Engineering Beyond Carbon:
Pulling Answers Out of the Air

by Trudy E. Bell

Many national and international scientists and policymakers urge reducing levels of atmospheric carbon dioxide (CO_2) dramatically and quickly because of its role in regulating Earth's climate and average temperature. An examination of the highest-level peer-reviewed literature reveals these salient points:

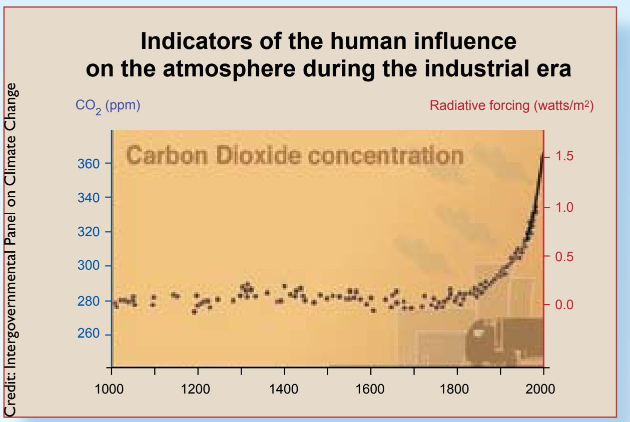
1. Independent measurements from air, tree rings, ice cores, and other sources show that today's global concentration of atmospheric CO_2 is 35 percent higher than during the millennia preceding the Industrial Revolution [see **Fig. 1**].
2. Carbon isotope ratios and other data also reveal that most of the increase over the past two centuries originates from human burning of fossil fuels. Also significant over the same period is the human removal of natural carbon sinks, chiefly forests, especially those actively growing [see **Fig. 2**].[1]
3. Carbon dioxide differs from other chemicals classed as atmospheric pollutants in two essential ways that are often misunderstood.
4. The challenge of capping the concentration of atmospheric CO_2 has several aspects that must be pursued in parallel and with dispatch if concentrations are to have a chance of leveling by 2050.
5. Lastly, and important to the members of Tau Beta Pi, engineers will have a crucial role in meeting that challenge through a portfolio of technologies, which may include reducing CO_2 emissions, capturing CO_2 at manufacturing sources and sequestering it, devising economical non-carbon sources of energy, increasing efficiency of energy use and transportation, and removing excess atmospheric CO_2 from the planet's ambient air.

It is not the intent of this literature review to argue a case linking atmospheric CO_2 and climate change. Readers wishing to scrutinize the scientific evidence first-hand are invited to peruse the references cited in the footnotes. Rather, this article's intent is to summarize the panoply of carbon-abatement proposals under discussion that would need astute and thoughtful engineering.

CO-Two misunderstandings

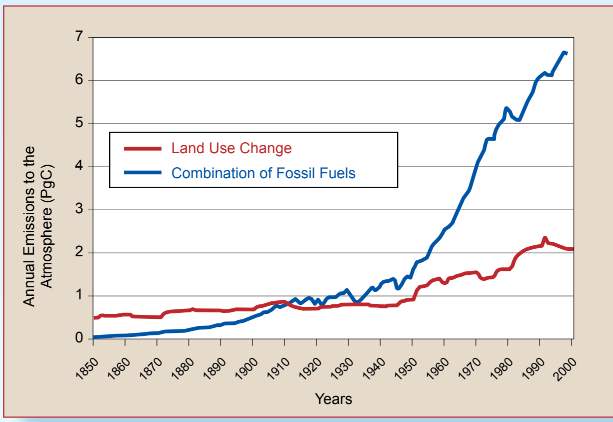
Carbon dioxide is somewhat analogous to table salt: while a little is absolutely essential for life, too much is another matter entirely.

Carbon dioxide is actually a trace constituent of the atmosphere. Its proportion is so minuscule that its concentration is specified not as a percentage but as parts per million by volume (ppmv). By dry volume, Earth's overall atmosphere is 78 percent nitrogen, 21 percent oxygen, and 0.9 percent argon. Of the remaining 0.1 percent, carbon dioxide makes up the lion's share, more than a third, currently 0.0379 percent or 379 ppmv—but keep reading. A host of other trace gases at even tinier concentrations make up the rest. Not counted in those dry-volume percentages is water



Credit: Intergovernmental Panel on Climate Change

Fig. 1 Concentrations of atmospheric CO_2 have hovered around 280 parts per million by volume (280 ppmv, or 0.028 percent) for the last millennium, but began rising with the burning of fossil fuels with the advent of the Industrial Revolution. Today's level of 379 ppmv is higher than any level measured in ancient tree rings, ice cores, or other sources for more than 650,000 years.



Credit: Woods Hole Research Center

Fig. 2 Annual emissions of CO_2 into the atmosphere have been accelerating, because of both increased combustion of fossil fuels with increasing industrialization worldwide and also the increased removal of the planet's natural carbon sinks—chiefly from deforestation and changes in land use. Numbers shown reflect the pure carbon equivalent of CO_2 gas, measured in petagrams or gigatons (1 Pg or Gt is 10^9 metric tons).

Carbon dioxide 101

Carbon dioxide (CO_2) is an odorless, colorless gas that is a normal waste product of human and animal respiration. We inhale oxygen, which circulates in our blood to all parts of our bodies. When cells oxidize food to get energy, CO_2 is produced, which the blood returns to our lungs for us to exhale.

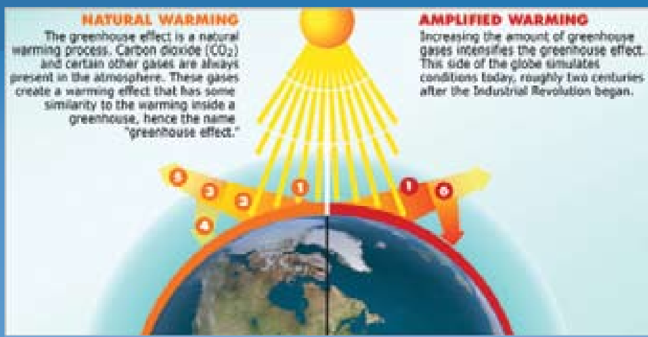
In a classic case of symbiosis, photosynthesizing green plants—especially young, fast-growing trees in forests and phytoplankton in the oceans—do just the reverse. Through transpiration, green plants take in CO_2, use the energy in sunlight to convert the carbon into carbohydrates for their own use, and release waste oxygen into the atmosphere; indeed, photosynthesizing plants have been the exclusive source of all the free oxygen in Earth's atmosphere. Cold ocean water at Earth's poles also dissolves atmospheric CO_2 and carries it down into the ocean depths as it sinks, although the ocean outgases it again in warmer upwelling water near the equator. [29]

Carbon dioxide is absolutely essential to life as we know it on Earth. Without it, green plants would die—and without green plants, animals and humans would die.

Moreover, CO_2 is largely responsible for the habitability of Earth. Carbon dioxide is transparent to the sun's energetic shorter-wavelength visible and ultraviolet radiation, but is opaque to long-wavelength thermal (heat) infrared. At any moment, the daytime half of Earth is being illuminated by the sun. About 30 percent of solar energy is immediately reflected back into space, but the balance is absorbed by the Earth and the atmosphere, mostly through the action of CO_2 [see figure at left]. This process is usually called the "greenhouse effect" in rough analogy to the way the transparent glass of a greenhouse admits visible sunlight but traps infrared.[30]

Absent the greenhouse effect, life as we know it could not have evolved on Earth. Based purely on its distance from the sun, the planet would have a global average temperature of 0°F (-7°C) with the oceans frozen solid, instead of its actual balmy global average of 59°F (14°C). The difference in those two temperatures is because of the greenhouse effect, two-thirds of it from atmospheric CO_2.

On the other hand, because just a trace concentration of atmospheric CO_2 has such a profound planet-wide effect, a significant change in that trace concentration also has profound consequences.



Carbon dioxide is crucial because of its effects in regulating the temperature of Earth, keeping it warmer than it would be just by virtue of its distance from the sun. This process is usually called the greenhouse effect (although the analogy to a glass greenhouse is imperfect). Sunlight at all wavelengths brings energy into the climate system; most of it is absorbed by the oceans and land (1). Heat (long-wavelength infrared) radiates outward from the warmed surface of the Earth (2). Some of the infrared energy is absorbed by CO_2 and other greenhouse gases in the atmosphere, which re-emit the energy in all directions (3). Some of the infrared energy further warms the Earth (4). Some of the infrared energy is emitted into space (5). So far, so good—but increasing concentrations of atmospheric CO_2 trap more infrared energy in the atmosphere than occurs naturally. The additional heat further warms the atmosphere and Earth's surface (6).

Credit (art and caption): Marian Koshland Science Museum of the National Academies

vapor, that is, individual water molecules (not droplets), which is concentrated primarily in the lowest few miles of the troposphere (the lowest level of the atmosphere); there, it alone can range from 1 to 4 percent of air, while in the upper atmosphere it is essentially zero.

Carbon dioxide is not a chemical pollutant in the same sense that the constituents of smog are; only at concentrations one or two orders of magnitude higher than found in air does it become toxic (as an asphyxiant). What's important is that relatively small increases in its trace concentrations significantly enhance the gas's trapping of long-wavelength infrared (heat) radiation from sunlight, a phenomenon that heats Earth in what is usually called the greenhouse effect [see **sidebar "Carbon dioxide 101"** above]. For the last 650,000 years, the concentration of atmospheric CO_2 varied between 180 and 300 ppmv and was about 280 ppmv in 1750 before the start of the Industrial Revolution.[2] Its concentration has been rising ever since at an accelerating rate—indeed, in 2005, its concentration was 379 ppmv, up more than 8 percent just since 1990 (350 ppmv).

Carbon dioxide is unlike chemical pollutants in another crucial way: it is not readily rained out in a matter of weeks or months like dust from volcanic eruptions or most of the constituents of smoke or smog. Once airborne, CO_2 has a residence time in the atmosphere of between half a century and *two centuries*, so emissions accumulate. Thus, for CO_2—unlike for most air pollutants—it is essential to talk about lowering concentrations as well as lowering emissions [see **Fig. 3**].

With that as prologue, here's the engineering challenge: Article 2 of the United Nations Framework Convention on Climate Change, a treaty signed by the European Community and its member nations (although not by the United States), states as its key aim the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[3] The European Union Council of Ministers agreed that this means not exceeding a limit that would produce a 2°C rise in global temperature. In effect, the treaty requires all developed nations to reduce CO_2 *emissions* to 15 to 30 percent below 1990 levels by 2020, so as to level off CO_2 *concentrations* by 2050.

Budgeting the carbon

Get ready for some big numbers. Remember, discussions about atmospheric CO_2 concern planet-wide phenomena, and potential engineering solutions might thus be on a commensurate scale. The units used in the literature are either in terms of gigatons or petagrams ($1\ Gt = 10^9$ metric tons = 10^{15} grams = 1 Pg) per year of either carbon or carbon dioxide; you'll know the difference because they are denoted either GtC/y or $GtCO_2/y$ (or PgC/y and $PgCO_2/y$). Data specifying CO_2 can be converted to their solid carbon equivalent by multiplying by the fraction 12/44 (the ratio of their molecular weights). For a perspective on the physical scale of the material, 1 GtC—1 billion tons of solid carbon—would occupy a volume of 1 cubic kilometer.[4]

First, the good news: engineers have some natural help. Earth's terrestrial and marine biosphere essentially acts as a giant biological scrubber, removing some 2 billion tons of carbon (2 GtC/y) from the atmosphere every year.[5] Atmospheric carbon is permanently removed when shellfish incorporate it into their shells that later fall to the bottom of the ocean, when corals fix it into reefs, or when vigorously growing young trees incorporate it into their structures. Carbon also gets cycled through the lithosphere and fixed into carbonate rocks, but at a far slower geological pace. In other ways, the terrestrial and marine biosphere act less like a scrubber and more like an offset: absorbed carbon is eventually released again into the atmosphere when green plants or mature trees die and decay, or when colder ocean water (which absorbs carbon dioxide well) becomes warmer (which absorbs CO_2 less well or actually gives off some of its dissolved CO_2). All this being said, the biosphere is also demonstrating signs of having reached saturation, the limits of what it can absorb.[6]

Stabilizing atmospheric carbon dioxide this century will require a portfolio of engineering options, including energy efficiency, reduced emissions, low-carbon fuels for power and transportation, geological or oceanic carbon sequestration, and even large-scale filtering of ambient outdoor air.

Now for the engineering challenge: globally, in 2005 alone (the most recent year for which statistics are available), the world's economies released just over 25 $GtCO_2$ (6.8 GtC) into the atmosphere. Furthermore, the rate of emissions is accelerating: of a total of 305 GtC released to the atmosphere from the consumption of fossil fuels and cement production between 1751 and 2003, fully *half* has been emitted since the mid-1970s [see **Fig. 4**].[7] Moreover, with humans adding close to 7 GtC per year to the atmosphere globally and the planet subtracting only 2 GtC/y, the difference represents the volume of CO_2 accumulating in the atmosphere each year.

The exact numbers vary by country. The U.S., with 5 percent of the world's population (and approximately 21 percent of the world's gross domestic product), released almost a quarter (23 percent) of that, or just over 6.0 $GtCO_2$ (1.6 GtC). This total reaches about 20 metric tons of CO_2 (5.3 metric tons of carbon) per year—that is, 120 pounds of CO_2 or 32 pounds of solid carbon per day per U.S. citizen from all sources: not only from heavy industry, but also from individual consumers driving automobiles, heating homes, and pursuing daily activities typical of our industrialized society. Moreover, that 2005 U.S. figure is more than 20 percent higher than the just under 5.0 $GtCO_2$ (1.4 GtC) the country emitted in 1990, showing an annual average growth in national carbon emissions of 1.2 percent during the past 15 years.[8]

Stabilizing atmospheric CO_2 emissions to the level picked by the U.N. Framework Convention on Climate Change—that is, to 15 to 30 percent *below* 1990 levels by 2020—would require dropping today's U.S. emissions down to between 3.5 and 4.25 $GtCO_2$ per year and dropping global emissions to between 15 and 18 $GtCO_2$ per year. Just to keep matters in perspective, even that lowest level is still double what the planet now annually subtracts.

Finally, the long residence time of CO_2 in the atmosphere poses an especially demanding challenge. In the words of one report published by the Pew Center on Global Climate Change, "Stabilizing atmospheric carbon dioxide concentrations at twice the level of pre-industrial times is likely to require emissions reductions of 65-85 percent below current levels by 2100"—and that only in a scenario in which existing fossil fuel plants are replaced.[9]

In short, even if all worldwide demand for fossil fuels stopped growing, today's current level of emissions is not sustainable. Indeed, today's levels of carbon emissions must be slashed by three-quarters if atmospheric CO_2

Credit: Intergovernmental Panel on Climate Change

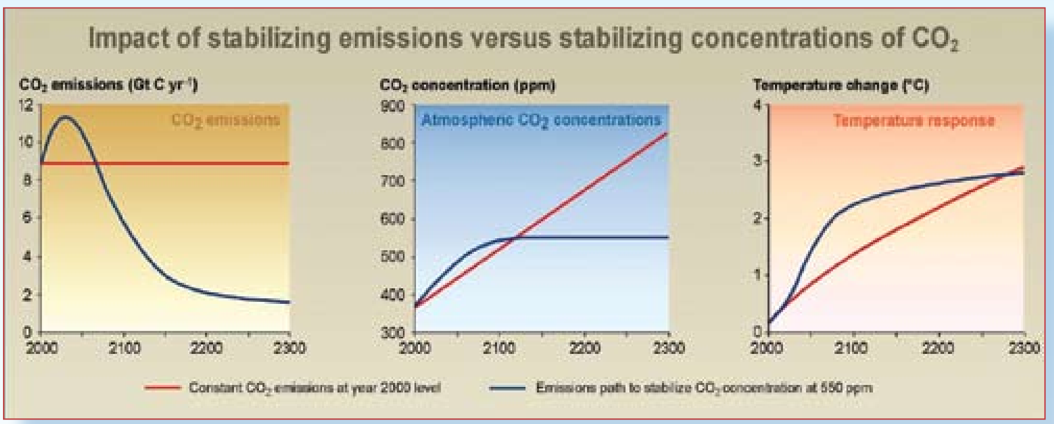


Fig. 3 Because of the centuries-long residence time of CO_2 in the atmosphere, it is essential to address stabilizing the concentrations as well as reducing emissions. The target shown here of 550 ppmv is still an unprecedented level 45 percent higher than today's concentration of 379 ppmv.

concentrations are to be stabilized this century at around 550 ppmv, an unprecedented level that is fully 45 percent *higher* than today's. Other studies suggest a range between 450 and 750 ppmv. More sobering, even that lowest figure of 450 ppmv is significantly higher than today's concentration of atmospheric CO_2—but at present rates of emissions, concentrations may top it within a decade.[10]

Engineers, sharpen your pencils.

Stopping carbon from entering the air

Worldwide power generation, heavy manufacturing, and transportation account for the majority of fossil-fuel use. In the U.S., the generation of electricity accounts for more than 38 percent of all emitted CO_2—the single largest category [see **Fig. 5**]; worldwide, the figure is similarly high, about 30 percent, and growing as developing nations rapidly industrialize.[11] Electricity is generated from half a dozen different energy sources of widely varying carbon content, ranging from coal and petroleum with high-to-medium carbon content, to natural gas (that is, methane or CH_4) with medium-to-low carbon content, to non-carbon sources including nuclear, hydroelectric, wind, and solar.

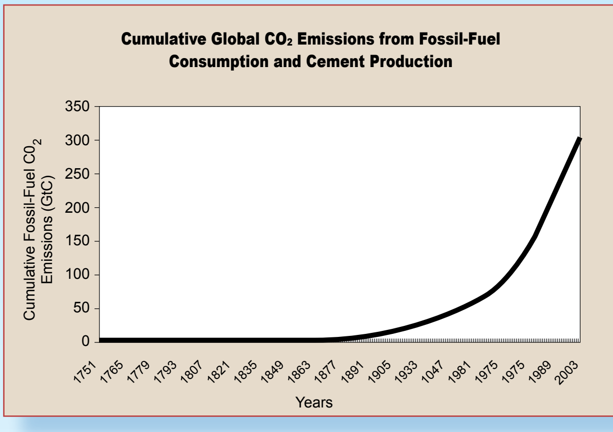
In the U.S., coal is by far the most abundant and cheapest energy source; it also gives reliable baseload power day and night regardless of weather, unlike wind and solar, which are intermittent. But coal—at least in conventional coal-fired power plants—is also by far the dirtiest in terms of CO_2 emissions, in 2001 accounting for 81 percent of carbon emissions from U.S. power generation [see **Fig. 6**]. There's also another reality of life: power plants are not cheap to build, so they are built to last, typically having lifetimes of 30 to 50 years. Because of this (and other reasons beyond the scope of this article), energy companies have strong financial disincentives to retire existing conventional coal-fired power plants early, even when the technology is outdated.

PROPOSAL 1: Carbon capture and sequestration. One interim measure under serious consideration that might allow existing conventional coal-fired power plants to keep producing until they can be phased out at the end of their full lives involve various technologies of carbon capture and sequestration (CCS). An existing plant could be retrofitted with an amine scrubber to capture 80 to 95 percent of CO_2 from combustion gases; the CO_2 would then be condensed into a liquid that would be transported and stored somewhere indefinitely where it could not leak into the atmosphere. If several hundreds or thousands of CCS systems were deployed globally this century, each capturing 1 to 5 $MtCO_2$ per year, collectively they could contribute between 15 and 55 percent of the worldwide cumulative mitigation effort until 2100.[12]

However: The engineering challenges are significant. First, CCS is an energy-intensive process, so power plants require significantly more fuel to generate each kilowatt-hour of electricity. Depending on the type of plant, additional fuel consumption ranges from 11 to 40 percent more—meaning not only in dollars, but also in additional fossil fuel that would have to be removed from the ground to provide the power for the capture and sequestration, as well as in additional CO_2 needing sequestration by doing so.[13]

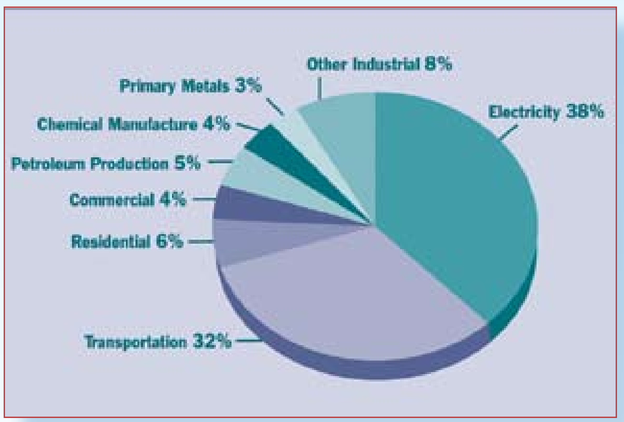
By far, the most cost-effective option is partnering CCS not with older plants, but with advanced coal technologies such as integrated-gasification combined-cycle (IGCC) or oxygenated-fuel (oxyfuel) technology. There is also a clear need to maximize overall energy efficiency if CCS itself is not merely going to have the effect of nearly doubling both demand for fossil fuels and the resultant CO_2 emitted.

Fig. 4 Since the advent of the Industrial Revolution, combustion of fossil fuels has added 305 gigatons of carbon into the atmosphere, so today's concentration is now 35 percent higher than it was 150 years ago. Half that total was emitted during the past three decades. Carbon dioxide accumulates in the atmosphere because its residence time is measured in centuries rather than in just weeks, months, or a few years as is volcanic ash or most other chemicals regarded as pollutants.



Credit: Carbon Dioxide Information Analysis Center of the U.S. Department of Energy

Fig. 5 Fully 70 percent of U.S. carbon emissions come from power generation (38 percent) and transportation (32 percent)—both industries also with low efficiencies (33 and 20 percent, respectively). Many engineering proposals focus on capturing and sequestering CO_2 emissions, increasing overall efficiency, and using low- or no-carbon sources of energy such as hydro, nuclear, and renewables.



Credit: Pew Center on Climate Change

Second, at the rate conventional coal-fired power plants produce CO_2, the amount of liquefied CO_2 to be stored each year would total about a billion tons, or 1 gigaton—that is, about 25 million barrels of CO_2 *per day* under typical reservoir conditions—equivalent to about a third of the total amount of liquid petroleum currently transported around the planet each day.[14] The biggest engineering questions concern its disposal: where such a mammoth volume of liquid could be stored and how it could be monitored to ensure that it does not leak into the atmosphere.

SEQUESTRATION POSSIBILITY 1A: Storage through direct injection underground in deep geological structures. Candidate structures are depleted oil or natural gas reservoirs, still-operational oil and natural gas fields (where liquefied CO_2 is useful for enhanced oil or gas recovery), deep saline aquifers (porous rocks currently permeated by very salty water), or unmineable coal beds (wherein the CO_2 adsorbs or chemically attaches directly to the coal's surface, often replacing natural gas). Best estimates suggest that there are geological structures worldwide with a capacity of at least some 2,000 $GtCO_2$ (545 GtC), sufficient for perhaps several decades of CO_2 produced at present levels.[15] Experts think underground storage holds promise because natural gas and natural CO_2 have been trapped in geological structures for millions of years.

However: A major engineering challenge would be ensuring that injected CO_2 could not migrate elsewhere, especially not making its way to the surface and into the air.

SEQUESTRATION POSSIBILITY 1B: Storage deep in the ocean. Pipelines either directly from the shore or towed by a ship might discharge liquid CO_2 at least 1,000 meters deep, where the liquid would disperse into the ocean water as it dissolved, presumably staying primarily at one depth because the ocean tends to be stratified by such characteristics as density, temperature, and salinity. Alternatively, the CO_2 could be formed into solid hydrates and dropped from a pipe to sink to the ocean floor, where they might either remain as solids or slowly dissolve into the ocean. Or liquid CO_2 could be discharged from a pipe at depths greater than 3,000 meters, where the oceanic pressure is so great that the liquid might form CO_2 lakes on the ocean floor, possibly mixing only very slowly with the surrounding water.

Fig. 6 More than half of U.S. power-generating plants use coal for fuel (below left), generating more than 80 percent of the electrical industry's carbon emissions (below right).

However: With ocean disposal, the principal unknowns concern just how permanent the storage might be and how the liquid's presence might alter the oceans. The oceans have deep currents that eventually rise to the surface in what is dubbed the *ocean conveyor belt*—the global three-dimensional thermohaline circulation driven by heat and salt that links all the oceans (the Gulf Stream is one part of it) and that transfers solar heat from the equator to poles. One circuit takes about 550 years; thus, ocean storage—especially if the liquid CO_2 dissolves in the ocean water—might be good for at best just a couple of centuries before rising currents begin releasing the dissolved CO_2 into the atmosphere.

Of shorter-term concern is the fact that CO_2 acidifies the ocean. Already in the twentieth century, elevated atmospheric levels of CO_2 have lowered the pH of the oceans 0.1 unit (equivalent to an increase of 30 percent more hydrogen ions—remember, the pH scale is logarithmic) with observable devastating effects on some coral reefs, phytoplankton, and other sea life. Deliberate injection is estimated to lower the pH by more than 0.4 unit (doubling or tripling the number of hydrogen ions) over about 1 percent of the ocean's volume.[16] Such acidification is known to impair the ability of shellfish, corals, and other marine ecosystems to do their own task of more permanent carbon sequestration.[17]

SEQUESTRATION POSSIBILITY 1C: Storage through mineral carbonation. Carbon dioxide can react with metal oxides (such as magnesium oxide and calcium oxide), which are abundant in natural silicate rocks such as serpentinite and in minerals such as amphibole. The result would be magnesium carbonate (magnesite), magnesium calcium carbonate (dolomite), or calcium carbonate (calcite, the primary constituent of limestone). One clear advantage is that the carbon is locked in place in a stable matrix with no danger of leaking into the atmosphere. Another is that Earth's crust has more than enough metal oxides to turn all the CO_2 from all available fossil fuels into rocks. The end product also has practical use as a construction material for buildings and roads, eliminating necessity to dispose of hazardous waste.

However: Mineral carbonation has its own engineering challenges. The natural chemical reaction is very slow (in nature it's the process of weathering), so research is needed to see whether it can be accelerated to a commercially useful rate. Fixing each metric ton of CO_2 requires mining, crushing, and milling between 1.6 and 3.7 tons of silicate rock. Thus, for this method to sequester gigatons per year, large-scale surface (strip) mining operations would be required, possibly displacing people or carbon-sequestering forests.

Mineral carbonation is also energy-intensive, adding an energy cost of another 30 to 50 percent to the energy cost of carbon capture. And it would likely produce solid material far faster than the construction industry could use, so volume of storage would be an issue—although leakage or safety hazards would be no greater than those posed by ordinary limestone.[18]

Not an Option: If the waste product CO_2 is so costly to capture and sequester, why not break up its constituent atoms of oxygen and inert elemental carbon? Not a useful option: combustion of coal is basically oxidation of carbon, so the oxidation state of CO_2 is a lower-energy form than pure carbon. Mineral carbonation works because limestone ($CaCO_3$), at an even higher oxidation state, is an even lower-energy form of carbon. But splitting CO_2 into C and O_2 is basically chemical reduction (going back upwards in energy) to return to coal (with some minor chemical differences). Reduction is what plants do in photosynthesis powered by sunlight, literally capturing and trapping solar energy—and what vegetation that now forms coal did 300+ million years ago[19]—which is why coal is an energy source in the first place and is sometimes even called buried sunshine.

Reducing demand for carbon

CCS is viewed by a number of groups as having promise for a few decades as an interim measure for reducing atmospheric carbon emissions relatively quickly and sharply while allowing conventional coal-fired power plants to last their full lifecycles. But the energy costs, the disposal challenges, and the fact that adding CCS to an existing plant actually boosts the overall consumption of fossil fuels all suggest that CCS is not an ultimate solution. However, the costs and complications of adding CCS to traditional power plants may change the comparative economics of alternative sources of energy.

PROPOSAL 2: Permanent reduction in demand. The most sustainable long-term strategy, of course, is permanently reducing all demand for carbon-based fossil fuels. To have any prospect of stabilizing atmospheric concentrations of CO_2 at even 550 ppmv by 2050, the power-generating industry will need to be 60 to 75 percent decarbonized by then,[20] translating to a decline in carbon emissions of 1 to 3 percent per year.

There are many proposals for reducing demand for carbon, some with immediate options and others for over the longer term. One set of options is to improve the energy efficiency of anything that uses fossil fuel. Another is to move to non-carbon fuels or sources of energy. A third is simple conservation. All have engineering opportunities, and some have caveats.[21]

In the United States, transportation accounts for almost a third (32 percent) of fossil-fuel use, second only to power generation (38 percent). Because both coal and petroleum are high-carbon fuels, electricity and driving together account for more than three-quarters of U.S. carbon emissions. Moreover, both sets of technologies have significant opportunities for efficiency improvements.

Power generation is only 33 percent efficient. Technologies that would cut energy usage by a quarter or a third not only would reduce carbon emissions but also would radically lower operating costs. Winter heating and summer cooling of residential homes and office buildings also account for major percentages of power demand, fossil-fuel use, and carbon emissions in the U.S. Designing truly efficient heating and cooling systems, hot-water heaters, and other appliances, as well as automatic set-back thermostats and motion-sensing light switches—especially for commercial office buildings as an alternative to leaving every light burning all night—are immediate steps that can be taken towards reducing demand. Over several decades, the energy savings would make a significant dent in CO_2 emissions.

Transportation is only about 20 percent efficient.[22] Despite technological advances since the 1980s, during the past two decades neither corporate average fuel efficiency (CAFE) standards nor the measured fuel efficiency of American-manufactured cars or trucks has improved; in fact, in the 1990s (the heyday of large and heavy sports-utility vehicles) overall U.S. motor vehicle fuel efficiency actually declined.[23] Meantime, in February 2007, the European Commission proposed that European auto manufacturers should be required to reduce CO_2 emissions 20 percent by 2012, from roughly 161 to 130 grams of CO_2 per kilometer through biofuel use and other technology.

Another big opportunity would be to accelerate the shift to low-carbon or non-carbon fuels. The successes of France in generating 78 percent of its electricity from nuclear power and of Canada in generating more than half of its electricity from hydroelectric show that fossil carbon is not the only source of reliable baseload power. And despite a long history of skepticism in the U.S. at national levels, nearly half of the individual states have set standards to include renewable sources of energy in their portfolios. Moreover, in January 2007, California became the first state to enact an executive order setting a *low-carbon fuel standard* that requires a 10 percent reduction in the greenhouse gas intensity of all passenger-vehicle fuels sold to providers in the state by 2020 and that aims to replace 20 percent of the state's on-road vehicles with those powered by non-carbon fuels.[24] Alternative fuels include ethanol from corn or, better yet, from cellulosic materials such as switchgrass or agricultural waste, which has even lower lifecycle carbon emissions than corn. Other possibilities include plug-in electric vehicles, hybrid/electric vehicles, or hydrogen vehicles that derive electric power from fuel cells.

However: There is one aspect about electric vehicles, ethanol, hydrogen fuel cells, and other biomass fuels that commonly escapes people in low-carbon discussions: these are not to be mistaken for being zero-carbon technologies. Plug-in electric vehicles that recharge by connecting to the power grid will be as carbon free as the fuel consumed by the power-generating plant, being carbon-free only if the power plant uses such energy sources as nuclear, hydro, solar, or wind. Similarly, ethanol will be as carbon-free as the agricultural products from which the ethanol is made; in carbon-emission bookkeeping, though, the net emissions are considered to be zero because corn and switchgrass absorb carbon in photosynthesis while growing, whereas removing fossil carbon from the ground is a one-way process. And in fuel cells, the hydrogen is commonly derived from natural gas, a process that gives off CO_2 that would need to be sequestered. Nonetheless, natural gas and biomass fuels have far less carbon than either petroleum or coal.

Removing carbon from air

PROPOSAL 3: Lowering the accumulated concentration of carbon dioxide already in the air. Is there any way of basically running the planet's atmosphere through gigantic air filters that selectively remove the CO_2? The answer appears to be yes, with two main classes of strategies: one natural, the other technological.

The natural class includes reforestation of deforested areas or marginal agricultural land and afforestation—or essentially tree-farming. Atmospheric CO_2 has been accumulating not only because of high emissions from the combustion of fossil fuels, but also because of the removal of natural carbon sinks, especially forests. The worldwide effect of the loss of carbon sinks is quite large, larger than many realize, accounting for 18 percent of the net emissions. The most effective carbon sinks are fast-growing young trees. It has been estimated that if 115 million acres of marginal farmland in the U.S.—amounting to about a third of land now under the till—were converted to forest, the trees could sequester some 270 million metric tons of carbon for a century, offsetting nearly 20 percent of current U.S. CO_2 emissions from fossil fuels (assuming, of course, that the local climates could support trees).[25]

Engineering-agricultural angles involve research of biomass fuels, including the cultivation of energy crops (ones with maximal energy-content crops), hybridizing plants to fix maximal carbon in soil, and devising low-till methods of commercial-scale agriculture (just turning over soil releases CO_2 that plants have fixed). Note: if the trees are burned, their carbon is released again into the air; it is permanently removed from the atmosphere only if the trees are allowed to keep growing or if their harvested wood either is used for long-lasting products such as houses or is burned in a plant with CCS.[26]

For a technological strategy to remove CO_2 from ambient outdoor air, at least a couple of approaches are on the drawing board or in the stages of experimental prototypes. One design recently tested in prototype would draw in large volumes of ambient air and expose it to a spray of sodium hydroxide (NaOH)—basically lye or caustic soda. The CO_2 chemically combines with the alkali to form sodium carbonate (Na_2CO_3). In a *causticizer*, the sodium carbonate is heated in the presence of lime (CaO), fixing the CO_2 into limestone ($CaCO_3$) and recovering the lye for reuse. The limestone could be used for construction purposes; alternatively, it could be further calcined (heated) to recover the lime for reuse in the process and to release the CO_2 for liquefaction and sequestering underground as in CCS.[27]

Conclusion

In the words of the lead author of a recent National Academies publication *The Carbon Dioxide Dilemma*:

> *Technology, especially in emotionally and ideologically charged environmental debates, almost never provides complete answers. But an array of technological options enables choice and thus increases the chances that we will be able to balance the disparate values, ethics, and design objectives and constraints implicit in the climate change discourse. Technology may help us respond to the world we are creating in responsible, ethical, and rational ways.*[28]

Regardless of which potential solutions are pursued, engineering expertise will be crucial.

Gratitude is expressed to M. Granger Morgan (Lord chair professor and head of the department of engineering and public policy) and Joshuah Stolaroff (post-doctoral research fellow) of Carnegie Mellon University for their generous time and review. Thanks go to Nicki Agron-Olshina, geologist with CSIRO Minerals (Commonwealth Scientific and Industrial Research Organisation) in Clayton, Victoria, Australia; Avi Olshina, geologist with GeoScience Victoria, Melbourne, Australia; and Dennis D. Swinford, editor of *McKinsey on Finance* and associate editor for *The McKinsey Quarterly*, McKinsey & Co., Seattle, WA.

Worthy of Mention

Geo-engineering Solution?

In the spirit of completeness, it should be mentioned that for some years there also have been various "geo-engineering" proposals for adjusting the imbalance of Earth's energy budget from accumulating atmospheric CO_2 without actually reducing the CO_2 itself. Most have to do with reflecting solar radiation on a planet-wide scale, compensating for the enhanced greenhouse effect of higher CO_2 concentrations. One proposal, mimicking the effects of tropical volcanoes that spew sulfate aerosols high into the stratosphere that often subsequently cool the planet for a year or two, suggests deliberately sowing sulfate aerosols, tiny reflective needles, or tiny hydrogen-filled reflective spheres into the stratosphere from high-flying aircraft. Another suggests placing giant gossamer reflectors in space between the sun and Earth to act as a parasol, partially shielding the planet from incoming sunlight.[31]

$25 million CO2 Prize Offered

In February 2007, Sir Richard Branson (founder of Virgin Atlantic airways and other enterprises) and his associates announced a $25 million prize "to encourage a viable technology that will result in the net removal anthropogenic, atmospheric greenhouse gases each year for at least ten years without countervailing harmful effects."[32]

The new global science and technology prize, called the Virgin Earth Challenge, was established, the announcement continues, "in the belief that history has shown that prizes of this nature encourage technological advancement for the good of mankind."

The challenge will award $25 million to the individual or group that is "able to demonstrate a commercially viable design…. This removal must have long-term effects and contribute materially to the stability of the Earth's climate."

Footnotes

[1] The most recent and strongest highest-level statement to this effect was the Summary for Policymakers of the report *Climate Change 2007: The Physical Science Basis* by the United Nations' intergovernmental panel on climate change released on February 2, 2007, [hereafter abbreviated *IPCC AR4 2007 SPM*] (*www.ipcc.ch/SPM2feb07.pdf* and downloadable from *ipcc-wg1.ucar.edu/*). This 2007 summary is the first of a series of documents the IPCC will be releasing as its fourth assessment report on climate change, representing the work of more than 2,000 scientists worldwide (the previous three assessment reports were published in 1990, 1995, and 2001; the full four-volume *Climate Change 2001: IPCC Third Assessment Report* [hereafter abbreviated *IPCC TAR*] can be downloaded from *www.grida.no/climate/ipcc_tar/*. The *IPCC AR4 2007 SPM* read in part, "Warming of the climate system is unequivocal…. The understanding of anthropogenic warming and cooling influences on climate has improved since the *Third Assessment Report*, leading to *very high confidence* [90 percent] that the globally averaged net effect of human activities since 1750 has been warming.… The global increases in CO_2 concentration are due primarily to fossil-fuel use and land-use change." (pp. 4, 3, 2) The U.S. National Academies have also published a dozen and a half reports since 1999 on the subject, which are summarized in the brochure "Understanding and Responding to Climate Change: Highlights of National Academies Reports," (March 2006, dels.nas.edu/basc/climate-high.pdf). See also K. A. Shein, editor, et. al., *State of the Climate in 2005*, NOAA/NESDIS/NCDC and the American Meteorological Society, June 2006, downloadable from *www.ncdc.noaa.gov/oa/climate/research/2005/ann/annsum2005.html*.

[2] *IPCC AR4 2007 SPM*, p. 2.

[3] More information on the United Nations Framework Convention on Climate Change appears at *unfccc.int/essential_background/items/2877.php*. The full text of its Article 2 appears at *unfccc.int/essential_background/convention/background/items/1353.php*.

[4] Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2005*, DOE/EIA-0573(2005), U.S. Department of Energy, 2006 [hereafter abbreviated *EIA GHG*] *www.eia.doe.gov/oiaf/1605/ggrpt/pdf/057305.pdf*, p. iii; See also U.S. Climate Change Science Program, *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*, September 2006 public-review draft, p. 2-2 (downloadable from *cdiac.ornl.gov/SOCCR/public_review_draft_report.html*). See also U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2004* (April 15, 2006, downloadable from *www.epa.gov/climatechange/emissions/usinventoryreport.html*).

[5] Jacobs, Gary K., "Using Terrestrial Ecosystems for Carbon Sequestration," *The Carbon Dioxide Dilemma: Promising Technologies and Policies* (National Academy of Engineering, National Research Council, 2003 [hereafter abbreviated *NAP CDD*], available from *www.nap.edu/catalog/10798.html*), p. 62.

[6] A recent full discussion of the biosphere as a natural-carbon sink is "Saturation of the Terrestrial Carbon Sink," Josep G. Canadell, *et al.*, Chapter 6 of *Terrestrial Ecosystems in a Changing World* (edited by Josep G. Canadell, Diane E. Pataki, Louis F. Pitelka, The IGBP Series, Springer-Verlag, Berlin Heidelberg, 2007), pp. 59–78.

[7] Marland, G., T.A. Boden, and R.J. Andres, "Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change," 2006. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Dept. of Energy, Oak Ridge, TN (*cdiac.esd.ornl.gov/trends/emis/tre_glob.htm*).

[8] Base figures are rounded from data in *EIA GHG*, p. ix, xi, 2, 13. See also the EIA's *International Energy Outlook 2006* (U.S. Department of Energy, DOE/EIA-0484(2006), June 2006, *www.eia.doe.gov/oiaf/ieo/index.html*).

[9] Granger Morgan, Jay Apt, and Lester Lave, *The U.S. Electric Power Sector and Climate Change Mitigation*, Pew Center on Global Climate Change, June 2005 [hereafter abbreviated *Morgan*] *www.pewclimate.org/docuploads/electricity_Final.pdf*, p. iv, 59.

[10] Most studies recommend on stabilizing at 450-550 ppmv, with even 550 ppmv being regarded as high risk. See, for example, Nicholas Stern, *The Economics of Climate Change: The Stern Review* (Cambridge University Press, January 2007[hereafter abbreviated the *Stern Review*]), Executive Summary, p. xv, downloadable from *www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm*. IPCC Special Report, *Carbon Dioxide Capture and Storage: Summary for Policymakers and Technical Summary* [hereafter designated IPCC CCS] (Intergovernmental Panel on Climate Change, 2005, downloadable from *arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm)*, p. 11. See also "Stabilising climate to avoid dangerous climate change– A summary of relevant research at the Hadley Centre," January 2005, pp. 14-16, *www.metoffice.gov.uk/research/hadleycentre/pubs/brochures/2005/CLIMATE_CHANGE_JOURNAL_150.pdf* and Hans Joachim Schellnhuber, *Avoiding Dangerous Climate Change* (Cambridge University Press, 2006, downloadable from *www.defra.gov.uk/environment/climatechange/internat/dangerous-cc.htm*. The call for stabilization at or below 550 ppmv is not limited to governmental bodies, but is an increasing concern of private enterprise; for example, see p. 6 of *A Call for Action* (U.S. Climate Action Partnership, January 2007, downloadable from *www.us-cap.org/*), a blueprint report published by a partnership of major businesses with major environmental organizations.

[11] *Morgan* says 38 percent, p. iii, and p. 3. *EIA GHA* says 40 percent, p. xiii.

[12] *IPCC CCS*, p. 3, 11, 43. See also IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Institute for Global Environmental Strategies, 2006 [hereafter abbreviated *IPCC GHG*], downloadable from *www.ipcc-nggip.iges.or.jp/*), chapter 5 "CO_2 Transport, Injection and Geological Storage" in volume 2 "Energy."

[13] *IPCC CCS*, p. 24.

[14] Frankin M. Orr Jr., "Sequestration via Injection of Carbon Dioxide into the Deep Earth," *NAP CDD*, p. 17.

[15] *IPCC CCS*, p. 11.

[16] *IPCC CCS*, p. 35.

[17] See, for example, The Royal Society, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide* (30 June 2005, downloadable from *www.royalsoc.ac.uk/document.asp?id=3249*).

[18] *IPCC CCS*, pp. 13, 36-37.

[19] The author expresses gratitude to Granger Morgan and Joshuah Stolaroff at Carnegie Mellon University for this explanation.

[20] A recent examination of such proposals is U.S. Climate Change Science Program, *Effects of Climate Change on Energy Production and Use in the United States*, Synthesis and Assessment Product 4.5, whose public comment draft (November 30, 2006) is downloadable from *www.ornl.gov/sci/sap_4.5/energy_impacts/documents.shtml*.

[21] For completeness, it should be noted that non-engineering strategies for reducing demand for fossil fuels—including but not limited to consumer conservation-education programs, elimination of oil subsidies, and enactment carbon taxes on both commercial enterprises and individual consumers—are widely discussed in carbon-reduction literature, but lie outside the focus of this engineering article. As examples, see three Congressional Budget Office studies: *The Economics of Climate Change: A Primer* (April 2003, *www.cbo.gov/ftpdocs/41xx/doc4171/04-25-ClimateChange.pdf*), "Limiting Carbon Dioxide Emissions: Prices Versus Caps" (March 15, 2005, *www.cbo.gov/ftpdocs/61xx/doc6148/03-15-pricevsquantity.pdf*), and *Evaluating the Role of Prices and R&D in Reducing Carbon Dioxide Emissions* (September 2006, *www.cbo.gov/ftpdocs/75xx/doc7567/09-18-carbonemissions.pdf*). See also Larry Parker, "Climate Change: The European Union's Emissions Trading System (EU-ETS)," Congressional Research Service Report for Congress, Order Code RL33581, July 31, 2006 (*vienna.usembassy.gov/en/download/pdf/eu_ets.pdf*).

[22] *EIA GHG* p. 16. See also Dale Simbeck, "The Forms and Costs of Carbon Sequestration and Capture from Energy Systems," *NAP CDD*, p. 74.

[23] U.S. Environmental Protection Agency, *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2005* (EPA, July 2005, downloadable from *www.epa.gov/fueleconomy/fetrends/420s05001.htm*).

[24] The California LCFS announcement appears at *www.greencarcongress.com/2007/01/california_gove.html*. An associated white paper "The Role of a Low Carbon Fuel Standard in Reducing Greenhouse Gas Emissions and Protecting Our Economy" appears at *gov.ca.gov/pdf/gov/alternativeFuels.pdf*.

[25] The figure of 18 percent appears in several references, including in the *Stern Review*, Executive Summary, p. xxv. Kenneth R. Richards, R. Neil Sampson, and Sandra Brown, *Agricultural and Forestlands: U.S. Carbon Policy Strategies* (Pew Center on Global Climate Change, September 2006, available from *www.pewclimate.org/global-warming-in-depth/all_reports/ag_forestlands/index.cfm*), p. iv. For more discussion, see *IPCC GHG*, volume 4 "Agriculture, Forestry and Other Land Use." The role of land use in the carbon cycle is discussed at length in *IPCC TAR 2001, The Scientific Basis*, Chapter 3 "The Carbon Cycle and Atmospheric Carbon Dioxide" and Chapter 7 "Physical Climate Processes and Feedbacks."

[26] See, for example, Keith Paustian et al. *Agriculture's Role in Greenhouse Gas Mitigation* (Pew Center on Global Climate Change, September 2006, downloadable from *www.pewclimate.org/global-warming-in-depth/all_reports/agriculture_s_role_mitigation/index.cfm*). The 18 percent figure for deforestation appears in several places, including in *The Stern Review* Executive Summary, p. xxv.

[27] Joshuah K. Stolaroff, "Capturing CO_2 from ambient air: a feasibility assessment," Ph.D. dissertation, Carnegie Mellon University, 2006, *wpweb2.tepper.cmu.edu/ceic/theses/joshuah_stolaroff_phd_thesis_2006.pdf*. The references at the end summarize literature on other different approaches.

[28] Braden R. Allenby, "Global Climate Change and the Anthropogenic Earth," *NAP CDD*, pp. 9–10.

[29] The climate role of CO_2 is outlined in, among other sources, A.P.M. Baede et al., "The Climate System: an Overview," *IPCC TAR*, Chapter 1 of the volume *The Scientific Basis*, United Nations Intergovernmental Panel on Climate Change, *unfccc.int/resource/cd_roms/na1/mitigation/Resource_materials/IPCC_TAR_Climate_Change_2001_Scientific_Basis/TAR-01.pdf*.

[30] The diagram accompanying this sidebar is greatly simplified, because there are many mechanisms in the atmosphere involved in the retention and reflection of solar radiation, CO_2 being the most important one. The planet's radiation budget and natural greenhouse effect are discussed in greater detail in Baede *et al.*, *IPCC TAR* , with Fig, 1.2 on p. 90 quantifying processes in watts per square meter. Note that the popular name *greenhouse effect* is a bit of a misnomer, because the greenhouse analogy is imperfect. Although glass blocks infrared from escaping a greenhouse, it also blocks air convection, as is evident if one opens an upper glass panel: warm air quickly escapes. In contrast, CO_2 does not block air convection on Earth—indeed, air convection through the Hadley, Ferrel, and Polar convection cells is the principal way atmospheric moisture and heat move from the planet's equator to the poles.

[31] See, for example, Roderick A. Hyde, Edward Teller, and Lowell L. Wood, "Active Climate Stabilization: Practical Physics-Based Approaches to Preventing Climate Change," *NAP CDD* pp. 87–94; a more recent example, which cites key earlier literature, is Michael C. MacCracken, "Geoengineering: Worthy of Cautious Evaluation? An Editorial Comment," *Climatic Change* (2006) 77: 235–243. The IPCC also discusses geo-engineering strategies, but notes that most papers on them "contain expressions of concern about unexpected environmental impacts, our lack of complete understanding of the systems involved, and concerns with the legal and ethical implications… Unlike other strategies, geo-engineering addresses the symptoms rather than the causes of climate change." *IPCC TAR*, *Mitigation*, Chapter 4 "Technological and Economic Potential of Options to Enhance, Maintain, and Manage Biological Carbon Reservoirs and Geo-engineering," p. 334.

[32]More about the judges and other particulars of Richard Branson's Virgin Earth Challenge is at *www.virginearth.com*. A cautionary commentary "Virgin, the Dynamo, and the Prize" by Kelpie Wilson, noting the existence of promising small-scale engineering possibilities with significant potential, appears at *www.truthout.org/docs_2006/021407J.shtml*.

Trudy E. Bell is a contract technical writer for the national coordination office of the federal government's networking and information technology research and development program *(www.nitrd.gov)*. A former editor for *Scientific American* (1971-78) and *IEEE Spectrum* (1983-97) and former managing editor of the *Journal of the Antique Telescope Society* (2003–06), she has an M.A. in the history of science and American intellectual history from New York University (1978). *(t.e.bell@ieee.org)*

Her interest in weather and climate began 12 years ago when she started photographing and writing about meteorological optics phenomena in the daytime sky, later augmented by her ongoing historical research into the 1913 flood. She has completed the volume *Weather* for the Smithsonian Science 101 set of books, to be published this year by HarperCollins. She is the author of *The Essential Bicycle Commuter* (Ragged Mountain Press, 1998) and *Bicycling With Children: A Complete How-To Guide* (The Mountaineers, 1999).

This article is her ninth for THE BENT since 2002; her "Testing Einstein: Engineering Gutsy Science on a Shoestring" (Summer 2005) won the American Astronomical Society's 2006 David N. Schramm award for science journalism.

Both in New York City and Cleveland (shown here), Trudy Bell has been a regular bicycle commuter since 1983, saving 40,000 miles on a motor vehicle with commensurate reduction in carbon emissions.