Martin Hoffert

An Energy Revolution for the Greenhouse Century

When there is no vision, the people perish.
—Proverbs 29:18

You see things: and you say, "Why?"
But I dream things that never were; and I say, "Why not?"
—George Bernard Shaw, *Back to Methuselah* (1921)

We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because the challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win. . . .
—John F. Kennedy, Rice University, 1962

THE REALITY OF GLOBAL WARMING FROM THE BUILDUP OF FOSSIL FUEL CARBON dioxide in the atmosphere is no longer in doubt. Arctic sea ice, tundra, and alpine glaciers are melting, tropical diseases like West Nile virus and malaria are penetrating higher latitudes, and sea surface temperatures have risen to the point where Katrina-like hurricanes are not only more probable, but actually occur. Also taking place are the extinction of plants and animals adapted to cooler regimes but unable to migrate poleward fast enough to keep pace with a warming climate. Polar bears, already far north, may have nowhere to go. Ominously, the melting of Greenland and Antarctic icecaps is accelerating, threatening worldwide major sea level rise and coastal inundation (Hansen, 2006; Gore, 2006; Kolbert, 2006; Flannery, 2006).

These are well-documented facts, not alarmist predictions by desperate environmentalists in search of funding (Crichton, 2003) or some colossal hoax on the American people (Inhofe, 2003). Atmospheric warming from water vapor, CO_2, and other greenhouse gases is a basic principle of atmospheric science. It is responsible for maintaining earth as a habitable zone for life, and for making Venus, with its pure CO_2 atmosphere 100 times thicker than earth's, hot as metaphorical Hell. Cooling can result from suspended aerosol particles also produced by burning fossil fuels, but aerosols remain in the atmosphere a much shorter time than CO_2 and their cooling effect, so far, has mainly served to mask the full impact of warming from CO_2 emissions. (Some propose "geoengineering" climate by intentionally injecting aerosols to cool regions most threatened by global warming, such as the Arctic; see for example Teller, Wood, and Hyde, 2002). Heat temporarily stored in oceans can also delay or mask committed greenhouse warming, as can variations in the output of the sun and volcanic eruptions. But volcanoes, the sun, and the oceans cause surface temperature to rise and fall in a narrow range. In retrospect, it was inevitable that the explosive growth (on a geological time scale) of human CO_2 emissions, driven by population growth, industrialization and, most of all, by fossil fuel energy use, made it inevitable that human-induced warming would overwhelm climate change from all the other factors at some point. And we are at that point.

That fossil fuel atmospheric carbon dioxide would warm the planet was predicted over a century ago (Arrhenius, 1896). Roughly half the CO_2 input by humans remains in the atmosphere. The rest mostly dissolves in the ocean, creating excess acidity that marine organisms may not be able to tolerate, which is another problem. By the third quarter of the twentieth century, CO_2 buildup in the atmosphere was evident, although greenhouse warming did not emerge from background "noise" until the late 1980s. Hans Suess and Roger Revelle recognized early on that transferring hundreds of billions of tons of carbon in fossil fuels (coal, oil, and natural gas) formed over hundreds of millions of years and locked up in earth's crust to the atmosphere as CO_2 in a few hundred years was "grand

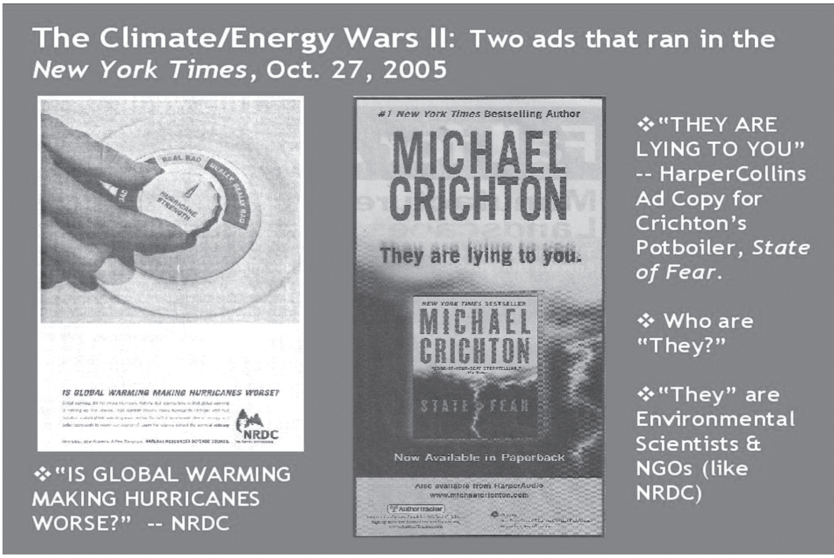


Fig. 1

geophysical experiment" on a scale unseen in human history (Revelle and Suess, 1957). Revelle was to be an influential professor of Al Gore's at Harvard, with ramifications reverberating today (Gore, 2006). By the late 1960s, Syukuro (Suki) Manabe, to my mind, an "Einstein" of atmospheric science, had worked out the detailed physics of how greenhouse gases affect atmospheric temperature from the surface to the stratosphere, including the water vapor feedback that roughly doubles warming from CO_2 alone (Manabe and Weatherald, 1967).

The discovery of global warming is a fascinating chapter in the history of science (Weart, 2003). Many phenomena that we are now seeing—heat going into the oceans, greater warming at the Arctic, volcanic and aerosol effects—were predicted decades ago. One group, including Steve Schneider, Richard Sommerville, Jim Hansen and this author, worked on this problem in the 1970s, primarily as an intellectual challenge in theoretical climate modeling and computer science at the Goddard Institute of Space Studies (GISS), a NASA-funded research institute near Columbia University started by Robert Jastrow while he was still in his twenties.

Back then, global warming was not yet politicized as it is now (figure 1). A "back of the envelope" calculation I did at GISS in the 70s suggested fossil fuel greenhouse warming would emerge from background temperature variations by the late 80s. So I thought it might be a good idea to publish some papers predicting this, which I did, as did colleagues at GISS and elsewhere. That limiting CO_2 emissions to avoid adverse global warming might disrupt consumerist civilization and multinational energy companies while putting a damper on industrialization of China and India was implicit, but academic.

Ironically, in light of the conclusive support for it developed at the research institute he founded (Hansen et al., 2005), Jastrow was highly critical of the global warming hypothesis. He never published peer-reviewed climate research, in stunning contrast to the present GISS director, Jim Hansen; but, on taking early retirement from NASA, Jastrow and Fred Seitz of Rockefeller University founded the Marshall Institute in Washington, D.C., a bastion of climate change deniers allied with the American Enterprise Institute, the Cato Institute, and other conservative think tanks in opposition to US participation in the CO_2-emissions-limiting Kyoto Protocol—the first implementation of the UN Framework Climate Change Convention (FCCC).

The United States, China, and India have not ratified Kyoto. Indeed, 850 new coal-fired power plants to be built in these countries by 2012 will overwhelm Kyoto emission reductions by a factor of five (Clayton, 2004). Avoiding "dangerous human interference with the climate system," the goal of the UN FCCC, is a daunting technological challenge because 85 percent of the world's energy comes from fossil fuel; and stabilizing global temperature at acceptable levels will require a revolutionary change in the world's energy systems (Hoffert et al., 1998; 2002; "Energy's Future," 2006). Although global warming is settled science, a public relations battle continues to rage.

Problems exist on both sides of the red-blue divide. In a searing critique of environmental nongovernmental organizations (NGOs) like the National Resources Defense Council and Environmental Defense, Shellenberger and Nordhaus (2005) argue that, despite major campaigns, environmental lobbies have had little success on the global warming front. The authors discount efforts by states in the United

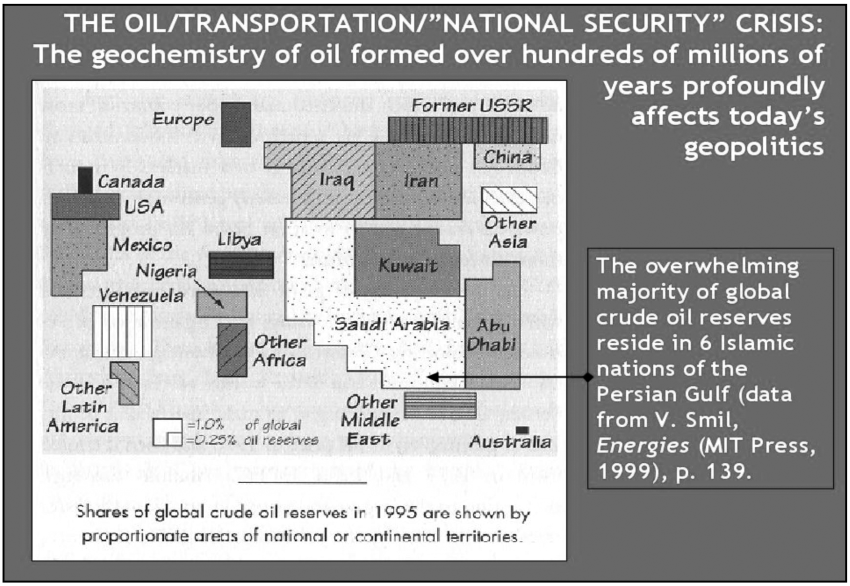


Fig. 2

States to create renewable energy portfolios with ambitious targets for alternate energy as so much public relations. They claim, with some justification, that "not one of America's environmental leaders is articulating a vision of the future commensurate with the magnitude of the crisis."

Why? Global warming is not only different in scale from prior environmental challenges (acid rain, heavy metal contamination, DDT, etc.)—its long-term planet-changing nature requires forethought and imagination to a much greater degree than the threats to which Homo sapiens has evolved adrenaline-pumping instinctive responses. The growth of human population, CO_2 emissions, and global warming in the past millennium are very recent from a human evolutionary perspective. For the first time in its history, Homo sapiens has begun to interact more or less as a unit with the global environmental system (Eldridge, 1996). Because modern technology developed *after* we evolved biologically, we lack appropriate instincts to deal with it—these having been unlikely to confer survivability in our evolutionary past. By default, we have to deal with the climate/energy problem cognitively. So far, we are not doing too well. As Carl Sagan observed, our reptilian brains motivate aggressive and tribal, as opposed to thoughtful, responses in ways we barely perceive and across many spheres of human behavior.

In the climate wars, deniers often get more vociferous as the evidence against their views gets stronger (Hoffert, 2003). The so-called hockey stick curve (developed by paleoclimatologist Mike Mann and colleagues) was recently attacked from the floor on Congress by Representative Joe Barton (R-Texas), based on cherry-picked information suggesting their statistics were flawed reported in the *Wall Street Journal*. Would that Rep. Barton, and legislators in general were better educated in statistical and scientific issues. But my experience briefing legislators and aides is that scientific illiteracy and intellectual laziness are rampant. Educated mainly as lawyers, many do not get it that nature does not care about human politics. (Unfortunately, some academics that should know better likewise argue that science is more a "consensual reality" than an objective description of nature deduced by the scientific method.) Too few bright and imaginative students pursue careers in science and engineering today. We need such students badly.

The hockey stick curve that shows a dramatic recent uptick in global temperature with much more to come is easily perceived as a threat not only to Big Oil and Big Coal, but also to election campaign funds. Easier to blame the messenger than think critically about this. The general trend of the Mann et al. (2003) hockey stick was independently verified by other researchers in a recent report by the National Research Council (NRC, 2006). Overwhelmingly, research-active climate scientists know we are entering climatic territory unseen in human history (Hansen, 2006). Our rapidly melting planet is so dominated by humankind's emissions that the present climatic era is being called the anthropocene (Crutzen and Ramanathan, 2003).

Most knowledgeable researchers are very concerned about global warming. Some, including this author, argue for research and development programs on an Apollo space program-like scale to create low-carbon alternate energy supply and demand-reducing technologies in time to make a difference (Hoffert et al., 1998, 2002; Rees, 2006). This effort should include prompt implementation of energy conservation, efficiency, and existing alternate energy sources (Lovins, 1989; Metz et al., 2001; Pacala and Socolow, 2004; Socolow, 2006).

Whatever the deep evolutionary reasons, the climate/energy issue competes for attention with other problems in the mind of the average citizen. A frequently asked question is: "Why even care about global warming and climate change?" The worst effects occur decades to centuries from now. In cost-benefit accounting, many economists strongly discount the present value of adverse future impacts and "externalize" (that is, neglect) the cost of environmentally degrading the global commons (Daly and Townsend, 1994). Economics is, of course, a legitimate branch of behavioral biology dealing with the allocation of scarce resources by Homo sapiens, one of millions of biological species inhabiting this planet. But, so far, in its predictive mode, it resembles astrology more than a hard science. Economist John Kenneth Galbraith went so far as to say, "The only reason for economists to produce forecasts is to make astrology look respectable" (Jaccard, 2005). Undaunted, Bjorn Lomborg, the "skeptical environmentalist" (Lomborg, 2001), convened a group of economists to prioritize investments in various challenges facing humankind. The group concluded in its "Copenhagen Consensus" that climate change, even if real, is near the bottom (Bohannan, 2004). Reading the group's findings, one is struck by how evolutionarily blind our species can be to existential threats. Among the problems with this indifference—noted by Harvard energy policy analyst John Holdren, and in his film and book, *An Inconvenient Truth,* by Al Gore—is that climate change is more an ethical than an economics problem.

An even more basic flaw to this physical scientist is that the environmental constraint of global warming on energy was entirely missed by the Copenhagen group. The late Nobel laureate Rick Smalley astutely observed that, although civilization has many problems, energy is key to them all. Smalley's list of problems encompasses energy, water, food, environment (including global warming), poverty, terrorism and war,

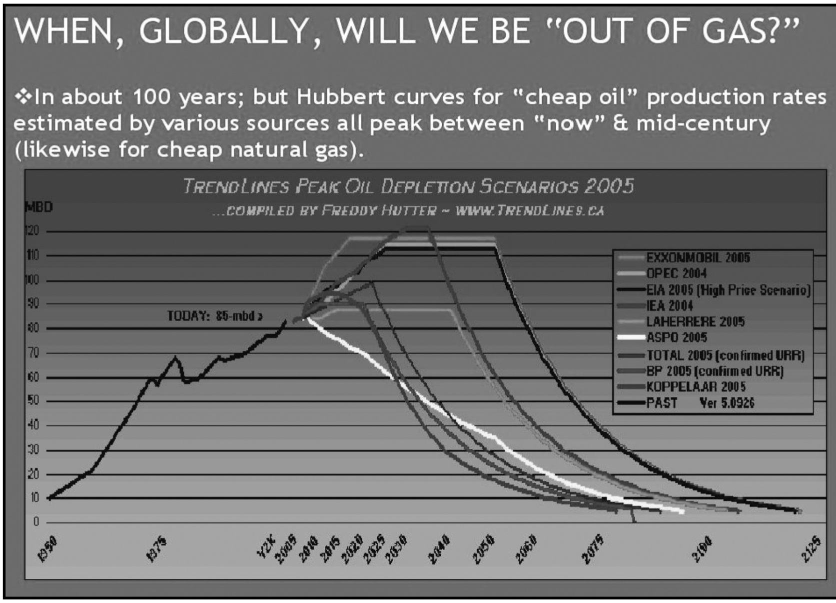


Fig. 3

disease, education, democracy, and population (Smalley, 2005). Energy is key because solving all these problems requires sustainable power on a global scale. Without it civilization collapses. Concentrated fossil fuels are a one-shot boon of nature. Coal being still relatively abundant, humankind might have deferred an energy revolution to another primary power source to the twenty-second century, or even later, were it not for global warming. Coal burned for electricity and even shortages caused by peak oil can be handled at higher cost by making synthetic fuels from coal. But potentially catastrophic global warming is the "canary in the mine." It trumps everything else; moving the climate/energy issue to the front of the list.

To generalize the Shellenberger-Nordhaus thesis, there is little evidence that politicians of *any* persuasion appreciate the magnitude of the problem, or can articulate a vision to address it. The most relevant questions are being asked by energy scientists and engineers: Are there technologies likely to lead to a low-carbon world in time and still allow global GDP to continue growing 2 to 3 percent per year ("Energy's Future," 2006)? What global energy systems should we be aiming at? Can we get there in time? One leading economist put it this way: "The trouble with the global warming debate is that it has become a moral crusade when it's really an engineering problem. The inconvenient truth is that if we don't solve the engineering problem, we're helpless" (Samuelson, 2006).

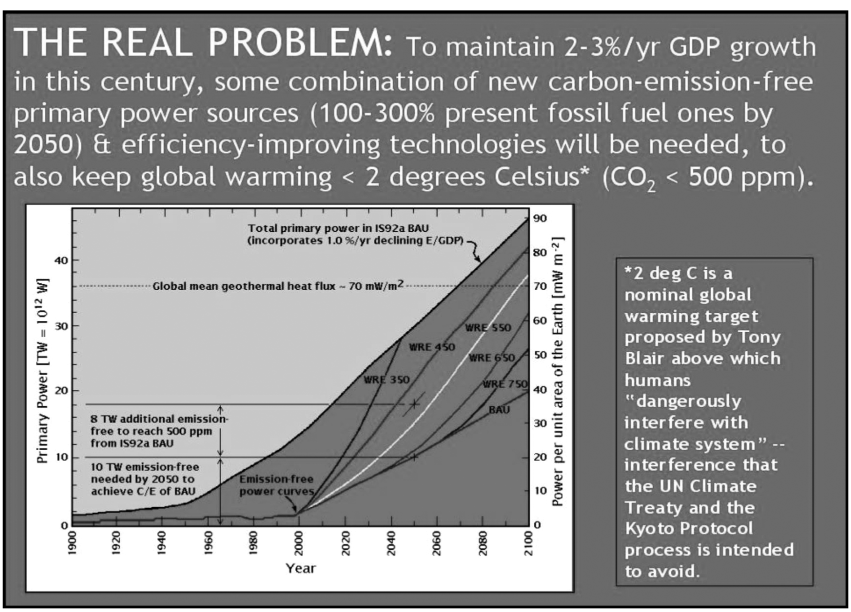
The issue of "energy security" makes the need for an energy technology revolution a viable policy option even for "red" states and others indisposed see global warming for the threat it is. Two hundred years of innovation—the famous "Yankee ingenuity"—are behind America's ascent to world power (Evans, 2004). Applied science and entrepreneurship enabled by government research and development since World War II (Bush, 1945) are a historically appropriate response for the United States.

The need is clear. Figure 2, from Smil (1999), shows oil reserves around the world, with the lion's share in the Persian Gulf. But Saudi Arabia, Iran, and Iraq are powderkegs of post-9/11 Islamic fundamentalism. Some Al Qaeda ideologues have drawn up a plan aimed at establishing an Islamic caliphate throughout the Middle East, in which attacks against the petroleum industry are critical to the deterioration of American power through constant expansion of the circle of confrontation (Wright, 2006). And because oil is internationally traded, it is irrelevant whether oil imports by the United States originate under a particular Middle Eastern desert. The more oil money that flows to Saudi Arabia, Iran, etc., the more money that flows to Al Qaeda, Hezbollah, and other terrorist groups that we are ostensibly at war with. As Tom Friedman of the *New York Times* has repeatedly emphasized, our addiction to oil combined with lack of any serious policy to develop alternatives is why the United States is funding *both* sides of the "War on Terror."

We know that world hydrocarbon resources are limited. Virtually all major crude oil and natural gas reservoirs have been mapped by seismic probes. Every day, the world consumes about 80 million barrels of oil, a rate that has been increasing with economic growth but is ultimately constrained by geological abundance to peak in coming decades (Deffeyes, 2001). From a global warming perspective, the coming oil peak, accelerated by China and India with booming GDPs, is problematic because it is forcing a transition back to coal for primary energy and thus "recarbonizing" the energy supply since coal emits more CO_2 per unit of energy than oil or natural gas. And, of course, oil prices are rapidly rising, headed for $100 per barrel or more. Figure 3 shows the current range of oil production rate projections. As with the climate change deniers, some "cornucopian" economists say the oil peak is overblown. But consider that oil companies are motivated to inflate, not deflate, their reserve estimates to raise their corporate valuations on Wall Street. Royal Dutch Shell, for example, was recently compelled by the US Security and Exchange Commission to revise its reserve estimate downward 20 percent, suggesting an oil peak sooner rather than later. In any case, most petroleum geologists agree the world will be "out of gas" by the end of the century.

I want to be clear that I am a technological optimist. I believe we can solve the climate/energy problem. But there is no silver bullet and it will not be easy. It will take the greatest engineering effort in history; bigger than the Manhattan project to build the bomb, bigger than the

Fig. 4



Apollo program to land a man on the moon, bigger than the mobilization to fight World War II. Moreover, the effort has to be international in scope with sufficient inducements for developing giants China and India to sign on. This problem will not solve itself through the invisible hand of the market. Relevant costs and values are not being captured. We are moving rapidly in the wrong direction. Particularly serious is that we are investing in the wrong infrastructures for a sustainable energy world. Vision and imagination are critical. Sooner or later the world will realize this. The longer we wait, the harder the job will be.

Exponential growth cannot be sustained indefinitely on a finite planet. We could, and I believe should, try to maintain 2 to 3 percent per year world GDP growth to the end of the century (a likely minimum for developing nations to attain income equity) as CO_2 emissions are held constant, decreased, and eventually phased out by mid-century. This would—based on our best current models—keep the atmospheric CO_2 concentration below 500 parts per million (ppm) and global warming below 2 degrees Celsius. Higher than 2 degrees could trigger dangerous human interference with the climate system, according to criteria recently adopted by the European Union (Edmonds and Smith, 2006). Two degrees may not sound like much, but more could put us on a planet-changing trajectory with irreversible melting of the Greenland and Antarctic icecaps, which would inundate the world's coastal zones (Hansen, 2006; Gore, 2006). A big job, given that atmospheric CO_2 has already risen to 380 ppm—100 ppm above the preindustrial level from fossil fuel burning and deforestation so far. To do it, some combination of emission-free primary power sources and primary power demand-reduction equivalent to generating 100 to 300 percent of present power from some as yet unidentified set of power systems will be needed by mid-century (figure 4, based of Hoffert et al., 1998; 2002).

How hard is that? Consider that 2050 is nearer in the future than when Fermi's first nuclear reactor (then called an "atomic pile") went critical in December 1942 at the University of Chicago is in the past. We now produce about 5 percent of primary energy worldwide from nuclear power (this is virtually all for electricity; roughly 18 percent

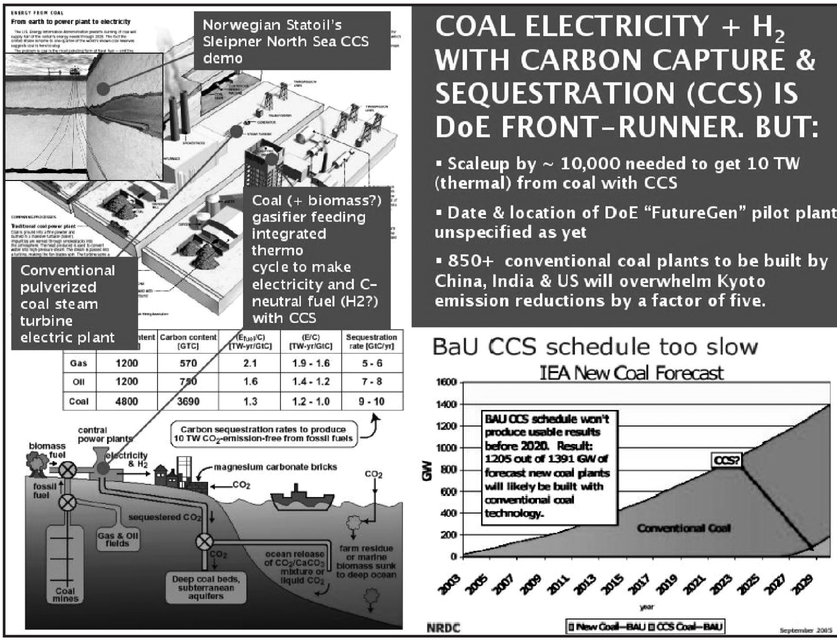
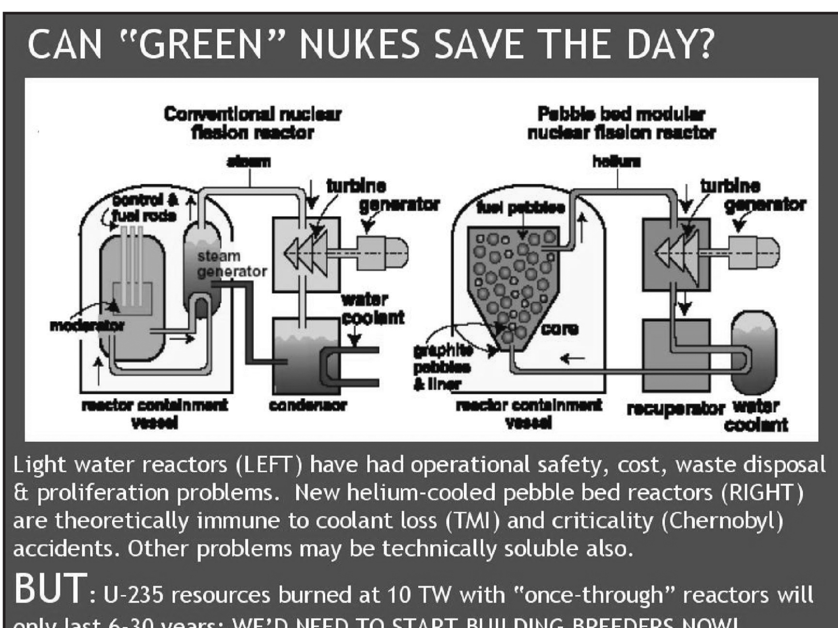


Fig. 5

of electricity generation is nuclear; the rest is from fossil fuels, mostly coal and hydroelectricity). If we need some new carbon-emission free "energy source X" 50 years hence, the implied growth of these new power sources is 20 to 60 times faster than nuclear power, the last revolutionary power source deployed on a large scale. Not impossible, but we do have to concentrate. Below are some ideas that could work if we get serious.

For starters, we could dramatically accelerate what some engineers believe is the most ready for prime time major emission-free energy source: coal with carbon capture and sequestration (CCS). Figure 5 depicts coal gasification plants making electricity and hydrogen with the CO_2 pumped to reservoirs underground, the rationale being that we have large coal resources that can play a role in a transition to a sustainable energy system if we can get the energy out while putting CO_2 (and other pollutants) away in reservoirs underground. One problem is that coal with CCS deployment is unlikely before pilot plants demonstrate that the combined technology works. Iindividual components like coal gasification, combined cycle power plants, and even CO_2 sequestration have been shown, but the technology is too costly without a carbon tax or "cap and trade" emissions policy in place. The United States, China, and India have not agreed on emission limits, and these are precisely the countries with massive coal resources where planned buildup of conventional coal electric power stations is most intense. The lower right panel of Figure 5 shows how conventional coal plants in the works will overwhelm proposed CCS plants. A Department of Energy-funded CCS pilot plant called "FutureGen" was cited by this administration at climate negotiations in Montreal as the US premier effort, in partnership with the coal industry, to combat global warming (Revkin, 2005). But this plant is unlikely before 2012 and its location is still unannounced. Experts believe it may be more expensive to retrofit conventional coal plans with CCS than build gasification plants with CCS from scratch. Suppose global warming got bad—really bad. Will conventional coal plants be abandoned, as the $6 billion Shoreham nuclear plant was after Three Mile Island (TMI) and Chernobyl? Once they are generating electricity from cheap coal, with capital costs "sunk" for 50 to 75 years, it might be so expensive to shut

Fig. 6



down and build new ones that ratepayers would balk even to slow a global warming juggernaut. This is not a good scenario.

Another class of low-carbon primary power now being reconsidered after a disastrous start is "green" nukes (figure 6). No one has started building a new nuclear reactor in the United States for the past 30 years, though some are planned. Classic problems of nuclear power are operational safety, waste disposal, and weapons proliferation. However, for global warming mitigation, the major constraint may be that planned reactors are "once through" and use the supply-limited uranium 235 (U-235) isotope, which makes up less than 1 percent of natural uranium. The energy content of U-235 in identified deposits is less than natural gas. We would run out of fuel in 30 years employing such reactors at rates sufficient to supply present primary power demand. As with coal, we do not have the luxury of investing in the wrong nuclear power infrastructure. Longer-term, we will need to breed U-238 (99 percent of natural uranium) into plutonium or more abundant thorium to U-233, a fuel I favor for several technical reasons. Why not start now? Infrastructure and weapons proliferations issues need to be faced now if we are serious about green nukes as alternative energy.

The third class of primary power, my own preference, is renewable energy, currently less than 1 percent of primary power (figure 7). Space limitations prevent an adequate discussion, but I and colleagues at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and elsewhere believe solar and wind power can be scaled up, with a proper infrastructure of transmission and storage, to provide 30 percent or more of primary emission-free power by midcentury (Pew Center, 2004). President Jimmy Carter, a strong advocate of renewables, created the Solar Energy Research Institute, the precursor of NREL. And Jerry Brown, dubbed California's "governor moonbeam" by critics, in the 1970s initiated tax and other incentives leading to the now cost-effective Altamont wind farms. It is hard to overestimate the damage done by Ronald Reagan who, on becoming president, symbolically ripped the solar panels Carter had put on the roof of the White House, likewise dismantling most of Carter's energy research and development initiative. We have not recovered. Carter's administration

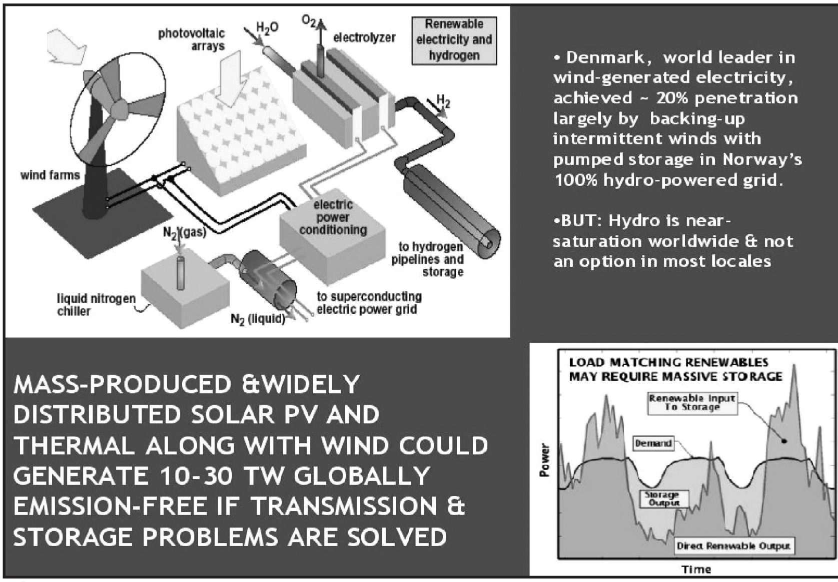


Fig. 7

a quarter century ago was the last time the US had a pro-active alternate energy policy. Unfortunately, the institutional memory of this has dimmed. Whatever the problems of Carter plan, and there were some, the United States, and because of our leadership, the world, was headed toward a sustainable energy future. Not now.

What colleagues and I propose as a goal is that by mid-century, renewables should supply roughly a third of the world's power; clean, safe and sustainable nukes another third; and coal gasification with CCS the final third. The total would amount to 100 to 300 percent of present energy demand. There are major roles for business and talented entrepreneurs, but I do not see how we get there without the stimulus of massive Apollo-like government-funded research and development, perhaps starting with ARPA-E (Advanced Research Projects Agency–Energy; after DARDA, the Defense Research Projects Agency, which gave us, among other things, the Internet) proposed by the National Academy of Science (Committee on Science, 2005).

At the same time, we need to implement everything we have in our alternate energy arsenal immediately. I do this myself as best I can. I drive a hybrid and get my home's electricity from green power, mainly wind power purchased by my utility from upstate New York (Hoffert, 2004). At this point, I pay a premium for this "privilege." I do not claim any special virtue as an early adopter. I do think both ethics and "cool" technology can be early drivers of alternate energy. At least until it become cost-effective to the average person, perhaps stimulated by carbon and gas taxes and/or cap-and-trade schemes. We need work on a broad spectrum of possible solutions; picking technology winners is notoriously uncertain, even by experts (Clarke, 1982).

This is not the forum to elaborate on the most innovative high-tech ideas that could allow us to live sustainably on the planet. Interested readers should consult Hoffert et al. (2002) and the special issue of *Scientific American* on "Energy's Future Beyond Carbon" (2006). Climate and sustainable energy is a political as well a science and engineering problem. With the memory of Rick Smalley's brilliant exposition in mind (he gave a most engaging and accessible public lecture at an Aspen Global Change Institute conference that I co-organized a few years ago), I hold that energy and global warming, not terrorism and mind-numbing dogma, are the appropriate organizing principles for this century. There is no guarantee high-tech civilization will survive into an ever richer future. But I find no solace in joining with the peak oilers to hunker down to a long slow decline with a return to agrarian (and eventually hunter-gatherer?) lifestyles as energy runs down and sea levels rise (Urstadt, 2006). Likewise, keep me away from Ted Kaczynski, the "Unabomber," who would destroy even a solar-powered high-tech world (Kaczynski, 2002).

I am optmistic enough about technology to believe policies based on science and engineering can solve the climate/energy problem; that with enough effort, thoughtful energy policies, instead of the usual pork packaged for public relations, can become part of political party platforms by the next US presidential election. The stakes are high. We owe to ourselves and generations to come to fight for our remarkable technological civilization, with all its imperfections, built on the shoulders of earlier generations. It will be hard. We will need every ounce of creative imagination. If we do make it through the twenty-first century without imploding, perhaps someday we might even find a way to cope with those problems our pre-technology evolutionary history has left us quite unprepared for.

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