Renewables Aren't Enough. Clean Coal Is the Future

- By Charles C. Mann 03.25.14

Coal supplies over 40 percent of global electricity needs, and that percentage is going up. The only real question is how to minimize the damage.

Proof that good things don't always come in nice packages can be found by taking the fast train from Beijing to Tianjin and then driving to the coast. Tianjin, China's third-biggest city, originated as Beijing's port on the Yellow Sea. But in recent years Tianjin has reclaimed so much of its muddy, unstable shoreline that the city has effectively moved inland and a new, crazily active port has sprung up at the water's edge. In this hyper-industrialized zone, its highways choked with trucks, stand scores of factories and utility plants, each a mass of pipes, reactors, valves, vents, retorts, crackers, blowers, chimneys, and distillation towers—the sort of facility James Cameron might have lingered over, musing, on his way to film the climax of *Terminator 2*.

Among these edifices, just as big and almost as anonymous as its neighbors, is a structure called GreenGen, built by China Huaneng Group, a giant state-owned electric utility, in collaboration with half a dozen other firms, various branches of the Chinese government, and, importantly, Peabody Energy, a Missouri firm that is the world's biggest private coal company.

By Western standards, GreenGen is a secretive place; weeks of repeated requests for interviews and a tour met with no reply. When I visited anyway, guards at the site not only refused admittance but wouldn't even confirm its name. As I drove away from the entrance, a window blind cracked open; through the slats, an eye surveyed my departure. The silence, in my view, is foolish. GreenGen is a billion-dollar facility that extracts the carbon dioxide from a coal-fired power plant and, ultimately, will channel it into an underground storage area many miles away. Part of a coming wave of such carbon-eating facilities, it may be China's—and possibly the planet's—single most consequential effort to fight climate change.

Because most Americans rarely see coal, they tend to picture it as a relic of the 19th century, black stuff piled up in Victorian alleys. In fact, a lump of coal is a thoroughly ubiquitous 21st-century artifact, as much an emblem of our time as the iPhone. Today coal produces more than 40 percent of the world's electricity, a foundation of modern life. And that percentage is going up: In the past decade, coal added more to the global energy supply than any other source.

Nowhere is the preeminence of coal more apparent than in the planet's fastest-growing, most populous region: Asia, especially China. In the past few decades, China has lifted several hundred million people out of destitution—arguably history's biggest, fastest rise in human well-being. That advance couldn't have happened without industrialization, and that industrialization couldn't have happened without coal. More than three-quarters of China's electricity comes from coal, including the power for the giant electronic plants where iPhones are assembled. More coal goes to heating millions of homes, to smelting steel (China produces nearly half the world's steel), and to baking limestone to make cement (China provides almost half the world's cement). In its frantic quest to develop, China burns almost as much coal as the rest of the world put together—a fact that makes climatologists shudder.

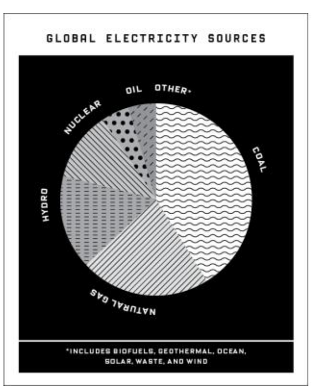
China already emits one-quarter of the world's greenhouse gases, more than any other country. The International Energy Agency (IEA), a Paris-based think tank sponsored by 28 developed nations, estimates that Beijing will double its ranks of coal-fired power plants by 2040. If that happens, China's carbon dioxide figures could double or even triple. "Coal is too low-cost, too plentiful, and too available from reliable sources to be replaced," says fuel analyst John Dean, president of the JD Energy consulting firm. "China is putting in solar and wind power at a tremendous pace, but it will have to use more and more coal just to keep up with rising demand."

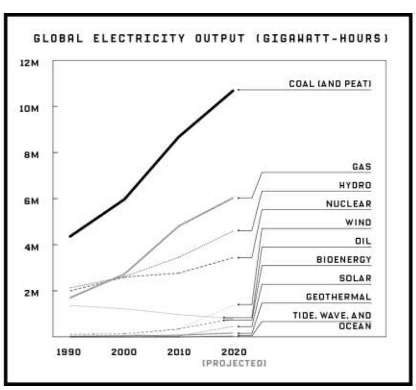
Dependence on coal is not just a Chinese problem, though. Countries around the world—even European nations that tout their environmental track records—have found themselves unable to wean themselves from coal. Germany, though often celebrated for its embrace of solar and wind energy, not only gets more than half its power from coal but opened more coal-fired power plants in 2013 than in any year in the past two decades. In neighboring Poland, 86 percent of the electricity is generated from coal. South Africa, Israel, Australia, Indonesia—all are ever more dependent on coal. (The US is a partial exception: Coal's share of American electricity fell from 49 percent in 2007 to 39 percent in 2013, largely because fracking has cut the price of natural gas, a competing fuel. But critics note, accurately, that US coal exports have hit record highs; an ever-increasing share of European and Asian coal is red, white, and blue.) According to the World Resources Institute, an environmental research group, almost 1,200 big new coal facilities in 59 countries are proposed for construction. The soaring use of coal, a joint statement by climate scientists warned in November, is leading the world toward "an outcome that can only be described as catastrophic."

Which brings me, in a way, back to the unwelcoming facility in Tianjin. GreenGen is one of the world's most advanced attempts to develop a technology known as carbon capture and storage. Conceptually speaking, CCS is simple: Industries burn just as much coal as before but remove all the pollutants. In addition to scrubbing out ash and soot, now standard practice at many big plants, they separate out the carbon dioxide and pump it underground, where it can be stored for thousands of years.

Many energy and climate researchers believe that CCS is vital to avoiding a climate catastrophe. Because it could allow the globe to keep burning its most abundant fuel source while drastically reducing carbon dioxide and soot, it may be more important—though much less publicized—than any renewable-energy technology for decades to come. No less than Steven Chu, the Nobel-winning physicist who was US secretary of energy until last year, has declared CCS essential. "I don't see how we go forward without it," he says.

Burn Rate





Our dependence on coal isn't ending anytime soon. Although renewable energy is expected to boom over the next decade, coal will remain by far the world's top power source. —Victoria Tang

Unfortunately, taking that step will be incredibly difficult. Even though most of the basic concepts are well understood, developing reliable, large-scale CCS facilities will be time-consuming, unglamorous, and breathtakingly costly. Engineers will need to lavish time and money on painstaking calculations, minor adjustments, and cautious experiments. At the end, the world will have several thousand giant edifices that everyone regards as eyesores. Meanwhile, environmentalists have lobbied hard against the technology, convinced that it represents a sop to the coal industry at the expense of cleaner alternatives like solar and wind.

As a consequence, CCS is widely regarded as both critical to the future and a quagmire. At a 2008 meeting of the Group of Eight (a forum for powerful Western nations, Russia, and Japan), the assembled energy ministers lauded the critical role of carbon capture and storage and “strongly” backed an IEA recommendation to launch “20 large-scale CCS demonstration projects” by 2010. But the number of such projects around the world is actually falling—except in China, which has a dozen big CCS efforts in planning or production.

It is perhaps appropriate that China should take the lead: It has the world’s worst coal pollution problem. In addition, its energy companies are partly state-owned; they can’t readily sue the government to stop its CCS program. At the same time, they won’t be penalized, either by the government or shareholder advocates, if developing this costly, experimental technology cuts into their profits. In any case, outsiders should be grateful that China is weighing in, says Fatih Birol, chief economist for the IEA. *Somebody* needs to figure out how to capture and store carbon dioxide on a massive scale before it’s too late.

“I don’t know of any other technology which is so critical for the health of the planet and at the same time for which we have almost no appetite,” Birol says. “The only place it seems to be increasing is China.”

Coal Can’t Be Ignored

Coal is MEGO—until you live near it. *MEGO* is old journalistic slang for “my eyes glaze over”—a worthy story that is too dull to read. In America, where coal is mostly burned far out of sight, readers tend to react to the word *coal* by hitting Close Tab.

But people in Hebei don’t think coal is MEGO, at least in my experience. Hebei is the province that surrounds Beijing. When the capital city set up for the 2008 Olympics, the government pushed out the coal-powered utilities and factories that were polluting its air. Mostly, these facilities moved to Hebei. The province ended up with many new jobs. But it also ended up with China’s dirtiest air.

Coal By The Numbers

- 7.6 billion tons of coal consumed worldwide last year.
- 2 pounds of carbon dioxide emitted for each kilowatt-hour of electricity generated via coal.
- 1 billion tons of coal used in global industrial steel production each year.
- 0 alternatives to coal in the industrial steel-making process.
- 44 degrees Fahrenheit: potential average global temperature rise if all remaining coal were burned.

Because I was curious, I hired a taxi to drive in and around the Hebei city of Tangshan, southeast of Beijing. Visibility was about a quarter mile—a good day, the driver told me. Haze gave buildings the washed-out look of an old photographic print. Not long ago, Tangshan had been a relatively poor place. Now the edge of town held a murderer’s row of luxury-car dealerships: BMW, Jaguar, Mercedes, Lexus, Porsche. Most of the vehicles were displayed indoors. Those outside were covered with gray crud.

Coal was everywhere, people said. One truck driver told me with a kind of mocking pride that we were breathing the world’s worst air. A university graduate in striped Hello Kitty socks remarked that every time she wiped her face the cloth had “black dirty stuff” on it. The stuff, she said, was PM2.5—technical jargon for particles that are 2.5 micrometers in diameter and therefore most likely to lodge in the lungs. Respiratory problems were common, she said. “Everybody is sick, but the government would never report it.” We gave a ride to a steelworker who told me that Tangshan had plans to clean itself up in 30 to 35 years. “We are a city of industry, a city of coal,” he said.

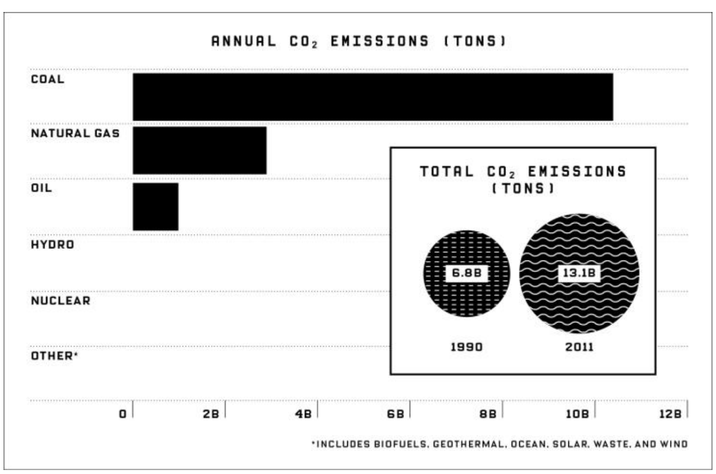
Dirty air is not solely a problem of obscure locations in flyover China. Face masks to help filter pollution are increasingly common in great cities like Shanghai and Guangzhou. One company, Vogmask, sells masks on which corporations can print their logos: smog as branding opportunity. A few days before my ride around Tangshan, the more than 10 million inhabitants of the northeastern city of Harbin were enveloped by coal pollution. Schools closed; people kept to their homes; highways shut down because drivers couldn’t see the road. During my visit, I picked up a Beijing newspaper with a full-page glossy ad insert for the city’s “first high tech condominium project that realizes real-time control of PM2.5 levels.”

According to one major research project involving almost 500 scientists in 50 nations, outdoor air pollution annually contributes to about 1.2 million premature deaths in China. Another study argued that eliminating coal pollution in northern China would raise average life expectancy there by nearly five years. (By contrast, wiping out all cancer would increase US life expectancy by just three years.) Last year 10 Chinese scientists calculated that reducing PM2.5 to US levels would cut the total death rate in big Chinese cities between 2 and 5 percent. A different way of saying this is that in some places, the side effects of breathing are responsible for as many as 1 out of every 20 deaths.

Understanding these numbers, affluent Chinese are beginning to send their children out of the country. Not-so-affluent Chinese, like the people I spoke to in Hebei, have little recourse. “What good are these jobs [in Hebei's new industry] if they’re at the expense of our health?” asked the woman in the Hello Kitty socks.

China’s coal fumes have effects far outside Hebei. Smoke from coal plants rises high and absorbs sunlight, heating the air. Black-carbon particles interact with clouds, helping them both trap heat and block solar radiation. Soot lands on glaciers and ice fields in a fine mist, covering them with a thin black film. Sunlight reflects less from smoky ice; indeed, the dusting of coal particles is helping to melt the poles and uncover the Himalayas. Last year an international team calculated that black carbon was the second-most important human emission contributing to climate change. The most important, of course, is carbon dioxide; coal is the greatest single source for it too.

CO_2 Rising



The combustion of coal is responsible for more than 70 percent of CO_2 emissions, dwarfing those from any other fuel used for generating electricity. With nearly 1,200 more coal-fired power plants planned in 59 countries, that cloud of greenhouse gas could grow by 4 billion tons, increasing nearly 50 percent by 2020. —V.T.

The simplest solution to all these woes would be to ban immediately all of the world’s 7,000 coal-fired power plants, including the almost 600 in the US—simple but impossible.

“For power generation, there are alternatives to fossil fuels,” says Barry Jones, a general manager of the Global CCS Institute. (The institute, an Australia-based association of international governments and energy companies, helped me make contacts in China but provided no financial assistance or editorial supervision.) “But for some industrial processes, there are no alternatives.” Examples include steel and cement, essential building blocks for all modern societies. Most steel is smelted in large blast furnaces. The furnaces require coke, a solid fuel made by burning coal in a low-oxygen environment. Not only an energy source, coke literally supports the iron ore in the furnace and participates in the chemical reactions that transform pig iron into steel. According to Vaclav Smil, an energy researcher and prolific author on the subject, producing a ton of steel requires almost half a ton of coke. Coal is also the primary fuel for cement manufacturers. "In theory, coal could be replaced," Jones says. "But that would involve rebuilding every cement plant in the world."

More important from China's perspective, more than one-quarter of its citizens still live on less than $2 a day. These people—more than 350 million men, women, and children, an entire United States of destitution—want schools and sewers, warm homes and paved highways, things that people elsewhere enjoy without reflection. China can't provide enough energy to make and maintain these things with oil or natural gas: The nation has little of either and not much incentive to import them at great cost. (Asian natural gas prices are roughly five times higher than US prices.) Nor can solar, wind, or nuclear fill China's needs, even though it is deploying all three faster than any other country. Meanwhile, it has the third-biggest coal reserves in the world.

China, like most of the rest of the world, "pretty much *has* to use coal," says Dean, the fuel analyst. "Or, I guess, leave people in the dark." And since coal is not going away, coal plants around the world will need to find a way to capture and store their emissions. "It's just crazy not to develop this technology."

Capture and Storage Is Our Best Option—for Now

Inner Mongolia is cold and dry and nearly treeless—the North Dakota of China. Long winters and summer sandstorms make people from other parts of China leery of moving there. Yet some are doing just that, because Inner Mongolia, like North Dakota, is a rising energy powerhouse, and jobs are plentiful. Two coal mines near the city of Ordos are the second- and third-biggest on earth. There are plans to develop part of another coal field; when complete, the area would be roughly three times that of Los Angeles. All are operated by Shenhua Group, a state-owned firm that is the country's largest coal producer.

In 2006, Beijing established a nationwide program to boost its coal production and develop its capacity to refine coal into liquid fuels, which would allow the country to use domestic coal to replace imported oil, gasoline, and natural gas, as well as the petrochemical products made from them. In response, Shenhua built a $2 billion facility near Ordos that transforms coal into something you can put in an automobile tank. Just outside the plant is one of the few filling stations on earth that sells liquefied coal.

Unfortunately, every kilowatt-hour generated by coal produces more than 2 pounds of carbon dioxide. (By contrast, natural gas emits about 1.2 pounds per kilowatt-hour; nuclear and solar, of course, emit none.) Turning coal into liquid fuel releases even more CO_2 than turning coal into electricity. Which partly explains why Shenhua has picked this coal-to-liquid plant in Inner Mongolia to house what is, by some measures, China's most important CCS initiative.

The project looms above a barren bluff over the Wulanmulun River (Ulan Moron, in Mongolian), which runs through a massive coalfield. The CCS project is small in dimension, employing only 20 of the 1,700 workers at the coal-to-liquids facility. But it has "large implications," says Maoshan Chen, its chief engineer. Shenhua launched the project, he says, because the company foresaw that Beijing's mandates to expand the use of coal would soon be followed by others to cut coal emissions. "It's inevitable that the government will set up carbon regulations," he says. "It's just a matter of time." Indeed, the first wave of emissions rules appeared in November—the government banned some types of coal mines and the use of particularly dirty coal. By then, Chen says, Shenhua had long since decided "to get ahead of everyone else" and launched the Wulanmulun project. GreenGen captures more carbon dioxide but at present is selling the gas to soft-drink companies rather than storing it (storage is planned for the next phase, in 2020). The Wulanmulun project, by contrast, already is the "complete package—capture *and* storage," Chen says.

Shenhua initiated feasibility studies in 2007 in consultation with the US Department of Energy. "A lot of US researchers took part in planning, both at DOE and Lawrence Livermore National Laboratory," Chen says. Further aid came from scientists at Beijing University, Beijing University of Chemical Technology, Tsinghua University, the Chinese Academy of Sciences, and petroleum-company geology departments. Also pitching in: China's Ministry of Science and Technology and the National Development and Reform Commission, the state planning agency. So many scientists were needed, Chen says, because CCS involves not only his field of chemical engineering but "geology, economics, atmospheric chemistry, industrial engineering—half a dozen different disciplines." Construction began in June 2010; the completed facility initiated tests six months later. Last year, its initial phase reached full capacity, capturing and storing more than 110,000 tons of carbon dioxide in an underground saltwater aquifer. By 2020, if all goes well, Shenhua could be putting away as much as 2 million tons of CO_2 every year.

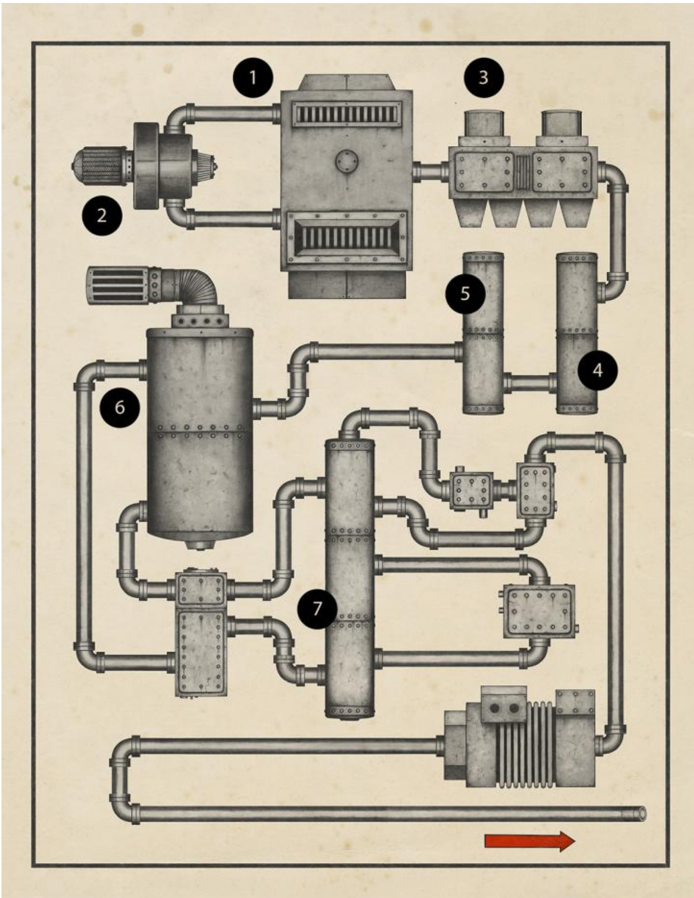
China is launching CCS schemes like the Shenhua facility faster than any other nation, and the country is unique in its determination to address the emissions from coal-fired plants. According to the Global CCS Institute, the world has just 12 fully operational large-scale carbon-capture projects, most in the United States. Not one of them is what is most needed: a facility that traps and stores emissions from a big coal-fired power plant. Instead they mainly take in CO_2 from natural-gas wells and refineries—a worthwhile task but of only secondary importance. This month, the first coal plant project, a $1.2 billion effort in Canada, is scheduled to open, but it remains true that the world has little experience with capturing and storing emissions from coal plants—so little that environmentalists charge that CCS is not much more than energy vaporware, a fantasy concocted by coal companies to greenwash an inherently dirty industry. Energy analysts put it differently. CCS is a real technology, but "it's real in the same way that stem cell medicine is real," Maggie Koerth-Baker wrote in *Before the Lights Go Out*, a fine recent study of the electric grid. "It's a concept car, not the minivan in your neighbor's driveway."

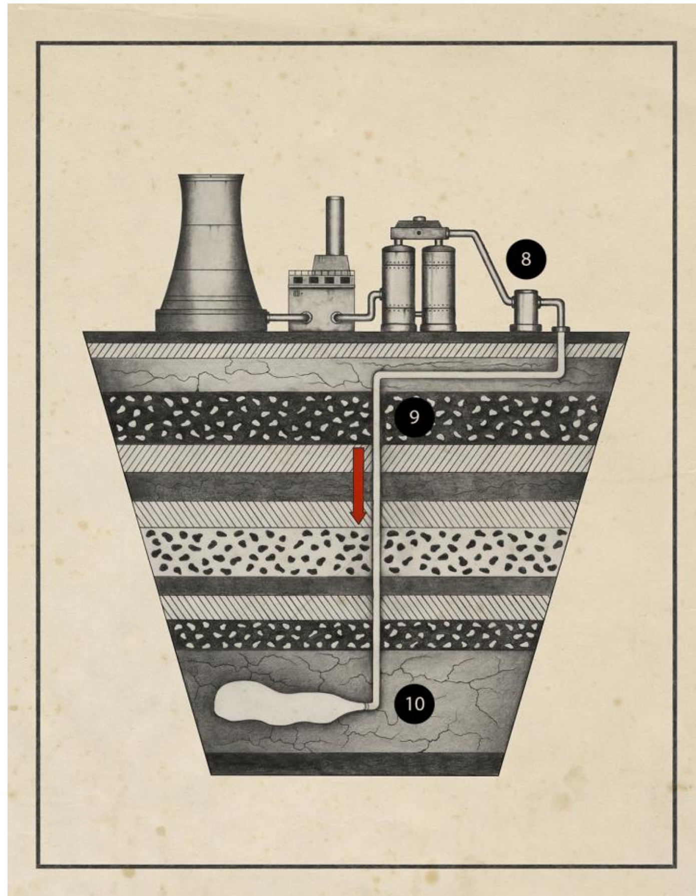
Getting CCS to the minivan stage requires surmounting multiple technical challenges. The most developed technique for capturing carbon from emissions is known as amine scrubbing**.** It involves bubbling the exhaust from burning coal through a solution of water and monoethanolamine. MEA is unpleasant: toxic, flammable, and caustic, with an acrid, ammoniacal smell. But it bonds to carbon dioxide, separating it from the other gases in the exhaust. The process creates a new chemical compound called, uneuphoniously, MEA carbamate. (More technically, CO_2 is a weak acid when dissolved in water—sometimes scientists refer to it as carbonic acid—and MEA is a weak base; in a reaction familiar from high school chemistry, they form a salt.) The MEA carbamate and water are pumped into a "stripper," where the solution is boiled or the pressure is lowered. Heat or expansion reverses the earlier reaction, breaking up the MEA carbamate into carbon dioxide and MEA. Carbon dioxide and water vapor gush out, ready to be buried; MEA returns to combine with the next batch of coal exhaust. (Because Shenhua's coal-to-liquids plant emissions have a much greater concentration of CO_2 than those from an ordinary power plant, the facility uses a somewhat different method.)

Carbon-Eating Machine

Energy experts believe that it will be at least a century before modern societies can truly convert to renewable energy. Until then, they argue, carbon capture and storage is the only way to deal with the

10.4 billion tons of carbon dioxide that the world's coal-fired power plants throw off annually. Here is an explanation of amine scrubbing—the best known method being tested—which typically recovers 90 percent of a plant's greenhouse gas emissions. —V.T.





1. BOILER
Coal burning in ambient air boils water and produces particulates (like soot and ash) and exhaust gases (like carbon dioxide and sulfur dioxide).

2. STEAM TURBINE GENERATOR
The boiling water generates steam, which spins a turbine to generate electricity.

3. SOLIDS REMOVAL
Vacuums or electrostatically charged plates are used to remove particulates.

4. DESULFURIZATION
Sulfur dioxide is removed by mixing the exhaust with lime slurry, ultimately producing gypsum, which can be disposed of or resold to make wallboard.

5. COOLER
The still-hot, desulfurized exhaust is cooled to the temperature at which it best combines with an amine-based scrubbing solution like monoethanolamine.

6. ABSORBER
The gas mixture combines with the amine solution. The carbon dioxide (a weak acid) latches onto the

amine (a weak base), yielding a CO_2 rich solution. Meanwhile, the remaining gas, stripped of almost all of its carbon dioxide, exits into the atmosphere.

7. STRIPPER
Heat or pressure reverses the reaction that combined the carbon dioxide and amine, resulting in a stream of nearly pure carbon dioxide, which is captured for sale or storage. Almost all of the remaining solution, which includes regenerated amines, can be recycled back into the absorber.

8. CO_2 COMPRESSION
High pressure is used to compress the captured carbon dioxide into a semiliquid state, which allows it to be transported easily in pipelines.

9. INJECTION
The CO_2 is injected several thousand feet below the earth's surface into appropriate geological formations like salt beds, exhausted oil reservoirs, or unminable coal seams.

10. STORAGE
Perhaps the greatest concern with carbon capture and storage is ensuring that the CO_2 doesn't escape. The best strategy is to inject it into a porous rock layer such as sandstone; the gas expands into the pores and slowly combines with the stone to form stable minerals. To prevent gas from percolating back up to the surface, ideal storage sites have layers of impermeable rock immediately above.

Scaling up this simple-sounding process into a plant that can physically process millions of tons of CO_2 is not easy. Big power plants produce big amounts of CO_2 and need big structures to capture it: multistory metal towers with pipes and valves. The compounds are corrosive and poisonous, ever trying to attack the machinery and kill the operators. Much of the MEA breaks down in every cycle and must be replenished at high cost.

Most important, constantly boiling a silo's worth of MEA carbamate solution requires a great deal of energy. Common estimates are that this kind of CCS will eat up 20 to 30 percent of a power plant's output. Given that typical coal plants can translate only 50 percent of the energy in coal into electricity, deploying CCS means that power plants will consume 40 to 60 percent more of the black stuff. Mitigating the environmental costs of digging up and burning coal thus means digging up and burning even more coal.

The industry jargon for these costs is *parasitic*. (Sample usage, from an energy consultant: "Holy crap, the parasitics are awful.") Often parasitic costs are estimated at $100 per ton of stored CO_2. A single 500-megawatt power plant emits roughly 3 million tons of carbon dioxide a year. Arithmetic suggests that sticking all that gas from thousands of plants in the dirt would cost $2 trillion a year, a figure that doesn't include the billions required to build the CCS facilities in the first place. This back-of-an-envelope calculation rests on implausible assumptions: coal plants of identical size, no technical progress, no economies of scale, no plant conversions to lower-emission natural gas, and so on. But the overall conclusion—that CCS based on present technology is prohibitively expensive—is all too plausible.

By contrast, the storage part of the equation—the S in CCS—seems relatively straightforward. Chen says that "nature is the proof of concept." What are oil and natural-gas deposits but natural storehouses of carbon? CCS simply re-creates or replenishes them.

As a rule, an oil or gas field consists of two layers of stone. The bottom layer is porous and spongelike, its holes filled with petroleum. Atop it is the second layer: a cap of nonporous stone. Oil or gas companies drill through the cap, releasing the liquids and gases below. CCS is the reverse: Companies pump liquid carbon dioxide through impermeable rock into permeable rock. After the rock is filled to the brim, the entrance is sealed permanently, a reliquary for humankind's energy obsession.

The continents are riddled with potential storage sites, geologists say, at least a century's worth in the United States alone. Obvious targets include saline beds—underground reservoirs of salty water—and exhausted oil fields. "Exhausted" does not mean the field has been pumped dry; rather, the remaining petroleum—as much as two-thirds of the total in the ground—is too thick and tarry to extract at a reasonable price. Injecting carbon dioxide changes the equation. Flowing into the pores of the rock, the gas mixes with the remaining crude oil, lowering its viscosity and squeezing it toward the wellhead. (After all possible oil is extracted, the well would be plugged.)

In principle, carbon dioxide could be tucked into such lairs until the sun explodes. In practice, it needs to be stored only for a century or so, the time required for the carbon dioxide to combine with the surrounding stone and form stable minerals. Still, nobody is yet sure how to safely contain CO_2 for even that long. At Shenhua's Wulanmulun project, Chen tallies the list of questions his team is trying to answer. Is the carbon dioxide leaking into the air? Is it spreading from one rock stratum to another? Is it reaching groundwater? Is it reacting chemically with the rock? What happens if the pressure in the pump changes? If the rock is fractured—fracked—to open more storage space? What about earthquakes? Using heavy machinery, Chen says, Shenhua is "hitting the ground really hard to see how it affects the spread of CO_2."

The innovation is needed. More than a century's worth of coal remains beneath the surface—an amount so large, two University of Victoria climate scientists calculated in 2012, that burning it all would raise Earth's average temperature as much as 44 degrees Fahrenheit. In fact, this estimate comes with an asterisk, because after temperatures hit a certain point, current climate models break down, making the future almost impossible to predict. "Our society will live and die by our consumption of coal," Andrew Weaver, one of the researchers behind the study, wrote in an email.

Soon after I received Weaver's note, China's National Development and Reform Commission reported that in 2013 it had approved new mining operations that would produce more than 100 million tons of coal, six times more than the previous year.

The storage part of Shenhua's CCS project is easy to miss. Covering about a quarter acre of land, it consists mainly of a cement platform holding up three big, sausage-shaped tanks. A pipe runs down from the tanks to a fair-size pump. From the pump emerges a second, smaller pipe that goes around the walls of the yard at about waist height before connecting to a red valve-covered device that vaguely resembles an antique fireplug. Next to it is a red-lettered sign informing visitors that the fireplug sits atop a shaft conducting pressurized carbon dioxide 8,185 feet below the surface.

At one end of the facility is an administration building with a small display showing how this works. On the walls are charts and diagrams not selected for visual interest. The accompanying texts describe the geology of Inner Mongolia, the chemistry of gases, the design of tests.

From the display, one would never learn that in the West CCS is controversial—that it has, in fact, been scoffed at by hosts of environmental activists, including the Sierra Club and the Rainforest Action Network. In 2008, Greenpeace issued a major study arguing that CCS is a "dangerous gamble," in part because "safe and permanent storage of CO_2 cannot be guaranteed." Instead of the "false hope" of carbon capture, Greenpeace and other activist groups contend that the "real solutions" to climate change are "renewable energy and energy efficiency."

Most scientists and engineers agree with Greenpeace that humankind will ultimately need a grid driven by renewables: three-quarters or more of the world's energy provided by sun and wind, bolstered by resources like tides and geothermal heat. Getting there is tricky, though. Indeed, former US energy secretary Chu believes that deploying solar and wind on this broad scale—a goal he strongly supports—cannot happen before the end of the century.

Chu ticks off the obstacles. No one has ever powered a nation solely, or even mostly, with sun and wind over the long term. “Never been done,” he says. Moreover, “there are times when you get a week of bad weather or a week of cloudy days over hundreds of miles. There are times when the wind stops blowing across all of Washington and Oregon for two weeks. During these times—guess what?—you still need a source of reliable power.”

Where will energy come from during big, protracted bouts of bad weather and windlessness? Several companies are experimenting with “load-shifting”—storing solar power generated in the day for use at night. But nobody has built facilities that can store enough energy to power entire regions for a week or two. Nor has anyone even begun to test an electric system that can transmit those huge amounts of extra power for long periods from those storage plants to where it is needed. Few doubt that the technology for such facilities could be invented, developed, and installed. Even so, the process of replacing the present coal-and-gas grid with a new, sun-and-wind grid—all the while keeping the old grid running—will be long, expensive, and risky. In contemporary societies, blackouts are more than an inconvenience; recall the awful events that occurred inside New Orleans hospitals when Hurricane Katrina caused a long power outage in 2005.

“Even if we cut demand by 50 percent,” Chu says, “something I would be very much in favor of, solar and wind can’t yet provide the kind of steady power needed by a modern society”—that is, one with continuously functioning factories and computer centers and traffic control systems. “For decades to come,” he says, “fossil fuels will be a very important factor, and we’ll need CCS to mitigate that.” Because fossil fuels will be needed as backup—and because they are vital to making steel, fertilizer, and cement—carbon capture inevitably will be part of tomorrow’s renewable-energy grid.

Unfortunately, outside of China, its prospects are dim, Yale economist William Nordhaus believes. (Nordhaus, president-elect of the American Economic Association, is probably the profession’s foremost researcher into climate change.) “CCS is caught in a vicious cycle,” he argued last year in his book *The Climate Casino*. “Firms will not invest in CCS because it is financially risky; it is financially risky because public acceptance is low and there are big hurdles to large-scale deployment; and public acceptance is low because there is so little experience with CCS at a large scale.”

Chu agrees, to some extent. “The parasitics right now are impossible,” he says. “We need something where we’re not doubling the cost of the electricity.” Still, he believes that the prospects for making CCS practicable in the near term are good. “From what I know,” he says, “I don’t see any show-stoppers—nothing insurmountable.”

After Chu left the Department of Energy, he went to Stanford. He also joined the board of one company: Inventys Thermal Technologies, a Vancouver-area CCS startup that he says might have “a better idea.” The idea consists of a ceramic-coated drum that rotates inside power-plant smokestacks. Carbon dioxide molecules adhere to the drum somewhat in the way that static cling makes pet hair stick to clothes. Steam washes off the carbon dioxide. One of the drum’s inventors has claimed that it can capture carbon for about $15 a ton, much less than the conventional amine method. When I ask Chu about the figure, he is carefully unspecific, to avoid giving away proprietary information. The larger point, in his view, is that the potential for innovation has barely begun to be explored.

Technological innovation will not be enough if CCS has no public support—and in the US, at least, neither the coal industry nor environmentalists have shown much interest. In January, the Obama administration proposed blocking the construction of new coal-fired power plants unless they use

CCS. The same coal companies that have long extolled the promise of “clean coal”—a marketing term for CCS—immediately began protesting that CCS was impossible. Inevitably, they have gone to court to thwart the requirement. Without strong support from environmental groups, the regulations are much less likely ever to be put into place and enforced.

The picture looks different from Beijing, where ample coal supplies are both a national treasure and a national emergency. The Chinese government faces twin imperatives: lifting people out of poverty and avoiding the worst consequences of industrialization. As a result, Chen tells me, “we must make CCS work.” A little later he smiles; a thought has occurred to him. “If we can make it work here,” he says, “maybe it will help other companies pick it up.” If we’re lucky, some of those companies might even be in the United States.