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

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Stabilizing the carbon dioxide–induced component of climate change is an energy problem. Establishment of a course toward such stabilization will require the development within the coming decades of primary energy sources that do not emit carbon dioxide to the atmosphere, in addition to efforts to reduce end-use energy demand. Mid-century primary power requirements that are free of carbon dioxide emissions could be several times what we now derive from fossil fuels (~10^{13} watts), even with improvements in energy efficiency. Here we survey possible future energy sources, evaluated for their capability to supply massive amounts of carbon emission–free energy and for their potential for large-scale commercialization. Possible candidates for 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 geoengineering. All of these approaches currently have severe deficiencies that limit their ability to stabilize global climate. We conclude that a broad range of intensive research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development.

More than a century ago, Arrhenius put forth the idea that CO_2 from fossil fuel burning could raise the infrared opacity of the atmosphere enough to warm Earth (*1*). In the 20th century, the human population quadrupled and primary power consumption increased 16-fold (*2*). The fossil fuel greenhouse theory has become more credible as observations accumulate and as we better understand the links between fossil fuel burning, climate change, and environmental impacts (*3*). Atmospheric CO_2 has increased from ~275 to ~370 parts per million (ppm). Unchecked, it will pass 550 ppm this century. Climate models and paleoclimate data indicate that 550 ppm, if sustained, could eventually produce global warming comparable in magnitude but opposite in sign to the global cooling of the last Ice Age (*4*).

The United Nations Framework Convention on Climate Change aims to stabilize greenhouse gas concentrations at levels that avoid "dangerous anthropogenic interference with the climate system (*5*)." Atmospheric CO_2 stabilization targets as low as 450 ppm could be needed to forestall coral reef bleaching, thermohaline circulation shutdown, and sea level rise from disintegration of the West Antarctic Ice Sheet (*6*). Wigley and colleagues developed emission scenarios to stabilize atmospheric CO_2 at 350, 450, 550, 650, or 750 ppm (*7*). They minimized early emission controls by initially following a business-as-usual scenario that combines economic growth of 2 to 3% year^{-1} with a sustained decline of 1% year^{-1} in energy intensity (energy use per gross domestic product). Much larger cuts than those called for in the Kyoto Protocol are needed later, because the levels at which CO_2 stabilize depend approximately on total emissions. Targets of cutting to 450 ppm, and certainly 350 ppm, could require Herculean effort. Even holding at 550 ppm is a major challenge.

Primary power consumption today is ~12 TW, of which 85% is fossil-fueled. Stabilization at 550, 450, and 350 ppm CO_2 by Wigley *et al.* scenarios require emission-free power by mid-century of 15, 25, and >30 TW, respectively (*8*). Attaining this goal is not easy. CO_2 is a combustion product vital to how civilization is powered; it cannot be regulated away. CO_2 stabilization could prevent developing nations from basing their energy supply on fossil fuels (*9*). Hansen *et al.* call for reductions in methane and black soot, which also cause warming (*10*). Such reductions are desirable but do not address fossil fuel greenhouse warming. The Kyoto Protocol calls for greenhouse gas emission reductions by developed nations that are 5% below 1990 levels by 2008 to 2012. Paradoxically, Kyoto is too weak and too strong: Too strong because its initial cuts are perceived as an economic burden by some (the United States withdrew for this stated reason); too weak because much greater emission reductions will be needed, and we lack the technology to make them.

Arguably, the most effective way to reduce CO_2 emissions with economic growth and equity is to develop revolutionary changes in the technology of energy production, distribution, storage, and conversion (*8*). The need to intensify research on such technologies now is by no means universally appreciated. Present U.S. policy emphasizes domestic oil production, not energy technology research (*11*). Misperceptions of technological readiness also appear in the latest "Summary for Policymakers" by the "Mitigation" Working Group of the Intergovernmental Panel on Climate Change (IPCC): "... known technological options could achieve a broad range of atmospheric CO_2 stabilization levels, such as 550 ppm, 450 ppm or below over the next 100 years or more. ... Known technological options refer to technologies that exist in operation or pilot plant stage today. It does not include any new technologies that will require drastic technological breakthroughs. ..." (*12*)

This statement does not recognize the CO_2 emission–free power requirements implied by the IPCC's own reports (*3*, *8*) and is not supported by our assessment. Energy

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sources that can produce 100 to 300% of present world power consumption without greenhouse emissions do not exist operationally or as pilot plants.

Can we produce enough emission-free power in time? Here we assess the potential of a broad range of technologies aimed at meeting this goal.

Improving Efficiency

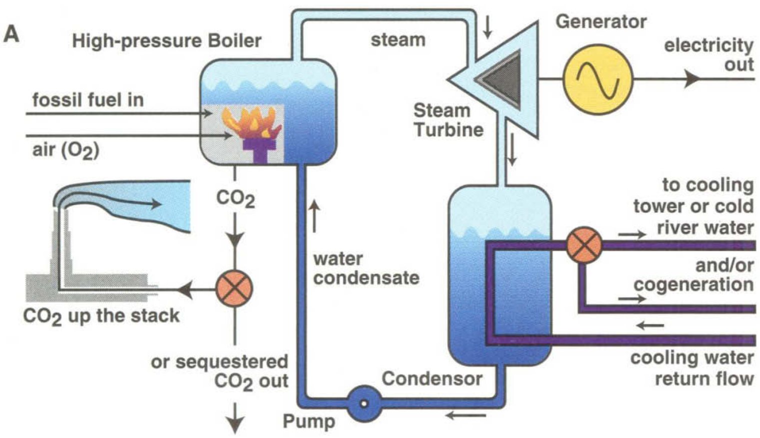
Efficiency is the ratio of usable energy output to energy input. Primary energy in metastable chemical and nuclear bonds includes fossil fuels, fission fuels, and fusion fuels. "Renewables" are primary energy in natural fluxes (solar photons, wind, water, and heat flows). Energy conversion always involves dissipative losses, losses that in many cases engineers have already expended considerable effort to reduce. Opportunities still exist to improve efficiency in power generation and end-use sectors: transportation, manufacturing, electricity, and (indoor) climate conditioning (*13*).

The efficiencies of mature technologies are well characterized (*14*, *15*). Most efficient are large electric generators (98 to 99% efficient) and motors (90 to 97%). These are followed by rotating heat engines that are limited by the second law of thermodynamics: gas and steam turbines (35 to 50%) and diesel (30 to 35%) and internal combustion (15 to 25%) engines. Electrolyte and electrode materials and catalysts limit electrochemical fuel cells (50 to 55% now; 70% eventually). Fuel cells may replace heat engines but will likely run on hydrogen. A seamless transition would use H_2 extracted from gasoline or methanol in reformers (75 to 80%). Renewable energy converters include photovoltaic (PV) cells (commercial arrays, about 15 to 20%; theoretical peak for single bandgap crystalline cells, ≈24%; higher for multiband cells, lower for more cost-effective amorphous thin films) and wind turbines (commercial units, about 30 to 40%; theoretical "Betz limit," ≈59%). High-pressure sodium vapor (15 to 20%), fluorescent (10 to 12%), and incandescent (2 to 5%) illumination generate more heat than light. Photosynthesis has a very low sunlight-to-chemical energy efficiency, limited by chlorophyll absorption bands (most productive ecosystems are about 1 to 2% efficient; theoretical peak independent of cell or ecosystem is ≈8%).

How much can energy efficiency improve? In a given technology class, efficiency normally starts low, grows for decades to centuries, and levels off at some fraction of its theoretical peak (*16*). 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 (Figs. 1A and 4A). Steam-cycle efficiencies (39 to 50%, including combined cycles and cogeneration) and overall primary energy–to-electricity efficiency (30 to 36%, including transmission losses) yield the nominal thermal-to-electric power conversion: 3 kW (thermal) ≈ 1 kW_e (electrical). Impressive reductions in waste heat have been accomplished with compact fluorescents, low emissivity windows, and cogeneration (*17*). More efficient automotive power conversion is possible (*18*, *19*). Emissions depend on vehicle mass, driving patterns, and aerodynamic drag, as well as well-to-wheels efficiency [(torque × angular velocity at wheels)/(fossil fuel power in)]. Power trains are typically 18 to 23% efficient for internal combustion (IC), 21 to 27% for battery-electric (35 to 40%, central power plant; 80 to 85%, charge-discharge cycles; 80 to 85%, motor), 30 to 35% for IC-electric hybrid (higher efficiency from electric power recovery of otherwise lost mechanical energy), and 30 to 37% for fuel cell–electric (75 to 80%, reformer; 50 to 55%, fuel cell; 80 to 85%, motor).

Lifestyles also affect emissions. Ultra fuel-efficient cars are available today that can travel up to 29 km liter^{-1} [68 miles per gallon (mpg) U.S. Environmental Protection Agency highway driving cycle (EPA hwy)]. But consumer demand for sport utility vehicles (SUVs) has driven the fuel economy of the U.S. car and light truck fleet to a 21-year low of 8.5 km liter^{-1} (20 mpg EPA hwy)

A



B

Fossil fuel	Energy content [TW-yr]	Carbon content [GTC]	(E_{fuel}/C) [TW-yr/GtC]	(E/C) [TW-yr/GtC]	Sequestration rate [GtC/yr]
Gas	1200	570	2.1	1.9 - 1.6	5 - 6
Oil	1200	750	1.6	1.4 - 1.2	7 - 8
Coal	4800	3690	1.3	1.2 - 1.0	9 - 10

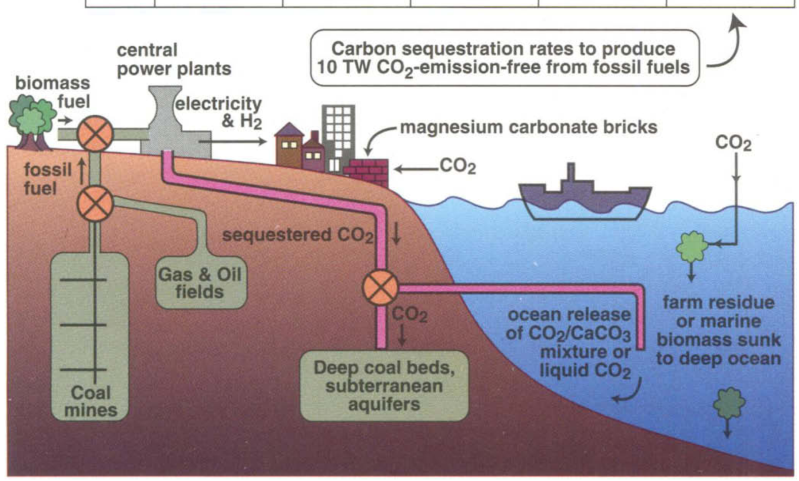


Fig. 1. (**A**) Fossil fuel electricity from steam turbine cycles. (**B**) Collecting CO_2 from central plants and air capture, followed by subterranean, ocean, and/or solid carbonate sequestration, could foster emission-free electricity and hydrogen production, but huge processing and sequestration rates are needed (5 to 10 GtC year^{-1} to produce 10 TW emission-free assuming energy penalties of 10 to 25%).

(*19*). Even with SUVs, doubling (or more) efficiency is quite feasible. Unfortunately, the effects of such efficiency could 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.) As a result, carbon-neutral fuels or CO_2 "air capture" may be the best alternatives to develop.

Decarbonization and Sequestration

Reducing 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 CO_2 per joule of heat (*20*). Continuation of the trend would lead to use of H_2, a carbon-neutral fuel, but H_2 does not exist in geological reservoirs. Processes requiring energy are needed for its synthesis. The energy can come from fossil fuel feedstocks. H_2 is produced today by steam-reforming natural gas ($2H_2O + CH_4 \rightarrow 4H_2 + CO_2$). Energy can be transferred to H_2 with an efficiency of about 72% from gas, 76% from oil, and 55 to 60% from coal (*21*). Per unit of heat generated, more CO_2 is produced by making H_2 from fossil fuel than by burning the fossil fuel directly. Emission-free H_2 manufactured by water electrolysis that is powered by renewable or nuclear sources is not yet cost effective.

Thus, the decarbonization of fuels alone will not mitigate global warming. The underlying problem is providing 10 to 30 TW emission-free in 50 years. Continuing the trend to lower carbon fuels requires disposing of excess carbon because the trend opposes the relative abundance of fossil resources—high-carbon coal being most abundant, followed by oil and gas (*22*, *23*). One vision of "clean" coal incorporates CO_2 capture and sequestration: Coal and/or biomass and waste materials are gasified in an oxygen-blown gasifier, and the product is cleaned of sulfur and reacted with steam to form H_2 and CO_2. After heat extraction, the CO_2 is sequestered and the H_2 used for transportation or electricity generation (*24*). Decarbonization is thus intimately linked to sequestration (*25*). Sequestration reservoirs include oceans, trees, soils, depleted natural gas and oil fields, deep saline aquifers, coal seams, and solid mineral carbonates (Fig. 1B). The main advantage of sequestration is its compatibility with existing fossil fuel infrastructures, including CO_2 injections for enhanced recovery from existing oil and gas fields and capture of CO_2 from power plant flue gases.

Recovery of fossil fuel CO_2 emitted from decentralized sources (like cars) may be needed. The simplest air capture is forestation. Tree and soil sequestration does not require combustion product separation or more fuel, but the capacity to absorb CO_2 is limited. Uptake occurs during growth of organic matter (CH_2O), when the net photosynthesis-respiration reaction is to the right: $h\nu + CO_2 + H_2O \rightarrow CH_2O + O_2$. Historical CO_2 data and models imply a temperate forest carbon sink today of 1 to 3 billion tons of carbon (GtC) year^{-1} (*3*), but some models show forests reversing from sinks to sources later this century as global warming increases soil respiration (*26*). The exchange time of CO_2 with trees is ~7 years. Turnover of iron fertilization–enhanced plankton uptake (*27*) can be similarly fast if organic detritus oxidizes near the surface. Biological sequestration approaches to longer term storage include sealing undecayed trees underground (*28*) and sinking agricultural residues to the deep ocean (*29*). Air capture by aqueous calcium hydroxide [$Ca(OH)_2$] in shallow pools, with CO_2 recovery by heating $CaCO_3$ in a retort to produce CaO and CO_2, has also been proposed (*30*). This reaction (calcination) is a key step in making cement from limestone, but breaking the Ca–CO_2 bond requires substantial energy.

Also being explored is longer term CO_2 sequestration in the deep sea (*31*). For a given emission scenario, ocean injections can substantially decrease peak atmospheric CO_2 levels, although all cases eventually diffuse some CO_2 back to the atmosphere (*32*). Back-diffusion and pH impacts of ocean CO_2 disposal could be diminished by accelerating carbonate mineral weathering that would otherwise slowly neutralize the oceanic acidity produced by fossil fuel CO_2 (*33, 34*). A far-reaching removal scheme is reacting CO_2 with the mineral serpentine to sequester carbon as a solid in magnesium carbonate "bricks" by vastly accelerating silicate rock weathering reactions, which remove atmospheric CO_2 over geologic time scales (*35*). Thus, carbon sequestration could be a valuable bridge to renewable and/or nuclear energy. However, if other emission-free primary power sources of 10 to 30 TW are unavailable by mid-century, then enormous sequestration rates could be needed to stabilize atmospheric CO_2 (Fig. 1B). Substantial research investments are needed now to make this technology available in time.

Renewables

Renewable energy technologies include biomass, solar thermal and photovoltaic, wind,

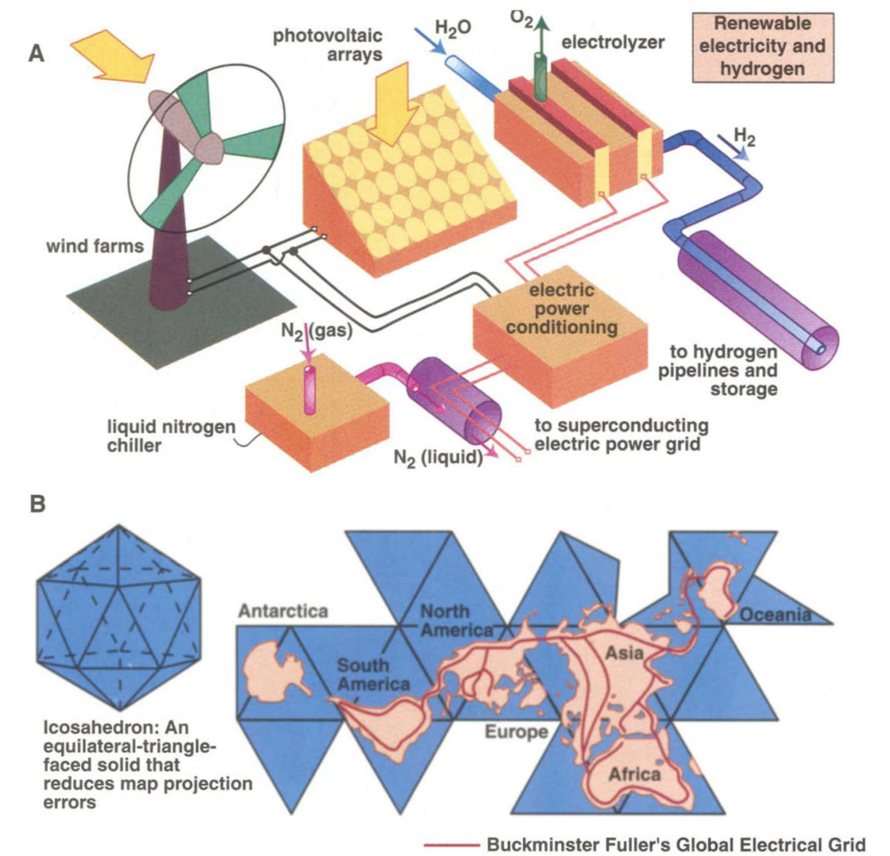


Fig. 2. **(A)** Mass-produced widely distributed PV arrays and wind turbines making electrolytic H_2 or electricity may eventually generate 10 to 30 TW emission-free. **(B)** The global grid proposed by R. Buckminster Fuller with modern computerized load management and high-temperature superconducting (HTS) cables could transmit electricity from day to night locations and foster low-loss distribution from remote, episodic, or dangerous power sources. (The resistivity of HTS wires vanishes below the 77 K boiling point of nitrogen available from air.)

hydropower, ocean thermal, geothermal, and tidal (*36*). 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. Biomass plantations can produce carbon-neutral fuels for power plants or transportation, but photosynthesis has too low a power density (~0.6 W m^{-2}) for biofuels to contribute significantly to climate stabilization (*14*, *37*). (10 TW from biomass requires >10% of Earth's land surface, comparable to all of human agriculture.) PV and wind energy (~15 W_e m^{-2}) need less land, but other materials can be limiting. For solar energy, U.S. energy consumption may require a PV array covering a square ~160 km on each side (26,000 km^2) (*38*). The electrical equivalent of 10 TW (3.3 TW_e) requires a surface array ~470 km on a side (220,000 km^2). However, all the PV cells shipped from 1982 to 1998 would only cover ~3 km^2 (*39*). A massive (but not insurmountable) scale-up is required to get 10 to 30 TW equivalent.

More cost-effective PV panels and wind turbines are expected as mass production drives economies of scale. But 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 (*40*).

"Balance-of-system" infrastructures could evolve from natural gas fuel cells if reformer H_2 is replaced by H_2 from PV or wind electrolysis (Fig. 2A). Reversible electrolyzer and fuel cells offer higher current (and power) per electrode area than batteries, ~20 kW_e m^{-2} for proton exchange membrane (PEM) cells (*21*). PEM cells need platinum catalysts, $\geq 5 \times 10^{-3}$ kg Pt m^{-2} (*41*) (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 (Fig. 2B). Even before the discovery of high-temperature superconductivity (*42*), Fuller envisioned electricity wheeled between day and night hemispheres and pole-to-pole (*43*). 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.

Space solar power (SSP) (Fig. 3, A and B) exploits the unique attributes of space to power Earth (*44*, *45*). Solar flux is ~8 times higher in space than the long-term surface average on spinning, cloudy Earth. If theoretical microwave transmission efficiencies (50 to 60%) can be realized, 75 to 100 W_e could be available at Earth's surface per m^2 of PV array in space, ≤1/4 the area of surface PV arrays of comparable power. In the 1970s, the National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE) studied an SSP 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 GW_e output. [10 TW equivalent (3.3 TW_e) requires 660 SSP units.] Other architectures, smaller satellites, and newer technologies were explored in the NASA "Fresh Look Study" (*46*). Alternative locations are 200- to 10,000-km altitude satellite constellations (*47*), the Moon (*48*, *49*), and the Earth-Sun L_2 Lagrange exterior point [one of five libration points corotating with the Earth-Sun system (Fig. 3C)] (*50*). Potentially important for CO_2 emission reduction is a demonstration proposed by Japan's Institute of Space and Aeronautical Science to beam solar energy to developing nations a few degrees from the equator from a satellite in low equatorial orbit (*51*). 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 (*52*). A major challenge is reducing or externalizing high launch

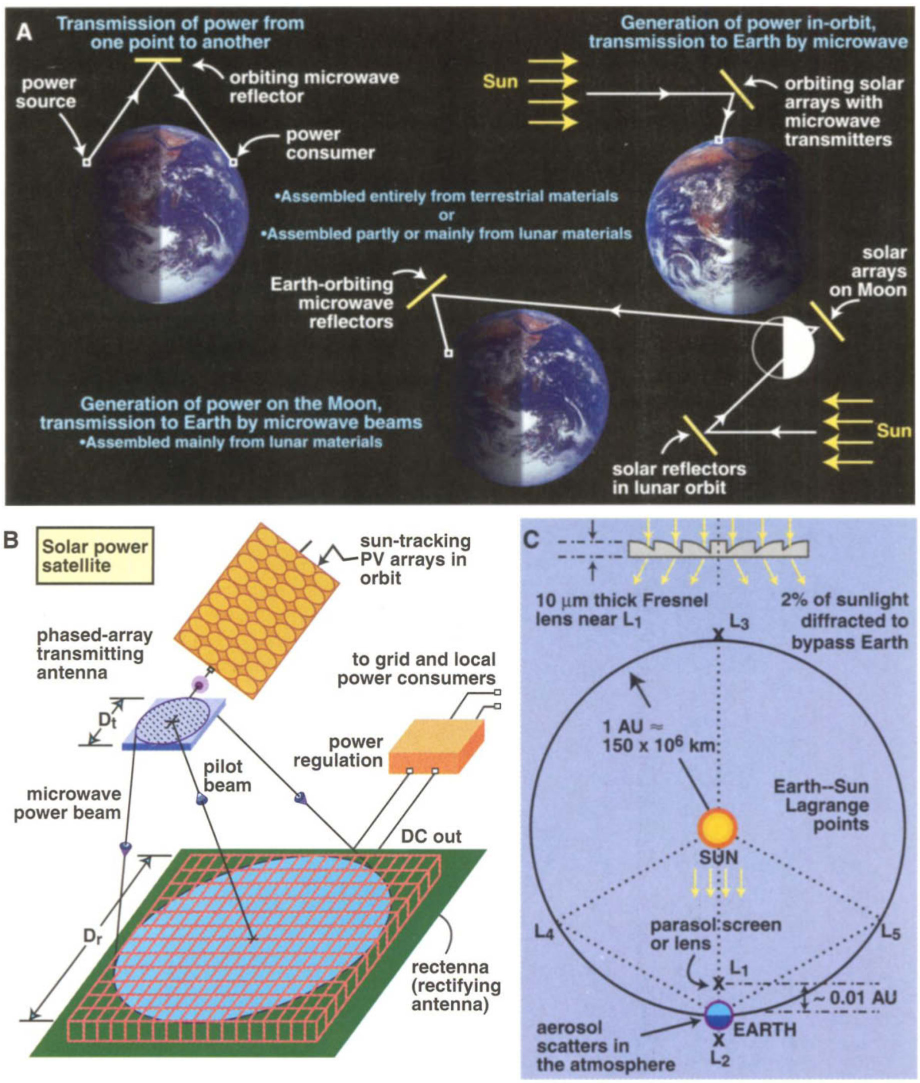


Fig. 3. Capturing and controlling sun power in space. **(A)** The power relay satellite, solar power satellite (SPS), and lunar power system all exploit unique attributes of space (high solar flux, lines of sight, lunar materials, shallow gravitational potential well of the Moon). **(B)** An SPS in a 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). **(C)** Space-based geoengineering. The Lagrange interior point L_1 provides an opportunity for radiative forcing to oppose global warming. A 2000-km-diameter parasol near L_1 could deflect 2% of incident sunlight, as could aerosols with engineered optical properties injected in the stratosphere.

costs. With adequate research investments, SSP could perhaps be demonstrated in 15 to 20 years and deliver electricity to global markets by the latter half of the century (*53*, *54*).

Fission and Fusion

Nuclear electricity today is fueled by ^{235}U. Bombarding natural U with neutrons of a few eV splits the nucleus, releasing a few hundred million eV ($^{235}U + n \rightarrow$ fission products + 2.43n + 202 MeV) (*55*). The ^{235}U isotope, 0.72% of natural U, is often enriched to 2 to 3% to make reactor fuel rods. The existing ~500 nuclear power plants are variants of ^{235}U thermal reactors (*56*, *57*): the light water reactor [(LWR) in both pressurized and boiling versions]; heavy water (CANDU) reactor; graphite-moderated, water-cooled (RBMK) reactors, like Chernobyl; and gas-cooled graphite reactors. LWRs (85% of today's reactors) are based largely on Hyman Rickover's water-cooled submarine reactor (*58*). Loss-of-coolant accidents [Three Mile Island (TMI) and Chernobyl] may be avoidable in the future with "passively safe" reactors (Fig. 4A). Available reactor technology can provide CO_2 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. Sailor *et al.* (*58*) propose a scenario with ^{235}U reactors producing ~10 TW by 2050. How long before such reactors run out of fuel? Current estimates of U in proven reserves and (ultimately recoverable) resources are 3.4 and 17 million metric tons, respectively (*22*) [Ores with 500 to 2000 parts per million by weight (ppmw) U are considered recoverable (*59*)]. This represents 60 to 300 TW-year of primary energy (*60*). At 10 TW, this would only last 6 to 30 years—hardly a basis for energy policy. Recoverable U may be underestimated. Still, with 30- to 40-year reactor lifetimes, it would be imprudent (at best) to initiate fission scale-up without knowing whether there is enough fuel. What about the seas? Japanese researchers have harvested dissolved U with organic adsorbents from flowing seawater (*61*). Oceans have 3.2×10^{-6} kg dissolved U m^{-3} (*62*)— a ^{235}U energy density of 1.8 MJ m^{-3}. Multiplying by the oceans' huge volume (1.37×10^{18} m^3) gives 4.4 billion metric tons U and 80,000 TW-year in ^{235}U. Runoff and outflow to the sea from all the world's rivers is 1.2×10^6 m^3 s^{-1} (*63*). Even with 100% ^{235}U extraction, the flow rate needed to make reactor fuel at the 10 TW rate is five times as much as this outflow (*64*). Getting 10 TW primary power from ^{235}U 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 (*65*). Steady progress has been made toward "breakeven" with tokamak (a toroidal near-vacuum chamber) magnetic confinement [Q ≡ (neutron or charged particle energy out)/(energy input to heat plasma) = 1] (Fig. 4B). The focus has been on the deuterium-tritium (D-T) reaction ($\rightarrow$ ^4He + n + 17.7 MeV). Breakeven requires that the "plasma triple product" satisfy the Lawson criteria: $n \times \tau \times kT \approx 1 \times 10^{21}$ m^{-3} s keV for the D-T reaction, where n is number density; τ, confinement time; T, temperature; and k, Boltzmann's constant (*66*, *67*). Best results from Princeton (Tokamak Fusion Test Reactor) and Europe (Joint European Torus) are within a factor of two (*68*). Higher Qs are needed for power reactors: Neutrons penetrating the "first wall" would be absorbed by molten lithium, and excess heat would be transferred to turbogenerators. Tritium (12.3-year half-life) would also be bred in the lithium blanket (n + $^6Li \rightarrow {}^4He$ + T + 4.8 MeV). D in the sea is virtually unlimited whether utilized in the D-T reaction or the harder-to-ignite D-D reactions ($\rightarrow$ ^3He + n + 3.2 MeV and $\rightarrow$ T + p + 4.0 MeV). If D-T reactors were operational, lithium bred to T could generate 16,000 TW-year (*69*), twice the thermal energy in fossil fuels. The D-^3He reaction ($\rightarrow$ ^4He + p + 18.3 MeV) is of interest because it yields charged particles directly convertible to electricity (*70*). Studies of D-^3He and D-D burning in inertial confinement fusion targets suggest that central D-T ignitors can spark these reactions.

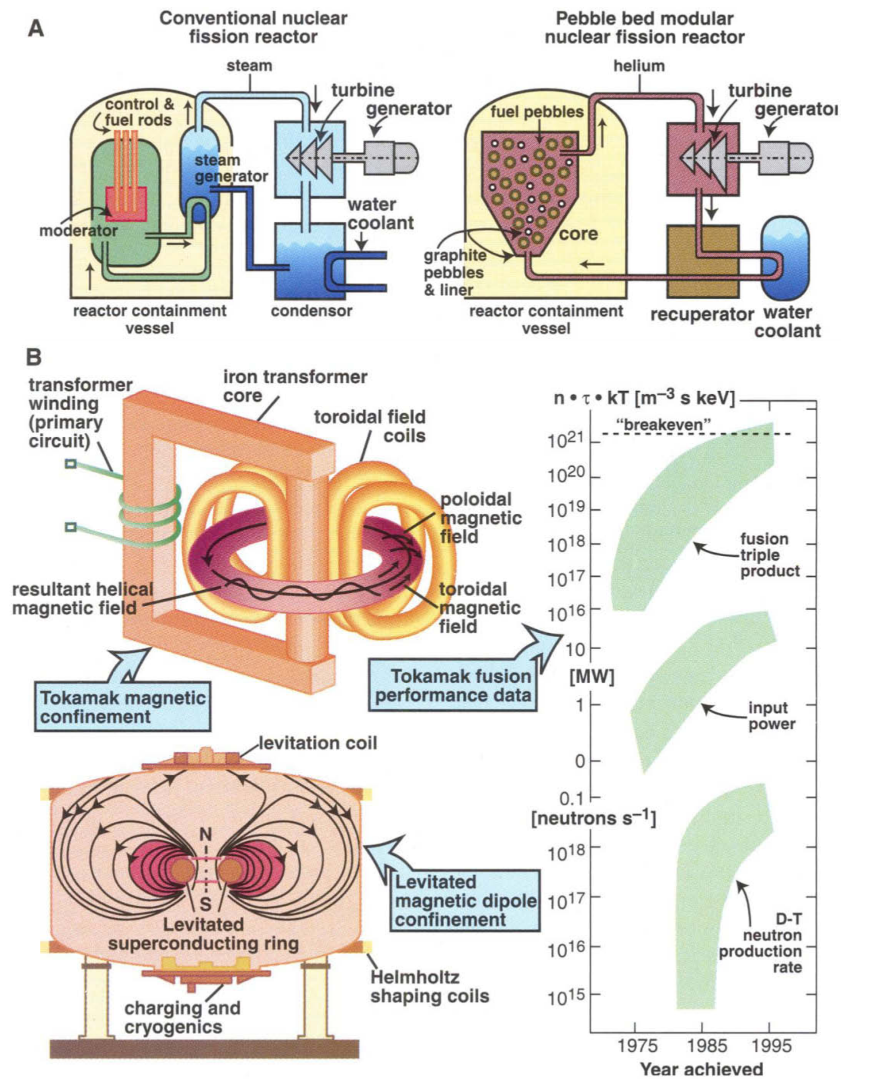


Fig. 4. **(A)** The conventional LWR employs water as both coolant and working fluid (left). The helium-cooled, graphite-moderated, pebble-bed, modular nuclear fission reactor is theoretically immune to loss-of-coolant meltdowns like TMI and Chernobyl (right). **(B)** The most successful path to fusion has been confining a D-T plasma (in purple) with complex magnetic fields in a tokamak. Breakeven occurs when the plasma triple product (number density × confinement time × temperature) attains a critical value. Recent tokamak performance improvements were capped by near-breakeven [data sources in (*68*)]. Experimental work on advanced fusion fuel cycles and simpler magnetic confinement schemes like the levitated dipole experiment (LDX) shown are recommended.

Ignition of D-T–fueled inertial targets and associated energy gains of $Q \geq 10$ may be realized in the National Ignition Facility within the next decade. Experiments are under way to test dipole confinement by a superconducting magnet levitated in a vacuum chamber (*71*), a possible D-^{3}He reactor prototype. Rare on Earth, ^{3}He may someday be cost-effective to mine from the Moon (*72*). It is even more abundant in gas-giant planetary atmospheres (*73*). Seawater D and outer planet ^{3}He could power civilization longer than any source other than the Sun.

How close, really, are we to using fusion? Devices with a larger size or a larger magnetic field strength are required for net power generation. Until recently, the fusion community was promoting the International Thermonuclear Experimental Reactor (ITER) to test engineering feasibility. Enthusiasm for ITER waned because of the uncertainty in raising the nearly \$10 billion needed for construction. The U.S. halted ITER sponsorship in 1998, but there is renewed interest among U.S. fusion scientists to build a smaller-sized, higher-field, nonsuperconducting experiment or to rejoin participation in a half-sized, redesigned ITER physics experiment. 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 (*74*)." 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 CO_2 stabilization by mid-century.

The conclusion from our ^{235}U fuel analysis is that breeder reactors are needed for fission to significantly displace CO_2 emissions by 2050. Innovative breeder technologies include fusion-fission and accelerator-fission hybrids. Fissionable ^{239}Pu and/or ^{233}U can be made from ^{238}U and ^{232}Th (*75*). Commercial breeding is illegal today in the United States because of concerns over waste and proliferation (France, Germany, and Japan have also abandoned their breeding programs). Breeding could be more acceptable with safer fuel cycles and transmutation of high-level wastes to benign products (*76*). Th is the more desirable feedstock: It is three times more abundant than U and ^{233}U is harder to separate and divert to weapons than plutonium. One idea to speed up breeding of ^{233}U is to use tokamak-derived fusion-fission hybrids (*68*, *77*). D-T fusion yields a 3.4-MeV alpha particle and a 14-MeV neutron. The neutron would be used to breed ^{233}U from Th in the fusion blanket. Each fusion neutron would breed about one ^{233}U and one T. Like ^{235}U, ^{233}U generates about 200 MeV when it fissions. 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. A related concept is the particle accelerator-fission hybrid breeder (*56*): Thirty 3-MeV neutrons result from each 1000-MeV proton accelerated into molten lead; upon injection to a subcritical reactor, these could increase reactivity enough to breed ^{233}U from Th, provide electricity, and power the accelerator efficiently (~10% of the output). The radiotoxicity of hybrid breeder reactors over time is expected to be substantially below LWRs.

These ideas appear important enough to pursue experimentally, 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

No discussion of global warming mitigation is complete without mentioning "geoengineering" (*78*, *79*), also called climate engineering or planetary engineering on Earth and terraforming on other planets (*80*). Geoengineering in the climate change context 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 CO_2 and other greenhouse gases. An early idea was to put layers of reflective sulfate aerosol in the upper atmosphere to counteract greenhouse warming (*81*). Variations on the sunblocking theme include injecting sub-micrometer dust to the stratosphere in shells fired by naval guns, increasing cloud cover by seeding, and shadowing Earth by objects in space (*82*). Perhaps most ambitious is a proposed 2000-km-diameter mirror of 10-μm glass fabricated from lunar materials at the L_1 (*83*) Lagrange point of the Sun-Earth system (*84*) (Fig. 3C). The mirror's surface would look like a permanent sunspot, would deflect 2% of solar flux, and would roughly compensate for the radiative forcing of a CO_2 doubling. Climate model runs indicate that the spatial pattern of climate would resemble that without fossil fuel CO_2 (*84*). Engineering the optical properties of aerosols injected to the stratosphere to produce a variety of climatic effects has also been proposed (*85*). Our assessment reveals major challenges to stabilizing the fossil fuel greenhouse with energy technology transformations. It is only prudent to pursue geoengineering research as an insurance policy should global warming impacts prove worse than anticipated and other measures fail or prove too costly. Of course, large-scale geophysical interventions are inherently risky and need to be approached with caution.

Concluding Remarks

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 may become more acute as the global economy grows and as larger reductions in CO_2-emitting energy relative to growing total energy demand are required. 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. We have identified a portfolio of promising technologies here—some radical departures from our present fossil fuel system. Many concepts will fail, and staying the course will require leadership. Stabilizing climate is not 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.

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$$\frac{202\text{MeV}}{235\ \text{amu} \times 1.661 \times 10^{-27}\ \text{kg/amu}} \times \frac{1.602 \times 10^{-13}\ \text{J}}{1\ \text{MeV}} \times \frac{10^3\ \text{kg}}{1\ \text{ton}} = 8.3 \times 10^{16}\ \frac{\text{J}}{\text{t}^{235}\text{U}}$$

The ^{235}U energy per ton natural U is therefore $0.0072 \times 8.3 \times 10^{16}$ J $t^{-1} \approx 6 \times 10^{14}$ J t^{-1}, and the energy in proven U reserves and ultimately recoverable resources is ~61 and 300 TW-year, respectively (1 TW-year = 31.5 EJ).
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$$10\ \text{TW} \times \frac{1.37 \times 10^{18}\ \text{m}^3}{8 \times 10^4\ \text{TW-year}} \times \frac{1\ \text{year}}{3.15 \times 10^7\ \text{s}} = 5.4 \times 10^6\ \text{m}^3\text{s}^{-1}.$$

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