Technologies for a Greenhouse Planet

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Forty years ago Roger Revelle and Hans Suess whimsically dubbed the then-hypothetical fossil fuel greenhouse a "grand geophysical experiment" (Revelle and Suess, 1957). Perhaps it was less evident then than now that this particular genie might not be so easy to put back in the bottle. As the century and millennium draw to a close, there is little reason for governments seeking to implement the United Nations Framework Convention on Climate Change to ignore relevant research. We know a lot more now.

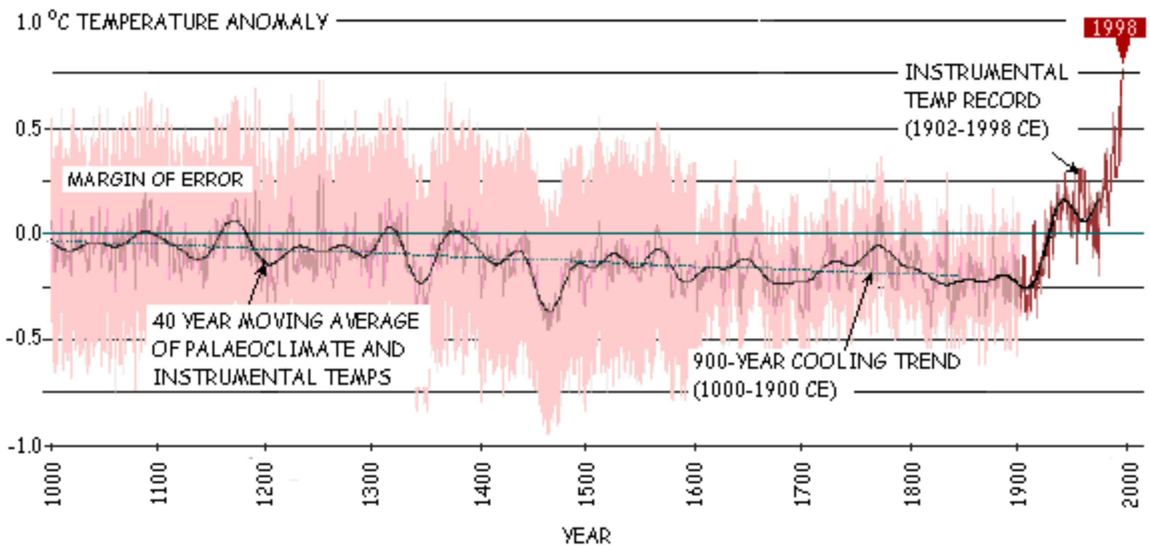


Figure 1. The Northern Hemisphere has been warmer in the 20th century than in any other century of the last thousand years, according to this reconstruction of the hemispheric temperature record by scientists at the University of Massachusetts and the University of Arizona. The sharp upward jump of the 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).

The finding, by United Nations Intergovernmental Panel on Climate Change (IPCC), that the balance of evidence already suggests 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 Schabel, 1998). In another study, a team of paleoclimatologists reconstructed Northern

Hemisphere temperature over the past millennia (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 because it's always possible for a given phenomena to have alternate explanations. There are still rogue geologists who don't accept plate tectonics, and immunologists who don't accept that H.I.V. causes AIDS. Incorrect theories are eliminated when they fail empirical tests. As Karl Popper put it, "Our belief in any particular natural law cannot have a safer basis than our unsuccessful critical attempts to refute it" (Popper, 1969). Theories left standing, like the greenhouse gas theory of global warming, are accepted until they are "falsified" or a better theory comes along .

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 aptly portrayed as "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.

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 tradeoffs 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 Kyoto as in "business as usual."

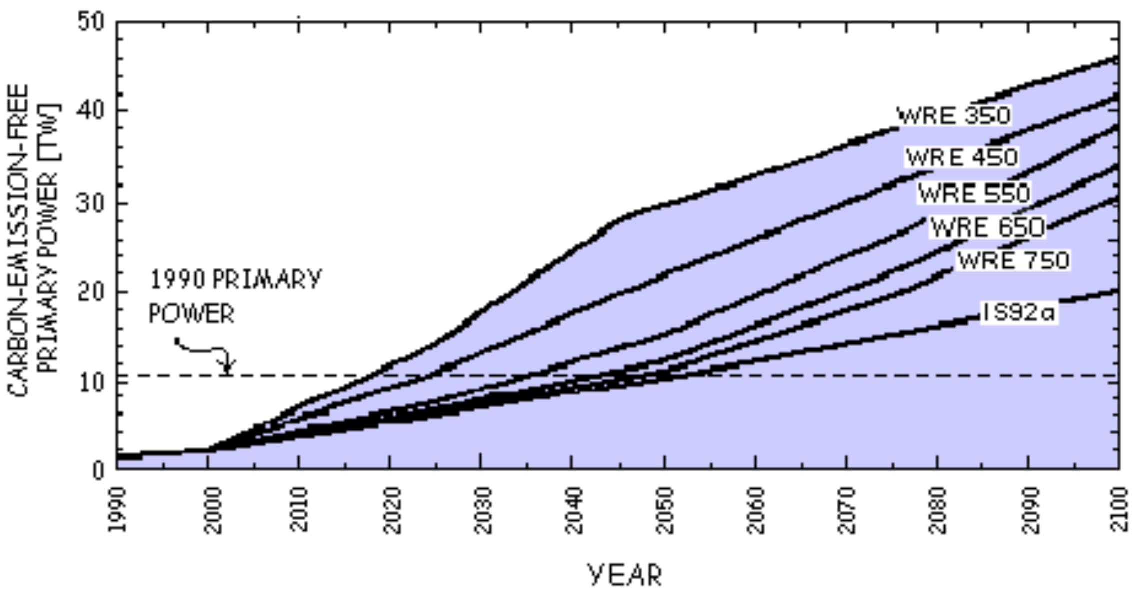


Figure 2 . Twenty-first century carbon-emission-free primary power required to achieve the economic goals of the IPCC Business as Usual scenario (IS92a: No emission controls, but a 1% per year improvement in the efficiency of creating GDP from primary energy). Also shown are the increasing carbon-emission-energy 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 recent study, I and colleagues found that stabilizing atmospheric levels of 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 CO_2 at twice the preindustrial concentration of 270 ppmv — an oft-cited target but high enough to cause significant climate change — without sacrificing economic growth requires that by the year 2050, 100-300% of today's global power come 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.

In a Workshop held at the Aspen Global Change Institute in the summer of 1998 a multidisciplinary group of scientists and engineers met to address the quantitative challenge of carbon-emission-free power without preconceptions. Our impression was that *the range of technology options under consideration for climate change mitigation was too limited*. At this time the most advanced concept actively being investigated by the Department of Energy (DOE) 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 others.

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 the 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, fusion and geoengineering idea were presented, and subjected to lively debate.

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 argue 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.

That may be; but based on estimates of carbon-emission-free power needed by the year 2025 shown in Figure 2, I computed a requirement for huge rates of carbon sequestration to subterranean reservoirs (Table 1). These numbers are a limiting case, because they assume that *all* carbon-emission-free primary power will come 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 (Flannery et al., 1997).

TABLE 1. CARBON SEQUESTRATION RATES BY 2025 TO ACHIEVE VARIOUS ATMOSPHERIC CO_2 STABILIZATION TARGETS FOR EMISSION FACTOR = f x 0.56 [GtC/TW–yr]

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

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 extract hydrogen (H_2) from fossil fuels, H_2 being an energy-carrier suited for use as motor vehicle fuel, if one is willing to pay the price of more total carbon emitted and entombed in subsurface sarcophagi. CO_2 capture and sequestration would thus leave in place, and indeed 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 even as the desirable hydrogen-rich fossil fuels run down? Granted the technological readiness of the technology, it is mind-boggling to imagine, less than thirty years from now, stuffing six to sixteen gigatonnes of carbon per year into deep reservoirs to stabilize atmospheric CO_2 at 550 ppmv (Table 1). Six gigatonnes of carbon per year is humankind's present total emission rate of carbon in the form of carbon dioxide.

In fairness, it is a massive challenge to any carbon-free energy technology to supply the amounts of primary power needed by 2050. There are candidate global primary power sources besides the fossil fuels (coal, oil and gas): renewables (hydro, wind, geothermal, biomass, terrestrial solar, biomass, and ocean thermal and tides), fission ("once-through" ^{235}U reactors and breeders), fusion (D/T and D/^{3}He fuel cycles) and space power (LEO and GEO orbits; lunar power systems).

Few researchers have made *quantitative* analyses of energy producing technologies that could stabilize atmospheric CO_2 emissions at the global scale. An exception is David Criswell at the Institute of Space Systems Operations, University of Houston, who pioneered comparative estimates of energy inventories, times to deplete, peak useful power, and limiting factors across an inclusive spectrum of global energy systems (Criswell, 1998). Cross-cutting studies are also needed of socio-economic infrastructures supporting energy technologies. It is possible that methods for analyzing historical trajectories of technology evolution, including fuel substitutions from coal to oil to gas, might prove useful (Ausubel and Langford, 1997). These have been mainly applied retrospectively, as opposed to projecting possible energy futures. Indeed, energy technology forecasting in general has been in disrepute since the Energy Crisis of the 1970s.

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). Putting it as paleontologist Steven Jay Gould might, How much technology evolution is the inevitable outcome of environmental (market) forces? And how much is random, "historical contingency" (Gould, 1989)? To get some insight into how a future transition to non-fossil power might work, it is worth reviewing how we acquired certain transformative technologies of the last hundred years.

Operating systems

In 1893, the Columbian World's Fair in Chicago banned coal as an energy source on site and displayed many windmills. Coal was gradually replaced by oil and later by gas, while wind power and the other renewables today fight for a few percent of the energy market share.

At the time of this 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: "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" (Cheney, 1981). Alternating current became the standard operating system for electric power transmission in most parts of the world (Ausubel and Marchetti, 1997). The 60 Hz AC standard (50 Hz in Europe) is a "locked-in" legacy of this period. Alternating current is readily stepped-up by transformers to high voltages for low-loss transmission to distant points. This led General Electric to eventually adopt AC despite Edison's "not invented here" reluctance to do so. Westinghouse and GE are, of course, around today, having exploited their early start while adapting to changing markets.

There are other examples where technical superiority leads to 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 at the Xerox Palo Alto Research Center, and commercialized by Steve Jobs and Steve Wozniac at 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 near-monopoly on operating systems, and its problems with the U. S. Justice Department on that score, are history — a history all about infrastructure. Today Microsoft is one of the largest concentrations of economic power on Earth, comparable to fossil energy multinationals collectively.

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 "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).

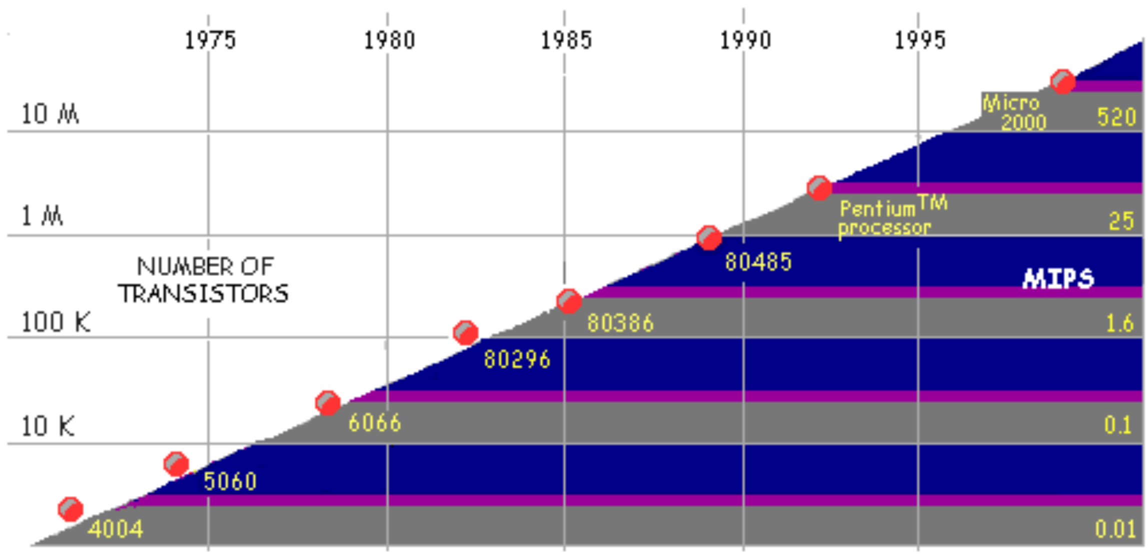


Figure 3. Moore's Law. In 1965, Intel co-founder Gordon Moore predicted transistor density on microprocessors would double every two years. This prediction, so far, has proven amazingly accurate. If it continues, Intel processors should contain 50 to 100 million transistors by the turn of the century and execute 2 billion instructions per second (2000 MIPS).

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. I argue below that market forces alone have been insufficient motivating factors in this century.

A necessary ingredient for innovation is scientific imagination (Dyson, 1996). Arthur C. Clarke has observed that "any sufficiently advanced technology is indistinguishable from magic" (Clarke, 1982). 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." When the vision fails, expect no miracles.

Regarding "vision," there is 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.

Since the beginning, there has been 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 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.

Like spaceflight, the possibilities of nuclear power were explored early in SF. Research in Berlin by radiochemists Otto Hann and Fritz Strassman (who worked with physicist Lisa Meitner before she fled Germany) in 1938 showed that the nucleus of uranium-235 will fission on absorbing a neutron, producing still more neutrons in a series of ferociously exothermic nuclear reactions. The well-known "Einstein letter" to Roosevelt (written by Leo Szilard, and signed by Einstein), dated August 2, 1939, alerted the President to these developments. It is often credited with initiating the Manhattan project. It said (Bronowski, 1973):

> "This new phenomena would also lead to the construction of bombs, and it is conceivable -- though much less certain -- that extremely powerful bombs of a new type might be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove too heavy for transportation by air. "

Less widely known is that as early as September 1940, Robert Heinlein had published in the 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 early 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 small — but not too far off "Little Boy" dropped on Hiroshima August 6, 1945 by the Enola Gay (Serber, 1992).

The German V2 rocket program and the American Manhattan project were both extraordinary achievements, developing radically transformative technologies successfully in short times under conditions of wartime urgency. 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 V2's was no more than the equivalent of a single British bombing raid. It can be argued 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 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 an 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 available 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 any of 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 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. At this time the dominant view at the U.S. DOE is that renewables are minor players in the energy field, primarily satisfying market niches remote from conventional sources. Breakthroughs in photovoltaic (PV) and wind turbine costs might not change this picture dramatically. The cost-pacer of a global renewables is distribution and storage. Hydrogen from water-splitting could become an important energy carrier in a nonfossil-powered world, particularly for vehicles. However, platinum catalysts needed for electrolyzers and fuel cells at a 10-30 TW level could exhaust terrestrial reserves (Appleby, 1999). The mining of platinum from asteroids

(Lewis, 1996) should not be ruled out in explorations of a global hydrogen/energy economy. Perhaps we should also look at the tradeoffs between hydrogen as an energy-carrier and a purely electrical system based on superconducting power transmission (Figure 4).

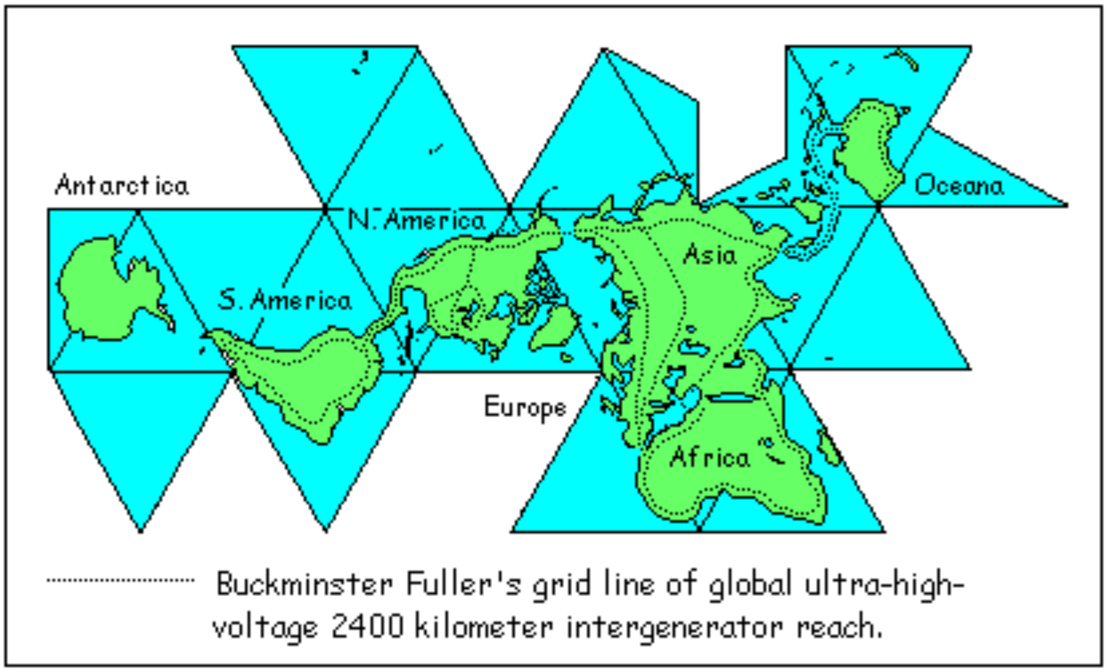


Figure 4. Prototype global electric power grid based on ultra-high -voltage grid proposed by Buckminster Fuller before the discovery of high-temperature superconductivity. This icosohedral map projection pioneered by Fuller shows the size of the world's land masses and oceans more realistically than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

Such a grid has implications for fission as well as renewables. Even if reactor safety could be assured, nuclear fission as a power source is subject to weapons proliferation from reactor fission products. A Fullerian global power grid could permit nuclear electricity generated in secure locations to be marketed 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.

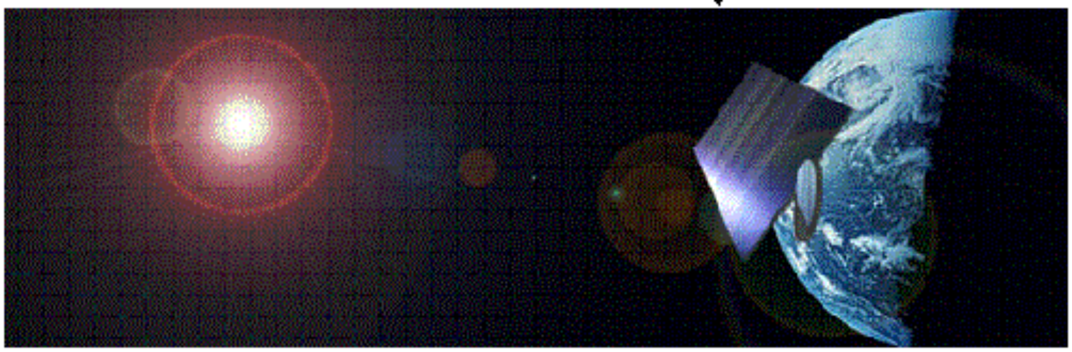
But times are changing. In 1986 Georg Bednorz and K. Alex Müller of IBM Zurich Research Labs discovered a class of perovskites (incorporating thin layers of copper and oxygen) that become superconducting above 77 K where nitrogen liquefies (Bednorz and Müller, 1986). Nitrogen is a constituent of air 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 be marketed safely to Iraq and North Korea — to cite a few possibilities.

Doing it in space

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; Lewis, 1996). Peter Glaser's geostationary orbit (GEO) solar power satellite (SPS) studied as the NASA/DOE SPS Reference System of the 1970s was an early conceptual step toward moving terrestrial energy production off the planet (Glaser, 1968). The advantages of collecting solar energy in orbit include higher average solar radiation and the ability to beam energy selectively to developing nations where energy future demand projections are highest. An innovative "SunTower" configuration from the recent NASA "Fresh Look" study (Mankins, 1997) is compared with the SPS Reference Design of the 1970s in Figure 5. My own ideas about technology evolution paths for space power based on constellations of communications satellites are discussed elsewhere (Hoffert and Potter, 1998).

NASA/DOE 1970s REFERENCE SPS



NASA 1990s "FRESH LOOK STUDY" SUNTOWER" SPS CONCEPT

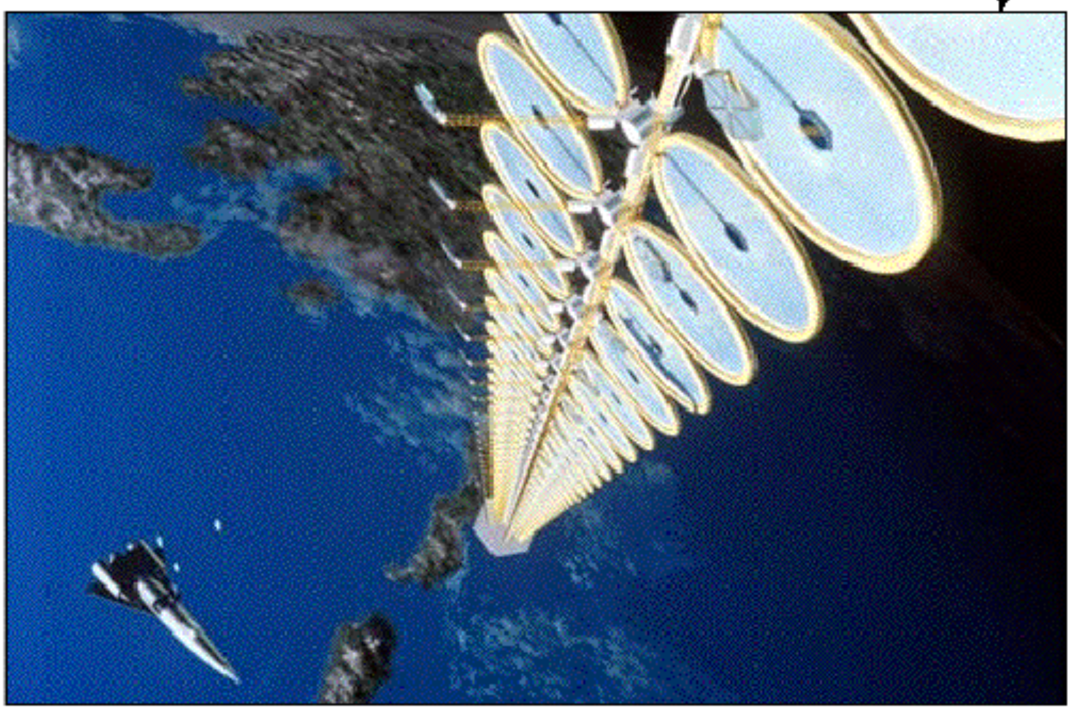


Figure 5. (TOP) Solar Power Satellite (SPS) studied in the 1970s. The NASA/DOE Reference Design shown, one possible realization of Peter Glaser's (1968) SPS idea, collects solar energy from 5 km x 10 km PV arrays in geostationary orbit 35,000 km above the equator, beaming 9 GW of microwave power to 10 km x 13 km rectifying antennas at mid-latitudes for transmission to power grids (Koomanoff and Bloomquist, 1998). (BOTTOM) A more recent design from NASA's "Fresh Look" study is the "SunTower," shown beaming 250 MW to globally dispersed communities from a phased array at its base as it overflys a sun-synchronous ground track (Mankins, 1997).

The cost-pacer of these technologies is access to space — right now, the cost to launch payloads to Low Earth Orbit (LEO). Remarkably, the energy difference between a kilogram on Earth's surface and in LEO, roughly 32 MJ/kg, is about the same as the energy needed to fly that 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 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 carried by a pure rocket as it flies through an ocean of air is 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 Lockheed Martin 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 all the rest of the structure and payload.

Gordon Woodcock of Boeing has 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 $4000 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 to Earth orbit components fabricated on the Moon.

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).

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 vacuum chamber called a "Tokamak," in which a deuterium-tritium (D/T) plasma heated to 100 million kelvins 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). ITER wouldn't actually produce net 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 problems: For one thing, Tokamak magnetic confinement requires (i) a toroidal field produced by coils surrounding a vacuum vessel; (ii) a poloidal field induced by a plasma current -- the secondary circuit of a transient "transformer" primary circuit; and (iii) additional coils around the outside of the vacuum vessel to shape and position the plasma. The "plumbing" and structural requirements of the superconducting magnets alone could be an engineering nightmare. Electric utilities feared radioactive reactor walls created by the neutron flux heating a surrounding lithium blanket (from which tritium is bred and heat transferred to steam turbines) would be environmentally unacceptable (Parkins et al., 1997). Some argue that any fusion power scheme based on the D/T fuel cycle is doomed because the flood of high-energy neutrons produced penetrates metal and disrupts its crystalline structure, causing it to expand and become dangerously brittle .

Today, after 40 years of fusion research, ITER is dead. But the payoff is too big to give up on fusion power. Researchers now emphasize smaller, less capital-risky, and more environmentally acceptable machines (Perkins, 1997;

Lawler and Glanz, 1998). Fusion power just turned out to be much harder than thought when H-bombs were detonated in the 1950s.

Deuterium and tritium in these weapons were considered as first-generation fuels because they burn most easily. Despite the more difficult job of igniting them, 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 ($D/^3He$) (Kulcinski and Santarius, 1998).

Deuterium is available from seawater. But helium is scarce on Earth and the ^3He isotope very rare (Walker, 1977). Abundant in stars, He is a light atom, rapidly lost to space from Earth's gravitational attraction, and unreactive with surface minerals. Surprisingly, analysis of Apollo moon rock samples showed ^3He conveyed by the solar wind is adsorbed in the lunar regolith at concentrations which may be economically recoverable. If aneutronic fusion power plants are workable, it may be cost-effective to fuel them with helium-3 mined on the Moon. Some suggest that atmospheres of gas giant planets may also become important sources of ^3He (Lewis, 1996).

What might an advanced fusion plant be like? One intriguing alternative to the complex magnetic confinement Tokamaks was suggested by Akira Hasegawa of Bell Labs in 1987 -- inspired by the "Io Plasma Torus" discovered by analysis of NASA Voyager flybys of Jupiter and its satellites (Figure 6). He theorized that magnetic confinement, similar to the ability of the Jovian magnetic field to capture and confine plasma derived from it's innermost moon, Io, might be achieved on Earth by a magnetically-levitated superconducting coil. Recently, a proposal solicitation by DOE for innovative fusion experiments was awarded to Michael Mauel of Columbia University and Jay Kesner of MIT to test this idea. These investigators are building a two tonne superconducting magnet they hope to levitate in a vacuum chamber by feedback-controlled magnetic fields for eight hours or more (Broad, 1999).

Whether such a device could raise plasmas to ignition temperatures, and confine them long enough to extract usable power, remains to be seen. A fusion plant with this configuration might require an aneutronic fuel mix like $D/^3He$ to avoid heating the magnet enough to destroy its superconductivity by absorption of high-energy neutrons.

Fusion plants confining plasmas by magnetic dipoles seem at this point simpler to build and maintain than Tokamaks. And getting the plasma hot enough to fuse will be a major problem. But if levitated-dipole plasmas in vacuum chambers can ignite, why not do the fusion in space? In orbit, weightlessness is equivalent to levitation, and near-vacuum is the natural environment. Experiments to test this could be "free flyers" from the International Space Station. If technical feasibility is shown, it may make sense to base fusion plants in orbit, beaming electricity to Earth by microwave. There is also some logic in basing fission power in space; to simplify radioactive waste disposal and render more difficult the diversion of weapons-grade materials by terrorists -- at least in the near term.

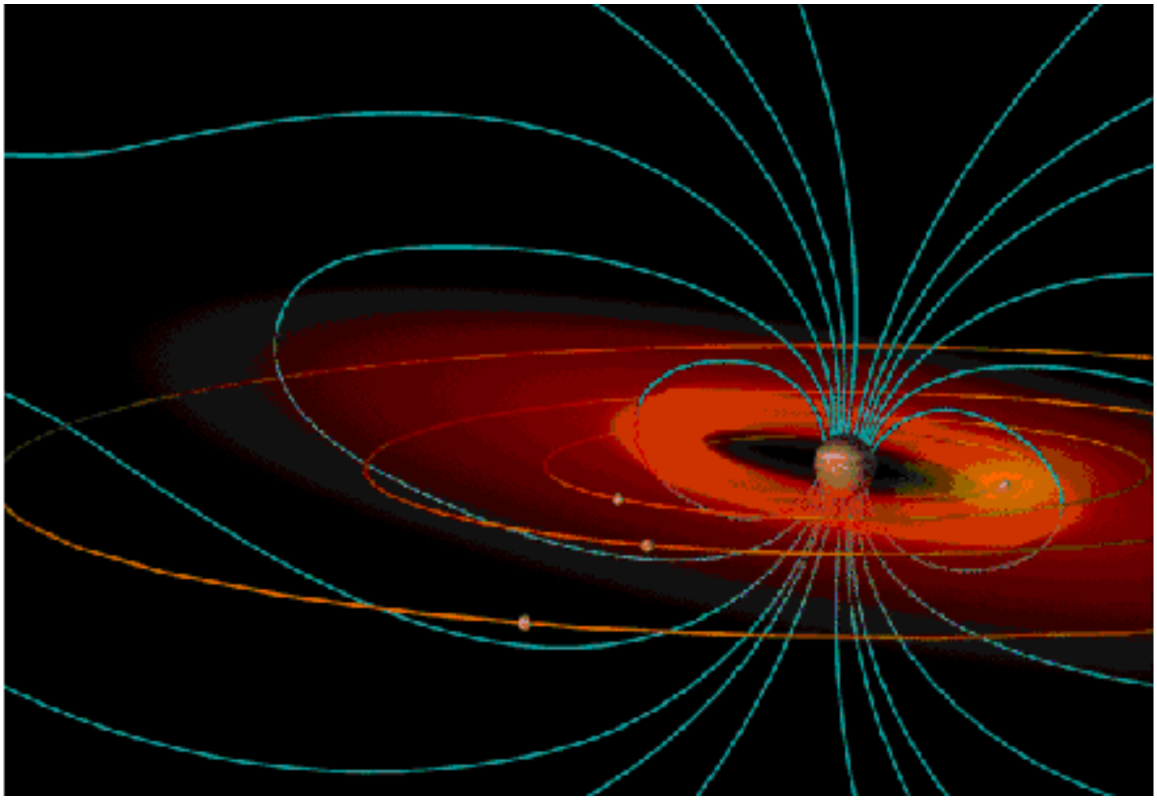


Figure 6. Inner Jovian magnetosphere. Jupiter's magnetic field is shown with blue lines, and the Io Plasma Torus (IPT), at the orbit of Io, in red. Orbits of the other Galilean satellites, Europa, Ganymede, and Callisto, are orange (illustration by John Spencer, Lowell Observatory). The IPT is maintained against diffusive loss by (i) volcanoes, the source of gas for Io's atmosphere and clouds, and (ii) the energetic plasma itself, which strips atmosphere and clouds of particles subsequently ionized and swept up by Jupiter's magnetic field, themselves becoming part of the plasma torus (McGrath, 1997). Prior to discovery of the IPT by Voyager flybys it was not realized that toroidal plasmas can be confined by a simple magnetic dipoles –– a possible route to controlled fusion power.

A common "operating system" for satellite power beaming would permit solar, fission or fusion power generated in space to reach parts of Earth where it is most needed -- particularly the 40% of the human population "off the grid." Solar collectors on the Moon could likewise transmit to satellite--based power grids for distribution to Earth. This evolutionary path illustrates intriguing synergies possible for space exploration, space resources and carbon-emission-free power on Earth. A space-based infrastructure could compliment global power grids on the surface discussed previously. We are likely to need all the carbon-free power we can get. With computerized load management, and a diversity of sources, it is at least plausible that a global energy transition from fossil fuels could be accomplished.

However "far our" these ideas may seem, they're based on real physics; and have already been explored by some contemporary hard science fiction writers. Perhaps we should pay attention. In his "Near Space" stories set in the twenty-first century, SF author Allen Steele developed a future history updated from Robert Heinlein's which includes several themes discussed here (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 joint 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...
>
> 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 that 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..."

Expanding on the "energy from space" scenario, mars exploration entrepreneur Robert Zubrin foresees the helium-three rich outer solar system as the "Persian Gulf" of the latter half of the twenty-first century (Zubrin, 1996). Of course, this may not happen. Almost certainly it won't happen this particular way. The point is that the range of options for mitigating the fossil fuel greenhouse is much broader than usually imagined. New technologies have already reworked economic infrastructures in comparably transformative ways this past hundred years.

Technology and its consequences

It is axiomatic that those advocating innovative technologies to stabilize atmospheric CO_2 buildup on Earth are technological optimists. We realize that there are those not disposed to solve problems created by technology by applying still more technology. Since fossil fuel CO_2 emissions are (among other things) proportional to population, some argue that it can be expediently mitigated by reducing human fertility (Gaffin and O'Neill, 1998). 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 these views. Niles Eldredge (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: "Currently at least two billion people are alive because the proteins in their bodies are built from nitrogen that came via plant and animals foods using [nitrogen fertilizers based on the Haber] process" (Smil, 1997).

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 put it, "When you have eliminated the impossible, whatever remains, however improbable, must be the truth" (Doyle, 1890).

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. Like biological evolution, technology evolution need 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 achievements, succeeded in the market. We must learn to do it better as the "grand geophysical experiment" unfolds. Our future depends on it.

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