fuels with renewable sources of energy. Germany hopes to generate at least 35% of its electricity from green sources by 2020; by 2050, the share is expected to surpass 80% (see 'Green growth').

The *Energiewende* — the world's most extensive embrace of wind and solar power as well as other forms of renewable energy — enjoys the support of all Germany's political parties and most of the population. It will probably continue whatever the results of the national election in September. Other nations are watching keenly to see how the experiment proceeds, and whether they should follow the German lead. "Germany's *Energiewende* can mobilize a global energy revolution," says Harry Lehmann, executive chairman of the World Council for Renewable Energies, who is based in Dessau, Germany.

To reach its goal, Germany is currently investing more than €1.5 billion per year

"Don't overturn the *Energiewende*," urges a supporter of Germany's plan to shift rapidly towards renewable energy.

in energy research. One of its chief aims is to improve and build more storage systems, such as the Stuttgart P2G plant. Another is extending and strengthening the electricity grid to wire up remote wind turbines and countless small photovoltaic installations. The research programme also seeks to improve the efficiency of energy production from sunlight, wind and biomass, and to encourage people to reduce energy consumption.

Most experts in Germany agree that the technical hurdles are surmountable. "We don't need technological leaps to accomplish the *Energiewende*," says Eberhard Umbach, president of the Karlsruhe Institute of Technology, who oversees the €500-million energy-research activities of Germany's national research centres.

But the economic challenges are daunting, with the total costs of the *Energiewende* estimated to top €1 trillion. Europe's deep financial crisis looms large over a project of that scale, warns Roger Pielke Jr, an environmental-policy researcher at the University of Colorado Boulder. "The German public has so far shown great willingness to pay for the transformation, but there will be limits to that willingness, especially if the economic climate gets rougher."

MONEY AND POWER

The *Energiewende* is already visible to anyone travelling the German countryside. Expensive solar panels cover more than one million houses, farms and warehouses, thanks to generous subsidies. Along the motorways, clumps of wind turbines sprout on ridges, particularly in the breezy northern regions. The country's green-energy portfolio is growing at a ferocious rate; last year, renewables supplied more than one-quarter of Germany's gross electricity needs.

The primary motivation for the *Energiewende* is to combat climate change. By 2020, Germany aims to cut its greenhouse-gas emissions by 40% below 1990 production levels, and it hopes to achieve a reduction of at least 80% by 2050. The government set those goals in 2005, but the targets became much more ambitious in the aftermath of the Fukushima nuclear accident in Japan in March 2011.

That crisis spurred German Chancellor Angela Merkel to speed up a planned move away from nuclear power, which provided 25% of the country's primary power in 2010. She closed eight nuclear plants immediately and pledged to shut the remaining nine by 2022. Suddenly, Germany needed to pick up the pace of its move towards renewable energy.

For German consumers, the costs of that shift are apparent in their monthly electricity bills. The statements include a litany of 'shared costs' that are split by all households to fund the *Energiewende* — and result in some of the highest electricity prices in Europe. (Heavy industries are currently exempt from paying the surcharge.)

The shared costs are a mechanism for promoting green forms of energy, which are more expensive to produce than electricity from coal and natural gas. Germany's Renewable Energy Act (EEG), the legal force behind the *Energiewende*, allows owners of solar panels and wind turbines to sell their electricity to the grid at a fixed, elevated price. Renewable-power producers cashed in an estimated €20 billion last year for electricity that was actually worth a mere €3 billion on the wholesale electricity market. The difference came out of the pockets of consumers.

GERMANY'S *ENERGIEWENDE* CAN MOBILIZE A GLOBAL ENERGY REVOLUTION

The EEG, first passed in 2000, has helped Germany to install many more wind and solar power systems than most other developed nations. But the subsidies are causing some grotesque distortions in the electricity market — to the point at which energy companies are sometimes forced to sell conventional power at a loss.

The effects of Germany's policies are also reverberating through the European energy market. One of Europe's biggest energy providers, E.ON based in Düsseldorf, announced in January that it plans to close several gas-fired power stations across Europe that were operating at a loss, even though they are far less polluting than coal-fired plants. The "unmanaged growth" of renewable-energy sources is forcing gas-fired plants to spend too much time idle, E.ON boss Johannes Teyssen told shareholders.

At the same time, Germany is subject to the vagaries of outside forces, such as the rapid expansion of natural-gas production in the United States, which has curbed domestic demand for coal. Excess US coal is now heading to Europe, helping to fuel a resurgence of coal use in the United Kingdom and Germany, among other countries. With Germany's imports of low-cost coal rising, the country's greenhouse-gas emissions increased by almost 2% in 2012 — bucking a long-term decline. Last August, federal minister of the environment Peter Altmaier made clear that coal-fired plants will be needed "for decades to come" to ensure energy supplies. Germany is currently building some 11 gigawatts of coal-fired plants and its existing capacity of around 55 GW will not shrink as quickly as the country had planned.

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The coal resurgence makes it unlikely that Germany will meet its 2020 emissions targets, says Pielke Jr. "You must accept the logic," he says. "If you opt out of nuclear power, your near-term emissions will go up."

But German officials say that even if emissions rise temporarily, that trend will turn around. State-of-the-art coal-powered plants, such as a new 2.2-GW facility near Cologne that burns lignite, or low-grade coal, will replace several older, less efficient plants. The net effect will be to reduce CO_2 emissions, says Altmaier.

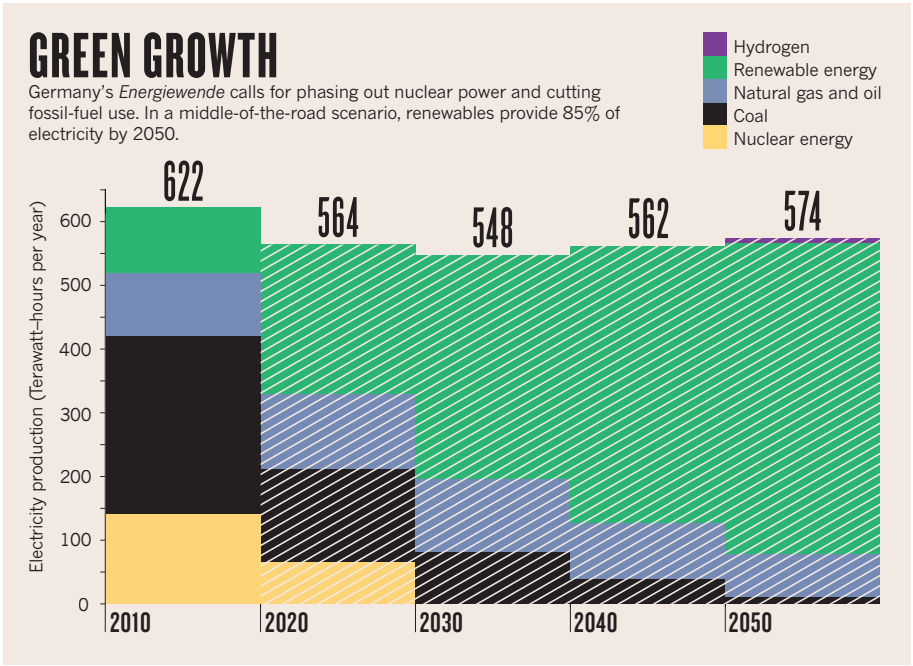
To sustain that trend, however, the costs of green energy need to come down. "Subsidies have helped to get the renewable thing started, but sooner or later renewable energy must become economically self-sustaining," says Brigitte Knopf, head of German and European energy strategies at the Potsdam Institute for Climate Impact Research.

That is where Germany is aiming many of its energy-research efforts, which will receive in excess of €3.5 billion from the government between 2011 and 2014. About €200 million is going towards developing and improving storage technologies.

"Renewable energy is a wonderful thing — provided you are able to store it at a large scale and distribute it efficiently," says Frithjof Staiß, managing director of the Center for Solar Energy and Hydrogen Research (ZSW) in Stuttgart, which operates the P2G plant. By making renewable energy more manageable and marketable, advanced storage technologies can ultimately help to reduce the cost of wind and solar power, he says.

Germany currently stores excess electricity by using pumps to push water uphill into reservoirs. When electricity demand goes up, the water is released through turbines to generate hydroelectric power. But there are limits to expanding this type of storage. With 30 pump facilities already in operation, Germany has few suitable sites left for building more; the country plans to increase pump-storage capacity by just 20% by 2020.

P2G, however, could provide a vast amount of new storage capacity and Germany is leading the way. The plant in Stuttgart has 250 kilowatts of electrolysis stacks, which use electricity from renewables to produce hydrogen from water. To make methane, the hydrogen is reacted with



CO_2 from decomposing sewage and agricultural waste at a nearby biogas plant. Other P2G plants could scrub CO_2 from the air.

But P2G is still an immature technology, with high upfront costs and an efficiency of only about 50% in converting electricity to methane. Synthetic methane plants have also struggled with the purity of their product. At the ZSW facility, the main goal is to routinely produce gas with low oxygen and hydrogen content.

Several other government-funded research groups are working to improve the membranes used in electrolysis reactions to produce the hydrogen for P2G plants. Advanced proton-exchange membranes, for example, can respond to electricity fluctuations within milliseconds, which could produce the very pure hydrogen needed for P2G and other clean-energy technologies.

Once P2G plants work out such issues, they could scale up, and synthetic gas could go directly into the network of pipelines and storage tanks currently used for natural gas. It could then be burned in power plants to produce electricity; by some estimates, this technology will be able to store up to 500,000 gigawatt-hours of electricity, enough to power Germany for more than six months.

The synthetic gas could be also used for heating or as a vehicle fuel. This prospect has piqued the interest of the car-maker Audi, which is currently building the first commercial P2G test facility in Werlte, northern Germany. The facility is expected to produce up to 4,000 cubic metres of synthetic methane per day — enough to fuel about 1,500 cars. Audi is also set to introduce a hybrid natural-gas-powered sedan later this year.

If Germans embrace this kind of vehicle, it could help to cut carbon emissions from the transport sector, which has lagged behind others in implementing the *Energiewende*. The government intends to have one million battery-powered cars on German roads by 2020, but experts view that goal as unrealistic. The industry lacks the capacity to produce that many electric cars, and motor-loving Germans have not shown much desire for them. The new Audi and similar models may turn more heads, because consumers can switch to normal fuel if they are running low on natural gas and cannot find a specialized refuelling station. That option is not available to owners of battery-powered vehicles that run low on charge.

SUPPLY AND DEMAND

Although transportation has been slow to change, the electricity sector has the opposite problem. The rapid rise in wind and solar power has created a nightmare scenario for grid operators, who face power surges when the wind blows and the Sun shines, and shortages when they don't. In 2011, more than 200,000 blackouts exceeding three minutes were reported — and experts warn of a growing risk of major power failures.

For the *Energiewende* to succeed, the grid must be able to accommodate millions of extra small solar installations and wind turbines, as well as autonomous sub-grids such as those that connect offshore wind farms, which intermittently send floods of power into the onshore grid.

In January, the government put out a €150-million call for research proposals for improving the electricity network. The government also announced last year that it would install almost 4,000 kilometres of high- and low-voltage power lines, with a total transmission capacity of 10 GW. The €20-billion project would help to carry energy to the south of Germany from wind farms in the north.

And Germany may look even farther afield. Having distant power sources outside the nation would facilitate the *Energiewende* because a calm, dark day in Germany could be balanced by energy from other countries, says Robert Socolow, an environmental economist at Princeton University in New Jersey.

Some companies have floated plans to build large thermal solar plants in the Sahara Desert, which gets enough sunshine to meet most of Europe's electricity demand. But this scheme, the multibillion-euro DESERTEC initiative, lost momentum late last year, when two major industry partners — Siemens and Bosch — backed out (see *Nature* **491,** 16–17; 2012). Energy analysts, moreover, doubt that Germany or any other European country would be willing to rely on substantial electricity imports from a politically unstable region.

Some question the need to ship power over long distances. "That the *Energiewende* depends on a huge expansion of the grid is a myth — and a very expensive myth, too," says Mathias Willenbacher, co-founder and managing director of juwi in Wörrstadt, a company that has successfully built small-scale renewable-energy projects. Willenbacher argues that it would be better to plough money into energy-storage options. "If you solve the storage issue, there is no need any more to transmit massive amounts of wind power from the North Sea to the Alps," he says.

However Germany sources its electricity, the *Energiewende* will not succeed unless the country can convince ordinary people to use energy more efficiently, says Umbach.

Researchers from the Karlsruhe Institute of Technology are currently running a field study to see whether they can alter the behaviours of 1,000 private citizens and commercial electricity customers in the city of Göppingen and the rural municipality of Freiamt. The trial, supported by the energy company EnBW in Karlsruhe, gives consumers smart-grid meters that provide information on their minute-to-minute energy use as well as the cost of power, which fluctuates throughout the day. The researchers aim to study whether people use the information to reduce their energy consumption.

How Germans will get by in the brave new energy world remains to be seen, says Umbach. "Will a computer tell them when to wash and cook?" he asks. "Or will they still want to fry their schnitzel when they feel like it?"

Surveying all the impediments to the *Energiewende*, Umbach is not sure that the transformation will come off as soon as planned. But he is convinced that Germany is the right country to try the great experiment. "If it fails it will be bad for Germany," he says. "But if it succeeds the whole world will profit." ■ SEE EDITORIAL P.137

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