





Innovative Energy Strategies for CO_2 Stabilization

A Report of the Aspen Global Change Institute
Elements of Change Series

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Editors

Aspen Global Change Institute

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A report on the Aspen Global Change Workshop
14 - 24 July, 1998
Aspen, Colorado USA

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Furthering the understanding of Earth Systems and global environmental change

FUNDING
The Aspen Global Change Institute gratefully acknowledges support for its 1994 summer science sessions
PROVIDED BY THE
National Aeronautics and Space Administration, Mission to Planet Earth
Grant Number NAG5-7453,
And support from the National Oceanic Atmospheric Administration's Office of Global Programs, and the National Science Foundation's Directorate for Geosciences.
United States Department of Agriculture - Forest Service.
Support was also provided by the United Engineering Foundation, Inc.

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The electronic edition of this report differs from the original hardcopy with minor changes to the layout, and without any change to the content; however, the original hardcopy document contained reporting on separate workshops in one report whereas the new electron version presents each workshop as a separate report document.

THE RECOMMENDED CITATION:
Hassol, S.J., and J. Katzenberger, eds. 1999, electronic edition 2008. Innovative Energy Strategies for CO2 Stabilization. Proc. of an Aspen Global Change Institute Workshop 14-24 July 1998, Elements of Change series, AGCI.

DESIGN AND PRODUCTION*:*
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Acronyms
Chemical Symbols
Unit Abbreviations

Acronyms

ACPI	Accelerated Climate Prediction Initiative
AEEI	Autonomous Energy Efficiency Index
AGHG	anthropogenic greenhouse gases
ASCI	Accelerated Strategic Computing Initiative
BaU	Business-as-Usual (often refers to IPCC scenario IS92a)
BWR	Boiling Water Reactor (nuclear)
CDM	Clean Development Mechanism
COM	cost of mitigation
COP	Conference of the Parties (FCCC)
DOE	U. S. Department of Energy
DOT	U. S. Department of Transportation
EIA	Energy Information Administration
ELWR	Evolutionary Light Water Reactor (nuclear)
EPRI	Electric Power Research Institute
FCCC	Framework Convention on Climate Change
GCR	gas-cooled reactor (nuclear)
GDP	gross domestic product
GEO	geostationary Earth orbit
GHG	greenhouse gas
HRST	highly-reusable space transportation
HVAC	heating, ventilation and cooling
IACS	Integrated Actinide Conversion System
ICF	Inertial Confinement Fusion
ICAM	Integrated Climate Assessment Model
IFE	Inertial Fusion Energy
IPCC	Intergovernmental Panel on Climate Change
IIASA	International Institute for Applied Systems Analysis
ITER	International Thermonuclear Experimental Reactor
LDC	less developed countries
LEO	low Earth orbit
LLFP	long-lived fission products
LLNL	Lawrence Livermore National Laboratory
LMR	Liquid Metal (cooled) Reactor (nuclear)
LWR	Light Water Reactor (nuclear)

MFE	Magnetic Fusion Energy
MRSS	Monitored Retrievable Surface Storage (of nuclear waste)
NAS	National Academy of Sciences
NCAR	National Center for Atmospheric Research
NE	nuclear energy
NEA	Nuclear Energy Agency
NPP	net primary productivity
NPP	nuclear power plant
OECD	Organization for Economic Cooperation Development
O&M	operation and maintenance
OPS	operations per second
OTA	Office of Technology Assessment
PIE	price induced efficiency
PNGV	Partnership for a New Generation of Vehicles
PPP	purchasing power parity
PV	photovoltaic
PHWR	Pressurized Heavy-Water Reactor
POP	Parallel Ocean Program
PWR	Pressurized Water Reactor (nuclear)
RBCC	rocket-based combined cycle
RD&D	research, development and deployment
RE	renewable energy
RLV	reusable launch vehicle
RTR	Radkowsky Thorium Reactor
SCNES	Self-Consistent Nuclear Energy Systems
SF	science fiction
SST	sea surface temperature
SSTO	single-stage-to-orbit
TMI	Three Mile Island
WEC	World Energy Council

Chemical Symbols

B	boron
C	carbon
Ca	calcium
CO_2	carbon dioxide
D or ^2H	deuterium
H	hydrogen
H_2SO_4	sulfuric acid
He	helium
Li	lithium
Mg	magnesium
N	nitrogen
N_2	molecular nitrogen
NH_3	ammonia

N_2O	nitrous oxide
NO	nitric oxide
NO_2	nitrogen dioxide
NO_3	nitrate radical
NO_x	nitrogen oxides ($NO + NO_2$)
O	oxygen
Pu	plutonium
S	sulfur
Si	silicon
Th	thorium
T or ^3H	tritium
U	uranium

Unit Abbreviations

BTU	British Thermal Unit
EJ	Exajoules
eV	electron volts
g	gram
GtC	gigatonnes of carbon
GW	gigawatt
GWe	gigawatts electric energy
GWt	gigawatts thermal energy
ha	hectare
kW	kilowatt
kWh	kilowatt hour
mol	mole
MMTC	million metric tonnes carbon
Mtonne	million metric tonnes
ppm	parts per million
ppmv	parts per million by volume
Quad	quadrillion BTU
TW	terawatts
W	watts
We	watts electric energy
Wh	watt hour
Wm^{-2}	watts per square meter
Wt	watts thermal energy

Symbol	Prefix	Power
E	exa	10^{18}
P	peta	10^{15}
T	tera	10^{12}
G	giga	10^{9}
M	mega	10^{6}
k	kilo	10^{3}
m	milli	10^{-3}

SESSION 1

Chair's Essay: Technologies for a Greenhouse Planet

By Martin Hoffert

It's easy to forgive Roger Revelle and Hans Suess for not realizing forty years ago when they whimsically dubbed the then-hypothetical fossil fuel greenhouse a "grand geophysical experiment" that this particular genie might not be so easily put back in the bottle (Revelle and Suess, 1957). Now, as the century and millennium draw to a close, there is little reason for governments whose negotiators recently met in Buenos Aires to implement reductions in greenhouse gas emissions as agreed to at Kyoto last December to ignore relevant research. We know a lot more.

The balance of evidence suggests that there is already a discernible human impact on global climate.

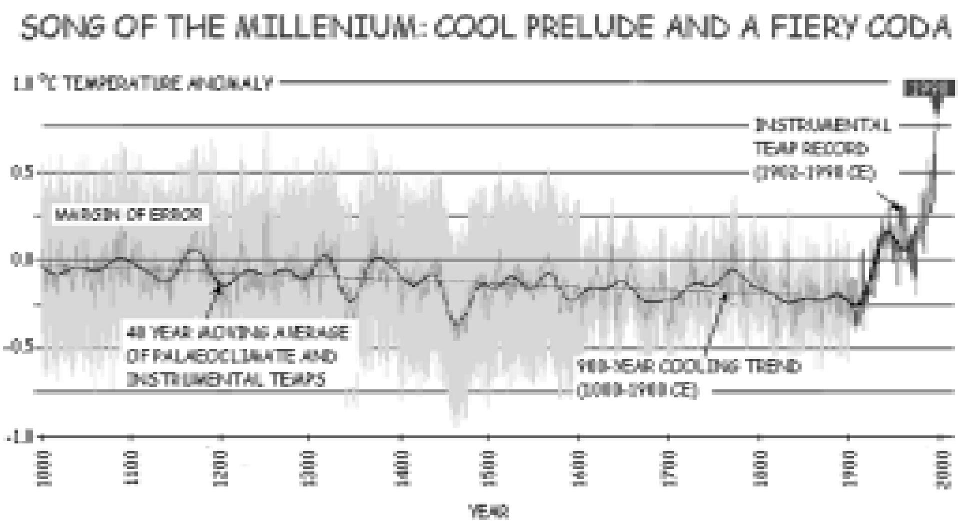

Figure 1
The Northern Hemisphere has been warmer in the 20th century than in any other century of the last thousand years, according to this reconstruction of the hemispheric temperature record by scientists at the University of Massachusetts and the University of Arizona. The sharp upward jump of the last 100 years was recorded by thermometers at and near the Earth's surface. Earlier fluctuations were reconstructed from "proxy" evidence of climatic change contained in tree rings, lake and ocean sediments, ancient ice, and coral reefs (Mann et al., 1999 and Stevens, 1999).

The Intergovernmental Panel on Climate Change finding that the balance of evidence suggests that there is already a discernible human impact on global climate (Santer et. al., 1996) is buttressed by recent studies: One showed that satellite measurements which first appeared to contradict surface temperature warming were inadvertently distorted by the satellites' orbital decay; and that when corrected for this effect both records agreed within their measurement accuracy (Wentz and M. Schabel, 1998). Another study by a team of paleoclimatologists reconstructed Northern Hemisphere temperature over the past millen-

nia (Mann et al., 1998). Their results indicate that the temperature rise of the past century is significantly larger than expected from natural climate variability (Figure 1).

In principle, one can never conclusively "prove" a scientific theory. There are still geologists who don't accept plate tectonics, and immunologists who don't believe the HIV virus causes AIDS. Incorrect theories are eliminated when they fail empirical tests. Those left standing, like the greenhouse gas theory of global warming, are accepted until they are "falsified" by data or a better theory comes along (Popper, 1969).

There is at this point in time a huge amount of data consistent with the CO_2 greenhouse warming hypothesis first advanced by Svante Arrhenius over a hundred years ago (Arrhenius, 1896). Although we recognize other anthropogenic greenhouse gases, CO_2 from fossil fuel burning is the major player. It produces most of the radiative forcing, and it has the longest lifetime of any greenhouse gas. Some fossil fuel CO_2 will remain in the atmosphere longer than Homo sapiens has been on Earth — what Wallace Broecker called "man's unseen artifact." "Global warming theory" as presently construed is deeply connected to our understanding of how the atmosphere and climate work. It continues to pass risky tests; and confidence is building to the point where we should think seriously about mitigation. There are vocal critics of the fossil fuel greenhouse theory. But in my opinion they are fighting a rearguard action. You can't fool Mother Nature.

The climate issue is too important to politicize too early because this can prematurely limit the range of policy options.

Climate change mitigation is another matter. It gets "political" fast. In the U. S. Congress, "global warming" is seen primarily as a political issue, perhaps because of the early endorsement of the theory by Vice President Al Gore, in his book, *Earth in the Balance.* There are at this point sufficient "nay" votes in the Senate to block ratification of the Kyoto Protocol. Some have characterized global warming as "liberal clap trap" designed to transfer U. S. taxpayers' dollars to the developing world. Indeed, authors of IPCC chapters have been attacked in the press for suggesting that a discernible effect on global climate has already occurred.

There is a danger in launching into ideological arguments before we understand greenhouse gas stabilization. Yet such arguments are a mainstay of political debate about global warming. These ideological arguments are about some of the most important and value-laden trade-offs of the next century: about the roles of governments versus industry, about emission cuts by developing versus developed nations, about energy conservation versus energy supply, about economic growth versus preservation of ecosystems versus population control. But the climate issue is too important to politicize too early because this can prematurely limit the range of policy options.

Editorially, *The New York Times* stressed the importance of early implementation and emissions trading within the framework of the Kyoto Protocol which commits the industrialized world to an average 5% reduction in greenhouse emissions below 1990 levels between 2008 and 2012 (Remember Global Warming? Nov. 11, 1998). These are politically ambitious and psychologically important targets even though scientists familiar with the problem know that atmospheric CO_2 levels will continue to rise almost as much under the Kyoto Protocol as in "business as usual."

The implied transition in the world energy system to non-CO_2 emitting sources of this magnitude fifty years hence is mind-boggling.

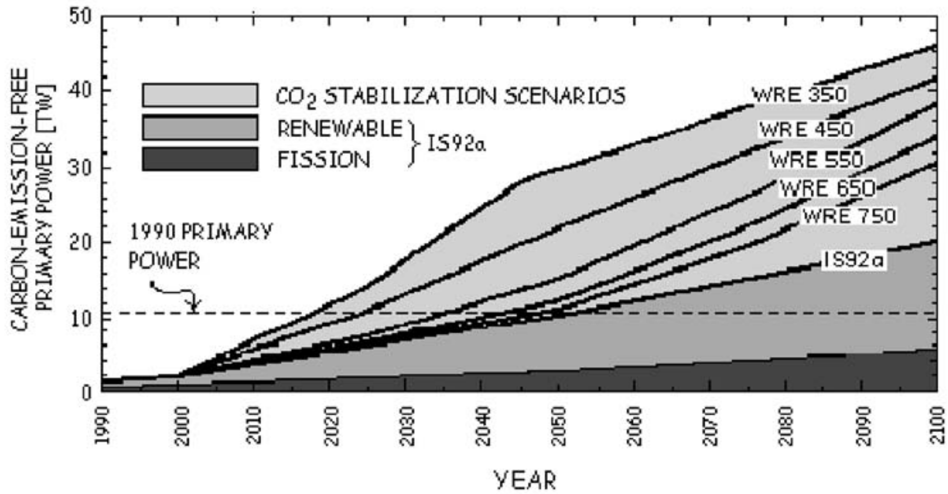

Figure 2
Twenty-first century carbon-emission-free primary power required to achieve the economic goals of the IPCC Business as Usual scenario
(IS92a: No emission controls, but a 1% per year improvement in the efficiency of creating GDP from primary energy). Also shown are the increasing carbon-emission-free power requirements if atmospheric CO_2 is stabilized at 750, 650, 550, 450 or 350 ppmv CO_2 according to the Wigley-Richels-Edmonds concentration paths (Hoffert et al., 1998).

In a paper that colleagues and I published last October in *Nature* we found that stabilizing atmospheric carbon dioxide will require a massive transition in the next century away from our predominantly fossil fuel system to some as yet undetermined source of primary power (Hoffert et al., 1998). To stabilize with continued economic growth at twice the preindustrial CO_2 concentration — an oft-cited target but still high enough to cause significant climate change — we will, by the year 2050, have to provide 100-300% of today's global power from carbon-emission-free sources (Figure 2). The implied transition in the world energy system to non-CO_2 emitting sources of this magnitude fifty years hence is mind-boggling. To put this in perspective, consider that Enrico Fermi's "atomic pile," the first nuclear reactor in 1943, is more distant in the past than the year 2050 is in the future. And nuclear power still provides less than 5% of the global energy supply.

On the positive side, a response to the challenge of global climate change through the development of carbon-free energy technologies — renewables, space solar power and fusion, and even fission (if problems of radioactive waste disposal, weapons proliferation, public perception of risk, and inadequate supplies of uranium-235 can be overcome) — could stimulate technological innovation and entirely new industries of the twenty-first century, as World War II and the Cold War did in the twentieth century.

We sought, in this AGCI Workshop, to address the quantitative challenge of carbon-emission-free power while attempting to limit preconceptions. Our impression was that the

range of options presently under consideration for climate change mitigation was too limited. At this point, the most advanced concept actively being investigated by the Department of Energy under its Carbon Management Program is CO_2 capture and sequestration, with continued primary dependence on gas, oil and increasingly coal well into the twenty-first century (Parson and Keith, 1998). This is a promising technology and was considered seriously at our Workshop. But there are other options.

Perhaps the most immediate response to the need for carbon emission reductions is to increase the efficiency of energy end use — an approach associated since the energy crisis of the 1970s with Amory Lovins and his Rocky Mountain Institute (Lovins, 1977). Indeed, the presentation by Lovins at our Workshop can be construed as the demand reduction end of an innovative technology spectrum in which innovative energy supplies from extraterrestrial sources formed the other end. In between, a series of innovative renewable, fission and fusion ideas, as well as geoengineering schemes were presented, and subjected to lively debate at our Workshop.

The very definition of "geoengineering," which involves some of the most futuristic technologies (Keith, in press; Teller et al., 1997), is controversial, and underscores the complex socio-political-technical interactions one encounters in mitigation studies. Some argued at our Workshop that the term "geoengineering" should be applied only to compensatory global-scale changes in the Earth's radiation balance (from space mirrors or artificial aerosol layers) and perhaps changes in the carbon cycle from fertilization of the oceans, but that capture and sequestration of CO_2 by burial in depleted natural gas reservoirs or the deep ocean should be called something else. It needs its own category like "Carbon Management," because of pejorative overtones of "geoengineering" as destructive of natural ecosystems.

That may be; but based on estimates of carbon-emission-free power needed by the year 2025 shown in Figure 2, I computed huge rates of carbon sequestration to subterranean reservoirs needed (Table 1). These numbers are a limiting case, because they assume all carbon-emission-free primary power required comes from fossil fuel energy. A carbon emission factor of 0.56 GtC/TW is assumed for the primary energy part which increases for capture and burial. The factors f = 1.5 and 4.5 are lower and upper bound estimates of additional carbon per unit of primary power to separate, compress and sequester the CO_2.

Table 1
Carbon Sequestration Rates by 2025 to Achieve Various Atmospheric CO_2 Stabilization Targets For Each Emission Factor

Scenario	Burial Rate [GtC/yr] f = 1.5	Burial Rate [GtC/yr] f= 4.0
Stabilize @ CO_2 = 350 ppm	11.6	30.9
Stabilize @ CO_2 = 450 ppm	8.9	23.7
Stabilize @ CO_2 = 550 ppm	6.1	16.4
Business as Usual CO_2 (IPCC IS92a) (CO_2 continues to rise)	4.9	13.0

A response to the challenge of climate change through the development of carbon-free energy technologies could stimulate technological innovation and entirely new industries of the twenty-first century.

On the positive side, carbon dioxide is already pumped into depleted oil and gas reservoirs for secondary recovery of hydrocarbon fuels — a factor tending toward near-term adoption. One can make hydrogen, an energy carrier suited for use as motor vehicle fuel whose combustion doesn't emit CO_2 to the atmosphere, from fossil fuels, if one is willing to pay the price of more total carbon emitted and entombed in subsurface sarcophagi. CO_2 capture and sequestration would leave in place, and even expand, the infrastructure of fossil fuel as a primary energy source; which may be why it is under active consideration by some oil companies as a fallback if emission controls are imposed.

But can we guarantee the integrity (non-leakage) of massive amounts of subsurface CO_2? For how long? And can we maintain such burial cost-effectively as fossil fuel use reverts from gas and oil back to coal? Granted the technological readiness of Carbon Management, it is mind-boggling to imagine stuffing six to sixteen gigatonnes of carbon per year into deep reservoirs less than thirty years from now to stabilize atmospheric CO_2 at 550 ppm (Table 1). Six gigatonnes of carbon per year is humankind's present total emission rate of carbon in the form of carbon dioxide.

SESSION 1

The range of options presently under consideration for climate change mitigation is too limited.

In fairness, it is a massive challenge to any carbon-free energy technology to supply the amounts of primary power needed by 2050. At our Workshop, we considered a broad range of global primary power sources: fossil fuels (coal, oil and gas), fission, renewables (hydro, wind, geothermal, terrestrial solar, tides, biomass, and ocean thermal), fusion (D/T and $D/^3He$ fuel cycles) and space power including low earth orbits (LEO), geo-stationary orbits (GEO) and lunar-based power systems. For each source, we endeavored to estimate maximum energy inventory, time to deplete, maximum useful power, limiting factors, and key research issues. This analysis, which builds on pioneering work by David Criswell (1998, see Appendix B), should be regarded as very preliminary. But it indicates the kind of cross-cutting research issues involved in global energy systems. These are not only technical but involve the evolution of social and economic infrastructures that support a given technology.

A central question is whether the U. S. and world energy systems are driven by autonomous technical forces; or whether they evolved from cultural preferences and choices of individuals combined with path-dependent constraints imposed by infrastructures and institutions created in earlier eras (Morgan, 1998). To get some insight into how a massive transition to non-fossil-fuel energy in the twenty-first century might work, it is instructive to review how we acquired certain critical technologies this last hundred years.

AC versus DC

There are often pitfalls in attempting to project the future. In 1893, the World's Fair in Chicago banned coal as an energy source and displayed many windmills. Coal was gradually replaced by oil and later by gas, while wind power today fights for a few percent of the energy market share.

At the time of this World's Fair, electric power was new and mysterious and a "battle of the currents" was underway over which operating system would prevail for its transmission. Westinghouse employed Nikola Tesla's alternating current system (AC). This was much

maligned by Thomas Edison, whose competing direct current (DC) was the mainstay of his General Electric Corporation's transmission system.

In a public relations coup, Westinghouse underbid General Electric on the illumination contract for the 1893 Fair (Cheney, 1981): "The Tower of Light flashed into brilliance with a thousand electric bulbs radiating the promise of a brighter future. . . . Everywhere the pulse of the future throbbed: alternating current." Due to its technical superiority, alternating current did become the standard operating system for electric power transmission in most parts of the world (Ausubel and Marchetti, 1997). Alternating current is readily stepped-up by transformers to high voltages for low-loss transmission to distant points. This eventually led General Electric to adopt AC despite its "not invented here" reluctance to do so. And Westinghouse and GE are both around today, a century later, having adapted to changing markets as well as technical realities.

There are other examples where technical superiority leads to a clear market victory, but only if an infrastructure is in place to support it. It made no sense to develop word processors, spreadsheets, graphics programs, E-mail and the Internet until the personal computer was well established. This required the development of transistors, integrated circuits, and computer chips, as well as software and "operating systems."

The commercial conflict between AC and DC electricity transmission systems a hundred years back is reminiscent of the more recent battle between Microsoft's Disk Operating System (DOS) and more intuitive graphical interfaces based on a "mouse" developed by a Xerox research lab in Silicon Valley and commercialized by Apple Computer (Cringely, 1993). The advantage of learning a computer operating system (OS) compatible with the eye-brain-hand coordination of humans as opposed to typing memorized commands is obvious to anyone familiar with both systems.

Apple held a brief monopoly on its graphical interface OS, but was unwilling to license it to other computer makers. Microsoft saw its customer base as all computer manufacturers. Once it's reverse-engineered copy of Apple's OS functionality was declared legal (not infringing on Apple's patents), the door was open for Microsoft to claim the lion's share of the OS market. The success of "Windows," Microsoft's present near-monopoly on operating systems, and its problems with the U. S. Justice Department on that score, are history — a history all about infrastructure.

But computers as we know them today could not exist without solid state "computer chips" — a transformative technology emerging from wartime research, whose significance and impact were wholly unappreciated at the time. Just before Christmas in 1947 a team of scientists at Bell Laboratories in Murray Hill, New Jersey, created the first transistor. Neither they nor anyone else knew where it would go. When the invention was unveiled publicly in 1948, it received scant attention.

A half-century later transistors have shrunk dramatically in size and cost. The runaway growth of integrated circuits composed of huge numbers of transistors, colloquially called

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"chips," has created a new industry and transformed society. In 1965, in the early days of this industry, Gordon Moore of the Intel Corporation realized that each new chip contained roughly twice the capacity of its predecessor, and that each chip was released within 18-24 months of the previous chip. If this trend continued, he reasoned, computing power would rise exponentially over relatively brief periods of time. Moore's observation, now known as Moore's Law, described a trend which has continued and is still remarkably accurate (Figure 3).

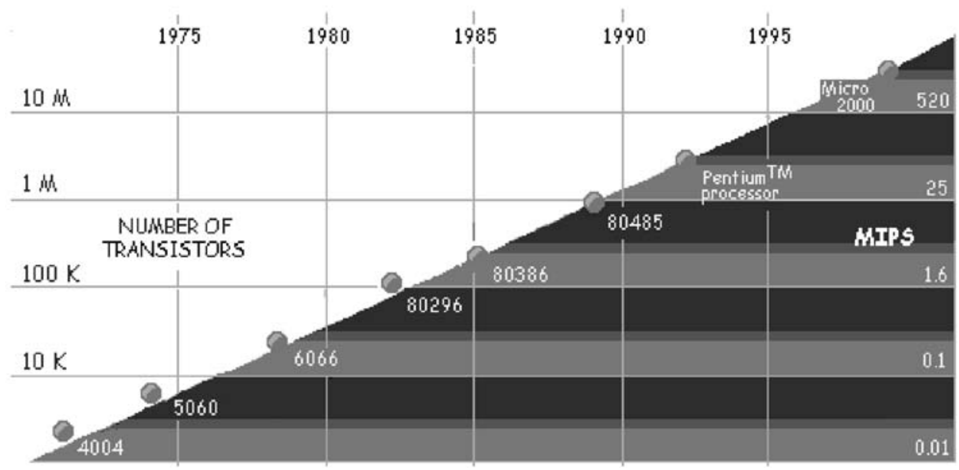

Figure 3

Moore's Law. In 1965, Intel co-founder Gordon Moore predicted transistor density on microprocessors would double every two years. This prediction, so far, has proven amazingly accurate. If it continues, Intel processors should contain 50 to 100 million transistors by the turn of the century and execute 2 billion instructions per second (2000 MIPS).

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This technological breakthrough was implicit in our understanding of solid state physics emerging from WW II research in radar and electronics. But it took sustained R&D during the Cold War and the Space Race with the Former Soviet Union, as well as industrial research under very unique conditions, to realize it.

The invention of the transistor at Bell Labs, and the computer chip and software industries of "Silicon Valley," are oft-cited examples of how the private sector can transform abstract research concepts into marketable products — perhaps a prototype for the development of carbon-emission-free energy industries to stabilize atmospheric CO_2. Michael Riordan, who has studied the history of Silicon Valley industries, thinks otherwise (Riordan, 1997):

> . . . postwar Bell Labs was a unique institution that would be very difficult — if not impossible — to replicate today. . . . it concentrated the intellectual energies of half a dozen eventual Nobel laureates under the roof of a single industrial laboratory in New Jersey. However, its parent firm, AT&T, was in a very special situation: It held a monopoly on telephone service throughout the United States. Therefore every time anyone placed a long-distance phone

call, she was in effect paying a basic research and development tax to support ongoing projects at the Labs.

AT&T has, of course, been broken up as a monopoly; though a very different "Bell Labs" lives on as Lucent Technologies. In today's highly competitive business climate, companies cannot afford to support research that will not produce a profit in 3 to 5 years. The contrast between the present situation and postwar Bell Labs is sardonically observed by Riordan: "In today's R&D environment, physicists at research universities and national laboratories continue to pursue imagined superstrings and leptoquarks that have no conceivable practical applications; meanwhile engineers at semiconductor labs focus on ways to etch ever finer features on silicon."

There is a hopeful message in Moore's Law. It is the message gleaned from the explosive development of nuclear power, rocketry and radar in WW II: If the possibility for a transformative technology exists in the underlying science, and if the motivation to succeed is strong, then vigorous and sustained investment of capital and intellectual resources can produce near-miracles. More often than not, market forces alone have been insufficient motivating factors in this century.

Another critical, and culturally-nurtured ingredient for innovation is scientific imagination (Clarke, 1982; Dyson, 1996). Arthur C. Clarke observed that "any sufficiently advanced technology is indistinguishable from magic." Radical, transformative technologies typically appear "impossible" when proposed, and obvious and inevitable once in place. To see things in a different way from those before you is a rare, but necessary, quality in an innovator. Getting there from here takes courage and determination in addition to intellect, and is often driven by an underlying vision that transcends rationality. Einstein, among others, understood the power of intuitive leaps — which must, of course, be followed by "perspiration." But when the vision fails, expect no miracles.

Regarding "vision," there is substantial evidence that what is called "hard" science fiction (SF), stories and novels exploring interactions between real science and technology and sentient beings — not always human — stimulated the imagination of creative scientists and engineers in this century, often in their younger years, in ways which changed the real world (Disch, 1998). By mid-century, many of the best SF writers, Robert Heinlein, Isaac Asimov and Arthur C. Clarke, for example, were themselves trained scientists or engineers, expressing their visions in literary terms. The hard SF tradition was represented at our Workshop by physicist Gregory Benford, whose critically acclaimed *Timescape* is considered by many the best novel in any genre about working scientists.

Since the beginning, there was a symbiotic relationship between SF and spaceflight. Here is a letter written in 1932 by American rocket pioneer Robert Goddard to H. G. Wells congratulating the novelist on one of his last birthdays (Lehman, 1988):

> In 1898 when I read your War of the Worlds, I was sixteen years old, and the new viewpoints of scientific applications, as well as the compelling realism... made a deep impression. The

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spell was complete about a year afterward, and I decided that what might conservatively be called 'high altitude research,' was the most fascinating problem in existence . . .

> How many years I shall be able to work on the problem, I do not know; I hope, as long as I live. There can be no thought of finishing, for 'aiming at the stars,' both literally and figuratively, is a problem to occupy generations, so that no matter how much progress one makes, there is always the thrill of just beginning . . .
>
> What I find most inspiring is your optimism. It is the best antidote I know for the depression that comes at times when one contemplates the remarkable capacity for bungling of man and nature . . .

While there were other important pioneers, it is rocket engineer Wernher von Braun who is most identified today with the development of space launch vehicles. An early spaceflight enthusiast and science fiction fan, von Braun catapulted to prominence while still a young man directing the development of the V2 rocket for the Nazis. He eventually led the Saturn Booster development team that brought American astronauts to the Moon.

SESSION 1

Any sufficiently advanced technology is indistinguishable from magic. Radical, transformative technologies typically appear "impossible" when proposed, and obvious and inevitable once in place.

Like spaceflight, the possibilities of nuclear power were explored early in SF. Research by Hann and Strassman in Berlin published internationally in 1939 showed that the nucleus of uranium-235 will fission on absorbing a neutron and produce still more neutrons in a series of ferociously exothermic nuclear reactions. As early as September 1940, Robert Heinlein published in the U. S. science fiction pulp magazine *Astounding*, edited by the legendary John W. Campbell, Jr., the story "Blowups Happen" — a fictional account of a nuclear power plant accident eerily prefiguring real accidents at Three Mile Island and Chernobyl many decades later.

Nuclear weapons too appeared first in SF. Cleve Cartmill's "Deadline," published in the March 1944 *Astounding* anticipated the highly explosive chain reaction in a critical mass of ^{235}U. The story brought military intelligence agents to author and editor inquiring who in the top-secret Manhattan project had been talking. But there was no espionage here. (The Rosenbergs and Klaus Fuchs were talking to someone else [Rhodes, 1995]). The author had merely been imaginatively exploring what the science of nuclear physics allowed. He spoke of ^{235}U isotope separation and described an actual bomb where the critical mass is obtained by explosive compression of two cast-iron hemispheres (Gunn, 1975); a bit too small — but not too far off from "Little Boy" dropped on Hiroshima August 6, 1945 by the Enola Gay (Serber, 1992).

From a purely economic point of view both projects were "irrational" (Edgerton, 1995). The $2 billion spent on the Manhattan project ($20 billion in 1990s dollars) produced two bombs whose destructive effects were no greater than those of conventional, if massive, firebombing air raids on Japanese cities. Likewise, the R&D and production costs of the German rocket program were about one quarter of the Manhattan Project and yet the destructive power of all the V2s was no more than the equivalent of a single British bombing raid. Edgerton argues convincingly that market forces would never have produced the V2 or the bomb. And yet, in combination, the bomb and rocket became the intercontinental ballistic missile

(ICBM), the key technology of the Cold War. The doctrine of Mutually Assured Destruction made possible by the balance of terror between U. S. and USSR nuclear-tipped missiles dominated international relations for fifty years.

These examples drawn from recent history show the fallacy of assuming that carbon-emission-free technology will, or should, evolve spontaneously from market forces alone.

Path dependence: the case of the nuclear light water reactor
A final example illustrates how the evolutionary path of a technology can be vitally important. At this point in time, the ~500 commercial nuclear reactors worldwide represent five technology variants — the light water reactor (LWR, in both pressurized and boiling versions); heavy water (CANDU); graphite moderated; steam-cooled (RBMK) like Chernobyl; gas-cooled graphite; and liquid-metal cooled fast breeders — some 85% are ^{235}U burners moderated by light water (Weinberg, 1992). It has been argued by nuclear engineers that helium-gas-cooled reactors are inherently safer than water-cooled ones which can experience loss-of-coolant accidents like Three Mile Island (TMI, a LWR) and Chernobyl (an RBMK) (see e. g., Teller et al, 1996). So, why are 85% of present-day nuclear power plants LWRs?

The answer seems to be that the first commercial nuclear reactor was based on the LWR developed by then Captain Hyman Rickover in 1950 in the early days of the Cold War for the first nuclear submarine, the Nautilus (Polmar, 1963). Rickover, who became an Admiral for his work on Nautilus had a well-deserved reputation as a "can-do" engineer despite what some felt was an abrasive personality. And the LWR was "on the shelf." When the Atomic Energy Commission (AEC), which touted the advantages of nuclear power as "too cheap to meter," went looking for a pioneering nuclear power plant at Shippingsport, Pennsylvania, they went to Rickover. He proposed an LWR derived from his submarine work and became personally involved with every aspect of the project. He was an officer in the U. S. Navy, yet he directed the creation of the first civilian nuclear power plant.

On December 2, 1957, fifteen years after Enrico Fermi's team produced the first sustained chain reaction, Hyman Rickover's driven work force produced criticality in the nation's first reactor devoted to powering an electrical generating plant. On December 28, the plant made a 100-hour run at 60,000 kWe and the Duquesne Light Company had a nuclear power plant to operate (Polmar and Allen, 1982).

The success of water-cooled nuclear reactors went unchallenged as more plants were built in the U. S. and around the world until concerns about reactor safety in the wake of the TMI and Chernobyl accidents halted the development of fission power in many parts of the world. As one involved with the decision to power the first nuclear submarine with a light water reactor, Alvin Weinberg expressed astonishment that the LWR became the dominant commercial reactor type — a choice he and other nuclear engineers say (in retrospect) that they would not have made on rational economic grounds (Weinberg, 1992).

Did things have to turn out this way? Could an earlier decision to develop gas-cooled reactors have led to different development path in which safe nuclear power would be avail-

These examples drawn from recent history show the fallacy of assuming that carbon-emission-free technology will, or should, evolve spontaneously from market forces alone.

able as an alternative to fossil fuels? We learned at our Workshop that there is probably not enough ^{235}U commercially available to power the world without seawater extraction (Krakowski, 1998) or breeder reactors (Teller et al., 1996). But that's a different story.

Were these technologies imagined at the time of the World's Fair of 1893? Remarkably, there's a record of what the best and brightest Americans at the Fair thought the future would bring (Walker, 1992). Their essays make fascinating reading. Like today's "experts," they exhibit extreme technological timidity, ignoring even the implications of inventions in their own time. They had electric lights, photography, internal combustion engines, and the telegraph; but none of these "experts" foresaw automobiles, airplanes, telephones, radio, or the movies just around the corner in the dazzling twentieth century.

What are we missing?

Despite a widely-supported UN Treaty to limit greenhouse gas emissions, global warming as a driver of economic growth is not an option represented very seriously thus far (Jepma and Munasinghe, 1998; IPCC, 1996). Most "integrated assessments" treat mitigation as a cost, like air pollution control, to be addressed by carbon taxes and emissions trading; not as a source of "nonlinear" revolutionary technology. These models typically assume that technologies of the next century will be those of today, but more cost-effective.

It is as if a group of scientists at the end of the nineteenth century predicted more aerodynamically efficient sailing ships, and relegated commercial aviation to the nethermost reaches of Jules Verne and H. G. Wells.

It is as if a group of scientists at the end of the nineteenth century predicted more aerodynamically efficient sailing ships for ocean transportation, regarding the steamship as the outermost limit of technology, and relegating commercial aviation to the nethermost reaches of Jules Verne and H. G. Wells. Of course, events proved Verne and Wells much nearer the mark than the expert scientists of the day.

Superconductivity and a global grid?

What recent technologies might impact in a transformative way our ability to produce carbon-emission-free primary power at a global scale? For one thing, I believe major opportunities exist for load-managing electrical transmission systems energized by carbon-emission-free renewable and nuclear sources on a global scale and in real time, thus minimizing the need for storage (Hoffert and Potter, 1997).

The global electrical grid proposed by Buckminster Fuller (1981) is an example of a revolutionary "enabling technology" (Figure 4). What Fuller envisioned was a grid where electricity produced in different parts of the world was "wheeled" between day and night hemispheres and pole-to-pole to balance supply and demand with minimum power loss.

Renewables (solar, wind, geothermal, and biomass) have failed to capture significant market share not only because of their low power density and the presently low cost of oil but more fundamentally because renewables are highly episodic and/or spatially dispersed, and hence unsuited to baseload power. It was clear at our Workshop that the some at the DOE see renewables as a minor player satisfying market niches remote from conventional sources. Breakthroughs in photovoltaic (PV) and wind turbine costs might not change this picture. The cost-pacer of global renewables is distribution and storage. Gene Berry at our Workshop indicated how hydrogen could fill the distribution and storage role in a renew-

able-powered world and described the hardware needed (compressors, pipelines, electrolyzers, and fuel cells). There are advantages to hydrogen; but perhaps we should look at the tradeoffs between hydrogen as an energy-carrier and a solid state system based on superconducting power transmission.

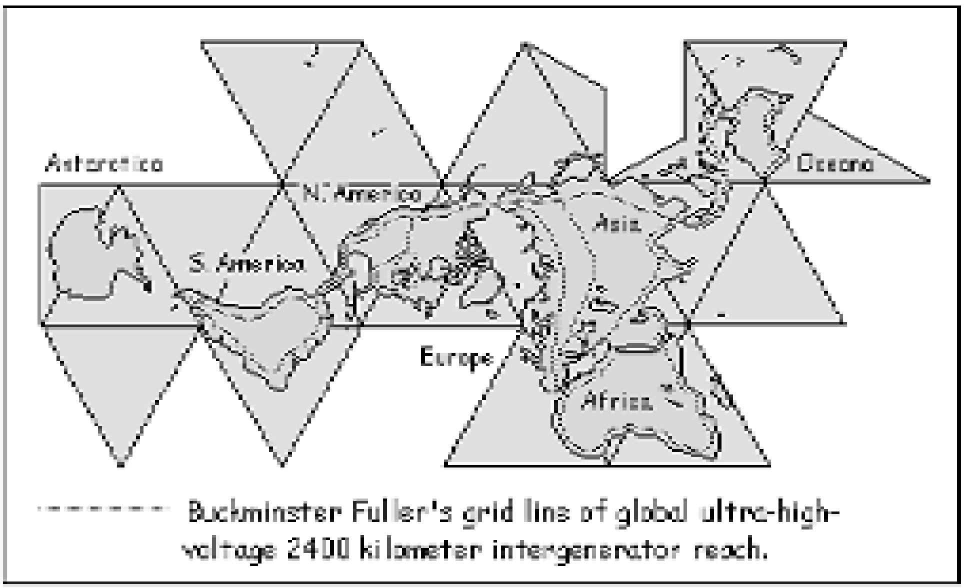

Figure 4
Prototype global electric power grid based on ultra-high-voltage grid proposed by Buckminster Fuller before the discovery of high-temperature superconductivity. This icosohedral map projection pioneered by Fuller shows the size of the world's land masses and oceans more realistically than Mercator projections, and emphasizes near-contact points where undersea connections to superconducting overland transmission lines could be made (Fuller, 1981).

Even if reactor safety could be insured by "fail safe" designs, nuclear fission as a power source for developing nations is subject to weapons proliferation using reactor fission products. A Fullerian power grid could permit nuclear electricity generated in secure locations to be marketed even in politically unstable parts of the world.

Electric utility deregulation and globalization of markets provide an economic environment to buy and sell power as a global commodity at a common price. But so far, there's no delivery system. In Europe, electricity is wheeled internationally (Ausubel and Marchetti, 1997). But even with very high voltage power lines, the inherent electrical resistance of copper and aluminum make global-scale transmission impractical. Classical superconductors discovered in 1911 are for various reasons (including scarcity of their liquid helium refrigerant) prohibitively expensive for power lines.

But times are changing: In 1986 Georg Bednorz and K. Alex Müller of IBM Zurich Research Labs discovered a class of perovskites (incorporating thin layers of copper and oxygen) that

The global electrical grid proposed by Buckminster Fuller is an example of a revolutionary "enabling technology." Electricity produced in different parts of the world would be "wheeled" between day and night hemispheres to balance supply and demand.

become superconducting above 77˚K where nitrogen liquefies (Bednorz and Müller, 1986). Nitrogen is a constituent of air and is much easier to maintain as liquid than helium which requires 4.2˚K. Within months, physicists packed the New York Hilton for a conference dubbed "The Woodstock of Physics," to report on this phenomenon. Now, twelve years later, *The New York Times* reports that an experimental N_2-cooled 100-meter-long superconducting cable fabricated by American Superconductor of Westborough, Massachusetts, will be tested in Detroit shortly as an electric power distributing replacement for copper cable (Brown, 1998). And that's not the only project. Southwire, of Carrolton, Georgia, is participating in a public-private experiment to test the viability of superconducting cables in the context of the deregulated electric utility environment.

What if superconducting cable costs followed a "Moore's Law" similar to computer chips? In this scenario, savings in power losses from resistance eventually tip the balance in favor of superconductors, and "Fuller's Global Grid" becomes cost-effective. With computerized load management, renewable electricity could be wheeled worldwide. Hoffert and Potter (1997) estimate 81% efficiency for a 10,000-kilometer-long N_2-cooled superconducting power line — the global scale. (The quite acceptable 19% power loss makes up for N_2 leakage.) Imagine: solar electricity from the Sahara desert transmitted to sub-Saharan Africa, to China and to India. With international competition and load management built into the grid, renewables might compete favorably with coal in the all-important developing nations. Wind power from the Netherlands could help industrialize Kenya and Uganda; and Australian nuclear power could be marketed safely to Iraq and North Korea — to cite a few possibilities.

SESSION 1

In the long run, expansion of the human experiment to space may be the only way to resolve the conflict between ever-increasing economic growth and a sustainable environment on planet Earth.

Doing it in space

Other innovative perspectives of our Workshop were space power, and the eventual employment of space resources for economic growth (Lewis, 1996). In the long run, expansion of the human experiment to space may be the only way to resolve the conflict between ever-increasing economic growth and a sustainable environment on planet Earth (Myers, and Simon, 1994; Arrow et al., 1995). Gregory Benford, David Criswell and John Lewis all spoke to this issue in their own ways. In addition, Peter Glaser, inventor of the geostationary orbit solar power satellite studied as the NASA/DOE SPS reference system of the 1970s, addressed us via conference call. My ideas about technology evolution paths for space power based on constellations of communications satellites are discussed elsewhere in this volume (see page 76) and in Hoffert and Potter (1998).

The cost-pacer of all these technologies is access to space — right now, the cost to launch payloads to Low Earth Orbit (LEO). Remarkably, the energy to put a kilogram in LEO is about the same as flying that same kilogram from New York to Los Angeles on a commercial airliner; and yet the cost to orbit is thousands of times greater, ~$20,000/kg for the Space Shuttle. The reasons are that expensive parts of the vehicle are thrown away with each launch, that an army of scientists and engineers is needed for preparation and checkout, and that the time the vehicle is in orbit is small compared with preparation for orbit. Moreover, the oxidizer is carried by a pure rocket as it flies through an ocean of air — likened by some to a fish carrying a canteen of water as is swims in the sea. In the Shuttle, the mass of on-board oxidizer (O_2) is eight times the fuel (H_2). Despite this motivation, building a workable hybrid air-breathing/rocket engine hasn't been easy.

As the cost of mature transportation technologies is typically two to four times the fuel (energy) costs, one expects substantial cost reductions as demand for launch services increases. A possible replacement for the Space Shuttle under development now for NASA by LockheedMartin Skunk Works of Palmdale, California, is the Venture Star, an arrowhead-shaped single-stage-to-orbit (SSTO) vehicle that take off and lands similarly to the Shuttle, but is a fully reusable launch vehicle (RLV). This is a challenge to composite structure technology because the rocket equation mandates that 90% of the mass of an SSTO using standard chemical propellants and oxidizers is the fuel/oxidizer mix, with only 10% allowed for both structure and payload.

Recently, Gordon Woodcock of Boeing analyzed launch costs to LEO of four vehicle classes (Woodcock, 1998). In addition to existing Shuttles and Venture Star class RLVs, he considered highly-reusable space transportation (HRST) systems with rapid turnaround and airline type operations; and advanced rocket-based combined cycle (RBCC) vehicles employing air-breathing propulsion part way to orbit — perhaps the most challenging technology. Woodcock finds an impressive potential to bring launch costs per kilogram down from $20,000 for Shuttles to $4,000 for RLVs to $800 for HRSTs to $46 for RBCCs. With sufficient motivation to put things in space there is ample opportunity here as well for a Moore's law reduction in space access costs. Some argue even more cost-effective space development is possible if one builds on the Moon (Criswell, 1998) or launches components fabricated on the Moon to Earth orbit.

A scenario where cheaper launches lead to cost-effective space power in the next century is not only an academic possibility but builds on developments taking place now. Space research is already being privatized by companies like Space Dev which may soon replace NASA for missions like asteroid exploration (Landesman, 1998). Entrepreneurs are also working on innovative ideas for launch vehicles independently of NASA to service the market created by the new generation of communication satellites (Petit, 1998). These ideas include towing a spaceplane part way to orbit (Kelly Space and Technology), rotating fuel pumps and autorotative vehicle recovery (Rotary Rocket), airline-type operation (Universal Spacelines), and aerial refueling of a spaceplane (Pioneer Astronautics).

A scenario where cheaper launches lead to cost-effective space power in the next century is not only an academic possibility but builds on developments taking place now.

In addition to beaming solar power collected in orbit or on the Moon to rectifying antennas (rectennas) on Earth for subsequent distribution to developing nations as an alternative to fossil fuels, the space power scenario includes the possible collection of fuels for innovative thermonuclear fusion cycles from the lunar regolith (the layer of soil and loose rock overlaying solid rock) or the atmospheres of the outer planets (Lewis, 1996).

Nuclear Fusion

Until a few years ago, the best hope for controlled fusion as a power source was the International Thermonuclear Experimental Reactor (ITER) — a ten billion dollar bagel-shaped chamber called a "Tokamak," in which a deuterium-tritium plasma heated to 100 million°K is confined by powerful magnetic fields long enough to output as least as much fusion energy (in the form of energetic neutrons) as the energy input to heat the plasma (Fowler, 1997). The ITER wouldn't actually produce electric power, but was supposed to be a "proof of

concept" experiment financed by an international consortium. It had to be physically large, and thus expensive, to prevent plasma instabilities and turbulence associated with the magnetic confinement scheme.

But the perception developed that ITER faced insurmountable engineering problems; and electric utilities argued that radioactive reactor walls created by the neutron flux heating a surrounding lithium blanket (from which tritium was bred and heat transferred to steam turbines) would not be environmentally acceptable in operational power plants (Parkins et al., 1997).

Today, after 40 years of fusion research, ITER is apparently dead. As reported to our Workshop by John Perkins, researchers are emphasizing smaller, less capital-risky, and more environmentally acceptable machines (Perkins, 1997; Lawler and Glanz, 1998). Fusion power turned out to be much more difficult to develop than originally thought when H-bombs were first detonated in the 1950s. Deuterium and tritium employed in these weapons were considered as first-generation fuels because they burn most easily. Despite the more difficult job of igniting them, for environmental reasons there is renewed interest in "advanced" fusion fuels whose neutron production rates are very low, even zero — a major cycle of interest being deuterium/helium-3 (Kulcinski and Santarius, 1998).

SESSION 1

However radical and "far out" these ideas might seem, they are based on real physics, and have already been explored by some contemporary hard science fiction writers. Perhaps we should pay attention.

Resources from space

There is little helium on Earth because it's a light atom, easily lost to space by gravitational escape, and very little of the helium-3 isotope. But ^{3}He exists in the solar wind and is adsorbed by the lunar regolith in amounts which are potentially economically recoverable. The energy per unit mass is so high that if deuterium/helium-3 fusion plants existed it might be cost-effective today to mine helium-3 on the Moon, even with exorbitantly high space access costs — though John Lewis believes collecting ^{3}He from the atmospheres of outer planets will be more productive.

However radical and "far out" these ideas might seem, they are based on real physics, and have already been explored by some contemporary hard SF writers. Perhaps we should pay attention. In his "Near Space" stories set in the twenty-first century, Allen Steele developed a future history updated from Robert Heinlein's which includes several themes of our AGCI Workshop (Steele, 1998): "With the beginning of the Golden Age of space exploration — the building of the powersat system, the colonization of the Moon, and the establishment of the first bases on Mars — Jupiter began to look neither so distant nor so formidable. The major technological breakthrough which made Jupiter reachable was made in 2028 by a join R&D project by Russian and American physicists at the Kurchtov Institute of Atomic Energy and the Lawrence Livermore National Laboratory; the development of the gas-core nuclear engine..."

Here is Allen Steele explicating the helium-3 mining of outer planet atmospheres as a fusion fuel in his fictional future history: "It had been known for almost a century that Jupiter's upper atmosphere was rich in helium-3. In fact, not only was the isotope more abundant than on the Moon, but since it was not molecularly bound with all the other elements in the

lunar regolith, it was theoretically easier to extract..." And maybe the prediction by space exploration advocate Robert Zubrin that the outer solar system will become the "Persian Gulf" of the second half of the twenty-first century will also come to pass (Zubrin, 1996).

Technology and its consequences

It is axiomatic that ideas developed in a Workshop on innovative technologies applied to CO_2 stabilization are those of technological optimists. We realize that there are those not disposed to solve the problems created by technology by applying still more technology. Scholars have also observed that technology often has unintended consequences and can "bite back" in unexpected ways (Tenner, 1996). Global warming is just such an unintended consequence of fossil fuel burning.

There is something to be said for this view. Niles Eldridge (1996) observed that with the advent of the Neolithic (agricultural) revolution 10,000 years ago came an unprecedented ecological change. Farming humans were no longer part of the local ecosystems, as were their hunter-gatherer ancestors who lived in small bands relying on the natural productivity of the land. But now the global human population is interacting as a block with the environment at the planetary scale (Figure 1). We didn't evolve for this role, and so have no appropriate instinctive responses. We have to deal with it cognitively, by reason, and in the face of uncertainties and risk. But we've come too far down the road of technology to turn back now. We couldn't feed the present human population without technology, and a hefty energy subsidy (Smil, 1997): Currently at least two billion people are alive because the proteins in their bodies are built from nitrogen that came via plant and animal foods using nitrogen fertilizers based on the Haber process.

Technology often has unintended consequences and can "bite back" in unexpected ways.

One thing we can say with some confidence: Without a dramatic change in the infrastructure of energy supply on a global scale, atmospheric CO_2 will continue to rise, and the global climate will change, for better or worse. It is only prudent to explore the options vigorously. As Sherlock Holmes said (Doyle, 1890), "When you have eliminated the impossible, whatever remains, however improbable, must be the truth."

There are emergent ideas with the potential to revitalize government, industrial and university laboratories. But they will need funding. Some are near-term, some longer-term, and some profoundly transformative of the energy system. Most will not succeed. But like biological evolution, technology evolution needs mutations from which markets can select.

Over the past half-century, government R&D produced commercial aviation, telecommunication satellites, radar, lasers, and the Internet. Industry can't afford to support ideas that don't yield profits three years or less down the pike. Congress must understand this. The most unrealistic approach may be to base climate change mitigation policy on more efficient versions of today's technology. We don't cross oceans on sailing ships any more, however efficient; we fly over them. Let's not lose the game from a failure of imagination.

Kyoto was a good start. But serious approaches to mitigating the global greenhouse need to focus on vital questions: How can we power our technological civilization with minimum climatic

impact while preserving economic growth and planetary ecosystems? How technologically, and how, in an increasingly globalized economy, can we do it in ways that stimulate new industries of the twenty-first century? Do we even know how to selectively accelerate technology development, as World War II and the Cold War did, without the adrenaline-pumping fear of blowing each others brains out? "Green energy" research, so calm and peaceful seeming, has not, despite some gains, succeeded in the market. We must learn to do it better as the "grand geophysical experiment" unfolds. Our future depends on it.

SESSION 1

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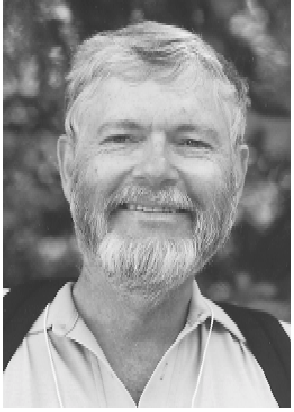
Do we even know how to selectively accelerate technology development? We must learn to do it better. Our future depends on it.



Sequestering of Atmospheric Carbon through Permanent Disposal of Crop Residue

Gregory Benford
University of California, Irvine
Irvine, California

and Robert Metzger
Georgia Institute of Technology

SESSION 1

Pulling CO_2 from the air enjoys a leverage factor of 2.2 over sequestering before emission, since the biosphere absorbs over half of all gross human emissions.

We propose the sequestering of crop residues to capture a significant fraction (26%) of present U. S. atmospheric carbon emissions. With adequate fractions of farm waste left in and on the soil to supply nutrients and retard erosion, the bulk of the waste could be shipped at low cost, using the existing crop transport network, at a cost of $22.5 billion per year. Disposal in river deltas may ensure carbon capture for perhaps a century. Deep ocean disposal would probably sequester carbon for millennia. Globally, roughly 20% capture of currently emitted carbon seems possible by this method. Costs are lowest for those nations already exporting grains, which have transport systems in place. The leverage of this approach comes from an acre of corn's ability to hold 400 times the carbon that human emissions deposit annually in the air above it. All such methods for pulling CO_2 from the air enjoy a leverage factor of 2.2 over sequestering before emission, since the biosphere absorbs over half of all gross human emissions. Implementation of this proposal would not only allow the U. S. to meet the emissions levels stipulated under the Kyoto Accord, but would permit the U. S. to continue its current carbon emission increase of 1.5% per year for the next 9 years.

Seen in the largest perspective, our current atmospheric buildup of CO_2 stems from our first great invention, the discovery of fire. Given that, our eventual discovery of fossil fuel and our political short time horizons made a greenhouse problem inevitable. Perhaps we can offset our species' greenhouse effects by using our second great invention, agriculture, with some help from the wheel. Farming is the largest scale human activity, covering about 10% of the globe. Perturbing this large effect seems a wise way to affect our atmosphere, based on a simple fact: a field of corn captures about 400 times as much carbon as there is in human generated atmospheric carbon in the entire column of air above the field, from ground to space [1]. Harnessing this prodigious method of arresting carbon could give us great leverage over the global CO_2 imbalance.

Worldwide human activities result in estimated annual carbon emissions of 7.1 gigatonnes of carbon (GtC), composed of industrial emissions of 5.5 GtC, with an added 1.6 GtC from biospheric burning [2]. These emissions produce an increase in global atmospheric CO_2 of

1.6 ppm/year, representing 3.2 GtC/year. The difference between the carbon emitted and that which remains in the atmosphere is due to the biosphere's ability to sequester 55% these emissions. In 1990, the U. S., with only 4% of the world's population, emitted approximately 19% of this CO_2, some 1,340 GtC, of which 740 GtC was sequestered in the biosphere, with 600 GtC remaining in the atmosphere [3].

There are two ways to cut this CO_2 rise: reducing emissions, and sequestering of atmospheric carbon. Sequestering offers many possibilities: tree growth, CO_2 disposal in oceans (gaseous, liquid and solid), trapping CO_2 in exhausted oil fields and beneath salt domes, and fertilizing plankton production in the oceans by using iron [4]. Sequestering of CO_2 after it has been emitted into the atmosphere offers a distinct advantage over emission reductions by taking advantage of the biosphere's ability to sequester 55% of those emissions, which gives a leverage factor of 2.2 times over emission reduction approaches [5]. This factor is shared by any process that removes carbon from the air. We propose a new sequestering approach, utilizing post-emission sequestering in order to take advantage of the high leverage factor, through the permanent storage of unwanted farm waste (crop residue) in river deltas or the deep oceans.

Advantages of sequestering carbon in farm waste are that it uses biomass that is now mostly left to rot in the fields, demands no new land, and requires no new technologies or transport systems.

The great advantages of sequestering carbon in farm waste are that this approach:

(a) uses biomass that is now mostly left to rot in the fields;
(b) demands no new land;
(c) uses residue that can be gathered and shipped with the same equipment used to bring in the crop; and
(d) requires no new technologies or transport systems.

In the global carbon budget, as illustrated in Table 2, the deep oceans sequester in the form of sediments, the vast bulk of the world's carbon. The oceans are not CO_2 saturated, and the deep ocean circulates carbon back to the surface on timescales measured in many centuries or even millennia [4, 6].

Table 2
The Global Carbon Budget

	GtC
Atmosphere	720
Biosphere	550-830
Soils	1,500
Fossil Fuel Reserves	6,000
Deep Oceans	38,000
Marine Sediments	20,000,000

We focus upon using farm waste in the U. S., for which data is extensive [6-9]. Generally, most crop residues have 40% by weight of carbon [10]. We analyze primarily corn production because it is the single largest U. S. crop in both acreage planted and crops produced. It is extremely efficient at fixing carbon, using a unique C4 photosynthesis process [11], yielding about three times more grain per acre harvested than wheat, which grows under more common C3 photosynthesis processes [7]. In 1996, according to U. S. Department of

Agriculture statistics, 79 million planted acres produced 236 million tonnes of corn, or 3 tonnes/acre. Crops typically generate 1.5 pounds of residue for each pound of harvested material, so in the case of corn, residues of 4.5 tonne/acre can be expected [8].

Most crop waste can be removed without nutrient penalty. Historically, farmers tilled residue back into the soil, believing that it would increase the soil organic matter (SOM) content. However, research shows that in fact this practice leads to long term reduction of organic matter in the soil, due to disruption of soil microfauna [12-16]. As a specific example, it was found that under no-till methods (in which crop residue was left on the soil surface), when compared to conventional tillage, that the carbon content in the soil was 35%, 39% and 53% greater for wheat, sorghum, and soybean crops, respectively [15].

Varying degrees of conservation tillage methods (of which zero tillage represents the extreme) — those in which at a minimum, at least 30% of the soil surface is covered by residue after planting — are available. Conservation tillage is used primarily on corn, soybeans and small grains [9] — those crops which we are proposing to use as our primary sources of crop residue. By 1994, more than 45% of corn and soybean acreage was conservation-tilled. Zero till methods for corn production more than tripled from 1989 to 1994, increasing from 5 to 17%. Such statistics clearly show trends toward less and less tilling, coupled with reduced erosion benefits [9]. This suggests that as conservation and zero tillage methods are more widely used, greater amounts of crop residue will be available for harvesting.

If we assume a typical erosion abatement policy that leaves 25% of the residue on the field, this yields a total potential carbon reserve in these crop residues of 180 MMTC. Permanently sequestering this 180 MMTC would represent 26.6% of the current U. S. carbon emission.

After corn, the three next largest U. S. crops by acreage are wheat (76 million acres), soybeans (63 million acres), and hay (61 million acres). For this analysis we assume that hay generates no collectable residues, since the crop is usually taken down to the roots. We also neglect rice, though in the U. S., much of its residue rots in moist fields, releasing methane, which molecule-for-molecule is a much more powerful greenhouse gas than CO_2. Crop residues of those we are interested in for this study typically yield 1.5 times the harvested crop mass [8], and we shall consider this also the case for soybeans for this analysis. (Often, though, soybean residues are plowed under to replace nitrogen in the soil. Whether this practice would survive a carbon credit pricing is unclear.)

Table 3 illustrates the amounts of residues available from these major crops as well as the equivalent carbon, based on an average carbon content in these crops of 40% [10].

Table 3

Crop	Acres Planted	Residue/Acre	Total Residue (million tonne)	Total Carbon (million tonne)
Corn	79 million	4.5 tonne	356	142
Soybeans	63 million	2.0 tonne	126	50
Wheat	76 million	1.5 tonne	114	46
Total			**595**	**238**

If we assume a typical erosion abatement policy that leaves 25% of the residue on the field, this yields a total potential carbon reserve in these crop residues of 180 MMTC (million

tonnes of carbon). Using the 1990 estimate of 600 MMTC as the amount of net carbon which U. S. activities permanently place in the atmosphere, and using the estimated annual increase of U. S. carbon emission of 1.5% [3], results in a 1998 U. S. atmospheric carbon placement of 676 MMTC into the atmosphere. Permanently sequestering this 180 MMTC would represent 26.6% of the current U. S. carbon emission.

The Kyoto Accord calls for a 7% reduction in CO_2 emissions below the 1990 level, 1,250 MMTC [3]. The 180 MMTC trapped in this approach is a post-emission reduction, and therefore equivalent to 396 MMTC if removed in the form of emissions reductions. If this crop residue were sequestered in 1998, the net carbon placed in the atmosphere by the U. S. would be 496 MMTC (676 - 180 MMTC). This is equivalent to 1,091 MMTC of emissions, well below the Kyoto requirement of 1,250 MMTC . If the U. S. continues to increase carbon emissions at a rate of 1.5% per year, and the sequestering of these crop residues were performed, U. S. emissions would stay below the levels stipulated by the Kyoto Accord through 2007. Thereafter, the 1,250 GtC level agreed upon at Kyoto for the 2012 emission levels could be maintained by reducing the annual increase of the U. S. emission rate from 1.5% to zero. At no time under this approach are any actual reductions in carbon emissions required in order to meet the Kyoto targets.

If the U. S. continues to increase carbon emissions at a rate of 1.5% per year, and the sequestering of these crop residues were performed, U. S. emissions would stay below the levels stipulated by the Kyoto Accord through 2007.

Because other nations, particularly those just developing, make more extensive use of their crop residue for animal fodder, fuel and manufacture, estimating waste in these locations is difficult. China appears to use about 40%, whereas Bangladesh is nearer 90% [4]. Availability will depend on any carbon credit which enters as another “market” to compete for these uses.

However, the potential can be estimated. Considering only grains (wheat, milled rice, and corn), the total combined world production in 1996 was 536 million tonnes of wheat, 372 million tonnes of milled rice, and 810 million tonnes of corn and other coarse grains, for a total of 1,718 million tonnes [7]. Assuming an average crop residue of 1.5 times the crop yield implies 2.58 Gt total available world crop residue, or 1.0 Gt of carbon. This represents 32% of that permanently placed in the atmosphere due to human activities. Were only half of this available globally, CO_2 emission could still effectively be reduced by 16% — surely significant.

Having established the availability of vast carbon sources in crop residues, how can one permanently sequester the carbon? Three possible methods appear practical:

(a) sequestering in exhausted oil/gas fields or beneath salt domes [4];
(b) sinking in oceans (both shallow and deep beneath the thermocline); or
(c) burning in power plants to replace oil and coal [4].

In each case the crop waste must first be harvested, baled, and readied for transport. Estimated costs for this range from $8 to $26 per ton for various studies and different crops, with a mean cost of about $20 per ton for biomass uses. (Currently, only 3% of U. S. biomass power production comes from farm waste [4]. Crop residue for energy production is generally undesirable, burning at low temperatures and depositing unwanted minerals on heat exchange surfaces.) [17].

Sequestering in depleted gas/oil fields and beneath salt domes would require grinding up the waste, and transforming it into a slurry to be pumped down. This is a distinct cost disadvantage, although there may be some advantages to this approach if one could use existing pipelines to transport it, and transportation distances might not be far. Both salt domes and depleted gas/oil fields are plentiful in the U. S. midwest, the region producing much corn waste. These methods should be explored, but face questions about how long the carbon will remain sequestered.

Here we propose two sequestering sites — near the coast in shallow waters above the thermocline, and further out, beneath the thermocline. Simply off-loading corn waste into an actively depositing river delta like the Mississippi's can bury it within days as later river silt falls upon it. We know of no study measuring how long deposited organic matter takes to decay into gas which reaches the surface (CO_2 or methane). Gulf deposits near the coast save on transport at sea, but uncertainty over deposition times may preclude their use.

In the Gulf of Mexico, excursions ~100 km from the delta reach deep ocean waters. Below ocean depths of about 1 km lies the thermocline, where there is little oxygen and temperatures are only a few degrees above 0°C. This anaerobic environment mixes with surface waters very slowly, requiring centuries to millennia [4]. Simply dropping baled waste, with weights attached to ensure that trapped air does not make the bales float, should then sequester the waste. The weights could be made of carbon-rich solid wastes which, left on land, would normally decay into CO_2; this sequesters more carbon.

Here we propose two sequestering sites — near the coast in shallow waters above the thermocline, and further out, beneath the thermocline.

SESSION 1

To make doubly sure, and extend the sequestering time, one might shape the waste into cylinders with conical weight heads. These "carbon torpedoes" would penetrate the bottom sediments to several meters, sealing in decay products. This may prove particularly useful, since then trapped methane or CO_2 can attain the concentration where stable hydrates of methane or CO_2 form, securing the carbon for very long time periods [18].

Depositing the entire disposable U. S. waste tonnage, 450 MT, would cost about $22.5 billion if total collection and transport costs were $50/ton [19]. Still, $22.5 billion seems a small cost to hide 26% of all U. S. emitted carbon; satisfying Kyoto levels in 1998 would cost in the range of $10 billion/year.

Scaling this result to other nations makes sense only for those nations already producing substantial crops that may be easily moved to ocean dumping sites. This probably includes some European states, the Ukraine and a few developing nations such as South Africa.

This proposal is qualitative, outlining areas that should be explored: the fate of wastes in deltas, shipping costs for farm residue, and other economic factors. Intended as stimulating, not definitive, we conclude with a few thoughts on tradeoffs and political realities.

Hiding waste carbon is a general strategy suggesting other approaches. There can be many local adaptations, large and small. For example, many cities separate organic waste during their trash collections and dump it in landfills or nearby ocean beds, where it quickly generates

both CO_2 and methane. New York City dumps most of its general wastes off the aptly named Fresh Kill point, creating a large, lifeless, anoxic zone. Far better to send barges of organic waste 200 miles offshore, where it would fall to the deep ocean bed beneath the thermocline.

The U. S. confronts an embarrassing mismatch between its high emissions and a general unwillingness to incur high costs to offset these. Estimates of up to $100 billion to comply with the Kyoto Accords are common. Much political opposition also arises from the perception that Kyoto means sending tax dollars to distant lands, through a system of carbon credits, for which there is little domestic support. Farm waste disposal promises to lower such costs, with political bonuses. The $10-20 billion per year spent to sequester farm residue will go to American workers such as farmers and truck drivers. It demands no new infrastructure and is easily stopped if unwanted effects occur.

A program of domestic carbon credits exchanged in a market could drive efficiencies in disposal. After all, waste need not be cleanly handled, as are edible crops; coal barges will serve nicely. Such bulk disposal is the simplest, lowest technology way to hide carbon from our atmospheric cycle. As a bonus, it will give ordinary working people a feeling that they, too, can do something active about climate change. And because farm waste plausibly rises with population, as does energy use, this sequestering method will then keep pace with the predicted rise of our numbers to ten billion within a half century.

This proposal is qualitative, outlining areas that should be explored. Hiding waste carbon is a general strategy suggesting other approaches.

Notes and References

1. This calculation assumes that an average acre of corn has a dry mass of 10 tonnes (grain, stalks, leaves and roots); 40% consists of carbon. In the air above the corn field, the additional CO_2 placed in the atmosphere due to human activities is 1.6 ppm per year, a total of 10 kg in the column of air above the cornfield to the reaches of space. Therefore, one acre of corn incorporates an equivalent amount of excess atmospheric carbon in the air column above 400 acres.

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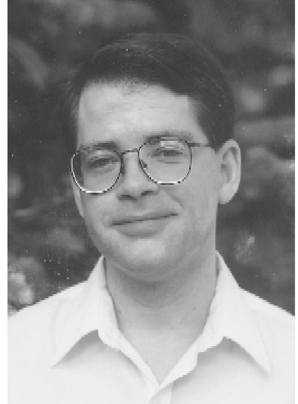
19. The $50/tonne estimate uses the average value of $20/tonne to collect and ready the crop residue for transport, with the remaining $30/tonne allocated for transportation costs.

SESSION 1

The U. S. confronts an embarrassing mismatch between its high emissions and a general unwillingness to incur high costs to offset these.



Coupling Hydrogen Fuel and Carbonless Utilities

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A number of previous analyses have focused on comparisons of single hydrogen vehicles to petroleum and alternative fuel vehicles or of stationary hydrogen storage for utility or local power applications. Lawrence Livermore National Laboratory's (LLNL) approach is to compare combined transportation/utility storage systems using hydrogen and fossil fuels. Computer models have been constructed to test the hypothesis that combining carbonless electricity sources and vehicles fueled by electrolytic hydrogen can reduce carbon emissions more cost effectively than either approach alone. Three scenarios have been developed and compared using computer simulations, hourly utility demand data, representative data for solar and wind energy sites, and the latest available EIA projections for transportation and energy demand in the U. S. in 2020. Cost projections were based on estimates from GRI, EIA, and a recent DOE/EPRI report on renewable energy technologies. Hydrogen technology costs were drawn from recent or ongoing analyses by Princeton University (Ogden 1995) and Directed Technologies Inc. (DTI) (Thomas 1998) for the Hydrogen Program.

Combining carbonless electricity sources and vehicles fueled by electrolytic hydrogen can reduce carbon emissions more cost effectively than either approach alone.

The key question guiding this analysis was: What can be gained by combining hydrogen fuel production and renewable electricity? Bounding scenarios were chosen to analyze three "carbon conscious" options for the U. S. transportation fuel and electricity supply system beyond 2020:

Reference Case	petroleum transportation & natural gas electric sector
Benchmark Case	petroleum transportation & carbonless electric sector
Target Case	hydrogen transportation & carbonless electric sector

A large number of assumptions were necessary to construct these scenarios, but preliminary model results indicate that if wind and solar electricity were massively deployed to replace fossil fuel electric generation in 2020, and costs approached today's levels, a carbon tax of $86 billion/yr (applied over 0.49 GtC/yr or $175/tonneC) would be needed for solar and wind electricity to compare favorably to efficient combined cycle natural gas electric plants.

This picture becomes more favorable if electrolytically fueled hydrogen vehicles are also deployed. Coupling a hydrogen transportation sector to augmented solar and wind electricity sources improved flexibility and utilization of renewables in a carbonless electricity system, reducing 75% more carbon emissions (0.86 GtC/yr) for only 10% greater system cost (Figure 5 is a conceptual representation of such a system). The addition of hydrogen

Advanced energy technologies using natural gas can be quite cost-effective albeit partial solutions to energy and environmental challenges.

transportation fuel demand reduced carbon emissions further while lowering likely carbon tax rates ($/tonneC). Given future long-term petroleum fuel prices of $1.50-2.00/gallon, carbon taxes of only $80-150/tonneC would be needed for solar and wind dominated carbonless electricity systems, combined with hydrogen production for vehicles, to compete with natural gas electric generation and petroleum vehicles.

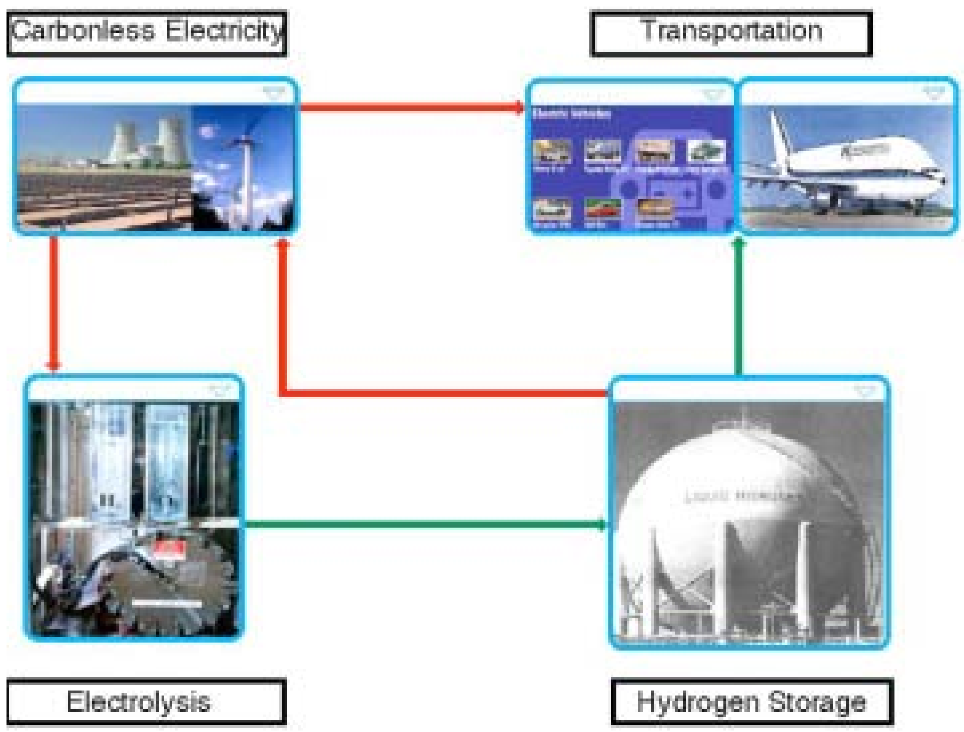

Figure 5
Conceptual representation of a coupled carbonless electricity and hydrogen transportation system and flows of electricity and hydrogen.
Electricity generated from nuclear, solar, wind, or other carbonless electricity sources meets electricity grid needs first. Surplus electricity can either directly fuel batteries or other electric storage on vehicles or produces hydrogen for ultiimate storage and use on vehicles. In periods of low solar and wind availability, stored hydrogen can be reconverted to electricity for use on conventional electricity grid. Note: A number of additional options are not pictured. These include: hydroelectric and biomass generation, as well as mixed systems of compressed and liquid hydrogen storage, and hydrogen use by commercial trucks, in addition to aircraft and light duty vehicles.

Conventional wisdom (*e. g.* Winter 1988, Ogden 1989) has rationalized the pursuit of hydrogen energy systems as a solution to problems stemming from the use of fossil fuels: energy security, pollution, and greenhouse gas emissions. But advanced energy technologies using natural gas can be quite cost-effective albeit partial solutions to these energy and environmental challenges. Cost-effective fossil energy technologies may seriously undercut the conventional rationale for widespread adoption of hydrogen energy systems.

The most notable example is probably natural gas vehicles which, while similar to hydrogen vehicles are likely to be more cost-effective at reducing air pollution, greenhouse gases, and oil imports. It is likely more cost-effective to begin reducing utility emissions through efficiency improvements, fuel switching to natural gas, and/or directly using relatively small amounts of solar and wind electricity (without energy storage), before producing hydrogen for transportation fuel or electricity load leveling (Thomas 1998).

It appears a strengthened rationale for hydrogen energy development can be constructed based on the need for deep greenhouse gas reductions — if significant synergies can be found between carbonless utilities and transportation coupled by hydrogen fuel (Berry 1996).

The largest benefit unique to hydrogen energy technology is the capacity for deep reductions in greenhouse gas emissions. The two largest greenhouse gas sources, utility electric generation and transportation fuel emissions, can be eliminated if electrolytic hydrogen and carbonless electric generation are sufficiently inexpensive. This analysis tests the hypothesis that carbon emission reductions can be more cost-effectively achieved if electrolytic hydrogen fuel production and electricity generation are closely coupled (see Figure 5). Our approach is to simulate transportation and utility sectors under a variety of cost, technology, and operational scenarios. The objective of this analysis is to determine the prerequisite economic and hydrogen technology developments for which this hypothesis can be relevant, and to identify corresponding hydrogen production, storage and utilization technology benchmarks.

The two largest greenhouse gas sources, utility electric generation and transportation fuel emissions, can be eliminated if electrolytic hydrogen and carbonless electric generation are sufficiently inexpensive.

Approach: Aggressive Fossil, Renewable, and Hydrogen Scenarios

Three scenarios were constructed and used in our computer models of utility and transportation sectors, a reference, benchmark, and target case. These three scenarios were chosen as aggressive, mature, boundary cases. These scenarios test the widest range of possibilities that were most interesting, while maintaining a balanced basis for comparison, and keeping the analysis as simple as possible. If the results of these scenarios are sufficiently compelling, then future analyses can explore more complex, detailed and perhaps more realistic transition scenarios. The year 2020 was chosen as the time period to analyze because of available Energy Information Administration (EIA) projections and because it also likely represents the fastest technically possible (and therefore most aggressive) transition to carbonless energy systems. It was felt that aggressive scenarios should be analyzed, since a hydrogen transition will not be attractive unless technology development (*e. g.* advanced electrolysis, low cost renewables, energy storage, etc.) is successful. The fossil reference case used for comparison was also aggressive for balance.

Each scenario had costs lower than today's energy systems. Aggressive technical and economic assumptions used in the benchmark renewable and target hydrogen scenarios included: high efficiency electrolysis, low cost renewable electricity and hydrogen storage, perfect demand and supply forecasting, etc. But the reference fossil energy case was equally aggressive, Partnership for a New Generation of Vehicles (PNGV) light-duty vehicle fleets are assumed, as well as very efficient use of natural gas to produce electricity. In line with EIA projections, no new capacity is assumed, in any scenario, for conventional carbonless electricity sources, such as nuclear or hydroelectric.

Methodology:
Only the detail necessary to capture supply and demand patterns

Our computer models used only as much data as necessary to establish the rough magnitude of the benefits gained by coupling hydrogen fuel production with carbonless electrical sources. Real electricity demand and wind and solar supply data for an entire year, at hourly resolution, was necessary. Data representative of both a summer peaking (*e. g.* California) and a winter peaking (*e. g.* Washington state) utility were gathered. Wind and solar data from "second tier" sites were chosen to approximate PV, solar thermal, and wind electricity sources based mostly in the West, Southwest, and Midwest (Iannucci 1998). Detailed time zone and regional effects were neglected for simplicity. Transportation fuel use patterns were based on 12-hour resolution DOT data for passenger vehicles (Klinger 1984), and monthly EIA data for commercial vehicles (EIA 1998).

Model construction was kept as simple as possible. National aggregates for transportation and electricity demand were used. Single reservoirs of electricity and hydrogen production and storage capacity, scaled to the entire U. S., were used to represent thousands of solar thermal and wind farms, liquefaction facilities, and hydrogen filling stations used by millions of vehicles. Lumped national average costs for electricity transmission and distribution were used. Utility energy storage when necessary was presumed to employ hydrogen storage and fuel cells. Decentralization of photovoltaics and hydrogen infrastructure was assumed to circumvent the complex issues of additional electricity transmission and distribution needs.

Financial calculations were kept as simple as possible. Operating costs were neglected where they were less than the resolution of capital cost or fuel estimates (typically ~10%). Capital investments were discounted at 6% over a cost-weighted average of ~25 years. Electricity prices reflected electricity transmission, distribution, conventional generation, and in the target scenario, prorated electric and hydrogen generation and storage investments.

These scenarios test the widest range of possibilities that were most interesting, while maintaining a balanced basis for comparison, and keeping the analysis as simple as possible.

Model Description: Scenario simulation and optimization

LLNL used two computer modeling approaches in this analysis: simulation and multiperiod (*e. g.*, 8,760 hours) equilibrium optimization. Simulation provides faster but simpler results. Any given simulation model run simply provides the energy and economic performance of a given energy system configuration and operational rules. An optimization model run is slower and more complex, but can, in principle, determine the lowest cost configuration of technologies and operation of those technologies to meet given electricity and hydrogen demand time series. To date LLNL's network optimization code "METAnet" (Lamont 1994) is still being fine-tuned for operational optimization of hydrogen electricity systems (typical optimization results are shown in Figure 6). Optimal renewable energy system configurations based on preliminary METAnet results appear capable of achieving costs 10-20% lower than simulation models, which may somewhat understate the attractiveness of intermittent electricity, and especially hydrogen fuel production, relative to conventional fossil fuel scenarios. Further development and analysis is needed, however. Consequently, the results generated from simulation models are used here.

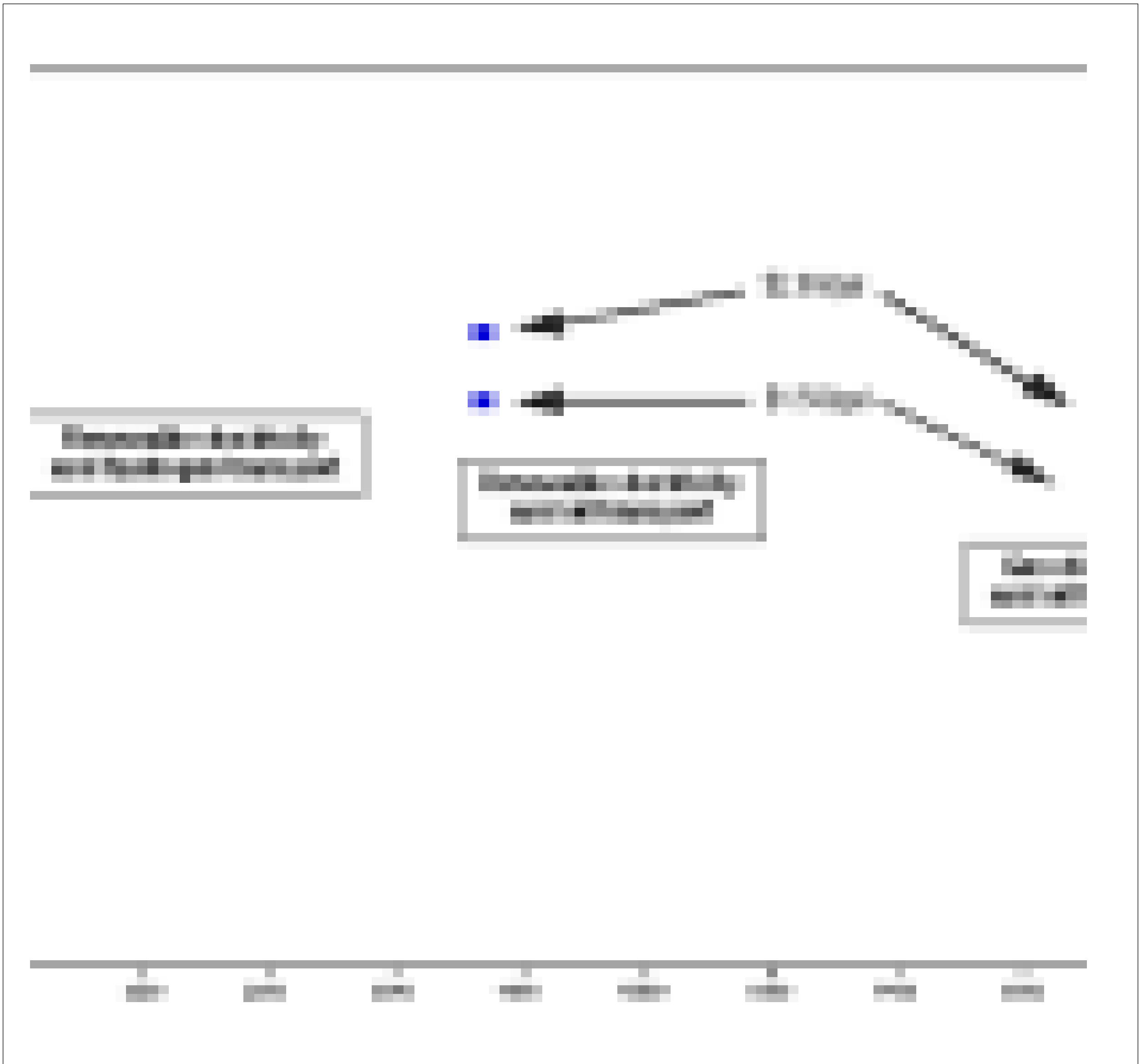

Figure 6
Typical output from LLNL's METAnet equilibrium network model. A 10-day period of hourly electric generation, marginal operating costs, and energy storage are shown. A scenario run typically covers an entire year (36 of the above periods). Many runs are used to arrive at optimal capacities of electricity and hydrogen production and storage.

The graphical interface simulation model software used for this study, STELLA, is commercially available (High Performance Systems Inc. of Hanover, NH). Visualization, conceptualization, and interconnection of technical, economic, or market variables is exceptionally easy. The value of each factor and its relationship to other factors are easily modified, allowing exploration of strategic parameter spaces such as production and storage scale, efficiency, discount rate, equipment lifetimes, fuel efficiency, and demand patterns.

Annual electricity flows from various sources (nuclear, hydroelectric, wind, solar thermal, and photovoltaic) to the electric grid and/or, stored as hydrogen (liquid, compressed, onboard, stationary, etc.), and ultimately to transportation use in light-duty vehicles and commercial trucks, aircraft, and trains were

modeled on an hour by hour basis. Supply and storage choices were simulated to operate as energy efficiently as possible while still meeting electricity and fuel demands.

Input Assumptions and Scenario Results

Preparation for a model run requires specification of equipment capacities, conversion efficiencies, and fuel use corresponding to a desired scenario. After each model run these parameters were varied to explore the sensitivities of results to individual parameters and to achieve lower projected costs, more efficient operation, etc. The final parameters chosen for each scenario and output results are given in Table 4. The data are discussed below.

Electricity Supply and Demand Assumptions

Solar and wind electricity generation patterns were based on annual data gathered at sites in California and Wyoming, as well as utility demand patterns from utilities in the Southwest and Northwest, provided by Distributed Utility Associates (DUA). These data were scaled up to meet the end-use electricity and hydrogen production needs based in EIA's reference case forecast for 2020. For example, U. S. electric generation capacity is projected by EIA to be 993 GW in 2020 (up from ~700 GW today) (EIA 1998). This was rounded to 1 TW for simplicity and became the scaling factor for both northern and southern utility demand pattern data from DUA. In the final results, southern utility demand data were used after model results were not strongly affected by which electricity demand pattern was used. Nuclear and hydroelectric capacity were taken from EIA data representing ~5% and ~10% of U. S. electric generating capacity in 2020 respectively.

After each model run these parameters were varied to explore the sensitivities of results to individual parameters and to achieve lower projected costs, more efficient operation, etc.

During the simulation, in periods of insufficient renewable electricity, (windless nights, cloudy days etc.) electricity from fuel cells was produced using hydrogen in compressed (if available) or liquid stationary storage. In periods of excess electricity availability, hydrogen was produced and stored.

Cost projections for renewable electric capacity were gathered by DUA using *Renewable Energy Technology Characterizations* (a joint project of EPRI and DOE). Natural gas fired electricity projections are from GRI. Transmission and generation electric costs were estimated by DUA, and scaled to meet a 1 TW peak demand (including coincident loads) (Iannucci 1998).

Hydrogen Transportation Fuel Demand and Use Assumptions

Transportation demand was modeled differently for different vehicle classes. Light-duty vehicle travel patterns (for days, nights, weekdays, and weekends) were taken from the 1983 Nationwide Personal Transportation Study (NPTS) completed for the National Highway Traffic Safety Administration (Klinger 1984). These patterns were then scaled to 12,000 miles/yr for a projected 270 million light-duty vehicles in 2020, equaling the 3.24 trillion vehicle miles traveled (vmt) projected by EIA for 2020. Drawing from the 1983 NPTS data, it was assumed that 15% (1800 miles/yr for an average driver) of vmt was due to long trips (<75 miles) and would require liquid hydrogen. PNGV fuel economy (~80 mpg) was assumed for hydrogen vehicles.

Commercial vehicle fuel demand was approximated using monthly energy demand patterns from 1995-1997 for diesel (trucks and trains), and jet fuel (aircraft) using EIA data, and aggregate projections of fuel demand in 2020. Trucks and trains were are powered by compressed hydrogen, with the same fuel economy projected by EIA for diesel fueled vehicles. Aircraft were fueled by liquid hydrogen, a 10% higher fuel economy than EIA projections due to hydrogen's low mass.

Hydrogen refueling patterns were identical to fuel use patterns (so that vehicles were essentially always full) except for light-duty vehicles which refueled less when station supplies were low for a few days, presuming a high fuel price sensitivity for drivers. Onboard hydrogen storage equipment costs for passenger vehicles and commercial trucks were included in the model.

Table 4
System parameters used in computer model scenarios

Scenario	Reference		Benchmark		Target	
Electricity Demand (trillion kWh/yr)	5		5		5	
Electric Supply (TW, trillion kWh/yr)	5		5.8		11	
Natural Gas ($600/kW, $3.05/GJ)	1.0	5	-	-	-	-
Nuclear ($2000/kW)	-	-	0.05	0.44	0.05	0.44
Hydroelectric ($2000/kW)	-	-	0.10	0.90	0.10	0.90
Wind ($655/kW)	-	-	0.85	3.2	0.85	3.2
Solar Thermal ($2510/kW)	-	-	0.35	1.1	0.85	2.4
Solar Photovoltaic ($1110/kW)	-	-	0.05	0.12	1.8	4.3
Fuel Cells ($200/kW)	-	-	1.0	(0.48)	1.0	(0.06)
Transportation Demand (trillion kWh/yr)	oil		oil		hydrogen	
Light-duty vehicles (urban)	1.16		1.16		1.16	
Light-duty vehicles (highway)	0.20		0.20		0.20	
Commercial trucks & rail	1.64		1.64		1.64	
Aircraft	1.63		1.63		1.45	
Hydrogen Supply (TW, kWh/yr)						
Electrolysis ($500/kW, 92% eff)	-	-	1.0		1.2	
Compression ($100/kw 92% eff)	-	-	1.0		1.2	
Liquefaction ($500/kW, 78% eff)	-	-	1.0		1.0	
Hydrogen Storage (kWh LHV H2)						
Onboard light-duty fleet ($150/kg H2)	-		-		15 billion	
Stationary Compressed ($150/kg H2	-		1.5 billion		4 billion	
Stationary liquid hydrogen ($10/kg H2)	-		275 billion		750 billion	
End-use Electricity Cost ($Billion/yr) (@6% discount rate)	192		290		275	
Transportation Fuel Cost (@$1.50/gal petroleum fuel)	216		216		275	
Electricity Carbon Emissions (GtC/yr)	.49		0		0	
Transportation Carbon Emissions (GtC/yr)	.37		.37		0	
Total Annual Carbon Emissions	.86		.37		0	
Total Cost ($Billion/year)	$420		$506		$550	
Breakeven Carbon Tax ($/tonneC)	-		$175		$150	

Scenario Assumptions

Reference Scenario (natural gas electricity and petroleum transportation)

The reference scenario was the simplest because no intermittent resources were used. It was designed to be a strong competitor to carbonless electricity and hydrogen scenarios. In the reference scenario, all transportation needs are met by petroleum. Light-duty transportation fleet efficiency has increased to PNGV levels (80 mpg or roughly 3 times greater than EIA projections for 2020). Petroleum demand for trucks, trains, and aircraft were taken directly from EIA projections. All electricity demand was met

The reference scenario was the simplest because no intermittent resources were used. It was designed to be a strong competitor to carbonless electricity and hydrogen scenarios.

by natural gas combined cycle plants with an average 57% efficiency. Natural gas prices in 2020 were $3.05/GJ as per EIA projections. A key optimistic assumption was that greenhouse gas emissions from natural gas (methane) leakage would be negligible (methane is believed to be 10-20 times more potent than carbon dioxide as a greenhouse gas). In our aggressive reference scenario, passenger vehicle efficiency and the efficient use of natural gas by utilities combine to reduce carbon emissions from transportation and utilities to only 870 mmtC/yr, compared to 1400 mmtC/yr projected by EIA for 2020 (EIA 1998).

Benchmark Scenario (solar, wind electricity and petroleum transportation)

The benchmark scenario assumes that all electricity demand is met by a mixture of solar thermal, wind, and photovoltaic (PV), instead of natural gas, as in the Reference Scenario. To meet a 1 TW capacity requirement, 0.85 TW of wind and 0.35 TW of solar thermal are assumed, as well as 0.15 TW (combined) of hydroelectric and nuclear. These capacities were chosen to match transmission and distribution capacity. A relatively small balance of electricity demand is supplied by distributed PV (0.05 TW). Utility energy storage is accomplished with steam electrolysis (Quandt 1986), and compressed or liquid hydrogen storage, as well as fuel cells. Transportation demand was met by petroleum, exactly as in the reference scenario. Carbon emissions were 370 mmtC/yr.

Target Scenario (solar, wind electricity and hydrogen transportation)

Carbon emissions from transportation and electricity production were, of course, zero for the target scenario.

The target scenario assumes that all electricity demand is met by a mixture of solar thermal, wind, and photovoltaic (PV), instead of natural gas, as in the Reference Scenario. To meet a 1 TW capacity requirement, 0.85 TW of wind and 0.85 TW of solar thermal are assumed, as well as 0.15 TW (combined) of hydroelectric and nuclear. These capacities were chosen to match transmission and distribution capacity. A relatively small balance of electricity demand is supplied by distributed PV (1.8 TW). Utility energy storage is accomplished with steam electrolysis and compressed or liquid hydrogen storage as well as fuel cells. Hydrogen not needed for electricity production is used as transportation fuel. Compressed hydrogen was used for 85% of light-duty vehicle fuel demand and all commercial trucking, while liquid hydrogen was used in aircraft and for long distance light-duty vehicle trips. As an efficiency measure, liquid hydrogen was only converted from ortho to para phases when necessary for long-term storage. Carbon emissions from transportation and electricity production were, of course, zero for this scenario.

Scenario Results

Summary energy balances, costs and emissions results from each scenario's computer model runs are given below. Detailed assumptions and output parameters are given in Table 4.

Reference Scenario (natural gas electricity and petroleum transportation)

In the 2020 reference scenario, assuming utility natural gas prices are $3.05/GJ, the U. S. can meet its 5 trillion kWh/yr electric demand (1 TW peak) with efficient combined cycle natural gas turbines at a cost of $192 billion/yr, and utility carbon emissions of 490 million metric tonnes per year (mmtC/yr). Land and air transportation demands are all met with only 144 billion gallons of petroleum/yr (due to PNGV light-duty vehicles) with attendant carbon emissions of 370 mmtC/yr. Fuel costs of $1.50/gallon would be another $216 billion/yr. The vast majority of petroleum demand is shared roughly equally between commercial trucks and aircraft. Passenger cars and trucks only account for <10% of petroleum use. Total annual cost is ~$420 billion/yr with total carbon emissions of 0.86 GtC/yr.

Benchmark Scenario (solar, wind electricity and petroleum transportation)

In the 2020 benchmark scenario, U. S. electric generation is completely carbonless, relying on small amounts of remaining hydroelectric and nuclear capacity, 850 GW of wind, 330 GW of solar thermal plants and 50 GW of photovoltaics to meet the same 5 trillion kWh/yr electric demand (1 TW peak). Daily and seasonal energy storage is accomplished using 1.5 billion kWh of compressed hydrogen and 275 billion kWh of liquid hydrogen storage. Roughly 7% of all electricity is lost in energy storage and reconversion. The capital investment for electric generation and hydrogen storage is estimated to be

$3.2 trillion, resulting in annual electric costs of $290 billion. All land and air transportation fuel demands are met by petroleum, just as in the reference scenario, with petroleum costs of $216 billion/yr (@$1.50/gallon) emitting 370 million metric tonnes of carbon annually. Total annual cost is therefore ~$506 billion/yr with carbon emissions of 0.37 GtC/yr.

Target Scenario (solar, wind electricity and hydrogen transportation)
In the 2020 target scenario, U. S. electric generation and transportation by car, truck and aircraft are completely carbonless. The electric generation system postulated in the benchmark scenario is augmented in the target scenario to provide electricity for additional hydrogen production, storage, and use. Solar thermal capacity is tripled to 0.85 TW, and photovoltaic capacity is expanded dramatically to 1.8 TW to meet additional electricity demands without transmission and distribution expansion. Two-thirds of electricity production is from solar thermal central receivers and distributed photovoltaics. Daily and seasonal energy storage is accomplished using 4 billion kWh of compressed hydrogen storage at refueling stations and 750 billion kWh of liquid hydrogen storage at stations and utilities. Eleven trillion kWh of electricity is produced annually, of which 5 trillion kWh is used directly, less than 1% of end-use electricity is lost through storage and reconversion by fuel cells. The remaining 7 trillion kWh of electricity are used to produce 4.6 trillion kWh of hydrogen for transportation use, meeting transportation demands identical to the reference case. Roughly half of hydrogen is liquefied for aircraft and long car trips, while half is used in commercial trucks and for short distance urban trips (<75 miles one-way) in light-duty vehicles.

The estimated $6.6 trillion coupled carbonless electricity and transportation fuel system has levelized costs (combined for both electricity and hydrogen fuel supply) of ~$550 billion/yr and produces no carbon emissions (offsetting 860 million metric tonnes of carbon from the reference scenario).

Key Results
The three scenario model runs summarized earlier, when taken and compared together, yield two key results:

1) It appears that, given inexpensive long-term oil and gas prices, improved natural gas electricity sources and very efficient (~80 mpg) passenger cars and trucks can be very competitive, producing lower carbon emissions in 2020 (0.86 GtC/yr) than the same sectors do today (0.98 GtC/yr) in spite of 50% higher electricity and travel demand. However, even given this extremely aggressive fossil scenario, it will be difficult to reduce carbon emissions below 0.86 GtC/yr without sequestration (likely creating a hydrogen transportation sector), improved electric generation efficiency (likely requiring utility fuel cells), improved aircraft and freight transportation efficiency (reducing the fuel cost barrier to hydrogen use), and/or widespread use of renewable electricity sources (creating a surplus for hydrogen production).

2) If such deep carbon reductions are needed, it appears coupling electrolytic hydrogen fuel production to solar and wind electricity can achieve much greater carbon reductions more cost-effectively than solar and wind electricity alone. Given petroleum fuel prices of $1.50/gallon in 2020 the hydrogen-based target scenario reduced 75% more carbon emissions than the benchmark scenario for only ~10% higher cost. These results are more striking because they illustrate the potential advantages of hydrogen-fueled vehicles even in scenarios where most carbon reductions are made in the electric sector,

It appears that, given inexpensive long-term oil and gas prices, improved natural gas electricity sources and very efficient (~80 mpg) passenger cars and trucks can be very competitive, producing lower carbon emissions in 2020 than the same sectors do today.

and PNGV light-duty vehicles (the likeliest market for hydrogen fuel to penetrate) are only 1/3 of transportation carbon reductions.

These results are likely dependent upon solar, wind, and hydrogen cost assumptions as well as fossil fuel prices and carbon taxes or credits. The figure below plots the estimated annual cost and carbon emissions of all three scenarios for petroleum fuel prices of $1.50-$2.00/gallon.

SESSION 1

Given petroleum fuel prices of $1.50/gallon in 2020 the hydrogen-based target scenario reduced 75% more carbon emissions than the benchmark scenario for only ~10% higher cost.

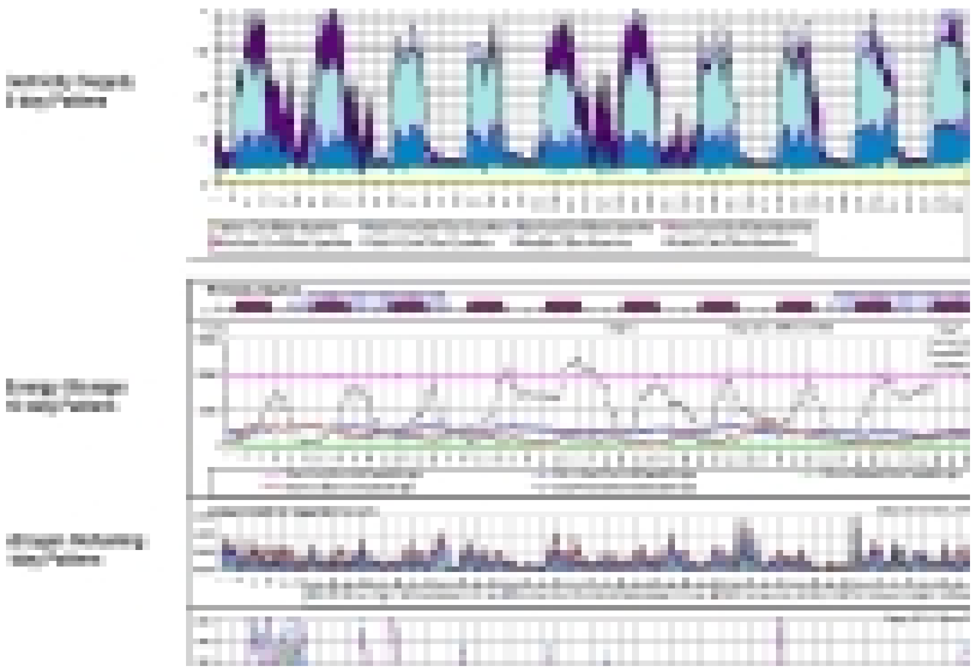

Figure 7
Annual cost versus emissions for reference, benchmark, and target scenario model runs and long-term petroleum fuel prices ranging $1.50-2.00/gallon.

The previous plot shows that for long-term petroleum fuel prices comparable to $1.50/gal, renewable hydrogen and electricity is more cost-effective at carbon reduction than renewable electricity alone, even given optimistic renewable electricity costs and low discount rates (6%). If future petroleum fuel prices rise high enough (to ~$2.00/gal) using hydrogen vehicles could actually lower the effective cost of renewable electricity while reducing carbon emissions. The previous plot also indicates carbon reduction differences between scenarios are much greater than cost differences.

Cost differences are greatest between the fossil reference scenario and the others. These differences are principally dependent on fuel price assumptions ($3.05/GJ for natural gas and $1.50/gal for transportation petroleum) and efficiencies. It should be emphasized that no efficiency advantage was presumed for hydrogen vehicles (except for aircraft) in comparison to their petroleum-powered counterparts, and no upstream carbon emissions or methane leakage were accounted for in the reference scenario.

Cost differences between the scenarios with hydrogen transportation (target scenario) and without it (benchmark) are again influenced somewhat by fuel prices, but this sensitivity is lessened due to the common technology assumptions employed in both (*e. g.* low-cost, efficient electrolyzers, advanced wind electricity, etc.). Only under the unlikely conditions of simultaneously low oil prices and high interest (discount) rates, would the two cases compare substantially differently.

Interestingly, even though the renewable and hydrogen intensive target scenario has a greater proportion of high cost renewable electricity sources (*e. g.* solar) and greater energy storage requirements than the benchmark scenario, it still had lower overall (combined transportation and electricity) costs. This supports the synergy hypothesis for the target scenario: that hydrogen fuel demand by vehicles can be a net benefit for renewable electricity systems. This also indicates that integrated hydrogen transportation/utility systems may be more attractive than stationary hydrogen utility storage alone.

Conclusions

High efficiency and coupling vehicles to utilities are most important. Although further sensitivity analyses and other refinements, such as new, nearer-term scenarios should provide an even clearer picture, two conclusions can be drawn from the results so far:

High efficiency hydrogen production and coupling vehicles to utilities are most important.

1) **Super efficient hydrogen production, storage and use are necessary for hydrogen to compete in both utility and transportation markets, even if optimistic renewable electricity targets are met.** All of the efficiencies (liquefaction, electrolysis, etc.) used in the hydrogen scenarios were best case. For reasons of end-use efficiency, compressed hydrogen was used in the simulations wherever possible, as was only partially para converted liquid hydrogen.

2) **Unless long term fossil fuel prices are very low *and* hydrogen vehicles have no efficiency advantage over fossil vehicles, coupling hydrogen fuel production to carbonless sources can be a substantial benefit.** Carbon taxes would be reduced, and might even be eliminated depending upon relative hydrogen/fossil fuel prices and efficiencies.

Recommendations

Technology Development Needs

High efficiency electrolysis, in some cases distributed on a small scale, is crucial. Cost targets for electrolysis of ~\$500/kW and efficiencies of at least 90% are likely to be necessary. Hydrogen storage is secondary but still of significant importance. Light-duty vehicles and commercial trucks which could use compressed hydrogen as much as possible would be an important efficiency step. Bulk hydrogen storage cost targets (*e. g.* liquid hydrogen) for very large vessels, of ~\$10/kg H_2 stored are necessary, unless future demand and supply patterns can be better matched than in the scenarios used here. Compressed hydrogen storage costs projected by others (Thomas 1998) of \$100-150/kg H_2 were sufficient.

Systems Analysis Needs

This analysis has shown that significant environmental and economic advantages can exist for renewable electricity sources when coupled with hydrogen fuel production for vehicles.

The next step is a clearer understanding of these advantages, their requirements, and their limitations, under economic optimization conditions. A wide range of future analysis directions are possible. Hydrogen technology cost benchmarks can be determined as a function of fossil fuel prices and allowable carbon taxes. A determination of the importance of small amounts of dispatchable carbonless electricity sources in the generation mix can be made. Transition scenarios for hydrogen vehicles and renewable electricity sources can be examined. LLNL plans to further develop its equilibrium optimization code to be able to answer these and similar questions.

Some new technical options could also be very important to examine in the future. One promising candidate would be a close-coupled steam electrolyzer/fuel cell using natural gas to produce electricity at night, storing waste heat to improve electrolysis efficiency during the day, when solar electricity is available, and in turn storing oxygen to improve fuel cell efficiency during the night. This could dramatically enhance the attractiveness of hydrogen production from renewable electricity, while providing a very efficient synergy with both fuel cells and natural gas utilities.

High efficiency electrolysis, in some cases distributed on a small scale, is crucial. Hydrogen storage is secondary but still of significant importance.

The most important market options to analyze will likely be the impact of small changes in seasonal demand patterns upon energy storage requirements, as well as hydrogen fuel use in individual sectors of the transportation market.

Acknowledgments
I gratefully acknowledge the helpful suggestions of Joe Iannucci and Susan Horgan of Distributed Utilities Associates (DUA) as well as copious amounts of useful utility and renewable energy data. I would also like to thank Alan Lamont and Thomas Gilmartin of LLNL for assistance modifying LLNL's existing energy modeling capabilities for this effort.

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Gene Berry makes a point to Bob Krakowski and Vaclav Smil.

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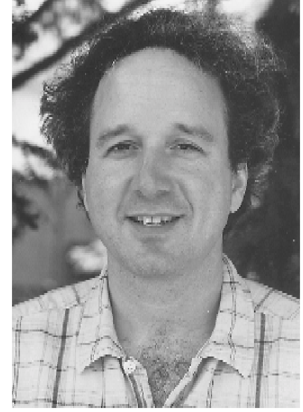

The Global Carbon Cycle: CO_2 as Greenhouse Gas in Earth History and the Human "Unseen Artifact"

Ken Caldeira
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The burning of fossil fuels, and the burning and decay of biomass associated with deforestation, has increased the carbon dioxide content of Earth's atmosphere by over a third since the onset of the industrial revolution.

The burning of fossil fuels, and the burning and decay of biomass associated with deforestation, has increased the carbon dioxide content of Earth's atmosphere by over a third since the onset of the industrial revolution. Even if we could accurately predict future carbon dioxide emissions, predicting future atmospheric carbon dioxide content would be challenging. Roughly half of the CO_2 emitted each year is absorbed by the oceans and the terrestrial biosphere, however that fraction will change (and probably diminish) in the future in ways that are not simple to predict.

Before discussing the impact of human carbon dioxide emissions on the global carbon cycle, it is useful to understand the natural operation of the global carbon cycle. On different time-scales, different processes dominate the behavior of the carbon cycle.

The long term

On time-scales of hundreds of thousands of years and greater, the amount of carbon in the atmosphere is dominated by the balance of CO_2 degassing from volcanic and geothermal environments, and CO_2 consumption in silicate-rock weathering and subsequent carbonate rock deposition (Figure 8).

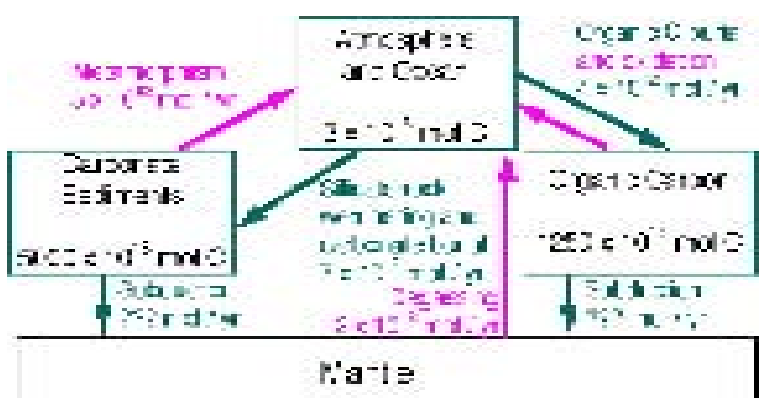

Figure 8
Schematic representation of the long-term carbon cycle.
On time scales of several hundred thousand years or more, atmospheric CO_2 content is controlled by interactions with the rocks, organic carbon sediments and the mantle.

In volcanic and geothermal environments, some primordial CO_2 may be released from Earth's mantle to Earth's surface. However, most of this CO_2 derives from metamorphism of carbonate and silicate minerals, brought to high temperatures and pressures. Schematically, the metamorphism of carbonate minerals may be represented

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2, \quad (1)$$

where the CO_2 released is contributed to the atmosphere.

This CO_2 is removed from the atmosphere through the processes of silicate-rock weathering and subsequent carbonate deposition. Silicate-rock weathering occurs primarily in groundwater in soils, and may be schematically represented

$$CaSiO_3 + 2\ CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2. \quad (2)$$

The dissolved calcium and bicarbonate ions flow down streams and rivers to the oceans, where corals, mollusks and plankton form carbonate shells, which can be represented

$$Ca^{2+} + 2HCO_3 \rightarrow CaCO_3 + CO_2 + H_2O. \quad (3)$$

Combining reactions (2) and (3), we have

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2. \quad (4)$$

In the oceans, the rate of carbonate deposition is limited by the availability of cations such as Ca^{2+} and Mg^{2+} that are provided by silicate-rock weathering on land, so the rate of reaction (2) controls the rate of the combined reaction (4).

If the rate of reaction (1) exceeds that of reaction (2), carbon dioxide accumulates in the atmosphere and ocean. If the rate of reaction (2) exceeds that of reaction (1), atmospheric and oceanic carbon content diminishes.

It is thought that, on global scales, the rate of silicate-rock weathering (reaction (2)) is controlled primarily by climatic factors such as precipitation and temperature. In a warmer, wetter world, silicate-rock weathering proceeds more rapidly. If volcanic CO_2 degassing were to increase for some reason, CO_2 would begin to accumulate in the atmosphere and oceans. Due to the CO_2 greenhouse effect, the Earth would begin to warm and the hydrological cycle would become more active, increasing the rate of silicate-rock weathering. CO_2 would accumulate in the atmosphere until a state was achieved such that the increase in silicate-rock weathering balanced the increase in volcanic degassing. The time scale for this equilibration is thought to be several hundred thousand years.

It is thought that, on global scales, the rate of silicate-rock weathering is controlled primarily by climatic factors such as precipitation and temperature.
In a warmer, wetter world, silicate-rock weathering proceeds more rapidly.

It is this process that will ultimately remove fossil-fuel CO_2 from our oceans and atmosphere, and this removal process will take hundreds of thousands of years.

The middle term

On time scales of a few thousand years, atmospheric CO_2 content may be influenced by carbonate dissolution reactions. If a volcano (or human activity) were to introduce CO_2 into the atmosphere and oceans, groundwaters and ocean water would become more acidic, dissolving some carbonate sediments, in reactions that may be schematically represented

$$CaCO_3 + 2\ CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-, \quad (5)$$

where the calcium and bicarbonate ions remain in solution in the oceans, removing CO_2 from the atmosphere.

The short term

On time scales shorter than several thousand years, variations in atmospheric CO_2 content are dominated by interaction with the terrestrial biosphere and oceans (Figure 9). Fossil fuel reserves contain on the order of 10,000 GtC, the terrestrial biosphere contains about 2,000 GtC, and the oceans contain about 40,000 GtC. Bi-directional fluxes between the atmosphere and ocean, and between the atmosphere and biosphere, are on the order of 100 GtC/yr. However, the net flux into these reservoirs is on the order of 2 GtC/yr (Figure 10).

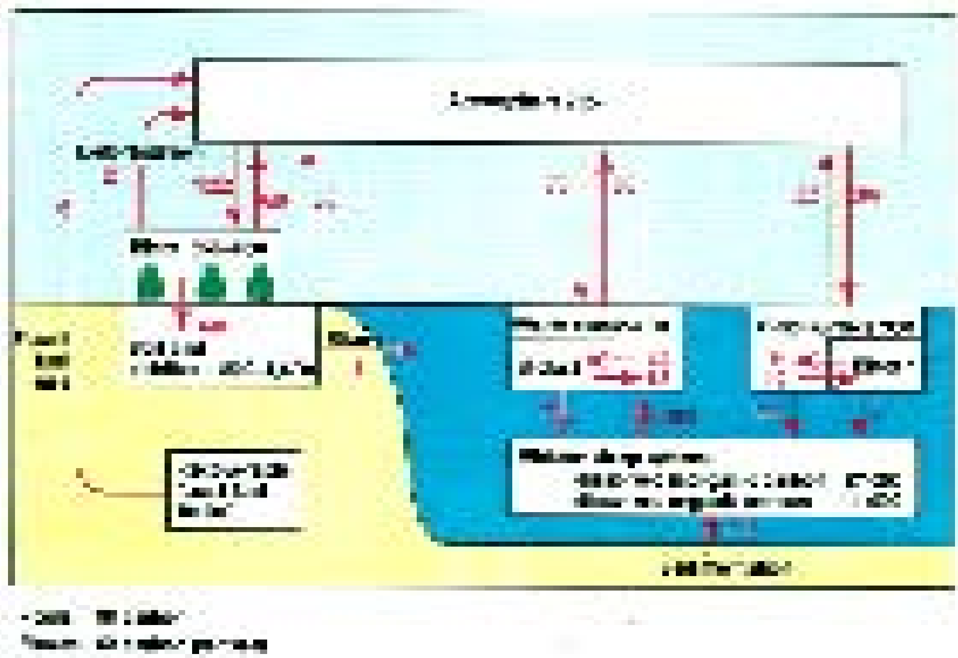

Figure 9

Schematic representation of the short-term carbon cycle. On time scales of seasons to thousands of years, atmospheric CO_2 content is controlled by interactions with the terrestrial biosphere, the oceans, and fossil fuel burning.

SESSION 1

As the ocean warms and absorbs atmospheric CO_2, it become less efficient at absorbing additional CO_2; hence the fraction of fossil-fuel carbon emissions absorbed by the ocean is likely to diminish over the coming century.

Increasing atmospheric CO_2 content may fertilize plant growth and allow plants to use water more efficiently. Nevertheless, it is uncertain whether the terrestrial biosphere will continue to be a sink for fossil-fuel carbon. For example, increasing temperatures will increase plant respiration and accelerate decomposition of organic matter. Hence, the decade-to-century scale outlook for CO_2 absorption by the terrestrial biosphere is unclear.

This indicates that the oceans will likely be the major natural sink for fossil-fuel carbon over the coming century; however, as the ocean warms and absorbs atmospheric CO_2, it become less efficient at absorbing additional CO_2; hence the fraction of fossil-fuel carbon emissions absorbed by the ocean is likely to diminish over the coming century.

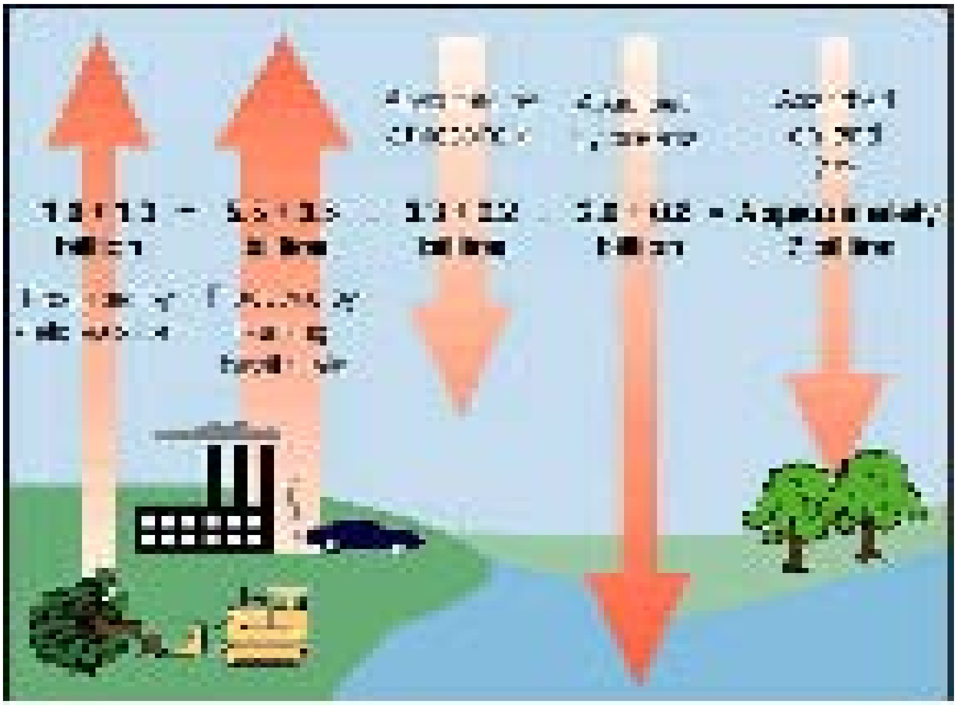

Figure 10
Schematic representation of the global carbon cycle ca. 1990.
Approximately 5.5 GtC were introduced into the atmosphere via fossil fuel burning and 1.6 GtC via deforestation and other land-use changes. Of this CO_2, approximately 3.3 GtC accumulated in the atmosphere, 2 GtC was absorbed by the oceans, and 2 GtC was absorbed by the terrestrial biosphere (principally regrowth of Northern Hemisphere forests).

Putting it all together

Figure 11 (next page) shows predicted atmospheric CO_2 content versus time for a business-as-usual carbon-dioxide emissions scenario. At its peak, atmospheric CO_2 reaches a maximum of over 5 times the pre-industrial value. Estimates of the global mean warming to this forcing range from 3.5 to 10.5°C, based on a climate-sensitivity to a CO_2-doubling of 1.5 to 4.5°C and a logarithmic climate response to increasing atmospheric CO_2 content. This degree of warming might be greater if the melt-back of ice-covered regions were considered. On a time scale of 300 years, atmospheric CO_2 approaches 2.5 times the pre-industrial value as CO_2 dissolves into the oceans. On a time-scale of about 6000 years, atmospheric CO_2 approaches 1.5 times the pre-industrial value (a 2 to 6°C global warming) as the dissolution of carbonate minerals neutralize carbonic acid. The remaining 50% increase in atmospheric CO_2 (relative to pre-industrial values — producing a 0.9 to 2.7°C global warming) will be removed from the atmosphere on a time scale of hundreds of thousands of years by silicate rock weathering. Hence, absent special measures, the unrestrained burning of fossil-fuels could dramatically alter climate over the next millennium and would have a significant climatic impact for hundreds of thousands of years to come.

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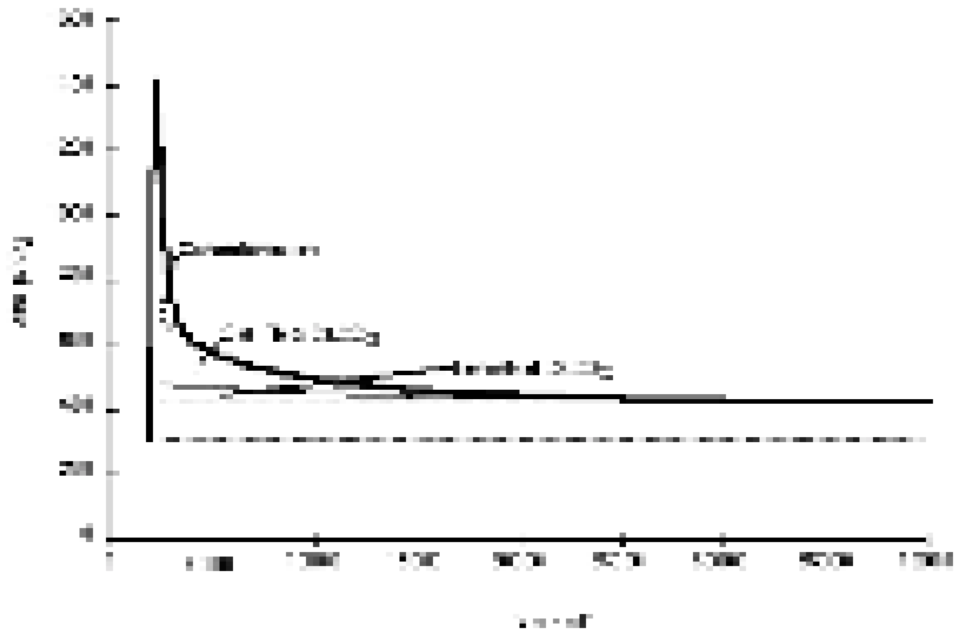
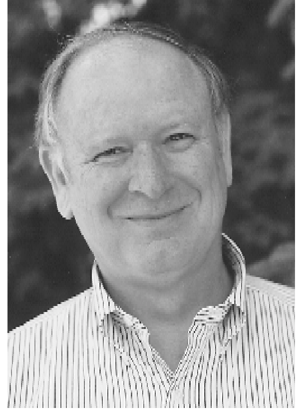


Figure 11
Plot of atmospheric CO_2 content versus time for a Business-as-Usual CO_2 emissions scenario.
Atmospheric CO_2 reaches a maximum of over 5 times the preindustriatial value. On the time scale of 300 years, atmospheric CO_2 approaches 2.5 times the pre-industrial value as CO_2 dissolves into the oceans. On a time-scale of about 6000 years, atmospheric CO_2 approaches 1.5 times the pre-industrial value as the dissolution of carbonate minerals neutralize carbonic acid. The remaining 50% increase in atmospheric CO_2 (relative to pre-industrial values) will be removed from the atmosphere on a time scale of hundreds of thousands of years by silicate rock weathering. (Figure from Archer, Kheshgi and Maier-Reimer, *Geophysical Research Letters*, 1998.)

A Lunar Solar Power System and Global Energy Needs



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Most humans will remain very poor without adequate, clean, low-cost commercial energy. Approximately 6 kWt/person or, eventually, 2 kWe/person can enable energy prosperity ("t" refers to thermal energy and "e" to electric energy). For a population of 10 billion people, anticipated by 2050, this implies a need for 60,000 GWt or 20,000 GWe globally (about 6 times more than now available). For purposes of discussion, assume that power usage continues to be 20,000 GWe to 2070. From 2000 to 2070 the world would consume approximately 3,000,000 GWt-Y or 1,000,000 GWe-Y of energy [1-4]. It is highly unlikely that conventional fossil, nuclear (thermal neutron), and terrestrial renewable power systems can provide the power needed by 2050 and the total energy consumed by 2070. They are restricted by limited supplies of fuels, pollution and wastes, irregular supplies of renewable energy, costs of creating and operating the global systems, and other factors.

It appears technically and economically feasible to provide at least 100,000 GWe of solar electric energy from facilities on the Moon. The Lunar Solar Power (LSP) System can supply power to Earth that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere. Inexhaustible new net electrical energy provided by the LSP System enables the creation of new net material wealth on Earth that is decoupled from the biosphere. Given adequate clean electric power, humanity's material needs can be acquired from common resources and recycled without the use of depletable fuels [4, 5]. LSP energy increases the ability of future generations to meet tomorrow's needs, and enables humanity to move beyond simply attempting to sustain itself within the biosphere to nurturing the biosphere. Figure 12 shows a future scenario with increasing available energy and declining use of fossil fuels.

The Lunar Solar Power System can supply power to Earth that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere.

The essential features of the LSP System are the Sun, Moon, microwave power beam from a power base on the Moon, and a microwave receiver or rectenna on Earth (see Figure 13). The LSP System uses bases on opposing limbs of the Moon as seen from Earth. Each base transmits multiple microwave power beams directly to Earth rectennas when the rectennas can view the Moon. Each base is augmented by fields of photoconverters just across the limb of the Moon. Thus, one of the two bases in the pair can beam power toward Earth over the entire cycle of the lunar day and night. The simplest version of LSP supplies extra energy to a rectenna on Earth while the rectenna can view the Moon. The extra energy is stored and then released when the Moon is not in view. More complex systems, especially those with relay satellites in orbit about Earth, can provide load-following power.

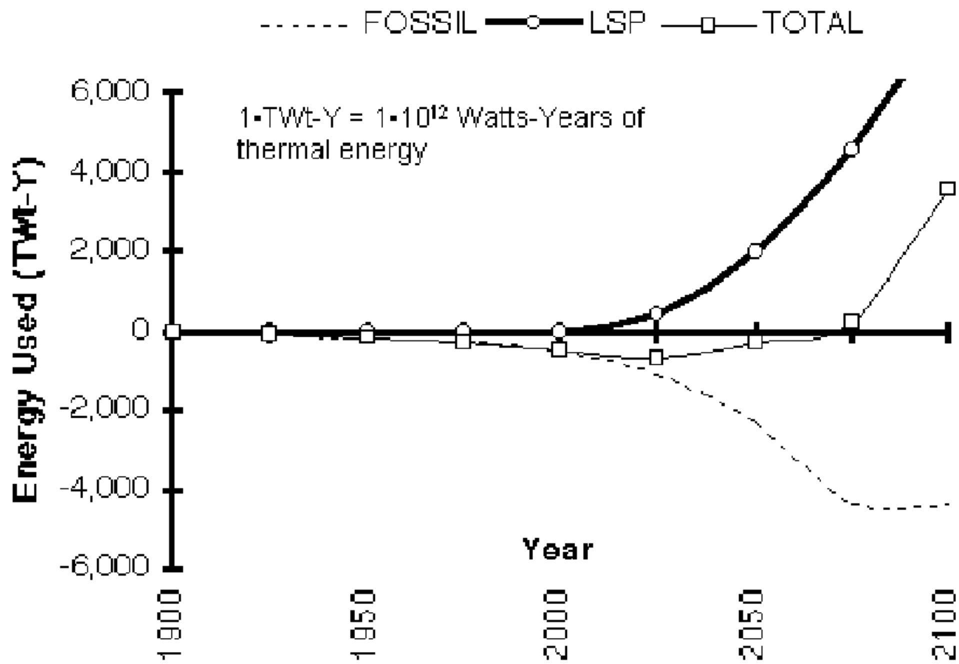

Figure 12
Net New Energy: 1900-2100

Conventional terrestrial power system problems

- Non-renewable: finite and uncertain supplies, polluting, rising costs
- Renewable: undependable, too small, polluting, distort bisphere
- May not produce net new wealth

Lunar Solar Power System provides to earth abundant (gretaer than 100 TWe), clean, dependable "net new energy" that enables "net new wealth."

The key operational technologies of the LSP have been demonstrated at a high technology readiness level.

The LSP System is an unconventional approach to supplying commercial power to Earth. However, the key operational technologies of the LSP have been demonstrated at a high technology readiness level (TRL ≥ 7). TRL = 7 denotes technology demonstrated at an appropriate scale in the appropriate environment [6].

To achieve low unit cost of energy, the lunar portions of the LSP System are made primarily of lunar-derived components [2, 3, 7]. Factories, fixed and mobile, are transported from the Earth to the Moon. High output greatly reduces the impact of high transportation costs from the Earth to the Moon. On the Moon the factories produce hundreds to thousands of times their own mass in LSP components. In the mature LSP System the construction and operation of the rectennas on Earth constitute greater than 90% of the engineering costs. Upfront costs can be reduced by using lunar materials to make significant fractions of the machines of production and support facilities. Most aspects of manufacturing and operations on the Moon can be controlled by personnel in virtual work places on Earth [7, 8].

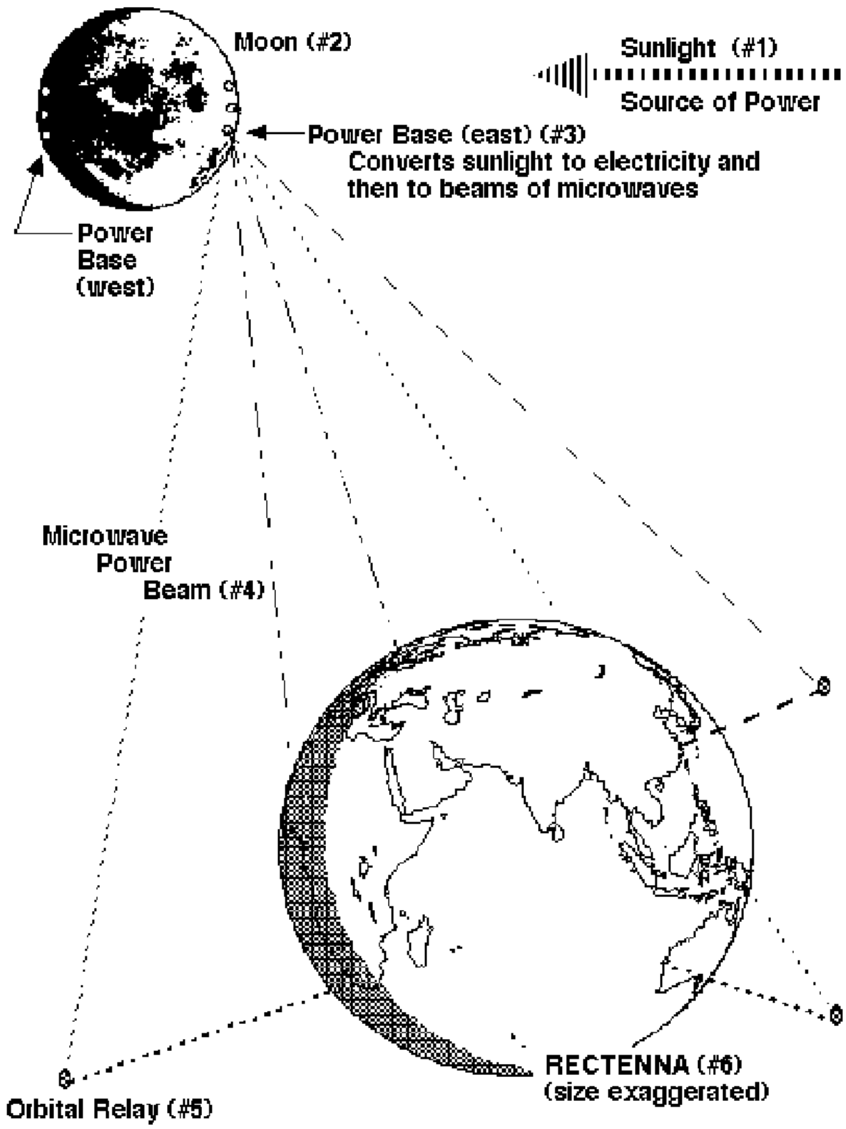

Figure 13
Lunar Solar Power (LSP) System Overview

An LSP System demonstration, scaled to deliver the order of 10 to 100 GWe, can cost as little as $20 billion over 10 years if added on to a human base on the Moon [2, 7, 9]. This assumes the establishment of a permanent base on the Moon, by one or more national governments, that is devoted to the industrial utilization of lunar resources for manufacturing and logistics. Such a base can draw on the hardware and operational capabilities that the space programs of the U. S., Europe, Russia, Japan, and others are developing through the International Space Station program. LSP development can also draw on and expand the many burgeoning commercial launch and satellite communications enterprises.

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LSP is projected to be practical with 1980s technology and a low overall efficiency of conversion of sunlight to Earth power of ~15%. Higher system efficiencies, ≥ 35%, are possible by 2020, and greater production efficiencies sharply reduce the scale of production processes and up-front costs. An LSP System with 35% overall efficiency will occupy only 0.15% of the lunar surface and supply 20,000 GWe to Earth. At large scales, energy costs are projected to be ≤ 1 cent per kWe-h, in principle low enough to provide ample power for all of humanity.

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SESSION 1

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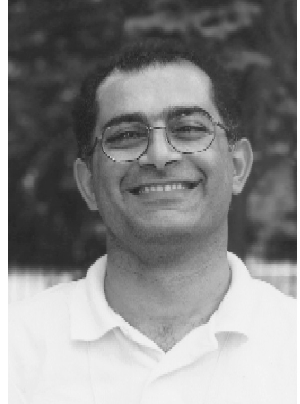

Challenges in Climate Policy Assessment: Coherence, Regime Change and Path Dependence

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Climate change assessment involves the study of public policy choices over time horizons spanning many decades to centuries. These assessments require the development of *scenarios* of how the future may unfold, and how policy may impact these evolutionary paths. While it is impossible to develop reliable visions of our distant future, we can state with confidence that marginal changes in current trends in greenhouse gas emissions (and their drivers) are not likely to provide relief from potentially disastrous anthropogenic changes to the Earth system. If anthropogenic climate change is judged to be a significant risk, we will need a regime change in the provision of energy for the earth's growing population and needs.

Long-term analyses involve projections of the needs of humanity and how we may go about providing them. Such models can include the dynamics of demographics, economics and technical change. The climate policy challenge is to do so without precipitating dangerous perturbations to the Earth's climate system. In such analyses, we often find:

- that the population of the globe has undergone a regime change, slowing its growth and leveling around 10 billion souls;
- that the formal economies of nations continue to grow at annual rates of between 2% and 5%;
- that economically recoverable oil and gas have been exhausted by 2050, driving up the price of energy, dampening overall energy demand, and CO_2 emissions; and,
- that technological change will improve the efficiency of energy use by about 1% per annum.

It is important to recognize that, more often than not, these are not the result of sophisticated computations in formal and informal models, but are in fact the exogenous "assumptions" of the analysts. I am comfortable with the issue of subjective judgements being part of assessments. In fact I encourage their explicit statement and exploration. What I am concerned about is attempts to conceal subjectivity as objectivity and inadequate consideration of empirical evidence contrary to popular subjective visions of the future. We can take each of these in turn and discuss why they may not occur. Furthermore, we can discuss why the conditions suitable for occurrence of one may have significant implications for another.

What I am concerned about is attempts to conceal subjectivity as objectivity and inadequate consideration of empirical evidence contrary to popular subjective visions of the future.

Let us consider the issue of *coherence* in projections of demographics and economic growth. Using time-series and cross-national socio-economic and demographic data, we can develop a model of demographic dynamics with such drivers as: household consumption, participation of women in the formal economy, access to medical services, and fraction of the population living in urban centers. This model, informed by history, rather than conjecture, still requires exogenous inputs such as assumed future trends in all the driving variables. We can use historic trends to inform these, but why should they remain as before? Even if these "trend extrapolations" are used to inform a model of the demographic transition, we do not observe an assured stabilization of the Earth's population at 10 billion (see Figure 14). In the case of the model used to generate these projections the probability of the Earth's population stabilizing at 12 billion is about 50%.

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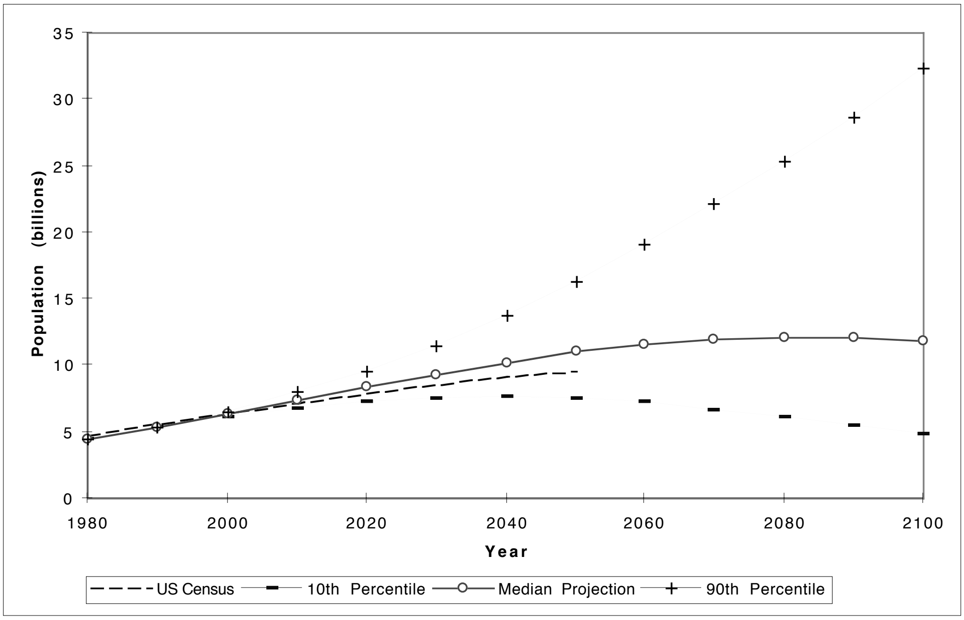

Figure 14
The probabilistic demographic model can be driven using ICAM to generate probabilistic population projections to 2100. These projections are made for each of the 12 regions in ICAM separately. The sum of these projections, the world population, is compared here to the estimates published by the US Bureau of Census for world population to 2050.

In order to develop the demographic model projections we have to supply information about the economic conditions surrounding typical households in each region. This information is itself strongly influenced by demographic issues. For example, the participation of women in the formal economy boosts the measured size of the economy (by about twice the income of the women). Furthermore, demographic transition to zero population growth requires that we experience a change in fertility rates and/or mortality rates. Few adults would consider shorter life expectancy as a desirable alternative, and thus focus on reduced fertil-

ity. This choice drives up the average age of society dramatically — see Figure 15. With over 15% of the society being over 65 years old, how might the economy evolve? What will happen to health care expenses? What will happen to savings and consumption patterns? What will it mean for lifelong education? In the absence of such social changes, what will happen to the technical agility of the society? Thus, it can be shown that the desired zero population growth projection is in conflict with business-as-usual economic growth! Coherent treatment of these issues is possible and represents the holy grail of *integrated assessments*.

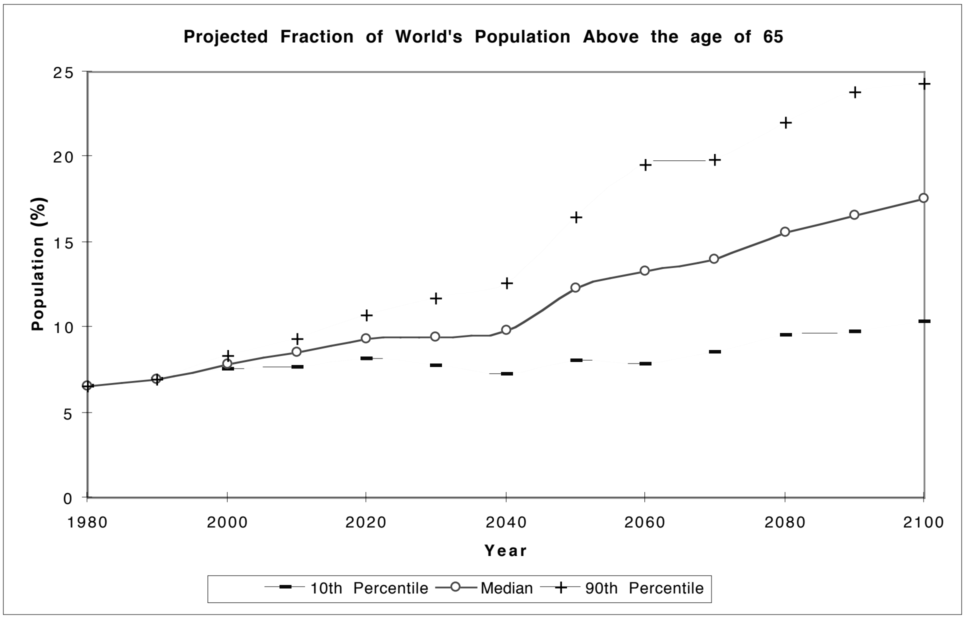

Figure 15
A demographic model permits projection of the age structure of the population. In ICAM we have a generally benign assumption that in most cases incomes rise, a higher fraction of the population live in urban settings, more women enter the formal economy, and there will be better access to physicians. The trends for these driver variables lead to lower probable fertility, and higher probable life expectancy. Thus, the fraction of the global population over the age of 65 is projected to increase dramatically.

Next let us consider the issue of *regime change*. Purposive regime change is the objective of most significant policy analyses. Interestingly, when economic models are used to explore these, the modeling framework itself is developed around marginal change from an "optimal status quo." Why are we exploring the regime change if what is going on is optimal? More often than not, the reason is that we have suddenly recognized that the present pattern of activity has some undesirable side effects. Outcomes that elude detection for so long are rarely reflected in the measure of "economic performance" used in the model. Otherwise, we would have optimized to keep these at a minimum also. Therefore, by construction, changes from status quo to meet the constraints posed by a new "concern" are always costly

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in terms of traditional measures of efficiency of performance. Furthermore, if we are interested in a changing regime, how can we evaluate the impact of policy using a framework based on marginal change?

In almost all energy-economics models technological optimism is reflected in a parameter known as the Autonomous Energy Efficiency Index (AEEI). This parameter stipulates the assumed rate of improvement in the efficiency with which energy is used to generate services and outputs valued by the society. Often AEEI is assumed to be about 1% per annum, or some linear function of economic growth rate. Intellectually, this assumption is a reflection of the notion of contributions of technological change to economic growth evinced by Robert Solow. However, the AEEI concept has two major drawbacks:

1) When a fixed AEEI is assumed, we fail to back-cast the U. S. patterns of economic growth and energy use, from 1955 to 1995 (Dowlatabadi and Oravetz, in press) — a period spanning the "energy crises" precipitating a regime change in the energy-economy of the world.
2) When a fixed AEEI is assumed, climate policy does not influence the rate and direction of technical change vis-à-vis energy or carbon efficiency!

SESSION 1

By adopting a marginal change framework we are over-estimating the cost of climate policy. The cost of mitigation when economies of learning are simulated is one half those calculated ignoring such possibilities.

Oravetz (Ph.D. Thesis) has employed historic data from Korea, Japan, Mexico, and the U. S. to develop a reduced form model of technical change, which can be incorporated into the current generation of energy economics models. We call this alternative to AEEI, Price Induced Efficiency (PIE for short). In this model, energy price shocks, and economic shocks influence capital depreciation rates, the efficiency of new technologies, and the price elasticity of energy demand. The incorporation of this model of regime changes in the role of energy in the economy leads to startlingly different paths for global energy efficiency in the future, the impact of CO_2 control policies, and the overall cost of CO_2 emissions control (see columns M1 and M3 in Table 5). In this table, the structural uncertainty in four aspects of energy modeling have been explored. The two shaded columns permit direct comparison of considering AEEI or PIE on emissions of CO_2, the cost of abatement towards a 550 ppm CO_2 concentration, and the impact of delaying the implementation of policy by 25 years. AEEI and PIE lead to a two-fold difference in the cost of mitigation. By adopting a marginal change framework we are over-estimating the cost of climate policy.

The modeling results presented in Table 5 can also be used to explore the implication of *path dependence*. A familiar example of path dependence is that by experience we can do things better, otherwise known as economies of learning. These economies have been observed in many human activities. Nonetheless, economies of learning are rarely represented in economic optimization models. The positive feedback entailed in learning by experience make such model formulations very unstable. Thus, this aspect of economic activity is often ignored! Again, using the ICAM simulation environment I have explored the implications of changing this structural assumption. The implications of contrasting world views in which economies of learning are absent (MI) and present (M4) are displayed in Table 5. In these simulations, there is negligible difference in unconstrained energy use and CO_2 emissions. However, the cost of mitigation when economies of learning are simulated is one half those calculated ignoring such possibilities.

Table 5
Energy Use, Emissions, Cost of Mitigation, and Impacts of Delay in Abatement Towards a 550 ppm Target [1,2]

		Model Variants								
Model Components		M1	M2	M3	M4	M5	M6	M7	M8	M9
Are new fossil oil & gas deposits discovered?		no	yes	no	no	yes	yes	no	yes	yes
Is energy using technical progress affected by fuel prices & carbon taxes?		no	no	yes	no	yes	yes	yes	yes	yes
Does the cost of abatement and non-fossil technologies fall with experience?		no	no	no	yes	no	no	yes	yes	yes
Is there a policy to transfer carbon saving technologies to non Annex 1 countries?		no	no	no	no	no	yes	yes	no	yes
TPE BAU in 2100 (EJ)	Mean	1975	2475	2250	2000	3425	2700	1450	3550	2850
TPE control in 2100 (EJ)	Mean	650	650	500	750	500	500	675	750	725
CO_2 BAU 2100 (10^9TC)	Mean	40	50	50	40	75	55	25	73	55
	Std. Deviation	*28*	*18*	*36*	*29*	*29*	*23*	*22*	*27*	*21*
Mitig. Cost (%Welfare)	Mean	0.23	0.44	0.14	0.12	0.48	0.33	0.05	0.23	0.17
	Std. Deviation	*0.45*	*0.23*	*0.23*	*0.22*	*0.28*	*0.12*	*0.07*	*0.12*	*0.11*
Impact of delay (%Welfare)	Mean	-0.1	0.2	-0.6	0.0	-1	-0.5	-0.1	-0.6	-0.4
	Std. Deviation	*1*	*0.3*	*1*	*0.7*	*1.2*	*0.9*	*0.5*	*0.8*	*0.6*

Notes

1) The assumption here is that all nations assume an equal burden of abatement, by having a global carbon tax
2) The mitigation costs and impacts of delay are discounted according to the convention proposed by Schelling (1994)

Sample size: 400

Table reproduced from:

Dowlatabadi, H. (1998). "Sensitivity of Climate Change Mitigation Estimates to Assumptions About Technical Change." *Energy Economics* **20**:473-93.

The entries in Table 5 can also be used to emphasize the importance of coherence in assumptions employed in modeling. For example, if we are willing to embrace human ingenuity in technological progress towards more efficient use of energy, why not consider the same ingenuity employed in bringing fossil fuels to market at lower cost? The pressure of higher energy prices will harness human ingenuity in both domains. The exciting visions of super efficient resource utilization brought forth by Amory Lovins and super abundant re-

If we are willing to embrace human ingenuity in technological progress towards more efficient use of energy, why not consider the same ingenuity employed in bringing fossil fuels to market at lower cost?

sources evinced by Julian Simon simply reflect the potential for ingenuity in the demand and supply sectors respectively. Reality lies in the path of evolution traced out by the teetering balance between innovations and inertia in supply and demand — a balance that rarely looks optimal in the harsh light of hindsight (Arthur 1987).

Other significant path dependencies revolve around the impact of delayed climate policy on the political economics of changing the energy infrastructure (Grubb, *et al.* 1995; Grubb 1997); the deregulation of energy systems (Keith and Parson, 1998); and the power of dual control policies (Dowlatabadi 1996).

- Grubb *et al.* (1995) argued that delay would lead to economies further entrenched in bad consumer habits fostered by fossil fuel combustion. These habits, such as patterns of housing and social organization, can be long lasting and difficult to reverse in a short time-span.
- Keith and Parson (1998) have argued that if energy deregulation leads to wide-spread and distributed generation of electricity using micro-generators consuming natural gas, the future potential for CO_2 management from power generation will be jeopardized.
- Elsewhere, I have argued that our knowledge about the dynamics of the socio-economic system is very uncertain. Policies can be designed to yield information about the dynamics of the socio-economic system. Thus, they will serve the dual purposes of abating some CO_2 emissions and helping us reduce uncertainties in our understanding of the system we hope to manage.

SESSION 1

While integrated assessments of climate change offer great promise, the current cluster of findings on the economics of temporal and spatial flexibility need to be viewed with caution.

In summary, I have shown various examples of standard practice in climate policy assessment where we have failed to consider factors such as: coherence of assumptions, the dynamics and drivers of regime change and path-dependency of outcomes. A great deal more is also troubling and catalogued elsewhere (Morgan and Dowlatabadi 1996; Schneider 1997; Morgan, *et al.* in press). It appears to me that while integrated assessments of climate change offer great promise, the current cluster of findings on the economics of temporal and spatial flexibility need to be viewed with caution. Prognostic modeling to 2020 and beyond is almost assuredly wrong! Diagnostic explorations of the dynamics of socio-economic systems however, hold the potential of informing the debate with a better understanding of the implications of coherent assumptions, consideration of the dynamics of regime change, and implications of path dependency.

Acknowledgements

The preparation of this manuscript was made possible through support from the National Science Foundation SBR-9711498 and SBR-9521914. All remaining errors are a reflection of the author's fallibility.

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Diagnostic explorations of the dynamics of socio-economic systems hold the potential of informing the debate with a better understanding of the implications of coherent assumptions, consideration of the dynamics of regime change, and implications of path dependency.

Hadi Dowlatabadi and Vaclav Smil in interdisciplinary debate.

Solar Power Satellite Systems

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Editor's Note
Peter Glaser has been considered an important figure in the field of space solar power since he first introduced the concept in 1968. He addressed the Aspen Global Change Institute meeting via conference call and engaged the participants in a discussion of the merits of solar power from space. The following is the rapporteur's record of his comments.

In 1968, I first publicly pronounced the SPS idea. In the three decades since then, there has been international strategic interest in solar power satellite (SPS) systems because they are one of the very few non-depletable, ecologically-compatible energy systems available for global application. Given the objective of meeting global energy demands with minimum ecological effects while being consistent with sustainable global economic development, SPS systems compare favorably with globally available energy sources. Currently operating energy conversion systems may not be able to supply future energy demands and most technical, economic and societal challenges.

From the viewpoint of climate change mitigation, SPS has a clear advantage over other electricity generation options. According to calculations by Prof. Yoshioko of Japan, in 1998, carbon emissions from coal-generated electricity were 1,225 mg/kWh; for oil, 846 mg/kWh; for natural gas, 631; for nuclear power, 22; and for SPS, 20. From that point of view alone, the SPS option deserves major attention.

Why is SPS needed?

1) resources limitations of fossil fuels
2) attempts to stabilize greenhouse gas (GHG) emissions to prevent interference with the climate system
3) ensure that all inputs and outputs of energy systems are useable for peaceful purposes only
4) excluding the possibility of catastrophic long-term health effects of energy systems
5) limits to terrestrial renewable systems ability to supply base load power demands

I have long been a strong advocate of terrestrial renewable energy and I believe that we must exploit terrestrial renewables to the greatest extent possible; but by themselves, they cannot do the job completely. We must pair these with SPS in order to fully utilize the sun's power for the benefit of humankind.

I believe that we must exploit terrestrial renewables to the greatest extent possible; but by themselves, they cannot do the job completely. We must pair these with SPS in order to fully utilize the sun's power.

We currently have a unique opportunity to develop SPS options over the next 20-30 years using well-known technologies. SPS is more a challenge to technologists than to physicists because the physics of SPS has already been demonstrated. Wireless power transmission to

receivers was discovered by Hertz in the last century, microwave transmission technology was proposed by Tesla, and Bequerel demonstrated photovoltaic conversion. The 800 million microwave ovens demonstrate the safety and effective uses of microwaves.

Three key demonstrations of SPS technology have been performed in the past 20 years by NASA, the Canadian Department of Communication, and universities and industries in China, Europe, Japan, India, Russia and Ukraine. Japanese, Russian and European investigators have been working on SPS for 25 years. The extensive literature on their efforts is available through NASA, and aerospace companies in the U. S. and other countries. In the past few years, there have been three technical conferences on SPS, as well as several sessions organized by professional societies.

NASA and the U. S. Department of Energy (DOE) conducted a study from 1975-80 on the SPS "reference system" and concluded that no single constraint would preclude the development of the SPS option for technical, economic, environmental, or societal reasons. This SPS reference system was not intended as a proposal for the SPS to be built but rather as a an investigation of technical, economic and environmental feasibility. In FY 1999, NASA received $15 million from the U. S. Congress to continue the development of the SPS option.

In order to reduce the challenges and spread out the costs associated with development of a macro-engineering project such as SPS, I proposed a "terracing" approach — reaching the ultimate goal by building from one technical achievement to the next. This approach can help us resolve technical uncertainties on schedule, maintain private and public investor confidence, and reduce potential environmental impacts in all stages of development on Earth and in space. I believe the development of SPS will include some manufacturing in space and some new rocket design and manufacture. It is important to identify obstacles that could affect schedules and costs.

We have the capability to fully develop, plan, control, and manage large complex space projects and to achieve higher performance and lower cost space systems. One example of this is our experience with electromagnetic levitation to accelerate payloads up to 10,000 gs. Most materials used for SPS will be similar to those used in other space programs. Robotics for assembly of large stations will also be necessary as we explore SPS and other space projects.

We are demonstrating that we can apply wireless transmission for use on Earth, including high-altitude, long-endurance aircraft, and power relay satellites. These projects are essential steps to achieving reliable and effective SPS operations.

We have to select the most appropriate technologies that comply with applicable standards and laws to protect people and the environment. SPS is just like other macro-engineering projects. SPS has to be designed and operated within the existing international legal and regulatory framework that exists for current applications of technologies in space.

Another issue to be resolved is the microwave frequency assignments problem. We need to choose the best frequencies available to minimize losses in the atmosphere; these are within

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the industrial, scientific and medical (ISM) band. Communication satellites are beginning to encroach on this ISM band, using frequencies that SPS would need in order to operate most cost effectively.

We will have to prove that the SPS can only be operated for peaceful purposes. One way to accomplish this is to have the system be an international one and show that no device such as a high power laser is hidden in the SPS that could threaten any country. I believe it is possible to do this and abide by relevant treaties to assure only peaceful uses of SPS. In addition, UN law requires that space activities be carried out for the benefit of all member states. SPS can meet this requirement and be used for the peaceful development of all nations.

There are currently various countries working on SPS-related technology. An international entity is still in the future. India, China, Japan, Russia, Ukraine, Europe, a number of South American nations, and the U. S. are working on SPS systems. Government-level, academic and industrial planning efforts are needed for an SPS-development program because electric utilities' planning horizons are not long enough to include SPS (though they should). The Electric Power Research Institute (EPRI), the utilities' trade organization, is favorably disposed towards the SPS concept.

The challenge today is to develop extraterrestrial resources over the next 10 to 30 years. It is important to remember that when the Wright brothers flew their airplane at Kitty Hawk it was not a 747.

Societal acceptance will be of crucial importance for SPS. Publicly-accessible information is needed during the planning, development and construction stages. The potential significance of SPS must be demonstrated to the public. Globally, SPS is one of the few promising steps leading to the hydrogen economy on Earth. One science experiment that has been in place since 1969 consists of a laser located in Hawaii with a receiver on the moon. With SPS in orbit or on the moon, powerful lasers can also be used to deflect comets and asteroids that might potentially impact Earth, providing an additional benefit of the SPS.

Conclusion

The challenge today is to develop extraterrestrial resources over the next 10 to 30 years. It is important to remember that when the Wright brothers flew their airplane at Kitty Hawk it was not a 747. Technology development is a gradual process but we must take the initial steps now. In 1974, a 30 kW microwave beam was converted directly to DC electricity at 80% efficiency, proving that this can be done without harming the birds and other animals in the area. Now is the time to select the most desirable energy options, including terrestrial renewable energy sources and SPS, before future commitments are made to other approaches that are unsustainable. This will ensure that the benefits of solar power will continue to sustain life on Earth and be available to all.

Questions and Answers

Q What are the latest developments in SPS?

A One of the most interesting developments is the level of interest in SPS by the Russians, Ukrainians and Japanese. The Japanese have been in touch with 40 equatorial countries to see if they are interested in receiving power from low-Earth orbit. China and

India have also expressed interest in SPS and have done a number of studies. This is to be expected as countries with very large populations will benefit most from SPS.

Q SPS is a technology that is very hard to start on a small scale; is there a way to break SPS technological development into manageable packages?

A Yes. Step 1 is to transfer power from one place to another on Earth as was accomplished in a California demonstration. Step two is to supply an aircraft with power from the ground; Canada has flown such an aircraft and the Japanese have flown a dirigible with power beamed from the ground. There are other tests and steps that will follow in a similar manner. I am a supporter of the International Space Station because many of the things we will need for SPS we can learn from Space Station development. Some examples include robotic assembly and providing space structures for a variety of activities. Many space station experiments involve crucial tests about technologies which will work best for SPS.

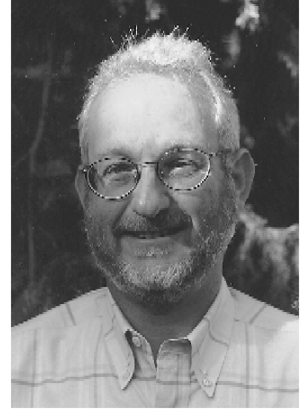
Q What about cost? Isn't SPS too expensive? Given that we have a range of energy options, where does SPS fit in?

A Back when the Wright brothers flew at Kitty Hawk, people would have thought that it would always be far too expensive to use airplanes to deliver mail! We must do the hard initial work, and we must take the right steps and try not go down blind alleys. This is how macro-engineering on large projects is done successfully. The difficulties we foresee now can be overcome in rational ways. SPS has not only passed the test of making sense from an economic, environmental and societal point of view, but it is one of the few major global options worth pursuing. We will be able to bring costs down with advancing technology. We should first do the straight-forward things with near-term time horizons which can be projected with confidence in terms of technical, economic, environmental and societal issues. Don't look at the current SPS studies as a final technical solution. Look instead at the broader issues. Keep proceeding through the required development steps. The technology is not the real issue; we have the capability to develop it, whether in low-Earth and geosynchronous orbits or lunar surface-based. No new revelations are needed; all components of the SPS system have been studied.

Q Nuclear fusion has received support on the order of a billion dollars a year for 20 years and still has no proof of concept. Is there a demonstration for SPS that could come out of NASA in the next ten years for less money?

A We should be able to very shortly produce a demonstration of SPS (10 to 100 MW) in low Earth orbit for a small fraction of the investment in fusion. The Japanese are on their way to doing this now. You have to ask the right questions to get the right answer. The NASA reference system was not designed to be built but rather just to have a credible reference for analyses. Now that most aspects of SPS have been studied, SPS is a challenge to engineers to design and build a workable system to supply energy to Earth.

When the Wright brothers flew at Kitty Hawk, people would have thought that it would always be far too expensive to use airplanes to deliver mail. We must do the hard initial work, and we must take the right steps and try not go down blind alleys. This is how macro-engineering on large projects is done successfully.



Carbon Dioxide Capture and Sequestration

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SESSION 1

In viewing the spectrum of responses to global climate change, there are a number of relatively low cost CO_2 mitigation technologies, sometimes termed "least regrets." They include improving energy supply and end-use efficiency, switching from coal or oil to natural gas where possible, forestation, and inexpensive renewable energy applications. The major drawback of this group of technologies is their limited impact. They may be sufficient to meet short-term goals, but there is a general belief that they will not be able to solve the problem in the mid- and long-term.

In light of the limited reduction potential of these options, additional, but more costly mitigation technologies must be considered, specifically CO_2 capture and sequestration, nuclear power, and large-scale renewable energy production. All three of these mitigation technologies have the potential to substantially reduce CO_2 emissions at comparable costs, yet all three suffer impediments (*e. g.*, nuclear power must solve issues of safety and public acceptance and renewable energy costs must decrease).

Since at least one of these options (if not all three) will be required to stabilize atmospheric levels of greenhouse gases in the mid- to long-term, it is prudent to examine all three. Compared with nuclear and renewable energy, the U. S. research effort to-date with respect to technologies for CO_2 capture and sequestration has been minimal. Thus, we should extend our efforts to understand CO_2 capture and sequestration technologies in order to better evaluate their potential and to reduce their associated costs and risks.

The main challenge regarding CO_2 capture technology is to reduce the overall cost by lowering both the energy and the capital cost requirements. While costs and energy requirements for today's capture processes are high, the opportunities for significant reductions exist, since researchers have only recently started to address these needs. One strategy that looks extremely promising is to combine CO_2 removal with advanced coal energy conversion processes that have features which will enable low energy intensity capture.

The main challenge regarding CO_2 capture technology is to reduce the overall cost by lowering both the energy and the capital cost requirements.

The major options for CO_2 storage are underground or in the ocean. Statoil is presently storing one million tonnes per year of CO_2 from Norwegian gas fields in an aquifer beneath the North Sea. A larger aquifer storage project may soon be undertaken by Exxon and Pertamina at their Natuna gas field in the South China Sea. Besides aquifers, geologic storage options include active oil wells (in connection with enhanced oil recovery), coal beds, and depleted oil and gas wells. The issues which need clarification include storage integrity and reservoir characterization. Ocean CO_2 disposal would reduce peak atmo-

spheric CO_2 concentrations and their rate of increase by accelerating the ongoing, but slow, natural processes by which most current CO_2 emissions enter the ocean indirectly. The capacity of the ocean to accept CO_2 is almost unlimited, but there are questions that still need to be addressed about effectiveness (*i. e.*, how long will the CO_2 remain sequestered) and about the environmental impacts associated with increased sea water acidity near the injection point.

While there are diverse niche opportunities for industrial utilization of power plant CO_2, these uses are all small compared to the total quantities of CO_2 emitted by the power sector. Multiple small uses can be an effective, but small, part of a mitigation strategy. Large scale chemical conversion of power plant CO_2 to fuels such as methanol requires so much energy that it produces marginal mitigation benefit, if any. Microalgae offer the potential for conversion of power plant CO_2 to biomass, but research is needed to achieve improvements in productivity that would reduce land requirements and costs. Storage as carbonate minerals is another possibility, but materials handling and waste issues make practicality uncertain without further investigation. In the nearer term, limited biomass energy farming, coupled with co-firing of farmed or waste biomass with fossil fuels is an attractive option. In the much longer-term, research on bioproduction of hydrogen or on artificial photosynthesis may provide new and significant pathways for mitigation.

The limited funding to date for CO_2 capture and sequestration has not allowed significant program development, making it difficult to fairly assess the potential of these technologies compared to other mitigation options for which substantial sums of money have been spent (*e. g.*, switching to nuclear or renewable energy sources). To date, the cumulative research dollars spent on CO_2 capture and sequestration technologies in the U. S. has been less than $10 million, limiting the research effort to small theoretical or laboratory studies. To allow needed program development, we recommend a budget that averages $50 million per year for 5 years.

To put this budget request in perspective, we can make the following comparisons:

- The total U. S. energy expenditures are approximately $500 billion annually, while the existing capital stock of the utility industry worldwide is estimated in excess of $2 trillion. It seems wise to investigate whether CO_2 capture and sequestration technologies can allow fossil fuels to remain a cost-effective energy source, while concurrently contributing to a significant reduction in greenhouse gas emissions.
- The proposed budget is modest in comparison to Japanese government expenditures on CO_2 capture and sequestration (by at least a factor of 2).
- The U. S. now spends about $1.6 billion annually investigating various aspects of the climate change problem. Spending at that level indicates that global climate change is being taken seriously. It seems prudent to spend 3 percent of that level to investigate the flexibility of one of the few possible longer-term mitigation solutions.

The limited funding to date for CO_2 capture and sequestration has not allowed significant program development, making it difficult to fairly assess the potential of these technologies compared to other mitigation options for which substantial sums of money have been spent.

Solar Power Satellites: Advanced Technology for CO_2 Stabilization

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SESSION 1

Why do it in space? The sun always shines brightly in space, with no clouds and no nighttime.

The ultimate in utility deregulation, and a technology that could have a major impact in mitigating global warming, could be "Orbital Light and Power" — utilities capable of delivering solar electricity from space, on demand, at competitive prices, anywhere on the planet; particularly to those 40% of Earth's inhabitants "off the grid." Why do it in space? The sun always shines brightly in space, with no clouds and no nighttime. By placing arrays of solar cells on satellites in geostationary orbit (in which the rotational period is equal to that of the Earth so that it appears stationary from Earth) the cells would be exposed continuously to the solar constant, making its productivity a factor of 8 to 10 better than if they were on Earth's surface.

For efficient power beaming, diffraction of electromagnetic (EM) waves requires that the product of transmitter and receiver apertures be at least as large as the product of wavelength and transmission distance, independent of power level. But wavelengths cannot be too short, or rain fade will significantly reduce efficiency as well. Thus microwave power transmission through the atmosphere from distant orbits requires large components, as in the NASA/DOE Solar Power Satellite (SPS) Reference Design of the 1970s in geostationary orbit (GEO, 36,000 km above the equator) shown in Figure 16 (Glaser, 1996; Glaser et al., 1998).

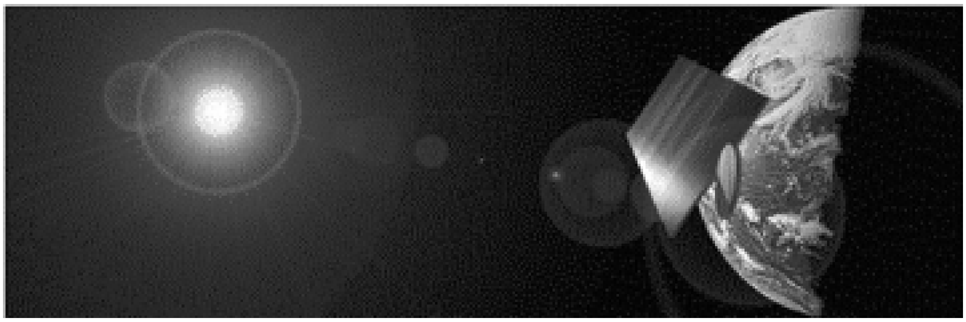

Figure 16
NASA/DOE SPS Reference Design in geostationary orbit

The advantages of GEO are that satellites appear fixed in space relative to receivers on Earth and that solar arrays are almost constantly exposed to sunlight. A disadvantage of GEO is that transmission of power beams over relatively large distances requires large

components and high first cost. For that reason, the SPS Reference design based on the original Peter Glaser proposal, with its 5 km x 10 km solar arrays producing 9 GWe at Earth's surface, has been called by some a "Battlestar Galactica" approach, and several alternate designs are being explored. Peter Glaser (who addressed our AGCI Workshop via conference call) has called for a "terraced" approach, in which the elements needed for cost-effective space power are developed on a pay-as-you-go basis.

To be competitive with fossil fuels, the cost objective for solar electricity is in the range of \$1,000 to \$3,000 per kWe for in-space components. (Electricity in space is considerably more expensive than on Earth, which is why some consider space-to-space the preferred early market for space power.) Assuming that developments in lightweight structures and fabrication techniques can bring satellite power densities to ~ 1 kWe/kg, and that half the system cost is lifting the satellite to orbit from the Earth's surface, implies break-even at payload launch costs of (1/2) x (1,000-3,000)\$/kWe x 1 kWe/kg, ~ 500-1500 \$/kg. This is more than an order of magnitude cheaper then present-day Space Shuttle launch costs to LEO. These launch costs are however within striking distance of those targeted for the next generation single-stage-to-orbit (SSTO) space vehicles, like as the Lockheed Martin Skunk Works Venture Star depicted in Figure 17. Placing such a system in space is just rocket science, which isn't "rocket science."

To be competitive with fossil fuels, the cost objective for solar electricity is in the range of \$1,000 to \$3,000 per kWe for in-space components. Placing such a system in space is just rocket science, which isn't "rocket science."

SESSION 1

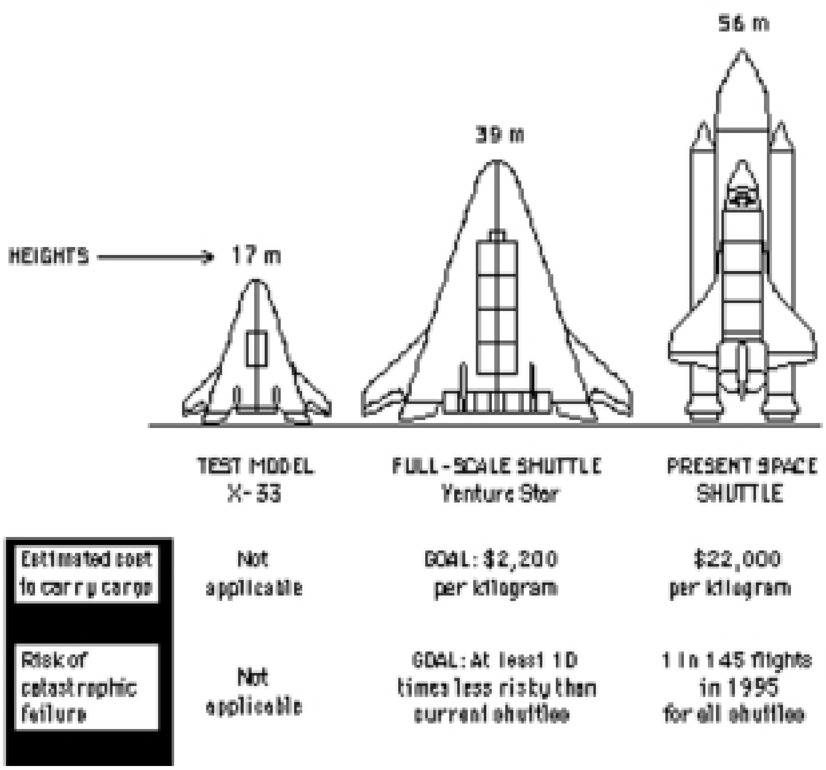

Figure 17
Comparative Cost, Risk, Size, and Mass of Rocket Options for SPSs

Concerns have been raised about the possible health and safety effects of microwaves, but their intensities in such a system, even at the center of the beam, are not problematic. Epidemiological studies have failed to demonstrate that these microwave intensities, comparable to those of microwave ovens and cellular phones, have an adverse effect on human health.

A concept that Seth Potter and I have been pursuing (Hoffert and Potter, 1997, see Figure 18) is that Solar Power Satellites (SPSs) could be integrated with the infrastructure of current communications satellites to enhance the system's cost-effectiveness. Communications satellites already focus beams onto Earth; carrier waves are modulated to carry information, but could similarly carry microwave energy. In the near future, there will be hundreds to thousands of communication satellites hundreds to thousands of kilometers above Earth's surface in low to mid Earth orbit for cell phones, data and video (Evans, 1998). The commercial enterprise of supplying high speed data links to all points on planet will drive down launch vehicle costs rapidly.

Solar Power Satellites could be integrated with the infrastructure of current communications satellites to enhance the system's cost-effectiveness.

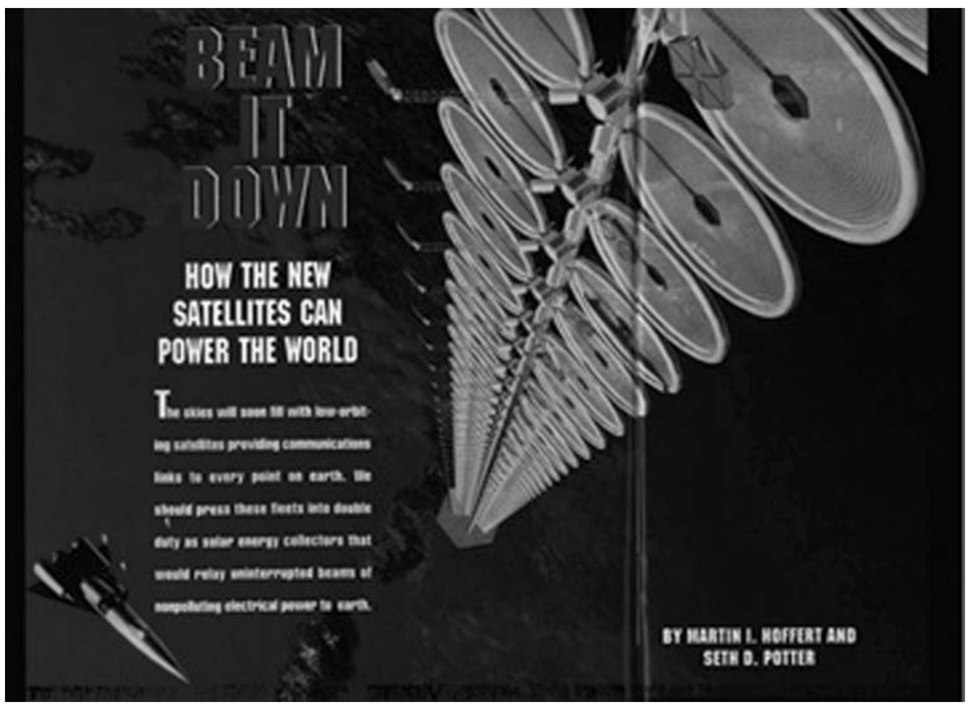

Figure 18
Cover story by Hoffert and Potter (1997) in MIT's Technology Review

We argue that the drive to increase bandwidth will inexorably lead to large antennas of order 100 meters diameter. Once we get to that point, we will have the ability to bring power beams, steered by phased array transmission, to Earth's surface. This integration of communication and power beaming functions is the easiest way to power the 40% of the world that is now off the grid.

This represents a global village concept for communication and a new industry to globalize the electricity market. An evolutionary path begins with satellite technology and could end with a lunar-based system as described by David Criswell elsewhere in this report. One major problem remains how to meter, bill, and collect the revenues. Unlike communications, we cannot encrypt electricity. But some combination of power and communication has potential; telecommunications companies and computer companies will probably develop this technology which will involve uplinks and downlinks and a system of connections between satellites.

Other interesting issues to be considered involve questions of centralized versus decentralized power production and thus possible uses as a method of social control. Who would own such a system and have the right to control it? Who controls the infrastructure of any energy system, and how can we best build an evolutionary system?

The Politics of Global Warming and SPS

It is worth mentioning that outside the scientific community actively working on it, global climate change from fossil fuel burning is viewed as a highly controversial and unsettled issue, particularly in the U. S. The UN Framework Convention on Climate Change (FCCC), agreed to in principle by the U. S. administration, not to mention virtually all other UN member nations, does have major economic and political implications. Among these is the unprecedented opportunity for the emergence of new global energy industries such as the nascent "Orbital Light and Power" discussed here.

This is not, however, the "spin" one normally sees when the issue is discussed on Capitol Hill and in the media. Because of its implications for carbon taxes and emission controls, "global warming" is depicted by some in the fossil fuel energy industry as undermining *all* economic growth and job production.

One result of this view is that it is extremely unlikely that the Kyoto Protocol of the UN FCCC will be ratified by the U. S. Senate. Since Al Gore's early advocacy of the theory of global climate change, and the proposal in his book, *Earth in the Balance*, that the global environment become a post-Cold-War organizing principle for international relations, climate change from human-produced greenhouse gases is seen as much as a "liberal" versus "conservative" political issue as a scientific theory involving atmospheric absorption bands and radiative balances.

Among other things, what space power and other high technology energy options bring to the table is an opportunity to see the problem from a more bipartisan perspective. Consider this: On October 24, 1997 Congressman Dana Rohrbacker (R, California) — well-known for his opposition to the IPCC's 1995 finding that the balance of evidence suggests a discernible human influence on global climate — conducted hearings on the efficacy of Space Solar Power, a technology he supports strongly (Rohrbacker and Weldon, 1998). In the course of these hearings, during which, incidentally the Hoffert and Potter communications/powersat idea was favorably discussed — Rohrbacker observes in an almost offhand way that the interests of those wanting to mitigate global warming and his own promotion of space power are in common cause:

What space power and other high technology energy options bring to the table is an opportunity to see the climate change problem from a more bipartisan perspective.

> And this is interesting in the sense that those of us who believe that global warming is liberal clap trap, and those of us believe — who are seriously concerned about global warming — actually are together in this particular instance.

If congressional opponents of "climate change theory" as virulent as Rohrbacker can see the problem this way, there may be more opportunities to address the issue though advanced technology than we know. The issues will be the relative roles of governments in R & D and regulation.

Changes in Status Quo are Often Resisted

This would not be the first time in the history of technology that government has been lobbied by an existing industry to protect it from an emergent one. As the technology of railroads began to gather steam (literally) the existing transportation systems protested. For example, Martin Van Buren, Governor of New York, wrote to President Jackson in 1829:

This would not be the first time in the history of technology that government has been lobbied by an existing industry to protect it from an emergent one.

The canal system of this country is being threatened by the spread of a new form of transportation known as "railroads." The federal government must preserve the canals for the following reasons:

> One — If canal boats are supplanted by "railroads," serious unemployment will result. Captains, cooks, drivers, hostlers, repairmen, and lock tenders will be left without means of livelihood, not to mention the numerous farmers now employed in growing hay for horses.
> Two — Boat builders would suffer and towline, whip and harness makers would be left destitute.
> Three — Canal boats are absolutely necessary to the defense of the United States. In the event of the expected trouble with England, the Erie Canal would be the only means by which we could ever move the supplies so vital to waging modern war.
>
> As you may well know, Mr. President, "railroad" carriages are pulled at the enormous speed of fifteen miles per hour by "engines" which, in addition to endangering life and limb of passengers, roar and snort their way through the countryside, scaring the livestock, and frightening our women and children. The Almighty certainly never intended that people should travel at such breakneck speed."

As it happened, the railroads won that particular battle in the ninetieth century, only to be superseded by trucks and commercial aircraft in the twentieth century.

SPS Versus Terrestrial Photovoltaics (PVs) for the Developing World

The key failure of the existing Earth-based renewables, often referred to as "appropriate technology," is that storage is expensive and solar and wind are intermittent. How can we fit technologies with how people live? SPS systems can provide power 24 hours a day. The following points contrast SPS with terrestrial PVs for the developing world:

1) SPS can generate higher long term average areal power densities, ~ 250 We/m^2 versus ~20 We/m^2 for terrestrial PVs. Hence, SPS competes less for land with human agriculture and biodiversity.
2) Unlike opaque PV cells, surface rectennae are visually transparent, permitting crop growth and even grazing beneath collectors. Costs of rectennae are less than PV cells; hence

developing nations can more easily afford capital investment and part ownership of the system.

3) SPS microwave beams can be focused where needed; geostationary systems are always available, obviating need for storage. Likewise, low-Earth orbit SPS constellations can provide continuous power using beam-hopping, and satellite-to-satellite links, similar to communication satellites.
4) Integrated powerbeam/communication satellite constellations could be developed using a common infrastructure of launch vehicles, antennae, satellites, and financing. Modulating the power/pilot microwave beam creates downlink/uplink for high bandwidth data, voice, and video communication channels. Advantages are potential rapid deployment of carbon-free electric power to developing nations where it is most needed.

The Way Forward

Some new technology, such as "inflatables" technology for spacecraft could be key for development of SPS. NASA could build the test for this system as they have for communications. NASA's "Fresh Look" study of solar power satellites (Mankins, 1997) includes an examination of gallium arsenide solar collectors, Fresnel lenses to concentrate the beam, and low-Earth and medium-Earth orbits other than geostationary. A NASA/DOE task force should be set up to develop a research plan for this system in a 6-month period to assess various proposals. Then, the logic of the marketplace should foster international cooperation on this technology.

Technological Advance Under Pressure

Rapid changes in technology often take place under intense pressure. In World War II, we had biplanes when we entered the war and jets and rockets by its end eight years later. This rapid change took place in a period of great urgency, not through the normal functioning of the marketplace. Similarly, the Manhattan project greatly accelerated technological development. Nuclear power, rocketry and radar, the three key inventions of WWII, were all accomplished under extreme pressure.

Global warming presents us with a similar opportunity. All of our key technologies were brought into being through investments by governments. The time horizons are too long for private industry to make the whole investment themselves. However, the politicized nature of the global warming issue presents a problem. As mentioned above, some in Congress see this as a way to transfer money from U. S. taxpayers to the developing world. The challenge is to overcome this partisanship and formulate a new policy which emphasizes innovative energy technology that lets people do well by doing good. There is at least a glimmer of light at the end of that tunnel.

Rapid changes in technology often take place under intense pressure. Global warming presents us with a similar opportunity. All of our key technologies were brought into being through investments by governments.

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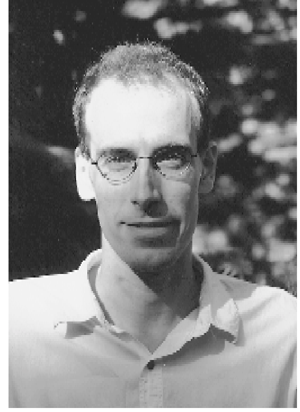
The challenge is to overcome this partisanship and formulate a new policy which emphasizes innovative energy technology that lets people do well by doing good.

Marty Hoffert makes a point to John Lewis and Gregory Benford.



Geoengineering Climate

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Geoengineering is the intentional large-scale manipulation of the global environment. The term has usually been applied to proposals to manipulate the climate with the primary intention of reducing undesired climatic change caused by human influences. These geoengineering schemes seek to mitigate the effect of fossil-fuel combustion on the climate without abating fossil fuel use; for example, by placing shields in space to reduce the sunlight incident on the Earth.

Possible responses to the problem of anthropogenic climate change fall into three broad categories: abatement of human impacts by reducing the climate forcings, adaptation to reduce the impact of altered climate on human systems, and deliberate intervention in the climate system to counter the human impact on climate — geoengineering.

It is central to the common meaning of geoengineering that the environmental manipulation be deliberate, and be a primary goal rather than a side-effect. This distinction is at the heart of the substantial moral and legal concerns about geoengineering. For example, while it may be argued that modern agriculture constitutes geoengineering, the global-scale transformations of the nitrogen cycle it causes is a side-effect of food production, and is usually viewed differently from the deliberate modification of the global environment.

It is central to the common meaning of geoengineering that the environmental manipulation be deliberate, and be a primary goal rather than a side-effect. This distinction is at the heart of the substantial moral and legal concerns about geoengineering.

Examples of Geoengineering Proposals

A variety of geoengineering schemes are summarized in Table 6. A taxonomy of geoengineering is presented in Figure 19. Technical discussion of geoengineering is omitted here. Summary articles are described in the annotated bibliography below.

Evaluating Geoengineering

Most discussion of geoengineering has focused on assessments of technical feasibility and approximate cost. However, it is probable that issues of risk, politics, and ethics will prove more decisive factors in real choices about implementation. This is true both because of the strong negative reactions often provoked by most geoengineering proposals, and because many geoengineering schemes are inexpensive relative to abatement or adaptation.

Economics and Risk Analysis

The simplest economic metric for geoengineering is to compute the “cost of mitigation” — the ratio of cost to the amount of mitigation effected (typically measured in dollars per ton of carbon emission mitigated). This measure permits comparison between geoengineering schemes and between geoengineering and the abatement of emissions. Table 6 includes the cost of mitigation for various schemes. The costs are highly uncertain. For albedo modification schemes additional uncertainty is introduced by the somewhat arbitrary conversion from albedo change to equivalent reduction in CO_2.

SESSION 1

Most discussion of geoengineering has focused on assessments of technical feasibility and approximate cost, but issues of risk, politics, and ethics will likely prove more decisive factors in real choices about implementation.

Geoengineering Scheme	COM*	Technical Uncertainties	Risk of Side Effects	Non-Technical Issues
Injection of CO_2 into the ocean.	30-80	Costs are much better known than for other geoengineering schemes. Moderate uncertainty about fate of CO_2 in ocean.	Low risk. Possibility of damage to local benthic community.	Like abatement this scheme is local with costs associated with each source. Potential legal and political concerns over oceanic disposal.
Injection of CO_2 underground.	30-80	Cost are know as for CO_2 in ocean; less uncertainty about geologic than oceanic storage.	Very low risk.	Is geologic disposal of CO_2 geoengineering or a method of emissions abatement?
Ocean fertilization with phosphate	1-3	Uncertain biology: can ecosystem change its P:N utilization ratio?	Moderate risk. Possible oxygen depletion may cause methane release. Changed mix of ocean biota.	Legal concerns: Law of the Sea, Antarctic Treaty. Liability concerns arising from effect on fisheries; N.B. fisheries might be improved.
Ocean fertilization with iron	0.3-3	Uncertain biology: when is iron really limiting?	As above.	As above.
Intensive forestry to capture carbon in harvested trees.	3-100	Uncertainty about rate of carbon accumulation, particularly under changing climatic conditions.	Low risk. Intensive cultivation will impact soils and biodiversity.	Political questions: how to divide costs? Whose land is used?
Solar shields to generate an increase in the Earth's albedo.	10-100	Costs are large and highly uncertain. Uncertainty dominated by launch costs.	Very low risk. However, albedo increase does not exactly counter the effect of increased CO_2.	Security, equity and liability if system used for weather control.
Stratospheric SO_2 to increase albedo by direct optical scattering.	$<< 1$	Uncertain lifetime of stratospheric aerosols.	High risk. Effect on ozone depletion uncertain. Albedo increase is not equivalent to CO_2 mitigation.	Liability: ozone destruction.
Tropospheric SO_2 to increase albedo by direct and indirect effects.	< 1	Substantial uncertainties regarding, aerosol transport and their effect on cloud optical properties.	Moderate risk: unintentional mitigation of the effect of CO_2 already in progress.	Liability and sovereignty because the distribution of tropospheric aerosols strongly effects regional climate.

Table 6
Summary comparison of geoengineering options.
(*) Cost of Mitigation (COM) is in dollars per ton of CO_2 emissions mitigated. While based on current literature, the estimates of risk and cost are the author's alone.

Examination of the cost of mitigation reveals that it varies by more than two orders of magnitude between various schemes, and that for some (*e. g.*, stratospheric aerosols) the costs are very low compared to either abatement or adaptation. However, such direct cost comparisons have little meaning given the very large differences in the non-monetary aspects of these responses to climate change; *e. g.*, risk of side effects, certainty of effect, and social distribution of cost.

Geoengineering as a Fallback Strategy

Geoengineering may serve as a fallback strategy by putting an upper bound on the costs of mitigation should climate change be more severe than we expect. In this context a fallback strategy must either be more certain of effect, faster to implement, or provide unlimited mitigation at fixed marginal cost. Various geoengineering schemes meet each of these criteria. The notion of geoengineering as a fallback option provides a central, or perhaps the only justification for taking large-scale geoengineering seriously. A fallback strategy permits more confidence in adopting a moderate response to the climate problem: without fallback options a moderate response is risky given the possibility of a strong climatic response to moderate levels of fossil-fuel combustion.

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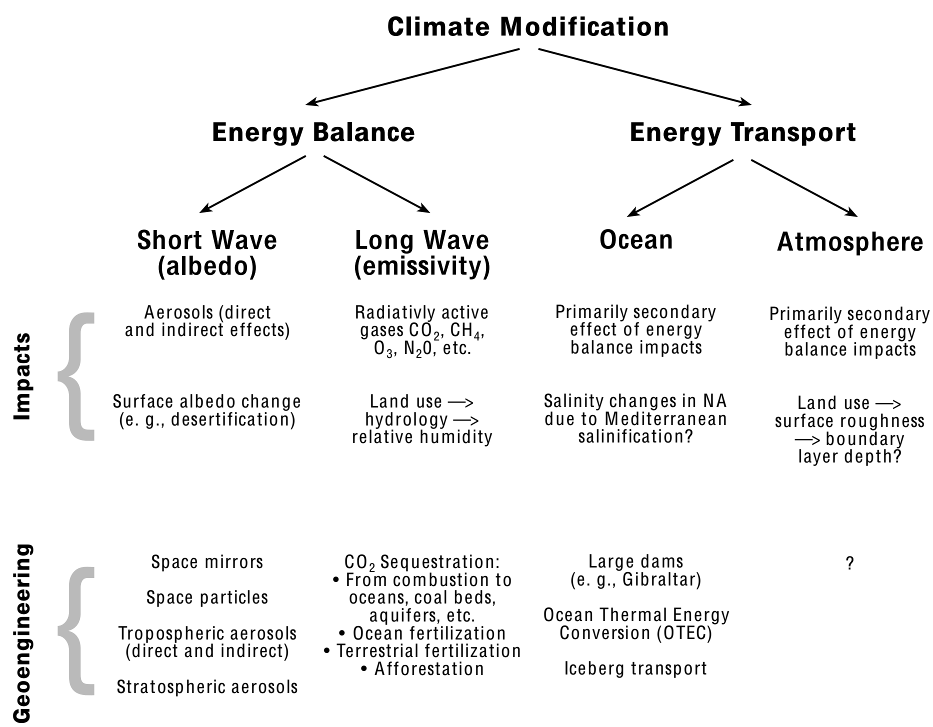

Figure 19
Taxonomy of Geoengineering and Climate Impacts
David Keith, 1998

Risk Assessment

Questions about the advisability of geoengineering revolve around risk: risk of failure and risk of side effects. Climate prediction is too uncertain to allow quantitative assessment of risk. However, if a geoengineering scheme works by imitating a natural process, we can make a qualitative risk assessment by comparing the magnitude of the engineered effect with the magnitude and variability of the natural process, and then assume that similar perturbations entail similar results. For example, the amount of sulfate released into the stratosphere as part of a geoengineering scheme and the amount released by a large volcanic eruption are similar. We may estimate the magnitude of stratospheric ozone loss by analogy. Even crude qualitative estimates of risk can give insight into the relative merits of various geoengineering schemes when considered in conjunction with other variables. Table 7 illustrates this with a comparison of risk and cost.

Table 7
Comparing risks and costs of various options

Risk	Cost		
	Low	**Medium**	**High**
Low	—	Intensive forestry for carbon sequestration	Solar shields CO_2 sequestration
Medium	Tropospheric SO_2 Ocean fertilization with iron	Inert stratospheric aerosols Ocean fertilization phosphate	Balloons in the stratosphere
High	Stratospheric SO_2	—	—

Political Considerations

The cardinal political reality of geoengineering is that unlike other responses to climate change (*e. g.*, abatement or adaptation), geoengineering could be implemented by one or a few countries acting alone. Various political concerns arise from this fact with respect to security, sovereignty, and liability; they are briefly summarized below.

Some geoengineering schemes raise direct security concerns; solar shields, for example, might be used as offensive weapons. A more subtle but perhaps more important security concern arises from the growing links between environmental change and security. Whether or not they were actually responsible, the operators of a geoengineering project could be blamed for harmful climatic events that could plausibly be attributed — by an aggrieved party — to the geoengineering. Given the current political disputes arising from issues such as the depletion of fisheries and aquifers, it seems plausible that a unilateral geoengineering project could lead to significant political tension.

In general, international law has little bearing on geoengineering. However, Bodansky (1996) points out that several specific proposals may be covered by existing laws; for example, the fertilization of Antarctic waters would fall under the Antarctic Treaty System, and the use of space-based shields would fall under the Outer Space Treaty of 1967.

Discussion of geoengineering commonly elicits strong negative reactions. Within the policy analysis community there has been vigorous debate about whether discussion of geoengineering should be included in public reports that outline possible responses to climate change.

As in the current negotiations under the Framework Convention on Climate Change, geoengineering would raise questions of equity. In this case, geoengineering might simplify the politics. As Tom Schelling (1996) points out, geoengineering "... totally transforms the greenhouse issue from an exceedingly complicated regulatory regime to a simple — not necessarily easy, but simple — problem in international cost sharing." One must note that not all geoengineering schemes are amenable to centralized implementation. For example, carbon management requires diffuse implementation at the manifold sources of fossil fuel combustion.

Ethics

Discussion of geoengineering commonly elicits strong negative reactions. Within the policy analysis community, for example, there has been vigorous debate about whether discussion of geoengineering should be included in public reports that outline possible responses to climate change. Fears have been voiced that its inclusion in such reports could influence policymakers to take it too seriously, and perhaps to defer action on abatement given knowledge of geoengineering as an alternative (see Schneider, 1996 for discussion of the debate over geoengineering in the 1992 National Academy of Sciences panel). While these concerns are undoubtedly serious and substantive, it is difficult to disentangle their various roots and, in particular, to separate pragmatic from ethical concerns.

Rather than attacking the problems caused by fossil fuel combustion at their source, geoengineering aims to add new technology to counter their side-effects.

Many of the objections to geoengineering that are cited as "ethical" have an essentially pragmatic basis. Three common ones are:

- **The Slippery Slope Argument:** If we choose geoengineering solutions to counter anthropogenic climate change, we open the door to future efforts to systematically alter the global environment to suit humans. This is a pragmatic argument, because in the future we will be as free as we are now to choose to what extent we wish to geoengineer. An ethical argument must define why such large-scale environmental manipulation is bad, and how it differs from what humanity is already doing.
- **The Kluge Argument:** Geoengineering is a technical fix, kluge, or end-of-pipe solution. Rather than attacking the problems caused by fossil fuel combustion at their source, geoengineering aims to add new technology to counter their side-effects. Such solutions are commonly viewed as inherently undesirable, but not for ethical reasons.
- **The Unpredictability Argument:** Geoengineering entails messing with a complex, poorly understood system; since we cannot reliably predict results, it's unethical to geoengineer. Because we are already perturbing the climate system with consequences that are unpredictable, this argument depends on the notion that intentional manipulation is inherently worse than manipulation that occurs as a side-effect.

One may analyze geoengineering using common ethical norms; for example, one could consider the effects of geoengineering on intergenerational equity, or on the rights of minorities (*e. g.*, the inhabitants of low-lying countries). However, these modes of analysis say nothing unique about geoengineering, and could be applied in a similar manner to many other technological choices. Some people would argue that such analysis fails to address a particular ethical abhorrence they feel about geoengineering and that we should look for an ethical analysis that addresses geoengineering in particular; *e. g.*, an environmental ethic.

The simplest formulations of environmental ethics proceed by extension of common ethical principles that apply between humans. A result is "animal rights" in one of its variants; *e. g.*, Regan (*The Case for Animal Rights*, University of California Press, Berkeley, 1983). Such formulations locate "rights" or "moral value" in individuals. When applied to a large-scale decision such as geoengineering, an ethical analysis based on individuals reduces to a problem of weighing conflicting rights or utility. As with analyses that are based on more traditional ethical norms, such analysis has no specific bearing on geoengineering. Alternative, and more controversial formulations of environmental ethics locate moral value in systems of individuals, such as a species or a biotic community (see for example Callicott, *In defense of the Land Ethic*, State University of New York Press, Albany, 1989). It is plausible that such a formulation of environmental ethics could more directly address the ethics of geoengineering.

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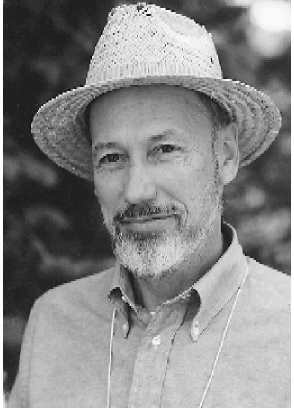
Schneider, S. H., Editor, *Climatic Change* **33**:291-302 (1996). This special issue contains many excellent papers about geoengineering.

Because we are already perturbing the climate system, the "unpredictability" argument depends on the notion that intentional manipulation is inherently worse than manipulation that occurs as a side-effect.

David Keith describes a geoengineering option.



Prospects for Ultra-High Resolution Climate Simulation in the Next Five Years

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SESSION 1

Computer models have been greatly hampered by lack of computer power to study the problem at sufficiently high resolution and with sufficiently detailed process descriptions. An opportunity has arisen to provide this power.

One of the most important problems confronting the global society is whether introduction of anthropogenic greenhouse gases (AGHGs) into the atmosphere will cause significant warming and related adverse impacts. To date, the balance of evidence suggests that this is the case, but considerable controversy surrounds this finding, and it is generally agreed that more detailed study is needed to reduce uncertainties further before the broader community becomes convinced of the problem and until the problem itself is sufficiently well understood to direct mitigation actions if needed. There is considerable urgency to get answers to these questions since projections suggest that early action to reduce AGHGs is warranted. In addition, societal planning needs better understanding (and predictability) of the present climate regardless of the ultimate magnitude of anthropogenic warming. One of the major roadblocks to acquiring this understanding is that computer models, on which many projections are based, have been greatly hampered by lack of requisite computer power to study the problem at sufficiently high resolution and with sufficiently detailed process descriptions. An opportunity has arisen to provide this badly needed computer power and the attendant expertise to use it efficiently.

Duplication of the DOE's Accelerated Strategic Computing Initiative (ASCI) for Climate Study

In response to the urgent need to replace nuclear weapon field testing expertise (which is rapidly being lost) with high performance computer modeling, the Department of Energy's Defense Projects office initiated the ASCI, which plans to construct within the next five years a computer capable of 100 tera-operations per second (tera-OPS). This initiative is well along in its development and provides an unparalleled opportunity to provide a similar capability to study global climate change. This has resulted in a proposal to essentially duplicate the ASCI computer architecture at an ASCI site (to accrue the advantages of scale, expertise and experience).

This plan would provide a computer capable of up to 40 tera-OPS, allowing routine simulations of the global climate over multi-decadal times at resolutions of 30 km horizontal in the atmosphere and 10 km in the ocean. Combined with requisite improvements in essential physical processes (such as cloud processes, turbulence, etc.), the ultra-high resolution would allow direct simulation of the small, but important current eddies in the ocean, inclusion of

important details of orographic topography over the land as well as detailed land and vegetation information, and make possible determination of impacts of snow and sea ice on the climate energy budget. Such a machine would, of course, also provide greatly improved capability to handle the massive data sets necessary for model validation and, conversely, for whose understanding such models will be required. This DOE activity has been designated the Accelerated Climate Prediction Initiative (ACPI). It would provide the 40 tera-OPS machine in less than 5 years, effectively accelerating development and use of the above-described climate models by 5-10 years.

Elements of the ACPI

ACPI recognizes that the expertise to provide the machine, related computer support, theory and numerical methods, and code development resides at the ASCI National Laboratories, but that the National Center for Atmospheric Research (NCAR) represents a major source of similar expertise and experience. In addition, experience with climate problems and expertise in analyzing both data sets and computer results also resides outside the ASCI Labs. Over the past ten years or more there has been increasing experience in fruitful collaborations among representatives of these complementary research communities. Thus, ACPI would support a large collaborative program of involvement among these overlapping research communities which include university faculty, students, post docs and researchers from other federal organizations.

The main goal would be to develop, test, and use several global climate codes which couple oceans, atmosphere, sea ice, and land models. Considerable emphasis will be placed on:

- improving process models such as those for clouds, radiation, boundary layer physics, turbulence, etc.;
- increasing understanding of climate predictability;
- coupling to even higher resolution regional and local models.

The main goal would be to develop, test, and use several global climate codes which couple oceans, atmosphere, sea ice, and land models.

A Recent Example of Ocean Modeling at the Required Spatial Resolution

The prospects for benefit from ultra-high resolution simulations of the oceans and atmosphere are not based entirely on conjecture. Already, in a highly successful test case, we have simulated the North Atlantic Ocean with the Los Alamos Parallel Ocean Program (POP) at the ultimate resolution planned for the future coupled code, *i. e.*, 10 km. horizontal and 40 vertical levels. Recently developed from an earlier code by Bert Semtner and Bob Chervin, POP has seen considerable renovation, and now is capable of realistic topography, sea surface height variation (which compares extremely well with satellite-TOPEX-POSEIDON-data), displaced north polar grid, etc. The zoning in this run was sufficiently fine to simulate all major energy carrying eddies, and to include tide-pulsed exchange with the Mediterranean Sea.

Figure 20 shows the domain extent of the calculation in a sea surface temperature (SST), color-coded representation (where red is warm and blue is cold). Figure 21 shows part of that region in a comparison with a NASA satellite SST plot. The agreement is remarkable, particularly in eddy size, shape, and distribution. The POP simulation is driven by daily winds, and seasonal temperature is input. The resulting SSTs result from advection of heat

SESSION 1

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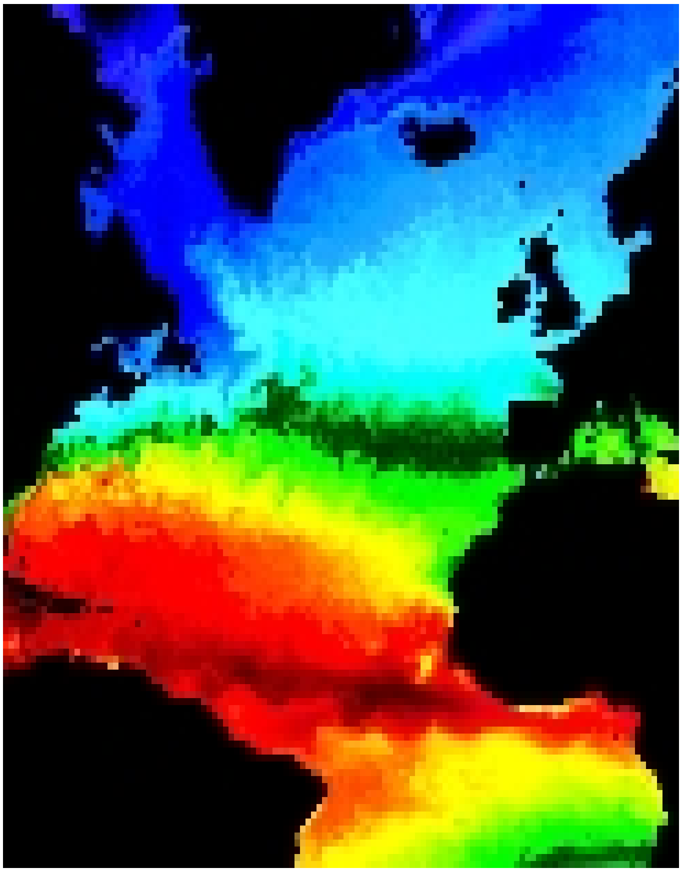
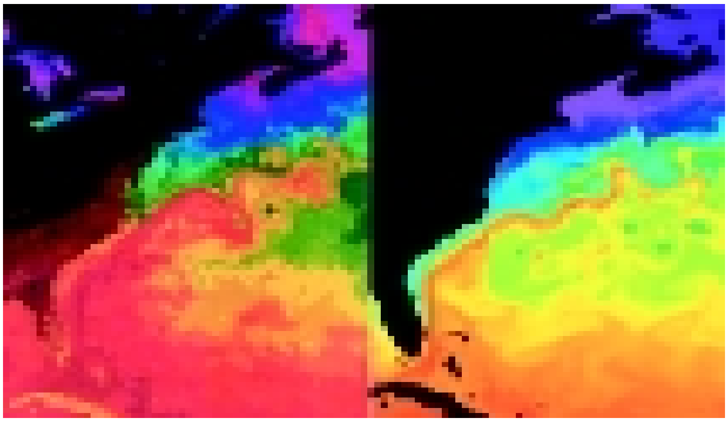


Figure 20
The domain extent of the calculation in a sea surface temperature (SST), color-coded representation (where red is warm and blue is cold).



Satellie Observation **POP 1/10˚ simulation**

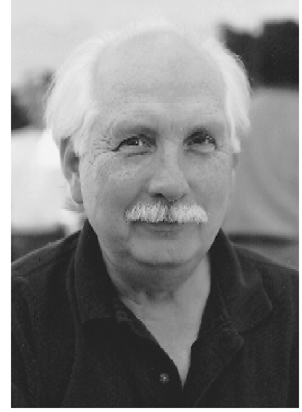
Figure 21
Sea Surface Temperature: Gulf Stream
Part of that region in a comparison with a NASA satellite SST plot. The agreement is remarkable, particularly in eddy size, shape, and distribution. The POP simulation is driven by daily winds, and seasonal temperature is input. The resulting SSTs result from advection of heat via the wind-driven ocean currents. The simulation reproduces observed south-north heat transport, and reproduces the thermohaline vertical circulation.

via the wind-driven ocean currents. The simulation reproduces observed south-north heat transport, and reproduces the thermohaline vertical circulation.

This example serves to show the benefits that result from adequately gridding the ocean model (with attendant improvements in physical processes and numerical methods), and gives support to the concept that proper collaboration among the ASCI labs and climate researchers from other institutions centered around an ACPI computer, supported with the expertise resident at an ASCI Laboratory can indeed provide the opportunity for dramatic increases in our understanding of the Earth's dynamic climate system.

POP is capable of realistic topography, sea surface height variation, displaced north polar grid, etc. The zoning in this run was sufficiently fine to simulate all major energy carrying eddies, and to sinclude tide-pulsed exchange with the Mediterranean Sea.

John Perkins, Tim Weston, Michael Schlesinger, and Chick Keller discuss climate and energy issues.



Re-Engineering Fission: Reactors for Safe, Globally Sustainable, Proliferation-Resistant, and Cost Effective Nuclear Power?

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SESSION 1

The four cardinal issues — waste, proliferation, cost, and safety — loom large, intermixed and unquantified in key public decision processes that determine from whence the next exajoule of primary energy will come.

Attracted by an abundant, inexpensive, and clean-burning fuel, energy from nuclear fission in the 2-3 decades following World War II saw enormous growth in commercial application; the worldwide rate of additions in nuclear-electric capacity reached ~30 gigawatts per year (GWe/yr) in the mid-1980s. That growth has decreased to a trickle of a few GWe/yr, with major industrial countries either experiencing stagnation, planned phasing out, or outright moratoria on the use of nuclear power. The uranium that feeds the nuclear fuel cycle is more abundant than first thought and remains inexpensive because of diminished demand relative to earlier expectations. The costs of building capital plant needed to convert this relatively inexpensive fuel have increased, while both fuel and capital costs of the fossil-fuel competition have diminished.

Additionally, the image of pristine conversion of nuclear energy into clean electricity has been dulled by the prospects/risks of accidental releases of dangerous materials that in (a portion of) the public's eye links civilian nuclear energy to the military dark side of things nuclear. Furthermore, civilian nuclear energy generates by-product materials of military interest, a situation that draws further attention to that dark side. Lastly, the longevity of the hazards associated with wastes created as a by-product of nuclear fission, and the inattention given so far to the long-term implications of that waste steam, have added further force to tilt the scales by which the public assays cost versus benefit. Although a few energy-strapped industrialized countries continue to sustain the meager worldwide growth in nuclear energy, the four cardinal issues — waste, proliferation, cost, and safety — loom large, intermixed and unquantified in key public decision processes that determine from whence the next exajoule of primary energy will come.

The large combinatorial of materials and configurations available to perform essential functions in a nuclear power plant (*e. g.*, efficient stewardship of neutrons sustaining the chain reaction, neutron moderation required of thermal-spectrum configurations, coolants, structural alloys, *etc.*) offers a rich array of options to harness nuclear energy safely and economically. Although approaches to nuclear power plants have narrowed significantly over the last three decades, options remain available to provide engineering resolution to the

aforementioned four cardinal issues. Can commercial approaches to nuclear energy be "re-engineered" in ways that lead to safer, globally sustainable, proliferation-resistant, and cost-effective nuclear power plants? Certainly yes. Will such "re-engineered" nuclear power plants be received by increased public acceptance? Probably not.

Current Types of Commercial Nuclear Fission Plants

BWR	Boiling Water Reactor
GCR	Gas-Cooled Reactor
LWR	Light-Water (fission) Reactor
PHWR	Pressurized Heavy-Water Reactor
PWR	Pressurized-Water Reactor (LWR)

Current Status

Introduced over four decades ago into the commercial electricity market, nuclear energy (NE) presently provides 18% of global electrical energy supply — ~8% of total primary energy. A total capacity of 351 GWe is generated in 442 nuclear power plants (NPPs) operated in 32 countries. The mix of these reactors (in 1993) includes PWRs (55%), BWRs (21%, PWR/BWR = 2.7%), GCRs (9%), PHWRs (7%), water-cooled/graphite-moderated reactors (4.5%, all in the former Soviet Union), and other kinds of reactors (3.5%). NE provides over 40% of the electricity to 9 countries and 20-40% of the electricity supply in 10 countries. The 1,118 TWh of electricity generated by NPPs in 1995 avoided approximately 8% of global carbon emissions. NE was introduced rapidly in the 1960s and 1970s. No new orders for NPPs have been placed in the United States since 1978, leading to that capacity being pegged at 98.8 GWe. Figure 22 indicates the impact of a 40-year plant-life license expiration schedule for key NE countries. Under conditions of capacity replacement coupled with a medium NE growth rate, Figure 23 illustrates the level of new NE capacity addition under conditions of moderate growth.

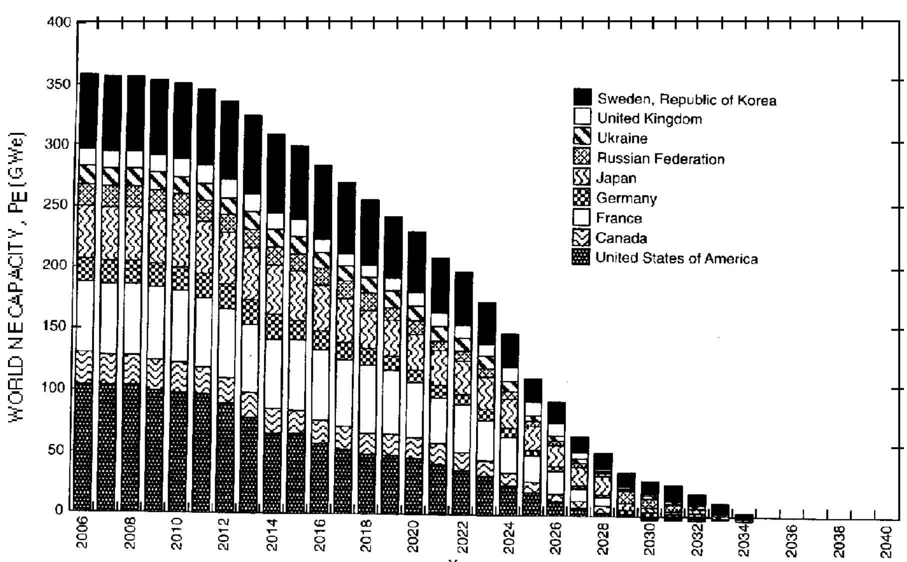

Figure 22

Expiration schedule for existing NPPs with capacity in excess of 500 MWe and for a 40-year plant lifetime.

Can nuclear energy be "re-engineered" in ways that lead to safer, sustainable, proliferation-resistant, and cost-effective nuclear power plants? Certainly yes. Will such "re-engineered" nuclear plants be received by increased public acceptance? Probably not.

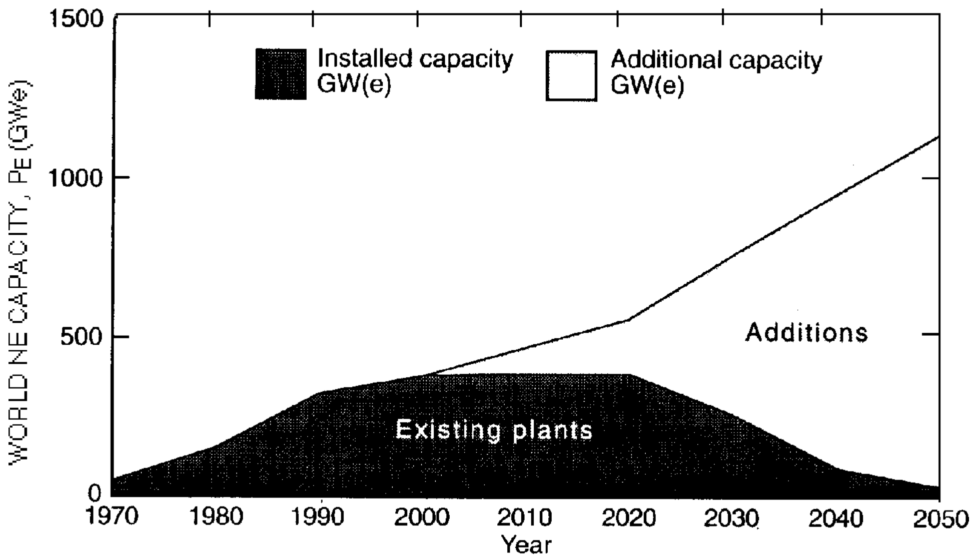

Figure 23
New NPP capacity additions required according to one Medium Variant scenario.

While variable from region to region, the overall operational and economic performances of NPPs have improved over the last few decades.

While variable from region to region, the overall operational and economic performances of NPPs have improved over the last few decades, as measured in terms of: a) collective radiation dose per unit of generated electrical energy; b) the dramatic decrease in radioactive liquid releases (without tritium) per unit of energy generated; and c) the number of accidents with significant radiological consequences per unit of generated energy. The economic performance of NE also varies somewhat from country to country. A recent survey of 15 Organization for Economic Cooperation Development (OECD) countries (Belgium, Canada, Denmark, Finland, France, Hungary, Italy, Japan, the Republic of Korea, the Netherlands, Portugal, Spain, Turkey, the United Kingdom, and the United States) and 5 non-OECD countries (Brazil, China, India, Romania, and Russia) on the cost of electricity generation from nuclear, coal, gas, biomass, solar (photovoltaic), and wind indicate that NE is competitive at a (bussbar) cost of electricity of 0.032 $/kWh. Similar results have been reported for U. S. operating and maintenance (O&M) and production cost trends for NE, which show both decreasing over the last decade, with NE production costs (not including annual changes related to capital costs and interest during construction) being competitive.

The world Proven Reserves of uranium correspond to 1.5 MtonneU, Reasonably Assured Reserves are 4.0 MtonneU, and Total Resources and Reserves equal 18.5 MtonneU (excluding recoverable low-concentration uranium in granite and seawater). Complete fissioning of all ^{235}U in the total reserves and resources (18.4 Mtonne) represents an energy resource of ~10,766 EJ ($1.5 * 10^6$ EJ if all uranium were fissioned). Including the less-known thorium (^{233}U) resource would increase the $1.5 * 10^6$ EJ by a factor of 2-3. Compared to the fossil-energy resource, the total uranium and fossil (including oil shale and clatherated methane) resources are comparable (*e.g.*, $1.5 * 10^6$ *versus* $1.0 * 10^6$ EJ for total uranium *versus* total fossil), but the ratio of uranium to fossil without oil shale and clatherates (97,892 EJ) amounts to ~15.3. The present world demands for total primary energy and for nuclear

energy (350 GWe, ~70% plant availability, 35% thermal-to-electric conversion efficiency) amounts to 360 EJ/yr and 22 EJ/yr, respectively. At the present NE demand rate, most (90.7%) of the ^{235}U in the Reasonably Assured Reserve category (4.0 Mtonne) would be consumed in a once-through (no plutonium recycle) fuel cycle by the year 2100. A linear increase in NE capacity to 2,000 GWe would increase this 100-year uranium requirement by a factor of 2.7 (9.8 Mtonne), which amounts to approximately half of the ^{235}U in the Total Reserves and Resource category.

Prospects

The rapid growth of NE in the 1960s and 1970s has diminished considerably. The main growth and prospects for growth in NE are occurring in East and South Asia, with Western industrialized countries experiencing a period of stagnation. A number of recent studies address a range of NE futures. A quantitative picture of NE competing in a changing electric-supply-industry market is given in Beck, 1994, wherein increased cost transparency, increased (short-term) market discipline, and the reduction of policy *per se* to a vestigial role creates an environment that is very different from that into which NE entered over two decades ago.

Using a more quantitative approach than that used in Beck, 1994, the three NE scenarios depicted in Figure 24 derive from Wagner, 1997. These scenarios were adopted from the 1995 World Energy Council/International Institute for Applied Systems Analysis (WEC/IIASA) study to suggest three possible NE growth scenarios. The High Variant (HV) assumes a high overall growth in GDP and energy consumption, no limits to human technological ingenuity, no environmental (*e. g.*, GHG emissions) constraints, and large-scale use of renewable energy (RE) and NE resources; by the year 2100, the HV scenario has almost equal reliance on NE, natural gas, biomass, and RE (mainly solar, with some wind and "new" RE). The Medium Variant (MV) case is an ecologically driven scenario based on less (than HV) ambitious economic growth and the use of both NE and RE to achieve sustainable growth in all regions of the world by 2100 (including developing countries). The Low Variant (LV) case is similar to the MV case, but with a politically driven phase-out of NE. The phase-out LV case is less aggressive in reducing the role of NE than the heuristic approach used in Beck, 1994. None of the cases depicted in Figure 24 require the introduction of breeder reactors prior to 2050, and only the HV case suggests such a resource-driven need near the end of the year 2100.

A 1998 Nuclear Energy Agency (NEA)/OECD study suggested the three alternative NE development paths depicted in Figure 25: Variant I assumes continued NE growth leading to 1,120-GWe NE capacity by 2050; Variant II is a phase-out scenario wherein power generation from NE would completely cease by 2045; and Variant III suggests an initial period of stagnation and possible reduction (driven by early retirement of NPPs), that is followed by a revival of NE in ~2020, which also leads to a NE capacity of 1,120 GWe by the year 2050. In terms of construction rate, financing, siting and land requirements, and uranium resources, each of the variants considered by the NEA/OECD study would present feasible challenges to the NE industrial sector. Improved economic competitiveness and increasing public acceptance represent the main challenges for Variant I. The maintenance of infrastructure effectiveness during the lengthy NPP decommissioning process and final waste

The rapid growth of NE in the 1960s and 1970s has diminished considerably. The main growth and prospects for growth are occurring in East and South Asia, with Western industrialized countries experiencing a period of stagnation.

disposal that are required in Variant II present key challenges, while non-NE sources must deal with increased problems of energy and environmental security; Krakowski, 1998, elaborates on concerns associated with any NE phase-out scenario. The main challenges associated with Variant III are reflected in the 75 GWe/yr construction rate required after the year 2035 (compared to 20 GWe/yr for Variant I), with this increased construction rate of advanced NPPs (*e. g.*, economically competitive with advanced fossil fuel and RE generation stations while dealing satisfactory with the waste, proliferation, and safety issues) occurring after a two-decade period of stagnation in the NE sector.

Techno-economic solutions and "re-engineering" approaches to waste, proliferation, cost, and safety are insufficient to impact the single element that will determine the fate of nuclear power — public concerns/fears that have diminished acceptance of NE.

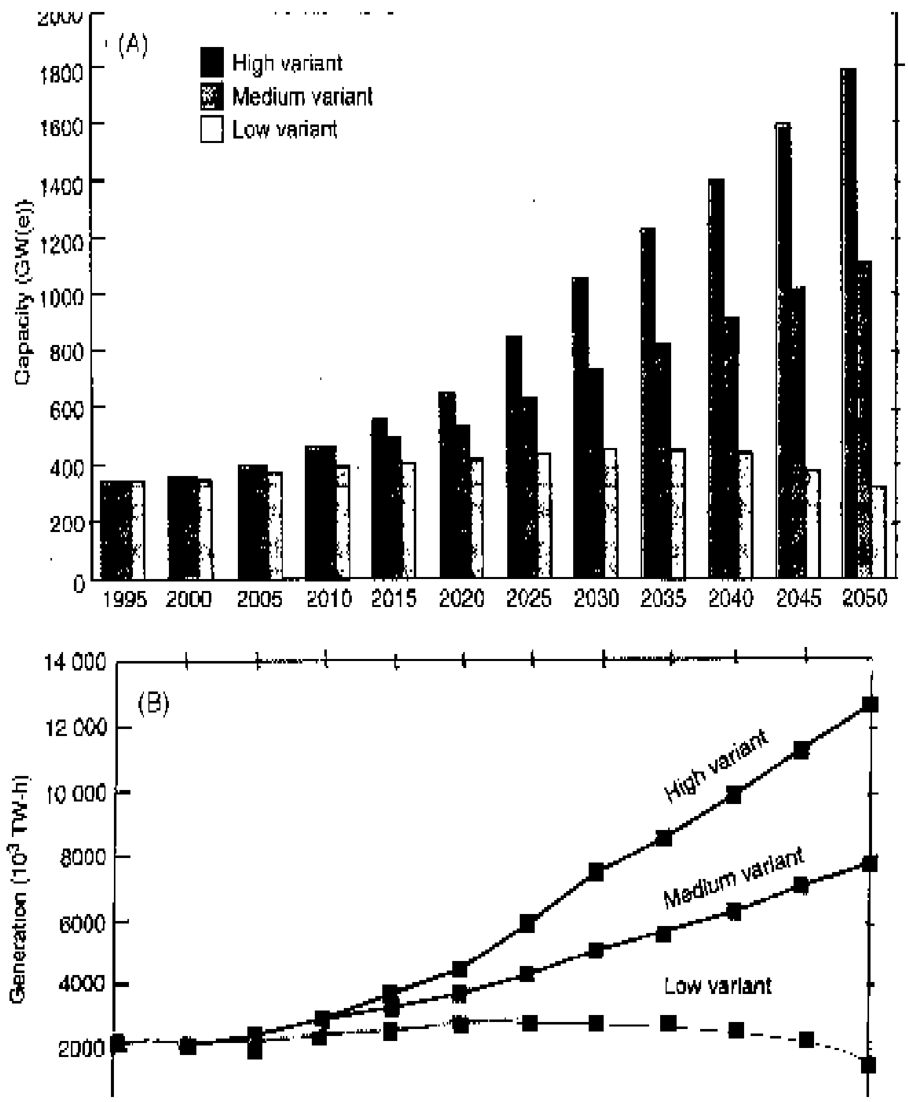

Figure 24
World NPP capacity (A) and generation (B) for three scenario variants.

SESSION 1

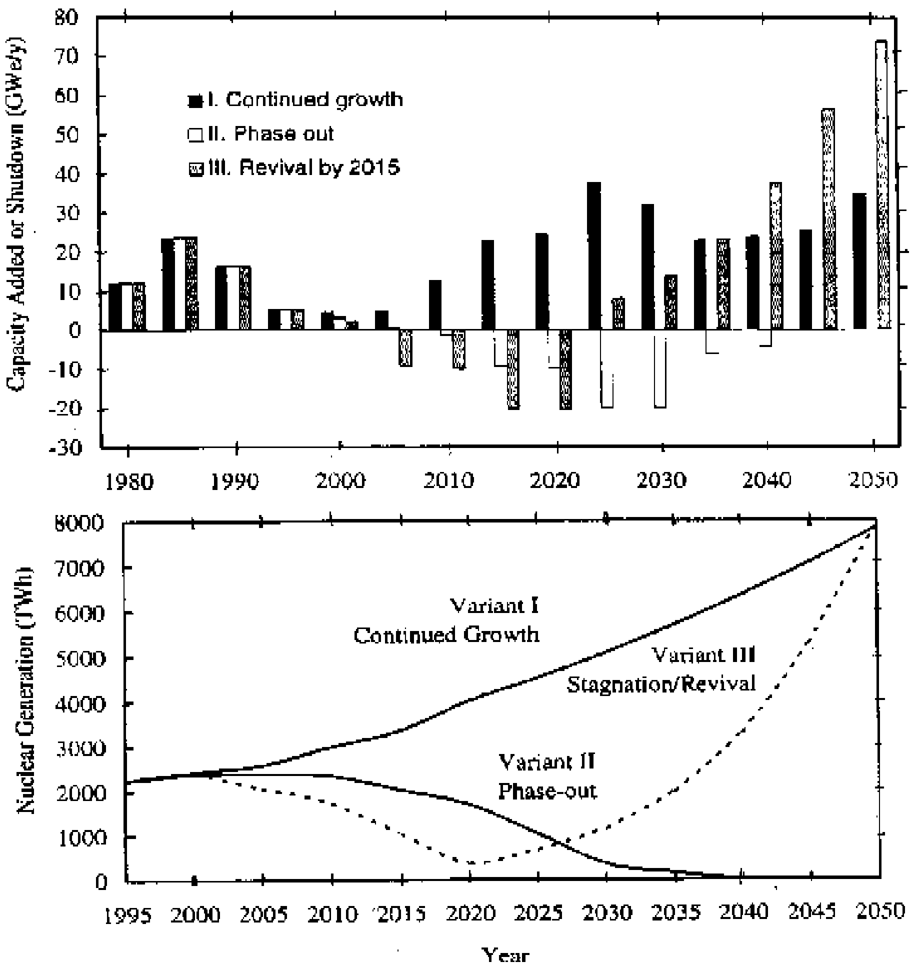

Figure 25
World NPP capacity (A) and generation (B) for three scenario variants.

Nuclear Legacy and Public Acceptance

The path taken by NE, as described by the limiting scenarios depicted in Figures 24 and 25, will be determined by the way in which the nuclear legacy is resolved for (by) the general public. Techno-economic solutions and "re-engineering" approaches to waste, proliferation, cost, and safety are insufficient to impact the single element that will determine the fate of nuclear power — public concerns/fears that have diminished acceptance of NE. The public acceptance issue is defined under a societal-cultural paradigm rather than in terms of a technological-economic one. The introduction of nuclear energy simultaneously with nuclear weapons created a kind of public schizophrenia that combined total acceptance of the new source of energy and complete fear of its military dark side. This separation dissolved as: a) the economic benefits portended by NE advocates diminished with increased development and commercialization; b) safety concerns became better quantified and ultimately were realized; c) the fear of nuclear holocaust grew with the increasing nuclear arsenals; d) and the level of public trust and credibility in governing and regulating institutions plummeted.

The introduction of nuclear energy simultaneously with nuclear weapons created a kind of public schizophrenia that combined total acceptance of the new source of energy and complete fear of its military dark side.

NE in its relative commercial infancy has suffered reduced public acceptance, and without public acceptance, this technology cannot advance, even if technical solutions to the four cardinal issues emerge. Key societal vectors associated with public concern are: a) the nature of risk perception by the public; b) the legacy of fear; c) the perception of benefit; d) value conflicts and shifting cultural settings; and e) diminished institutional credibility and trust. The migration of public opinion over the earlier years (1975-96) of commercial NE in the U. S. has shown a strong shift from the favorable to the opposed. Results from a more recent (1995-98) survey of U. S. public attitudes towards nuclear power, however, indicate not only a significant shift towards a more positive disposition, but also that those expressing favorable opinions thought (mistakenly) that the majority of the U. S. public held negative views.

In the context of the existing societal/cultural paradigm, the following multiple pathways to increased public acceptance of NE have been identified:

- Demonstrate a record of safe operation of present NPPs;
- Contain the potential for catastrophic risk:
  - — continue to improve present NPPs;
  - — develop new, reduced-risk and standardized NPPs;
- Separate NE from nuclear weapons;
- Rediscover the benefits of NE to:
  - — reduce impacts of future oil price shocks/increase energy security;
  - — mitigate greenhouse gas emissions;
  - — improve price competitiveness;
- Steady progress on waste management, leading to sustainable NE:
  - — begin with specific waste facilities (repositories, Monitored Retrievable Storage [MRS]);
  - — close the fuel cycle;
  - — plan, develop, implement no-actinide, minimum-(long-lived)- fission-product systems
- Create and implement fair, open, equitable institutions for the administration of NE.

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This approach to dealing with the all-determining public-acceptance issue revolves around adhering to a dedicated plan for breaking with the past to open new pathways to the resolution of social-cultural barriers that impede technological-economic advancements.

Nuclear Energy Technology Futures

Where needed, a rich array of technical solutions to the four cardinal issues can be identified. This richness of technical solution and innovation is reflected in the large combinatorial of materials available to perform the essential/basic functions needed to generate thermal and/or electrical energy from nuclear fission: fuels sources (uranium, thorium), fuel types (^{233}U, ^{235}U, $^{239,241}Pu$), fuel forms (metal alloys, oxides, carbides, nitrides, fluids), neutronically compatible (in terms of neutron economy, material longevity, and waste generation) structural materials, coolants (waters, liquid metals, gases), and neutron moderators (if needed, waters, graphite). Furthermore, nuclear reactors are “tunable” to create materials, destroy materials, provide process or space heat, *etc.*, simultaneously with the generation of electrical power. The material and intellectual resources needed to re-engineer fission to be safe, sustainable, proliferation-resistant, and cost-effective are not in short

supply. A three-stage growth scenario for NE can be implemented using some of these resources:

- **Phase I**
  Secure existing NPPs (mainly LWRs) through license renewals (pressure-vessel life, small-component replacement); increased O&M effectiveness and associated cost reductions (robotics, remote-monitoring, coolant chemistry control, waste and dose reduction, validated reliability); and reduce challenges to safety systems (optimized balance between passive control and operator intervention in matters of plant safety); and (begin) gaining control of the waste issue [initiate a system of International Monitored Retrievable Surface Storage (IMRSS) systems for used fuels in preparation for Phase III activities]; begin reduction of separated, inadequately-secured plutonium inventories;
- **Phase II**
  Bridge to the future though the continued development and deployment of evolutionary LWRs [economically competitive, safer, standardized, flexible capacities, simplified, (fewer valves, fewer pumps, reduced piping, less HVAC ducting, reduced seismic building volume, less control cable) *etc.*]; meet key life-cycle requirements (close the fuel cycle under conditions required prior to attaining sustainability (*e.g.*, fissile fuel breeding); optimize balance between passive and active safety systems; address diseconomies-of-scale issues on a per-region/application basis [~600 MWe and expandable, grid matching, size *versus* configuration *versus* coolability, fission-product quantity *versus* number of sites, reduce (installed) capital costs, modularity (factory *versus* site fabrication, site capacity)];
- **Phase III**
  Enter into technologies required for a competitively sustainable NE future that includes proliferation-resistant breeding of fissile fuels from the world's uranium and thorium resources; non-electric applications (if competitive); and either direct or support facilities that eliminate all actinides and long-lived fission products (LLFPs) from passing through to the externalities in which Phase III operations will be conducted.

Specific attributes and elements of each of these three Phases are elaborated in Krakowski, 1998, which focuses on a number of approaches to Phase III that emphasize both actinide and LLFP control; this emphasis is essential to dealing with two of the more crucial of the four cardinal issues — waste and proliferation. It remains for the technologist to assure that resolutions of these key issues are presented while assuring good progress on the remaining two (cost and safety).

Possible Future Nuclear Technologies

ALMR	Advanced Liquid-Metal Reactor
FSB	Fast-Spectrum Burner
IFR	Integral Fast Reactor
MHTGR	Modular High-Temperature Gas (Cooled) Reactor
MOX	Mixed (Plutonium, Uranium) Oxide Fission Fuel
OT/LWR	Once-Through Light Water Reactor
PUREX	Plutonium-Uranium Recovery Extraction
SCNES	Self-Consistent Nuclear Energy Systems

We could bridge to the future though the continued development and deployment of evolutionary LWRs (economically competitive, safer, standardized, flexible capacities, simplified).

Five potential (and incomplete) approaches to a nuclear future are:

a) Once-Through LWRs (OT/LWR);
b) MOX recycle in LWRs (MOX/LWRs);
c) actinide (and possibly Long-Lived Fission Products [LLFP]) destruction in ALMR/IFRs;
d) IFR-based SCNES that permit no actinide or LLFPs to leave the reactor site;
e) Accelerator-Driven Systems for actinide fissioning and LLFP transmutation; and
f) enriched-uranium (20%) driven thorium blankets assembled into existing LWRs (Radkowsky Thorium Reactor).

These generally partial/incomplete concepts, however, (with the exception of the stand-alone OT/LWRs and MOX/LWRs) have the following common goals:

- eliminate present stocks of separated plutonium through the generation of energy therefrom, and to prevent the accumulation of future stocks of separated plutonium;
- keep all but operationally necessary MOX inventories in strong intrinsic (fission products) and protecting radiation fields during all fuel cycle operations;
- reduce or eliminate the flow of:
  — all actinides from the fuel cycle to the repository;
  — all LLFP from the fuel cycle to the repository.

These goals represent strategic elements of an architecture that offers a means to bridge to the sustainable future for nuclear power.

These goals represent strategic elements of an architecture that offers a means to bridge to the sustainable future for nuclear power illustrated in Figure 26.

Impacts/Trade-offs

The behavioral economics ("top-down") ERB model of Edmonds, Reilly and Barns was used to perform impact and trade-off studies examining (primarily) the flows and inventories of civilian plutonium, and (secondarily) the roles and limitations of NE in mitigating the emission of greenhouse gases (GHGs). This computer model provides a discipline and consistency to the creation of long-term future scenarios describing possible interactions between regional and global issues concerning nuclear energy and nuclear materials.

The influences of supply-side and demand-side forces on the application of NE to regional and global energy mixes, and the economic (GDP) and environmental impacts that result are examined. Supply-side forces are simulated through the surrogate of carbon taxes imposed at varying rates, C-TAX($/tonneC/15yr). Demand-side forces are modeled through non-priced driven improvements in the efficiency with which secondary energy (gases, liquids, solids, and electricities) is used to provide energy services to the residential/commercial, industrial, and transportation sectors — the Autonomous Energy Efficiency Improvement (AEEI). Results are reported for nominally "business-as-usual" (BAU) conditions, which are expressed in terms of a Basis Scenario. The Basis Scenario used for most these illustrations assumes: a) a world population in the year 2,100 of ~11.7 billions; no carbon taxation; non-price (AEEI-like) improvements of ε_k = 0.0100/yr; and an annual increase in productivity that varies over the range 0.3-2.0 %/yr, depending on time and region. Many of these input assumptions have been subject to parametric sensitivity, which in addition to C-TAX and AEEI variations reports on the sensitivities of NEs role in mitigating greenhouse gas emission to carbon taxation mode (*e.g.*, coupling back to the regional economies *vis à vis* GDPs) and the cost of NPPs. Figure 27 indicates an approximate trade-off between

supply-side (C-TAX) drivers and demand-side (ε_k) drivers in mitigating the impacts of global warming, as computed from accumulations of atmospheric CO_2 in the form of the average global surface temperature response.

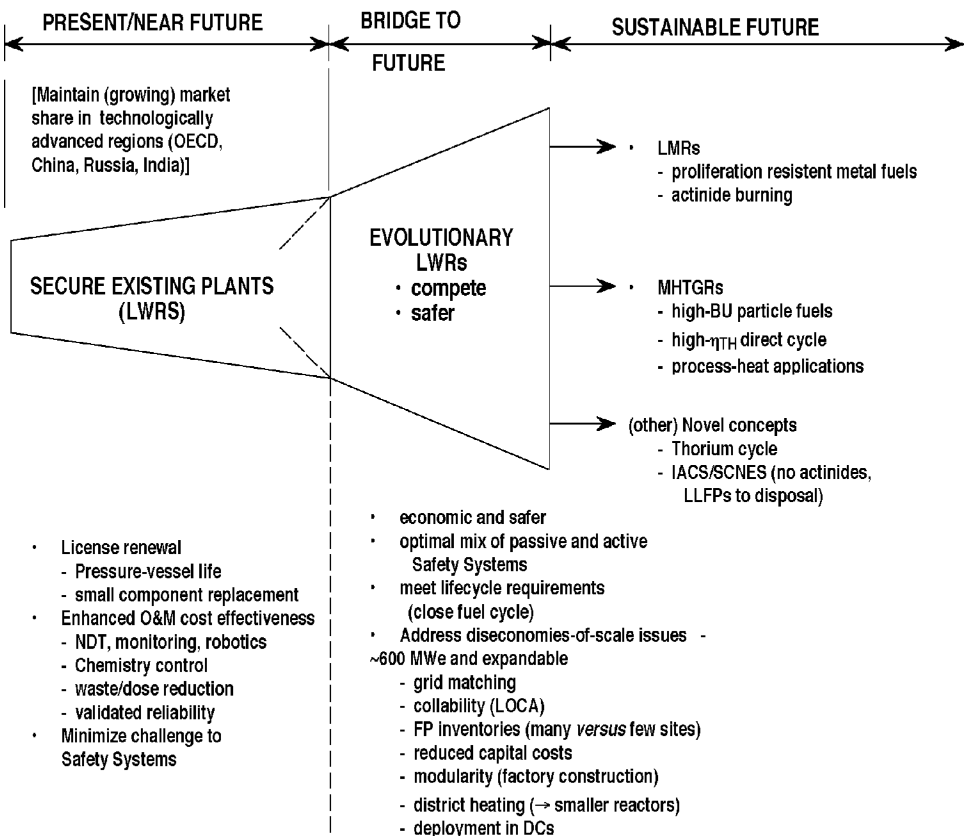


Figure 26
One possible bridge to a sustainable future for nuclear power

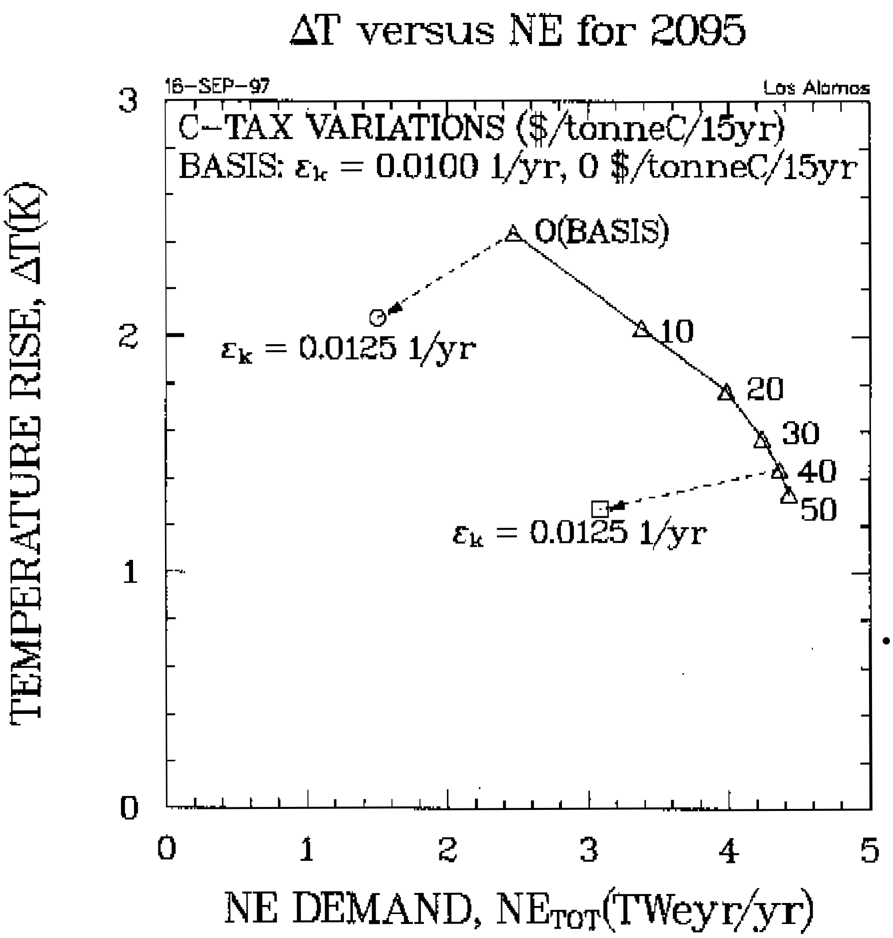
Summary and Conclusions

Key findings from this synthesis and analysis are:

- The electric supply industry is the only market for civilian nuclear energy and in this regard the nuclear industry is on tap, but not on top.
- Public response to nuclear energy is value-laden and cultural in context; this condition has far-reaching implications for efforts to win greater acceptance of this technology.
- The forces shaping public attitudes towards nuclear power are social-cultural in nature, and are not (directly) resolved within a technological-economic paradigm; these forces are related to:
  — no perceived urgency (for new electric generation capacity);
  — perceived as more costly than alternatives;
  — concerns of not sufficiently safe;
  — little trust in governmental or industrial advocates;

The electric supply industry is the only market for civilian nuclear energy and in this regard the nuclear industry is on tap, but not on top.

— concerns about health effects of low-level radiation;
— concerns that means for dealing with high-level radioactive waste do not exist;
— proliferation of nuclear weapons through the civilian nuclear fuel cycle.



Equally substantial increases in renewable energy sources, particularly solar, will be needed.

Figure 27

Impact of carbon-tax-induced increase in nuclear energy, NE_{TOT}, on reduced (final-year, 2095) average global surface temperature rise, DT(K); impact of increasing AEEI (Autonomous Energy Efficiency Improvement) parameter, e_k (1/yr), from Basis Scenario value (e_k = 0.0100 1/yr) is also shown.

- While important in dealing with the four cardinal issues for nuclear energy (waste, proliferation, cost, safety), "re-engineering" of nuclear systems alone will be ineffective in recovering public acceptance of this technology; Pathways for increased public acceptance include:
  — demonstrated record of safe operation of all nuclear facilities;
  — containment of catastrophic risk potential;
  — total separation of nuclear energy from nuclear weapons;
  — re-discover the benefits of nuclear energy;
  — deal satisfactory with the waste;
  — re-establish fair, equitable, open institutions;

— to the extent necessary for opening the above pathways, break with the past.

- Bridging to a nuclear-energy future requires that:
  - — existing NPPs be secured through license renewal, continued reductions in O&M costs, and reduced demands on safety systems, and;
  - — evolutionary LWRs continue towards safer and more competitive systems;
  - — substantial progress be made on the technologies required to assure that prior to the year 2100:
    - — all but the operationally minimal stocks of separated plutonium be eliminated;
    - — all inventoried plutonium remains unseparated and isolated by a high radiation barrier;
    - — all waste direct to repository be free of both actinides and long-lived fission prod ucts to the maximum extent practicable;
    - — the world NPPs operated with the minimum inventories of plutonium in all forms.
- Given that a bridge (e. g. Figure 26) to a viable nuclear-energy future can be established, a range of technologies remain to be explored and developed that assure: a) fully minimize separated/accessible fissile material; and b) waste streams emanating from the NE fuel cycles of the future contain neither actinides nor long-lived fission products:
  - — the stewardship philosophies embodied in the Self-Consistent Nuclear Energy Systems (SCNES) or the Integrated Actinide Conversion System (IACS) concepts should be translated into technical realities;
  - — the reality of any viable NE future will depend on limits to growth as established by: a) rate at which barriers to public acceptance of this technology is lowered; b) energy demand shifts and growths; c) economic (financing) limitations; d) fuel resource limi tations;
  - — within the ground rules and reality checks listed above, the following approaches to a long-term NE future should be explored:
    - — the long-term need for and economics of fissile-fuel breeders *versus* uranium-from-seawater/IACS (plutonium burning);
    - — use of the thorium resource vis à vis the RTR.
- Given that a bridge to a viable NE future cannot be constructed, the technological,(nuclear-materials) inventory, and overall infrastructural implications of a nuclear phase out should be explored on both regional and global levels.
- Nuclear energy can make an important contribution to mitigating greenhouse gas emissions, but only by occupying market shares vacated by a more expensive (*e. g.*, taxed) fossil fuel; stabilization to present CO_2 emission rates will require:
  - — NPP capacities of 4,500-5,000 GWe by the year 2,100, corresponding to deployment rates of 80-90 GWe/yr after ~2030;
  - — depending on uranium resource assumptions, breeder reactors will have to be deployed sometime around 2050 at a rate largely determined by the availability of startup plutonium;
  - — equally substantial increases in renewable energy sources, particularly solar, will be needed.

A range of technologies remain to be explored and developed that assure: a) fully minimized separated/ accessible fissile material; and b) waste streams emanating from the NE fuel cycles of the future contain neither actinides nor long-lived fission products.

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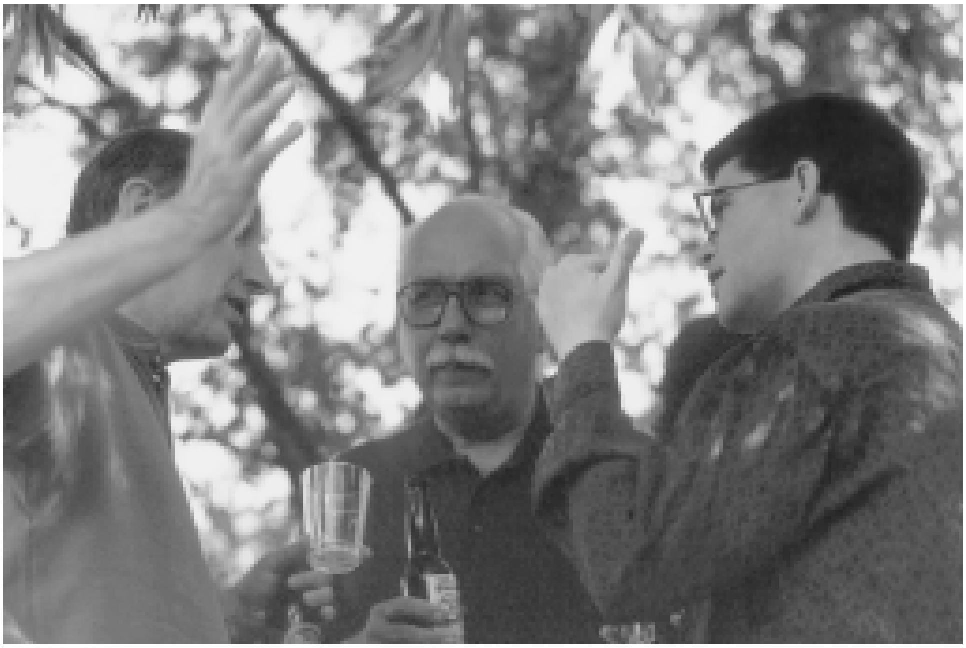
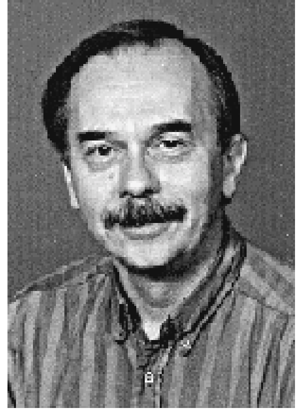
Nuclear energy can make an important contribution to mitigating greenhouse gas emissions, but only by occupying market shares vacated by a more expensive (*e. g.*, taxed) fossil fuel.



Vaclav Smil, Bob Krakowski and Gene Berry discuss possible energy futures.



Mining the Sky: Resources of Asteroids

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Space science and technology can be applied to the problem of supplying the future energy needs of humankind. Here I consider the use of the material resources of near-Earth space to build Solar Power Satellite constellations in orbit around Earth; and the extraction and retrieval of helium-3 from non-terrestrial sources for use in helium-3/deuterium fusion reactors on or near Earth.

The logistical attractiveness and great wealth of resources contained in near-Earth asteroids make them the most desirable targets of future efforts for space resource utilization. Near-Earth asteroids are "playing on the freeway" in Earth's orbit; one-third will eventually hit Earth. Current projections suggest that there are roughly 2,000 asteroids in near-Earth orbit with diameters greater than one kilometer, plus 1,000 comets. Another 565,000 near-Earth asteroids are thought to be larger than 100 meters (0.1 km) in diameter. About 23 known near-Earth asteroids and a projected 380 would be energetically easier to reach than the Moon. While it is unlikely to be worthwhile to mine cheap materials, such as iron, in space, it is conceivable that we might economically import such valuable resources as cobalt and platinum from asteroids.

The logistical attractiveness and great wealth of resources contained in near-Earth asteroids make them the most desirable targets of future efforts for space resource utilization.

The composition of asteroids is inferred from laboratory study of meteorites and also from spectral reflectivity studies of asteroids at ultraviolet, visible and near-infrared wavelengths. The near-Earth asteroids are very diverse in their spectral properties, ranging from metallic iron (M-type) to very black (C-type) material. Carbonaceous or C type asteroids are believed to make up about 50% of the kilometer-sized near-Earth asteroid population. They are rich in carbon compounds (0.2 to 4% carbon) and water (5 to 20% chemically-bound water) and are a potential source of hydrogen and oxygen propellants; they are similar to oil shale in composition. These volatile-rich bodies have enormous resource interests.

Solar Power Satellites

Ferrous metals retrieved from near-Earth asteroids could make Solar Power Satellites (SPSs) economically competitive with any known source of electric power for future use on Earth's surface. The high-technology components of the SPSs, such as guidance, control, communications, power conversion, and microwave transmission systems would be lifted from Earth, while the low-tech, massive components of the system, such as wires, cables, girders, bolts, fixtures, station-keeping propellants, and silicon solar cells, would be manufactured in space from asteroidal materials. Such a scheme reduces the total mass that must be launched out of Earth's deep gravity well during SPS construction by several-fold.

SPS constellations built high in Earth orbit from asteroidal materials have a number of important criteria of merit including: low Earth launch energy requirements, low return energy requirements, resource richness and physical state, and the availability of needed technologies for extraction, processing, transport, and fabrication. There are a number of potential sources for materials (Earth, Moon, near-Earth asteroids, Phobos and Deimos) and a number of possibilities for construction sites. Outbound launch energy requirements place the best near-Earth orbits ahead of the Moon for any potential construction site in Earth orbit.

The resources of the Asteroid Belt are enormous, dwarfing those of Earth's crust. The near-Earth asteroids provide ideal sites for re-launch to the Asteroid Belt; the energy and water usage would be about the same from Earth to a near-Earth asteroid as from the near-Earth asteroid to the Asteroid Belt.

Economics

The most important single factor governing the cost of future space activities is the cost of launch from Earth. Governmental monopolies of launch services, and the perpetuation of launch vehicles based on the propulsion technologies of the 1950s and 1960s, have not only made it very difficult to reduce launch costs appreciably, but also left the responsible launch agencies with little or no incentive to seek ways to reduce costs. These agencies are also unwilling to incur the developmental risks and costs associated with putting advanced technologies into service. But application of advanced rocket technology to commercial, competitive launch services holds an immediate promise of reducing launch costs per kilogram by a factor of ten, with further cost reductions of another factor of ten likely as completely reusable boosters, operated like commercial airlines, become available over the next few years.

The resources of the Asteroid Belt are enormous, dwarfing those of Earth's crust. The near-Earth asteroids provide ideal sites for re-launch to the Asteroid Belt.

A mass payback ratio of 100:1 means that each ton of equipment sent from Earth retrieves about 100 tons of asteroidal material over its operational lifetime. Calculations suggest that mass payback ratios will typically be 16:1 to 25:1 after 3 round trips and considerably higher thereafter. We can expect this to increase to nearly 100:1 when vehicle lifetimes reach 15 to 16 years of operation. Having people on launch vehicles is not recommended because it greatly raises the costs. At some point, technologies that enable massive reductions in the cost of manned missions may make it cost-effective to have human visits to mine sites to diagnose, upgrade and repair equipment.

Helium-3 for Use in Fusion Reactors

Clean fusion energy, fueled by helium and deuterium, involving far fewer neutrons than current fusion technologies, could become a reality. Helium-3 is a negligible resource on Earth, since it escapes readily from the upper atmosphere. Tritium decay in fusion warheads provides far too little inventory to justify a large-scale power generation program. Helium-3 is, however, a universal constituent of the Sun and gas-giant planets. There are two plausible sources for extraterrestrial helium-3: the solar-wind-implanted gases in the lunar regolith (the layer of soil and loose rock overlaying solid rock), wher the best concentrations can be found at low latitude on the dark side, and Uranus. Studies suggest that the atmosphere of Uranus would be the preferable source, beating helium-3 from the moon in energy payback by 1000 to 1 because the concentration is so much greater. Some new tech-

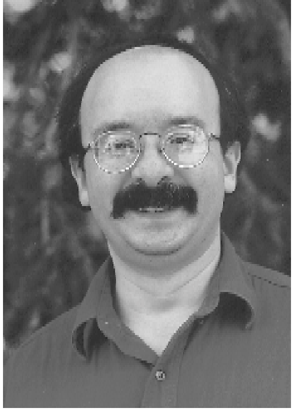
nologies would be required to retrieve helium-3 from Uranus, notably an advanced gas-processing refrigeration system and a liquid-core nuclear rocket more powerful than currently available.

Propellants from Space

Space resources are vast. The energy and material resources of nearby space exceed those of Earth's crust by a factor of about 100,000,000. Declining launch costs will make these resources economically accessible in the near future. The large majority of the mass launch on ambitious space projects is propellant. The raw materials of propellants (water and carbon) are common on most bodies nearby in space. Missions on the moon rest on a surface with a 40% oxygen content; missions on the surface of Mars are embedded in CO_2 gas; about half of all near-Earth asteroids are ice-bearing extinct comet cores — all of these are propellant sources. The most accessible solar system bodies, both for landings and round-trip missions, are near-Earth asteroids and Phobos/Deimos, many of which are propellant-rich. Space-derived propellants give enormous payback, often reaching factor of 100 improvements over propellants transported from Earth.

Space resources are vast, exceeding those of Earth's crust by a factor of about 100,000,000. Declining launch costs will make these resources economically accessible in the near future.

Cheri Morrow, Richard Somerville, Karl Taylor, and Tim Weston discuss the role of scientists in science education.



Energy Efficiency and Climate Change: Making Sense and Making Money

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The scientific uncertainties don't matter because saving energy strengthens the economy and incidentally solves the climate problem.

The climate debate should be recast: climate protection is not costly, but profitable, because saving energy saves money. Enough energy can be saved quickly to protect the climate if we remove the barriers that keep the market from working. This is very different from the obsolete view that climate protection requires ruinously high energy prices which will depress the economy and constrain lifestyles. It is this painful scenario which has led to action being delayed and the focus being placed on debating scientific uncertainties. In the new view of the climate debate, the scientific uncertainties don't matter because saving energy strengthens the economy and incidentally solves the climate problem (whether or not it needs solving). There are no sacrifices to be distributed, only profits.

There are three basic principles for such profitable climate protection:
1) Displacing carbon and using energy efficiently are profitable because saving fuel costs less than buying it (ignoring any environmental benefits of not burning it).
2) Huge opportunities for profitable energy efficiency remain unbought because of dozens of specific barriers that keep the market from working.
3) Turning each of these obstacles into a business opportunity can save vast amounts of energy very quickly even at today's energy prices.

Climate policy has been held hostage to a tacit presumption that if saving a lot more energy were possible at an affordable price, it would already have been implemented. That's like not picking up a $100 bill from the sidewalk because if it were real, someone would have previously picked it up. The models that drive policy are based on this false assumption and ignore real-world conditions. Most economic models calculate large costs for mitigating climate change because they assume rigid, constrained, and unintelligent responses to economic signals.

Barriers to Energy Efficiency

If such large savings are both feasible and profitable, why haven't they all been pursued already? Because the free market is burdened with subtle imperfections that can be classified into eight categories:
1) Capital Misallocation: Energy is only 1-2% of most industries' costs, and most managers pay little attention to seemingly small line items, forgetting that overhead savings go straight to the bottom line. Further, discount rates, cashflow and payback criteria are not properly assessed, leading to large discrepancies between criteria for energy supply options versus efficiency.

2) Organizational Failures: Old habits die hard. Scheduling constraints take precedence over sensible design. Few firms carefully measure how their buildings and designs actually work, leaving their assumptions untested and often incorrect; no measurement, no improvement. Departments often don't or can't cooperate. Rewards for saving are rare; if you save, your budget may just be cut.
3) Regulatory Failures: Regulated utilities are generally rewarded for selling more energy. Standards intended to be floors are misinterpreted as being ceilings or economic optimums (*e. g.*, in a typical lighting circuit, the next larger wire size yields about a 169% per year after-tax return; but an electrician who uses that wire loses the bid which is judged on first cost). Heavily subsidized sectors, such as transportation, distort the market severely, leading to bad decisions.
4) Informational Failures: Most people do not know where to get what they'd need to optimize their energy use, how to shop for it, how to get it properly installed, and who would stand behind it. People also don't know how much energy their existing equipment uses or how much they pay for a unit of energy.
5) Risks to Manufacturers and Distributors: Industry has limited confidence that consumers will buy unconventional products due to the other market failures discussed here. Efficient equipment often is not available when and where it's needed, especially on short notice.
6) Perverse Incentives: Compensation to architects and engineers is based on a percentage of the cost of building or equipment specified. Designers who eliminate costly equipment (such as a heating or cooling system) are therefore penalized rather than rewarded. Split incentives are widespread, in which one party (*e. g.*, the builder) selects the technology based on lowest first cost, while another pays its lifetime energy costs. Owners and renters have similar split incentives.
7) False or Absent Price Signals: Energy prices are often badly distorted by subsidies or uncounted external costs. Energy price signals are diluted by other costs, *e. g.*, the cost of gasoline in the U. S. is only one-eighth the cost of driving; why buy a 50- instead of a 20-mpg car when both cost about the same per mile to own and run? Customers are not given information that links costs to specific devices. Many firms never even see their energy bills, which are sent to a remote accounting department for payment. Tax asymmetries distort choices, *e. g.*, energy purchases are deductible business expenses while investments to save energy are capitalized.
8) Incomplete Markets and Property Rights: There is currently no market in saved energy; it cannot be bought, sold or traded. Property rights need to be vested in resource depletion avoidance and pollution avoidance.

Correcting these barriers should top the policy agenda. Combining barrier-busting with desubsidizing the energy sector and internalizing externalities would yield the fastest possible energy savings.

Combining barrier-busting with desubsidizing the energy sector and internalizing externalities would yield the fastest possible energy savings.

Even Cheap Energy Can Be Saved Quickly

The experience of the "energy crisis" in the U. S. in the 1970s and 80s demonstrated that energy efficiency could increase rapidly; from 1973 to 1986, U. S. energy consumption remained constant at about 74 quads while GNP grew by 35%. But this was forced by high energy prices. Is the only way to return to high rates of efficiency improvement to have high

energy prices again? Price is not the only tool available. We can substitute rising skill and attention focused by political leadership, public concern, competitive pressures, and private sector leadership.

For example, from 1990-1996, utility facilitation by Seattle City Light enabled electric customers in Seattle (with the cheapest electricity of any major U. S. city) to save electric load nearly 12 times as fast as those in Chicago, and electric energy more than 3,600 times as fast, even though Seattle's electricity prices are about half of Chicago's. This shows that creating an informed, effective, and efficient market in energy-saving devices and practices can substitute for a bare price signal, and indeed can influence energy-saving choices even more than can price alone. That is, people and firms can save energy faster if they have extensive ability to respond to a weak price signal than if they have little ability to respond to a strong one.

People and firms can save energy faster if they have extensive ability to respond to a weak price signal than if they have little ability to respond to a strong one.

SESSION 1

Conclusions

The uncertainties in climate science don't really matter because we should be taking the same actions in any case: purchasing energy efficiency to save money. Whoever goes first will gain the most benefit so why wait? There should be no argument about sharing the burdens — this is about who gets the profits. Carbon taxes may be helpful and appropriate but present prices are ample to elicit all the energy savings we need, if we just get serious about vaulting the barriers that keep the market from working properly.

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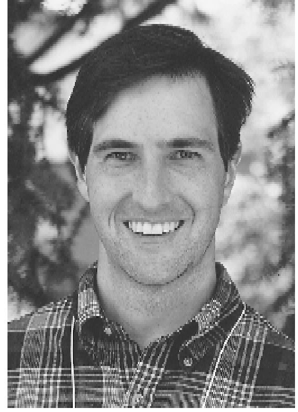

Exploring a Technology Strategy for Stabilizing Atmospheric CO_2

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Jae Edmonds and Marshall Wise
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The goal of the Framework Convention on Climate Change (FCCC) is to stabilize the concentration of greenhouse gases in the atmosphere at levels which avoid dangerous anthropogenic interference with the climate (United Nations, 1992). Work by the Intergovernmental Panel on Climate Change (IPCC, 1995; WG1) and others (Wigley *et al.*, 1996; WRE) have explored the issue of stabilizing the concentration of atmospheric CO_2. This work developed emissions trajectories consistent with various atmospheric concentration ceilings. Since an emissions path is not uniquely prescribed by a concentration ceiling, various criteria have been added to shape trajectories, including implied climate impacts and costs.

The attraction of efficient instruments for achieving atmospheric stabilization is great, and most of the analysis to date has focused on either tradable permits or taxes as the instruments of implementation (Hourcade *et al.*, 1996). Clearly, efficient instruments are a first-best alternative for achieving any emissions mitigation objective. But they are not without their own difficulties, not the least of which is the income distribution problem.

We examined the performance and cost characteristics of an alternative, technology-based policy instrument. Such instruments are of interest because they potentially offer a strategy for stabilizing the atmosphere, while requiring relatively minor financial transfers and allowing economic development to proceed. They accomplish these goals at the expense of economic efficiency, although our study shows the effect of the economic inefficiency is limited to approximately 30%. On the other hand, a technology strategy approach can offer wide technological flexibility in meeting the performance standard.

The technology protocol we study here requires new powerplant and coal-based synthetic fuels capacity to scrub carbon from the waste gas stream in Annex I nations, and provides a mechanism by which non-Annex I nations can graduate into obligations. We examine this protocol under two alternative reference energy futures: one dominated by coal and the other dominated by unconventional oil and gas.

We show that under the coal dominated reference future (CBF) the simple protocol effectively stabilizes the concentration of CO_2 in the atmosphere. If the protocol is initiated in the year 2020 the atmosphere stabilizes at approximately 510 ppmv, less than double the pre-industrial concentration. Under the unconventional oil and gas dominated reference future (OGF) the simple protocol holds concentrations to approximately double the pre-industrial

Alternative, technology-based policy instruments are of interest because they potentially offer a strategy for stabilizing the atmosphere, while requiring relatively minor financial transfers and allowing economic development to proceed.

level, but the atmosphere is not stabilized. Emissions are rising at the end of the century (Figure 28).

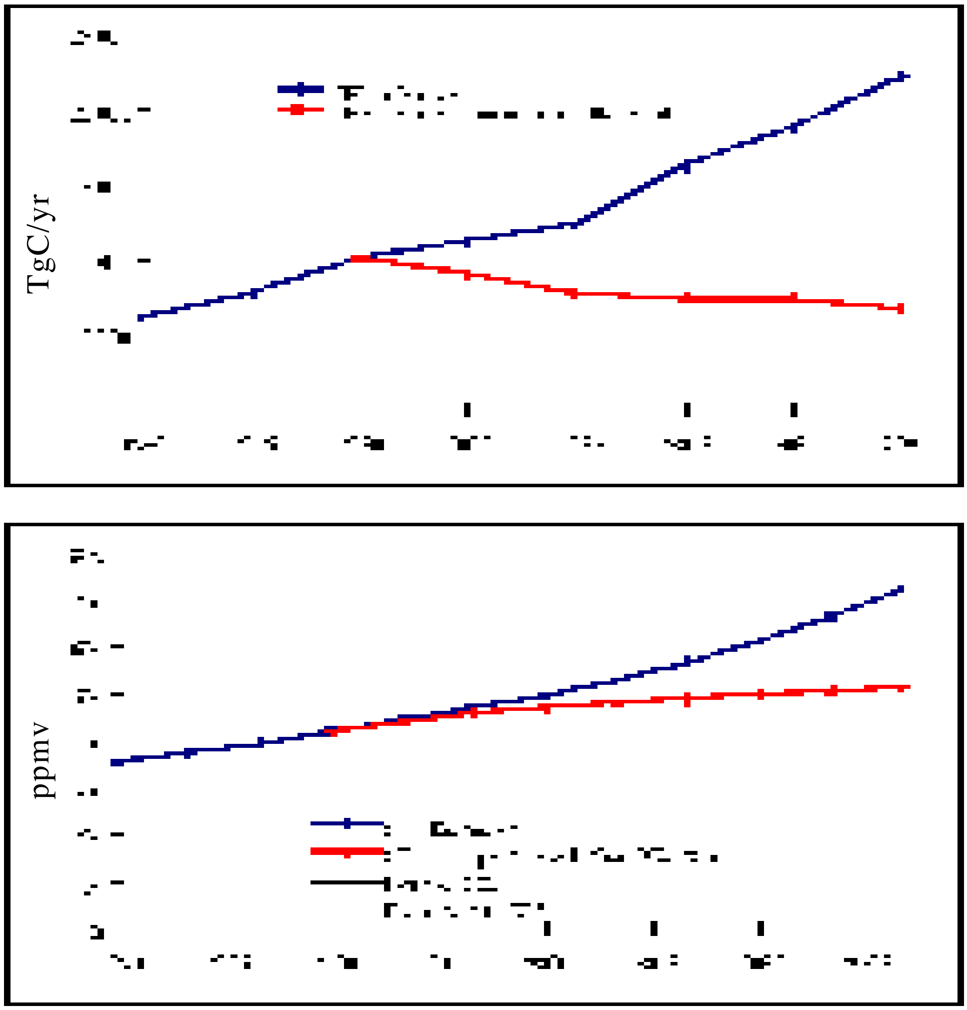

Figure 28
CBF: Global Carbon Emissions and CO_2 Concentrations
CBF reference carbon emissions and concentrations are shown. Emissions increase throughout the next century, rising to more than 20 PgC/yr and continuing to rise in the year 2095. As a consequence CO_2 concentrations rise above 700 ppmv, with concentrations continuing to increase in the year 2095.

SESSION 1

Atmospheric stabilization under the OGF requires a second stage to the protocol beginning 30 years after the initiation of the simple protocol.

Atmospheric stabilization under the OGF requires a second stage to the protocol beginning 30 years after the initiation of the simple protocol (Figure 29); the second stage would require that new refining and processing capacity remove all carbon from the fuel stream in Annex I nations, with imports of refined and process fuels phased out over a 45-year period, and the same graduation mechanism for non-Annex I nations as in the simple protocol. The imposition of this second stage leads to the creation of an energy system utilizing hydrogen

and electricity in end-use applications and enforces atmospheric stabilization in the OGF as well as the CBF.

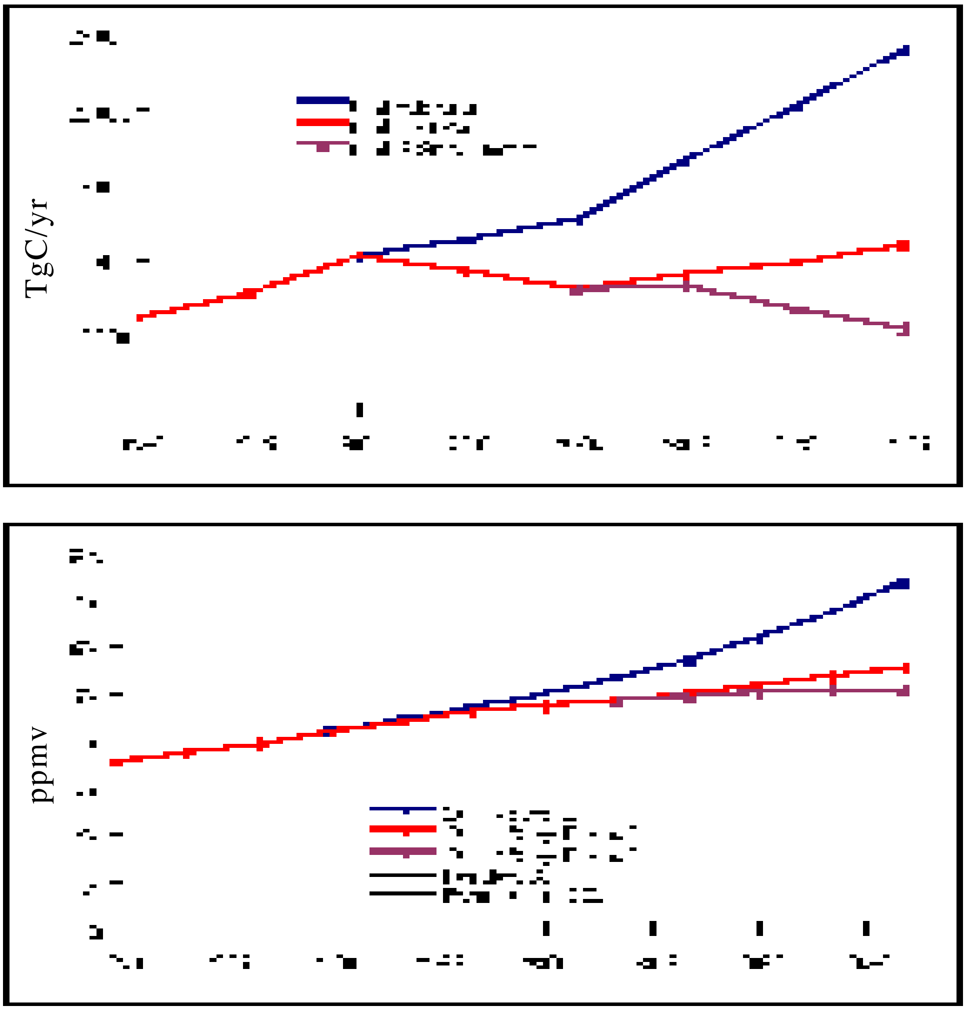

Figure 29
OGF: Global Carbon Emissions and CO_2 Concentrations

The date at which the protocol goes into effect strongly influences the concentration in the year 2100.

The date at which the protocol goes into effect strongly influences the concentration in the year 2100. From this study, we found the year 2100 concentration of CO_2 approximately a linear function of the date at which the protocol is initiated in Annex I nations. Starting in 2005 gives a lower bound of CO_2 concentration levels reachable under the protocol, a level near 450 ppmv. Keeping the concentration of CO_2 below 550 ppmv requires that the first stage of the protocol be initiated between 2030 and 2040, depending on fossil energy technology developments.

Initially, annual costs under the protocol are higher than an equivalent efficient policy. As the second stage of the protocol becomes effective in the later years, the inefficiency of the protocol diminishes.

The cost inefficiency penalty associated with the technology protocol varies with time (Figure 30). Initially, annual costs under the protocol are higher than an equivalent efficient policy. As the second stage of the protocol becomes effective in the later years, the inefficiency of the protocol diminishes. However, the present discounted costs of the technology protocols are about 30% higher than efficient costs when summed over the next century. The inclusion of joint implementation mechanisms could reduce the cost penalty of the hypothetical protocol and is a promising avenue for further work.

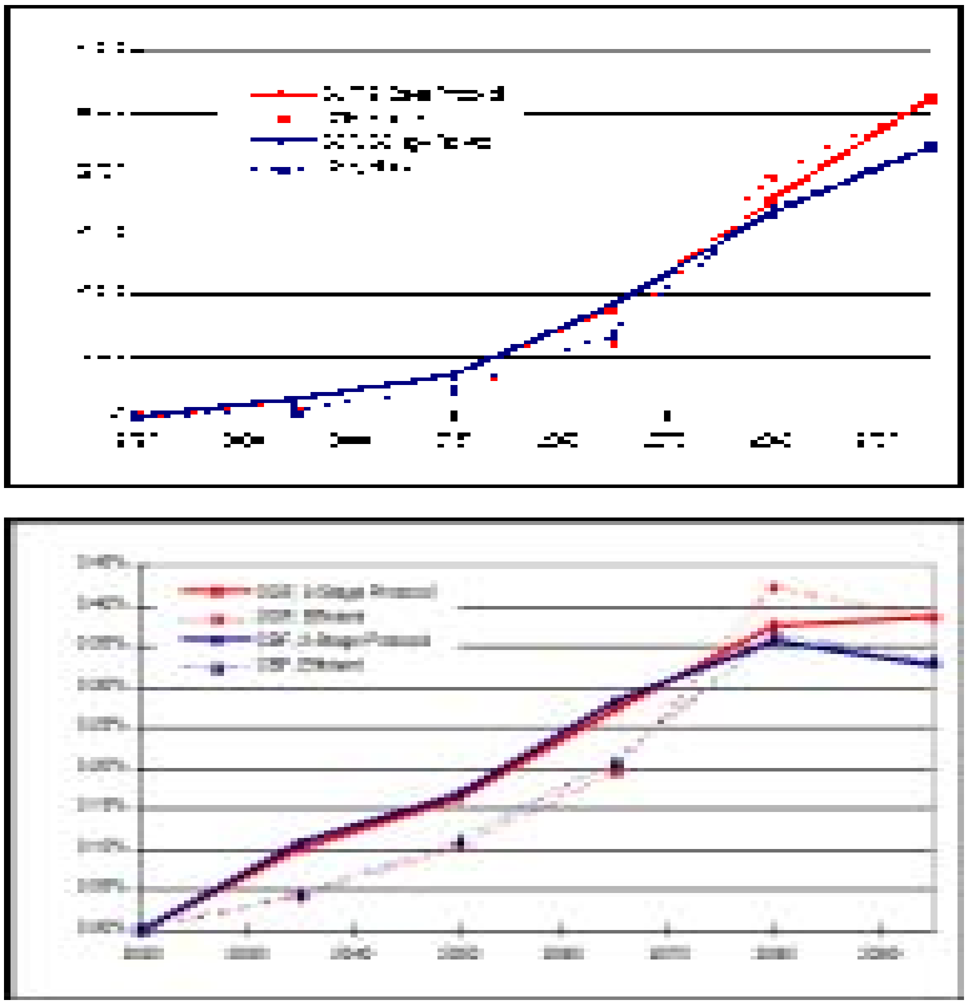

Figure 30
Comparison of Technology Protocol to Efficient Mitigation: Global Annual Costs. This figure shows annual costs for the protocol and the efficient cases under the CBF and OGF futures. Over the first half of the next century, the corresponding efficient cases are less expensive than the technology protocol by approximately 50 to 25%. During the second half of the next century, as nations come under the second stage of the protocol, the cost profiles for the protocols and the efficient cases tend to converge. This convergence is not surprising since the second stage of the protocol affects all fossil fuel carbon emissions, much like an ideally efficient mechanism would. Also note that in year 2080 the efficient

cases show slightly higher costs. Although this result is counterintuitive from a static analysis, it arises from the dynamics of higher costs in the earlier years of the protocol cases shifting investment away from fossil fuel production.

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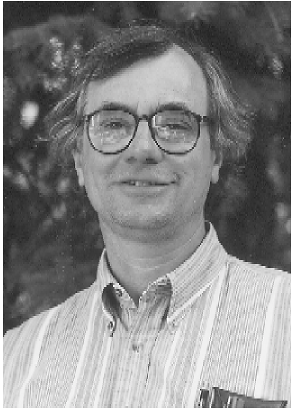
Hadi Dowlatabadi, Bob Watts and Don Wuebbles discuss innovative energy futures.



The Contribution of Biomass Energy Systems to the Global Carbon Balance

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SESSION 1

Biofuels currently provide some 14% of world primary energy use. Most of this consumption occurs in developing countries.

In the search for energy systems that have minimum impact on the concentration of greenhouse gases in the atmosphere, biomass fuels appear to offer a carbon neutral, renewable source of energy. Plants extract carbon dioxide from the atmosphere during photosynthesis and release carbon dioxide back to the atmosphere during combustion.

To give perspective to the role that biomass fuels might play in mitigating the increasing concentration of carbon dioxide in the atmosphere, we raise three fundamental questions: 1) how much energy do biofuels supply now, 2) how much energy might they supply in the future, and 3) what is the true reduction in carbon emissions from the use of biomass energy? We briefly discuss questions one and three and carefully avoid speculation on question two.

Question 1

The contribution of biomass fuels to the current world energy system is not well documented nor well understood, largely because much of the fuel is not traded in formal markets. Best estimates suggest that biofuels currently provide energy at a rate of approximately 50 exajoules per year, some 14% of world primary energy use (Woods and Hall, 1993). Most of this consumption occurs in developing countries, where biofuels provide 38% of total primary energy on average and over 95% of total primary energy in countries like Nepal, Chad, and Tanzania.

Bioenergy provides a smaller fraction of total primary energy in most developed countries. Use of bioenergy in countries like the US and Austria, for examples, amounts to about 4% and 10% of total primary energy use, respectively, although consumption of about 13 Gj per capita in both countries is comparable to that in many developing countries (Schlamadinger and Marland, 1996). Biofuels are used very differently in different countries. In developing countries biomass fuels are used primarily in the household sector for heating and cooking whereas in Austria and Sweden, for example, they have found wide application in district heating plants, and in the US they are used primarily for industrial applications in the forest products sector.

Question 3

It is often perceived that biofuels are neutral with respect to emission of the greenhouse gas carbon dioxide because the CO_2 released during combustion is subsequently withdrawn from the atmosphere when the biomass is regrown. Ideally this is a renewable, solar energy system where photosynthesis produces a fuel that is easily stored and used, and the carbon dioxide emissions are recycled in a sustainably managed production system. If we examine the full system, however, we find that production, harvest, transport, and conversion of biofuels requires significant input of energy and that this energy is generally provided by fossil fuels. These fuel inputs could be supplied with biofuels but the net effect would be to reduce the net available production of biofuels on a parcel of land. The limiting resource defining the potential of biofuels for greenhouse gas mitigation is then the land that is available, plus the net fuel production possible per unit of land and the opportunity to use that land in other ways (*e. g.,* reforestation).

We find that if the productivity of land is high, if biomass is produced and used efficiently, and if one has a long time perspective, then there is large per-hectare potential to use biofuels to displace fossil fuels and reduce net CO_2 emissions, and biofuels production will yield greater carbon benefits than other land uses such as reforestation. If productivity is limited and/or biomass is produced and used with low efficiency, then production of biofuels is likely to produce less benefit (with respect to net CO_2 emissions) per hectare than other land-use alternatives.

If the productivity of land is high, if biomass is produced and used efficiently, and if one has a long time perspective, then there is large per-hectare potential to use biofuels to displace fossil fuels and reduce net CO_2 emissions.

It is worth noting that the Kyoto Protocol to the Framework Convention on Climate Change treats biofuels in such a way that there are no reportable carbon dioxide emissions from a sustainable system. The Protocol provides that CO_2 emissions from biomass be reported as changes in carbon stocks. This approach effectively recognizes the link between the fuel source and the point of combustion so that there are no CO_2 emissions at the point of combustion but net emissions will be captured at the forest if the fuel is not produced sustainably and there is a net loss of forest.

In Figure 31 we use our carbon accounting model, GORCAM, to illustrate the net effect on CO_2 emissions to the atmosphere when 1 hectare of land is used to produce a woody fuel on a short harvest-rotation cycle and the fuel is used to displace coal in an electric power plant. The diagram shows total savings in emissions of CO_2 to the atmosphere because carbon is sequestered in the biosphere and because fossil fuel is displaced by the biofuel. The numeric details of the scenario shown are less important than the demonstration of principles and relationships, but the parameter values used here suggest what is possible with modern technology on highly productive land in the U. S. (see Schlamadinger and Marland, 1996, for details).

Note that the top line in the figure shows the gross fuel displacement, but the line just below it, marked with the arrow, shows net fuel displacement when we acknowledge that the biofuel system would require more input of fossil fuels for operation of the fuel cycle than would the coal-based system it displaces. Schlamadinger and Marland (1996) show that the CO_2 benefit per hectare is much smaller for a system based on producing ethanol fuel from corn

because of the large energy input required by corn and the large energy losses in conversion to a liquid fuel.

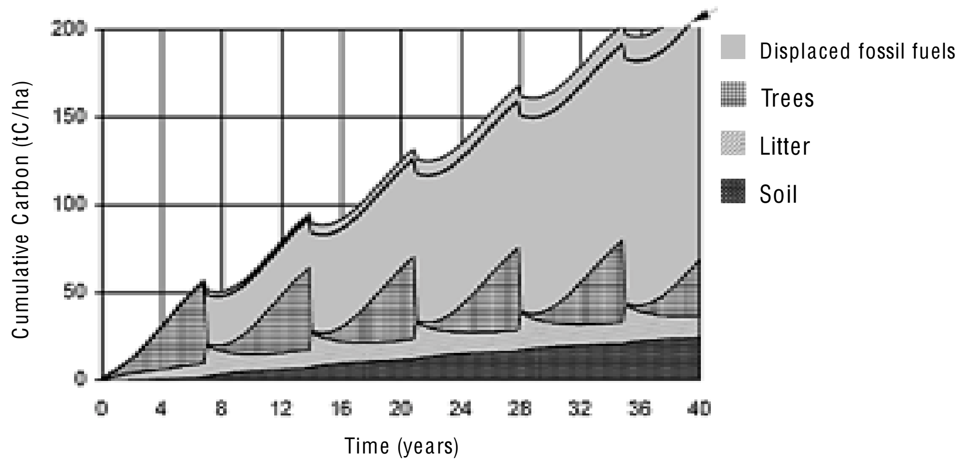

Figure 31
The net effect on CO_2 emissions when 1 hectare of land is used to produce a woody fuel which is then used to displace coal in an electric power plant. Note that the top line in the figure shows the gross fuel displacement, but the line just below it, marked with the arrow, shows net fuel displacement when we acknowledge that the biofuel system would require more input of fossil fuels for operation of the fuel cycle than would the coal-based system it displaces.

SESSION 1

Whereas displacement of fossil fuel emissions would produce credits under the Kyoto Protocol by reducing national CO_2 emissions, removing carbon from the atmosphere in growing biomass would produce credits in only limited and prescribed circumstances.

As noted above, when considering how to use land to mitigate the atmospheric increase in CO_2 there are tradeoffs between different land uses and between storage of carbon on site and displacement of carbon emissions through the use of biomass products. Analysis of full systems suggests that forest management choices can affect the global carbon cycle by affecting the carbon stored in the forest, the carbon stored in wood products, the extent of direct fossil fuel displacement, and the extent to which forest products substitute for alternate products with different levels of energy required for their production and use.

Many view the value of displaced fossil carbon to be greater than the value of sequestered biomass carbon. Underlying reasons are that: a) it is argued that emissions from fossil fuels can be measured and verified more easily than changes in the carbon stocks in biomass and soils, b) reductions in fossil-fuel emissions in one year are not at risk of being reversed at some later time whereas some biotic carbon stocks might be lost to the atmosphere at a later time, and c) carbon sequestration is a one-time option whereas biofuels can produce GHG benefits by displacing fossil fuels on a continual basis. The Kyoto Protocol (an international treaty intended to reduce net emissions of greenhouse gases to the atmosphere – see UN, 1997), for example, does not treat all carbon the same. Whereas displacement of fossil fuel emissions, *e. g.*, through use of biofuels, would produce credits under the Kyoto Protocol by reducing national CO_2 emissions, removing carbon from the atmosphere in growing biomass would produce credits in only limited and prescribed circumstances (Schlamadinger and Marland, 1998).

Question 2

The bottom line is that biofuels can displace fossil fuels and can yield net benefits in terms of CO_2 emissions to the atmosphere. The magnitude of the net benefit will be determined by the amount of highly productive land available and on the incremental benefit of using the land for fuel production rather than for other purposes. Wright and Hughes (1993) have suggested that the land available for biofuels in the U. S. may be as much as 28×10^6 ha and that this could eventually reduce U. S. fossil-fuel CO_2 emission by an amount equivalent to 20% of the 1990 total. The potential global contribution of bioenergy has been estimated to be between 60 and 145 EJ in 2025, and between 95 and 280 EJ by 2050 (various sources cited in Hall and Scrase, 1998).

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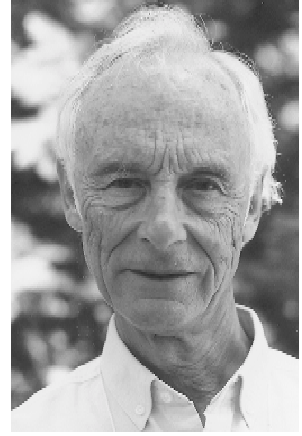

Energy, Economic Development and Carbon Emissions in China

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In this paper, first some of the numbers characterizing energy, economic development and carbon emissions are briefly reviewed. Next, some conclusions from past experience with China and international environmental agreements are noted. Finally, some alternatives are given for establishing baselines to be used under the Clean Development Mechanism (CDM) provision of the Kyoto Protocol.

SESSION 1

Chinese GDP measurement is fraught with both theoretical and practical uncertainties.

Some Numbers: GDP Growth in China [1]
Annual GDP growth rate in China measured at exchange rates has varied from 7 to 12% in past decade. The Purchasing Power Parity (PPP) adjustment is large, averaging around 4% now, and varies with time, sector of the economy and region. Chinese GDP measurement is fraught with both theoretical and practical uncertainties. On the theoretical side, with about half of economy state-owned and many prices regulated, including some oil and electricity, the prices to be assigned to much final production are uncertain. This factor alone has led to informed estimates as low as 5-7.5%. On the practical side, the accuracy of statistical reporting varies with year and with regions.

The usual GDP growth forecasts assume a continued favorable environment for growth: no war or large-scale domestic unrest, no world depression, continued market liberalization. As a result, they are plausible upper limits rather than predictions, with annual growth numbers like 7-10% usually quoted for the near term. In the long run, GDP growth is more likely to average 4% annually.

Some Numbers: Energy Consumption Growth in China
Energy consumption and production growth have ranged around 5% per year over the past decades. This growth rate may be somewhat less uncertain than the GDP growth rate since the theoretical basis is firmer. Many of the same practical uncertainties affect both however. Again forecasts, which usually project the past 5% average forward for the near term should be considered as plausible upper limits.

Energy intensity (energy use E per unit GDP Y, $I = E/Y$) is higher in China than in developed countries, mainly owing to Chinese poverty. Energy intensity decreases if wealth grows faster than energy consumption, as it has in China. The decrease, given the uncertainties in both energy use and GDP, may have ranged between 2% and 5% per year. China as a whole uses about half as much energy as the U. S. (1/10 U. S. energy per capita) and has

about a tenth the income (1/50 per capita) at exchange rates, leading to a ratio in energy intensity of 5. Much of this disparity vanishes when a PPP adjustment is made.

The energy elasticity with GDP, defined as:

$$\varepsilon = (\delta E/E)/(\delta Y/Y)$$

is a somewhat more stable indicator than intensity to which it is related by

$$\varepsilon = 1 + (\delta I/I)/(\delta Y/Y).$$

In the equation: $\varepsilon = (\delta E/E)/(\delta Y/Y)$
E = energy consumption (of a country, industry, sector, person)
δE = change per annum of that consumption in a given year
Y = gross economic product (of that country, industry, sector, person)
δY = change per annum of that product in that same year
If the energy intensity I is defined by $I = E/Y$
and δI = change per annum in I, then the equation:
$\varepsilon = 1 + (\delta I/I)/(\delta Y/Y)$ follows.

Energy elasticity in China has been 0.5-0.7 most of the past two decades, much lower than it was earlier, and much lower than the values in most developing countries, which are above unity [2]. The decrease is ascribed by most researchers to both efficiency improvements and sectoral production shifts [3]. By comparison, energy elasticity in the U. S. is around 0.4, indicative of U. S. economic growth being mainly in low-energy consumption sectors such as health and other services, and high technology products.

Composition of Commercial Energy Use and Energy Resources in China

Coal provides over 70% of energy used in China (worldwide average 30%), oil about 20% (worldwide average 40%), hydroelectric power about 7% (a quarter of electricity, which accounts for about a third of total energy use and is growing relatively), natural gas about 2%, nuclear less than 1%. Coal consumption pattern is unusual in that, not only does coal provide about 70% or more of electricity (versus 56% for the U. S. for instance), but it also provides much more of the industrial, commercial and residential energy than is the norm worldwide. Non-commercial energy, mainly biomass, is not included in the above statistics. Estimates of its contribution are even more uncertain than estimates of commercial energy, ranging from 10 to 20% or more by heating value.

Not only does coal provide about 70% or more of electricity in China but it also provides much more of the industrial, commercial and residential energy than is the norm worldwide.

Coal will continue to dominate supply for several decades if not longer. China has over 100 years of coal supply at foreseeable rates of use, more than half of it low sulfur, higher grades, but those resources are located in the North, far from the centers of energy use. Efficiency is low in all applications except the most modern electric power plants, but has been steadily improving.

Oil use has been growing from a low base somewhat faster than overall energy use (6%). Oil is cheap now. China provides most (about 80%) of its own oil. Present known reserves are peaking, as is the case throughout East Asia and perhaps elsewhere. Total oil resources in China, as in the world at large, are poorly known, but could be quite large. Future

Chinese oil use will depend on price and on infrastructure choices. There are agreements and plans for oil pipelines from Central Asia into China, but so far none of them is funded.

Natural gas usage in China is much lower than elsewhere in East Asia, despite the probably presence of large resources. Mainly for reasons of bureaucratic organization, gas exploration has not been given priority adequate to its potential value. This may be in the course of being remedied. Natural gas has more potential for making inroads into coal use and reducing coal pollution than any other fuel in the next two decades. Investment in pipelines, both domestic and between East and Central Asia, is needed. Again, plans have been made but funding is for the most part not identified.

Nuclear power use in China is also low, with two operating 900 MWe Framatom reactors and one domestically built 300 MWe unit. Eight more reactors (to be built by France, Canada, Russia and domestically) are at various stages of negotiation and construction. About 150 GWe of nuclear capacity is planned for 2050. If realized, that would constitute perhaps 15-20% of projected electricity capacity then, versus upwards of 40% for the rest of East Asia. Nuclear plants in China to date have a good safety and capacity factor record.

For the future, it is plausible that, if economic growth and market liberalization continue, efficiency gains will continue to be made and bring continued decarbonization.

By most estimates, hydroelectric power will grow in step with overall electric power over the next few decades. Some of that growth, but by no means the majority, is slated to come from the Three Gorges Dams. China has the largest hydroelectric potential resource in the world (over 300 GWe) but it is mostly in remote areas.

Recent and Future Carbon Emissions in China
Carbon emissions in China are estimated to have grown at about 4% in the past decade, somewhat less than total energy consumption.

1989	1.22%	1993	5.52%
1990	0.00%	1994	6.70%
1991	4.59%	1995	4.27%
1992	3.44%	1996	1.57%

Source: DOE Energy Information Administration

Carbon intensity of energy consumption is defined as tonnes of carbon emitted C per exajoule of energy consumed E. In 1995,

$C/E_{CH} = 23$ $C/E_{US} = 16$ $C/E_{WORLD} = 15$

Not surprisingly, China's energy use is more carbon intensive than that of the U. S. or the world. Nevertheless, China's carbon intensity is decreasing.
A carbon (or GHG) elasticity of energy consumption may be defined as:

$$K=(\delta X/X)/(\delta E/E)$$

Averaged over the years 1992-96:

$K_{CH} = 0.9$ $K_{US} = 1.8$ $K_{WORLD} = 0.4$

The decrease in carbon intensity is mainly due to gradual increase in the proportion of modern turbines used in electricity generation, and other improvement in utilization of coal,

starting from a very low base. The caveats given above regarding the accuracy of estimates apply here also. Most projections again are essentially linear extrapolations of the past record. Here, as with energy use and GDP, growth rates vary by a factor of at least three among various geographic regions and various sectors of the economy.

For the future, it is plausible that, if economic growth and market liberalization continue, efficiency gains will continue to be made and bring continued decarbonization. In China as elsewhere, there is considerable room for cost-effective improvement in end-use efficiency as well as efficiencies in production and intermediate processes, including transportation, although the details of these improvements will be different from the details in developed countries.

Decarbonization owing to fuel switching, principally to natural gas and, on a slower time scale, nuclear power and some renewables to the extent they become cost-competitive, will depend on investment choices by a mix of central and local government authorities and the private and semi-private sectors. At present, the central government, or at least some of its ministries and centers of authority, may have a longer and more positive view of the desirability of investing in natural gas and nuclear energy than do local governments and others, but this conclusion is tentative and needs supporting research. The motivation is strategic security of energy supply and local pollution abatement rather than decarbonization per se.

China is changing. Many of the components of change, such as privatization, decentralization, price reforms, etc., will have ambiguous consequences for enforcing environmental regulations.

China and Environmental Agreements

China's experience with existing environmental agreements to which it is party leads Oksenberg and Economy [4] to the following conclusions:

- **Short-term benefits are needed.** This is likely to be particularly true in the case of any future agreement to reduce carbon emissions, where benefits, if any, are distant and global.
- **The accession stage, lead actors and dynamics among these actors affect the implementation.** An accurate understanding of the governmental, semi-governmental and private entities involved in implementation, together with their objectives and the constraints acting upon them, is needed if implementation is to be successful.
- **Throwing money at the implementing agency does not help.**
- **Expected necessary equipment, technology, training and financing must be provided over a protracted period.** The project cannot simply be started and then left to local authorities. In general, training and financing must be planned and carried out over several years.

As a result of this experience, institutional development at the local and provincial levels is essential. The lead agency in the central government by itself lacks the power to ensure compliance. However, the central government retains the power to mobilize the bureaucracy and the population on behalf of certain goals and, in particular, to rate local officials and to a degree control their advancement. Chinese officials at all levels are rated for performance and promotion by certain criteria. Criterion #1 everywhere is control of population growth. Criterion #2 is growth of output, measured by jobs and per capita "prosperity." Improving the environment accounts for only a small percent of evaluation today,

although that percentage is slated to increase in areas of high local pollution and consequent damage to health, crops and other essentials.

It cannot be overemphasized that China is changing. Many of the components of change, such as privatization, decentralization, price reforms, etc., will have ambiguous consequences for enforcing environmental regulations. In addition, conditions in China are extremely varied, ranging from extreme poverty and relative backwardness to comparative prosperity and a sophisticated industrial base. What will prove feasible politically and desirable economically in one region will not in another region.

Kyoto Article 12, Clean Development Mechanism and Baselines

Under Article 12 of the Kyoto Protocol signed in December 1997 (but not ratified by any state to date, and formally rejected by the U. S. Senate), Annex I countries can get emission credits toward meeting their obligations by investing in Non-Annex I country projects resulting in "certified emission reductions." Reductions will be certified on the basis of "real, measurable, and long-term benefits related to the mitigation of climate change." These certified reductions must be "additional to any that would occur in the absence of the certified project." This is the Clean Development Mechanism (CDM).

Doing more for the sake of lowering GHG emissions is probably a non-starter for now, both because there is no money and because this is felt to be a distant problem at best.

While preliminary assessments show that emissions trading in general and use of the CDM in particular can significantly lower the cost or increase the benefits to Annex I countries of meeting Kyoto protocol obligations (assuming these obligations are ever undertaken), nevertheless the CDM brings up serious questions, some of which are:

- No one knows how to define "real, measurable, and long-term benefits related to the mitigation of climate change." The usually accepted proxy is GHG emissions, usually carbon emissions. If this is to be a valid proxy for mitigation of climate change (leaving aside questions of what mitigation of climate change is), the net effect of a project on the emissions of the entire system connected with it, from production to end-use, must be calculated.
- Use of the CDM requires additionality, as noted above, and therefore baseline emission projections. Baselines may be defined for a country, a sector, a locality or a project, each with its own pros and cons. They may assume the application of all or some laws, policies, economically warranted improvements, etc. Baselines will evolve in time and will be subject to ups and downs of economic development.
- Non-Annex I countries assume no obligations or caps on their emissions under the protocol. In the absence of caps or other obligations, there will remain questions about leakage, moral hazard, adverse selection of projects. How serious any of these questions is will be affected by the particular choice of baselines, but it is likely that no choice can eliminate them entirely. The author and his colleagues are undertaking further research on this issue.

A Tentative Conclusion Regarding China

China already spends roughly 2% of its GDP on environment, the same percentage as the U.S. and some developed nations do. The actual sum is much lower, of course, and the Chinese problems are often much worse. Pollution abatement is minimal, focusing mainly

on particulates from large installations. Health, agricultural and other consequences of pollution from coal use are extremely serious, costing perhaps a tenth of GDP and forming the main source of mortality in certain cities. Pollution abatement is now the object of a growing domestic government effort, though it is still in practice a lower priority than jobs and increased wealth.

Doing more for the sake of lowering GHG emissions is probably a non-starter for now, both because there is no money and because this is felt to be a distant problem at best. On the other hand, there are efficiency improvements at all stages of energy production, transportation and consumption which would be economical in the local situation and which would significantly lower carbon emissions. If China is going to help deal with the GHG problem, such cost-effective GHG reductions are likely to provide the only way to do it.

There are efficiency improve-ments at all stages of energy production, transportation and consumption which would be economical in the local situation and which would significantly lower carbon emissions.

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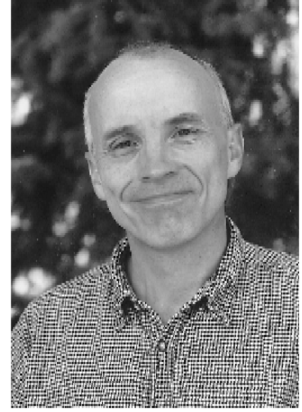
1. The numbers in this and the following sections are based on data from four sources: the Department of Energy's Energy Information Administration web pages, 1996-8; the International Energy Agency web pages; *China Energy Databook*, Jonathan Sinton, editor (Berkeley, CA: Lawrence Berkeley National Laboratory, University of California Berkeley, LBL-32822 Rev. 3, 1996); and the China Statistical Yearbook of the State Statistical Bureau of the PRC, 1997. Elasticity calculations, tables and graphs are the author's.

2. For instance, recent values for India have been 1.2, for Brazil 3.0. *International Energy Annual, 1993*, Energy Information Administration, U. S. Department of Energy, Washington, D. C., May 1995, p. vii.

3. Xiannuan Lin's *China's Energy Strategy: Economic Structure, Technological Choices, and Energy Consumption* (Westport, Connecticut: Praeger Publishers, 1996) takes a detailed look at these changes, concluding that "most of the energy savings between 1981 and 1987 came from energy-efficiency improvement" (p. 10). That is also the conclusion reached by Mark Levine and Jonathan Sinton, "Changing Energy Intensity in Chinese Industry: The Relative Importance of Structural Shift and Intensity Change." *Energy Policy*, **22**:239, March 1994.

4. Most of the results in this section are due to Michel Oksenberg and Elizabeth Economy, "China's Accession to and Implementation of International Environmental Accords 1978-95," Asia-Pacific Research Center, Stanford University, February 1998. Reprinted from Edith Brown Weiss and Harold K. Jacobson, editors, *Engaging Countries: Strengthening Compliance with International Environmental Accords* (Cambridge, MA: The MIT Press, forthcoming in 1998), Chapter 11. They also reflect private communications from Oksenberg and from Len Ortolano.



Fusion Energy: The Ultimate Energy Source or God's Little Joke?

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SESSION 1

Although we have made enormous progress in the scientific understanding and development of this field, we have, as yet, no clearly identified route to an attractive commercial fusion power plant.

Fusion, the release of nuclear binding energy from the light nuclei and its practical exploitation, has been a major world research discipline for the past four decades. Fusion promises an energy resource capable of indefinitely sustaining humanity under all conceivable scenarios of population growth and energy demand. In fact, it is the only energy source indigenous to the Earth that will last as long as the Earth exists. However, although we have made enormous progress in the scientific understanding and development of this field, we have, as yet, no clearly identified route to an attractive commercial fusion power plant that will sell in the energy marketplace of the 21st century and beyond. Arguably, this situation has been exacerbated by the premature concentration on a single route to fusion power. Because we are still at a relatively early stage of fusion development, it is essential to strive for a diversified program that is robust to the physics and technological uncertainties that accompany any single class of fusion reactor concepts.

It is commonly asked whether there will be a *need* for fusion energy in the next century. Here at least there is an answer. Electrical power generation in the 21st century will be a forty-trillion-dollar industry with an assured and significant growth in demand from the developing world. Thus, what we are really asking is: Do we have a sufficiently attractive fusion reactor product that will compete in this marketplace? If we do, then fusion will be "needed."

Fundamentally, therefore, the future viability of fusion energy comes down to the question of the competition: What else is out there? In the near term, the answer is fossil fuels in general and natural gas in particular. However, once our access to such fossil fuels has been foreclosed due to either exhaustion, environmental constraints or sequestering for other, more critical needs, there remain only two indigenous energy sources that are capable of fully sustaining humanity for the foreseeable future. These are fission and fusion. Therefore, a primary question is: How does our ultimate conception of a fusion reactor compare with fission?

Both fission and fusion are forms of nuclear energy but can be differentiated by various attributes including capital costs, safety, environmental issues, nuclear weapons proliferation, and fuel availability. The presently known reserves of fission fuels, if required to sustain the full electrical energy needs of future populations, would likely last around a century or less if utilized in conventional thermal reactors with a "once-through" fuel cycle. Such reserves could, however, be extended to thousands of years if efficiently utilized in breeder reactors with a reprocessed fuel cycle. Uranium could also, in principle, be extracted from sea water but with as yet unknown technology or costs. By contrast, lithium, the primary fuel

for first generation deuterium-tritium fusion reactors is significantly more abundant in the earth's crust than either of the primary fission fuels, uranium or thorium, and is about fifty times more abundant than uranium in sea water. Deuterium, arguably the ultimate fusion fuel for subsequent generation deuterium-deuterium fusion, comprises 0.015 atomic-% of all hydrogen on Earth. Thus, (deuterium) fusion at least is a fuel reserve that will be available to us for as long as the Earth continues to exist.

In regard to safety and the environment, the stored energy in the fuel of a fission core is sufficient for approximately two years of operation. Therefore, although adequately safe fission reactors probably can be designed, this source term for a severe accident remains at some level. By contrast, the amount of fuel present in the core of a fusion reactor of any class we can conceive of today is sufficient, at most, for only a few seconds of operation and would be continually replenished. Secondly, at the end of their life, the fuel rods in a fission core contain gigacuries of radioactivity in the form of fission products and actinides, some with half-lives extending from hundreds to millions of years, and necessitating disposal in a securely-guarded, deep geologic repository. By contrast, the main potential for generating radioactive waste in fusion comes from neutron activation of the surrounding structural materials. Consequently, a judicious choice of such materials can reduce fusion's biological hazard potential by many orders of magnitude relative to spent fission fuel.

Perhaps most importantly, with regard to the weapons proliferation issue, we must recognize that the necessary exploitation of breeder reactors to extend the fission fuel reserves of uranium and/or thorium beyond the next century will result in a significant reprocessing traffic of ^{239}Pu and/or ^{233}U. While international safeguards and security can no doubt be implemented, the diversion and exploitation of only a few kilograms of either of these fissile materials would be a severe test of the public's stamina for this energy source.

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We have made tremendous scientific progress in the world fusion program over the past forty years. That is incontrovertible. Our basic understanding of the rich and complex phenomena underlying plasma physics has increased profoundly, as has our ability to control these processes to our ends. In particular, our achievement of the basic figure of merit for magnetic confinement fusion — the product of the plasma density, energy confinement time and plasma temperature, $n\tau T$ — has increased by around six orders of magnitude over this period and is now approaching the value required to realize a sustained thermonuclear burn from a mixture of deuterium and tritium (d-t) fuel.

To date, we have expended the majority of the world's fusion research funds on the tokamak approach. Because of the tokamak's capacity for holding heat and its effectiveness in achieving the required magnetic field configuration, it has proved the best research tool so far for achieving fusion conditions in the laboratory. In the near future, for example, the Joint European Torus (JET) tokamak at Culham in the UK should approach, and hopefully exceed, "scientific break-even," whereby the output fusion energy exceeds the external energy injected to drive the reaction. So we have some confidence that the tokamak can conceivably produce a fusion power reactor that works.

For these reasons, the International Thermonuclear Experimental Reactor (ITER) project, a current international engineering design study of a burning fusion plasma experiment, has focused on the tokamak as its vehicle of choice. However, it is not clear that the conventional tokamak approach will lead to a practicable commercial power plant that anyone will be interested in buying. This is a consequence of its projected low power density, high capital cost, high complexity, and expensive development path. After all, the acid test for fusion energy is, ultimately, not its scientific achievements but its adoption by the marketplace. Certainly, the tokamak is a valuable scientific research tool for studying high temperature plasma physics and must be continued to be supported to that end. However, such support should not, and must not, come at the exclusion of other, potentially viable routes.

It is beyond the scope of this summary to examine an exhaustive list of alternative fusion concepts but, fortunately, a number do exist at varying stages of maturity. Within magnetic confinement fusion, the spherical torus, the spheromak and the field-reversed configuration suggest the potential of a significantly cheaper, more compact fusion power core and are certainly worth pursuing to the proof-of-principle stage. In particular, below I offer a class of fusion concepts which can be considered a step change in their manner of realizing fusion energy.

It is not clear that the conventional tokamak approach will lead to a practicable commercial power plant that anyone will be interested in buying. Inertial Fusion Energy provides a route to a fusion power plant which is a paradigm shift from that of a tokamak.

In "inertial fusion" energy (IFE), a millimeter-size capsule of fusion fuel is compressed by an energetic pulse of energy from a "driver," typically a heavy-ion accelerator or laser (Figure 32). The drive energy is delivered in a precise way to cause the fuel capsule to implode and, during the very short inertial time before the target flies apart, creates the very high densities and temperatures necessary for fusion to occur. Whereas both magnetic and inertial fusion are at approximately the same stage of scientific understanding, the scientific and technological criteria by which these two distinct approaches will succeed or fail are very different. In particular, IFE provides a route to a fusion power plant which is a paradigm shift from that of a tokamak and indeed all other fusion concepts of the magnetic confinement class. It offers the potential for lifetime fusion chambers with renewable liquid coolants facing the targets, instead of solid, vacuum-tight walls that would suffer damage due to heat and radiation. Thus protected, all reactor structural materials would be lifetime components and their minimal residual radioactivity would qualify them for near-surface, on-site burial at the end of the fusion plant life. Use of such thick liquid protection probably also eliminates the need for an expensive R&D program on exotic, low-activation materials. Moreover, note that IFE plants are inherently modular in that several, independent fusion chambers could be constructed around a single driver. This provides operational redundancy and the option of phased plant expansion to match demand growth, both important characteristics for future multi-GWe electrical reservations.

The science of inertial confinement fusion will be significantly advanced early in the next century by the completion and operation of the "National Ignition Facility" (NIF) at Lawrence Livermore National Laboratory in the U. S. Indeed, NIF may be the first laboratory device to realize fusion "ignition." This is the process whereby the energy deposited by energetic alpha particles from the d-t fusion reaction promotes a self-sustaining burn in the surrounding fuel, resulting in significant fusion energy gain.

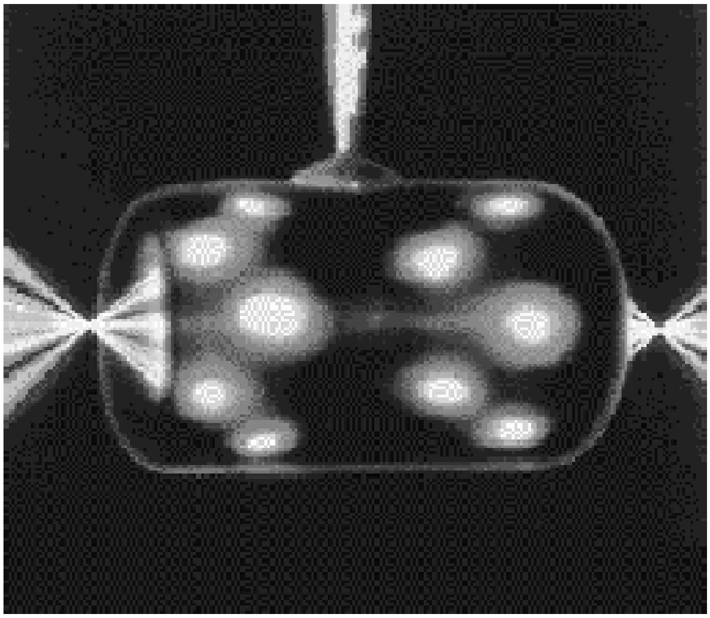

Figure 32
X-ray image of a thin wall, inertial confinement fusion target illuminated by the NOVA laser. Five laser beams enter the sub-centimeter-size houlrahm case at each end and are converted to X-rays in the cavity. The millimeter-size fusion fuel pellet (not visible) would be contained inside this case. *(Photo courtesy of LLNL Laser Programs)*

Conclusions
I contend that advances leading to a clearly economical fusion reactor lie in the parallel investigation of alternative approaches rather than simply in engineering the nuts and bolts for the present conventional approach. This is particularly important for the U. S. where fusion research budgets have declined in recent years and where a fresh, vigorous rationale is required. Thus, the smartest investment of our world research budgets is to press for innovation and understanding of the physics of various advanced concepts — because this is where the greatest uncertainties lie and where there is the greatest potential for improving the economics of the ultimate fusion power plant. Note also that alternative physics approaches are particularly important if we are ever to exploit the so-called “advanced” fusion fuels, such as d-d, d-3He, p-11B (see Table 8).

Such fuels have several advantages over d-t — for example, lower or zero neutron output and the potential to directly convert charged fusion products to electricity without need for a conventional thermal cycle — but would require significantly higher plasma densities and temperatures to realize even the same fusion power density. As in cancer research, the world fusion program has made enormous progress in the fundamental understanding of its field. However, also like cancer research, we have not yet arrived at our ultimate goal. Therefore, because of the profound benefit to future humanity of the ultimately successful end point — a limitless energy source for all time — we must continue with an innovative and, most importantly, diverse fusion research program until that goal is accomplished.

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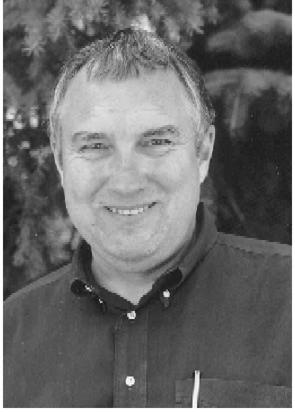
Table 8

Candidate fusion reactions with low-Z fuel nuclei. First generation fusion reactors will probably employ the d-t reaction. Subsequent generation reactors may exploit the other, so-called “advanced” fusion fuels.

d-t:	2H + 3H $\rightarrow$ 1n + 4He + 17.6MeV
d-d:	2H + 2H $\rightarrow$ 1H + 3H + 4.0MeV
	2H + 2H $\rightarrow$ 1n + 3He + 3.3MeV
d-3He:	2H + 3He $\rightarrow$ 1H + 4He + 18.7MeV
p-6Li:	1H + 6Li $\rightarrow$ 3He + 4He + 3.9MeV
d-6Li:	2H + 6Li $\rightarrow$ 1H + 7Li + 4.9MeV
p-11B:	1H + 11B $\rightarrow$ 3 4He + 8.7MeV

Alternative physics approaches are particularly important if we are ever to exploit the so-called “advanced” fusion fuels.

Hadi Dowlatabadi, Bob Watts, Don Wuebbles, Marty Hoffert, and Greg Benford in conversation at AGCI.



The Framework Convention on Climate Change: Rio, Kyoto, and Beyond

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The Framework Convention on Climate Change, the treaty that was agreed to at the 1992 Earth Summit in Rio de Janeiro and entered into force in 1994, along with the subsequent 1997 Kyoto Protocol to the Climate Convention, form the centerpiece of the international policy context for addressing the issues of global climate change.

In the Climate Convention the nations of the world: (1) recognize that potential anthropogenic climate change is a problem that must be addressed; (2) recognize a need for developed industrialized countries ("Annex I" parties in the terms of the treaty) to take the lead in mitigation; (3) acknowledge that the global nature of climate change requires the widest possible participation and cooperation by all countries, "in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions;" and (4) recognize that, in order for developing countries to progress toward the goal of sustainable development, their energy use will need to grow, while taking into account the possibilities for achieving greater energy efficiency and controlling greenhouse gases.

The Climate Convention creates a framework for global cooperation and establishes a process for taking future action on specific actions and commitments.

The 36 Parties included in Annex I to the Convention made a somewhat indirectly-worded commitment to the aim of returning their anthropogenic emissions of greenhouse gases (those not already controlled by the Montreal Protocol on the ozone layer) to their 1990 levels by the year 2000, and agreed to review this commitment and take appropriate action at the First Conference of the Parties. In addition, the 25 Parties included in Annex II (the developed countries not including the former Soviet Union and Soviet Bloc) agreed to provide new and additional financial resources to meet the costs incurred by developing countries in meeting their obligations (*e. g.,* national emissions inventories, national reports, and planning for mitigation and adaptation), and to facilitate and finance the transfer of environmentally sound technologies.

The Climate Convention is a step toward building institutions for global governance in the absence of a global government. It creates a framework for global cooperation and establishes a process for taking future action on specific actions and commitments. It takes steps that are generally agreed to make sense even in the context of scientific uncertainties, while encouraging scientific research and national data collection and planning. It includes a mechanism for being strengthened through the adoption of additional protocols and amendments, as scientific understanding and policy making develop.

Since the Climate Convention was negotiated, most nations' emissions have continued to increase. The First Conference of the Parties (COP-1), in 1995, concluded that the voluntary actions being implemented under the Convention were insufficient to move toward its stated ultimate objective to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The Parties agreed to negotiate binding targets and timetables for reducing net emissions. This "Berlin Mandate" reaffirmed the distinction between Annex I and developing countries in setting commitments. Further negotiations resulted in the Kyoto Protocol, agreed to at COP-3 in December 1997.

The Kyoto Protocol would require Annex I parties, individually or jointly, to ensure that their aggregate anthropogenic CO_2-equivalent emissions of six greenhouse gases are reduced by at least 5% below 1990 levels in the 2008-2012 time frame (*i. e.*, averaging over those five years). The U. S. would be required to reduce emissions by 7% below the 1990 level. Parties could use net changes in emissions by sources and removal by sinks resulting from direct human-induced land-use change and forestry activities, measured as verifiable changes in carbon stocks, in meeting their commitments. Decisions about methods for quantifying net emissions were left for future meetings, as were decisions about commitments in the post-2012 period.

SESSION 1

The Protocol contains a set of what have been called "flexibility mechanisms" intended to facilitate and cut the costs of emissions reductions.

The Protocol contains a set of what have been called "flexibility mechanisms" intended to facilitate and cut the costs of emissions reductions. These provisions include: (1) trading of emissions allowances among Annex I countries; (2) joint implementation among Annex I countries, in which Parties may transfer or acquire emissions reduction units in exchange for implementing projects that reduce net emissions that are additional to what would otherwise occur; and (3) a Clean Development Mechanism, via which Annex I countries may use certified emissions reductions from certified projects implemented in developing countries to contribute to meeting their own requirements. All specific procedures for implementing these flexibility mechanisms remain to be established by the Parties at future meetings, as do procedures and mechanisms to determine and address cases of noncompliance with the Protocol.

The Protocol's "entry into force" would occur when 55 Parties to the Climate Convention, including Annex I parties that accounted in total for at least 55% of the total Annex I CO_2 emissions in 1990, have ratified the Protocol. There are important distinctions between the nations' "agreement" to the Protocol by diplomatic negotiators in Kyoto, "signing" of the Protocol by heads of government or their representatives, "ratification" of the Protocol as law in each of the signatory countries (which, in the U. S., requires a vote in the Senate), entry into force after the requisite number of Parties have ratified, agreement on specific procedures for implementation, and the actual implementation of the Protocol by the Parties. It is unclear when and whether the Protocol will enter into force, and it is not binding in a formal, legal sense on the Parties unless and until it does so. As of late November, 1998, 64 countries had signed the Protocol, but only the two Pacific island nations of Fiji and Tuvalu had ratified it. None of the Annex I countries have ratified. Theoretically, the Kyoto Protocol could enter into force without U. S. ratification, but politically this may be unlikely.

In the meantime, the Climate Convention remains the only agreement in force. The Fourth Conference of the Parties (COP-4) was held in Buenos Aires in November, 1998. The Parties at COP-4 adopted the Buenos Aires Plan of Action, which is intended to prepare for the future entry into force of the Kyoto Protocol and to maintain political momentum by continuing the planning and negotiating process on specific unresolved issues in advance of future COPs, with a commitment to reach agreement on a number of key issues in time for COP-6 in the year 2000.

The Kyoto Protocol has created a new element in the U. S. policy process. For the first time since the potential for global warming became a salient public issue in the late 1980s, Congress has been confronted with the possibility of having to act on a major controversial legislative issue related to climate change. In contrast to the Climate Convention, which the Senate ratified without significant controversy in 1992, ratification of the Protocol would entail a willingness to adopt a legally binding target and timetable for significant reductions in U. S. emissions of greenhouse gases. A 7% reduction from the 1990 level by 2008-2012 would require on the order of a 30% reduction from the projected level of U. S. emissions in that future time period. There is considerable controversy among analysts with varying methods and assumptions about the potential economic implications of achieving this reduction.

In Congress, prior to 1997, climate change tended to be of interest primarily to a small group of Members with a specialized interest in scientific and environmental issues. Most Members had no clearly identifiable position on climate science and related diplomatic developments, except that most tended, when called upon, to line up either on a partisan basis, for or against the perceived policy of the current President, or in predictable ways vis-à-vis major economic stakeholders in their states or districts. The Kyoto Protocol, on the other hand, has brought into active play a number of Members who had not been associated primarily with scientific and environmental issues in the past, and whose concerns have been expressed primarily in terms of potential economic implications. Much of the current controversy in Congress, which has held numerous hearings on the issues raised by the Kyoto Protocol, also has clear partisan overtones.

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However, one key issue that has drawn bipartisan support is about the role of the developing countries. In the summer of 1997, the Senate adopted unanimously the Byrd-Hagel resolution, which called on the President to not agree to a Kyoto Protocol unless it contained "scheduled commitments to limit or reduce greenhouse gas emissions for Developing Country Parties within the same compliance period" as those for Annex I Parties. The resolution also stated that submission of a Protocol for Senate ratification should be accompanied by "an analysis of the detailed financial costs and other impacts on the U. S. economy that would be incurred by implementation."

The Senate position expressed in this resolution is a key political development. Opponents of the Kyoto Protocol and a stronger U. S. mitigation policy obtained substantial leverage with the issue of differential commitments for Annex I and developing country parties, which had not previously been controversial. The President has not submitted the Protocol to the Senate, where it would face decisive rejection at this time, pending further diplomatic steps

SESSION 1

to secure a commitment by developing countries to a more active role in constraining their emissions. Further, the President promised to refrain from taking steps within the Executive Branch to implement Kyoto Protocol commitments prior to Senate ratification, and the Congress reinforced this agreement through a number of actions during the FY 1999 appropriations and legislative oversight processes.

While the Kyoto Protocol presents a number of issues that remain unresolved in negotiations, the issue of developing country participation remains a stumbling block. Most of the "G-77/China" coalition of developing countries has been opposed — with China and India adamantly opposed — to adding new requirements for developing countries, contending instead that Annex I countries should focus on implementing the commitments they have already made.

The Kyoto Protocol may be taken as a signal to governments, businesses, and citizens generally that climate change is a serious policy issue, that limits will be required on future emissions, and that now is the time to begin developing the necessary technologies. Some governments and private sector firms may begin to take actions to reduce emissions in anticipation of more stringent requirements going into effect in the future. Some may anticipate gaining an economic advantage from adopting or marketing technologies that reduce emissions. However, there is a question whether voluntary and market-driven actions alone will be sufficient to drive a transition to a sustainable energy system that will help achieve the ultimate objective of the Climate Convention, or whether strong national and international policy commitments will be necessary. On the other hand, there is a question whether diplomacy and policy will be sufficient to effect a transition unless a compelling path to technological solutions emerges.

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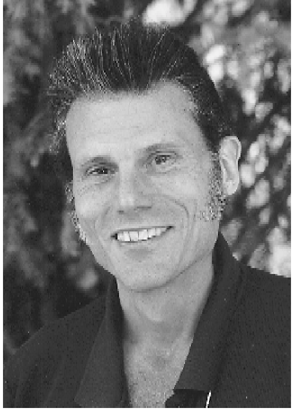
Reference

The full text of the Framework Convention on Climate Change, the Kyoto Protocol, a "Preliminary Version of COP 4 Decisions and Resolutions" agreed to at the Fourth Conference of the Parties to the FCCC in Buenos Aires in November 1998, and other related documents, are available at http://www.unfccc.de/, the official web site of the Climate Change Secretariat.



Exploratory Modeling, Robust Adaptive-Decision Strategies, and the Impacts of Climate Variability on Near-Term Policy Choices

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The key step in solving a complex problem is often asking the right question. We believe that the proper question for the climate-change problem is "what actions should we take, given that we cannot predict the future course of climate change nor the effort that may be required to prevent it?" The answer is that society should seek strategies that are robust against a wide range of plausible climate-change futures. By definition, a robust strategy is insensitive to our uncertainty about the future. It would perform reasonably well, at least compared to the alternatives, even if confronted with surprises or catastrophes. In addition, a robust strategy may provide a more solid basis on which to build a consensus for political action among stakeholders with different views of the future because all would agree it would provide reasonable outcomes no matter whose view proved correct. Clearly, a robust strategy for climate change would be a good thing to pursue. The question is, do such strategies exist and, if so, do we have the means to find and assess them?

Society should seek strategies that are robust against a wide range of plausible climate-change futures.

Exploratory Modeling

Over the last several years we have developed a set of computational methods for decision-making under conditions of extreme uncertainty that are well-suited to find and assess robust strategies for climate change (Lempert, Schlesinger and Bankes (1996), henceforth LSB; Lempert, Schlesinger, Bankes, and Andronova (Lempert *et al.* 1999), henceforth, LSBA). These methods, called exploratory modeling (Bankes 1993; Bankes and Gillogly 1994), are designed to exploit the qualitatively new capabilities of modern computers, in particular, large quantities of inexpensive memory; fast, networked processors; and powerful visualization tools. Exploratory modeling confronts uncertainty by creating a large database of plausible futures that can be used to distinguish among policy choices. As applied to the climate-change problem, these exploratory modeling methods begin with computer-simulation models that describes the climate, economic, and related systems. Using time series and other data to constrain the model inputs, we project a very large number of plausible paths into the future, without necessarily assigning likelihoods to any of them. Next, we compare the performance of a variety of alternative strategies against this "landscape of

plausible futures" to create a large database of scenarios. We use one or more metrics to distinguish among those scenarios with desirable and undesirable outcomes. We can then use search techniques and visualizations to extract information from this database that can distinguish robust from non-robust strategies.

A key idea behind exploratory modeling – that we can regard the output of a simulation model as a large, multi-dimensional dataset – is useful for the climate-change problem because it allows great flexibility in the search for robust strategies. On the one hand, traditional optimization techniques that provide a systematic method for comparing alternative strategies, also impose strict constraints on the types of feedbacks that can be included in the underlying model. Since promising candidates for robust strategies often employ complex information feedbacks, this greatly limits the types of strategies that optimization methods can consider. On the other hand, many simulation approaches that can treat such complex feedbacks employ something of a "flight simulator" approach (Holland 1995) to examining the consequences of different assumptions. That is, the analyst will personally examine a small number of potential paths into the future and report on those that seem most interesting. Such analyses offer scant basis on which to extrapolate insights to the cases not considered.

Our exploratory modeling work on robust strategies argues that society can adopt adaptive decision-strategies as a robust response to climate change. Such strategies are designed with the expectation that they will be adjusted in the future based on observations.

In contrast, exploratory-modeling analyses attempt to make systematic arguments from a simulation model by using the computer to search through a very large set of plausible runs looking for cases that support or disprove particular lines of argument. This approach often yields fruit because we often have a great deal of information about the future which, while not capable of supporting predictions, can help argue that one set of strategies is more robust than any proposed alternatives. However, the flexibility provided by regarding the model outputs as a database is important because it is not generally obvious, a priori, what strategies the available information can distinguish nor what criteria for robustness ought to be used. Rather, we must often work through an iterative process – explore – looking for arguments about strategies that can be supported by the available information. With exploratory modeling one can return repeatedly to the simulation models to generate more data points when that would prove useful. In particular, the analyst can use interim results to generate new ideas for potential strategies that might prove more robust than the ones under consideration. For example, recognizing that strategy A outperforms Strategy B in some plausible futures but does poorly in others, an analyst might guess that a particular mixture of A and B might perform reasonable well across all futures, and could test this hypothesis by running the new strategy against the set of plausible futures.

Robust, Adaptive-Decision Strategies

The analytic ability to find robust strategies does not, of course, guarantee that they exist. Our exploratory modeling work on robust strategies argues, however, that society can adopt adaptive decision-strategies as a robust response to climate change. Such strategies are designed with the expectation that they will be adjusted in the future based on observations of changes in the climate and economic systems. In LSB we compared the performance of a very simple adaptive-decision strategy with that of two static alternatives, "Do-a-Little" and "Emissions-Stabilization," commonly proposed in the political debate over climate change. As the names imply, the "Do-a-Little" policy has no near-term emissions reductions and is

similar to that advocated by many opponents of the commitments negotiated at the Conference of Parties in Kyoto in December 1997, while the "Emissions-Stabilization" policy returns and holds global emissions close to their 1990 levels through the mid-21st century and is similar to the policies proposed by many advocates of the Kyoto agreement. We compared the performance of these three strategies, using the present value of net costs and benefits as the measure, against a broad range of plausible futures, including ones in which damages due to climate change turn out to be very large, futures where damages are very small, futures in which technological innovation radically reduces the cost of greenhouse-gas-emissions abatement, and futures where it does not. We compared the expected value of these strategies for a wide range of expectations about the likelihood of these alternative futures, and found that even a very simple adaptive-decision strategy on average significantly outperforms either of the best-estimate policies unless society is highly certain, on the order of 95%, that either "Do-a-Little" or "Emissions-Stabilization" is the best policy.

This result is not particularly surprising. The "Do-a-Little" and "Emissions-Stabilization" policies perform well if their underlying assumptions turn out to be valid, but can fail severely in those cases where their assumptions turn out to be wrong. The adaptive-decision strategy can make midcourse corrections and avoid significant errors. Furthermore, the search for robust, adaptive-decision strategies offers an important recasting of the climate-change-policy problem which may better address the needs of decision-makers than other approaches such as optimum policies based on subjective probabilities.

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Nominally, the focus of the international political process addressing climate change is on binding targets and timetables for the reduction of near-term greenhouse-gas emissions. Analytic approaches that intrinsically assume that there is some optimum level of near-term reductions, are naturally supportive of, and make it difficult to critique, this emphasis. Nonetheless, the output of the actual negotiations more closely resembles an evolving set of actions designed to shape the future political landscape and influence private-sector investments than it does any consensus about the optimum level of emissions reductions. An incremental approach is probably quite sensible given the political constraints, but raises the broader question of whether or not the current potpourri of actions is sufficiently robust. That is, are the world's nations taking a combination of actions that will avoid major failures no matter what future comes our way? Given that policy actions will change over time, is society currently placing too little effort in some areas and too much in others? And given that there is at present no way to determine what is the correct level of emissions reductions, what ought to be to goals of climate-change policy?

An analytic approach that searches for robust, adaptive-decision strategies offers a framework to address such questions. As a first step, our work suggests that climate change ought to be viewed more as a contingency problem than an optimization problem. Either society will have to make very large reductions in greenhouse-gas emissions over the course of the next century or it will not. Since society does not yet know which future will happen, it needs to prepare for both. Thus the most important near-term goals of climate-change policy may be to: (i) reach consensus on the observations that will indicate a need for drastic action to curtail greenhouse-gas emissions, (ii) take actions that will make large future reductions more feasible and less costly if, in fact, they are needed, and (iii) do this in such a way as to

avoid over-allocating resources to a problem that turns out to be minor or insufficiently preparing for what we discover is an emerging catastrophe.

The Impacts of Climate Variability on Near-Term Policy Choices

In our recent work we have made initial forays into addressing these issues. In LSBA we examine the performance of adaptive-decision strategies in the face of climate variability. This is a key question because variability may reduce the benefits of such strategies by masking adverse trends until it is too late to act or, conversely, fooling society into taking too-strong actions. We find that in most cases adaptive-decision strategies are still robust even with quite large levels of climate variability.

In LSBA we consider a large number of alternative adaptive-decision strategies that differ in the rate of near-term emissions reductions, the confidence they demand that observed damage trends are real before responding to them, and the aggressiveness with which they respond to potential innovations that could reduce the cost of greenhouse-gas reductions. We find a set of robust, adaptive-decision strategies as a function of expectations about the future of climate change. That is, for each set of expectations of the future, we find the adaptive-decision strategy that is close to the optimum for that set of expectations and also performs well over a wide variety of other expectations.

In most cases adaptive-decision strategies are still robust even with quite large levels of climate variability.

Two interesting patterns emerge as one examines this set of robust strategies as a function of expectations about the future. First, there is a tradeoff between the rate of near-term emissions reductions and the confidence one should require in observations of damage trends before acting on them. That is, in the face of variability in the climate system, policy-makers can choose a response threshold for observed damages that can compensate, to a greater or lesser extent, for any choice of near-term emissions-reduction target. Second, the rate of near-term emissions reductions depends most sensitively on expectations about the future, while the aggressiveness with which society ought to respond to innovations are the least sensitive. That is, the policy choice at the focal point of the current negotiations may be the most controversial component of a robust strategy, in part because stakeholders with different expectations will have the most divergent views as to the proper target, while the least controversial components may be at the periphery of the negotiations.

Conclusion

It is of course a political judgment as to whether or not the most controversial elements ought to be at the center or the periphery of diplomatic negotiations. The role of policy analysis, however, is to ensure that the decision space is clear. The search for robust, adaptive-decision strategies suggests that a robust response to climate change should employ a number of different types of government and private sector actions, from technology development to emissions trading, and that there is a wide variety of reasonable, and a wider variety of unreasonable, combinations of such actions. More broadly, it suggests that a climate-change strategy that puts more emphasis on policies such as establishing the physical and institutional capability to monitor the relevant climate and economic systems, establishing the capability to effectively regulate greenhouse gases, and encouraging the use of new emissions-reducing technologies (Jacoby *et al.* 1998) would be at least as successful as the current declared approach of meeting particular targets for reductions in greenhouse-gas emissions.

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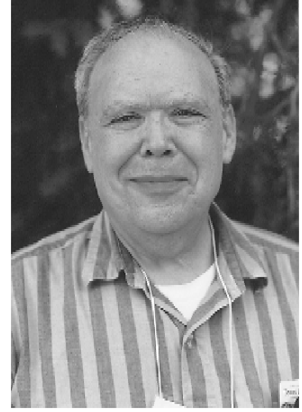
Michael Schlesinger makes a point to AGCI Director, John Katzenberger.

A robust response to climate change should employ a number of different types of government and private sector actions, from technology development to emissions trading.



The Effect of Energy Consumption on Climate Modification

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A scenario was built in the simple spreadsheet modeling study discussed in this paper for projecting the atmospheric concentration of CO_2 and the other infrared absorbing trace gases in order to estimate future global average temperatures.

In this work, per capita energy growth patterns were used to project the growth of atmospheric CO_2. Population of less developed countries is projected to grow 2.7 times from 50% to 67% of world population from 1991 to 2100. Over the same period, world population is projected to grow from 5.0 to 10.3 billion people, and energy use from 15 to 50.7 terawatts (TW). Less developed country (LDC) energy use is projected to grow disproportionately faster, increasing from 20 to 46% of world energy, while the share of energy use in industrialized countries is projected to decline from 30 to 22% of world energy. It is anticipated that the global standard of living will improve substantially while relative energy consumption will decrease on the order of 1.1% per year due to conservation and efficiency improvements. Non-fossil energy sources consisting mostly of nuclear energy are projected to overtake fossil energy consisting mostly of coal in the year 2075. The growth of CO_2 emissions from 6 to 18.2 GtC/yr is projected to result in an average global temperature increase of 3˚C due to this source only. However, CO_2 is only about half the problem. When all infrared absorbing gases are considered, an average increase of 5.6˚C is projected for 2100. This scenario is similar to the IPCC scenario IS92a.

The atmospheric monitoring program by Keeling, *et al.* (1997) shows that the level of carbon dioxide in the atmosphere has increased about 16% over the last 39 years and now stands at about 365 ppmv. This observed increase is believed to be the continuation of a trend that began in the middle of the last century with the start of the Industrial Revolution. Fossil fuel combustion, cement manufacturing, and the clearing of virgin forests (deforestation) are considered to be the primary anthropogenic contributors, although the relative contribution of each is uncertain because forestation changes appear to have been a net source during some periods of time and a sink during other periods.

Predictions of the climatological impact of a CO_2-induced greenhouse effect draw upon various mathematical models to gauge the global average temperature increase. The scientific community generally discusses the impact in terms of doubling pre-industrial atmospheric CO_2 content in order to get beyond the normal fluctuations (noise level) of climate data. A scenario was built in the simple spreadsheet modeling study discussed in this paper for projecting the atmospheric concentration of CO_2 and the other infrared absorbing trace gases in order to estimate future global average temperatures. The scenario is based on data presented by Rogner (1986) on regional energy consumption, global energy requirements by Häfele (1981) with modifications from various industrial projections, growth pro-

jections of CH_4, N_2O, CFC-11, CFC-12, and other CFCs by Ramanathan (1985) and Wigley (1987) as summarized by Krause, *et al.*, (IPSEP, 1989), and energy efficiency improvement and conservation measures from various sources. The scenario discussed here is similar to the business-as-usual scenario IS92a in the IPCC study (Pepper, *et al.*, 1992).

Methodology

The impact of per capita energy growth patterns on future energy demand and growth of atmospheric carbon dioxide was evaluated by subdividing the globe into six regions. Within each of these regions, there are similar sociopolitical backgrounds and population growth rates. The six regions considered are: (1) North America (U. S. and Canada) [NA], (2) Middle East (North Africa and Persian Gulf States) [ME], (3) Commonwealth of Independent States and Eastern Europe [CISEE], (4) China and other centrally planned Asiatic economies [CPAE], (5) Industrialized Countries (including Western Europe, Australia, New Zealand, Israel, Japan, and South Africa) [IC], (6) Less Developed Countries (including all of South and Central America, Central Africa, and the rest of Asia) [LDC].

Population and Energy

Although economic considerations are critical in determining per capita energy use, this study did not independently evaluate economics, but used the projections of Edmonds, *et al.*, (1984). It was found that 50% of the world's population currently residing in LDC will grow to 67% by 2100, while world population will grow from 5.0 to 10.3 billion people in the year 2100. Consequently, the world's energy needs are predicted to grow from 15 to 50.7 TW (Figure 33) while the LDC needs will grow from 20 to 46%, and the IC needs are projected to decrease from 41 to 22% (Figure 34). The apparent decrease in energy demand by the IC is not anticipated to affect the standard of living, because substantial increases in energy efficiency are expected to be implemented (*e. g.*, power plant efficiencies are 45% in the year 2000, 53% in 2050, and 56% in 2100).

The impact of per capita energy growth patterns on future energy demand and growth of atmospheric carbon dioxide was evaluated by subdividing the globe into six regions.

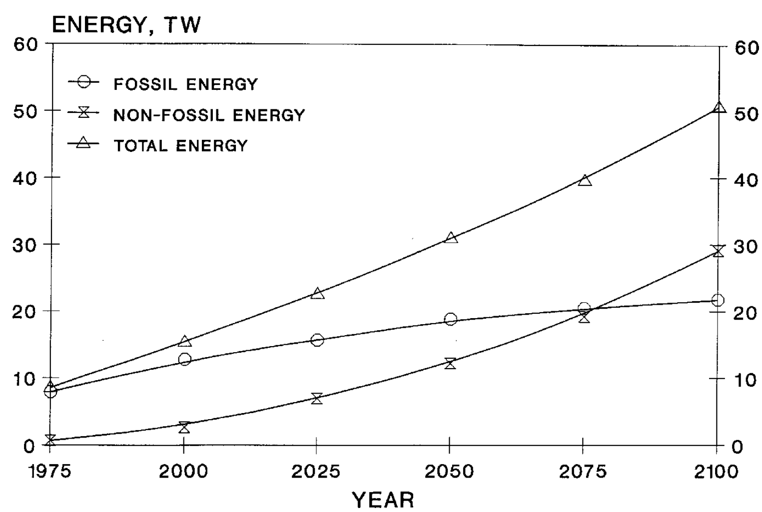

Figure 33

Comparison of Total Primary Fossil and Non-Fossil Energy Sources as projected by H. Shaw's model

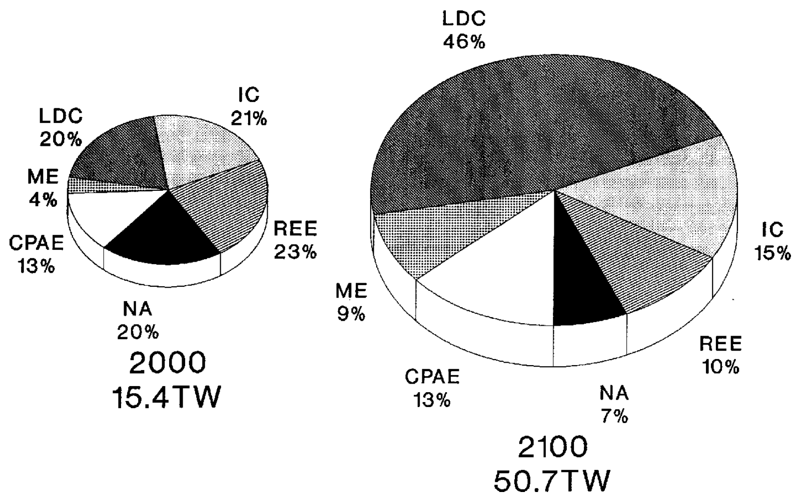

Figure 34
Total Primary Energy Comparison by Region as projected by H. Shaw's model

Non-fossil energy sources are projected to grow faster than fossil fuels and cross about the year 2075.

Per capita energy use is projected to decrease in NA as a consequence of energy demand reductions of about 30% by the year 2100. This corresponds to 1.1% per year energy decrease after considering the effect of increasing population. Similar conservation and efficiency improvements are projected worldwide. Power plant and automotive efficiency improvements were explicitly considered; other effects such as decreasing consumption of electricity for lighting, heating, refrigeration, and air conditioning (with fluids other than banned chlorofluorocarbons) were assumed as part of the model based on Geller's (1986) projections and reasonable market penetration and replacement rates.

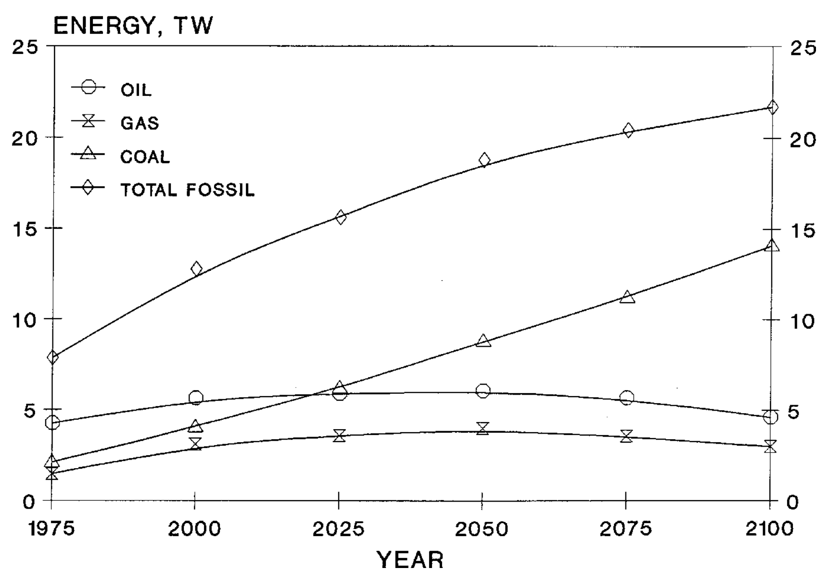

Figure 35
Primary Fossil Energy Sources as projected by H. Shaw's model

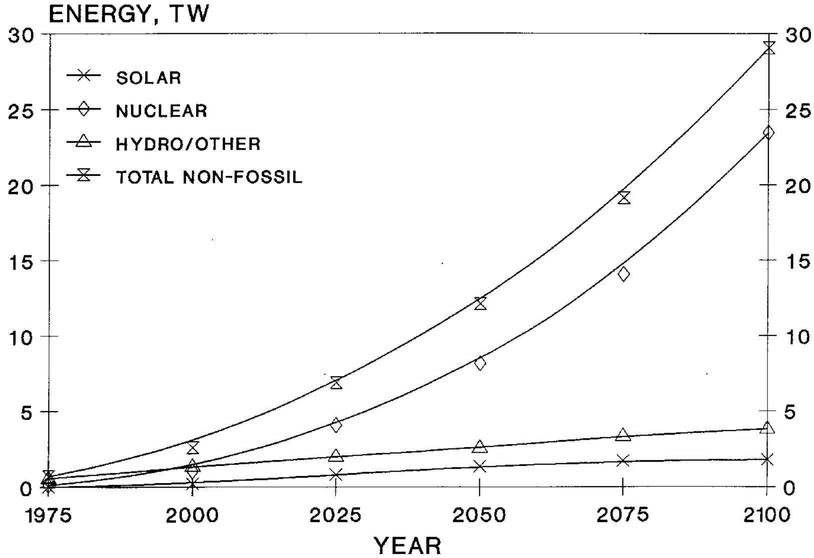

Figure 36
Primary Non-Fossil Energy Sources as projected by H. Shaw's model

Non-fossil energy sources are projected to grow faster than fossil fuels and cross about the year 2075 (Figure 33). After 2025, the predominant fossil fuel is projected to be coal (Figure 35) and the predominant non-fossil energy source, nuclear (fission, fusion or both) (Figure 36). The use of renewable energy will grow exponentially, but is not projected to dominate as a non-fossil fuel source because it is very area intensive, thus conflicting with population growth. It should also be noted that most of the fossil fuel energy will be used in transportation and not for stationary power or other industrial energy uses.

Carbon Emissions

Carbon emissions are estimated to grow from the current 6 to 18.2 GtC/yr in 2100 (Figure 37). Per capita emissions of carbon will decrease for NA and CISEE, and increase for the rest of the world. But, the relative order for the six global regions will remain the same between 1975 and 2100. It should be noted, however, that the percentage contribution from the LDC and ME is projected to increase from 23 to 55% (Figure 38).

It is projected that the 1975 atmospheric CO_2 concentration will double by 2100, resulting in an equilibrium global average temperature increase of 3°C due to this constituent only. These results agree well with the Edmonds, *et al.*, (1984) median case (B) projections, albeit under different synthetic oil projections. Another global average temperature projection due to CO_2 only can be made on the assumption that the equilibrium global average temperature exceeded the 0.5°C normal temperature fluctuation level in 1980, and the preindustrial concentration was 280 ppm CO_2. The latter projection predicts a temperature increase of 2.4°C in 2100. When the other radiatively and chemically active trace gases are included in a model using the radiative forcing constants for CO_2, CH_4, N_2O, CFC-11, CFC-12, and all other CFCs, then one predicts a temperature increase of 5.6°C in 2100. These estimates do not consider possible negative feedback mechanisms such as high cloud

It is projected that the 1975 atmospheric CO_2 concentration will double by 2100. The percentage contribution from the Less Developed Countries and the Middle East is projected to increase from 23 to 55%.

formation. The question of which predictions and which models best simulate a carbon dioxide and other trace gas-induced climate change is still being debated by the scientific community. The incremental temperature increase would not be uniform over Earth's surface. The poles are likely to see temperature increases on the order of 10°C while there may be little, if any, temperature increase at the equator.

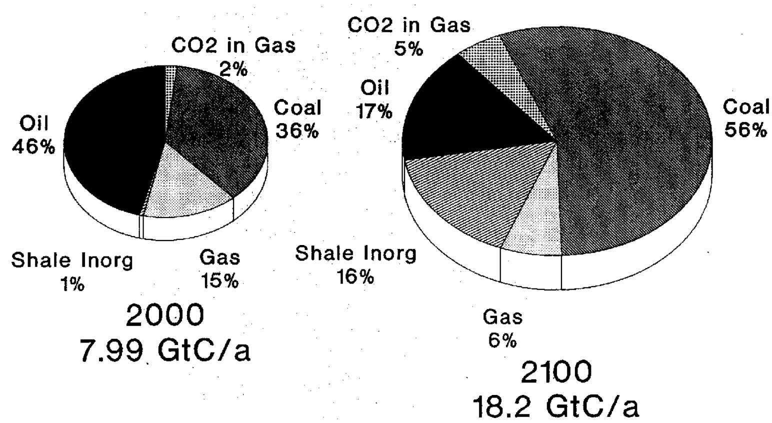

Figure 37
Comparison of Carbon Emissions by Source as projected by H. Shaw's model

There is concern among some scientists that once the effects are measurable, they might not be reversible.

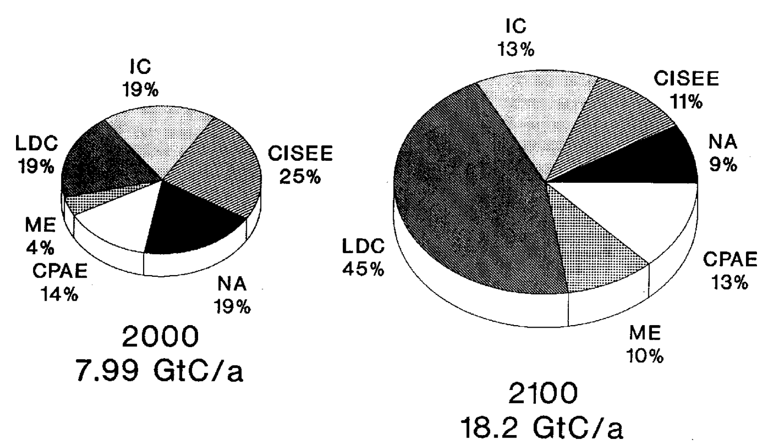

Figure 38
Comparison of Carbon Emissions by Region as projected by H. Shaw's model

Climate

The author of this study believes that there is currently no definitive scientific evidence that the Earth is warming. If the Earth is in a warming trend, we are not likely to detect it conclusively before the year 2000. This is about the earliest projection of when the temperature might rise above the 0.5°C needed to get beyond the range of normal temperature fluctuations. On the other hand, if climate modeling uncertainties have exaggerated the temperature rise, it is possible that an enhanced greenhouse effect induced by infrared

absorbing gases may not be detected until 2020 at the earliest. It should be noted that the equilibrium response of climate, as estimated by global average temperature, lags the measured temperature by about two decades due to the thermal inertia of the oceans.

Further, it is this author's opinion that the greenhouse effect is not likely to cause substantial climatic changes until the average global temperature rises at least 1°C above today's level. This could occur in the first to second quarter of the next century. However, there is concern among some scientists that once the effects are measurable, they might not be reversible, and little could be done to correct the situation in the short term. Therefore, some call for action now to prevent a potentially undesirable situation from developing in the future.

Mitigation of the greenhouse effect would require major reductions in fossil fuel combustion. Shifting between fossil fuels is not a feasible alternative because of limited long-term supply availability for certain fuels, although oil does produce about 18% less carbon dioxide per kWh of heat released than coal, and gas about 32% less than oil. The energy outlook suggests synthetic fuels will have a negligible impact, contributing less than 10% of the total carbon dioxide released from fossil fuel combustion by the year 2050. This low level includes the expected contribution from carbonate decomposition that occurs during shale oil recovery and assumes essentially no efficiency improvement in synthetic fuel processes above those currently achievable. After 2050, however, the contribution of carbonate decomposition may account for as much as half the total carbon emitted from oil utilization, and CO_2-contaminated natural gas from remote deposits may account for half the natural gas CO_2 emissions.

The model discussed in this paper can be used to evaluate alternative scenarios dealing with different population growth rates, distribution of primary energy sources, sequestration of CO_2, and geoengineering approaches.

SESSION 1

Conclusions

Based on the business-as-usual model presented here, one can conclude that global climate modifications will not occur as rapidly as predicted in the early 1970s and still quoted today. Consequently, time should be available to resolve uncertainties regarding the overall carbon cycle and the contribution of fossil fuel combustion, as well as the role of the oceans as a reservoir for both heat and carbon dioxide. During this time, additional research must be conducted to better define the effect of carbon dioxide and other infrared absorbing gases on climate. The model discussed in this paper can be used to evaluate alternative scenarios dealing with different population growth rates, distribution of primary energy sources, sequestration of CO_2, and geoengineering approaches for mitigating global climate change. The similarity between the simple spread sheet model presented here and the IPCC IS92a model can facilitate rapid and inexpensive scenario comparisons.

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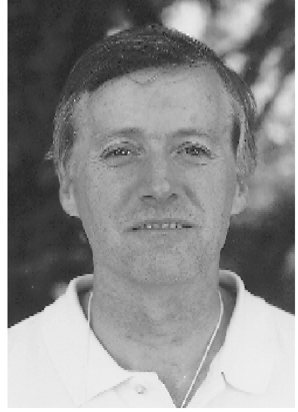
The similarity between the simple spread sheet model presented here and the IPCC IS92a model can facilitate rapid and inexpensive scenario comparisons.



Renewable Energy: How Much? How Soon?

Walter Short
National Renewable Energy Laboratory
Golden, Colorado

There have been a number of recent estimates made within the U. S. Department of Energy of the potential for renewable energy technologies to reduce U. S. emissions of greenhouse gases (GHG). These include the Annual Energy Outlook 1998 (AEO98), the "5 Lab report" on Scenarios of U. S. Carbon Reductions, and the "11-Lab report" on Technology Opportunities to Reduce U. S. Greenhouse Gas Emissions. Each of these reports was designed for a different purpose and with different assumptions, and the potential they show for renewables to reduce GHGs is notably different. The AEO98 takes a conservative business-as-usual approach in the development of its reference case that shows non-hydro renewables increasing from 10 gigawatts of electric energy (GWe) in 1996 to 15 GWe by 2020, equivalent to reducing carbon emissions by only approximately 7 million metric tonnes of carbon per year (MMTC/yr).

The Business-as-Usual paradigm of the AEO98 can be contrasted with the more optimistic estimates of the 11-Lab study. The 11-Lab study estimates that by 2020, renewables could reduce U. S. carbon emissions by 30-60 MMTC/yr, contrasted with 7 MMTC in the AEO98 reference case. Only a small portion of this difference can be attributed to the fact that the 11-Lab study was designed to estimate potential, not market penetration as in the AEO98. The vast majority of the difference can be attributed to differences in assumptions as to future improvements in renewable energy technologies and the magnitude of the renewable resources themselves.

The 11-Lab study estimates that by 2020, renewables could reduce U. S. carbon emissions by 30-60 MMTC/yr, contrasted with 7 MMTC in the AEO98 reference case.

The large amount of renewables that might be deployed in a climate change scenario will require the use of resource sites that are not as attractive as the best sites available today. Typically, deployment of renewables will occur first at the most economic sites and later, at less attractive sites. The value of a site is determined by a host of factors, including not only the quality of the renewable resource itself, but also physical access to the site, transmission access, terrain considerations in construction, etc. The results shown below for the potential of renewables to reduce U. S. GHG emissions, consider both future RD&D-driven reductions in the cost of renewable energy and increases in the cost of renewable energy as less attractive sites are used.

Approach of This Study

Unlike the AEO98 and 11-Lab studies, we show below (Figure 1) the amount of carbon emissions that might be reduced as a function of the cost of the reduction expressed in terms of dollars per metric tonne of carbon. Such a representation is comparable to a standard supply curve, but differs in that the axes are inverted and in that the curve represents the supply of both renewables and carbon-reduction opportunities. For cases in which the carbon reduction opportunities are limited, competition occurs not only with fossil fuels, but

also between the different renewable energy forms. The technology that can reduce carbon emissions at the lowest cost wins the competition, assuming perfect markets with no market failures or barriers. Actual market penetration is expected to be considerably smaller, and will begin to approach these estimates of potential only with R&D success, expanded technology transfer activities, and energy policy that makes energy market transactions reflect the full cost of energy use.

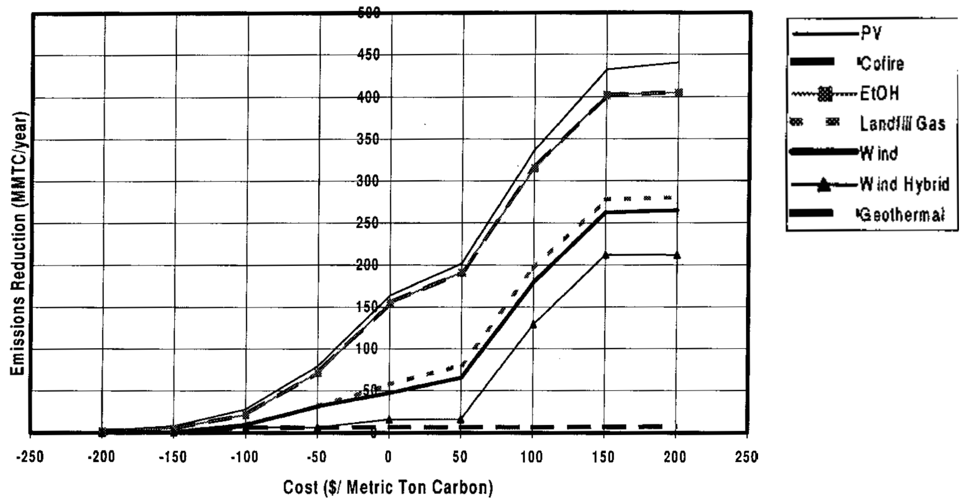


Figure 39
Renewable Energy Carbon Reduction Supply Curve for the Year 2020

The technology that can reduce carbon emissions at the lowest cost wins the competition, assuming perfect markets with no market failures or barriers.

The supply curve of Figure 39 is for the year 2020. Separate, national carbon reduction supply curves have been developed for every five years from 2000 to 2020. Each single-year curve represents a snapshot of the economic potential of renewables if the renewable technologies were installed instantaneously in that year. Deployments would have to occur over a longer period of time to come close to the potentials shown. Of course, developments over a longer period of time would reflect dynamic market conditions, not the static conditions assumed here for the particular year of each curve. Each year's curve assumes fossil fuel prices and demand for energy in the U. S. grow in accord with the reference case of the Annual Energy Outlook 1998 (DOE/EIA 1997). Demands, prices, and renewable resources are disaggregated to the state and regional level.

Not all renewable energy forms are included. The results shown are cumulative with the bottom curve representing geothermal, and the difference between the bottom curve and the next curve representing wind hybrid. Subsequent curves represent wind, landfill gas, ethanol, biomass co-firing of coal plants, and photovoltaics (PV) in buildings. PV in buildings is assumed to compete against retail electricity rates, while all other renewable electric technologies compete against either the full amortized cost of new combined-cycle natural gas plants, or the variable operating costs of existing fossil-fuel-fired plants. Due to its intermittent availability, wind alone is restricted to no more than 15% of the nameplate capacity in any region. However the 15% constraint does not apply to the "wind hybrid"

system which includes backup capacity in the form of a combustion turbine. This concept is a proxy for either a true hybrid with co-located wind and gas plants, or a contractual representation promoted by a power marketer of wind and gas or whatever power is available on the spot market. Bioethanol competes at the national level as an oxidant, a blended fuel, and/or a neat fuel. Competition between bioethanol and biopower for the biomass resource can limit the deployment of these technologies.

The cost of carbon reduction by a renewable energy technology is the difference between the levelized marginal cost of energy of the renewable source and the cost of the fossil-fueled competitor, divided by the difference in carbon emissions per unit energy between the renewable and the fossil technologies. The cost of energy from all technologies is assumed to decrease over time as shown in Figure 40 for the renewable energy technologies.

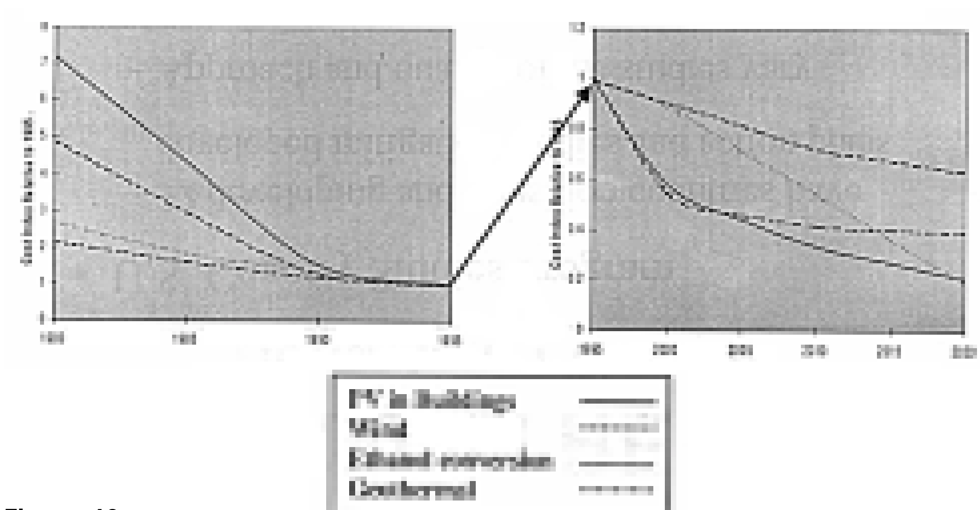


Figure 40
Renewable Energy Cost Projections (source: EPRI/DOE)

Results

As shown in Figure 39, the combination of geothermal, wind, landfill gas, ethanol, biomass cofiring, and PV in buildings has the potential in 2020 to reduce U. S. carbon emissions by as much as 200 MMTC/yr at under $50/tonne. Most of the reductions are derived from wind and bioethanol as a result of the cost reductions assumed for 2020 (DOE/EPRI 1997). These reductions are equivalent to 14% of the 1,463 MMTC emitted by the U. S. in 1996. They are also more than 40% of the reductions required of the U. S. in 2010 by the Kyoto protocol. However, the potential for cost-effective reductions by renewables in 2010 are considerably less as shown in Figure 41. This is largely because R&D efforts and industrial learning are not expected to reduce the cost of energy from renewables to competitive levels until closer to 2020.

The combination of geothermal, wind, landfill gas, ethanol, biomass cofiring, and PV in buildings has the potential in 2020 to reduce U. S. carbon emissions by as much as 200 MMTC/yr at under $50/tonne.

While Figure 39 shows that renewables can help the U. S. move towards the levels required by the Kyoto Protocol, it also shows that renewables, as represented here, fall short in two respects. First, renewable energy costs will not be widely competitive until after the Kyoto Protocol time frame of 2008 to 2012. Second, the deep reductions in greenhouse gases required to arrest global climate changes (*i. e.*, beyond the Kyoto levels) can probably not be

achieved with only this set of renewable energy technologies and will certainly require additional technology cost improvements.

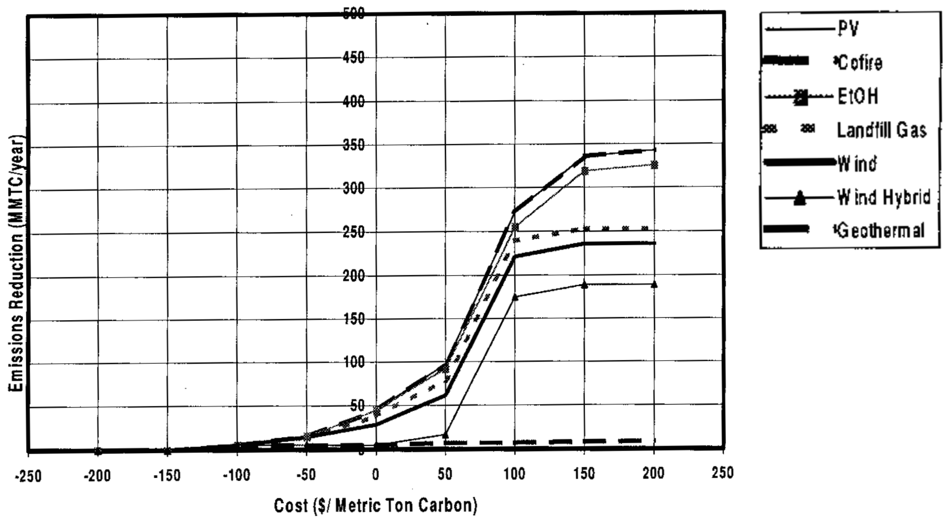


Figure 41
Renewable Energy Carbon Reduction Supply Curve for the Year 2010

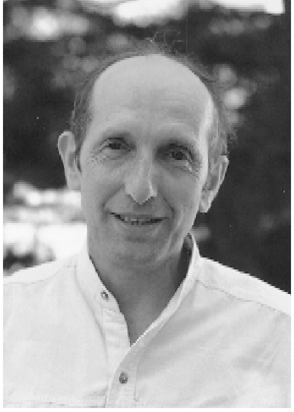
Renewables can be combined with other technologies to eliminate U. S. carbon emissions.

There are several possibilities for dealing with these problems:

- Further cost reductions in renewable energy technologies are possible beyond 2020. Such reductions should provide opportunities for other applications of renewables, *e. g.,* central PV.
- Secondly, renewables can be combined with other technologies to eliminate U. S. carbon emissions. For example, we examined the possibility of wind hybrid systems that included gas combustion turbines. In addition, advanced carbon separation and sequestration technologies could be employed to prevent the combustion turbine emissions from entering the atmosphere, or fuel cells could also be used in hybrid configurations with intermittent renewables.
- Third, the scope of application of renewable electric technologies could be expanded to include transportation emissions through the development and deployment of advanced technologies. Electricity from renewables could be used to electrolyze hydrogen from water to be used in vehicle-based fuel cells, or used to charge electric vehicles when intermittent renewables are available.
- Fourth, superconducting transmission lines could be combined with renewables to overcome both intermittency and non-uniform geographic dispersion of renewable resources.
- Finally, advanced space-based solar power systems could be developed to take advantage of higher insolation levels, continuous supply, and perhaps, even lunar-based manufacturing.

These additional opportunities for renewables need to be explored if the full potential of renewable energy is to be realized in a world forced to eliminate its voracious appetite for fossil fuels.

Impacts of Energy Use on Global Biospheric Cycles



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Carbon, nitrogen and sulfur are the only three elements — besides hydrogen and oxygen whose rapid biospheric turnover is assured by the water cycle — that are cycled on time scales ranging from minutes to millions of years and on spatial scales extending from tiny bits of soils to the entire biosphere. These ranges are possible because the three elements enter not only into a huge variety of water soluble organic and inorganic compounds but because they also form stable atmospheric gases. Unlike mineral nutrients, which merely piggyback on the water cycle, these doubly mobile elements can be thus rapidly transferred over long distances.

Possibility of global climate change caused largely by increasing levels of CO_2 has brought an unprecedented degree of attention to the carbon cycle. But significant as it is, our interference in the carbon cycle is relatively small: annual emissions of about 8 Gt C (75% from fossil fuels, the rest from land use changes) are a small part of the photosynthetic-respiration C flux or the atmosphere-ocean C exchange (both about 100 Gt C/year in one direction). In contrast, annual additions of anthropogenic nitrogen are now about twice as large as all natural N-fixation processes, and sulfur emissions are at least 2 to 3 times as large as natural inputs by biota and volcanoes.

Releases of both of these elements are also difficult to control, and ecosystemic disturbance caused by their increased flows will be with us for generations to come. While most people are aware that combustion of fossil fuels is the single largest source of anthropogenic sulfur, the role of high-energy civilization in changing the biospheric nitrogen cycle is much less appreciated.

While most people are aware that combustion of fossil fuels is the single largest source of anthropogenic sulfur, the role of high-energy civilization in changing the biospheric nitrogen cycle is much less appreciated.

Human Alteration of the Nitrogen Cycle

Applications of nitrogen fertilizers are the largest anthropogenic input into the global nitrogen cycle. Even complete recycling of all organic wastes would not be sufficient to supply all nitrogen needed by rising crop harvests required to feed today's six billion people. Haber-Bosch synthesis of ammonia, first demonstrated on a commercial scale in 1913, has removed the nitrogen limit on food production and modern civilization now depends on this synthesis more than it does on fossil fuels; even if there would be no danger of global climatic change fossil fuels would eventually be displaced by non-fossil energies, but there is no way to replace nitrogen in living molecules.

While it is conceivable to endow all non-leguminous plants with nitrogen-fixing capacity, this step goes far beyond altering or inserting a single gene, and it is a safe bet that we will not have such miraculous plants during the next generation or so. And even success at this

endeavor would come at a high price: all N-fixing leguminous grains yield considerably less (mostly between 1 and 2.5 tonnes per hectare) than cereal grains (2-8 t/ha for small grains, 4-10 t/ha for corn).

Consequently, modern civilization is now critically dependent on constant flow of synthetic nitrogenous fertilizers. Global production of NH_3 now amounts to about 110 Mt/year: miscellaneous uses and losses account for some 10 Mt, chemical syntheses consume 20 Mt, and 80 Mt go for fertilizer (a minority does so directly, the rest is used as a feedstock for synthesizing urea and other solid or liquid fertilizers). This enterprise has a significant energy cost. The best NH_3 plants need about 30 GJ/t of NH_3-N, and production of urea roughly doubles that total. This means that the world's N fertilizer industry annually consumes about 5 EJ of energy (about 115 Mtoe), mostly as natural gas and electricity, or about 1.5% of all primary energy.

Much larger impacts on global biospheric cycles arise after the application of nitrogen fertilizers. Crops typically take up no more than 50% of applied nitrogen, with extremes as low as 25% in some Asian rices and as high as 70% in wheats grown in cool and wet Northwestern Europe. The remainder — that is some 40 Mt N per year — enters the waters through leaching, runoff and soil erosion, and the atmosphere through nitrification, denitrification, and volatilization. Losses to the atmosphere — as NO_X, NH_3, and N_2O — account for about half of the total, or around 20 Mt N/year. This means they are now somewhat smaller than the fixation of atmospheric N_2 during high-temperature combustion in boilers of electricity-generating stations, in gas turbines and in internal combustion engines.

Modern civilization is now critically dependent on constant flow of synthetic nitrogenous fertilizers. This enterprise has a significant energy cost. Much larger impacts on global biospheric cycles arise after the application of nitrogen fertilizers.

Nitrogen present in fossil fuels produces only a small part of this roughly 25 Mt N/year flux which arises overwhelmingly from high-temperature breakdown of N_2 and the subsequent formation of NO and NO_2. Although we have been very successful in controlling these NO_X emissions from cars by installing catalytic converters (reductions of >90% since the early 1970s in North America and Japan), increases in both numbers of vehicles and annual travel per vehicle have resulted in virtually unchanged overall emissions, and in no, or only marginal improvement in frequency and intensity of photochemical smog in large urban areas. Controls of NO_X from stationary sources have yet to be commercialized on a large scale.

No matter where they come from, nitrogen oxides rapidly form atmospheric nitrates which are now a major (in summer in some regions the most important) source of acidification, a gradual ecosystemic change affecting pH-sensitive water biota, soils and vegetation. Atmospheric deposition of reactive nitrogen (be it NO_3 or NH_3) fertilizes natural ecosystems and can promote, particularly when combined with higher CO_2 levels, higher rates of primary productivity. But N deposition also leads to excessive leaching of the element as well as of alkaline micronutrients, and it can change species composition by biofixation and by favoring nitrophilic species. Many surface and underground waters, in both intensively farmed and highly industrialized areas, already have nitrate levels above the recommended hygienic limit of 50 mg/L. In addition, increased denitrification arising from fertilizer applications and from atmospheric deposition produces more N_2O, a greenhouse gas which absorbs outgoing IR radiation about 200 times as much as CO_2 does.

Even if the world's population were to stabilize at around 10 billion people and if the application efficiencies of N fertilizers were to increase appreciably, producing food for an additional 4 billion people expecting a higher standard of living would require between a third and a half more fertilizer than used annually during the late 1990s. Increases of at least such a magnitude must be expected for the generation of thermal NO_X. Human interference in the nitrogen cycle will thus inevitably intensify and we will have much to learn about its complex environmental effects.

Human Alteration of the Sulfur Cycle

Human interference in the sulfur cycle peaked during the late 1980s when about 100 Mt per year of the element were released into the atmosphere, about 90% from the combustion of fossil fuels, the rest largely from smelting of color metals (Cu, Zn, Pb) and from synthesis of H_2SO_4. Progressing desulfurization of flue gases (about two-thirds of large U. S. coal-fired power plants now have this technology), drastic falls in energy use by the countries of the former Soviet Union, and rising consumption of S-free natural gas have since reduced the annual S flux to just over 70 Mt/year. Because atmospheric S compounds usually remain aloft for only 30-40 hours before they are removed by wet or dry deposition, ecosystemic effects of intensifying S cycling are spatially limited.

Producing food for an additional 4 billion people expecting a higher standard of living would require between a third and a half more fertilizer than used annually during the late 1990s.

Acid deposition has been the most intensively studied ecosystemic change caused by enhanced sulfur cycling: the National Acid Precipitation Assessment Programme of the 1980s cost the U. S. taxpayers more than a half a billion dollars, and hundreds of millions have been spent on acidification research in Europe since the early 1970s. The three regions most affected by the process have been eastern North America, most of Europe, and East Asia. Lowered pH of lakes and streams leading to elimination or reduction of sensitive aquatic biota, leaching of alkaline elements from acidifying soils, and reduced growth of forests have been the most publicized consequences of acid deposition. Fortunately, aquatic acidification can be successfully managed by addition of alkaline compounds, and research has shown that the forest dieback has a multitude of causes (nitrogen deposition, ozone, drought, severe winters) and cannot be simplistically ascribed to acidification alone.

Unfortunately, the recent decline of global S emissions is a temporary phenomenon. Rising consumption of high-S Middle Eastern oil in Asian economies and further increases in coal combustion in China and India will soon make Asia the continent with the largest S emissions. Presence of terrigenic alkaline dust in drier parts of the continent precludes acidification of large parts of the continent, but the combination of high-S coals and wet climate has already turned rains throughout most of South China as acid as those of the Western Europe of the 1980s. Westward transport of acidifying compounds from China is a growing concern in South Korea and Japan.

European and North American S emissions in 2050 may be substantially lower than today, a shift that might intensify a possible warming trend on a regional basis. In contrast, East Asia will almost certainly have higher concentrations of cooling sulfates, and global S emissions will, once again, rise above 100 Mt a year. Only an early and aggressive transition from fossil fuels to non-fossil energies would greatly reduce future S emissions.

SESSION 1

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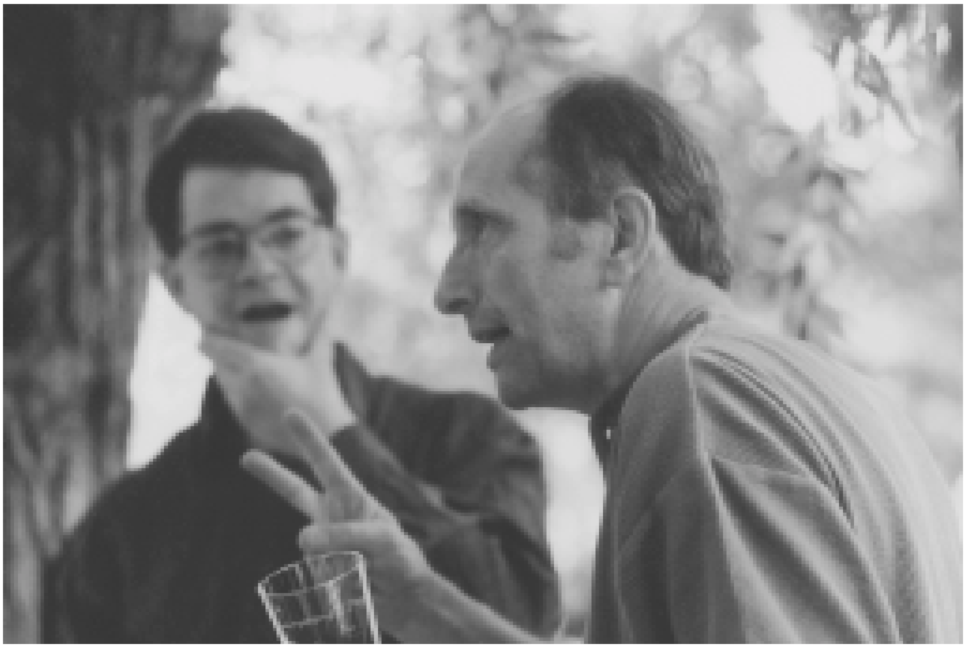

Vaclav Smil makes a point while Gene Berry looks on.

Vaclav Smil and Richard Wilson discuss energy futures.

Analysis of Cloud-Radiation Interactions Using Field Observations and a Single-Column Model

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In this study, observations are used to test the realism of results produced by various cloud parameterizations. The observations come from the Atmospheric Radiation Measurement (ARM) program of the U. S. Department of Energy, at a field site in Kansas and Oklahoma. The primary tool used to compare the measurements with parameterizations is a single-column model (SCM). The cloud parameterizations tested differ with regard to the inclusion of cloud liquid water, the specification of the effective cloud droplet radius, and the parameterization of the cloud optical properties (both solar and terrestrial). The SCM is a diagnostic model resembling a single vertical column of a 3-dimensional general circulation model (GCM). The one-dimensional SCM is forced with horizontal advection terms derived from either observations or numerical weather prediction analyses (Randall et al. 1996). In this study, the horizontal advective terms were derived from observations taken during the Summer 1995 (July 18-August 2) and Spring 1996 (April 16-May 5) Intensive Observing Periods (IOPs) at the ARM site. This research is part of an ongoing effort to improve the treatment of cloud-radiation processes in climate models (Byrne et al. 1996, Lee and Somerville 1996, Lee et al. 1997, Somerville et al. 1996).

In this study, observations are used to test the realism of results produced by various cloud parameterizations.

Parameterizations

Two basic approaches to the parameterization problem were tested. One is due to Slingo (1987). In this scheme, the stratiform cloud amount depends upon the large-scale relative humidity, vertical velocity and static stability, while convective cloud amount is parameterized as a function of convective mass flux. The other is due to Tiedtke (1993). This scheme introduces two new prognostic equations for cloud liquid water/ice and cloud amount. Terms representing the formation of clouds and cloud water/ice due to convection, boundary layer turbulence and stratiform condensation processes are included in these equations. Cloud water/ice is removed (and clouds are dissipated) through evaporation and conversion of cloud droplets and ice to precipitation. Within these two basic frameworks, the SCM was run in the following three configurations:

NOCW (no cloud water): Cloud amount is determined using the Slingo scheme while cloud optical thicknesses are parameterized using model temperature, humidity and pressure following McFarlane et al. (1992).

CWRF (cloud water radiative forcing): The parameterization of Tiedtke (1993) is used to

calculate the cloud liquid water/ice and cloud amounts. Cloud optical thickness is calculated as a function of the cloud water path and effective cloud droplet radius using the formula of Slingo (1989). The cloud droplet radius is fixed at 10 microns.

CWRI (cloud water radiative forcing with ice): This experiment is the same as CWRF except that the effective cloud droplet radius is parameterized as a function of the liquid water content for water clouds (Bower et al. 1994) and as a function of cloud temperature (Suzuki et al. 1993) for ice clouds.

In all the experiments, cloud IR emissivity (e) was calculated using the formula of Platt and Harshvardhan (1988) e = 1.0 - exp (-0.75 * TAU), where TAU is the cloud optical thickness. The SCM also employed the cumulus convection scheme of Zhang and McFarlane (1995) and the longwave and shortwave radiation parameterizations of Morcrette (1990) and Fouquart and Bonnel (1980), respectively. A vertical resolution of 19 layers (10 mb spacing near the surface; 100 mb spacing in mid-troposphere) and a timestep of 7.5 minutes were used in all the experiments. The model configurations are summarized in Table 9.

SESSION 1

Based on these limited data alone, it is difficult to determine which of the model configurations produces the most realistic results.

Variable	NOCW	CWRF	CWRI
Cloud scheme	Slingo	Tiedtke	Tiedtke
Cloud water	None	Explicit	Explicit
Cloud optical thickness	Specified	Calculated	Calculated
Effective drop radius	Not applicable	Fixed at 10 microns	Calculated

Table 9
SCM Configurations

Results
Each of the three configurations of the SCM were run using forcing data from an objective analysis data set (derived from ARM measurements) for both the Summer 1995 and Spring 1996 IOP. In these runs the model temperature and humidity were relaxed to observed values using a time constant of 24 hours to avoid unacceptable predictability error growth.

The mean downwelling surface shortwave flux (DWSF), outgoing longwave radiation (OLR) and total cloud amount from runs with each model configuration (NOCW, CWRF, and CWRI) for both IOPs (Summer-95 and Spring-96) are shown in Table 10, together with corresponding observed means. The units for DWSF and OLR are watts per square meter. The model results show significant variation between the 3 configurations. However, based on these limited data alone, it is difficult to determine which of the model configurations produces the most realistic results. Nevertheless, one consistent feature seen in the model results from both IOPs is that larger values of DWSF and OLR are produced by configuration CWRI compared to CWRF.

The mean vertical profile of cloud fraction, cloud IR emissivity and cloud extinction (cloud optical depth normalized by layer depth) from the model runs during the Spring 1996 IOP

were examined to understand the differences noted in Table 10. All 3 model configurations produce maximum cloudiness in the upper troposphere at approximately 300 mb. Differences in the DWSF and OLR noted above are due to larger values of high cloud extinction and high cloud emissivity in model configuration CWRF compared to CWRI. Future work is planned to evaluate the vertical cloud properties with ARM observations when these measurements become available from future IOPs.

Summer 1995 IOP	DWSF	OLR	Cloud fraction
NOCW	282	263	0.43
CWRF	265	253	0.42
CWRI	283	259	0.42
Observations	267	255	0.49
Spring 1996 IOP	**DWSF**	**OLR**	**Cloud fraction**
NOCW	290	258	0.29
CWRF	277	246	0.41
CWRI	289	252	0.40
Observations	255	241	0.49

Table 10
Time-averaged model results compared with observations

The model clouds usually lagged the observations by several hours.

During our analysis a systematic deficiency in the model cloud results became apparent when the time series of cloud fraction was compared to satellite observations from GOES-8. During the Spring 1996 IOP, there were several events in which large increases in cloud amount were observed. In most instances, the model also produced an increase in cloudiness. However, the model clouds usually lagged the observations by several hours. In some instances, the model did not produce any clouds at all.

To better understand this model shortcoming, a short 48-hour segment (April 21-22) of the Spring 1996 IOP was further analyzed. The time-series of several quantities from this 48-hr SCM run were examined along with corresponding observations. Observations from GOES-8 indicate significant cloudiness on April 20 while the model maintains clear skies. This observed cloudiness is also apparent in concurrent decreases in the observed DWSF and OLR and a concurrent increase in the downwelling surface longwave flux. A relatively modest reduction in the observed downwelling surface shortwave flux and small values of observed liquid water path indicate that these observed clouds are most likely high optically thin cirrus clouds. It is interesting that cloud base height data from a Belfort Laser Ceilometer at the ARM site indicated no clouds on April 20. However, it is quite likely that these clouds were above the 7.5 km range of this instrument.

In summary, using an interactive cloud droplet radius in the parameterization decreases the cloud optical thickness and cloud IR emissivity of high clouds, which acts to increase the

downwelling surface shortwave flux and the outgoing longwave radiation. It is difficult to evaluate the realism of the vertical distribution of model-produced cloud extinction, cloud emissivity, cloud liquid water content and effective cloud droplet radius, because observations of these quantities are not yet available. Future planned measurements of cloud microphysical properties at the ARM site will be an extremely valuable tool to evaluate and improve cloud-radiation parameterizations. The tested cloud parameterizations often underestimated the observed cloud amount during the Spring 1996 IOP. This underestimation may be due to the horizontal advection of clouds into the model domain. Analysis of ARM observations indicates the presence of clouds at times when the corresponding maximum relative humidity is less than 80%. This implies that the underlying principles of a critical relative humidity of around 80% for cloud formation, which are used in many cloud parameterizations, may deserve further critical scrutiny.

Using an interactive cloud droplet radius in the parameterization decreases the cloud optical thickness and cloud IR emissivity of high clouds, which acts to increase the downwelling surface shortwave flux and the outgoing longwave radiation.

SESSION 1

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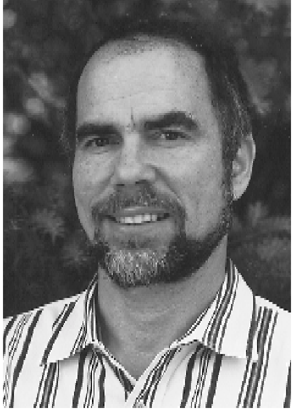

Evidence of Global Climate Change

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Global mean surface temperature has risen by about 0.5°K over the last century, with slightly larger changes over land than over ocean. It is now warmer than at any other time during the current millenium.

The evidence is growing that global climate is changing more rapidly than is likely explainable by natural variability alone. Some of this evidence will be briefly summarized here. First I describe the historically measured surface temperature record and discuss how it compares with the more recent record of lower tropospheric temperature inferred from microwaves measured by satellites. Then I present results from climate models used to predict patterns of climate change by known human influences and show how these predictions compare with observed changes. Finally, I mention how evidence inferred from paleodata appears to be consistent with model predictions, providing greater confidence in their results. I conclude by listing a few major uncertainties that provide focus for ongoing research.

Global mean surface temperature, derived from station data on land and ship measurements at sea, has risen by about 0.5°K over the last century, with slightly larger changes over land than over ocean. The record shows a rise of a few tenths of a degree prior to 1940, then a leveling off or slight cooling followed by a sharper rise since about 1970. The first 6 months of the present year (1998) have been warmer than any on record with the recent El Niño event certainly contributing to this unprecedented warmth.

Temperatures in the lower troposphere have been routinely recorded with reasonably complete global coverage only over about the last 40 years, and temperatures derived from microwave sounding unit (MSU) data obtained by satellites are available since 1979. The interannual variability evident in these records of global mean lower tropospheric temperatures are generally consistent with the surface temperature record. The warming trend since 1980 in surface temperature is not, however, seen in the lower tropospheric record, causing some to question the reliability of the surface temperature record. The apparent discrepancy between these two records is the subject of ongoing research concerning uncertainties in various corrections applied to the data, differences in data coverage, and the physics of thermal coupling between the surface and lower atmosphere. This work shows that there may indeed be a slight difference in trends between temperatures in the lower troposphere and those at the surface, but the inference that the surface temperature record must be wrong is certainly unwarranted.

Global warming of less than a degree over the last century may seem insignificant, but paleodata (primarily tree rings) indicate that it is now warmer than at any other time during the current millenium. Although the accuracy of paleo-reconstructions remains uncertain, the current warming trend does in fact appear to be unusual. This fact alone, however, does

not allow one to confidently conclude that recent warming is attributable to anthropogenic influences on climate. More compelling evidence for a conclusion of this kind comes from comparisons of model predictions with the observational record.

Climate models can be used to predict how climate might respond to human influences. Increases in greenhouse gases (notably carbon dioxide, methane, halocarbons, and nitrous oxide) and increases in sulfate aerosols alter the incoming and outgoing radiative energy, disturbing the near balance necessary for stable climate. Climate models have been run with imposed increases in greenhouse gases and with representations of sulfate aerosols that correspond to changes over the last century and are attributable to human activities (*e. g.*, fossil fuel burning). The effect of increasing greenhouse gas concentration is to warm the Earth (by "trapping" outgoing infrared radiation) and the effect of increases in sulfate aerosols is to cool the earth (by scattering incoming sunlight back to space). Surface temperature response to these radiative perturbations is determined not only by the magnitude of the forcing, but also the feedbacks within the system and the time delay due to the thermal inertia of the oceans. Important feedbacks include water vapor, snow and sea ice, and probably clouds (although the sign and magnitude of cloud feedbacks are unknown). Depending on estimates of these feedbacks, climate sensitivity is currently uncertain within a factor of about three. Within this factor of three it appears that the global mean temperature change over the last century is indeed consistent with model estimates resulting from realistically imposed increases in greenhouse gases and sulfate aerosols.

This overall agreement between models predictions and observed changes is not by itself evidence enough to conclude that the recent warming must be a result of human activities. There are, after all, other reasonable explanations, for example, an unusual natural fluctuation of the climate system. More compelling evidence for an anthropogenic influence on global temperature is found in looking at the patterns of change that have occurred historically. Here we find that the Southern Hemisphere has warmed more than the Northern Hemisphere and the warming in the troposphere is accompanied by cooling in the stratosphere. This same large-scale pattern of change is predicted by models: the stratospheric cooling is what is expected when carbon dioxide concentration increases; the differential rate of warming of the two hemispheres is found in model simulations because sulfate aerosols are concentrated over the populated regions of the north, tending to counteract greenhouse warming there.

Compelling evidence for an anthropogenic influence on global temperature is found in looking at the patterns of change that have occurred historically.

Statistical analyses have been carried out that show an increasing correspondence between the observed pattern of change and model-predicted patterns of change (over the last 50 years in the case of surface temperature and over the last 25 years in the case of the vertical profile of temperature change). Again it is possible that this increasing correlation could occur by chance, but it is impossible to assess this possibility based on the observational record because that record is too short, comprising two independent samples of trends of appropriate duration. A rigorous statistical evaluation of the statistical significance of the apparent increasing correlation between observed and model-predicted patterns of change can be based on coupled atmosphere-ocean climate models that have been run for long periods of time without externally imposed forcing. These models simulate naturally occur-

ring internal variability within the climate system that on decadal time-scales appears to be qualitatively consistent with the observational record. The thousand year runs of these models produce unforced climate changes that represents "noise" in the context of detecting anthropogenic climate change. All studies to date show that this "noise" is not large enough to explain the changes in climate that have been observed. This evidence augmented by paleodata that show that climate models probably have not grossly underpredicted climate sensitivity and other evidence led to the conclusion of the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment that "the balance of evidence suggests a human influence on global climate."

Because the attribution of observed climate change to human influences is based most convincingly on model results, substantial work is underway to evaluate and improve those models. Significant uncertainties in cloud feedbacks, as simulated by the models, remain. Likewise, the accuracy with which coupled models can simulate decadal and longer term variability remains uncertain. Thus, the objective of several observational programs is to improve climate models, and the systematic evaluation of climate models is being encouraged through model intercomparison projects such as the Atmospheric Model Intercomparison Project (AMIP).

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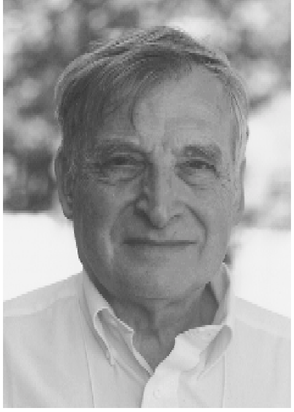

What Nuclear Power Can Accomplish to Reduce CO_2 Emissions

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The U. S. now emits 11% more CO_2 than in 1990; and at Kyoto we promised to reduce CO_2 emissions to 8% below 1990 levels in 10 years for a decrease of 19% below today's levels. If all the electricity now generated by nuclear power were to be generated by coal that would increase CO_2 another 8% making it more difficult to meet our commitment if we abandon nuclear power. My purpose today is to explain to you that we *could* meet this commitment, or nearly so by a nationwide, and of course hopefully worldwide decision to use nuclear energy. Nor should it be too expensive.

Electricity from nuclear energy *has* been both safe and cheap. Twenty five years ago, Maine Yankee nuclear power plant had just been completed for $180 million, or $200 per kWe installed capacity. Connecticut Yankee nuclear power plant was producing electricity at 0.55 cents per kWh busbar cost, some part of which was paying off the mortgage. The operating cost was perhaps only 0.4 cents per kWh. Even allowing for inflation and taking no credit for learning, we could, if we decide to return to the optimism and procedures of 25 years ago, do as well.

In 1975 to 1985, five to ten nuclear power plants were being completed in the U. S. every year. In 1980 to 1990, five were being completed each year in France. The following countries now have the industrial capacity to build nuclear power plants and have built large fractions of them: U. S., UK, Canada, France, Germany, Sweden, Russia, China, Korea, Japan, and India. Even allowing for no more countries to enter the industrial race the world could build 10 nuclear power plants a year. This could only be after a delayed start of perhaps 5 years. The industry has wound down over the last 10 years and needs winding up. For example only one western country now makes large pressurized reactor vessels. Nonetheless a hundred large reactors a year seems possible for a total world wide installed capacity of 3,000 kWe by 2030. On this scenario, the U. S. would miss the Kyoto deadline by about 10 years but be on the way to meeting future commitments.

The nuclear industry has wound down over the last 10 years and needs winding up.

It is useful to remember that one can choose almost any mixture of the following for a reactor:

Fuel:	3% enriched U, pure ^{235}U, Natural U, ^{233}U, Thorium, ^{239}Pu
Fuel Matrix:	sintered oxide, metal, carbide, pebbles
Moderator:	H_2O, D_2O, C, none
Heat transfer medium:	H_2O, Na, Pb/Bi, CO_2, He
Generator:	Steam Turbine, Gas Turbine

The present Light Water Reactors use the first entry in each row and this choice was influenced by success of the naval reactors sponsored by Admiral Rickover — although the actual detailed designs are very different. It would take a billion or two dollars to develop an alternate although it is possible that one or another might turn out to be a cheaper and/or safer choice.

The Uranium Institute reports that we have about 18 million metric tons of uranium in ore, proven reserves and reasonably assured supplies at prices (up to $200 per kg) that we can afford. This would produce in a light water reactor system about 4×10^{15} kWh of electricity, or enough for a century at the postulated year 2030 demand of 3,000 kW. After perhaps half a century it would be wise to reconsider a breeder reactor using fast neutrons. Fast neutron reactors *have* been built and *do* work. The first nuclear powered electricity was from the EBRI reactor in Idaho when a whole town was lit by this electricity as a public demonstration. But the cost, even after some experience and learning, might be 20% higher than light water reactors. Nonetheless, it should be competitive with other alternatives. If we have a breeder reactor system we can use all the ^{238}U in the fuel and increase the effective fuel supply a factor of 100; we can use thorium which is 5 times as plentiful as uranium, and since the utilization of fuel is so much greater we can afford to use more expensive fuel. We can, for example, take the uranium from fly-ash from coal burning plants, noting that there is more available energy from the uranium in coal than from the carbon. We might also extract the uranium from sea water. All in all, a factor of 1,000 increase in fuel supply seems not unreasonable. It would be impudent to project the existence of the human race beyond the 100,000 years that this implies.

There is more available energy from the uranium in coal than from the carbon. We might also extract the uranium from sea water.

The present limitation is public acceptance which drives excessive regulation, and increased cost. This increased cost often reaches a factor of three even after correction for inflation. Safety in 1973 was probably better than for other comparable industrial facilities, but it has been improved since then. It is important to realize that the safety improvements have mostly come from improved analysis — which is cheap. Many public opinion polls suggest that the anti-nuclear groups are a minority of the people. I suggest that the majority could then take action along the following lines:

- **Education:** Explain, for example, that even the Chernobyl accident (which could not happen in the light water reactors discussed here) killed few people and even the number of calculated deaths is exceeded by the number of respiratory deaths, similarly calculated from one year of fossil fuel burning in the former USSR.
- **Proliferation:** Explain that nuclear power *has not* in the past been a major engine driving nuclear proliferation and ensure that it is unlikely to be so in the future. The South African experience shows, for example, how much easier it is to build a bomb (using ^{235}U separated with a Becker nozzle) than to build a power plant.
- **Regulation:** Demand that NRC use performance based regulation instead of the prescriptive regulation that is now commonly used. These should be based soundly upon the need to protect the health of the public and NOT to meet public pressure. Demand for example that they modify their regulations so that they do not demand the expenditure to reduce radiation exposure of more than their own guideline of $1,000 per Man Rem. This was established by NRC rule making (RM-30-2) 23 years ago and has now

been effectively updated to $2,000 per person Rem. Demand that no regulation be promulgated, no old regulation be enforced and no draconian action be taken against a utility company to reduce the frequency of core melt below the NRC guideline of 1/10,000 per year.

- **Public and legal action:** Repudiate publicly any person who talks nonsense in the name of science. Take action in the courts to oppose the use of junk science in the courts. Support politically, for example, those who actively want nuclear waste in their own backyard, *e. g.*, Ward Valley, California, and Skull Valley Indian Reservation, Utah.

We can get close to meeting Kyoto if we wish. But we must be active and not merely talk about it.

The present limitation is public acceptance which drives excessive regulation, and increased cost.

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Geoengineering and Nuclear Fission as Responses to Global Warming

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Geoengineering: Prospects for Physics-Based Modulation of Climate

It has been suggested that large-scale climate changes due to atmospheric injection of greenhouse gases connected with fossil fuel-fired energy production, should be forestalled by internationally-agreed reductions in carbon emissions. The potential economic impacts of such limitations are large. We propose that for far smaller costs, the mean thermal effects of greenhouse gases may be obviated in any of several distinct ways, some of them novel. These suggestions are all based on scatterers that prevent a small fraction of solar radiation from reaching all or part of the Earth. We propose research directed to quite near-term realization of one or more of these inexpensive approaches to cancel the effects of greenhouse gas injection. While the magnitude of the climatic impact of greenhouse gases is currently uncertain, the prospect of severe failure of the climate, for instance at the onset of the next Ice Age, is undeniable. The proposals in this paper may lead to quite practical methods to reduce or eliminate all climate failures.

Increases in average worldwide temperature of the magnitude currently predicted can be canceled by preventing about 1% of incoming solar radiation (insolation) from reaching Earth. This could be done by scattering into space from the vicinity of Earth an appropriately small fraction of total insolation. Such operations would act like false volcanoes, only cleaner. If performed near-optimally, we believe that the total cost of such an enhanced scattering operation would probably be at most $1 billion per year, an expenditure two orders of magnitude smaller in economic terms than those underlying currently proposed limitations on fossil-fired energy production. Some of these insolation-modulating scattering systems may be re-configured to effectively increase insolation by an amount, perhaps 3%, sufficient to prevent another Ice Age.

Increases in average worldwide temperature of the magnitude currently predicted can be canceled by preventing about 1% of incoming solar radiation (insolation) from reaching Earth.

There are several types of scatterers and several choices of sites for their deployment on scales of interest for insolation modulation. Earth's stratosphere is by far the least expensive location, but it is a chemically uncongenial location due to the high flux of ultraviolet radiation from the Sun and the presence of oxygen, particularly in the more reactive form of ozone. Deployment in low-Earth orbit is an obvious alternative, one which offers potentially very long term positional stability combined with excellent durability of many materials.

Technologies that could greatly decrease the cost of space launch could make a telling difference in the practicality of all types of space-deployed scattering systems of scales appropriate to insolation modulation. Light pressure arising from the momentum imparted to the scatterer by sunlight may significantly perturb the orbital elements of the scatterer, and managing this momentum poses an additional technical challenge to scatterers deployed in low Earth orbit.

Three specific possibilities for modulating the total insolation of the Earth by about 1% follow.

- **Sub-Microscopic Oxide Particulates**
  During the present decade, the eruption of Mt. Pinatubo in the Philippines induced a transient drop in the global mean temperature of ~0.5˚K, apparently due to insolation modulation by volcanic particulates. It is believed that this cooling was induced predominantly by scattering of sunlight by SO_2-based particulates of sub-micron scale, ones which may have grown into more effective scatterers by scavenging residual stratospheric water and cations, resulting in myriad still-sub-micron droplets of high-concentration sulfur acids and salts. It may well be feasible to transport and disperse enough SO_2 (or SO_3 or H_2SO_4) into the stratosphere to produce the desired insolation modulation effect. It has also been suggested that alumina injected into the stratosphere by the exhaust of solid-rocket motors might scatter non-negligible amounts of sunlight.
- **Conducting Sheets**
  The reference 1% reduction in insolation might be obtained by deploying electrically-conducting sheeting, either in the stratosphere or in low-Earth orbit. Three quite different physical mechanisms comprise the foundations of the three distinct approaches which we consider. In the first, mixtures of suitable metals are deposited in ultra-thin layers and convenient area, and are then protectively coated. Platelets of such material are then deployed in the stratosphere, or perhaps in low-Earth orbit, and act to absorb sunlight by the photoelectric effect; the absorbed energy is then thermally re-radiated, with about half escaping into space. In the third, optimized metallic-walled balloons are self-deployed into the stratosphere from ground level where they serve to scatter insolation.
- **Quasi-Resonant Scatterers**
  A third approach involves the use of quasi-resonant scatterers, also deployed in the stratosphere. While the potential mass efficiency of this class of scatterers is singularly high, practical considerations centered on photochemical durability in the stratosphere indicate that total masses of 10^6 tons of material may have to be deployed but may only have to be replaced twice per decade. For near-term, relatively low-risk insolation modulation studies, we propose the use of sub-microscopic particulates composed of frozen perfluorohydrocarbon "nano-droplets" loaded with embedded molecules of selected organic dyes.

Some of these insolation-modulating scattering systems may be re-configured to effectively increase insolation by an amount, perhaps 3%, sufficient to prevent another Ice Age.

Fine-Grained Insolation Modulation

We note technical possibilities of modulating insolation in a latitude-dependent manner. Consistent with the slow latitudinal mixing time of the stratosphere well above the tropopause, different amounts of scattering material might be deployed (*e. g.*, at middle stratospheric altitudes, ~25 km) at different latitudes, so as to vary the magnitude of insolation modulation for relatively narrow latitudinal bands around the Earth, *e. g.*, to reduce heating in the tropics by preferential loading of the mid-stratospheric tropical reservoir with insolation scatterer.

Indeed, scatterers of sunlight could be deployed at some latitudes to decrement insolation, while scatterers of Earth-emitted long-wavelength infrared radiation (LWIR, which effectively increment insolation) could be deployed at other latitudes. Differential cooling and heating, respectively, of underlying land-and-ocean latitudinal bands could thereby by accomplished. Furthermore, use of scatterers of varying stratospheric residence times to simultaneously modulate insolation and LWIR radiative losses in a specified latitude band might be employed to fine-tune, e. g, diurnal or seasonal temperature variability.

Conclusions

Two of the insolation modulation systems we have considered in this study (quasi-resistant scatterers for intra-atmospheric applications and the small-angle-scattering system for deep space use) are apparently novel and involve 2 to 5 orders of magnitude less mass than that of most interesting previous proposals. We conclude that the insolation modulation approach to prevention of climate failure is certainly technically feasible in principle, and that the total costs of its best examples may be *de minimis*.

An ideal reactor should be designed to be the long-term-stable burial cask of all the radioactive waste products it generates throughout its life.

Nuclear Fission and Global Warming

Nuclear fission power reactors represent a potential solution to many aspects of global change possibly induced by inputting of either particulate or carbon or sulfur oxides into Earth's atmosphere. Of proven technological feasibility, they presently produce high-grade heat for large-scale electricity generation, space heating and industrial process-energizing around the world, without emitting greenhouse gases or atmospheric particulates; importantly, electricity *production* costs from the best nuclear plants presently are closely comparable with those of the best fossil-fired plants.

However, a substantial number of issues currently stand between nuclear power and widespread substitution for large stationary fossil fuel-fired systems. These include perceptual ones regarding both long-term and acute operational safety, plant decommissioning, fuel reprocessing, radioactive waste disposal, fissile materials diversion to military purposes, and readily quantifiable concerns regarding long-term fuel supply and total unit electrical energy cost. We sketch a road-map for proceeding from the present situation toward a nuclear power-intensive world, addressing each of the concerns which presently impede widespread nuclear substitution for fossil fuels, particularly for coal in the most populous and rapidly developing portions of the world, *e. g.*, China and India.

Features of Proposed 21st Century Nuclear Power Plants

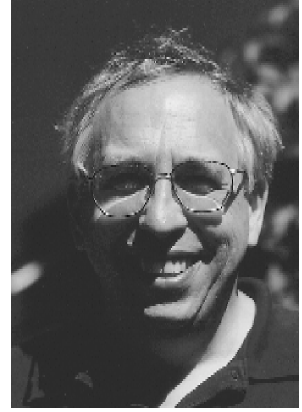
Some of the key concerns about nuclear fission involve nuclear fuel, radioactive waste, plant safety, and economics. With regard to fuel, any nuclear fuel chosen must be reliably available in sufficient quantity at reasonable costs to give 10 billion people a First World energy standard-of-living for at least a century. All the fuel a power reactor needs during its entire operational life (30 years at full power) should be built into it as it is manufactured, eliminating refueling operations. Furthermore, an ideal reactor should be designed to be the long-term-stable burial cask of all the radioactive waste products it generates throughout its life, so that once it is emplaced and its fuel charge ignited, it is not significantly disturbed or removed thereafter for tens of millennia.

With regard to operational safety, reactors should be designed to be incapable of suffering damage, no matter how seriously their controls might be mishandled by operators. They should also be incapable of damage due to loss-of-coolant accidents, and highly immune to sabotage. As for economics, total unit energy costs of nuclear electricity should be reduced by at least two-fold relative to classic light water reactor values. The costs of nuclear electricity should not be significantly in excess of those attainable from the best fossil fuel-fired options. Based on these requirements, four basic design considerations emerge: life-cycle-oriented design; inexpensive standardized construction; minimum-essential operator controls; and underground siting.

Conclusions

Nuclear power systems tailored to local needs and interests and having a common advanced technology base could reduce present-day worldwide CO_2 emissions by two-fold, if universally employed. By application to small mobile demands, a second two-fold reduction night be attained. Even the first such halving of carbon intensity of stationary-source energy production worldwide might permit continued slow power-demand growth in the highly developed countries and rapid development of the other 80% of the world, without active governmental suppression of fossil fuel usage, while also stabilizing rates of carbon input into Earth's atmosphere. The second two-fold reduction might obviate most global warming concerns.

Nuclear power systems tailored to local needs and interests and having a common advanced technology base could reduce present-day worldwide CO_2 emissions by two-fold, if universally employed.



Scenarios for Future Levels of Carbon Dioxide and their Implications

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The purpose of this presentation is to examine the available analyses of projections of atmospheric concentrations of carbon dioxide. This study draws heavily on the findings of our evaluation of the energy implications of such scenarios in Hoffert et al. (1998). In addition, we will examine the implications of the Kyoto Protocol on future projections of carbon dioxide.

SESSION 1

By far the largest effect on radiative forcing has been the increasing concentration of carbon dioxide, accounting for about 64% (1.56 Wm^{-2}) of the total change in forcing.

Past Growth in Carbon Dioxide

Published analyses of the direct radiative forcing on climate due to the changes in greenhouse gas concentrations since the late 1700s are generally in good agreement, giving an increase in radiative forcing of about 2.1 to 2.6 Wm^{-2} (2.45 Wm^{-2} in IPCC, 1995, 1996a). Of the 2.45 Wm^{-2} change in radiative forcing from greenhouse gases over the last two centuries, approximately 0.5 Wm^{-2} has occurred within the last decade. By far the largest effect on radiative forcing has been the increasing concentration of carbon dioxide, accounting for about 64% (1.56 Wm^{-2}) of the total change in forcing. The change in concentrations of CH_4, N_2O, and CFCs and other halocarbons provide another 0.9 Wm^{-2}. Projections of greenhouse gas emissions into the future suggest that carbon dioxide will become an ever-increasing portion of the change in radiative forcing.

Accurate measurements of atmospheric CO_2 concentration began in 1958 at the Mauna Loa Observatory in Hawaii. The annually averaged concentration of CO_2 in the atmosphere has risen from 316 ppmv (parts per million by volume) in 1959 to 364 ppmv in 1997. The CO_2 measurements exhibit a seasonal cycle, which is mainly caused by the seasonal uptake and release of atmospheric CO_2 by terrestrial ecosystems. The average annual rate of increase over the whole time period is about 1.2 ppmv or 0.4% per year, with the rate of increase over the last decade being about 1.6 ppmv/year (IPCC, 1996). Measurements of CO_2 concentration in air trapped in ice cores indicate that the pre-industrial concentration of CO_2 was approximately 280 ppmv. These data indicate that carbon dioxide concentrations fluctuated by ± 10 ppmv around 280 ppmv for over a thousand years until the recent increase to the current 360+ ppmv, an increase of over 30%.

Why has the atmospheric concentration of CO_2 increased so dramatically? Analyses with models of the atmosphere-ocean-biosphere system of the carbon cycle indicate that human activities are primarily responsible for the increase in CO_2. Two types of human activities are primarily responsible for emissions of CO_2: fossil fuel use, which released about 6.0 GtC into the atmosphere in 1990, and land use, including deforestation and biomass burn-

ing, which may have contributed about 1.6 ± 1.0 GtC in addition to that from fossil fuels (IPCC, 1995, 1996a).

Carbon dioxide is emitted when carbon-containing fossil fuels are oxidized by combustion. Carbon dioxide emissions depend on energy and carbon content, which ranges from 13.6 to 14.0 MtC/EJ for natural gas, 19.0 to 20.3 for oil, and 23.9 to 24.5 for coal. Other energy sources such as hydro, nuclear, wind, and solar have no direct carbon emissions. Biomass energy, however, is a special case. When biomass is used as a fuel, it releases carbon with a carbon-to-energy ratio similar to that of coal. However, the biomass has already absorbed an equal amount of carbon from the atmosphere prior to its emission, so that net emissions of carbon from biomass fuels are zero over its life cycle.

Anthropogenic emissions from fossil fuel use have been estimated as far back as 1751. Before 1863, emissions did not exceed 0.1 GtC/yr. However, by 1995 they had reached 6.5 GtC/yr, giving an average emissions growth rate slightly greater than 3% per year over the last two and a half centuries. Recent growth rates have been significantly lower, at 1.8% per year between 1970 and 1995. Emissions were initially dominated by coal. Since 1985, liquids have been the main source of emissions despite their lower carbon intensity. The regional pattern of emissions has also changed. Once dominated by Europe and North America, developing nations are providing an increasing share of emissions. In 1995, non-Annex I (developing countries, including China and India) nations accounted for 48% of global emissions.

Atmospheric CO_2 stabilization at 450 ppmv by 2100 would require reductions to about a third of today's emissions levels.

Future Projections of CO_2

Since our current understanding of the relationship between observed increases in atmospheric CO_2 and past fossil fuel emissions is imperfect, our ability to project future CO_2 concentrations is also in doubt. However, all evidence indicates that fossil fuel use can raise CO_2 levels to twice the pre-industrial concentration over the next 50 years. Drastic emissions reductions would therefore be required in order to hold CO_2 constant. Current models of carbon storage and exchange suggest that for atmospheric concentrations to stabilize below 750 ppmv, human-related emissions must eventually decline relative to today's levels. Stabilization at 450 ppmv by 2100 would require reductions to about a third of today's levels. All of the models used in recent IPCC (1995, 1996a) studies indicate that holding emissions constant at 1990 levels would still result in increasing concentrations of atmospheric CO_2 that would reach 500 ppmv around 2100.

IPCC working groups developed six scenarios for greenhouse gas emissions based on socioeconomic projections. Scenario IS92a incorporated widely accepted projections and the then-current consensus on population, economic development and energy technology to generate projections of greenhouse gas emissions for the 21st century assuming "no new climate change policies." This baseline IS92a scenario has been dubbed "Business as Usual (BaU)."

Stabilization of atmospheric greenhouse gas concentrations is often used as a target against which to evaluate the possibility of emission reductions, and estimate future concentrations. A variety of CO_2 concentration ceilings and associated global net emissions trajectories

have been considered. Those of Wigley *et al.* (1996) are displayed in Figure 43. From these figures, it is obvious that, regardless of ceiling, global emissions initially increase, reach a maximum some time in the next century, and eventually begin a long-term decline that continues through the remainder of the analysis period out to 2300. While emissions must eventually peak and decline, fossil fuel carbon need not. Technologies that capture and sequester carbon could provide a mechanism by which fossil fuels could continue to play an important role in future global energy systems without concurrent emissions growth.

Regardless of ceiling, global emissions initially increase, reach a maximum some time in the next century, and eventually begin a long-term decline.

Calculations of future concentrations of greenhouse gases are presented based on modeling the processes that transform and remove the carbon dioxide from the atmosphere. Here, future concentrations of CO_2 are calculated with the carbon cycle model of Jain *et al.* (1996), which takes into account exchanges of CO_2 between the atmosphere, the oceans, and the terrestrial biosphere.

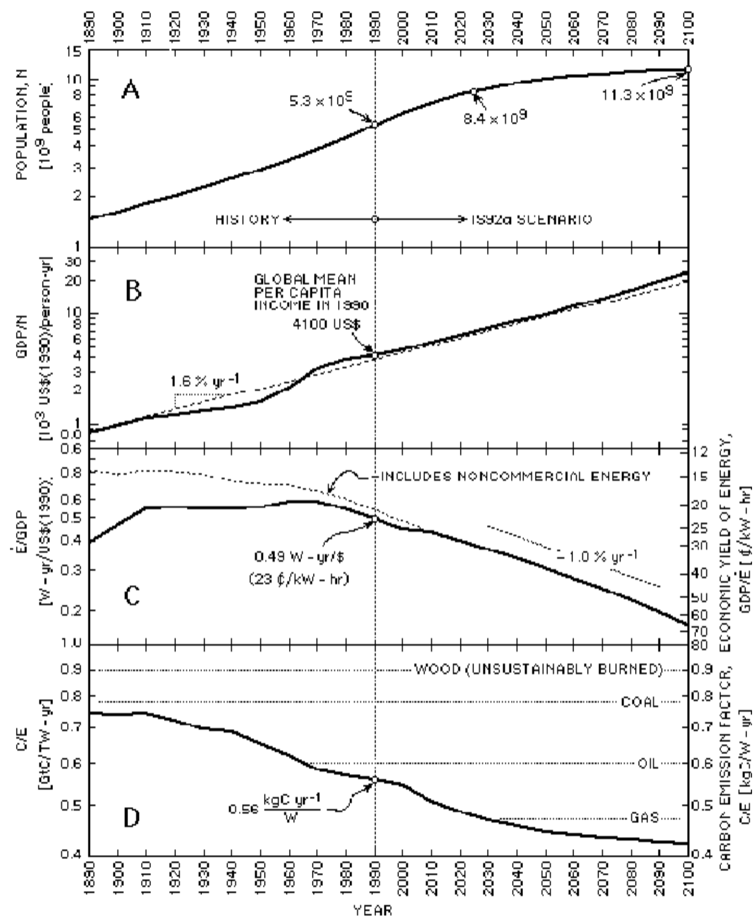

Figure 42
The Four Factors of the Kaya Identity Evaluated Globally from 1890-2100
Hoffert et al., 1998.

Energy Implications of Future CO_2 Scenarios

Following Hoffert et al. (1998), this section analyzes the required carbon-free energy in order to meet the scenarios for CO_2 described above. In general, the rate of carbon emitted (as CO_2) by energy production is given by the *Kaya identity*, expressing emissions as the product of: (i) population (N), (ii) per capital gross domestic product (GDP/N), (iii) primary energy intensity (E/GDP), and (iv) carbon intensity (C/E). Here, we express the rate of primary energy consumption from all fuel sources (the "burn rate") in watts (W) and the gross domestic product in dollars per year (1990 US \$ yr^{-1}) so their ratio, the *energy intensity*, has units of W yr $\$^{-1}$. *Carbon intensity*, the weighted average of the carbon-to-energy emission factors of all energy sources, has the units kgC W^{-1} yr^{-1}. To illustrate the relative contributions of the factors historically and under IS92a, we evaluated each of them globally over the 210-year period from 1890 to 2100 (see Figure 42) from historical data before 1990, and from documents defining IPCC scenarios after 1990.

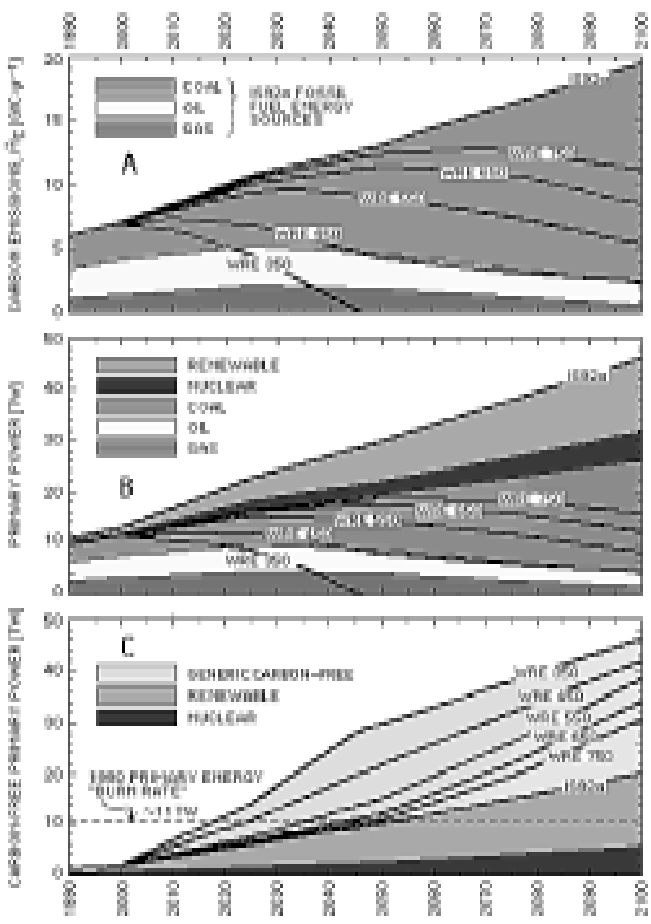

Figure 43
Carbon Emissions, Primary Power Levels, and Carbon-Free Primary Power Required Over the 21st Century for IS92a and Various CO_2 Stabilization Levels
Hoffert et al., 1998

The rate of carbon emitted (as CO_2) by energy production is given by the *Kaya identity*, expressing emissions as the product of: (i) population (N), (ii) per capital gross domestic product (GDP/N), (iii) primary energy intensity (E/GDP), and (iv) carbon intensity (C/E).

While illustrating the big picture, aggregating Kaya decomposition terms globally can mask regional developmental differences. Data for individual nations indicate E/GDP typically *increases* during economic development, reaching a maximum as infrastructure investments peak, and declines only after some lag as economic productivity rises and the economy shifts structurally to less energy intensive activities (e. g., services). Apparently declining, energy intensities of India and China today are still 2 to 5 times the global mean. To focus on energy supply issues we provisionally accept the IS92a projections of 1% yr^{-1} improvement in global E/GDP, recognizing that achieving this will depend crucially on the technology and structural changes adopted by developing nations.

Another opportunity for emission reductions is continuation of the "decarbonization" of the past hundred years reflected in decreasing carbon intensity of the global energy mix. Under IS92a, the global mean C/E continues to decrease monotonically over the next century (Figure 42D). Indeed, the evolving global energy mix based on assumed declining costs of nuclear and carbon-free energy backstops relative to fossil fuels has global C/E dropping to that of natural gas by 2030; and it declines even more thereafter. Such rapid decarbonization is possible only by the massive introduction of carbon-free power, ~10 TW by 2050. Even with this much carbon-free power and sustained 1% yr^{-1} improvements in energy intensity the net effect of the factors in the Kaya identity more than doubles 1990 emissions by 2050.

Even with 10 TW of carbon-free power and sustained 1% yr^{-1} improvements in energy intensity the net effect of the factors in the Kaya identity more than doubles 1990 emissions by 2050.

Figure 43 shows (A) carbon emissions, (B) primary power levels and (C) carbon-free primary power required over the twenty-first century for IS92a and CO_2 stabilization scenarios. Even the optimistic decline of the last two factors in the Kaya identity cannot prevent emissions from increasing from 6 GtC yr^{-1} in 1990 to ~20 GtC yr^{-1} by 2100 under BaU (Figure 43A). Also shown as differently shaded zones are the relative contributions of natural gas, oil and coal to emissions. A feature of IS92a worth noting is that the share of carbon-intensive coal, relative to less carbon-intensive natural gas and oil, rises after 2025, but the carbon intensity (C/E) of the fuel mix declines overall, a feature possible only by the massive introduction of carbon-free energy sources.

The curves in Figure 43A are allowable emission levels over time which ultimate stabilize atmospheric CO_2 at 750, 650, 550, 450 and 350 ppmv computed for the Wigley, et al. (WRE) stabilization paths. These delayed stabilization paths which follow IS92a emissions early on, with large rollbacks later (hereafter, WRE 350, 450, ..., 750 scenarios), could buy time to attain CO_2 stabilization goals. This is possible because a given atmospheric CO_2 concentration goal depends roughly on cumulative carbon emissions and can be approached by an infinite number of paths, some of which constrain emissions early, some later. However, WRE did not consider whether their paths were a realistic transition from the present fossil fuel system. They emphasized that their "results should not be interpreted as a 'do nothing' or 'wait and see' policy'", calling for prompt and sustained commitment to research, development and demonstration to insure that low-carbon and carbon-free energy alternatives are available when needed.

The thick black curve in Figure 43B shows the evolution of total primary power required to meet the economic goals of IS92a, with gas, oil, coal, nuclear, and renewable components

shown as colored areas. Also shown are allowable primary power levels from fossil fuel sources computed for WRE stabilization scenarios. The difference between the IS92a total primary power, , and fossil fuel power allowable for CO_2 stabilization, $_{f,}$ must be provided by carbon-free sources if the economic and "efficiency" assumptions of IPCC "Business as Usual" are maintained; an increasingly challenging goal as the CO_2 concentration target is lowered.

Figure 43C shows carbon-free power required for IS92a and for CO_2 stabilization via WRE 350 through 750 paths in a world economy growing as IS92a and with the same improvement rate in /GDP. In that case stabilizing CO_2 concentrations at 1990 levels according to WRE 350 will require ~10 TW of carbon-free primary power by 2018, equal to the total 1990 primary power of the world economy. WRE 550, which leads to an approximate doubling of pre-industrial atmospheric CO_2, requires this much carbon-free power by 2035. These results imply a massive transition from the present fossil-fuel-dominated energy infrastructure to carbon-free sources in the coming decades to stabilize CO_2 at reasonable target values. Even IS92a requires ~10 TW of carbon-free power by 2050.

Stabilizing atmospheric CO_2 at twice pre-industrial levels while meeting the economic assumptions of BaU implies a massive transition to carbon-free power, particularly in developing nations. There are no energy systems technologically ready at this time to produce the required amounts of carbon-free power. Some suggest the answer may be integrated energy systems based on fossil fuels in which carbon dioxide or solid carbon is sequestered in reservoirs isolated from the atmosphere, or "geoengineering" compensatory climate changes. Despite potentially serious environmental and cost problems, these approaches would allow fossil fuel, increasingly coal, to continue its historic rise as the primary energy source of the next century.

Stabilizing atmospheric CO_2 at twice pre-industrial levels while meeting the economic assumptions of BaU implies a massive transition to carbon-free power. There are no energy systems technologically ready at this time to accomplish this.

It is time now to look hard at the engineering feasibility of transformative technologies that can change the way primary energy itself is produced. It is within the range of climate change and impact projections that stabilization of atmospheric CO_2 at some level below the IS92a baseline is necessary to mitigate major adverse effects on global economies and ecosystems. In that case, a massive infusion of new energy producing technologies at the required scale could be needed to prevent "dangerous anthropogenic interference with the climate system."

The Kyoto Protocol

The Framework Convention on Climate Change (see FCCC; United Nations, 1992), signed by more than 155 nations, has as its ultimate objective, *"...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."* (p.5). This goal leaves the precise concentration to be defined at a later date. No concentration objective had been identified after the first three meetings of the parties to the convention.

At the third conference of the parties to the FCCC in December 1997, the Kyoto Protocol was negotiated by over 130 nations as a response to the climate change issue. One of the most

prominent features of the agreement is the obligation of parties included in Annex B[1] to constrain their emissions of a basket of greenhouse gases including CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs. In total, these nations agreed to reduce their emissions to 5.2% below 1990 levels on average during the period 2008 to 2012. Should the Protocol enter into force, and even if its terms were renewed throughout the remainder of the twenty-first century, it would not achieve the goal of the FCCC, i. e., it would not stabilize the concentration of CO_2. The Protocol would delay the date by which a concentration of 550 ppmv was exceeded by less than a decade. Results were presented based on the Jain et al. model that demonstrated that the Protocol would reduce the year 2100 concentration by less than 55 ppmv.

Whether or not the Kyoto Protocol ever enters into force, more will be needed to achieve the objective of the FCCC. The cost of emissions abatement is a major consideration in determining the degree and timing of regional and global greenhouse gas emissions mitigation. Considerable work has been undertaken to explore the major factors affecting costs of achieving alternative objectives. Cost depends on a wide array of factors including the policy instruments employed, the degree of emissions mitigation required, and the timing over which emissions mitigation must occur.

SESSION 1

The Kyoto Protocol would delay the date by which a concentration of 550 ppmv was exceeded by less than a decade.

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[1] The nations included in Annex B are: Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, European Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States of America.

Appendix A
Working Group Reports

Following the presentations summarized in this report, the meeting participants divided into several working groups to review and assess the potential of various technologies to help meet future energy requirements. The groups addressed a set of questions for these selected technologies (not intended to be exhaustive): nuclear fission, nuclear fusion, energy efficiency, lunar-based solar power systems, and Earth-based renewable energy sources. Representation of experts in the various topics was uneven, and each group approached the questions differently. The following is a summary of the working groups' deliberations. It is important to note that the answers to many of these questions are subjective and as such, the answers reported here are based on the participants' opinions as well as their knowledge. Further, they are limited to what was specifically discussed among those present in each group.

The meeting participants divided into several working groups to review and assess the potential of various technologies to help meet future energy requirements.

Nuclear Fission

1 A. What is the total energy exploitable by this technology?

Table 11 shows the occurrences of natural uranium. An additional amount equal to approximately ten times Total Reserves and Resources (18.5 Mtonne U) exists in the oceans. Using 2.57 GWtyr/tonne fissioned, the fissioning of the entire 18.5 Mtonne U corresponds to $1.5x10^6$ EJ (47,620 TWtyr). Of this total uranium resource, 0.7205% is comprised of the ^{235}U isotope. If used at a rate of 20 TWt, the total and ^{235}U resources would last 2,380 and 17 years respectively. The thorium resource is estimated to be ~3 times that of uranium.

Table 11
Global Occurrences of Natural Uranium (Mtonne)[a]

	Mtonne	1000 EJ [b]
Reasonably Assured Conventional Reserves (<80$/kgU)	4.0[c]	324
Undiscovered Conventional Resources (80-130$/kgU)	2.8	227
Speculative Conventional Resources (>130$/kgU)	2.0	162
Speculative Unconventional Resources (130-600$/kgU)	9.7	786
Total Reserves and Resources	**18.5**	**1,500**

(a) Uranium 1995: Resources, Production and Demand, Organization of Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA). Paris (1996)3
(b) Based on complete fissioning of all uranium of which 0.7205% by atom (0.711% by mass) is ^{235}U
(c) 1.5 Mtonne (122,000. EJ) Proven Reserves

1 B. What is the maximum rate at which this energy can be exploited?

The rate of exploitation is dependant on the rate at which ^{235}U (light water reactors, LWRs) and/or ^{238}U (liquid-metal reactors, LMRs, which operate on plutonium generated by neutron absorption in the abundant ^{238}Us) burners can be deployed. Given ~10 nations presently capable of building LWRs, each producing 5 LWRs/yr, ~50 GWe/yr could be pro-

duced for these ~1 GW units. At ~2$/We, the (total) capital requirements amount to 100B$/yr. The deployment of LMRs is limited both by RD&D needs and the availability of plutonium required for startup (30-40 tonnePu/GWe). As seen in Figure 44, ~2,000 tonne Pu will be available by the year 2010 for startup of LMRs given that the RD&D is completed and that this LWR-generated plutonium is not thrown away into repositories.

The deployment of LMRs is limited both by RD&D needs and the availability of plutonium required for startup.

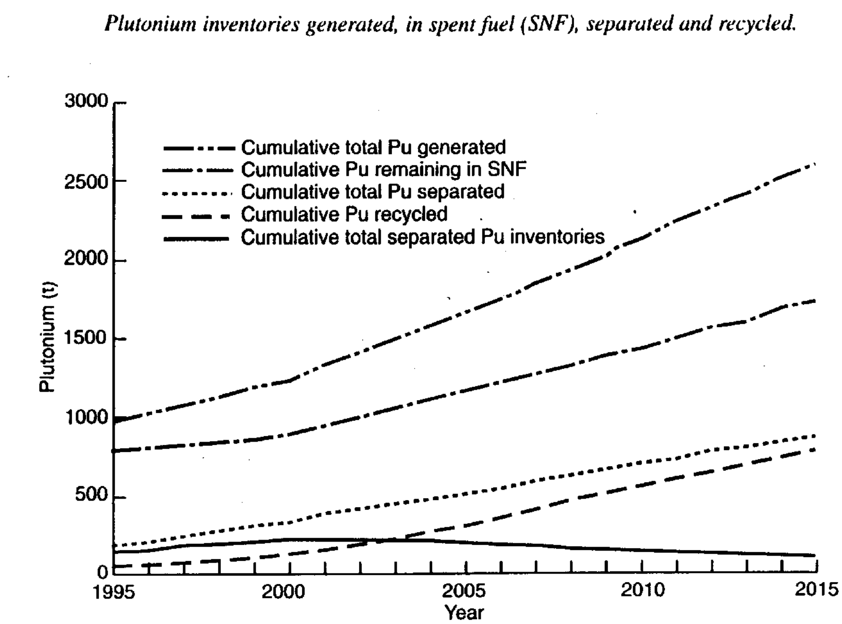

Figure 44
Plutonium Inventories Generated in Spent Fuel (SNF), Separated and Recycled
Source: A. Gloaguen, (1997), "Key Issues Paper No, 2: Present Status and Immediate Prospects of Plutonium Management," International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, Vienna, Austria (June, 1997), International Atomic Energy Agency, Vienna.

Also ~1,000 tonnes of highly enriched uranium (HEU) is available from the nuclear weapons programs. Together, this ~3000 tonnes HEU and Pu could be used to startup ~100 LMRs (~1GWe each). With a doubling time of ~20 years, by the year 2050 ~400 GWe of LMRs could be deployed, with most of the world plutonium inventory tied up as active inventory within these LMRs. Finally, at an LWR deployment rate of ~50 GWe/yr, the year 2050 would see 2,880 GWe capacity and the generation of 1.24 Mtonne of spent fuel containing 12,400 tonne of plutonium and the use of 7.44 Mtonne of natural uranium; integrated over this 2000-2050 period, the LWR-generated plutonium could lead to at least a doubling of the LMR population by the year 2050 to ≥ 1,000 GWe. The total installed nuclear energy by 2050 could amount to ≤ 50% of uranium resource, and the launching of an LMR economy by 2050 that represents ≥ 30% of the total nuclear energy capacity. It should also be noted that at this point 6.2 Mtonne of depleted uranium would be available from the enrichment plants to feed the LMR breeding blankets for the production of fissile plutonium.

1 C. If exploited to its potential, how long would it take to deplete this energy resource?

If fissioned at a rate of 20 TWt, the 18.5 Mtonne of natural uranium would be consumed (by LMRs) in a period of 2,380 years; all the ^{235}U would be fissioned in 17 years. Use of the thrice more plentiful ^{232}Th resource via ^{233}U fission would give an added 3 x 2,380 or 7,140 years at the fission rate, for a total of 9,520 years.

1 D. Is this energy resource renewable naturally; if so, at what rate?

While not renewable, a depletion horizon as described above, expandable to ~30,940 years if the oceanic uranium resource, believed to be ten times as great, is tapped, makes the renewable issue irrelevant.

2. Is there an Achilles' Heel that could prevent the application of this technology?

Yes. The Achilles Heel is embodied in lack of public acceptance. The driving motives and causes of this complex and evolving issue are discussed by Krakowski and Wilson in this volume. In brief, this issue involves how risk/hazard is judged by the public; fear that stems from the nuclear-weapons/nuclear-energy connection; value conflicts such as the multi-generational nuclear-waste burden; and institutional trust/credibility issues. Pathways for increasing public acceptance would involve demonstrating a record of safe operation; reducing risk potential associated with catastrophic consequences of nuclear facilities accidents by improving current plants, developing new reduced-risk plants, and standardizing; increasing the separation of weapons and energy technologies; rediscovering benefits such as reduced oil dependence and greenhouse-gas reduction; progress in waste management leading to sustainable nuclear energy by closing the nuclear fuel cycle; and re-establishing fair, equitable and open institutions responsible for the development, deployment, and regulation of this technology.

The Achilles Heel of nuclear fission energy is embodied in lack of public acceptance.

3 A. What are the purely scientific/technological constraints?

The top-level scientific/technological constraints deal primarily with the RD&D needed to implement this technology on a scale and at a rate suggested in the answer to question 1 D. Examples are:

- Complete the process of "stabilizing" technologies associated with the construction, operation, and decommissioning of the existing LWRs and moving forward on the Evolutionary LWRs as elaborated in Figure 26, in Krakowski. Evolutionary development of reactors is an ongoing process and improvements can be expected in many areas including:
  - Increased use of passive safety systems (leading to optimum use of passive and active system to maximize safety);
  - Core and fuel designs to improve fuel integrity under accident conditions and to maximize the energy obtained from the fissile material;
  - Advanced containment systems to provide better protection against potential releases of radioactivity to the environment;
  - Higher plant availability and better load factors;
  - Lower capital, operating and maintenance costs;
  - Increased thermal efficiency;

- Improved load following capability;
- High fuel burn (more energy per unit of fuel mass);
- Shorter construction times supported by an improved licensing program.

(Source: D. Meneley, (1997) "Key Issues Paper No. 3: Future Fuel Cycle and Reactor Strategies," International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, Vienna, Austria (June, 1997), International Atomic Energy Agency, Vienna.)

- Develop a "dry" (non-aqueous) processing scheme that gives a waste stream free of all actinides and long-lived fission products (LLFPs) as elaborated and suggested in Figures 45 and 46 below:

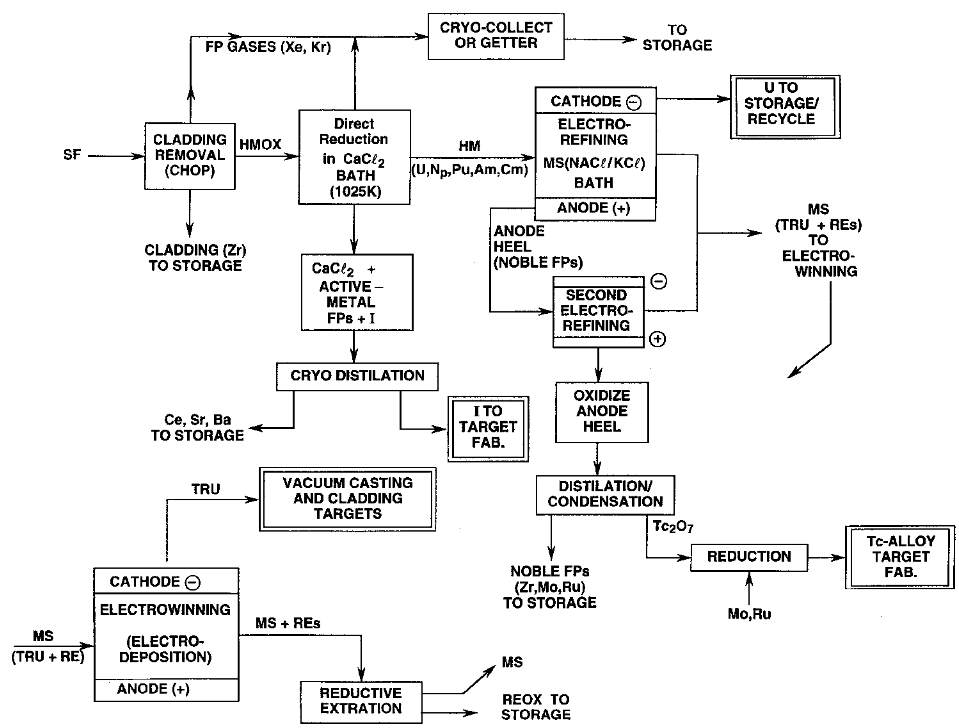

Figure 45
Elaboration of Pyrochemical Processing Scheme Under Development for Use with Fast-Spectrum Burner of Plutonium.
M. A. Williamson, "Chemistry Technology Base and Fuel Cycle of the Los Alamos Accelorator-Driven Transmutation System," Proc. Global '97 Conf. I, 263, Yokahama, Japan, October 5-10, 1997.

- Develop advanced thorium burner, as elaborated in Figure 47 below, that opens the full thorium resource (estimated to be about three times that of uranium) in a way that uses existing technologies (LWRs) and deals with the proliferation issue.
- Develop the LMR as either a breeder or a burner using integrated processing (Figure 45).
- Develop very high burn-up fuel forms.
- Develop a fully integrated process that bridges nuclear energy into a sustainable future that addresses the public acceptance issues (Figure 26 in Krakowski, p. 103).

Improvement is needed in developing a fully integrated process that bridges nuclear energy into a sustainable future that addresses the public acceptance issues.

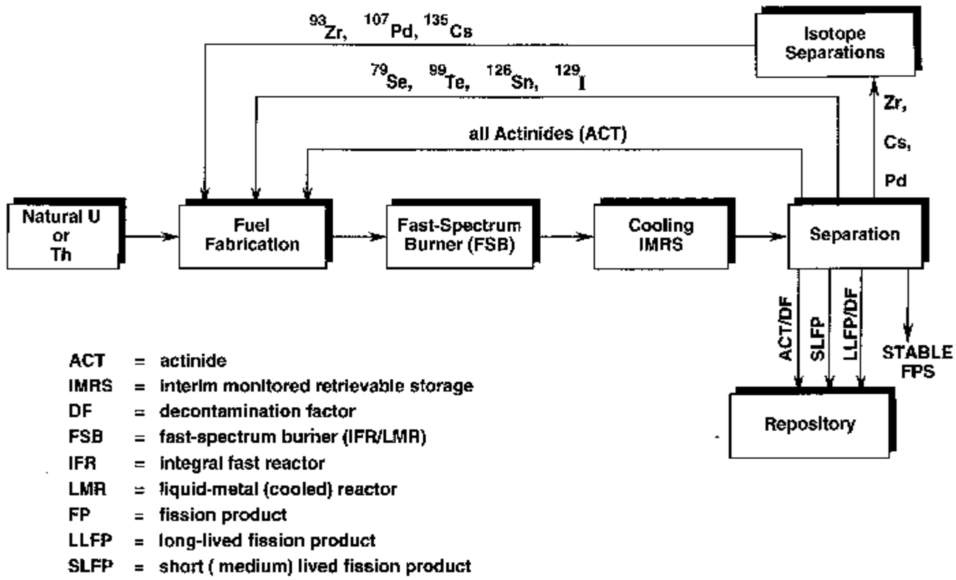

Figure 46
Self-Consistent Nuclear-Energy System (SCNES)
N. Takaki, R. Takagi, and H. Sekimoto, "Effect of Decontamination Factor of Recycled Actinide and FP on the Character of SCNES," *Prog. in Nuclear Energy*, 32 (3/4):441 (1998).

4. What are the smallest and largest scales at which this technology might be economically exploited?

Depending on electric-grid structure, this technology can be economically applied in 0.5-1.5 GWe units. Both front-end (mining and fuel fabrication) and back-end (reprocessing, Interim Monitored Retrievable Surface Storage [IMRSS]) infrastructure is best suited to service ≥ 5-10 of the basic generation units (i. e., 5-10 GWe); the used of advanced Fast Spectrum Burner (fast-reactor or accelerator-based neutron transmutors of actinides and/or long-lived fission products) would be most economically deployed according to schedules that support 8-10 "client" reactors.

5. What is the required infrastructure?

In addition to the front-end, generation, and back-end infrastructure elements described above, the following infrastructure is crucial to a global nuclear energy system:

- Education and training in nuclear sciences and technologies;
- Standards promotion, updating, broadcasting, and enforcement;
- Regulatory units including regional (safety) and global (safeguards);
- Manufacturing to nuclear standards;
- Hazardous-material transport.

6 A. What could be the growth path for this technology if there were no social or political constraints?

A number of growth scenarios can be envisaged for nuclear energy that must deal with the public perception/acceptance issue while facing economic and global climate change (e. g.,

A number of growth scenarios can be envisaged for nuclear energy that must deal with the public perception/acceptance issue while facing economic and global climate change (e. g., needing ~10TW by 2050?) constraints.

needing ~10TW by 2050?) constraints. These scenarios include:

- LWRs with and without plutonium recycle;
- LWRs transiting to the thorium (Radkowsky Thorium Reactor, or related concepts) fuel cycle;
- Application of the Integrated Actinide Conversion System (IACS, Figure 47) and/or the Self-Consistent Nuclear Energy System (SCNES, Figure 46) as a bridge to a publicly acceptable, sustainable nuclear future;
- Combination of above with a focus on the “classical” LWR to LMBR scenario.

7. When would widespread application of this technology be feasible and what are the preconditions and drivers that might make it feasible?

This technology is to begin implementation now following a path sketched above. The RD&D outlined in answer to question 3A must be pursued immediately.

8. What is the expected cost-trend for this technology?

The LWR to Evolutionary LWR (short-term) scenario depicted in Figure 26 in Krakowski (p. 103) has as a major goal a nuclear energy system that is cost-competitive (or better) with present natural gas-fired fossil fuel plants. Cost-reducing design changes in the switch to advanced passive LWRs include an estimated 60% fewer valves, 35% fewer pumps, 75% less pipe, 80% less heating, ventilating and cooling ducting, 50% less seismic building volume, and 80% less cable. Detailed conceptual design studies indicate that a high-capacity LMR can be less expensive than a current Pressurized Water Reactor (PWR). Extensive standardization and massive deployment should greatly reduce costs. The added back-end costs associated with the IACS (Figure 47) or the SCNES (Figure 46) remain to be determined, but could be high.

SESSION 1

The LWR to Evolutionary LWR (short-term) scenario depicted in Figure 26 in Krakowski has as a major goal a nuclear energy system that is cost-competitive (or better) with present natural gas-fired fossil fuel plants.

INTEGRATED ACTINIDE CONVERSION SYSTEM (IACS) ARCHITECTURE FOR NE IN THE 21st CENTURY SHOWING FIVE KEY ELEMENTS

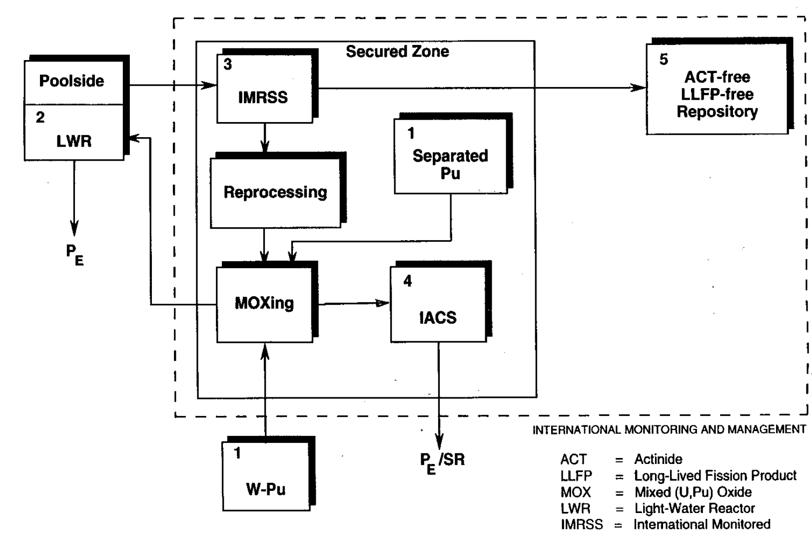

Figure 47
Integrated Actinide Conversion System (IACS) Architecture
E. D. Arthur, P. T. Cunningham, and R. L. Wagner Jr., An Architecture for Nuclear Energy in the 21st Century,” Los Alamos National Laboratory, document LA-UR-98-1931 (June 29, 1998).

9. What would the social, environmental, political, biogeochemical, etc. consequences of widespread exploitation of this technology be?

The social and political consequences of adopting widespread nuclear power are related to the long-term infrastructure implication of working with a highly centralized, hazardous, large technology; central, long-term controls will be required. Given that schemes like IACS (Figure 47) and/or SCNES (Figure 46), or alternatives are successful in generating an actinide-free and LLFP-free waste stream that in a period of a few hundred years (i. e., not millennia) will be reduced to a level of toxicity that differs little from the natural-uranium feed stream, particularly of high-throughput "dry" processing schemes (Figure 45) are technically and economically feasible, the environmental and biogeochemical impacts should be low.; note that simply achieving a waste stream that meets a "natural-uranium" standard does not translate to a "return to initial conditions," in that that ultimate condition does not equate to a pre-(uranium) mining condition.

10. What are the misunderstandings about this technology commonly encountered when communicating with the public, policymakers, media, etc.?

The nature of risk/hazard is judged differently by experts versus the general public (the public tends to over-estimate low-probability potentially catastrophic events and to under-estimate high-frequency, chronic diseases). Also, a fear factor exists that stems from the nuclear energy/nuclear weapons connection. Value conflicts also exist that can shift with changing cultural settings such as that involved in the multi-generational burden of nuclear waste. Also, see answers to Question 2.

11. What are high priority R&D issues in this area?

These have been listed in the answer to Question 3A.

12. What crises would cause a regime change for this technology (i. e., dramatically increase the need for, implementation rate of, etc., this technology?

Given that the atmospheric accumulation of anthropogenic GHGs are found to be driving global climate change, and that nuclear energy is realized to be the only non-carbon technology that is available, operating, and capable of large-scale application in the mitigation of GHG emissions, a new scenario will be needed, if indeed nuclear energy at the 10-20 TWt power level is required by 2050 and sustained thereafter. For lower non-carbon capacity requirements applied on a more extended 2050-2100 time scale, uranium resources are adequate, and the LWR to LMR scenario will not be required until after 2100, if ever. The latter condition applies if the Radkowsky Thorium Reactor or related schemes prove feasible; if IACS and/or SCNES schemes based on either an accelerator-driven or LMR(IFR)-driven system prove feasible/acceptable and are implemented; and/or if the seawater uranium resource can be tapped for unit costs below ~100 \$/kgU (along with means to control/limit the accumulation of plutonium and minor actinides associated with pure uranium burning).

The social and political consequences of adopting widespread nuclear power are related to the long-term infrastructure implication of working with a highly centralized, hazardous, large technology; central, long-term controls will be required.

Nuclear Fusion

1 A. What is the total energy exploitable by this technology?

- Deuterium-tritium (DT): limited by lithium (Li —> T conversion) resources, which corresponds to roughly 1,000 years at present world energy consumption.(at a use rate of 360 EJ/yr, corresponding to 11,430 TWyr for 7.7 GWyr/tonneLi and 1.5 Mtonne Li);
- Deuterium-helium3 (D^3He): available on the moon, in quantities thought to be approximately equal in potential energy output to Earth's remaining coal resource (Proven + Additional Recoverable, 37,930 EJ = 1,204 TWyr),
  - possibly (infinitely) large resource available from Saturn;
- Deuterium-deuterium (DD): nearly infinite resource from Earth's oceans ($1.8 * 10^{18}$ tonne of ocean translates into $2.78 * 10^{13}$ EJ or $8.8 * 10^{11}$ TWyr).

1 B. What is the maximum rate at which this energy can be exploited?

The energy extraction rate will be dictated more by physics/technology progress than by the rate of fuel resource extraction. Competing uses for lithium resource will play for the DT fusion fuel cycle, which in terms of physics and technology is much easier to achieve.

Although R&D in fusion has proceeded for ~5 decades, beset by advances and setbacks, this technology remains largely on paper in conceptual design form.

1 C. If exploited to its potential, how long would it take to deplete this energy resource (20 TWt)?

- DT: 572 years
- D^3He(Lunar ^2He): 60 years
- DD: nearly infinite

1 D. Is this energy source renewed naturally; if so, at what rate?

Renewed at a very slow rate (e. g., replenishment of lunar ^3He is at an equivalent rate of ~200MWt.

2. Is there an Achilles' Heel that could prevent application of this technology?

Although R&D in fusion has proceeded for ~5 decades, beset by advances and setbacks, this technology remains largely on paper in conceptual design form, and success of fusion technologies depends crucially on advances in physics of plasma heating/confinement/burn/exhaust. Generic (e. g., magnetic, inertial, electrostatic, combinations) Achilles' Heels for fusion are:

- Large, low-power density (MW/tonneFPC, FPC = Fusion Power Core encompassing plasma chamber, vacuum system, blanket, shield, magnetic coils [if any], and related support structure and systems) systems that are costly to build and operate and generate large volumes (albeit, relatively low specific activity) of radioactive waste.
- "Consumption" of large quantities of expensive engineering materials (alloys, coated surfaces, etc.) through radiation damage; potential for destroying and otherwise consuming large amounts of expensive materials/systems per unit of energy generated.
- Potential for large fraction (15-20%) of net power generated being recycled to sustain fusion process.
- Overly complex/fragile (FPCs leading to a potential for unacceptable plant capacity factors (frequent FPC failures, long repair times); inertial confinement fusion (ICF) reduces this problem (separates FPCs from drivers, etc., liquid (metal, salt) walls.

- Need to operate high-heat flux surfaces > 5-10 MW/m^2 under both normal and off-normal conditions (e. g., plasma disruptions) as well as large pulse eddy currents in structures.

3 A. What are the purely scientific/technological constraints?

Scientific constraints: achieving a sustained (or pulsed) plasma fusion that yields ≥ 30 times more energy than required (from the "wall plug") to create/maintain the plasma. Some technological constraints are discussed above in the answer to question 2.

3 B. What are the environmental/sociopolitical/economic/environmental constraints?

Dealing with the public and the legendary axiom that "fusion is always 30-50 years away" while maintaining RD&D budgets; also dealing with the oft-cited promise that fusion is a "clean" energy source (i.e., no dangerous radioactive products/wastes, when and if fusion is brought to commercial fruition; also, the accounting of material resources (as well as carbon/kWh) required of the ultimate fusion reactor embodiment may present a cultural constraint/concern. The constraints can be summarized as follows:

- Sustaining a perpetual fusion energy R&D program;
- Dealing with environmental problems on both public and operational level (e. g., radiation exposure, magnetic fields) as well as potential for large volumes of waste generation;
- Cost/resource issues related to low engineering power densities of some designs;
- Reactor-site "foot-print" and land-use issues;
- Discovery by the public that fusion power is in fact a "nuclear" energy source, with different but related operational (e.g., afterheat and loss-of-coolant concerns, occupational and off-side radiation exposure) and back-end (waste) problems, along with fusion-specific concerns (e.g., strong magnetic fields, large stored energies, etc.).

One constraint is dealing with the legendary axiom that fusion is always 30-50 years away.

3 C. How can these barriers be overcome?

- Explore a variety of alternative approaches to fusion that address the power density/cost issues, while mitigated the problems/concerns listed above (e.g., operational and back-end);
- Explore configurations that are amenable to dealing with the *significantly* more difficult physics and associated more difficult technologies (high-heat-flux surfaces, heating efficiency, etc.) that have been well-documented;
- Be more frank with the public; fusion is a science program and, while ultimately an energy program, cannot project impacts until new physics emerges and new engineering systems are fashioned around that physics;
- Develop advanced materials that are low activating and compatible with the fusion environment while not being expensive/exotic, and promising sufficient longevity in the harsh fusion environment.

4. What are the smallest and largest scales at which this technology might be economically applied?

Generally, the degree to which most fusion concepts "beat" energy balance (i. e., achieve acceptable engineering energy gain Q_E = net electric power/gross input power > 6-7) favors larger systems, but the variability in size and energy balance is great among fusion concepts: new approaches to beating this size/scale issue need to be pursued more vigorously.

5. What is the required infrastructure?
Except for plasma physics/plasma engineering, the infrastructure will similar to that required for other approaches to nuclear energy based on fission (see previous section); proper and successful choice of advanced materials can go a long way in mitigating the long-term radioactive waste problem that is inherent to fusion energy.

6 A. What could be the growth path for this technology if there were no social or political constraints?
The definition/charting of required (and acceptable) growth path(s) is nearly impossible without significant and new breakthroughs in the physics of fusion. At present, only the *approaches* to a new "growth path" can be charted, which should take advantage of the rich cache of approaches that heretofore have been stunted or killed by an over-zealous "conventional" tokamak program. This range of "new" physics should include representatives from MFE (including advanced tokamaks) and IFC, all of which offer real solutions to the well-documented problems identified for the "conventional"-tokamak route.

SESSION 1

The definition/ charting of required (and acceptable) growth path(s) is nearly impossible without significant and new breakthroughs in the physics of fusion.

6 B. What could be the growth path for this technology taking social or political constraints into account?
The present reassessment of the direction taken by fusion energy in large part reflects the impact of social/political constraints being imposed by the past, ITER-centric program that was expensively going nowhere commercially towards a viable end product; hopefully the richness of the fusion approaches that have and are being examined on small scale will overcome the present "crisis" of re-direction and allow the quest for fusion energy to be continued along more promising lines, while (at least) maintaining the intellectual infrastructure that is vital for needed advances on this problem.

7. When would widespread application of this technology be feasible, and what are the pre-conditions and drivers that might make it feasible?
Commercial fusion remains $\geq$ 50 years away (compared to 20 years in the 1960s and 30-40 years in the 1970-80; interestingly, if one plots these projections versus time of projection, commercial fusion should have occurred in the late 1940s!) and remains in the lands of the muses; fundamental new physics ideas/approaches are needed.

8. What is the expected cost-trend for this technology (up/down/level)?
While the (commercial cost) targets are determined by known and/or projected competition, neither the shooting position nor the modality are known; while the focus to date has been place largely on fusion-electric power, other applications of this potentially prodigious neutron source to deal with some of the *cardinal issues* listed above for fission energy (e.g., waste, proliferation, safety, and cost), with roles to be played in the former two through transmutation.

9. What would the social, environmental, political, biogeochemical, etc., consequences of adopting widespread exploitation of this technology?
Although difficult to assess in view of the vague state of a commercialized end-product that might evolve from this technology, based on the complex, nuclear (radioactive products), large-scale nature of this technology, the answer to this question may not differ much from that for nuclear fission energy. The flexibility of configurational and material choices available to fusion however, can in principle reduce these impacts, leading to improved power

systems, reduced costs and reduced radioactive wastes; whether all three of these desirable attributes can be achieved simultaneously remains to be determined by yet to be resolved/achieved physics.

10. What are the misunderstandings about this technology commonly encountered when communicating with the public, policymakers, media, etc.?

The public/policymakers, etc. are generally unaware of the nuclear nature of fusion technologies and related hazards, although the complexity and difficulty of applying fusion principles to commercial power are being realized (particularly by policymakers), as the promised date for commercialization is pushed further into the future. Generally, an inability to deliver a "green" fusion reactor (i. e., no radioactive waste, no radioactive emissions, no "meltdown" risk, no proliferation risk) to the public will be very damaging, if that public still holds tightly to apprehension/mistrust/etc. perceptions in relation to nuclear fission energy. Within the energy community, however, fusion holds a position somewhere between a sincere hope and a suspicious joke.

11. What are the high-priority R&D issues?

- Direct the plasma physics program to examine more thoroughly configurations that address the problems highlighted by three decades of trying to extend the "conventional" tokamak to the status of an attractive commercial energy system; both MFE and ICF approaches, or possible hybrids (e. g., magnetized target fusion, MTF) should be considered;
- Better understand the way in which the physics drives the technology, and connect more firmly to end-product attractiveness at operational, environmental, and economic levels;
- Research and develop plasma systems that in themselves are endogenously responsible to the greatest extent possible for basic plasma functions (e. g., heating, confinement, burn control, current drive, fusion-ash removal, etc.);
- Develop materials better suited for operation in a fusion environment in terms of increased longevity (under particle bombardment of all kinds) and decreased activation (from waste, after-heat, and maintenance/recycle view points);
- Generally, perform both physics, engineering, *and materials* research on commercially appropriate configurations that address the issues raised (in part) by the answers to questions 2 and 3 above.

It is not likely that a physics breakthrough of sufficient magnitude will occur that will lead to a rapid commercialization of fusion power.

12. What crisis would cause a regime change?

It is not likely that a physics breakthrough of sufficient magnitude will occur that will lead to a rapid commercialization of fusion power; nor is such a breakthrough needed as too many plentiful (albeit, some may be or are environmentally hurtful) options for energy generation are available. The use of less-efficient, low-Q_E plasma neutron sources, however, may find a competitive niche if demands grow for mitigating either actinide/fission-product waste generated in a growing nuclear fission economy. Fission/fusion hybrids could also appear much earlier than "pure" fusion reactors either to create fuel for a burgeoning Liquid Metal Fast Breeder economy (not enough plutonium fuel to wait for safety-related intrinsically long doubling times), or as a fission-amplified power generator in its own right; either case gives fusion an important symbiotic role, with the vectors reversed in either case. In any event, such a crisis (e. g., need to transmute LLFPs/actinides, or generate plutonium fuel) could cause an (earlier) regime change for fusion energy.

Energy Efficiency

Introductory Comments

The rate of energy efficiency improvement has an important bearing on the need for future carbon-free power. The energy intensity of an economy, that is how much energy is used to produce a unit of GDP, is often used as an measure of aggregate energy efficiency. There are many problems with this approach (see e. g., Schipper, et al. 1998). Firstly, technological paradigms change radically over long time horizons. Secondly, there is great uncertainty as to whether energy efficiency is improving or economic output is increasing. Thirdly, country comparisons are fraught with potential for misinterpretation due to reliance on measures of market GDP instead of GDP at purchasing power parity (PPP), and lack of knowledge of country's energy use and economic performance. Despite such problems, E/GDP is still the most widely used measure, though other methodologies are evolving (see e. g., Schipper, et al. 1998). (For a more complete discussion of this subject, see the energy efficiency chapter by Susan J. Hassol and Neil D. Strachan in the forthcoming book *Innovative Energy Strategies for CO_2 Stabilization*, edited by Robert Watts.)

The rate of energy efficiency improvement has an important bearing on the need for future carbon-free power.

Depending on the rate of decrease in energy intensity, we may need as little as 5 TW of carbon-free power in 100 years (half as much total energy as the world uses today) or as much as 90 TW. In Figure 48 below, Azar and Dowlatabadi (1998) estimate the amount of carbon-free power needed in the future for a 450 ppmv CO_2 stabilization target assuming energy intensity declines of 0%, 1% and 2% per year. In Figure 49, Hoffert et al. (1998) tackle the same issue. Both studies indicate that sustained efficiency improvements in the range of 2% per year lead to modest requirements for carbon-free power in the coming century, while smaller efficiency gains mean an increasingly large need for such power.

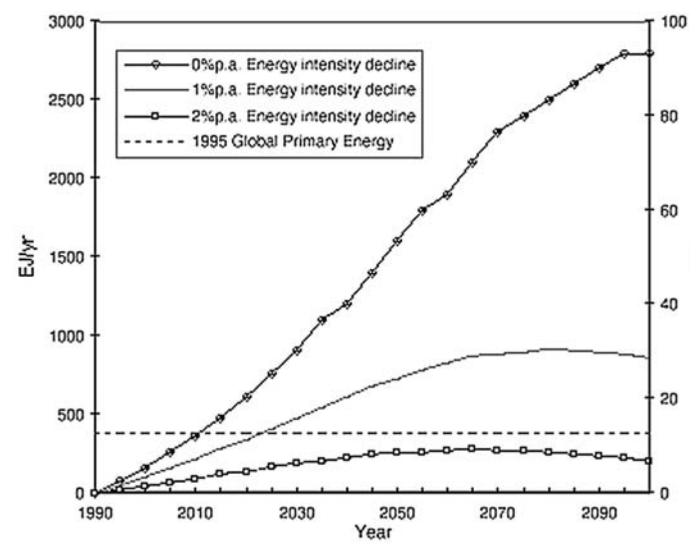

Figure 48
Carbon Free Energy Needed to Meet a 450 ppm Carbon Dioxide Target
Model predictions of required carbon-free energy for different rates of energy intensity decline for a 450ppp CO_2 target. Present total energy supply is indicated by the dotted line. Source: Azar and Dowlatabadi (1999). With permission from the *Annual Review of Energy and the Environment*, Vol. 24, ©1999 by Annual Reviews.

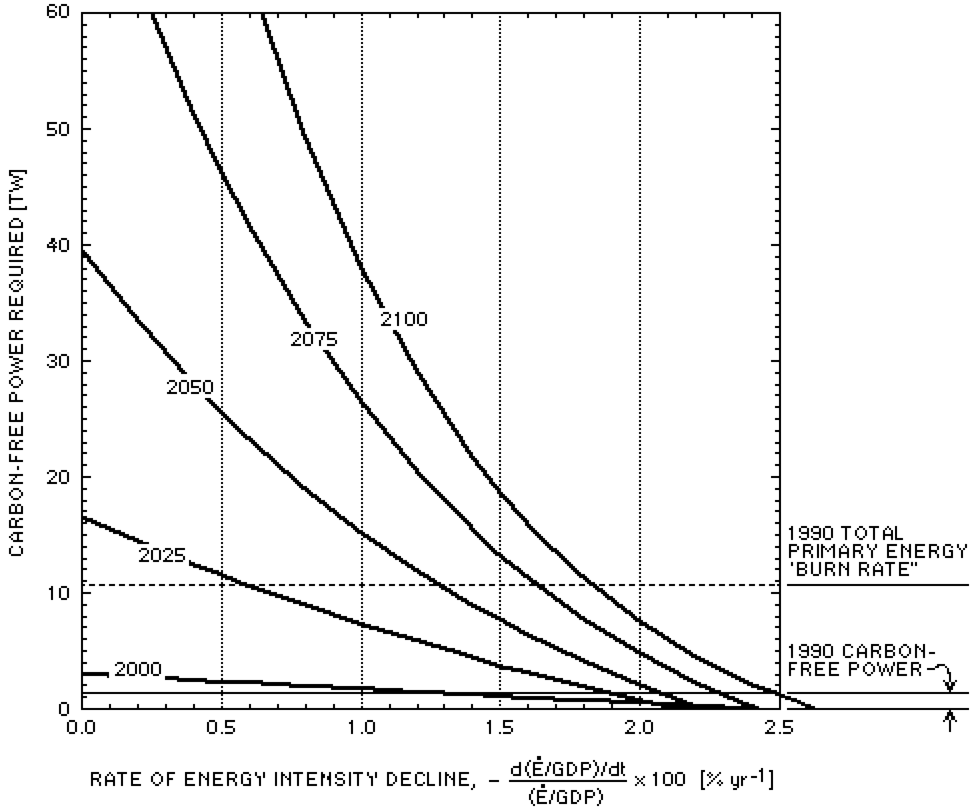

Figure 49

Trade-off Between Carbon-free Power Required and Various Rates of Energy Intensity Decline for a 2x Pre-Industrial CO_2 target following the WRE550 Path

Hoffert et al., 1998

How much sustainable energy-intensity decline can we expect? The authors of the IPCC central "Business-As-Usual" scenario (IS92a) believed that an exponential improvement in energy intensity of ~1% per year would be sustainable over the next century. Various studies model or otherwise forecast long-term rates of energy intensity decline ranging from less than 1% per year to greater than 2% per year. Others point to historical precedents for even more rapid improvement — ~3%/year in the U. S. from 1979-1986 — saying that a concerted effort could mean even greater efficiency gains with wide collateral benefits (e. g., von Weizsacker et al. 1997, Lovins, 1998).

Key factors distinguishing high from low estimates of future energy intensity are price and policy. Simply put, when energy is cheap, there is little incentive to save it. But price is not the only factor. Tax structure, RD&D investments, efficiency standards, and innovative efforts to commercialize new technologies are also important policy elements. Public policies that correctly price energy by internalizing externalities (such as climate-change impacts) and helping to overcome market failures can go a long way towards leveling the playing field for efficiency improvements to compete with supply options.

Key factors distinguishing high from low estimates of future energy intensity are price and policy.

Energy prices in constant dollars have remained flat for at least a generation. In the current U. S. political climate, it seems politically untenable to create meaningful price signals by, e. g., internalizing external environmental costs. Even extremely modest gasoline taxes have been quickly rejected by Congress. In the absence of price signals, what can be done? While no substitute for getting prices right, standards and other regulations are proven efficiency successes. U. S. Corporate Average Fuel Economy (CAFÉ) standards doubled auto efficiency in ten years. Appliance standards that set minimum efficiencies for refrigerators have been similarly successful, and standards are on the way for a variety of other appliances as well as lighting. Such standards should be revised and expanded so that, e. g., auto efficiency standards include Sport Utility Vehicles and other light trucks.

De-subsidizing the energy sector (or equalizing subsidies) would also go a long way toward leveling the playing field for efficiency to compete with supply options. A recent study (Alliance to Save Energy, 1993), documents that the federal government provided $35 in subsidies to traditional energy supplies (coal, petroleum, natural gas, and nuclear) for every $1 provided energy-efficient and renewable energy sources.

SESSION 1

On the private discretionary front, we are losing overall efficiency, largely due to the popularity of Sport Utility Vehicles and larger houses with more energy-consuming devices.

In the U. S., 1978-1985 saw a rapid increase in efficiency as energy prices rose. But even after prices collapsed in 1985, efficiency still continued to increase, particularly in the industrial sector. Industry went up the learning curve quickly during the energy crisis and then continued, as projects put in place continued to pay back, making money for chemical refineries and other industries. Additional help may now come from the sustainable development movement as well as ISO 14000 (International Standard Organization) certification, under which more stringent international efficiency standards are coming into effect; this is a quiet revolution, and companies who want to compete will have to comply. The industrial, commercial, and agricultural sectors are still increasing energy efficiency. On the other hand, on the private discretionary (domestic, autos, etc.) front, we are losing overall efficiency, largely due to the popularity of Sport Utility Vehicles and larger houses with more energy-consuming devices. We've gotten more efficient at making less fuel-efficient cars, as gasoline is cheaper than ever. Gains in engineering efficiency have gone to increase size, power and other features, rather than getting more miles to the gallon.

For utilities, capital costs of new plant construction or refurbishing are huge so it makes sense for utilities to reduce demand through Demand-Side Management (DSM) programs instead of building new plants. This incentive might decrease in another 50 years or so. There has been a down turn in DSM due to deregulation in the utility field. In terms of economic efficiency, it makes sense for utilities to support energy efficiency, although the word "subsidize" is a misnomer for such a practice. In cases in which a utility would have to build new capacity, it always makes sense for that utility to fund efficiency improvements. This is true because if a utility can reduce its demand by a kW, it can afford to pay up to the capital recovery factor of that installed kW for the advantage of not putting the additional new capacity into its fuel charge. Even in some cases where a utility has sufficient plant, it is sometimes cheaper to save energy than produce it. If the efficiency improvement is lower in cost than the average capital recovery factor, then this is possible.

In addition, since one of the problems with increasing penetration of efficiency technologies is the issue of first cost, utilities can serve a useful role in simply financing efficiency improvements. This is also not really a subsidy, as the power company can share in the savings while providing positive cash flow to their customers. If the financing required is less than the capital per unit power required for new capacity, then such financing makes economic sense for the utility. Also, since the utility can borrow money at a lower interest rate than the individual consumer, it is economically efficient for the utility to do the financing.

Lack of information and split or otherwise perverse incentives are problematic, and true economic incentives must be in place. Energy should be valued as though each individual is paying the bill. This will require changes in some institutional settings. In addition, designers of buildings need incentives for making choices that will result in energy efficiency over the lifetime of a building. At present, the builder's incentive is to design and choose products for lowest first cost, with no regard for energy efficiency since he will not be paying the utility bills. Changes in the incentive structure are needed to ensure, for example, that lighting systems would be designed with motion sensors and other efficient technologies with rapid paybacks.

Studies are available that detail how much energy we could realistically save and at what costs (see e. g., ASE, 1998; ASE, ACEEE, 1997). There are free savings, like turning down hot water heater temperatures and properly inflating car tires. There are very inexpensive savings like increasing insulation on water heaters and homes, and choosing low-emissivity (low-e) windows. Pathways to making the economy more energy efficient have been outlined in a variety of studies by the American Council for an Energy Efficient Economy, the Alliance to Save Energy, and others.

Efficiency can make renewables do-able — it is much easier to power a 10 TW world than a 30 TW world, with current renewable energy technology. We can get 2% per year efficiency improvement by doing things we should be doing anyway for a variety of reasons from economic to environmental. The developed world should lead by example and help the developing countries join in. Foreign aid could be tied to energy efficiency and developing countries should transfer best technology to less-developed nations. The trend toward urbanization in the developing world presents a huge opportunity for energy efficiency.

Efficiency can make renewables do-able — it is much easier to power a 10 TW world than a 30 TW world, with current renewable energy technology.

Answers to the Questions Posed

1 A. What is the total energy exploitable by this technology?

We estimate 3.6 TW globally by ~2050.

1 B. What is the maximum rate at which this energy can be exploited?

1.5% ± 0.5% per year is one reasonable estimate; 2% ± 1% per year is another (see Figure 50); it is possible to do more than this with policies designed to maximize efficiency. There is a wide variance of opinion on this topic, however.

1 C. If exploited to its potential, how long would it take to deplete this energy resource?

Not applicable.

Inadequate price signals and perverse subsidies are among the constraints to energy efficiency improvment.

SESSION 1

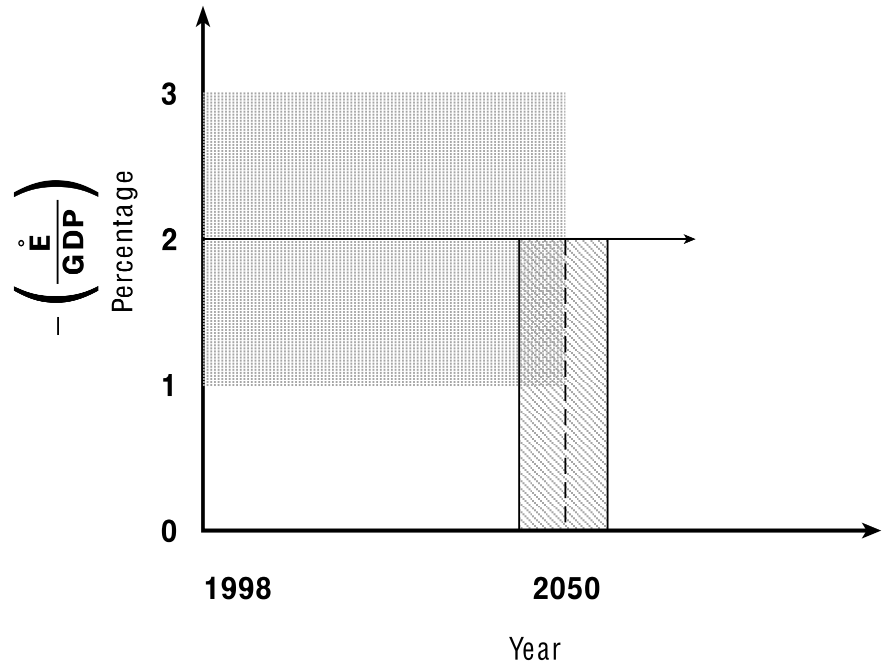

Figure 50
An Estimate of the Range of Potential Energy Intensity Decline

1 D. Is this energy source renewed naturally; if so, at what rate?
Higher efficiencies emerge from human ingenuity and are only limited by physical laws.

2. Is there an Achilles' Heel that could prevent application of this technology?
No.

3 A. What are the purely scientific/technological constraints?
See 1B; Carnot cycle limitation.

3 B. What are the environmental/sociopolitical/economic/environmental constraints?

1) Inadequate price signals
2) Perverse subsidies
3) Public apathy
4) Perceived futility of individual action
5) Incremental change not perceived as important
6) Unfamiliarity and lack of information
7) Upfront capital a constraint on small scale; perceived investor risk a constraint on large scale

3 C. How can these barriers be overcome?

1) fix the constraints in 3B, i. e., get energy prices right (by including externalities, etc.),

remove perverse subsidies, provide information, design financing options to over come upfront cost issue; etc.

2) enlightenment (education + reversing apathy)
3) participation of energy service organizations and utilities
4) policies at all levels to encourage energy efficiency (e. g., economic incentives, etc.)
5) engaging CEO's commitment to increase energy efficiency (top-down effect)
6) ISO 14000

4. What are the smallest and largest scales at which this technology might be economically applied?

Scale independent; applicable at all scales.

5. What is the required infrastructure?

1) Physically, from none (e. g., more efficient light bulbs) to extensive (e. g., gas pipe lines, superconducting transmission lines);
2) Economically, provide capital to facilitate diffusion of technologies;
3) Coalition of interested people to promote the multifaceted benefits of more enlightened/efficient use of energy.

6 A. What could be the growth path for this technology if there were no social or political constraints?

See *e. g.*, von Weizsacker, et al. (1997), for maximum technical potential estimates and pathways. Also see ASE, ACEEE (1997, 1998).

6 B. What could be the growth path for this technology taking social or political constraints into account?

see 1B

7. When would widespread application of this technology be feasible, and what are the pre-conditions and drivers that might make it feasible?

Application has been underway for about two centuries and it is very far from being fully exploited; much more widespread application is possible. As indicated earlier, when energy costs are high, increasing energy efficiency receives greater attention and then has effects that persist even if prices subsequently decline. Also, see 3C.

8. What is the expected cost-trend for this technology (up/down/level)?

Costs will decrease per unit energy. Mass production will help reduce the cost of individual technologies.

9. What would the social, environmental, political, biogeochemical, etc., consequences of adopting widespread exploitation of this technology?

The consequences are numerous and all positive. See e. g., ACEEE, ASE.

- Social: increases employment in manufacturing
- Environmental: In addition to reducing global warming, energy efficiency improvements reduce air, water, soil, thermal pollution & degradation; all benefits rather than negative impacts

The barriers to efficiency can be overcome by getting energy prices right, removing perverse subsidies, providing information, and designing financing options to over come upfront cost issues.

- Political: Improve independence & competitiveness; potential for improving international cooperation
- Biogeochemical: Every biogeochemical cycle will improve due to reducing polluting inputs.

10. What are the misunderstandings about this technology commonly encountered when communicating with the public, policy makers, media, etc.?

See 3B and 3C.

Misconceptions include the notions that:

- Energy-efficient technologies are expensive (life-cycle costs not understood);
- Individual can make little or no difference;
- Subsidies to energy efficiency un-level the playing field; if it were good, it would thrive by itself;
- Media and public perceive energy efficiency as boring, incremental plodding.

11. What are the high priority R&D issues in this area?

Need to expand R&D to include another D, deployment. This is key for efficiency where many technologies are under-deployed.

The social, environmental, political, and biogeochemical consequences of widespread exploitation of efficiency technologies are all positive.

12. What crises would cause a regime change for this technology?

A sustainable response, not a crisis response is needed. A crisis response could cause the choice of not the least-cost solution. But a crisis might speed-up deployment and have residual benefits.

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A sustainable response, not a crisis response is needed.

Lunar Solar Power System

A 20,000 GWe lunar solar power system will deliver to Earth within 100 years the total thermal energy used by humankind since the start of industrial era.

1 A. What is the total energy exploitable by this technology?
The sun provides the energy. Refer to 1(B) for the approximate maximum flux. The total net new energy delivered to Earth increases with time. A 20,000 GWe system will deliver to Earth within 100 years the total thermal energy used by humankind since the start of industrial era.

1 B.What is the maximum rate at which this energy can be exploited?
An additional flux of microwave photons/electric energy can be provided to Earth up to the order of 100,000 GWe-Years each year. This level of high-quality microwave/electric energy can be off-set by reflecting to space an equal flux of low-quality solar photons each year from the area of the rectennas.

Development of the Moon as a central supplier of commercial-scale power to Earth enables the rapid growth of material and service industries on the Moon, between the Earth and the Moon (cis-lunar), the near-Earth asteroids, and beyond. This will dramatically increase humankind's use solar power.

1 C. If exploited to its potential, how long would it take to deplete this energy resource?
Approximately 5 billion years.

1 D. Is this energy source renewed naturally; if so, at what rate?
The sun outputs approximately $4*10^{19}$ GWt. The solar hydrogen, helium, carbon, nitrogen and other elements that participate in fusion reactions in the sun will be converted to higher mass nuclei over the remaining 5 billion years of the life of the sun.

2. Is there an Achilles' Heel that could prevent application of this technology?
There are no obvious technical "show-stoppers." If humankind refuses to expand past the boundaries of Earth then utilization of the Moon will be delayed or not occur.

3 A. What are the purely scientific/technological constraints?
Total power delivered to Earth will likely be limited by the intensity-level of microwaves that are scattered into the biosphere from the power beams and the reradiation from rectennas. Several techniques have been proposed to limit stray microwaves to a tiny fraction of the transmitted power (higher frequencies, airborne rectennas, others).

3 B. What are the environmental/sociopolitical/economic constraints,
- Environmental – See 3(A).
- Sociopolitical – Concerns over control of lunar resources and operational power systems; perceived risks.
- Economic – Initial expenditures for R&D and commercial scale demonstrations; who pays, how much, and equity issues.

3 C. How can these barriers be overcome?
- Environmental – There is rapidly increasing use of microwaves within society. Examples

include microwave ovens, cellular telephones, radar, FM radio, and television. IEEE and other standards organization support extensive and long-term studies of the safety of microwave systems because the use of these systems is so important the world economy.

4. What are the smallest and largest scales at which this technology might be economically applied?

LSP is projected to supply commercial power at levels as low as a few hundred gigawatts-electric. The maximum level is yet to be determined. It is likely between 20,000 to 100,000 GWe. Utilization off-Earth can be many orders of magnitude larger.

5. What is the required infrastructure?

- On the Moon: Mobil facilities to construct from lunar materials the solar collectors/converters and microwave transmission systems.
- On Earth:
  - Microwave receivers/rectifiers (rectennas) are needed on Earth. The rectennas would receive beams of 20 to 250 W/m^2. These limits correspond to approximately 2% to 20% of the intensity of sunlight at noon on a clear day.
  - Power storage must be provided on Earth if a given rectenna receives a power beam only when the rectenna can view the Moon. Approximately 18 hr of power storage is required. Power storage increases the cost of load-following electric energy.
- In orbit about Earth: Load-following power is enabled by *redirectors* in orbit about Earth to redirect beams from the Moon to rectennas on Earth that cannot directly view the Moon. Redirectors can, in principle, either reflectors or retransmitter satellites.

6 A. What could be the growth path for this technology if there were no social or political constraints?

Engineering and cost models indicate that LSP can be installed at rates in excess of 500 GWe/Yr received at Earth at a total cost that is significantly less that alternative power systems.

6 B. What could be the growth path for this technology taking social or political constraints into account?

That is not clear.

7. When would widespread application of this technology be feasible, and what are the pre-conditions and drivers that might make it feasible?

- The fundamental operational technologies have been feasible since 1980. RDT&E on the production technologies are needed. The key production technologies can be fully demonstrated on Earth prior to deployment to the Moon. Extensive technology bases exist on the essential production technologies of excavation, beneficiation, glass-forming, chemical extraction, metal-forming, solar cell production, electronic assembly, and mobility on the Moon.
- Engineering and cost models indicate that the LSP System can provide > 2 kWe/person to everyone on Earth by 2050 at a lower cost per kWe-h than other systems. The level of power can decouple the material needs (industrial goods, agricultural products, fresh water) and services (transportation, commercial and residential, etc.) of humankind from the resources of the biosphere and fossil fuels. Low cost and clean energy is needed

Engineering and cost models indicate that the LSP System can provide > 2 kWe/person to everyone on Earth by 2050 at a lower cost per kWe-h than other systems decoupling the material needs of humankind from the resources of the biosphere and fossil fuels.

world wide to enable a rapid increase in global prosperity. Thus, the desire for prosperity can drive the development of LSP.

8. What is the expected cost-trend for this technology (up/down/level)?

The long term trend is toward lower cost energy. The LSP System is similar to communication satellites. Once the system is in place the power is continuously delivered with no additional costs except maintenance. There are no fuel or significant labor costs. The three major learning curves should progressively lead to lower costs as experience is gained in producing and maintenance. They are:

- Evolving design and production experience on the Moon and via teleoperations from Earth;
- Use of lunar materials in the logistics;
- Use of lunar materials to build significant fractions of the lunar machines of production; and
- Production and emplacement of rectennas on Earth.

Once the lunar solar power system is in place the power is continuously delivered with no additional costs except maintenance. There are no fuel or significant labor costs.

9. What would the social, environmental, political, biogeochemical, etc., consequences of adopting widespread exploitation of this technology?

- Social – Provide adequate clean energy to remove energy supply as a major consideration in the growth and maintenance of local, regional, and global economies.
- Environmental – Net new clean energy would be available to decouple humankind's material and service needs from the biosphere and remediate the damage that has been done to the biosphere.
- Political – The political system can focus on clean economic growth and the expansion of humanity to the Moon and beyond.
- Biogeochemical – LSP System energy can enabling clean recycling of materials, agricultural chemicals, and water.

10. What are the misunderstandings about this technology commonly encountered when communicating with the public, policy makers, media, etc.?

- Perceived danger of microwave power beams.
- High cost of returning to the Moon and constructing power collectors and transmitters on the Moon.
- Combination of several technologies that are not linked into a single physically connected system (ex. compared to a coal fired plant connected by wires to your home or factory).
- It is not generally recognized that the properties of the common lunar materials and the lunar environment are very well understood.
- It is not recognized that the common lunar materials can be processed into power system components using well understood terrestrial materials/industrial techniques.

11. What are the high priority R&D issues in this area?

Conduct a series of progressively larger and more realistic demonstrations of:

- The Moon as a platform for beaming of microwave power to Earth (signal level, sub-commercial level, commercial level).
- Transmission of commercial-level power beams from Earth to low orbit and back to a full scale rectenna on Earth.

- Demonstration of the production of key LSP lunar components (laboratory scale, prototype scale on Earth, and production-scale on Earth and on the Moon).

12. What crises would force changes in human behavior toward development of non-carbon fuel systems?

- Disruptions of oil supplies.
- Another energy war.
- Acceleration of CO_2 effects (global warming, severe weather, etc.)

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SESSION 1

Net new clean energy would be available to decouple humankind's material and service needs from the biosphere and remediate the damage that has been done to the biosphere.

Earth-Based Renewables

The Earth-based Renewable Energy working group addressed issues for six renewable technologies. The five issues they addressed are:

- Limiting Factors
- Long Term Cost Trend
- Technical Feasibility in 2050
- Economic Feasibility in 2050
- Social Feasibility in 2050

The six renewable technologies are:

- Hydroelectric
- Geothermal
- Ocean Thermal
- Wind
- Solar Photovoltaic
- Solar Thermal

Some issues are not addressed for particular technologies because they are not applicable or because no information was available.

A limiting factor for hydroelectric is that high flow rates for peak electricity can have significant environmental impacts downstream.

Hydroelectric

Limiting Factors

- Environmental impact on selected sites
- High flow rates for peak electricity can have significant environmental impacts downstream
- Limited sites (although the use of smaller genrating plants expands the number of available sites)
- Impact of fromation of reservoir on wildlife, towns, etc.

Long Term Cost Trend

- Once very high up-front capital costs are overcome, O&M costs should remain steady

Technical Feasibility in 2050

- Likely to supply less than 10% of necessary power

Social Feasibility in 2050

- Not likely to be accepted on very large scale because of potential environmental impacts
- NIMBY (Not-in-my-backyard)

Geothermal

Limiting Factors

- Local depletion of energy source
- Large scale required because of high up-front exploration costs
- Limited hydrothermal sites
- Economics of hot dry rock sources (?)

Long Term Cost Trend

- High up-front capital and exploration costs

- Long-term costs will vary with improvements in turbine technology

Technical Feasibility in 2050
- Very large potential resource

Economic Feasibility in 2050
- Not likely

Social Feasibility in 2050
- No significant social concerns

Ocean Thermal

Limiting Factors
- Land-based sites limited by available coastline areas that are constrained because of aesthetic and recreational concerns
- Cost of ship- or platform-based OTEC facilities
- Possibility of large-scale ocean temperature conversion

Long Term Cost Trend
- Very high start-up costs to develop ship- and platform-based facilities
- Land-based sites will become more expensive as supply becomes limited
- Sea-based sites likely to have steady costs

Technical Feasibility in 2050
- High potential resource

Economic Feasibility in 2050
- Not likely because of high start-up costs

Social Feasibility in 2050
- Positive benefits from aquaculture at site
- Negative impacts regarding coastal areas for aesthetic reasons

Wind

Limiting Factors
- Intermittency
- Remote access to potential sites
- Impact on birds

Long Term Cost Trend
- Decreasing due to technical improvements
- Site costs increase as best sites are used up

Technical Feasibility in 2050
- High potential to satisfy at least 10% of required energy

For wind power, feasibility will increase substantially with increasing ability to handle intermittency.

- Feasibility increases substantially with increasing ability to handle intermittency

Social Feasibility in 2050

- Concerns about the death of birds
- Limited concern about the aesthetic value of windmill-free hills

Solar Photovoltaic

Limiting Factors

- Intermittency

Long Term Cost Trend

- Technology costs are decreasing over time
- Input costs (silicone, etc.) may increase as scale of production increases beyond current levels

Technical Feasibility in 2050

- Huge potential resource if distribution and storage problems can be overcome

Economic Feasibility in 2050

- Competing against wholesale price of other sources of electricity if used to supply grid
- PV in buildings will compete against retail price of electricity and therefore may have more potential

Social Feasibility in 2050

- Desert aesthetics may play very small role
- Attitude generally positive – high-tech, quiet, clean, hidden in the desert, etc.

Solar Thermal

Limiting Factors

- Geographic limitations because of quality of sunlight required for operation (non-uniform distribution of sites regionally)
- Large scale

Long Term Cost Trend

- High capital cost
- Limited potential for future improvement in costs – depends largely on improvements in turbine technology

Technical Feasibility in 2050

- Very large resource

Economic Feasibility in 2050

- Not economically feasible

PV in buildings will compete against the retail price of electricity and therefore may have more potential in 2050.

Social Feasibility in 2050

- Socially acceptable

Answers to the Questions Posed for the Six Technologies Outlined Above:

1 A. What is the total energy exploitable by technology?
Hydroelectric

- Theoretical Potential of 44,000 TWh per year
- Technically possible amount of 20,000 TWh per year
- Technically exploitable amount of 15,000 TWh per year
- 1988 production of 2,000 TWh, 0.5 TW capacity

Geothermal

- 10^{24} joules within 5 km of the earth's crust
- Resources estimated to be 10^{21} joules
- Identified reserves of 10^{18} joules

For wind, the maximum estimated potential, using 23% of the world's land, is 500,000 TWh per year. It is technically feasible to generate 53,000 TWh per year.

Wind

- Maximum estimated potential, using 23% of the world's land, is 500,000 TWh per year
- Technically feasible 53,000 TWh per year

1 B. What is the maximum rate of exploitation?
Not known.

1 C. If exploited to its potential. how long would it take to deplete this energy resource?
Not applicable.

1 D. Is this energy resource renewed naturally: if so, at what rate?
All six technologies are naturally renewed.

2. Is there an Achilles' Heel that could prevent application of this technology?
Hydroelectric

- Social resistance to development

Geothermal

- Hydrothermal: limited number of sites
- Very large economies of scale

Ocean Thermal

- Limited quality of energy from small temperature change

Wind

- Intermittency
- Remote access

Solar Thermal

- Quality of sunlight required at site
- Large economies of scale for power tower and trough systems

Solar Photovoltaic

- Intermittency
- Remote access

3 A. What are the purely scientific/technological constraints?

Hydroelectric

- Limited sites (although the use of smaller generating plants expands the number of available sites)

Geothermal

- Local depletion of energy source
- Large scale required because of high up-front exploration costs
- Limited hydrothermal sites

Ocean Thermal

- Land-based sites limited by available coastline areas that are constrained because of aesthetic and recreational concerns
- Possibility of large-scale ocean temperature conversion

Wind

- Intermittency
- Remote access

Solar Thermal

- Geographic limitations because of quality of sunlight required for operation (non-uniform distribution of sites regionally)
- Large scale required

Solar Photovoltaic

- Intermittency
- Remote access

3 B. What are the environmental/sociopolitical/economic constraints?

Hydroelectric

- Environmental impact on selected sites
- High flow rates for peak electricity can have significant environmental impacts downstream
- Impact of formation of reservoir on wildlife, towns, etc.

Geothermal

- Economics of hot dry rock sources
- Large economies of scale

For ocean thermal, land-based sites are limited by available coastline areas that are constrained because of aesthetic and recreational concerns.

Ocean Thermal
- Cost of ship- or platform-based OTEC facilities

Wind
- Impacts on local bird populations
- Reduced aesthetic value of sites

Solar Thermal
- Large economies of scale

Solar Photovoltaic
- Reduced aesthetic value of sites

3 C. How can these barriers be overcome?
Hydroelectric
- Difficult to overcome barriers

Wind
- Development of storage capability to address intermittency
- Improved T&D technology

Solar Thermal
- Difficult to overcome barriers

Solar Photovoltaic
- Development of storage capability to address intermittency
- Improved T&D technology
- R&D on improved film materials

For hydroelectric, large scale systems are currently most common, but future emphasis should be on smaller scale systems.

4. What are the smallest and largest scales at which this technology might be economically applied?
Hydroelectric
- Large scale systems currently with future emphasis on smaller scale systems

Geothermal
- Large scale only

Ocean Thermal
- Large scale only

Wind
- Range of scales feasible

Solar Thermal
- Large scale only
- Dish technology feasible on smaller scale

Solar Photovoltaic

- Range of scale feasible

5. What is the required infrastructure?
Hydroelectric

- Transmission and distribution from site to consumers or grid

Geothermal

- Transmission and distribution from site to consumers or grid

Ocean Thermal

- Transmission and distribution from site to consumers or grid
- Ship- or platform-based OTEC systems

Wind

- Transmission and distribution from site to consumers or grid
- Storage or other means of producing electricity to cover intermittency of supply

Solar Thermal

- Transmission and distribution from site to consumers or grid

Solar Photovoltaic

- Transmission and distribution from site to consumers or grid
- Storage or other means of producing electricity to cover intermittency of supply

6 A. What could be the growth path for technology if there were no social or political constraints?
Solar Photovoltaic

- Distribution of systems for use in areas without access to the grid
- Penetration of PV in buildings linked to the grid
- Penetration of hybrid PV and hydrogen (or other storage/generation options) systems
- SPS or lunar-based systems used in conjunction with terrestrial systems

7. When would widespread application of this technology be feasible, and what are the preconditions and drivers that might make it feasible?
Hydroelectric

- Currently feasible

Geothermal

- Currently feasible for large scale operations

Wind

- Currently technically feasible

Solar Thermal

- Currently technically feasible for large scale plants

For all six renewable technologies addressed, the required infrastructure is for transmission and distribution from the site to consumers or grid.

Solar Photovoltaic

- Technically feasible now, but not economically feasible until 2030

8. What is the expected cost trend for this technology (up/down/level)?
Hydroelectric

- Once very high up-front capital costs are overcome, O&M costs should remain steady
- Improvements in turbine technology will decrease long-term costs

Geothermal

- High up-front capital and exploration costs
- Long-term costs will vary with improvements in turbine technology

Ocean Thermal

- Very high start-up costs to develop ship- and platform-based facilities
- Land-based sites will become more expensive as supply becomes limited
- Sea-based sites likely to have steady costs

Improvements in turbine technology will decrease long-term costs for several renewable technologies.

Wind

- Decreasing due to technical improvements
- Site costs increase as best sites are used up

Solar Thermal

- High capital cost
- Limited potential for future improvement in costs — depends largely on improvements in turbine technology

Solar Photovoltaic

- Technology costs are decreasing over time
- Input costs (silicone, etc.) may increase as scale of production increases beyond current levels

9. What would be the social, environmental, political, biogeochemical, etc. consequences of adopting widespread exploitation of this technology?
Hydroelectric

- Environmental impacts: flooding of natural or developed areas to create reservoir, changes in fish migration, change in downstream supply of water for agriculture, etc.
- Social impacts: recreational benefits and costs, change in aesthetic value of area, relocation of dwellings for creation of reservoir, potential loss of life from dam failure
- Biogeochemical impacts: bacterial decomposition of biomass in flooded areas

Geothermal

- Environmental impacts: disruption of site to build facility
- Social impacts: Negligible
- Political Impacts: Negligible
- Biogeochemical impacts: Unknown

Ocean Thermal

- Environmental impacts: unknown impact on ocean population, potential benefits from aquaculture
- Social impacts: Negligible
- Political Impacts: Negligible
- Biogeochemical impacts: potential benefits from aquaculture, disruption of ocean energy balance

Wind

- Environmental impacts: negative impact on local bird populations
- Social impacts: slight reduction in aesthetic value of sites
- Political Impacts: Negligible
- Biogeochemical impacts: Unknown

Solar Thermal

- Environmental impacts: Negligible
- Social impacts: reduction in aesthetic value of sites
- Political Impacts: Negligible
- Biogeochemical impacts: Unknown

Solar Photovoltaic

- Environmental impacts: land-use changes for solar collection sites
- Social impacts: reduction in aesthetic value of sites
- Political Impacts: Negligible
- Biogeochemical impacts: Unknown

10. What are the misunderstandings about this technology commonly encountered when communicating with the public, policymakers, media, etc.
Solar Thermal and Solar Photovoltaic

- "Solar power is free."

A common misunderstanding is the idea that "solar power is free."

11. What are the high priority R&D issues?
Hydroelectric

- Management of impact on fish populations

Geothermal

- Reduction of exploration and drilling costs
- Efficiency of conversion process

Wind

- Improvements in variable-speed operation
- Efficiency of windmills (number of blades, etc.)

Solar Photovoltaic

- Efficiency of film

12. What crises would cause a regime change?
For all six renewable technolgies

- Local air quality issues
- Fossil fuel resource depletion
- Climate change impacts: temperature change, sea level rise, etc.

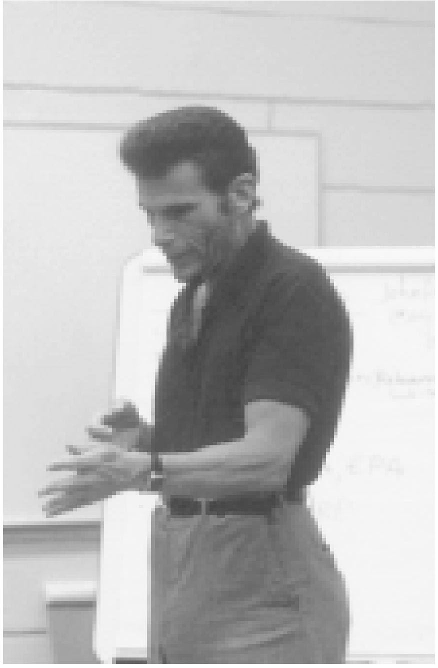
13. Resources

Source for #1a : Williams et al. 1993 “Renewable Energy: Sources for fuel and electricity.” United Nations.

IPCC 1992, Working Group II

SESSION 1

An environmental impact of wind power is a possible negative effect on local bird populations.



Michael Schlesinger discusses adaptive decision-making strategies.

Bob Watts leads a group discussion to plan a forthcoming book on innovative energy strategies for CO_2 stabilization.

Appendix B
Options for Providing Future Energy

Options For Providing 20 TWe (=2kWe/person • 10^{10} people) or 60 TWt by 2050

Editor's Note

During this AGCI Workshop, the participants considered a broad range of global primary power sources. The tables on the following five pages are the result of the pioneering work of one partipant, David Criswell, to quantify the potential contributions of a variety of energy sources. While this work should be regarded as preliminary, it does indicate the kind of cross-cutting issues involved in global energy systems.

Table B1
Mixed and carbon-based sources of thermal and electric power systems

1 Power System	2 Maximum energy inventory on Earth (TWt-y)	3 Annual renewal rate (TWt)	4 Key non-technical issues @ ≤ 20 TWe	5 Limiting technological factors @ 20 TWe	6 Deplete or exhaust (Y) @ 20 TWe or 60 TWt	7 Pollution products	8 Long-term trend of total costs @ 20 TWe	9 Feasible electric output by 2050 in X•TWe
1 **Mixed System Ref. 4, 5**	Non-renew ≤ 3,200 @ 2050	7.7 System output	• All issues (#2-19)	• All issues (#2 - 19)	<100 for coal @2050	• All issues (#2 - 19)	• Rising • All new systems by 2150	~11 Ref. 4 Case 2A used in #1 - #19
2 **Bio-resources**	< 230 @ 2000	< 50 (primarily wood)	• Cost • Less biodiversity • Political objections	• Supply • Mass handling • Nutrients • Water • Land Use	≤ 3	• Smoke • Methane • Diseases • Erosion • Increased CO_2	• NA (Not applicable)	< 0.2
3 **Peat**	< 60 @ 2000	~ 0	• Destroy - wetlands - Agricultural uses	• Supply • Transport (< 100 km)	< 1	• Dust • Fire ash	• NA	~ 0
4 **Coal**	<4,500 @ 2000	0	• Coal lost to future • Land recovery • Environ. impacts	• Supply • Pollution control	≤ 100	• CO_2 • Ash, acids, heavy metals • Waste heat	• NA	• ≤ 4 Steady to decreasing
5 **Oils/Gas**	<1,300 @ 2000	0	• HCs lost to future • CO_2	• Supply	≤ 30	• CO_2, acids • Waste heat	• NA	• ≤ 8 Sharply decreasing

Table B2
Renewable terrestrial systems in 2050

1 Power System	2 Maximum energy inventory on Earth (TWt-Y)	3 Annual renewal rate (TWt)	4 Key non-technical issues @ ≤ 20 TWe	5 Limiting technological factors @ 20 TWe	6 Deplete/ exhaust (Y) @ 20 TWe or 60 TWt	7 Pollution products	8 Long-term trend of total costs @ 20TWe	9 Feasible electric output by 2050 in X•TWe
6 **Hydroelectric**	<14	<5	• Costs • Multi-use - Site - Fresh water	• Sites • Rainfall • NSA (Not stand-alone)	< 1	• Sediment • Flue water • Dam failure	• NA	< 1.6
7 **Tides**	0	< 0.07 (tech. feasible)	• Costs • Shoreline effects	• Sites • Input • NSA	< 0.01	• Change local tides • Fish kills?	• NA	≤ 0.02
8 **Waves**	0	1 to 10 (global deep waters)	• Costs • Shore processes • Navigation	• NSA • Good sites	< 0.1	• Transfer - Gases - Nutrients - Heat - Biota	• NA	< 0.1 or much less
9 **Ocean thermal**	~2×10^6 Perhaps ≤ 4,000 affordable to access	~30	• Costs • Oceans circulations • Cooling surface waters	• Sites • Low efficiency • Bio-fowling • Transmission to shore	< 200 @ 7% conv. effic.	• #7 above • OTEC - mass - rusts - fowling • La Niña effects	• NA	< 0.1
10 **Geothermal**	≤ 9×10^6 (global in top 7 km)	<30 global Mostly low grade	• Costs • Geologic risks • Reinjection effects?	• Local depletion • Flow resistence • Efficiency	< 1 @ 10%effic.	• Waste - heat - minerals	• NA	< 0.5 on continents @ 10% effic.
11 **Wind**	0	< 100 on land ~ TBD off-shore	• Costs • Intrus-iveness • Biota hazards	• Diffuse & irregular • NSA • 10 MWe/ km^2 for wind farms	Ample global supply	• Land Use • Noise • Modify winds (?) - local - global	• Possibly down • Requires low cost storage & transmission	≤ 6

Table B3
Terrestrial Solar Power Systems

1 Power System	2 Maximum energy inventory on Earth (TWt-y)	3 Annual renewal rate (TWt)	4 Key non-technical issues @ ≤ 20 TWe	5 Limiting technological factors @ 20 TWe	6 Deplete or exhaust (Y) @ 20 TWe or 60 TWt	7 Pollution products	8 Long-term trend of total costs @ 20 TWe	9 Feasible electric output by 2050 in X•TWe
12 Terrestrial solar power (thermal) Ref. 4, Case C	0	≤ 1 to 20 MWe/km^2 output of regional system	• Very high systems costs • Local climate change • Weather	• Irregular flux • NSA	$> 10^9$ $> 10^9$	• Waste heat • Induced climates • Production wastes • Land use	• Possibly down • Slow learning	< 3.3 • Sum of 12 & 13
13 Terrestrial solar power (photovoltaic)	0	≤ 1 to 20 MWe/km^2 output of regional system	• Very high systems costs • Area climate change • Weather	• Irregular flux • NSA		• Waste heat • Induced climates • Production wastes • Land use	• Down • Slow learning (50 Y for cost/10)	• Above (#12)

References for Tables B1-B5

Ref. #1 Criswell, D. R. and Waldron, R. D., 1991, "Results of analysis of a lunar-based power system to supply Earth with 20,000 GW of electric power," *Proc. SPS'91 Power from Space: 2nd Int. Symp.*, pp. 186-193. Also – in *A Global Warming Forum: Scientific, Economic, and Legal Overview,* Geyer, R. A., (editor) CRC Press, Inc., 638 pp., Chapter 5, pp. 111-124, 1991.

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Ref. #3 Criswell, D. R., 1999 in preparation, Energy Prosperity Within the 21st Century: Options and the Unique Roles of the Sun and the Moon, Robert Watts, editor, based on the 1998 Aspen Global Change Institute Workshop on Innovative Energy Systems for CO_2 Stabilization

Ref. #4 Nekicenovic, N., A. Grubler, and A. McDonald (editors), 1998, *Global Energy Perspectives*, 299 pp., Cambridge University Press.

Ref. #5 Trinnaman, J. and Clarke, A. (editors), 1998, Survey of Energy Resources 1998, 337 pp., World Energy Council, London.

Table B4
Nuclear power systems

1 Power System	2 Maximum energy inventory on Earth (TWt-y)	3 Annual renewal rate (TWt)	4 Key non-technical issues @ ≤ 20 TWe	5 Limiting technological factors @ 20 TWe	6 Deplete or exhaust (Y) @ 20 TWe or 60 TWt	7 Pollution products	8 Long-term trend of total costs @ 20 TWe	9 Feasible electric output by 2050 in X•TWe
14 Nuclear fission (No breeder)	< 430 @ < 130 $ per kg U	0	• Full life cycle costs • Political acceptance	• Wastes control • Reactor life time	≤ 7	• Radio-active - fuels - parts - wastes	• NA	< 1.5
15 Nuclear Breeder (U^{238}/Th)	≤ 33,000	0	• Above • Prolif-eration	• Above	≤ 550	• Above • Weapons grade materials	• Perhaps constant or decreasing	• Contribution to 13
16 Nuclear Breeder (U in sea water)	< $6*10^6$ @ 3.3 ppb of U	0	• Above • Higher uses	• Above	≤ 300,000	• Above	• Above (#14)	• Above
17 Nuclear fusion – fission or accelerator (D-T with U-Th)	< $1 x10^9$	0	• Above	• Above • Rate of fuel production per unit of power	18,000	• Above • Radioactive (much lower)	• Possibly Decreasing	• Above
18 Nuclear fusion (D-T)	>> $1 x 10^9$	0	• Above	• Practical fusion • Reactor life time	> $1*10^9$ • Lithium limited (tbd)	• Above (#16) • Tritium • Waste heat	• TBD	• 0 likely
19 Nuclear fusion (D-^{3}He lunar)	≤ 100 to $1 x 10^5$	~ 0 (9.5 kg/Yr)	• Lunar mining • Gas releases	• Above • ^{3}He inventory	≤ 1 to 5,000	• Above	• TBD	• 0 likely

Table B5
Space and lunar solar power systems

1 Power System	2 Maximum energy inventory on Earth (TWt-y)	3 Annual renewal rate (TWt)	4 Key non-technical issues @ ≤ 20 TWe	5 Limiting technological factors @ 20 TWe	6 Deplete or exhaust (Y) @ 20 TWe or 60 TWt	7 Pollution products	8 Long-term trend of total costs @ 20 TWe	9 Feasible electric output by 2050 in X•TWe
20 **Geo-Solar Power Sats (from Earth)**	• 0 with power relay satellite • ~ 0.01 with storage	20 to 250 We/m^2 times rectenna area	• Life cycle costs • Fleet - visible - variable - life • System likely not NSA	• Geo-arc • Managing - satellites - shadows • Load following	> 10^9	• Shadowing Earth • New sky objects • Orbital debris • Micro-wave noise • Transport - noise - exhausts	NA Down from very high initial costs	≤ 1 even with ~100 decrease in Earth-to- oribt transport costs
21 **LEO/MEO-Solar Power Sats**	• 0 with sat to satellite re-beaming • 0.01 – 0.05 with storage	≤ 250 •D We/m^2 times rectenna area •D = duty cycle .01 < D < 0.3	• Life cycle costs • Fleet - visible - variable - life time • NSA	•Managing - satellites - shadows - debris • Load following • Microwave spectrum availability	> 10^9	• Orbital debris • Earth - shadow - illuminate • Micro-wave noise • Transport - noise - exhausts	• Up due to maintenance for debris	≤ 0.1
22 **Beyond-Geo Solar Power Sats (with lunar or asteroidal materials)**	• 0 to 0.01 with excess capacity in space	20 to 250 We/m^2 times rectenna area	• Life cycle costs • Fleet life • Potential for stand-alone system	• Very large deep space industry • Power use on Earth	> 10^9	• New sky objects • Micro-wave noise	Down	<#20
23 **Lunar Solar Power System**	• 0 with EO beam redirectors • .01 moon eclipse • 0.04 No EOs	20 to 250 We/m^2 times rectenna area	• Life cycle costs	• Area of Moon • EO beam redirector satellites • Power use on Earth	> 10^9	• Debris of Redirectors • Micro-wave noise	• Potentially ~ 0.1 ¢/kWe-h	≥ 20 to ~1,000 in 22nd century

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SESSION 1

Innovative Energy Strategies for CO_2 Stabilization

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