What to do

Cheap, plentiful coal is expected to fuel power plants for the foreseeable future, but can we keep it from devastating the environment?

BY DAVID G. HAWKINS, DANIEL A. LASHOF AND ROBERT H. WILLIAMS

OVERVIEW

- Coal is widely burned for power but produces large quantities of climate-changing carbon dioxide.
- Compared with conventional power plants, new gasification facilities can more effectively and affordably extract CO_2 so it can be safely stored underground.
- The world must begin implementing carbon capture and storage soon to stave off global warming.

Burning coal sends nearly 10 billion metric tons of carbon dioxide into the atmosphere every year.

about Coal

More than most people realize, dealing with climate change means addressing the problems posed by emissions from coal-fired power plants. Unless humanity takes prompt action to strictly limit the amount of carbon dioxide (CO_2) released into the atmosphere when consuming coal to make electricity, we have little chance of gaining control over global warming.

Coal—the fuel that powered the Industrial Revolution—is a particularly worrisome source of energy, in part because burning it produces considerably more carbon dioxide per unit of electricity generated than burning either oil or natural gas does. In addition, coal is cheap and will remain abundant long after oil and natural gas have become very scarce. With coal plentiful and inexpensive, its use is burgeoning in the U.S. and elsewhere and is expected to continue rising in areas with abundant coal resources. Indeed, U.S. power providers are expected to build the equivalent of nearly 280 500-megawatt, coal-fired electricity plants between 2003 and 2030. Meanwhile China is already constructing the equivalent of one large coal-fueled power station a week. Over their roughly 60-year life spans, the new generating facilities in operation by 2030 could collectively introduce into the atmosphere about as much carbon dioxide as was released by all the coal burned since the dawn of the Industrial Revolution.

Coal's projected popularity is disturbing not only for those concerned about climate change but also for those worried about other aspects of the environment and about human health and safety. Coal's market price may be low, but the true costs of its extraction, processing and consumption are high. Coal use can lead to a range of harmful consequences, including decapitated mountains, air pollution from acidic and toxic emissions, and water fouled with coal wastes. Extraction also endangers and can kill miners. Together such effects make coal production and conversion to useful energy one of the most destructive activities on the planet [*see box on page 73*].

In keeping with *Scientific American*'s focus on climate concerns in this issue, we will concentrate below on methods that can help prevent CO_2 generated during coal conversion from reaching the atmosphere. It goes without saying that the environmental, safety and health effects of coal production and use must be reduced as well. Fortunately, affordable techniques for addressing CO_2 emissions and these other problems already exist, although the will to implement them quickly still lags significantly.

Geologic Storage Strategy

THE TECHNIQUES that power providers could apply to keep most of the carbon dioxide they produce from entering the air are collectively called CO_2 capture and storage (CCS) or geologic carbon sequestration. These procedures involve separating out much of the CO_2 that is created when coal is converted to useful energy and transporting it to sites where it can be stored deep underground in porous media—mainly in depleted oil or gas fields or in saline formations (permeable geologic strata filled with salty water) [see "Can We Bury Global Warming?" by Robert H. Socolow; Scientific American, July 2005].

All the technological components needed for CCS at coal conversion plants are commercially ready—having been proved in applications unrelated to climate change mitigation, although integrated systems have not yet been constructed at the necessary scales. Capture technologies have been deployed extensively throughout the world both in the manufacture of chemicals (such as fertilizer) and in the purification of natural gas supplies contaminated with carbon dioxide and hydrogen sulfide ("sour gas"). Industry has gained considerable experience with CO_2 storage in operations that purify natural gas (mainly in Canada) as well as with CO_2 injection to boost oil production (primarily in the U.S.). Enhanced oil recovery processes account for most of the CO_2 that has been sent into

Affordable methods that prevent CO_2 from reaching the atmosphere exist; the will to implement them quickly lags.

underground reservoirs. Currently about 35 million metric tons are injected annually to coax more petroleum out of mature fields, accounting for about 4 percent of U.S. crude oil output.

Implementing CCS at coal-consuming plants is imperative if the carbon dioxide concentration in the atmosphere is to be kept at an acceptable level. The 1992 United Nations Framework Convention on Climate Change calls for stabilizing the atmospheric CO_2 concentration at a "safe" level, but it does not specify what the maximum value should be. The current view of many scientists is that atmospheric CO_2 levels must be kept below 450 parts per million by volume (ppmv) to avoid unacceptable climate changes. Realization of this aggressive goal requires that the power industry start commercial-scale CCS projects within the next few years and expand them rapidly thereafter. This stabilization benchmark cannot be realized by CCS alone but can plausibly be achieved if it is combined with other eco-friendly measures, such as wide improvements in energy efficiency and much expanded use of renewable energy sources.

The Intergovernmental Panel on Climate Change (IPCC) estimated in 2005 that it is highly probable that geologic media worldwide are capable of sequestering at least two trillion metric tons of CO_2—more than is likely to be produced by fossil-fuel-consuming plants during the 21st century. Society will want to be sure, however, that potential sequestration sites are evaluated carefully for their ability to retain CO_2 before they are allowed to operate. Two classes of risks are of concern: sudden escape and gradual leakage.

Rapid outflow of large amounts of CO_2 could be lethal to those in the vicinity. Dangerous sudden releases—such as that which occurred in 1986 at Lake Nyos in Cameroon, when CO_2 of volcanic origin asphyxiated 1,700 nearby villagers and thousands of cattle—are improbable for engineered CO_2 storage projects in carefully selected, deep porous geologic formations, according to the IPCC.

Gradual seepage of carbon dioxide into the air is also an issue, because over time it could defeat the goal of CCS. The 2005 IPCC report estimated that the fraction retained in appropriately selected and managed geologic reservoirs is very likely to exceed 99 percent over 100 years and likely to exceed 99 percent over 1,000 years. What remains to be demonstrated is whether in practice operators can routinely keep CO_2 leaks to levels that avoid unacceptable environmental and public health risks.

Technology Choices

DESIGN STUDIES indicate that existing power generation technologies could capture from 85 to 95 percent of the carbon in coal as CO_2, with the rest released to the atmosphere.

The coal conversion technologies that come to dominate will be those that

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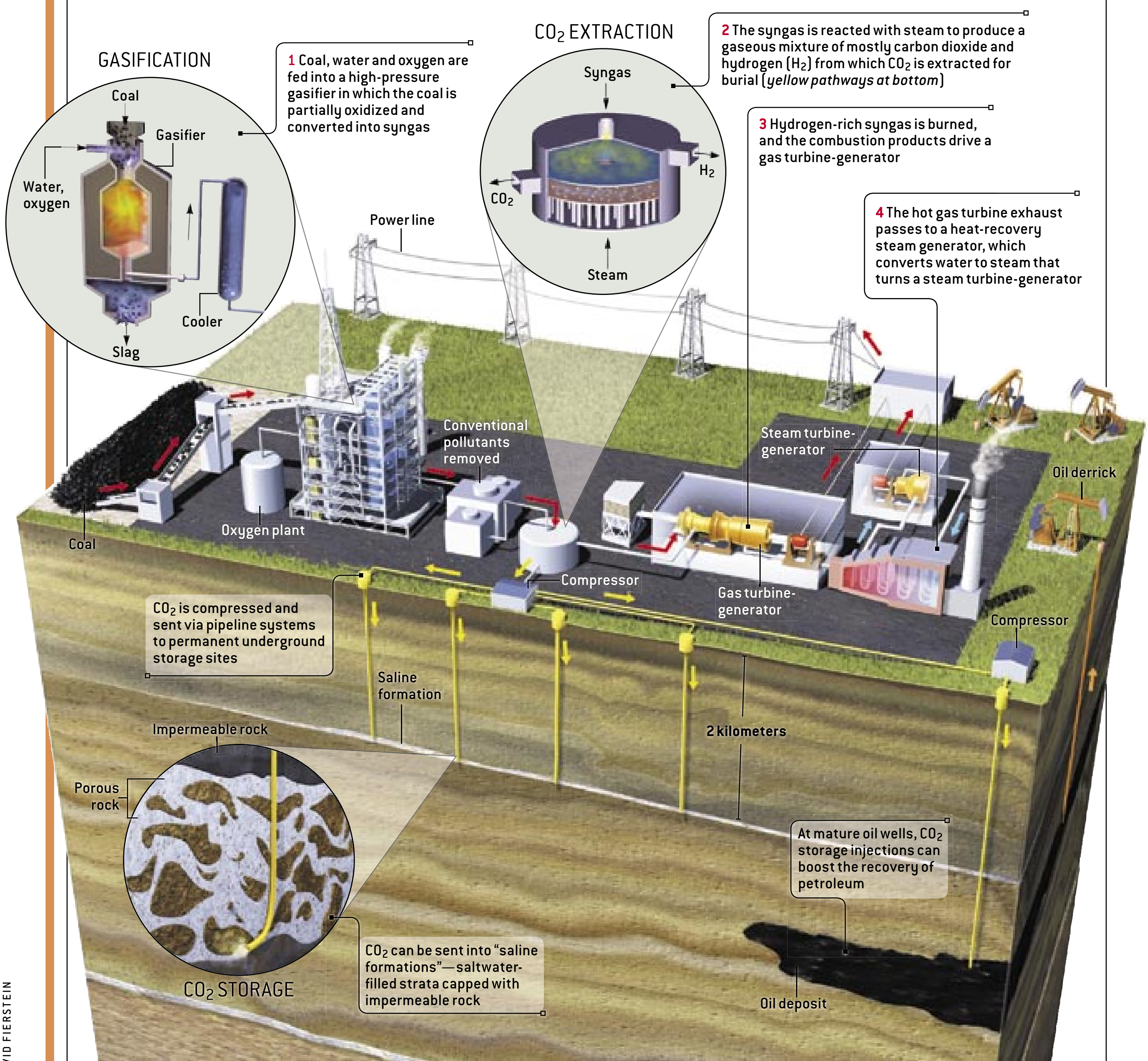
EXTRACTING AND STORING CARBON DIOXIDE

To slow climate change, the authors urge power providers to build integrated gasification combined cycle (IGCC) coal power plants with carbon dioxide capture and storage (CCS) capabilities (*below*) rather than conventional steam-electric facilities. Conventional coal plants burn the fuel to transform water into steam to turn a turbine-generator. If CCS technology were applied to a steam plant, CO_2 would be extracted from the flue exhaust. An IGCC plant, in contrast, employs a partial oxidation reaction using limited oxygen to convert the coal into a so-called synthesis gas, or syngas (mostly hydrogen and carbon monoxide). It is much easier and less costly to remove CO_2 from syngas than from the flue gases of a steam plant. The hydrogen-rich syngas remaining after CO_2 extraction is then burned to run both gas and steam turbine-generators. The world's first commercial IGCC project that will sequester CO_2 underground is being planned near Long Beach, Calif.



DAVID FIERSTEIN

can meet the objectives of climate change mitigation at the least cost. Fundamentally different approaches to CCS would be pursued for power plants using the conventional pulverized-coal steam cycle and the newer integrated gasification combined cycle (IGCC). Although today's coal IGCC power (with CO_2 venting) is slightly more expensive than coal steam-electric power, it looks like IGCC is the most effective and least expensive option for CCS.

Standard plants burn coal in a boiler at atmospheric pressure. The heat generated in coal combustion transforms water into steam, which turns a steam turbine, whose mechanical energy is converted to electricity by a generator. In modern plants the gases produced by combustion (flue gases) then pass through devices that remove particulates and oxides of sulfur and nitrogen before being exhausted via smokestacks into the air.

Carbon dioxide could be extracted from the flue gases of such steam-electric plants after the removal of conventional pollutants. Because the flue gases contain substantial amounts of nitrogen (the result of burning coal in air, which is about 80 percent nitrogen), the carbon dioxide would be recovered at low concentration and pressure—which implies that the CO_2 would have to be removed from large volumes of gas using processes that are both energy-intensive and expensive. The captured CO_2 would then be compressed and piped to an appropriate storage site.

In an IGCC system coal is not burned but rather partially oxidized (reacted with limited quantities of oxygen from an air separation plant, and with steam) at high pressure in a gasifier. The product of gasification is so-called synthesis gas, or syngas, which is composed mostly of carbon monoxide and hydrogen, undiluted with nitrogen. In current practice, IGCC operations remove most conventional pollutants from the syngas and then burn it to turn both gas and steam turbine-generators in what is called a combined cycle.

▲ Commercial power plants using IGCC technology, such as this one in Italy, have been operating since 1994. Together they generate 3,600 megawatts of electricity.

ERG GROUP

In an IGCC plant designed to capture CO_2, the syngas exiting the gasifier, after being cooled and cleaned of particles, would be reacted with steam to produce a gaseous mixture made up mainly of carbon dioxide and hydrogen. The CO_2 would then be extracted, dried, compressed and transported to a storage site. The remaining hydrogen-rich gas would be burned in a combined cycle plant to generate power [*see box on preceding page*].

Analyses indicate that carbon dioxide capture at IGCC plants consuming high-quality bituminous coals would entail significantly smaller energy and cost penalties and lower total generation costs than what could be achieved in conventional coal plants that captured and stored CO_2. Gasification systems recover CO_2 from a gaseous stream at high concentration and pressure, a feature that makes the process much easier than it would be in conventional steam facilities. (The extent of the benefits is less clear for lower-grade subbituminous coals and lignites, which have received much less study.) Precombustion removal of conventional pollutants, including mercury, makes it feasible to realize very low levels of emissions at much reduced costs and with much smaller energy penalties than with cleanup systems for flue gases in conventional plants.

Captured carbon dioxide can be transported by pipeline up to several hundred kilometers to suitable geologic storage sites and subsequent subterranean storage with the pressure produced during capture. Longer distances may, however, require recompression to compensate for friction losses during pipeline transfer.

Overall, pursuing CCS for coal power facilities requires the consumption of more coal to generate a kilowatt-hour of electricity than when CO_2 is vented—about 30 percent extra in the case of coal steam-electric plants and less than 20 percent more for IGCC plants. But overall coal use would not necessarily increase, because the higher price of coal-based electricity resulting from adding CCS equipment would dampen demand for coal-based electricity, making renewable energy sources and energy-efficient products more desirable to consumers.

The cost of CCS will depend on the type of power plant, the distance to the storage site, the properties of the storage

THE AUTHORS

DAVID G. HAWKINS, DANIEL A. LASHOF and ROBERT H. WILLIAMS have endeavored to help stave off climate change problems for decades. Hawkins is director of the Climate Center at the Natural Resources Defense Council (NRDC), where he has worked on air, energy and climate issues for 35 years. Hawkins serves on the boards of many bodies that advise government on environmental and energy subjects. Lashof is science director and deputy director of the NRDC's Climate Center, at which he has focused on national energy policy, climate science and solutions to global warming since 1989. Before arriving at the NRDC, Lashof developed policy options for stabilizing global climate at the U.S. Environmental Protection Agency. Williams is a senior research scientist at Princeton University, which he joined in 1975. At the university's Princeton Environmental Institute, he heads the Energy Systems/Policy Analysis Group and the Carbon Capture Group under the institute's Carbon Mitigation Initiative (which is supported by BP and Ford).

reservoir and the availability of opportunities (such as enhanced oil recovery) for selling the captured CO_2. A recent study co-authored by one of us (Williams) estimated the incremental electric generation costs of two alternative CCS options for coal IGCC plants under typical production, transport and storage conditions. For CO_2 sequestration in a saline formation 100 kilometers from a power plant, the study calculated that the incremental cost of CCS would be 1.9 cents per kilowatt-hour (beyond the generation cost of 4.7 cents per kilowatt-hour for a coal IGCC plant that vents CO_2—a 40 percent premium). For CCS pursued in conjunction with enhanced oil recovery at a distance of 100 kilometers from the conversion plant, the analysis finds no increase in net generation cost would occur as long as the oil price is at least $35 per barrel, which is much lower than current prices.

CCS Now or Later?

MANY ELECTRICITY producers in the industrial world recognize that environmental concerns will at some point force them to implement CCS if they are to continue to employ coal. But rather than building plants that actually capture and store carbon dioxide, most plan to construct conventional steam facilities they claim will be "CO_2 capture ready"—convertible when CCS is mandated.

Power providers often defend those decisions by noting that the U.S. and most other countries with coal-intensive energy economies have not yet instituted policies for climate change mitigation that would make CCS cost-effective for uses not associated with enhanced oil recovery. Absent revenues from sales to oil field operators, applying CCS to new coal plants using current technology would be the least-cost path only if the cost of emitting CO_2 were at least $25 to $30 per metric ton. Many current policy proposals for climate change mitigation in the U.S. envision significantly lower cost penalties to power providers for releasing CO_2 (or similarly, payments for CO_2 emissions-reduction credits).

Yet delaying CCS at coal power plants until economy-wide carbon dioxide control costs are greater than CCS costs is shortsighted. For several reasons, the coal and power industries and

COAL'S TOLL

Despite the current popularity of the term "clean coal," coal is, in fact, dirty. Although carbon capture and storage could prevent much carbon dioxide from entering the atmosphere, coal production and consumption is still one of the most destructive industrial processes. As long as the world consumes coal, more must be done to mitigate the harm it causes.

MINING DANGERS

Coal mining is among the most dangerous occupations. Official reports for 2005 indicate that roughly 6,000 people died (16 a day) in China from coal mine floods, cave-ins, fires and explosions. Unofficial estimates are closer to 10,000. Some 600,000 Chinese coal miners suffer from black lung disease.

The U.S. has better safety practices than China and achieved an all-time low of 22 domestic fatalities in 2005. U.S. mines are far from perfect, however, as evidenced by a series of fatalities in early 2006.

ENVIRONMENTAL EFFECTS

Conventional coal mining, processing and transportation practices scar the landscape and pollute the water, which harms people and ecosystems. The most destructive mining techniques clear forests and blast away mountaintops. The "overburden" removed when a coal seam is uncovered is typically dumped into nearby valleys, where it often buries rivers and streams. Strip-mining operations rip apart ecosystems and reshape the landscape. Although regulations require land reclamation in principle, it is often left incomplete. As forests are replaced with nonnative grasslands, soils become compacted and streams contaminated.

▲ Acid runoff from a Pennsylvania coal mine stains this creek bed orange.

Underground mining can cause serious problems on the surface. Mines collapse and cause land subsidence, damaging homes and roads. Acidic mine drainage caused by sulfur compounds leaching from coal waste into surface waters has tainted thousands of streams. The acid leachate releases heavy metals that foul groundwater.

TOXIC EMISSIONS

Coal-fired power plants account for more than two thirds of sulfur dioxide and about one fifth of nitrogen oxide emissions in the U.S. Sulfur dioxide reacts in the atmosphere to form sulfate particles, which in addition to causing acid rain, contribute to fine particulate pollution, a contaminant linked to thousands of premature deaths from lung disease nationwide. Nitrogen oxides combine with hydrocarbons to form smog-causing ground-level ozone.

Coal-burning plants also emit approximately 48 metric tons of mercury a year in America. This highly toxic element persists in the ecosystem. After transforming into methyl mercury, it accumulates in the tissues of fishes. Ingested mercury is particularly detrimental to fetuses and young infants exposed during periods of rapid brain growth, causing developmental and neurological damage.

—D.G.H., D.A.L. and R.H.W.

RICK SMITH *AP Photo*

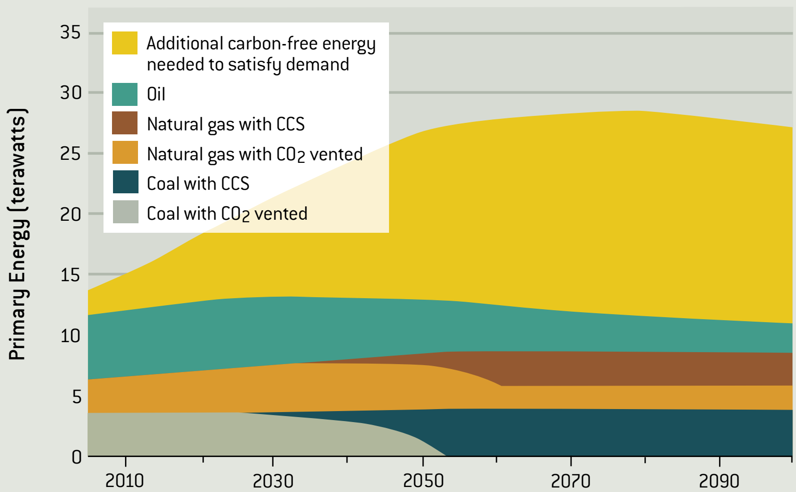
THE PATH TO CO_2 MITIGATION

Our calculations indicate that a prompt commitment to carbon capture and storage (CCS) would make it possible to meet global energy demands while limiting the atmospheric carbon dioxide concentration to 450 parts per million by volume (ppmv). This goal could be attained if, by midcentury, sequestration is applied for all coal use and about a quarter of natural gas use, while energy efficiency increases rapidly and carbon-free energy sources expand sevenfold. Under these conditions, overall fossil-fuel consumption could expand modestly from today: by midcentury, coal use could be somewhat higher than at present, oil use would be down by a fifth and natural gas use would expand by half.

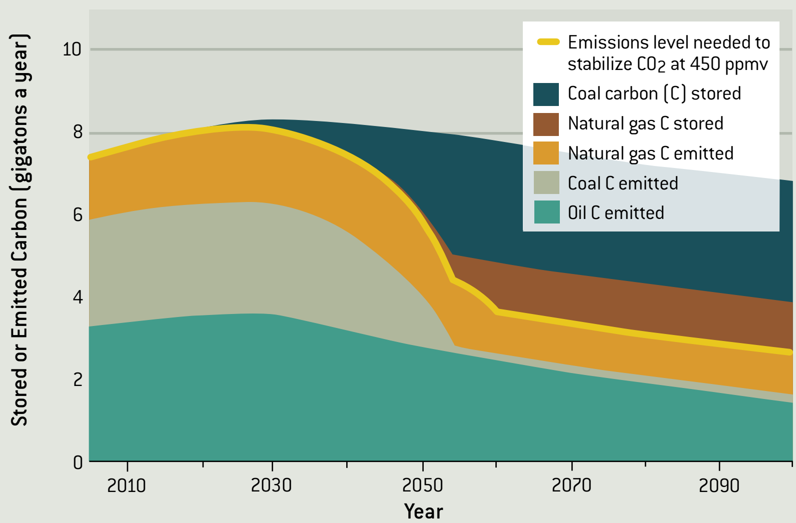
To realize this pathway, growth rates for fossil-fuel use would have to be reduced now, and CCS must begin for coal early in the next decade and for natural gas early in the next quarter of a century. The top graph below depicts the energy provided by the various sources if this mitigation path were followed. The bottom graph shows total quantities of carbon extracted from the earth (emissions plus storage).

—D.G.H., D.A.L. and R.H.W.

FOSSIL AND CARBON-FREE ENERGY MIX FOR CO_2 STABILIZATION



FATE OF CARBON FROM FOSSIL ENERGY SYSTEMS



society would ultimately benefit if deployment of plants fitted with CCS equipment were begun now.

First, the fastest way to reduce CCS costs is via "learning by doing"—the accumulation of experience in building and running such plants. The faster the understanding is accumulated, the quicker the know-how with the new technology will grow, and the more rapidly the costs will drop.

Second, installing CCS equipment as soon as possible should save money in the long run. Most power stations currently under construction will still be operating decades from now, when it is likely that CCS efforts will be obligatory. Retrofitting generating facilities for CCS is inherently more expensive than deploying CCS in new plants. Moreover, in the absence of CO_2 emission limits, familiar conventional coal steam-electric technologies will tend to be favored for most new plant construction over newer gasification technologies, for which CCS is more cost-effective.

Finally, rapid implementation would allow for continued use of fossil fuels in the near term (until more environmentally friendly sources become prevalent) without pushing atmospheric carbon dioxide beyond tolerable levels. Our studies indicate that it is feasible to stabilize atmospheric CO_2 levels at 450 ppmv over the next half a century if coal-based energy is completely decarbonized and other measures described in the box at the left are implemented. This effort would involve decarbonizing 36 gigawatts of new coal generating capacity by 2020 (corresponding to 7 percent of the new coal capacity expected to be built worldwide during the decade beginning in 2011 under business-as-usual conditions). In the 35 years after 2020, CO_2 capture would need to rise at an average rate of about 12 percent a year. Such a sustained pace is high compared with typical market growth rates for energy but is not unprecedented. It is much less than the expansion rate for nuclear generating capacity in its heyday—1956 to 1980—during which global capacity rose at an average rate of 40 percent annually. Further, the

JEN CHRISTIANSEN

expansion rates for both wind and solar photovoltaic power capacities worldwide have hovered around 30 percent a year since the early 1990s. In all three cases, such growth would not have been practical without public policy measures to support them.

Our calculations indicate that the costs of CCS deployment would be manageable as well. Using conservative assumptions—such as that technology will not improve over time—we estimate that the present worth of the cost of capturing and storing all CO_2 produced by coal-based electricity generation plants during the next 200 years will be \$1.8 trillion (in 2002 dollars). That might seem like a high price tag, but it is equivalent to just 0.07 percent of the current value of gross world product over the same interval. Thus, it is plausible that a rapid decarbonization path for coal is both physically and economically feasible, although detailed regional analyses are needed to confirm this conclusion.

Policy Push Is Needed

THOSE GOOD REASONS for commencing concerted CCS efforts soon will probably not move the industry unless it is also prodded by new public policies. Such initiatives would be part of a broader drive to control carbon dioxide emissions from all sources.

In the U.S., a national program to limit CO_2 emissions must be enacted soon to introduce the government regulations and market incentives necessary to shift investment to the least-polluting energy technologies promptly and on a wide scale. Leaders in the American business and policy communities increasingly agree that quantifiable and enforceable restrictions on global warming emissions are imperative and inevitable. To ensure that power companies put into practice the reductions in a cost-effective fashion, a market for trading CO_2 emissions credits should be created—one similar to that for the sulfur emissions that cause acid rain. In such a plan, organizations that intend to exceed designated emission limits may buy credits from others that are able to stay below these values.

Enhancing energy efficiency efforts and raising renewable energy production are critical to achieving carbon dioxide limits at the lowest possible cost. A portion of the emission allowances created by a carbon cap-and-trade program should be allocated to the establishment of a fund to help overcome institutional barriers and technical risks that obstruct widespread deployment of otherwise cost-effective CO_2 mitigation technologies.

Delaying carbon capture and storage at coal power plants is shortsighted.

Even if a carbon dioxide cap-and-trade program were enacted in the next few years the economic value of CO_2 emissions reduction may not be enough initially to convince power providers to invest in power systems with CCS. To avoid the construction of another generation of conventional coal plants, it is essential that the federal government establish incentives that promote CCS.

One approach would be to insist that an increasing share of total coal-based electricity generation comes from facilities that meet a low CO_2 emissions standard—perhaps a maximum of 30 grams of carbon per kilowatt-hour (an achievable goal using today's coal CCS technologies). Such a goal might be achieved by obliging electricity producers that use coal to include a growing fraction of decarbonized coal power in their supply portfolios. Each covered electricity producer could either generate the required amount of decarbonized coal power or purchase decarbonized-generation credits. This system would share the incremental costs of CCS for coal power among all U.S. coal-based electricity producers and consumers.

If the surge of conventional coal-fired power plants currently on drawing boards is built as planned, atmospheric carbon dioxide levels will almost certainly exceed 450 ppmv. We can meet global energy needs while still stabilizing CO_2 at 450 ppmv, however, through a combination of improved efficiency in energy use, greater reliance on renewable energy resources and, for the new coal investments that are made, the installation of CO_2 capture and geologic storage technologies. Even though there is no such thing as "clean coal," more can and must be done to reduce the dangers and environmental degradations associated with coal production and use. An integrated low-carbon energy strategy that incorporates CO_2 capture and storage can reconcile substantial use of coal in the coming decades with the imperative to prevent catastrophic changes to the earth's climate. SA

MORE TO EXPLORE

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