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STOKING THE FIRE

China burns more coal than any other country; how it does so in the future will determine our planet's climate. **Jeff Tollefson** reports from Beijing.

CHINA

Huang Bin, a 30-year-old engineer, is surveying the scene at one of China's showcase energy projects: a retrofit that will make the Gaobeidian coal-fired power plant in Beijing burn just a little bit cleaner. Three engineers in red hard hats pore over a blueprint, their fingers tracing lines on paper splayed across a steel tank. Two workers adjust a valve nearby, one of hundreds on a two-storey platform erected alongside two 30-metre-high vessels that will house the chemical reactions at the heart of the project. Sparks fly as welders connect pipes; the buzz of grinders comes and goes. The ground was broken on this project just three months ago, and even an outside observer can tell that there is plenty still to do. But no one seems to doubt that the world's latest carbon-capture pilot plant will be finished in three weeks' time. "Chinese speed," Huang says with a smile.

That was in late June. Last week, as planned, the new unit began stripping carbon dioxide out of a small stream of exhaust from the plant, a high-efficiency, 1,065-megawatt monster that churns out 10% of Beijing's power and one-third of its hot-water heat. The Huaneng Group, the government-owned company that runs the plant, plans to collect less than 1% of the CO_2 emitted here, ultimately to provide some of the fizz in locally made carbonated drinks. It is a modest goal, but for China the project is a gesture of goodwill, a tentative step into the kinds of technologies needed to decarbonize an economy that derives more than two-thirds of its energy from coal.

For years, China has lagged behind the West in researching ways to burn coal more cleanly, but that is beginning to change. Huang and his colleagues are coming of age in an era in which the Chinese learn by doing, and what they are doing today is advanced coal technology. The total time for the Gaobeidian retrofit from announcement through design and commissioning was nine months.

Chinese speed has raised entire cities and built modern highways, all while providing at least basic energy services to most of its 1.3 billion people. It has also frightened a world already alarmed by global warming. The planet's most populous nation has added some 170 gigawatts of coal-fired power capacity in the past two years alone — more than double Britain's entire electricity-generating capacity, installed over a century — and has overtaken the United States as the world's largest emitter of greenhouse gases.

Yet China's single-minded determination to get things done, if properly harnessed, could drive down costs and commercialize advanced coal technologies that have languished in labs and boardrooms in the West. In many ways, China has already positioned itself at the forefront of coal technology, but 'advanced' does not necessarily mean clean. Climate-friendly technologies would enable companies to capture and pump CO_2 underground, eliminating most of the emissions from coal. By contrast, even new technologies for converting coal into transportation fuels without carbon capture might increase China's reliance on coal, as well as its emissions.

"It's relatively easy for me to imagine the Chinese will get way out in front of us in the United States and Europe," says Kelly Sims Gallagher, an expert in China energy at Harvard University in Cambridge, Massachusetts. "The Chinese are committed to installing advanced technology. The question right now is which technology it will be."

So far, China's industrial revolution resembles a compressed version of that experienced in the West, with all the associated environmental problems and resource limitations. Evidence suggests that solutions, too, may come in rapid-fire fashion. An oft-cited statistic is that the Chinese bring a new power plant on line every week or two; less appreciated is that today's power plants generally employ state-of-the-art combustion technology, whereas older, less-efficient plants are being shut down.

N. BEHRING/PANOS

The main goal is to save coal. China's coal reserves rank as the world's third largest; the country mined and then devoured some 2.5 billion tonnes of coal last year, more than double the tonnage of the next-largest user, the United States. Still, the mining industry has struggled to meet demand, and imports are on the rise.

Efficiency drive

The government has also made energy efficiency its de facto climate policy (see 'Kicking the coal habit', overleaf), beginning with an ambitious effort to cut energy intensity (the amount of energy consumed per unit of gross domestic product) by 20% from 2006 to 2010. The emphasis is on the manufacturing industries, such as iron, steel and cement, which consume 68% of the nation's electricity and even more of its overall energy. It's not clear whether China will meet that goal on time. For many observers, though, what makes the policy real is the fact that national communist leaders now grade local officials according to their progress on energy efficiency.

The government is also taking aim at conventional pollutants from coal-fired power plants, hoping to curb acid rain and the dense smog that envelops many of China's cities. Roughly half of China's power plants are now equipped with 'scrubbers' for sulphur dioxide emissions. Most of these have been installed since 2006, and there are more to come. "China now has more scrubber capacity than all of the rest of the world put together," says Robert Williams, a senior scientist at the Princeton Environmental Institute in New Jersey. Nitrogen oxides are likely to be next on the clean-up list.

According to the official government line, such efforts are intended to create a wealthier and more 'harmonious' society. At the same time, leaders are under pressure from an increasingly large and vocal middle class that aspires to a cleaner, more prosperous lifestyle. Also telling is that the government has acknowledged in public documents the cold economics of pollution-related deaths and disease. Pollution is likely to slash the country's gross domestic product by anything from 2% to an eye-popping 18% by 2020, depending on how successful the clean-up initiatives are, according to Ming Lei, an environmental economist at Peking University.

Those estimates do not include the potentially enormous effects of climate change. Both politicians and scientists foresee huge problems with increased floods, dwindling crop yields, and less freshwater run-off as Himalayan glaciers recede (see page 393). But only a new carbon economy or a regulatory directive from the government — probably preceded by some kind of international climate agreement — is going to change the status quo, as businesses currently have no incentive to curb CO_2 emissions. "Unless you tell them this will make them money, then they say 'no'," says Zhang Hai, an engineering professor at Tsinghua University in Beijing. "Nobody is a volunteer."

> "When the Chinese government says it is going to do something, it will do it." — Lu Xuedu

Fifty kilometres southeast of Beijing, in the industrial city of Langfang, China's energy economics are on display at the new headquarters and research facilities of ENN. This independent company with global ambitions is now betting big on technologies for converting coal into a substitute for diesel fuel. A visitor is driven up to the new, six-storey office building in a black company Audi, complete with tinted windows. Outside, bulldozers are clearing land for three new labs; already standing are pilot plants for coal gasification, biofuels and solar projects, as well as a solar-cell manufacturing plant. All of this has been achieved in the past year, during which ENN has hired some 4,000 employees, boosting its workforce by 20%. The facility has its own hotel, restaurant and golf course. Next up: a university.

ENN began as a rental-car company in 1989 and made its money as a distributor of natural gas and other fuels. It is now pursuing coal gasification, an old technology that glimmers whenever petroleum supplies seem threatened, and is a leader in the new wave of interest in underground gasification. At its simplest, the technique involves drilling a well, igniting the coal within it and adding oxygen; another well sucks out the resulting 'syngas', a mixture of mostly hydrogen, carbon monoxide and CO_2. The syngas can then be condensed to make liquid fuel or chemicals. Most of the early research projects in this area have run their course, although one commercial project has been operating in Uzbekistan for more than four decades. Other companies are planning projects in the United States, Canada and beyond. ENN says it has been operating two pilot projects in Inner Mongolia since last year and is now developing a commercial-scale facility.

Gan Zhongxue, ENN's chief scientist, readily admits that his company is several years behind some of the most advanced Western companies pursuing gasification technologies. ENN purchased its first gasifier from US-based General Electric, one of several multinationals

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seeking a piece of the action in China. Gan says that the company is now talking to a different US firm about a partnership that would allow ENN to deploy new technologies in the field. If it works, both companies could profit from subsequent growth and exports back to the United States and Europe.

Advocates argue that underground gasification could be one of the wisest ways to use coal, in part because it eliminates the cost — and energy — of mining and transportation. Cooking the coal in place also leaves unwanted pollutants in the ground, and any CO_2 stripped out during the chemical processing can be pumped right back where it came from. ENN isn't interested in burying CO_2 (at least not until there is money in it), although Gan is trying to diversify his energy portfolio and thus envisages using the CO_2 to stimulate the growth of algae for biofuel.

And that's the problem: unless the carbon is actually captured at its source and sequestered in some form, even the newest and fanciest coal-based liquid fuels put roughly double the CO_2 into the atmosphere compared with fuels derived from oil. China is under pressure to avoid doing exactly that, and the state-owned Shenhua Group is considering carbon capture and storage for the US$1.5-billion coal-to-liquids plant it expects to start up this year in Inner Mongolia. Shenhua is using its own technology to convert some 3.5 million tonnes of coal into diesel and other transportation fuels, equivalent to more than 24,000 barrels of oil per day. The plant will also recycle water and waste products, making it cleaner than older coal-to-liquids technologies, says Julio Friedmann, a researcher at Lawrence Livermore National Laboratory in Berkeley, California. "It's an engineering marvel."

China views the Mongolia plant as a technology showcase, and many think that Shenhua will eventually move forward with a plan to bury as much as 85% of the plant's CO_2 emissions. Without making promises, Ren Xiangkun, Shenhua's vice-president and head of its Coal Liquefaction Research Centre, says that the company attaches "great importance" to carbon management. Coal-to-liquids projects will move forward in "close connection" with the development of carbon-capture and sequestration technologies, he says. Even if CO_2 is captured during production, however, the carbon in the fuels remains. That means the best hope is to come out neutral on greenhouse emissions.

Deep burial

The economics seem to be enough to support sequestration. Qingyun Sun of West Virginia University in Morgantown is working with Shenhua and the US Department of Energy on the project, and says that the plant will make money as long as the price of oil is above $45 per barrel. Capturing and storing carbon emissions adds another $5–8 per barrel, but with the oil price hovering at around $130 per barrel, "that is still very profitable", Sun says. Nearby oil and gas fields could hold some of the extracted CO_2, but with volumes exceeding 3 million tonnes of CO_2 annually — larger than any sequestration project in the world so far — the ultimate target will have to be saline aquifers or deep coal seams.

Any lessons learned here might need to be applied throughout the industry. Shenhua's plant isn't even on line yet, and the company is already planning an expansion. Shenhua is also

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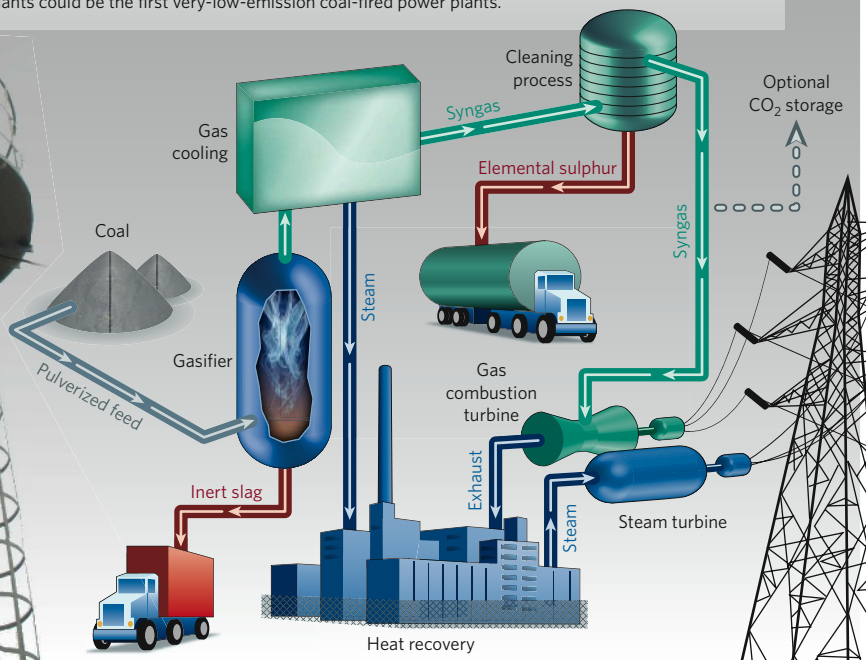
TACKLING EMISSIONS

While China works to retrofit conventional coal plants with carbon-capture technology (at left, the Gaobeidian plant in Beijing), others are working to design a next-generation coal-fired plant that sequesters most of its CO_2 emissions. Below is an outline of how an 'integrated gasification combined cycle' (IGCC) works. With the optional step of capturing and sequestering the CO_2 given off, IGCC plants could be the first very-low-emission coal-fired power plants.



Kicking the coal habit

Wei Fengrui lifts the metal lid off of an old coal-fired water boiler in a shed attached to his house. Inside are jagged lumps of coal. Two years ago he spent the equivalent of US$430 on several tonnes of coal to heat his home in Erhe Zhuang, an hour southwest of Beijing. Last winter he was able to cut his bill in half while boosting the average inside temperature from 12 to 17 °C. The trick? Insulation and double-glazed windows.

"I'm very happy," says Wei, a farmer. "It saves energy, and the rooms are warmer."

Wei's home was one of the first ten to be retrofitted under a new project led by researchers at Tsinghua University in Beijing. The team hopes to have the entire 200-residence village outfitted by next year. Insulation alone could cut coal consumption in half. If the researchers can get a facility for manufacturing pellets of biomass fuel off the ground, the village might well be able to kick the coal habit altogether, conceivably making it China's first village to wean itself off coal.

Saving a tonne or two of coal here and there might seem like a trivial pursuit, but China's rural areas are home to several hundred million people who collectively burn some 190 million tonnes of coal each year. This is equal to less than 8% of the nation's coal consumption, but only here would that be a small number. Just five countries in the world, including China itself, consume more than this.

Tsinghua professor Yang Xudong hopes the project could serve as a national model under a new government programme intended to "build a new socialist countryside". He says that the village — relatively wealthy by rural Chinese standards — is picking up 80% of the costs, which typically range from $2,400 to $3,000. Families can recoup their investment within five or six years, and so far the villagers have been receptive to the idea. "Coal is expensive, and they want to save money," Yang says. "Some families spend one-third of their income on coal."

Many Chinese villages already rely on crop residues and other biomass for energy, and Yang thinks that they have proved their ability to adopt new and varied energy solutions. Inside the same shed as Wei's boiler is his shower; a hose runs through a hole to the solar water heater on the roof. The television in his living room is a sure sign of modernity, but his bed doubles as a stove; in the winter he builds a small fire in a chamber underneath his mattress.

Switching to a new generation of high-efficiency biomass stoves would also reduce indoor air pollution, which is responsible for an estimated 380,000 deaths a year, says Kirk Smith, an expert in rural energy at the University of California, Berkeley. In some places, he says, the entire village population has been disfigured by the use of what he calls "poisonous coal" — that contaminated with fluorine and arsenic. "The simplest kind of coal stove you see, I don't think it's changed since Genghis Khan," Smith says. "This is the time to solve the problem. We've got the technology, we've got the know-how and we've got the money." **J.T.**

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Coal blocks are used as fuel.

partnering with South African coal-to-liquids giant Sasol to build another pair of plants that could each produce 80,000 barrels of fuel, or 3.4 million tonnes, per day. In all, seven coal-to-liquids plants are under construction in China, according to Sun, and many more are in the planning stages.

China has also been given an opportunity — one that it didn't ask for — to lead the world in developing the first low-emission coal-fuelled power plant, by coupling coal-gasification technology with carbon capture and storage. Integrated gasification combined cycle (IGCC) is a leading technology at present because the gasification process strips out conventional pollutants and produces a clean gas to generate power (see graphic). The two-stage electrical generation converts more energy into electricity, and the plant can be configured to produce a relatively pure stream of CO_2 that can be siphoned off — for a price.

Until earlier this year, the United States had been the assumed leader in the race to build the first IGCC plant with carbon capture. But in January, the US Department of Energy cancelled the signature project, called FutureGen, citing disputes with its industry partners over the $1.8-billion cost. The decision baffled and angered Chinese officials and scientists at the Huaneng Group, who were partners in the project. "This will not happen in China," says Lu Xuedu, who handles global environmental affairs as deputy chief of China's Ministry of Science and Technology. "When the Chinese government says it is going to do something, it will do it, surely."

Race for the future

With FutureGen off the table (at least in its original design or until the White House has a new occupant), the race is on between China and Australia to build the first plants. In China, Huaneng is leading a consortium that hopes to complete a 250-megawatt pilot IGCC plant by next year, then commission by 2015 a 400-megawatt plant complete with hydrogen production, fuel-cell electricity generation and carbon sequestration. Total cost: $1.5 billion, almost entirely funded by industry, although project officials say that figure could rise. The final permit has yet to be approved by China's National Development and Reform Commission (NDRC), but 'GreenGen', as it is known, has already — unofficially — broken ground along the coast in Tianjin, south of Beijing.

"China has an extensive base of real-world gasification experience."
— John Thompson

The Australians are taking a different approach with the Aus$1.2-billion (US$1.17 billion) 'ZeroGen' IGCC plant in Queensland. Project managers aim to commission a 115-megawatt pilot plant with 75% CO_2 capture and storage by 2012, followed by a 400-megawatt unit with 90% CO_2 capture by 2017. ZeroGen has already brokered agreements with local landowners and begun drilling test wells into a saline aquifer. "If we can crack it, then that has the greatest commercial application all around the world," says Chai McConnell, corporate affairs manager for the ZeroGen consortium.

Aside from GreenGen, the Chinese Ministry of Science and Technology has supported several demonstration projects that target either IGCC or 'polygeneration', which uses gasification technology to produce both power and chemicals. In addition, companies have submitted at least a dozen other IGCC applications to the NDRC, according to multiple industry sources. All these projects are pending, generating endless speculation, but few within the coal industry expect the government to approve them all. Lu thinks that as few as one or two will make it through. That's not nearly enough to make much of a difference in terms of overall greenhouse-gas emissions, given that China could bring hundreds of coal-fired plants on line in the coming years.

The problem is the cost. An analysis by Gallagher and her colleagues suggests that IGCC capital technology costs upwards of 50% more than pulverized coal in China — and that's without adding carbon capture and storage. Advanced coal power plants thus need more

government subsidies or higher electricity costs, which in turn eat into government priorities such as poverty relief and economic growth. Lu says that many companies are ready to take the lead on IGCC technology, but the government has to make its own decision. If companies fail, he says, "they come to the government saying, 'give me the money'".

Irrespective of how these initial IGCC plants fare, China will continue to develop its expertise in gasification technologies for producing chemicals. In some cases, these plants might even deploy small-scale power production on the side, a trend that some experts think is already under way. A new gasifier patented by East China University of Science and Technology, for instance, has been licensed at nearly 30 plants in China, according to the Clean Air Task Force, a US-based environmental group. "What China has going forward is an extensive base of real-world gasification experience," says John Thompson, who handles coal issues for the group. "That counts for a lot."

Even as new coal-fired plants come on line, the old ones might eventually need to be shut down or retrofitted with carbon-capture equipment. China and Australia are collaborating on several retrofit projects, including the Gaobeidian plant and some in Australia. Plenty of other pilot-scale projects are under way around the world, but the United Kingdom might well be the first country to implement post-combustion capture on a large scale. Last November, the UK government launched a competition to demonstrate 90% capture and storage on a 300–400-megawatt plant by 2014. This is also the only candidate to meet the criteria for a broader call by the European Commission for upwards of a dozen commercial-scale coal power plants with carbon capture and storage by 2015 (it's not yet clear, though, where the money will come from).

"This is what I like about GreenGen. The Chinese government decided 'we will do this' and it will be done. We in Europe rather dither about it," says Derek Taylor, who works on energy issues at the European Commission. "We've had projects announced in Europe, but none of them is that far down the line. Politicians are quiet when it comes to spending massive amounts of money on it, but massive amounts of money need to be spent."

"Politicians are quiet when it comes to spending massive amounts of money."
— Derek Taylor

Carbon credit

In the end, the issues faced by all these technologies are who pays, and how much. One possible source of money is the Clean Development Mechanism (CDM) of the Kyoto Protocol, which allows companies in developed nations to pay for projects that reduce emissions in developing countries. But the sums of money currently changing hands are too small. Contracts under the European emissions-trading scheme could bring in roughly $7 billion in credits to China between 2008 and 2012. That might be a hefty figure but it's not enough to affect broader energy trends in China, says Fu Ping, who works on the CDM programme under the Chinese finance ministry.

Moreover, the CDM programme would need to be revised and ramped up if it is to work for even one integrated carbon-storage project. First of all, it cannot currently be used to promote underground carbon storage, simply because the rules and regulations are not in place. Fu says that the United Nations, which administers the programme, has already had talks about changing that, but it might not make much of a difference until the prices for carbon storage and credits converge. CO_2 credits currently sell for $13–20 per tonne on the primary market in China, he says, and estimates for the cost of storing CO_2 from coal-fired power plants generally hovers around $50 per tonne.

Last year, the Bush administration proposed an international fund for direct investment into these types of technologies. The idea has garnered international support among the G8 leading industrialized nations, which have so far committed roughly $6 billion. Such a fund could be used to support clean-energy projects and, in the case of China, help pay for the additional costs of managing CO_2 emissions. The World Bank would manage the fund, but no decisions have been made on exactly how much money there would be or how it would be administered. Harvard's Gallagher has been advocating this approach for some time, arguing that a simpler and more aggressive tool than the CDM is needed to change the development pattern in China and other developing countries.

One idea being aired in climate circles in China is that the country could halve its energy intensity by 2020, then commit to levelling out emissions in the subsequent decade. A similar idea arose last year in a study sponsored by WWF China and headed by Lu and other government officials. That document also pegged the necessary investment in clean-energy technologies at roughly $220 billion. Lu plays down that number, pointing out that everything that everybody, including the Chinese, thought they knew about energy development in China five years ago was wrong.

He is also confident that China can and will tackle the problem one way or another. But if the goal is a rapid transition to a green economy, he says, the West would be wise to open the money spigot a little wider and send along its best technologies as well. "We need help," he says. ■

Jeff Tollefson covers climate from *Nature*'s Washington DC office. To hear him talk about coal in China, download the 24 July podcast at www.nature.com/podcast

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