Advanced Technology Paths to Climate Stabilization

"Stabilizing the carbon dioxide-induced climate change is an energy problem. Stabilization requires energy sources that do not emit carbon dioxide to the atmosphere.

Mid-century primary power requirements will be three times what we now derive from fossil fuels even with improvements in energy efficiency. We must triple available power while reducing carbon dioxide emission to one third. A broad range of intensive research and development is urgently needed to allow both climate stabilization and economic development. Atmospheric carbon dioxide stabilization as low as 450 ppm could be needed to forestall coral reef bleaching, thermohaline, circulation shutdown, and a sea level rise of three to five feet.

Kyoto Protocol scenarios to stabilize atmospheric carbon dioxide minimize early emission controls by initially following a business-as-usual scenario that combines economic growth of 2 to 3% year with a sustained decline of 1% for year 1 in energy intensity or energy use per gross domestic product.

Much larger cuts than those called for in the Kyoto Protocol are needed. The level at which carbon dioxide stabilizes depends on total emissions. Holding where we are today at 350 ppm, will require Herculean effort. Even holding at 550 ppm is a major challenge.

Primary power consumption today is 12 Terawatts, of which 85% is fossil-fueled. Stabilization at 350 ppm requires emission-free power by mid-century of 30 Terawatts.

The Kyoto Protocol calls for greenhouse gas emission reductions by developed nations that are 5% below 1990 levels by 2008 to 2012. The United States withdrew from the accord for the stated reason that these cuts are an economic burden. But much greater emission reductions will be needed, and we lack the technology to make them. The developing nations are now reneging on Kyoto because they feel that if the leading nations cannot accept the economic burden, neither can they. They will be accelerating their energy use the only way they can, by burning fossile fuels.The only way to reduce emissions with equitable economic growth is to develop revolutionary changes in the technology of energy production, distribution, storage, and conversion. But Present U.S. policy emphasizes domestic oil production, not technology research.

There are no known technological options that exist today. Energy sources that can produce 100 to 300 per cent of present world power without greenhouse emissions do not exist; either operationally or as pilot plants. New technologies will require drastic technological breakthroughs. Carbon dioxide is a combustion product vital to how civilization is powered; it cannot be regulated away. But carbon dioxide stabilization would prevent developing nations from easing their energy supply on fossil fuels.

Primary energy sources include terrestrial solar and wind energy, solar power satellites, biomass, nuclear fission, nuclear fusion, fission-fusion hybrids, and fossil fuels from which carbon has been sequestered. Non-primary power technologies that could contribute to climate stabilization include efficiency improvements, hydrogen production, storage and transport, superconducting global electric grids, and geo-engineering. All of these approaches currently have severe deficiencies that limit their ability to stabilize global climate. Improving Efficiency energy in metastable chemical and nuclear bonds includes fossil fuels, fission fuels, and fusion fuels. "Renewables" are primary energy in natural fluxes; solar photons, wind, water, and heat flows. Energy conversion always involves dissipative losses. Efficiency can be improved in power generation and end-use sectors: transportation, manufacturing, electricity and indoor climate conditioning.

Mature technologies are most efficient. Large electric generators are 98 to 99% efficient and electric motors are 90 to 97%. Rotating heat engines are limited by the second law of thermodynamics: gas and steam turbines to 35 to 50%, diesel to30 to 35% and internal combustion at 15 to 25% efficiency. Electrolyte and electrode materials and catalysts limit electrochemical fuel cells from 50 to 55% now; to 70% eventually. Fuel cells may replace heat engines but will likely run on hydrogen.

A seamless transition would use H2 extracted from gasoline or methanol in reformers at 75 to 80%. Renewable energy converters include hoto voltaic cells at 15 to 24%; and wind turbines at 30 to 40%; Biomass schemes are limited. Photosynthesis has a very low sunlight-to-chemical energy efficiency, limited by chlorophyll absorption bands with the most productive ecosystems at about 1 to 2% efficient; with a theoretical peak of 8%. In a given technology class, efficiency starts low, grows for decades, then levels off at some fraction of its theoretical peak.

It took 300 years to develop fuel cells from 1%-efficient steam engines. The earliest gas turbines could barely turn their compressors. The development of fusion could be similar: The best experiments are close to balancing power to ignite the plasma; power is carried off by fusion-generated neutrons, but no net power output has occurred yet.

Fossil and nuclear fuels are much closer to their limits with steam-cycle efficiencies of 39 to 50%, including cogeneration and overall primary energy-to-electricity efficiency of 30 to 36%. Impressive reductions in waste heat have been accomplished with compact fluorescents, low emissivity windows, and cogeneration. More efficient automotive power conversion is possible . Emissions depend on vehicle mass, driving patterns, and aerodynamic drag, as well as well-to-wheels efficiency. Power trains are 18 to 23% efficient for internal combustion, 21 to 27% for battery-electric; 35 to 40%, 30 to 35% for IC-electric hybrid and 30 to 37% for fuel cell-electric.

Ultra fuel-efficient cars are available today but consumer demand for sport utility vehicles has driven the fuel economy of the U.S. car and light truck fleet to a 21-year low of 20 mpg on the highway. Even doubling efficiency we will be overwhelmed if China and India follow the U.S. path from bicycles and mass transit to cars. Asia already accounts for 80% of petroleum consumption growth.

Advances in efficiency and conservation by themselves cannot solve the problem. Carbon neutral fuels are necessary.

Decarbonization and Sequestration the amount of carbon emitted per unit of primary energy is called decarbonization. The long-term trend has been from coal to oil to gas, with each fuel emitting progressively less carbon dioxide per joule of heat.

Continuation of the trend would lead to use of H2, a carbon-neutral fuel, but H2 does not exist in geological reservoirs. Processes requiring energy are needed for its synthesis. The energy can come from fossil fuel feedstocks. Per unit of heat generated, more carbon dioxide is produced by making H2 from fossil fuel than by burning the fossil fuel directly. Emission-free H2 manufactured by water electrolysis powered by renewable or nuclear sources is not yet cost effective.

But the decarbonization of fuels alone will not mitigate global warming. The problem is providing 30 Terawatts emission-free in 50 years. High-carbon fossil resources such as coal are most abundant, followed by oil and gas. Lower emissions requires disposing of excess carbon.

One vision of "clean" coal incorporates carbon dioxide capture and sequestration: Coal, biomass and waste materials are gasified, cleaned of sulfur and reacted with steam to form H2 and carbon dioxide. .After heat extraction, the carbon dioxide is sequestered and the H2 used for transportation or electricity generation. Decarbonization is thus linked to sequestration. Sequestration reservoirs include oceans, trees, soils, depleted natural gas and oil fields, deep saline aquifers, coal seams, and solid mineral carbonates.

Sequestration uses existing fossil fuel infrastructures, including carbon dioxide injections for enhanced recovery from existing oil and gas fields and the capture of carbon dioxide from power plant flue gases.

The simplest air capture is forestation. Tree and soil sequestration does not require combustion product separation or more fuel, but the capacity to absorb carbon dioxide is limited. Uptake occurs during growth of organic matter.Historical data and models imply a temperate forest carbon sink today of 1 to 3 billion tons of carbon per year but some models show forests reversing from sinks to sources later this century as global warming increases soil respiration and as the trees decay.

The exchange time of carbon dioxide with trees is 7 years. On the oceans fertilization enhanced plankton carbon uptake can be as fast if organic detritus oxidizes near the surface.

Biological sequestration approaches to longer term storage include sealing undecayed trees underground and sinking agricultural residues to the deep ocean, but this is not efficient..

Air capture by aqueous calcium hydroxide in shallow pools, with carbon dioxide recovery by heating, has also been proposed , but breaking the Ca-carbon dioxide bond requires substantial energy.

Ocean injections can substantially decrease peak atmospheric carbon dioxide levels, although all cases eventually diffuse some carbon dioxide back to the atmosphere. Back-diffusion and pH impacts of ocean carbon dioxide disposal could be diminished by accelerating carbonate mineral weathering that would otherwise slowly neutralize the oceanic acidity produced by fossil fuel carbon dioxide.

A far-reaching removal scheme is reacting carbon dioxide with the mineral serpentine to sequester carbon as a solid in magnesium carbonate "bricks" by vastly accelerating silicate rock weathering reactions, which remove atmospheric carbon dioxide over geologic time scales Thus, carbon sequestration could be a valuable bridge to renewable and/or nuclear energy. However, if other emission-free power are unavailable by mid-century, enormous sequestration rates could be needed to stabilize atmospheric carbon dioxide . Substantial research investments are needed now to make this technology available in time.

Renewables energy technologies include biomass, solar thermal and photovoltaic, wind, hydropower, ocean thermal, geothermal, and tidal. With the exception of firewood and hydroelectricity (close to saturation), these are collectively <1% of global power.

All renewables suffer from low areal power densities. They aren't where you need them in concentration. Biomass plantations can produce carbon-neutral fuels for power plants or transportation, but photosynthesis has too low a power density for biofuels to contribute significantly to climate stabilization. Obtaining 10 Terawatts from biomass would requires 10% of Earth’s land surface, comparable to all of human agriculture.

PV and wind energy need less land, but other materials can be limiting. For solar energy, U.S. energy consumption may require a PhotoVoltaici array covering a square 160 kilometers on each side; a total of of 26,000 square kilometers.

The electrical equivalent of 10 TW would require a surface array of 470 km on a side for 220,000 square kilometers. However, all the PV cells shipped from 1982 to 1998 would only cover 3 square kilometers. A massive scale-up is required to get to 30 Terawatts.

More cost-effective Photo Voltaic panels and wind turbines are expected as mass production drives economies of scale. But Earth-based renewables are intermittent, dispersed sources unsuited to baseload without transmission, storage, and power conditioning.

Wind power is often available only from remote or offshore locations. Meeting local demand with PV arrays today requires pumped-storage or battery-electric backup systems of comparable or greater capacity. "Balance-of-system" infrastructures could evolve from natural gas fuel cells if reformer H2 is replaced by H2 from PV or wind electrolysis. Reversible electrolyzer and fuel cells offer higher current (and power) per electrode area than batteries, 20 kWe m 2 for proton exchange membrane (PEM) cells. PEM cells need platinum catalysts, a 10-TW hydrogen flow rate could require 30 times as much as today's annual world platinum production). Advanced electrical grids would also foster renewables.

Even if PV and wind turbine manufacturing rates increased as required, existing grids could not manage the loads. Present hub-and-spoke networks were designed for central power plants, ones that are close to users. Such networks need to be reengineered. Spanning the world electrically evokes Buckminster Fuller's global grid.

With high-temperature superconductivity, electricity can be trasferred between day and night hemispheres and pole-to-pole. Worldwide deregulation and the free trade of electricity could have buyers and sellers establishing a supply-demand equilibrium to yield a worldwide market price for grid-provided electricity. Mass-produced widely distributed PV arrays and wind turbines making electrolytic H2 or electricity may eventually generate 30 TW emission free.
\

The global grid proposed by Buckminster Fuller with modern computerized load management and high-temperature superconducting cables could transmit electricity from day to night locations and foster low-loss distribution from remote, episodic, or dangerous power sources.

Space solar power exploits the unique attributes of space to power Earth. The Solar flux is 8 times higher in space than the surface average on the spinning, cloudy Earth. If theoretical microwave transmission efficiencies of 50 to 60% can be realized, 75 to 100 We could be available at Earth's surface per square meter of PV array in space, One fourth the area of earth surface PV arrays of comparable power.
In the 1970s, the National Aeronautics and Space Administration and the U.S. Department of Energy studied a SPACE SOLAR POWER design with a PV array the size of Manhattan in geostationary orbit (GEO) 35,800 km above the equator that beamed power to a 10-km by 13-km surface rectenna with 5 GWe output.

10 TW equivalent requires 660 of these SPACE SOLAR POWER units. Alternative locations are 200- to 10,000-km altitude satellite constellations, the Moon, and the Earth-Sun L2 Lagrange exterior point. Japan's Institute of Space and Aeronautical Science will attempt to beam solar energy to developing nations a few degrees from the equator from a satellite in low equatorial orbit. Papua New Guinea, Indonesia, Ecuador, and Colombia on the Pacific Rim, and Malaysia, Brazil, Tanzania, and the Maldives have agreed to participate in such experiments).

A major challenge is reducing or externalizing high launch costs. With adequate research investments, SPACE SOLAR POWER could deliver electricity to global markets.

Capturing and controlling sun power in space.The power relay satellite, solar power satellite (SPS), and lunar power system all exploit unique attributes of space of high solar flux, lines of sight, lunar materials and the shallow gravitational well of the Moon.

(B) An SPS in a low Earth orbit can be smaller and cheaper than one in geostationary orbit because it does not spread its beam as much; but it does not appear fixed in the sky and has a shorter duty cycle ;the fraction of time power is received at a given surface site.

Fission and Fusion electricity today is fueled by Uranium 235. Bombarding natural Uranium with neutrons of a few eV splits the nucleus, releasing energy. The 235U isotope, is often enriched to 2 to 3% to make reactor fuel rods.

The existing 500 nuclear power plants are variants of water-cooled submarine reactors. Loss-of-coolant accidents such as Three Mile Island and Chernobyl may be avoidable in the future with "passively safe" reactors. Available reactor technology can provide carbon dioxide emission-free electric power, though it poses well-known problems of waste disposal and weapons proliferation.

The main problem with fission for climate stabilization is fuel. Current estimates of Uranium in recoverable proven reserves are 17 million metric tons, This represents 60 to 300 Terawatt-years of primary energy At 10 TW, this would only last 6 to 30 years--hardly a basis for energy policy.

Japanese researchers have harvested dissolved Uranium from flowing seawater But even with 100% 235U extraction, the flow rate needed to make reactor fuel at the 10 TW rate is five times as much as the outflow from all the worlds's rivers. Getting 10 Terawatts primary power from 235U in crustal ores or seawater extraction may not be impossible, but it would be a big stretch.

Despite enormous hurdles, the most promising long-term nuclear power source is still fusion. Steady progress has been made toward "breakeven" with tokamak toroidal near-vacuum chamber, magnetic containments.The focus has been on the deuterium-tritium reaction.

Deuterium in the sea is virtually unlimited.but there is very little Tritium on earth. If Deuterium-Tritium reactors were operational, lithium bred to Tritium could generate 16,000 Terawatt-years, or twice the thermal energy in fossil fuels.

The Deuterium -Helium 3 (D-3He) reaction yields charged particles that are directly convertible to electricity. Ignition of D-T-fueled inertial targets and associated energy gains of Q 10 may be realized within the next decade.

Experiments are under way to test a D-3He reactor prototype. Rare on Earth, 3He may someday be cost-effective to mine from the Moon. It is even more abundant in gas-giant planetary atmospheres. Seawater Deuterium and outer planet 3He could power civilization longer than any source other than the Sun.

Devices with a larger size or a larger magnetic field strength are required for net power generation. A "burning plasma experiment" could produce net fusion power at an affordable scale and could allow detailed observation of confined plasma during self-heating by hot alpha particles. The Fusion Energy Sciences Act of 2001 calls on DOE to "develop a plan for United States construction of a magnetic fusion burning plasma experiment for the purpose of accelerating scientific understanding of fusion plasmas." This experiment is a critical step to the realization of practical fusion energy. Demonstrating net electric power production from a self-sustaining fusion reactor would be a breakthrough of overwhelming importance but cannot be relied on to aid carbon dioxide stabilization by mid-century.

The conclusion from our 235U fuel analysis is that breeder reactors are needed for fission to significantly displace carbon dioxide emissions by 2050. Breeding could be more acceptable with safer fuel cycles and transmutation of high-level wastes to benign products.Fission is energy rich and neutron poor, whereas fusion is energy poor and neutron rich. A single fusion breeder could support perhaps 10 satellite burners, whereas a fission breeder supports perhaps one. But both fission and fusion are unlikely to play significant roles in climate stabilization without aggressive research and, in the case of fission, without the resolution of outstanding issues of high-level waste disposal and weapons proliferation.

Geoengineering

"Geoengineering" is planetary climate engineering on Earth and terraforming on other planets. Geo-engineering refers mainly to altering the planetary radiation balance to affect climate and uses technologies to compensate for the inadvertent global warming produced
by fossil fuel carbon dioxide and other greenhouse gases.

SunBlock early idea was to put layers of reflective sulfate aerosol in the upper atmosphere to counteract greenhouse warming. Variations include injecting submicrometer dust to the stratosphere in shells fired by naval guns, increasing cloud cover by seeding, and shadowing Earth by objects in space.

A proposed 2000-km-diameter mirror fabricated from lunar materials would be placed at the L1 Lagrange point. The mirror's surface would look like a permanent sunspot, and would deflect 2% of solar flux to compensate for carbon dioxide heating. The deflected sunlight might be directed to the moon to light the shadowed side.

Geo-engineering research is an insurance policy should global warming impacts prove worse than anticipated and other measures fail or prove too costly. Large-scale geophysical interventions are inherently risky and need to be approached with caution. Even as evidence for global warming accumulates, the dependence of civilization on the oxidation of coal, oil, and gas for energy makes an appropriate response difficult. The disparity between what is needed and what can be done without great compromise will become more acute the longer we wait. Energy is critical to global prosperity and equity.

If Earth continues to warm, people may turn to advanced technologies for solutions. Combating global warming by radical restructuring of the global energy system could be the technology challenge of the century. radical departures from our present fossil fuel system
are needed. .Staying the course will require leadership. Stabilizing the climate will not be easy. At the very least, it requires political will, targeted research and development, and
international cooperation. Most of all, it requires the recognition that, although regulation can play a role, the fossil fuel greenhouse effect is an energy problem that cannot be simply regulated away."

From Science Magazine - November 2002

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet

- **Martin I. Hoffert[1,*], Ken Caldeira[3], Gregory Benford[4], David R. Criswell[5], Christopher Green[6], Howard Herzog[7], Atul K. Jain[8], Haroon S. Kheshgi[9], Klaus S. Lackner[10], John S. Lewis[12], H. Douglas Lightfoot[13], Wallace Manheimer[14], John C. Mankins[15], Michael E. Mauel[11], L. John Perkins[3], Michael E. Schlesinger[8], Tyler Volk[2], Tom M. L. Wigley[16]**
- *[1] Department of Physics,*
- *[2] Department of Biology, New York University, New York, NY 10003, USA.*
- *[3] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.*
- *[4] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA.*

- [5] *Institute of Space Systems Operations, University of Houston, Houston, TX 77204, USA.*
- [6] *Department of Economics, McGill University, Montreal, Quebec H3A 2T7, Canada.*
- [7] *MIT Laboratory for Energy and the Environment, Cambridge, MA 02139, USA.*
- [8] *Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA.*
- [9] *ExxonMobil Research and Engineering Company, Annandale, NJ 08801, USA.*
- [10] *Department of Earth and Environmental Engineering,*
- [11] *Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA.*
- [12] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.*
- [13] *Centre for Climate and Global Change Research, McGill University, Montreal, Quebec H3A 2K6, Canada.*
- [14] *Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375, USA.*
- [15] *NASA Headquarters, Washington, DC 20546, USA.*
- [16] *National Center for Atmospheric Research, Boulder, CO 80307, USA.*