LIVING WITH COAL

Climate policy's most inconvenient truth

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Governments around the world are now struggling with the question of how to reduce emissions of the greenhouse gases that cause global warming. The task is bigger than any other environmental challenge humanity has faced. Carbon dioxide, the leading human cause of global warming, is an intrinsic byproduct of burning the fossil fuels that power the world economy and thus difficult to regulate.

All fossil fuels emit carbon dioxide when burned, but the real heart of the warming problem is coal. Emissions from coal are growing faster than from any other fossil fuel. Beyond greenhouse-gas pollution, coal is linked to a host of other environmental troubles such as local air pollution, which is why a powerful coalition of environmentalists in the richest and greenest countries is rallying to stop coal. Mired in opposition, barely any new coal plants are being built anywhere in the industrialized world. Coal, it may seem, is on the precipice.

Yet coal remains indispensable. No other fuel matches its promise of cheap and abundant energy for development. About half the electricity in the United States comes from burning coal. Germany, the anchor of old Europe's economy, is a coal country. Poland, the heart of new Europe, gets 90 percent of its electricity from coal. The fast-growing economies of Asia, in particular China and India, are all coal-fired. Indeed, while the outlook for coal consumption in the industrialized world is flat, soaring Asian growth is expected nearly to double world consumption by 2030.

The central task of any serious (and politically viable) global-warming policy, then, is to reconcile these diverging patterns. Measured by this standard, the world's leading governments have barely begun to get serious, as the troubled efforts to negotiate a successor to the Kyoto treaty, which expires in 2012, have revealed. The largest hurdle is reaching agreement on the division of efforts between the highly industrialized and the still-emerging countries. The rich industrialized nations account for most historical emissions and seem to care the most about global warming, yet essentially all growth in emissions now occurs within the emerging countries. China is, by far, the world's largest coal burner and therefore the world's largest emitter. A host of new technologies make it possible, in theory, to burn coal while safely burying nearly all the pollution underground; "carbon capture and storage" plants using this technology are the industry darlings. But enthusiastic talk about such technologies notwithstanding, real investment in this very expensive option is a bare whisper.

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Coal thus sits at the center of the most inconvenient truth about global-warming policy: the countries that proclaim greatest concern about global warming are barely investing in the new coal plants that could help chart a better path for the world. Meanwhile, the fastest-growing countries have few incentives to invest in new climate-friendly technologies. And simplistic solutions, such as banning coal outright, are politically naïve because the fuel is so easy to use and offers the cheapest way to electrify most of the world.

Coal has been the fuel of choice for industrial economies since the early nineteenth century, when fossil fuels began to power growth. Initially, most coal was moved to where it was needed and burned directly in industrial boilers, at steel mills, on railroads, and in homes and offices. But because it was dirty and cumbersome, governments and industries found ways to keep the coal away from the people and move just the useful energy. New industries arose to heat coal, which transformed it into a less polluting gas that could be moved into towns and cities by pipe. The round brick buildings that still stand in the outskirts of towns across New England and Europe are a legacy of these early coal-gas companies.

Electricity proved the best way to move the energy from coal to where it was needed. It is much easier and cleaner to wire power to the customer than to send railcars of lumpy coal. When the National Academy of Engineering in the United States marked the millennium by ranking the most important industrial innovations of the twentieth century, it put electric power on top. Looking to a future where computers and other electric appliances dominate nearly every aspect of economic life, electricity is likely to be even more essential. Even in transportation, where oil has enjoyed a near monopoly, electricity is making tentative inroads with electric cars and better batteries. The future is electric. And, in most of the world, coal offers the cheapest way to make electric power.

Coal's advantages as a fuel derive from basic geology. Oil and gas are relatively scarce because they arise only under special circumstances. Most oil fields, for example, form only when the baking and cooking of ancient plant matter underground creates liquids that persist because an impermeable "cap rock" keeps them in place. The best oil fields in fact require a trifecta of well-cooked plants, large cap rocks, and a lot of subterranean gas to keep the stuff under pressure and easy to extract. As a result, the least expensive oil and gas supplies are concentrated in a handful of countries.

Coal does not require such lucky geology. The world's coal resources are distributed more liberally across the planet. (That is why few policy planners lose sleep worrying about dependence on foreign or flaky coal suppliers.) To be sure, the distribution of coal is not uniform. Measured by what is in the ground, and assuming today's technology and levels of consumption, the United States is particularly well-endowed, with about 250 years of coal on hand. But China and India also have considerable resources; so, too, do Australia and Russia. In fact, nearly all the world's major economies—France and Japan are among the few exceptions—have become powerhouses by tapping prodigious local coal deposits. Aside from being widely dispersed, coal does not move by itself (it needs no cap rock to hold it in place) and is easy to extract (no gas is needed to pressure it to the surface). The fuel is plentiful and sits ready for easy digging.

Nobody is sure just how much is buried around the planet. The World Energy Council estimates "proven reserves": what is surely on hand and recoverable at a reasonable price. Worldwide, proven reserves give the planet around 120 more years of coal. (The best estimates for proven reserves of oil and gas are 42 and 60 years, respectively.)

But total resources are always much greater than the proven reserves that accountants and bankers allow on the official books. In the coal industry, this gulf is likely to be particularly large because the fuel is so plentiful that there have been few incentives to hunt for more. In Indonesia, where efforts to find coal are still underway and miners often just dig the coal out rather than formally prove its existence, the country's total resource is destined to be two or three times larger than what accountants recognize as proven. Much of Indonesia's unproven coal resource is probably on Kalimantan and Sumatra, where the coastal areas are rich in coal and few have bothered to look further inland under the tangled, interior jungle. China, the world's largest coal user, has only about 40 years left of proven reserves on its books, but that country, too, is barely surveyed and likely to hold much greater reserves.

In addition, official statistics often poorly estimate very low–grade coal, known as lignite or "brown coal." Historically, brown coal has been a dirty stepchild of black coal—harder to burn and often laden with a nastier array of pollutants. Today, better power plant technology is

making brown coal a worthier competitor, and larger amounts of it will likely enter the ranks of proven coal reserves. Eastern Europe is littered with the stuff, and German companies are intensively pursuing efficient ways to burn lignite at competitive costs.

Because geology makes coal so easy to find, commercial success in the coal industry largely hinges on the logistics of mining and transporting the fuel to markets.

The popular image of coal mining conjures blackened faces, hard hats with grimy lamps, and the occasional vigil for miners trapped underground. Underground mining is indeed dangerous, which makes it unattractive for miners who have other job opportunities. It is also expensive, which makes it unattractive for investors who can find higher margins in less risky pursuits. This style of mining survives where the quality of the coal compensates for the effort: in the United States, that means Appalachia. But even there, in the heart of America's underground mining industry, "mountaintop removal" is becoming more common as a way to access deeply buried coals. Moreover, the eastern coal industry in the United States, a chief backer of railroad regulations that kept easier-to-mine western coal from markets, has been on a long, final slide since 1980, when deregulation hit the railroads. Although the energy in a pound of Wyoming coal is only two thirds that of the best Illinois or Appalachia coals, cheaper and more flexible rail rates help make it practical to send these western coals long distances. Western coals are also generally less laden with sulfur, a nasty pollutant.

Most of America's coal now comes from huge, open strip mines in the West, where a ton of coal can be extracted at barely one-fifth the cost of underground mining. The coal industries in China and India are seeing a similar revolution unfold—made possible because working above ground allows mining at a massive scale. Modernization of old state-owned mining companies along with cheaper labor explain why the best Chinese and Indian mines perform at even lower cost than their Western counterparts. (The worst are known for bloated payrolls, hazardous conditions, and massive cost. India's worst-performing state-owned mines need roughly five times the workforce of the best mines in order to achieve the same output.)

The much lower cost of open-pit mining comes from a host of innovations and opportunities. Better explosives, bigger draglines—giant cranes that drag buckets of dirt out of the way—heftier dump trucks to haul the coal, and smarter computer systems to link these components into a fiercely efficient organism have helped drive down costs. This equipment requires huge amounts of energy, and the best mines electrify all they can because electricity (when powered with coal) is the cheapest source of motion. Ever larger and smarter mine systems promise still-lower costs in the future.

These major improvements in efficiency work in tandem with better logistics that make it cheaper to transport coal to markets. These forces are transforming the coal industry from a series of national and regional outfits into a global enterprise.

In the mid-1970s less than 300 million metric tons of coal moved annually across international borders. Most of that was in specialized markets, such as coal Soviet planners ordered around the railroads that linked Eastern Europe's closed economies and, especially, highly pure (and valuable) coal used for making steel. Since then international trade in coal has tripled, and essentially all the growth has come from shipping lower-grade coals for power plants—so-called steam coal—ever larger distances by boat.

Demand for steam coal has risen so quickly that it has forced many countries to look abroad for new supplies. Countries with little coal at home—notably Japan, Taiwan, and Western European nations—have been the lead investors in global coal trading. All have secure contracts that deliver distant coal to their shores. Investments in coal infrastructure financed with these long-term contracts have allowed integrated companies to build an ever-larger global enterprise for coal trading while finding ways to cut costs throughout the chain. Thus even traditional coal powerhouses find themselves unable to compete with more recent entrants. In Germany, for instance, importing coal mined in South Africa or Columbia costs less than paying high wages to German miners to extract difficult and increasingly scarce local coals.

As the coal trade has gone global, so has coal pricing. In just the last decade, spot markets for coal have sprung up in Europe and Asia. Prices in those markets, though physically separated by more than ten thousand shipping miles, are often tightly correlated. As markets have connected, the flows of coal have chased the best price. In the summer of 2008, a spike in European coal prices attracted coal traditionally bound for east-coast U.S. markets. At times, a cheap cargo from Australia even travels all the way to dear markets in Europe. Coal is still not nearly as liquid and flexible as oil, but it is decisively headed in that direction. In fact, as with oil markets, trading of coal derivatives in European markets has surpassed trade of the physical commodity.

Global coal markets are forcing some rethinking about "energy security." According to conventional wisdom, which has been forged mainly through experience with oil, dependence on foreign energy suppliers is dangerous. Indeed, most big oil consumers—such as the United States, Europe, China, Japan, and India—rely heavily on imports and live with the constant worry that suppliers will cut them off. Countries that depend heavily on gas imports have similar insecurities. Europe gets about one-third of its natural gas from Russia, which has twice cut off supplies in the last four years—always in January, when contracts expire and cold temperatures serve as a reminder of Russia's leverage.

In contrast, by allowing more diverse sources of supply, a global coal industry offers greater security, while making the fuel more competitive with its rivals. Because most coal is still supplied locally, coal insecurities usually reflect local troubles such as unreliable mines and railroads. (That is one reason why most power plants keep a 30-day supply of coal on hand.)

Today, the country most visibly grappling with coal security is India. About 70 percent of Indian electricity is fired with coal, and that fraction is likely to grow. But the Indian coal-supply system is famously unreliable—for reasons of politics, not geology. Much of the coal is spread across the eastern part of the country, which is plagued by rebellions, most famously the communist "Naxalite" insurgency. Many of the richest coal deposits are in forests where India's strong environmental and property laws make it hard to get clear title and permission to mine. The railroads, which move most of the coal, are badly run and unreliable because they have been financially insolvent and rely on high tariffs for moving freight to subsidize politically popular low fares for moving people. Thus, coal power plants that are far from the mines have faced surging demand for power and thinning fuel supplies. While others are worrying about global warming, India's energy elite fret mainly about how to secure enough coal to meet the ambitious national goal of sustaining economic growth at 8 percent per year.

Imports provide one solution to India's coal troubles. The Indian government is now encouraging private investors to build fourteen "ultra-mega" complexes of power plants. All would be coal-fired, and roughly half would rely on imports. The first project that is likely to be built—sponsored by the Indian conglomerate Tata and located at Mundra in the western state of Gujarat—would import coal from Indonesia. For Tata, shipping coal from Indonesia is more secure and cost-effective than purchasing it within India. If others follow Tata, India could become the world's largest coal importer in the next two decades, a shift that could dramatically divert traditional European energy supplies into Asia.

Other countries are pursuing similar logic in the global coal market, though at smaller scale. Plant managers in southern China import some of their coal from Vietnam, Indonesia, and Australia—from suppliers that are, at times, more reliable and less expensive than the Chinese competition. Similarly, power companies along the Gulf Coast in the United States buy coal from Colombia, which is safer than relying wholly on coal from Wyoming sent over 1800 miles of rail track. When the Midwest flooded in the summer of 2008, the coal trains that are the lifeblood of the electric power system across the Midwest and southern parts of the country slowed (and stopped for a time). In the Middle East, Abu Dhabi and Saudi Arabia (among others) plan to build power plants fired with imported coal, rather than burning local supplies of more valuable natural gas and oil.

As coal goes global, some countries stand to gain more than others. In part, the geopolitics of coal will depend on proximity. South Africa is a pivotal player because its coal mines—which are linked by rail to

A Food We Once Ate Is Mentioned by Name

And we are filled with a fog-like discontent.
And we are unsure of even the personal value of our observations.
It's as if we're asking one another to sleep in small beds built for children.
It's as if by walking we're disfiguring those underground.
Being present at the initial event was deemed unsafe in October 2000.
Being present was like holding sparklers that wouldn't go out.
When we lost Gold River, the trees became metaphysical and our brains wooden.
When we forgot our families' faces, we became more lovely at sunset like a toxic cloud.
Dogs were everywhere, sniffing and tracking, and a wonderful thing happened.
Dogs were nudging us to get up, it was wet, we looked down, and a wonderful thing happened.

Afterward, new role models better demonstrated not knowing those we love.
Afterward, with needles, we made our symbiosis more frankly biological.
Once again our former home is preserved inside the mountain on which we've awakened.
Once again each speck of dirt is a frontier.
What will be tossed down the well?
What will be the first words of the covenant because that's all we'll remember?
The dead and the living hang from each moment like bats.
The dead and the living are a pattern that can be hummed.
Now even I am being held in someone's arms and it turns out the river is a type of bone.
Now even the dead, when seen from close enough, turn out to be moving.

—Catie Rosemurgy

the world's largest coal-exporting port, in Richard's Bay near Durban—can send coal west into the Atlantic Ocean or east to India. India imports from South Africa and Indonesia, and Indonesia—the top coal exporter today—ships coal to China, Japan, Korea, and Taiwan. But geography alone does not determine which countries will dominate the global coal market. Indonesia's coal-mining regulations are unreliable, which makes investors wary about committing the long-term funds that enable a world-class coal industry. Australia, much further physically from many lucrative coal markets, is politically and economically at the epicenter of the globalizing coal industry. Indonesia's political instability is Australia's competitive advantage in the geopolitics of coal.

South Africa, too, is a wild card in coal geopolitics, as it struggles to muster the investment needed to expand its industry. Russia's role in global coal is similarly precarious. In the Soviet era, Russian coalfields were artificially "closer" to big markets in Europe because planners greatly underpriced the cost of railroading. Higher, more realistic rail rates have now landlocked Russia. Private investors see huge risks in upgrading Russia's infrastructure.

Clean coal technologies remain more prevalent in PowerPoint presentations than power plants. Putting a price on emissions is necessary for encouraging investment.

Every stage of the coal business is hard on the environment. Clearing and moving such huge amounts of material releases dust; transporting it by truck and train releases still more dust. Some mines catch fire, which wastes coal and produces pollution. Every year, up to ten million metric tons of coal go up in smoke in India's coal mine fires. Some underground coal fires have burned for more than a hundred years. A few mining practices are particularly damaging, such as mountaintop removal, which harms both the mountain and the stream valleys where the blasted tops are sometimes dumped. That approach to mining now accounts for the balance of the coal mined in central Appalachia because it is much cheaper than digging tunnels, and it has earned most of the environmentalist ire in the region. (The Obama administration, in one of its first environmental policies, tried to raise the hurdle for licensing new mountaintop haircuts. The move was unpopular in Appalachia, most of which did not vote for Obama, but an easy victory for environmentalists.)

However, mining's visible scars are not coal's most troubling impact. Indeed, coal mining, measured by its footprint, is not much different from other parts of the energy business. A large, world-class coal mine—such as those in China, Australia, and Wyoming—actively mines an area of about 25 square miles and generates on average about 30–100 million tons of coal per year. A wind farm sitting on the same surface area, even with stiff winds, would probably deliver less than one percent of that annual energy output. And the footprint of a mine is not always lost, since open pit mines are usually required to recover their handiwork so that, in time, the land (sitting a bit lower after the rich coal seam has been removed) can revert to farms or pastures. Most mining is far from people and the footprint and local environmental effects are not decisive.

The real trouble with coal is combustion, and the first problem with combustion is pollution.

Roughly speaking, societies have tried to cut pollution from coal combustion on three tracks: by making energy systems more efficient, by switching away from coal to rival fuels such as natural gas or renewables, and by finding ways to burn coal more cleanly.

California, for example, has been on the efficiency track for some time. An aggressive program that began in the 1970s has helped keep per-capita power consumption about flat even as demand for useful energy services has risen. Success has come on a thousand fronts by opening a million wallets. Regulations require companies to supply new refrigerators and air conditioners that are much more efficient than the old ones. Towns and cities have installed better traffic lights that use one-tenth the electricity of the old lights with incandescent bulbs, and the lights last longer, which saves maintenance costs as well. Some of the policy success has come from convincing Californians to conserve energy, but most is from finding clever ways to provide the same energy services while using less power. New electric meters and pricing systems promise still more savings in the future. It has been hard to pin down exactly what California's energy efficiency costs, and smart analysts disagree over how much of the state's savings is due to policy instead of other factors. But the achievement is hard to ignore.

In much of the world, renewable energy—geothermal, wind, and solar—has been the chief beneficiary of efforts to shake fossil fuels. With today's technologies, most bets for renewable power focus on wind. But two major constraints still prevent wind from achieving the kind of massive inroads into the world's power grids that would substantially reduce the combustion of coal. The first is financial: wind, like most renewable energy technologies, thrives in part because consumers generally are not exposed to its full costs. Where wind is expanding most rapidly, it relies on large public subsidies. On the Texas power grid, which has the largest penetration of wind power in the United States, power prices are, at times, negative. Yet wind generators happily sell their product at a loss thanks to the gen-

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erous subsidies. Subsidies were originally intended to help wind (and other technologies) gain a foothold in the market, but the industry is still not viable without them. As wind installations grow, so will the cost and visibility of these subsidies, raising questions about their political sustainability.

The genuine cost of coal, too, is opaque to the consumer. However, while measuring all the externalities of any power source is very difficult, coal today seems to be competitive even at its full cost. For example, if coal generators paid more than twice the carbon dioxide penalty envisioned under legislation in Congress right now, society would still find it cheaper to build new coal plants than to harvest the wind in most places. The near halt in new coal plants across the industrialized world is largely the result of regulatory and political troubles, not raw economics.

The second constraint, which is technical, is even more difficult to overcome. Reliance on large amounts of wind and other intermittent renewable power poses new demands on electric grid operators. The North American Electricity Reliability Corporation (the power industry's reliability watchdog) has documented growing fears of grid unreliability as investors build more renewables. In Texas on February 26, 2008, a sudden drop in wind power took the near-equivalent of two coal plants offline in a period of ten minutes and almost caused massive outages across the state. While some have blamed these troubles on the Texas grid operators and the lack of standby supplies, the reality is that this event is a harbinger of things to come anywhere engineers try to integrate large amounts of wind into power grids. Bigger investment in storage to smooth supplies over the day, "smart grids" that could seamlessly switch power to where it is needed, and better-designed market incentives to match suppliers and users of power could help solve these problems. But these technologies and markets are not keeping pace with policymakers' goals for renewable power. California, for example, aims for 33 percent renewable power by 2020, up from about 13 percent today. Absent new technologies and markets, that goal will be extremely difficult to meet.

In the United States, wind accounts for just one percent of the actual electrons supplied to the power grid, although it is the fastest-growing electricity source in percentage terms. In fact, wind is the fastest-growing source in many countries, and a few other places—such as Denmark, Germany, Spain, China, and the Indian state of Goa—are investing heavily. But worldwide, wind power is just 0.7 percent of the total electric supply. Wind and other renewables will not unseat coal any time soon. In fact, worldwide, coal-fired electricity has grown more (in absolute terms) than any other source since 2000.

Only three of the world's large economies have made a wholesale shift away from coal over the last five decades. Britain fortuitously found a lot of natural gas under the North Sea. Russia, too, has found enough natural gas to make the switch from coal to gas (and some nuclear power), but it may swing back to coal as local gas prices rise. France moved from coal to nuclear power and probably has the most successful nuclear program in the world today, though the cost of that shift is uncertain because it was borne by state enterprises that operated without the hard budget constraints that make private industry more sensitive to risk and expense. All the other big coal-burning countries—such as the United States, China, Germany, and India—have made only small changes in their dependence on coal.

Thus, for most of the world economy, lightening coal's environmental impact is mainly about finding new ways to burn the fuel more cleanly. The modern coal plant is a Rube Goldberg affair, with the machinery of combustion eclipsed by an ever-larger array of pollution-control equipment. Giant filters and settling rooms—known as "baghouses"—help cut particulate pollution, a leading cause of respiratory disease. As many as half of the world's large coal plants are fitted with scrubbers, and that fraction is rising with regulation and retirement of older unscrubbed units. The scrubber, which works by mixing the plant's

exhaust with limestone, is a giant machine that can be as large as the rest of the power plant and is bolted in between the boiler, where the coal is burned, and the smokestack. A growing number of plants, though still the minority, also include elaborate chemical reactors to remove nitrogen oxides, especially when they are located near cities where those pollutants contribute to smoggy skies. Some plants now inject carbon around the scrubbers and baghouse, which helps remove toxic mercury from the exhaust.

All this gear comes at a price. Up to half the cost of a fully fitted modern plant is pollution-control equipment; compared with its dirtier ancestors, the modern plant is physically about twice the size. And running the gear saps 2–4 percent of the power plant's electricity output.

Plant operators are finding that it is also possible to cut pollution and costs by making that combustion more efficient. The most common approach involves raising the temperature and pressure of the steam that is made by burning coal. Technology of this type, known as "supercritical," converts about 40 percent of the energy in coal into useful electricity. Today's most efficient plants, "ultra-supercritical" units that sport even higher temperatures and pressures, can achieve about 45 percent efficiency. Only a few companies can master the materials and engineering needed for such plants, but the good news is that the market for power plant technology is truly global, so wherever governments have investor-friendly policies in place, the best technologies can readily flow.

China is one of the largest builders of ultra-supercritical plants in the world, relying mainly on imported technology, although Chinese versions are soon to arrive. Chinese interest in supercritical plants is rooted in smart economics—for many years, coal was cheap, but market-oriented reforms in China's coal industry, along with huge demand for the stuff, is making the fuel much more costly and supplies, at times, less reliable. All that puts a premium on efficiency. National policies are also forcing efficiency because Beijing fears that China's stellar economic output will falter if the country is not more frugal with its resources and more caring for the natural environment. Especially in the richest and most modern areas of China, such as Shanghai, pollution control is a political imperative. Most new power in Shanghai comes from some of the most modern coal plants in the world, and the Shanghai government has required all the area's power plants to install state-of-the-art digital monitors to ensure that installed pollution-control equipment operates as planned.

For three decades now, environmental regulation has focused on finding new ways to cut pollution. In a masterful study, researchers at the University of California, Berkeley and Carnegie Mellon University have shown that tighter sulfur regulations introduced in the 1970s forced radical improvements in scrubbers. In most countries, regulators tell the power plants which technologies to install, which creates the opportunity to force faster changes in technology but also introduces the danger that regulators will make bad choices. In China, which is often tarred in the West for its poor environmental record, there are more sulfur scrubbers in operation today than anywhere else in the world. Most of the country's power plants are young, and regulators are increasingly forcing them to use the latest pollution gear. A careful survey of Chinese coal-fired power plants by two MIT political scientists has shown that newer plants, indeed, are run much better than the older vintage, but much of the new pollution-control equipment still is not operating as well as it should. The survey also found that just bringing Chinese plants in line with world standards could make a big dent in that country's pollution.

A few countries have experimented with strategies for cutting pollution that rely less on regulation and more exclusively on markets. The most important has been a program to cap emissions of sulfur dioxide—one of the components of acid rain—from U.S. power plants at less than half the level of the 1980s (with still tighter caps over time). Plant operators are allowed to trade sulfur credits, which has helped cut the cost of pollution control roughly in half when compared with a less flexible system based on regulatory command. China has experimented with a similar market system in a few provinces although not yet mandated the scheme widely.

The really big environmental and regulatory challenge for coal power, however, is not local pollution, but global warming. Burning fossil fuels is a chemical reaction; the carbon in the fuels reacts with air to make a lot of heat and also great volumes of carbon dioxide. With current technology, release of carbon dioxide is unavoidable if fossil fuels are the starting point. The amount of carbon dioxide varies with the carbon content of the fuel. Natural gas is particularly light in carbon, and coal is heavy. (Gas is also cleaner on nearly all other fronts.) But coal usually wins the contest to supply electricity, especially in cost-sensitive (and less environmentally minded) developing countries. Large new supplies of natural gas may change the equation, but it is still too early to know whether such gas can be produced at the scale needed to displace coal and have a decisive effect on emissions.

Only radically new kinds of power plants can significantly decrease carbon dioxide emissions from coal. Higher efficiency will help, but even the fanciest ultra-supercritical plants will not be enough, because taming global warming is likely to require very deep cuts in emissions—a worldwide reduction of about half by 2050, according to many scientists. For the countries that care the most about global warming, a global halving of emissions means making much deeper cuts of their own so that developing countries that put a lower priority on the problem have room to grow. (Today, world emissions are divided roughly evenly between industrialized and developing countries. Levels of the former are flat, while levels of the latter are growing like weeds.)

It is feasible to burn coal without much emission of carbon dioxide, but doing so will require redesigning power plants and will not be cheap. All the strategies involve using new carbon dioxide control equipment or building a new plant from scratch to capture the carbon dioxide in pure form, which makes it relatively easy to store safely underground. Separately, each element of "carbon capture and storage" (CCS), as it is known, is familiar to the energy business. The trick is integrating all the elements from capture through storage into a single system that works reliably without causing a politically toxic rise in electric power costs. And even after mastering that technical trick, investors must still find a way to make money building these plants in the large numbers needed to make a difference.

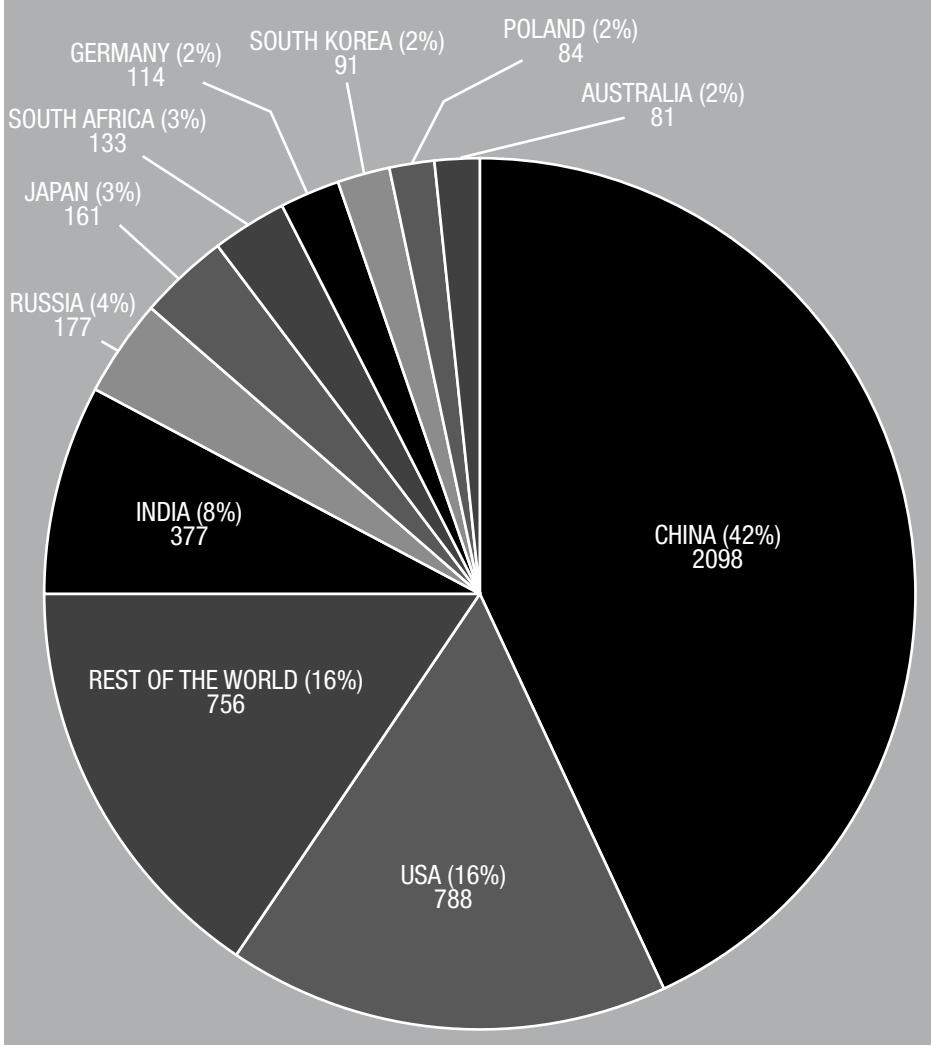
Once captured, the carbon dioxide must be stored in a way that prevents its release into the atmosphere over hundreds of years. Such storage is technically straightforward, although no one is sure how to guarantee against accidental releases in the distant future. Already the oil and gas industry injects large quantities of carbon dioxide underground to help push more oil out of aging fields. Oil companies pay handsomely for that carbon dioxide: for example, companies mine the carbon dioxide from natural underground formations in Colorado and ship by expensive pipeline across New Mexico to the Texas oil patch. The first few power plants to capture their carbon dioxide could tap this lucrative market, which initially would help offset the high cost of capture.

Looking to the future, the really big opportunity for storing carbon dioxide lies in injecting the pollution deep underground in the salty aquifers that cover much of the planet. Compared with capture, storing carbon dioxide is cheap and will probably account for less than 10 percent of the cost of fully integrated CCS systems. But injecting such huge volumes of pollution will push frontiers in law and pipelining. In places where mineral rights are privately owned, as in most of the United States, securing property rights for huge underground areas is largely uncharted legal territory. (Some states, generally those with industry-friendly oil and gas commissions, are already working out the details.) If some states will not allow underground carbon dioxide storage, then the gas might have to be moved to friendlier states through a huge new network of pipelines, potentially larger than the entire existing U.S. interstate gas pipeline system. If legal entanglements prove too formidable, power plants could be built on top of the nation's most welcoming carbon dioxide storage sites, sending electricity to distant customers over a vastly larger and longer electric power grid. Engineers can imagine many solutions; what lawyers and local politics will allow remains less certain. But even the engineers will find daunting the sheer volume of carbon dioxide that must be moved and stored if CCS is implemented at scale. In the United States, for example, widely deployed CCS would require moving and storing ten times the carbon dioxide currently handled in the country's entire oil industry.

The pivotal issue for CCS is cost. Schemes that would bolt on new equipment to capture carbon dioxide from smokestacks are expected to double the cost of plants. This option is nonetheless attractive to the power industry because it could be added not just to new plants but also retrofitted to existing units. However, installation will not even be possible at physically hemmed-in power plants where bulky new gear just won't fit. If used, the monster equipment must be fed with heat and electricity. Nobody is quite sure how much extra fuel

Coal Consumption in 2008

Consumption by country and share of global total (in millions of metric tons)



Source: International Energy Agency Coal Statistics 2009. Consumption is expressed in "million tons of coal equivalent" and has been normalized by the IEA to reflect differences in coal qualities. Numbers may differ from national estimates.

ILLUSTRATION BY BRAD LARRABEE

will be needed to make coal clean this way, but estimates suggest that one-quarter of all coal will power CCS alone. (Still, coal is so cheap that this option may still be less expensive than building big nuclear plants or massive wind farms.)

The costly inelegance of bolt-on capture has inspired other attempts to clean coal. For example, the coal might be burned in pure oxygen, which would yield a more purified pollution that is easier and cheaper to handle. The best ways to make pure oxygen are still costly, but improvements are on the horizon. A plant in Germany started testing a new oxygen strategy in late 2008, but its efforts were hindered by community opposition to underground carbon storage. A perennial obstacle to the environmental movement is the "not in my backyard" (NIMBY) mentality, but carbon storers are now confronting "NUMBY," as neighbors worry about what is under their property.

Another leading contender in cleaning up coal gasifies the fuel by running it through the same kinds of ultra-efficient turbines found in the best natural gas plants. These gasification plants are much more efficient than standard coal-fired steam boilers, and the gasified coal is useful not just in making electricity but also in manufacturing a variety of chemicals.

So-called integrated gasification combined cycle (IGCC) systems look sexy to engineers who have a lot of experience gasifying fuels in the chemical industry. But they make the electric power industry uneasy because their reliability is untested. Bankers are also nervous. Without more practical experience, the cost of IGCC cannot be pinned down, but best guesses predict a 2-3 cents-per-kilowatt hour increase in the cost of generating electricity. That does not sound like much, but real retail power prices have been roughly flat since the early 1970s at about 8 cents per kilowatt hour. Any rise is likely to engender strong political blowback—no modern environmental regulation has visibly increased retail power prices by more than a few tenths of a cent.

Because the costs are high, and because so few governments have made serious efforts to cut carbon, IGCC and other clean coal technologies remain more prevalent in PowerPoint presentations than power plants. Putting a price on carbon dioxide and other emissions is a necessary first step to encouraging more real investment. A few small jurisdictions have adopted carbon taxes over the last decade, but the European Union is the only major economy to adopt a system-wide strategy. The European Union's approach is "cap and trade," similar to the scheme that the United States is using to tame acid rain. It is a start, but it has not had much direct impact on coal technology because carbon prices are still too low. CCS technologies will probably require a reliable price on carbon of about $50-$100 per ton in order to be economically viable. So far, the European cap-and-trade system has delivered volatile prices barely one-third that level. (The recession has sapped demand for energy, and thus the price of carbon dioxide credits has plummeted to about $15.) For most of the time since the European carbon trading scheme began in 2005, prices have not even been high enough to offset the much cheaper cost of coal relative to natural gas (even though gas-fired power plants emit half as much carbon dioxide, they are usually more costly to run). And to keep the well-connected coal and power lobbies at bay, most of the emission credits in Europe have been given to existing emitters for free, creating little incentive to change investment patterns. In the current round of trading, which ends in 2012, some of the biggest power companies have actually made large profits by pocketing the value of their free emission credits. European regulators are fixing this problem and plan to charge emitters more fully, while also subsidizing investments in low-emission power plants. At this writing, the United States is crafting its own cap-and-trade legislation to put a price on carbon dioxide emissions.

Current carbon pricing alone will not justify investment in coal plants with radically lower emissions. Beyond a few demonstration plants, no investor is willing to pay the high cost of the first plants that might prove to engineers, bankers, and utility executives that the technology works. In the past, governments provided guarantees for first investments and subsidies to shepherd nascent technologies to market. The nuclear power industry, among many others, got its start this way. Applied to coal, that lesson dictates that CCS will be stillborn until governments offer more credible funding commitments. The U.S. government had hoped to take the lead in launching IGCC and CCS with a "FutureGen" project in coal-rich Illinois, but the Bush administration, in its twilight, pulled the plug when costs soared, and the government lost sight of the dangerous politics of crossing big coal. (The Obama administration is reviving the project.) Private investors watch such experiences and wonder if fresh promises to spend more on clean coal, as in the February 2009 economic stimulus program, are credible. Australia, Canada, the European Union, and China have better track records thus far in following through on clean-coal programs. The first movers in clean coal may have less to do with good engineering and more with governments acting on their commitments. But the current promises from governments worldwide are probably not big enough to make clean coal commercially viable.

Many politicians and titans in the coal industry expect that clean coal will begin deployment widely in the next decade as the technology is proven viable. We expect a much slower rollout because the technical and financial obstacles will take time to clear. Introducing large-scale, risky, expensive technologies is extremely difficult, and the history of that process suggests that no more than a dozen commercial-scale plants will be built by 2020. With luck and diligence, clean coal might account for 3-5 percent of the coal fleet by 2030. Many scientists, concerned about urgent dangers related to global warming, are uneasy with such slow rates of change. But industries such as electricity that depend on costly, fixed infrastructures tend to evolve slowly. In the meantime, conventional coal plants will continue to be built around the world, probably locking in several future decades of greenhouse-gas emissions.

Because coal is ubiquitous, its future depends on dozens of policy decisions taken by many governments. "Global" coal

policy will arise from the bottom up rather than through some grand strategy. But one country, China, holds the key position. China's coal consumption dwarfs all others. The second-place U.S. coal industry is only about one-third the size. India's coal industry is barely one-fifth the size of China's.

While acknowledging the uncertainty that pervades any effort to predict the future in an economy that changes as quickly as China's, the International Energy Agency in Paris expects that two out of every three new tons of coal mined in the world will be for China. Indeed, China's coal-fired economy is growing so rapidly that about one-quarter of China's coal plants are less than seven years old.

It is hard to envision any path for China that does not hinge on coal combustion. None of the alternatives can expand at the scale and speed needed to make much of a difference. After coal, hydroelectric generation is the next important source of electricity. Tens of thousands of small hydro dams have helped China electrify more rural people—about 500 million in the last 30 years—than any other country. But small hydro does not scale easily. And big hydro, historically cheap, is getting very expensive and controversial. The giant Three Gorges dam project required moving one million people and incurred nearly twice the capital cost of the same coal-fired capacity; it also has a heavy footprint on the local ecology. China's aggressive wind development will likely make it the fastest-growing market for wind power in 2009, but Chinese power grid operators do not like patchy, intermittent power any more than their American counterparts do. Power grid upgrades in the Chinese stimulus package, while significant, are focused on making more electrons from coal, not competing with Silicon Valley smart-grid entrepreneurs. Natural gas is also limited, and imports are subject to the same political wariness as oil. Wind and gas are, for the foreseeable future, tiny sources of electricity.

Nuclear is another option, but China's six nuclear plants provide just 2 percent of the country's power at present. China will start building five new plants in 2009 alone, but even the most aggressive (and unlikely) government plan for nuclear power would see that source grow to just 5 percent by 2020.

It is hard to escape the logic of China's industrial planners. China's economy is growing mainly through industrial investment, and industrial growth requires large amounts of energy. And as a thoughtful Peterson Institute of International Economics study of China's energy system shows, Chinese industrial growth means coal. Indeed, China is also now the world's largest investor in converting coal to liquid fuels for transportation, with the aim of reducing the country's dependence on foreign oil. Many other countries, notably the United States, tried this route in the wake of the 1970s oil crises but found it expensive and polluting. If China pursues this option on a large scale, its emissions of carbon dioxide will swell even further.

Because coal's most serious environmental impact comes from combustion, the types of investments China's state power companies make will largely determine its drain on the global environment. Today, the typical Chinese power plant is about 30 percent efficient; the world's best, in Europe, are about 45 percent efficient. China's "Big Five" state-owned power companies and some provincial power companies are already building about a dozen of these superior plants. If they invest, over time, to lift the whole existing and new fleet of power plants to this standard, then the Big Five alone could cut China's coal consumption perhaps one-third below the country's projections for the next two to three decades. By 2030 such an effort could reduce emissions from China's coal combustion by 20 percent—likely more than all emissions from Japan that year. While there are many sources of carbon dioxide in China, the Big Five power companies have perhaps more leverage than any other institution in affecting the planet's future warming.

Achieving clean coal in China over the long term will be a tougher challenge than building efficient plants. Carbon capture and storage is already prohibitively expensive in the European Union and United States, where incomes are higher and where people profess to care enough about global warming to spend some cash on solutions. While Chinese firms are involved in a few possible demonstration projects, building CCS at scale is much harder to square with China's economic and political priorities. Used widely, CCS may raise the cost of generating electricity in China by half. It would also increase China's demand for coal 20–30 percent above already-bullish projections over the next few decades, which would put additional demands on a coal supply infrastructure that even now struggles to keep pace with growth. A smarter system of incentives to compensate China for the extra cost, or other incentives to convince the Chinese to spend their own money on this technology, will be needed.

The Kyoto treaty on global warming includes a scheme known as the Clean Development Mechanism (CDM) that was designed to help finance low-carbon investments. Yet in practice the CDM has disproportionately focused on small-scale projects and also been plagued by accounting scams that have made it hard to distinguish false claims from genuine new investments that reduce emissions. So far, it does not include any rules that would allow credits for CCS plants. Even if it did include such rules, the carbon prices generated by the CDM (about five to twenty dollars per ton in recent years) are a fraction of the levels that will induce investors to gamble on CCS projects. Other mechanisms might be used, such as direct financial transfers. But except in support of a few small projects, none of the industrialized countries has been willing to spend what could be billions of dollars for a large Chinese CCS program. Mustering political support for subsidies to a formidable economic competitor seems to be a non-starter, especially in hard economic times. Some analysts envision im-

Ever was

That there ever was a land
That land hoisted itself on the shoulders of the road
it collapsed against as if road set the pace
That land had a mind it used to picture itself
while you who walked it did not
Being figment
Being hind of hands, forth of legs
That the mind of land might know itself
as the one who walked it
Joints here and there, never the one place twice
That land occupied itself in snapshots
That there was a place among last instances of this land
deserted by the one who walked it
by the action of hands swinging
and the mechanism of feet leaving one thing
approaching another
That land sensed no roundness in you to roll upon
no finitude or furniture
That a mind ever threw itself across dry grass
stumbling and roaming on steel rims
A hum at the gums both motor and weather
As mind built upward curves
as incremental extensions of the land that pictured it
Yet flat
Walking yet
Structures built on that land
wholly dependent on falling down
That some creatures might attach their sticky flight to this state
or walk a porous nature and call it ground

—Tom Thompson

posing trade sanctions if China does not control emissions, which could boost Chinese investment in clean technologies. But that road is fraught with difficulty since the world trading system is already in fragile shape. Politicians in China and the West are still struggling to find a serious solution to the problem of China's emissions.

Candidate Obama told the *San Francisco Chronicle* that his environmental policy would "bankrupt" coal. President Obama and the rest of his cabinet now realize that coal is unavoidable. Economics and politics alike put coal at the center of most national energy systems. And solving energy problems such as global warming will require, first and foremost, grappling with coal.

Getting serious about global warming will require efforts on three fronts. One is to put a price on carbon dioxide and emissions of the other warming gases. Higher prices will help encourage efficiency and some switching to less carbon-heavy practices. But even in Europe, where carbon dioxide prices are the highest in the world, prices are still much lower than needed to stimulate investment in low-emission coal technologies, notably CCS. And prices in the United States are likely to be even lower than Europe's.

A second effort must be technological. Stopping global warming will require deep cuts in emissions worldwide over the coming decades. Reductions on that scale will require new technologies. No private company will back those technologies on its own initiative. A major effort is needed to find new, more efficient ways to burn coal and also to bury the pollution. So-called clean coal is now the object of scorn from skeptical observers, but to serious engineers and environmentalists it is a key venture in need of support. Only governments can credibly justify and afford the kinds of investment required.

Developing countries sit at the third vital front. Coal is abundant, cheap, and indispensible. Developing countries, which already account for most of the world's coal consumption and nearly all of the coal industry's growth, are not likely to shift to rival fuels. Huge success in driving down the cost of technologies such as advanced wind and nuclear power systems might allow them (and the rest of the world) to shift away from coal without much economic pain. The decreasing cost of more efficient coal technologies has already made it possible for China and India, among others, to justify buying some of the most advanced technologies on commercial terms. But the more likely scenario is that the best low-emission technologies, including clean coal, will be more expensive than what these governments are willing to pay on their own. An indication that the world is not yet really serious about global warming is that no system exists to finance the use of these technologies in the countries that will dominate the energy future.

The United States has a critical role to play in this effort. At home it must adopt serious policies to push investment in new technologies to reduce emissions. Abroad, it must be prepared to help pay developing countries to test and deploy these technologies as well. And the keystone to all these efforts is coal. So far, however, real investment in low-emission coal is at a tiny fraction of the level needed. As the politicians dither, the world keeps warming. ♦

Dear Modifications

You are the following dangerous words: 1. heart 2. love 3. mind 4. beauty and 5. eyes
(I don't consider beauty a failure, but that's just my opinion).
I wanted to save you because you are all so hackneyed;
maybe some of the words that typically surround you, I thought,
could give you some life?
So for example, for *eyes*, I wrote: *four eyes*, *private eyes*, *snake eyes*,
When Irish Eyes Are Smiling and *Don't Shoot Until You See the Whites of Their Eyes*.
For *love* I listed *Hiroshima, From Russia with Love,*
Love and Rockets, Love Is a Battlefield and *You Can't Buy Me Love*.
Maybe you were more political than I realized.
I subtracted you from these phrases, then scrambled your neighbors
into what I called a poem, but the end result was a solipsistic,
awkward definition for each of you
(I think I was trying to do something semiotic).
When I was about seven or eight, I found a blue jay with a broken wing in some nearby woods.
I ran home and told my mom, who gave me a shoe box and a pair of ski gloves
to handle him. My mom rushed us to the vet, and I felt so relieved.
But when we called later that afternoon to check on our patient, the vet had put him to sleep;
there was nothing he could do, he said.
Plato, in the *Republic*, says that poets must be exiled.
Shelley calls poets "the unacknowledged legislators of the world."
I remember the blue jay's eyes, looking up at me through the foot-length ferns
like I was going to kill him.
Just the exact opposite, I thought, cradling him in ski gloves.

—Trey Sager

The Pithouse West open-pit coal mine near Sheffield, U.K., in 1993. The site was later restored as part of a park.