Making Dirty Coal Plants Cleaner

A daunting task awaits the utility industry as it scrambles to catch the carbon spewing from today's generation of plants

PITTSBURGH, PENNSYLVANIA—American Electric Power (AEP), the biggest user of coal in the United States, has long supported research on ways to curb carbon emissions from its 26 generating plants. But this spring, Michael Morris, its CEO, surprised an audience of fossil fuel scientists, engineers, and business executives gathered here when he pronounced that techniques to extract carbon from flue gases could be developed soon—if consumers are willing to pay for them. "If we want cleaner air, it's going to cost something," he declared. The fact that a power industry executive is even talking in these terms is a new departure, says Sarah Forbes of Potomac-Hudson Engineering Inc., a Bethesda, Maryland–based consulting firm. She sees it as a "bold" signal that the Columbus, Ohio–based utility, at least, is getting serious about carbon capture.

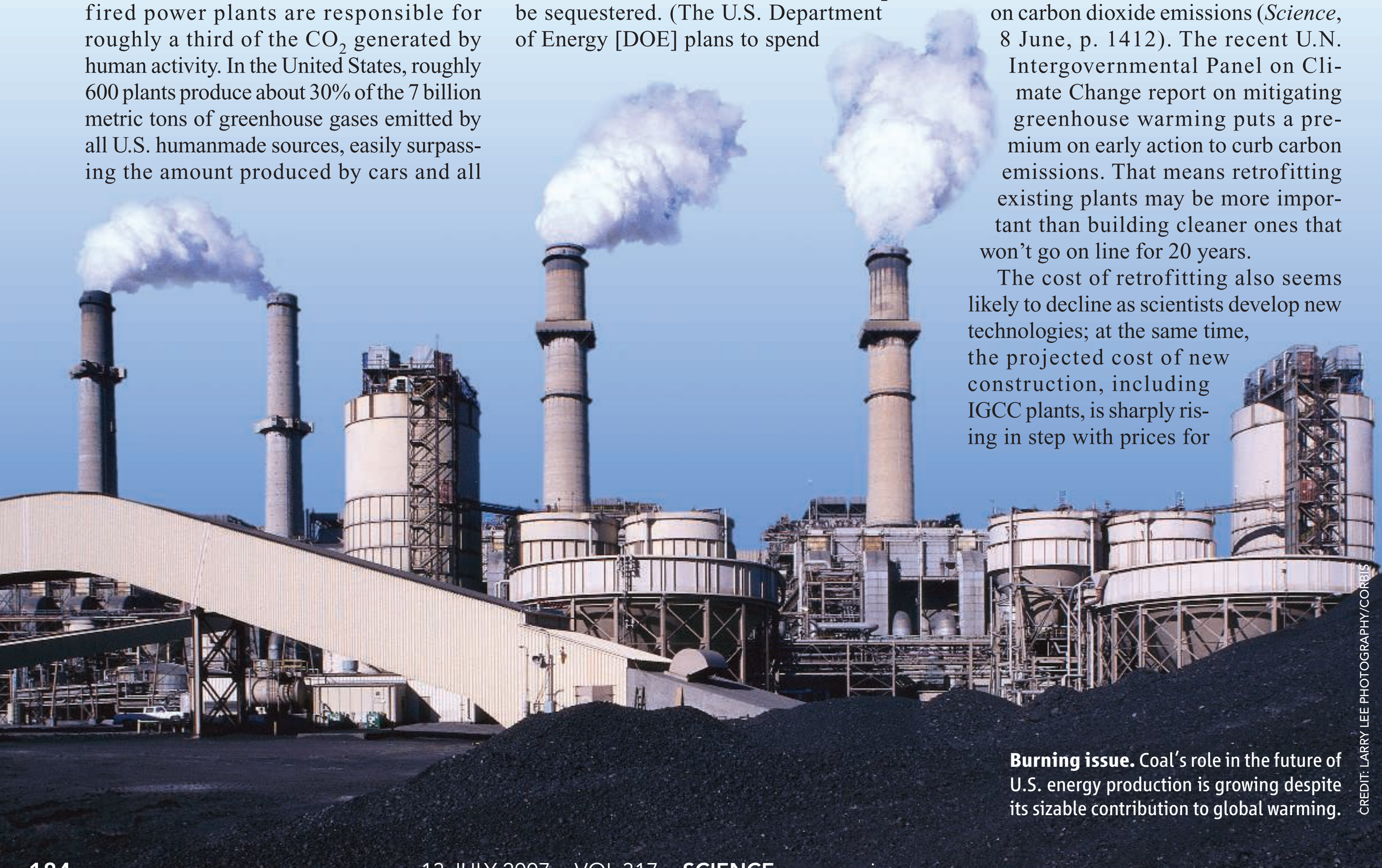
Emissions from the world's 2100 coal-fired power plants are responsible for roughly a third of the CO_2 generated by human activity. In the United States, roughly 600 plants produce about 30% of the 7 billion metric tons of greenhouse gases emitted by all U.S. humanmade sources, easily surpassing the amount produced by cars and all other industries combined. Additionally, the share of electricity generated by coal in the United States is expected to climb from 48% today to 55% by 2030. And the United States is not alone. Last year, China, which derives about 80% of its electricity from coal and recently surpassed the United States as the world's biggest CO_2 emitter, brought online two major coal plants a week. "If we don't solve the climate problem for coal, we're not going to solve the climate problem," says Princeton physicist Robert Williams, a coal expert.

In practice, making coal plants cleaner means removing as much of the CO_2 generated from flue gases as possible before they are vented into the atmosphere. One approach popular with industry and the federal government is called the Integrated Gasification Combined Cycle (IGCC), which creates hydrogen to burn and CO_2 to be sequestered. (The U.S. Department of Energy [DOE] plans to spend $1 billion for a full-scale public-private plant called FutureGen that's scheduled to open in 2012.) Once extracted, the carbon dioxide would then be stored, most likely underground, at a cost and by an exact method that are still uncertain.

But only a handful of such plants are running commercially worldwide, and none currently stores the CO_2 underground. A second approach, applicable to most existing plants, would remove the CO_2 from the flue stream after combustion. The industry standard, in limited use today, employs a molecule called monoethanolamine (MEA), which has been used for decades as a solvent to bind with CO_2 and separate it from natural gas.

Planners have long figured that building new facilities optimized for reduced emissions would be cheaper than retrofitting existing plants, in part because of the large amount of energy needed to extract the CO_2. But the retrofit option is becoming more attractive. One reason is the growing support for near-term caps on carbon dioxide emissions (*Science*, 8 June, p. 1412). The recent U.N. Intergovernmental Panel on Climate Change report on mitigating greenhouse warming puts a premium on early action to curb carbon emissions. That means retrofitting existing plants may be more important than building cleaner ones that won't go on line for 20 years.

The cost of retrofitting also seems likely to decline as scientists develop new technologies; at the same time, the projected cost of new construction, including IGCC plants, is sharply rising in step with prices for



Burning issue. Coal's role in the future of U.S. energy production is growing despite its sizable contribution to global warming.

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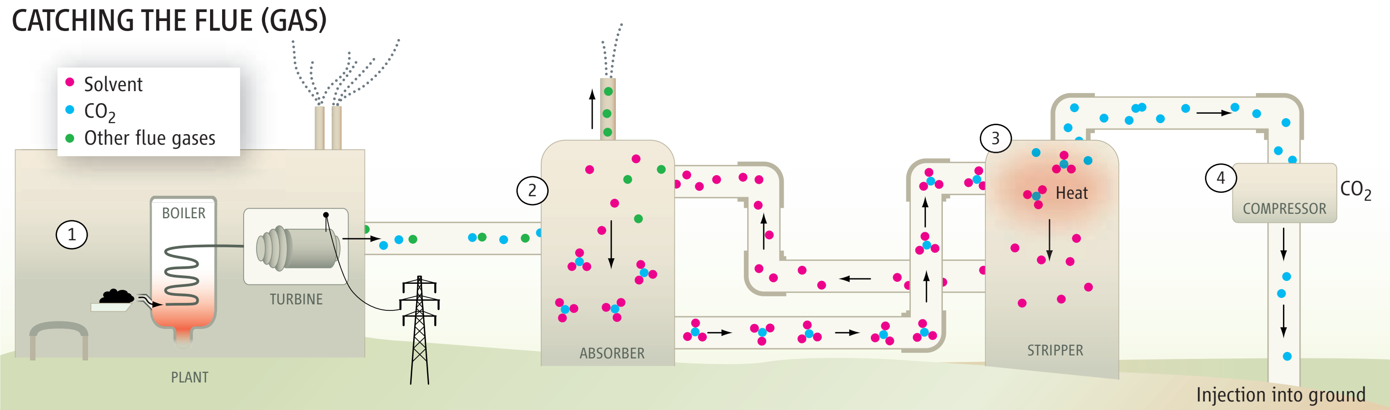


How a retrofit works. (1) Most coal plants burn coal to create steam, running a turbine that produces electricity. After treatment for pollutants, the flue gas, a mixture of CO_2 (blue) and other emissions (green), goes out a smokestack. To collect CO_2 for storage, however, the mixture of gases is directed to an absorber (2), where a solvent like MEA (pink) bonds with the CO_2 molecules. The bonded CO_2–solvent complexes are separated in the stripper (3), which requires heat. More energy is needed for the next step (4), which produces a purified CO_2 stream for ground storage as well as solvent molecules that can be reused. (Schematic not to scale.)

industrial materials like concrete and steel. "It's a big change," says engineer Jonathan Gibbins of Imperial College, London. "For a long time carbon capture meant [methods like] FutureGen, which was something wonderful that was 15 or 20 years ahead."

Taking a sip

Nestled among the green hills of coal country in Cumberland, Maryland, about 2 km from the Potomac River, the 7-year-old Warrior Run plant burns 652,000 metric tons of coal each year. That makes it one of the newest and smallest facilities operated by its owner, AES corporation. But what also sets it apart is its ability to collect some of the carbon dioxide from the emissions generated in its boiler and sell it commercially to beverage gas distributors. "If you've had a Coke today, you've probably ingested some of our product," says plant manager Larry Cantrell.

Cantrell's experience operating Warrior Run gives him some insight into the economics of capturing carbon, and the numbers aren't very encouraging. Warrior Run must generate 202 megawatts (MW) of power to meet its target of selling 180 MW. Roughly 4 MW of the gross total produced goes to provide the energy required for the MEA process to grab CO_2, which captures only 5% of the plant's CO_2 emissions. Grabbing more would divert much more energy; the cost of removing the carbon dioxide by pipeline, truck, or geological injection would drain profits even further.

Although current off-the-shelf technologies for carbon capture are improving, they still have a long way to go. A 2001 DOE study of a 433 MW plant in Conesville, Ohio, calculated that adding an MEA unit to capture 96% of its CO_2 emissions would cut the plant's net output by about 40%. And using the technology would raise electricity bills by 36% or more, according to a recent Massachusetts Institute of Technology study. Last year, DOE updated its Conesville study and found that the use of improved MEA technology, including more concentrated mixtures, more heat sharing, and larger and more tightly packed columns (see diagram), would allow the plant to capture 90% of CO_2 with only a 30% reduction in power output. That's better, but it's still a big hit.

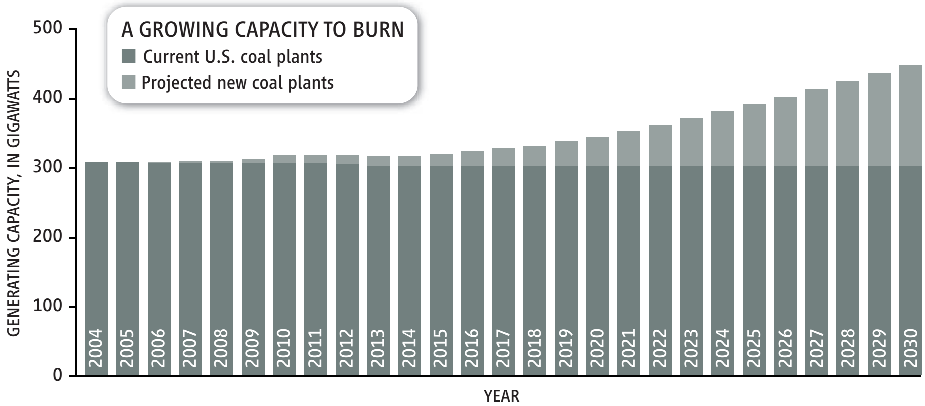
Rearranging the inner workings of a plant's heat exchangers and turbines promises to make a bigger difference than simply siphoning steam off for a retrofit bolted onto the plant's edge, says engineer Wolfgang Arlt of Universität Erlangen-Nurnberg, Germany. His recent simulated retrofit with MEA produced a 9% loss in total plant efficiency instead of 11% without the reoptimizing tweaks. "That's a big difference" over years of operation and thousands of plants, says Arlt.

Some scientists think that alternatives chemically similar to MEA offer greater hope. One uses a cooled stream of ammonium carbonate as the solvent to pull carbon dioxide from flue gas, releasing the gas when boiled. Data from a year-long experiment with chilled ammonia at the bench scale, run by the French energy giant Alstom, suggests that the method needs only 15% as much steam from the plant to capture the same amount of CO_2 as an equivalent MEA effort. That's because the solvent grabs CO_2 less tightly, requiring less energy to release it.

Alstom is now building a 30-meter-tall unit to capture 15,000 metric tons of CO_2 per year from a Pleasant Prairie, Wisconsin, coal plant operated by We Energies. AEP plans to try the technique at plants in West Virginia and Oklahoma, where engineers hope to use the gas to help extract additional oil from nearby fields. The main goal of the work is to quantify the energy demands, says Alstom's Robert Hilton, but he's also hoping to power the process with heat now wasted instead of precious steam.

A grab bag of approaches

The reason solvents are needed at all is because CO_2 makes up only a small fraction of the flue gas created and emitted by coal plants. Another retrofitting technique



Mainstays. New plants are projected to be built in the U.S. soon, but the current fleet is going nowhere fast.

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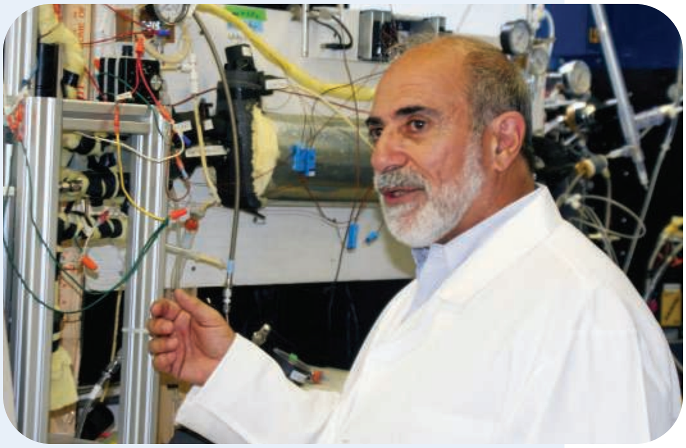
A CAREER CO_2 HUNTER GOES AFTER BIG GAME

For 30 years, Michael Trachtenberg, a fast-talking, 66-year-old former neuroscientist, has been working on an enzyme that removes carbon dioxide from various environments. Now, with the coal industry and government finally focusing on reducing greenhouse gas emissions, Trachtenberg is hoping to parlay his expertise and moxie into a commercial success.

Improbably, Trachtenberg began his career as an epilepsy researcher, studying the connection between that disorder and the brain's ability to process carbon dioxide with an enzyme called carbonic anhydrase. While working at the University of Texas Medical Branch in Galveston, he learned that oil companies pump carbon dioxide into depleted wells to extract more crude. In 1991, Trachtenberg formed a company, Carbozyme, with the goal being to use the enzyme to grab carbon dioxide from coal plant emissions and sell it to oil firms. The venture flopped, but by then he was hooked on CO_2. Applying his knowledge in work funded by NASA, Trachtenberg next created a device to maintain CO_2 and moisture levels inside an astronaut's space suit that was smaller and cheaper than what the space agency was using at the time.



Using your noggin. Michael Trachtenberg's technique for carbon capture involves an enzyme found in the human brain.

Now that "everyone and their mother" are suddenly interested in capturing carbon, Trachtenberg predicts an industry consolidation in which "there won't be many of us little guys [left]." But he's hoping Carbozyme, reconstituted in 2003, can hold its own against the likes of Mitsubishi and General Electric. A $7.4 million grant this year from the Department of Energy (DOE)—the biggest award to one team from a $24 million pot—will allow the Monmouth Junction, New Jersey, company and its industry partners to carry out basic and applied research on post-combustion CO_2 capture. (Carbozyme's technology uses the enzyme in membranes to catalyze the conversion of CO_2 to bicarbonate ions, reversing the process with the same enzyme by altering the pressure.) He says that preliminary results show that his CO_2 absorber is dozens of times more cost efficient than the current state-of-the-art technology using a molecule called monoethanolamine.

Trachtenberg's schedule at a recent carbon capture conference in Pittsburgh, Pennsylvania, showed how far he's come since his days as an academic scientist: In addition to attending presentations, he juggled hushed sit-downs with some of the biggest names in the coal industry. A gregarious self-promoter, he's also learned how to protect his intellectual property. Scrutinizing slides before a public meeting with other DOE grantees, he explains: "I'm making damn sure that there's nothing proprietary in those presentations." **–E.K.**

involves the seemingly paradoxical goal of producing flue gases that are richer in CO_2. The method, called oxy-firing, burns coal in a pure oxygen stream, producing CO_2 and little else. After only minor processing, the flue gas can be injected into the ground. Such equipment could be attached to existing boilers "more or less as is," says University of Utah chemical engineer Eric Eddings.

Last year, boilermaker Babcock and Wilcox ended a 7-year oxy-firing test in Alliance, Ohio, using a burner only 5% the size of those used in a typical coal plant. Preliminary results suggest that oxy-firing would raise a typical U.S. customer's electric bill by 44%—compared with more than 50% for MEA—without accounting for storage costs. Complicating the equation, says Babcock and Wilcox's Kip Alexander, is that "everyone is trying to get cost estimates on equipment that hasn't been built yet."

One drawback to oxy-firing, says University of Texas chemical engineer Gary Rochelle, is the need to make permanent changes to the boiler, the heart of a coal plant. By contrast, treating flue gas gives operators the option of changing the carbon-stripping technique by swapping equipment off the end of the plant. That flexibility could make emissions cuts easier for industry: The Conesville study, for example, suggested that capturing half the carbon emissions from the plant would cost half as much as capturing all of the CO_2.

Keeping options open for relatively new steam-powered plants is a big worry of coal experts, especially for those eyeing the Asian juggernaut. Gibbins hopes to spread the word about technical advances during a visit to China later this year. He plans to encourage Chinese utilities to include particular features—such as space for new equipment and certain steam fittings—on their prodigiously growing coal fleet so that they're ready if researchers, mostly in the West, succeed in making capture cheaper over the next decade.

Other methods to grab CO_2 from flue gas are still at the bench stage. They include giant molecules that can pluck out CO_2 with spindly arms called dendrimers, cagelike molecules that capture the CO_2, or biological catalysts (see sidebar). The initial barrier for each technology is the high cost of producing the molecules. But the methods also hint at some attractive benefits. One problem with MEA is its volatility, which requires a company to run a chiller plant on site to remove the evaporated solvent from the concentrated CO_2. But ionic liquids, a relatively new class of chemicals that are liquid at room temperature, have low volatility, and chemists are finding they might be useful for removing carbon dioxide.

The search for carbon-clutching tools is attracting researchers from a variety of fields previously unrelated to coal, like nanotechnology. Researchers at the University of Notre Dame, for example, were trying to use ionic liquids to make environmentally friendly solvents for the chemical industry when they discovered that the CO_2 involved kept dissolving in the ionic liquid. "We didn't expect the carbon dioxide to be so soluble," says Notre Dame chemical engineer Edward Maginn.

Now, DOE is funding basic work with the chemicals for carbon capture, and Maginn's team is examining how to make cheap-to-synthesize solvents that grab CO_2 just firmly enough. "It's a very small [but] growing field," he says. And every little bit helps a community that's trying to tackle a problem from a virtual standing start, says Babcock and Wilcox's Alexander. "We need to demonstrate a lot of things," he says.

–ELI KINTISCH

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