

Fourteen Grand Challenges

What engineers can do to prove we can survive the 21st century. **By Marty Hoffert, Ken Caldeira, and Gregory Benford**

WHO SHOULD YOU ENTRUST with the nation's future? That's one of the subliminal messages of the debate over global warming. Unfortunately, the choice is often framed as the level-headed energy industry professional versus the slightly hysterical environmental advocate. As between a bright future of unbroken technological progress or finite horizons marked by reduced economic growth and limited human potential.



But that's a false choice.

We are part of a group of engineers, atmospheric scientists, physicists, and economists who have studied the relationship between climate and energy use over many years. Our findings, which have been published in the journals *Nature* and *Science*, are highly relevant to the ongoing debate over global climate change and energy policies. The goal of climate and energy research and development, we argue, should be to create technology options that can mitigate adverse climate change.

Not everyone agrees. Some skeptics still doubt the reality of global warming. As a substitute for action, they want to study issues most atmospheric scientists consider settled. And some who accept the global warming consensus see the climate/energy problem as mainly economic: Solutions will flow from treaties, carbon taxes, and the creation



Many of the lights of the Eastern Hemisphere, shown in this NASA compilation of satellite images, are powered by burning fossil fuels. But we must begin to switch over to emissions-free energy sources or we will face repercussions in the global climate.

Marty Hoffert is a professor of physics at New York University. Ken Caldeira is a researcher at Lawrence Livermore National Laboratory in California. Gregory Benford is a professor of physics at the University of California, Irvine.

of markets in emission permits (the so-called “cap and trade” proposal).

Markets are efficient at selecting from existing technologies, but long-term and targeted investment in technological innovation (often for defense applications) has historically been the key to creating new technology options. To us, the highest priorities now should be research and demonstration of technologies capable of



Today's electrical grid is not well-suited to handle renewable energy. Superconducting power lines could transmit electricity from one hemisphere to another.

radically transforming the world energy system into one that drastically limits greenhouse gases emitted to the atmosphere. Without such options, markets and governments are powerless.

Now is the time for a broadly based Apollo-style program for alternate energy research. Following the lead of the defense establishment, especially the Defense Advanced Research Projects Agency, this research program should target a range of technologies—both near-term and long-term. There should be a push toward understanding the strategic subtechnologies and to overcoming technical barriers through key experiments and demonstration projects.

AN ALTERNATIVE ENERGY POLICY

The national energy policy that Vice President Dick Cheney unveiled in 2001 stated that there was a looming energy crisis. But in a very narrow sense, this is false. There's enough coal, if we burn it all, to sustain civilization for at least another hundred years, even with increased global population and economic growth. Granted, fossil fuels are formed over hundreds of millions of years from photosynthesized organic carbon leaked from the biosphere, while they are being consumed in several hundred years at present rates. Because we're using fossil fuels millions of times faster than nature makes them, sooner or later we're going need other primary energy sources or our technological civilization will collapse.

Facing the eventual end of fossil fuels, we could pursue renewables, fission, and fusion leisurely over this century and perhaps figure out how to make hydrogen work as a clean transportation fuel. Until then, fossil fuels could sustain us.

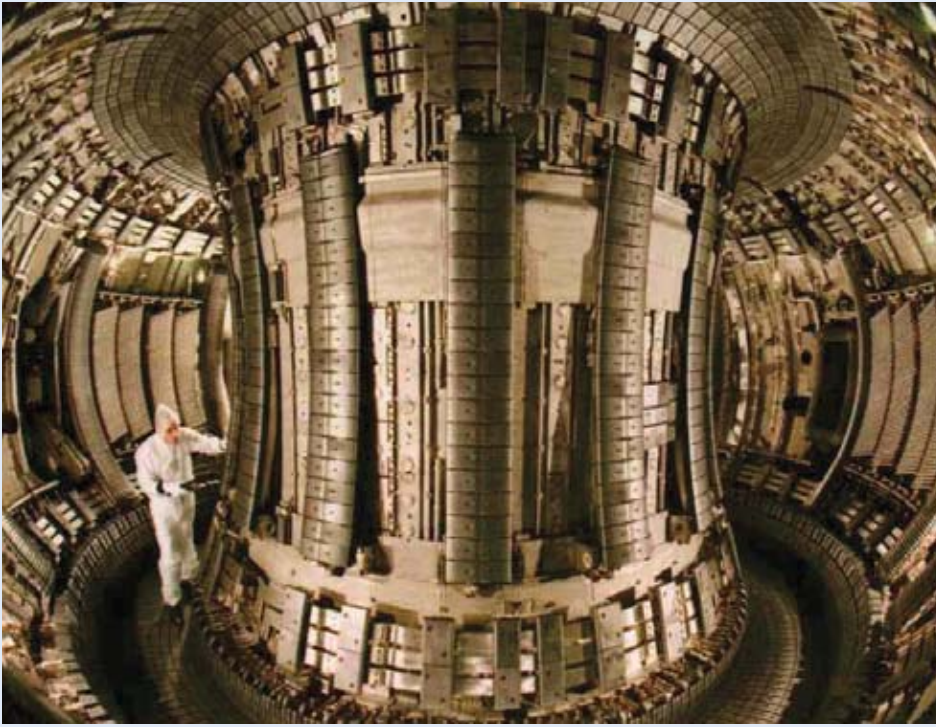
There is a problem with this rosier of scenarios. Most atmospheric scientists find the evidence for major global warming from continued fossil fuel burning in this century is now compelling.

The idea that global warming could originate from carbon dioxide emitted by fossil fuel burning has a long scientific history. Greenhouse physics is a cornerstone of science explaining the atmospheric thermal structures observed on Venus, Earth, Mars, and Saturn's moon, Titan. It has also played a key role in understanding past climatic changes in the geological record. Ice Ages, for example, are triggered by slow changes in Earth's orbital elements—mainly its spin axis tilt and precession of the equinoxes. But air bubbles trapped in Antarctic ice cores going back 420,000 years document how these astronomically paced, glacial-interglacial cycles can become amplified by positive feedback from a CO₂ greenhouse effect.

In the present era, the atmosphere has seen a dramatic increase in the CO₂ concentration arising from burning fossil fuels. Almost hand in hand, there has also been a rise in worldwide surface temperatures and in the observed heat uptake by the oceans. The most recent piece of the puzzle to fall in place is reconciling satellite-derived atmospheric and surface temperature histories by careful reanalysis of satellite data reduction algorithms.

Very quickly, the signal for global warming has risen above the noise of natural variability. The scientific consensus is that we are now living in a kind of “super-interglacial.”

Skeptics of global warming—and its roots in fossil fuel burning—still remain, of course. Maybe they are driven by the deep roots of coal, oil, and gas as primary energy sources of our civilization. Maybe they are simply unfa-



A worker examines the interior of the Joint European Torus, a fusion experiment in Abingdon, England. In the near term, the best use of fusion may be breeding fuel for conventional nuclear reactors.

miliar with the physics, the empirical evidence, and the risks of inaction. Whatever their motivation, they wield influence that is out of proportion to their numbers. The skeptics attacked the modest emission reduction goals of the Kyoto Protocol, for example. While acknowledging the importance of global warming, the present administration has nonetheless withdrawn the United States from Kyoto.

Ignoring global warming could be a serious miscalculation. There's enough carbon in fossil fuel resources to warm the planet by 10°C—to an average temperature last seen 100 million years ago. The economic dislocation caused by such a climate shock—whether from crop failures or the spread of tropical diseases or devastating weather—is as yet incalculable. A wait-and-see response would have society tackle those crises before taking on global warming; by then, the cost of building an alternative energy infrastructure from scratch would be astronomical. Since the problem isn't going away, we need an alternative policy.

Even if we begin today, retooling the energy infrastructure to limit greenhouse emissions will be a major challenge. Allowing for reasonable energy efficiency increases and climate change uncertainties, to sustain economic growth while limiting global warming to just 2°C requires carbon emission-free primary power at least equal to the world's present power consumption of 10 terawatts by 2050—and possibly three times that much.

To put the alternate energy challenge in perspective, consider that Enrico Fermi's atomic pile, the first nuclear reactor, is farther in the past than 2050 is in the future. And today, primary power production from nuclear reactors is still less than 5 percent of the world total.

Reaching this ambitious goal will take a concerted

effort on the part of industry and governments around the world to develop the alternative energy that's needed. The current state of the art is not sufficient to provide 10 to 30 TW of carbon-free primary power.

The shortfall isn't mainly in basic science, but rather in developing and demonstrating technology. Just as travel to the moon was theoretically possible but technically unfeasible on May 25, 1961, when President John F. Kennedy declared it a national goal to a joint session of Congress, curbing fossil fuel use to stave off global warming is now beyond our reach.

It is heartening that Apollo 11 landed on the moon less than a decade after the program started. A concerted

Apollo-like program can, we believe, likewise conquer the technical problems of global warming mitigation. The investment would be high, but so would the reward.

On the way to the moon landing, the space program demonstrated a number of benchmarks, from John Glenn's first orbit of the Earth to Apollo 8's first trip around the moon. Likewise, an Apollo-like energy program should be able to demonstrate several important benchmarks to show progress toward its goal. What would those benchmarks look like? We envision key experiments and real-world projects that engineers could use to demonstrate that these technologies are both workable and cost-effective.

A BETTER TOMORROWLAND

What would make a powerful demonstration? How about **running a renewable energy theme exhibit at Disney World exclusively on solar and wind power?**

Solar photovoltaics and wind power are promising technologies, but require massive scale-up and a revolution in energy transmission and storage infrastructure. A dramatic near-term way to explore these technologies would be to demonstrate them at a world-class venue visited by millions of people each year.

Technologies previewed at widely attended expositions have historically fueled consumer demand—like General Motors' "Democracy" pavilion at the 1939 World's Fair showing superhighways connecting suburbs to city cores. Suburban housing developments, private cars, and freeways exploded after World War II.

It need not be Disney World, of course. But Disney theme parks already have Tomorrowlands and a section of EPCOT (an acronym for "Experimental Prototype Community of Tomorrow") in Orlando, Fla., devoted

to energy. These exhibits are somewhat dated. “The future,” as author Arthur C. Clarke observed, “is not what it used to be.”

Imaginative new exhibits demonstrating present-day visions of renewably powered communities, fuel cells, transmission and storage schemes, applications for developing nations, and space solar power may be just the ticket to expand public consciousness and support for renewable energy paths.

Another technological direction, improving end-use energy efficiency, is popular because it suggests a relatively painless path to low-cost emission reductions. And many of the needed breakthroughs are already in hand. Construction could begin today on a **super-energy-efficient, fully solar- or wind-powered model community, with renewable hydrogen generated locally by electrolysis driving fuel cells for vehicle propulsion.** More important than cost-effectiveness here would be to explore land use and the size of collectors needed for the typical U.S. family lifestyle, and how efficient renewable energy technologies could be integrated into a community. In time, such communities might become commercial real estate developments as economies of scale kick in.

Renewable energy sources, such as wind and solar, are generally dispersed, episodic, and low in power density. That means the keys to making renewables work on the global scale are transmission and storage of energy, and smart power conditioning. **Effective hydrogen storage for transportation applications** is an as-yet unsolved problem; pressure tanks, cryogenics, and metal hydrides all



Solar cells like these could help to power a model neighborhood that incorporates energy-efficient technology. Such an experience could teach engineers how to better integrate renewable energy sources into the community.

have major technical problems. The most likely first deployment of fuel cell cars will have onboard reformers making hydrogen from gasoline or methanol. All of these systems have to be tested to characterize them realistically.

A potentially critical technology for renewables is electricity transmission on the continental and global scale. **Ultra-low-loss transmission lines incorporating newly discovered high-temperature superconductors in underground cables cooled by liquid nitrogen** could create a global electrical grid. This was first envisioned by the American innovative genius Buckminster Fuller, who wrote, “We must be able to continuously integrate the progressive night-into-day and day-into-night hemispheres of our revolving planet. With all the world’s electric energy needs being supplied by a 24-hour around, omni-integrated network, all of yesterday’s one-half-the-time-unemployed, standby generators will be usable all the time, thus swiftly doubling the operating capacity of the world’s energy grid.”

Sunshine energy that’s collected on the daylight hemisphere could be transmitted with low losses to the

The Greenhouse Effect Explained

MANY SKEPTICS OF GLOBAL WARMING bash the research behind it as “junk science.” But the theoretical underpinnings are hard to refute.

As first laid out in 1967 by Syukuro Manabe and Richard Weatherald, the greenhouse effect involves “convective adjustments” that restore buoyant stability to atmospheric gas columns heated from below by maintaining approximately constant vertical temperature gradients. The solar radiation that’s absorbed is balanced by infrared radiation lost into space. This radiative cooling comes, on average, from atmospheric layers near the surface.

Greenhouse gases (such as water vapor, carbon dioxide, and ozone) make the lower atmosphere opaque in the infrared. Because of that, it must re-emit cooling

radiation to space from higher altitudes.

Increasing CO₂ from fossil fuel burning and other greenhouse gas emissions will cause radiative cooling to come from still higher, and colder, altitudes, creating an imbalance called radiative forcing. To restore the energy balance, the lower atmosphere—which is linked by convective adjustments—must warm, and this raises surface temperatures.

Global warming from the early Earth’s atmosphere, which was much denser in carbon dioxide, is believed to have been crucial for the evolution of life. Early in Earth’s history, the sun was 30 percent dimmer than it is today. Even now, without the greenhouse effect our planet would likely be a frozen, lifeless iceball.



NASA engineers have looked at building giant orbiting power stations that would capture solar energy in space and beam it to the surface.

nighttime hemisphere where people want to turn on the lights. Computer-controlled load matching could balance supply and demand globally by wheeling electricity from decentralized sources to users over planetary distances. Such a global grid could evolve over time, but has key elements that must be developed and demonstrated in the near term. Before such a grid becomes fully operational, national energy laboratories could build small-scale grids to demonstrate the principle, and a regional superconducting grid could help deliver wind and solar power from the Midwest to the cities of the East Coast.

GETTING CO₂ OUT

The idea of separating the carbon from fossil fuels as CO₂ and sequestering it in underground reservoirs is receiving major attention as a tool against global warming. Given our deep dependence on fossil fuels, and the abundance of coal, it's not surprising, since perfecting this concept would mean we could keep burning carbon fuels without suffering the climate consequences.

The U.S. Department of Energy recently announced plans to build a **zero-emission coal-fired pilot plant** within a decade. Such a plant may include an oxygen-blown gasifier derived from coal gasification plants, and produce hydrogen or electricity, or both. At this point, depleted gas and oil reservoirs and deep saline aquifers are the preferred geological reservoirs for sequestration.

Harder than sequestering from point sources such as power plants, albeit more attractive for maintaining the in-

frastructure of gasoline and diesel fuels, is capture of CO₂ directly from the atmosphere. Preliminary ideas include capturing atmospheric carbon dioxide by aqueous calcium hydroxide or other sorbants. **Demonstrating cost-effective direct capture of CO₂ from air** could help delay a total overhaul of the transportation infrastructure.

But for all its popularity, sequestration has yet to prove that it can play a significant role in limiting carbon emitted to the atmosphere. Although the concept has been demonstrated by the Norwegian company Statoil at its Sleipner North Sea gas field, to remove 10 TW worth of carbon emission with this technology, it will need to scale up by a factor of a thousand. Even more important, engineers need to **show that CO₂ will remain permanently in underground storage**. Even leakage rates as low as one-tenth of 1 percent per year could be a problem for future generations if we bury most of the carbon in fossil fuel resources as carbon dioxide.

Another potential source of carbon-neutral energy is biofuel—fuel derived from plant matter. The main problem with this is that natural photosynthesis is very inefficient—harnessing less than 1 percent of solar energy falling on it—and therefore consumes large swathes of land. To produce 10 TW, more than 10 percent of the earth's land surface would have to be planted with biofuel crops. That's an area equal to the total acreage currently employed in agriculture. And other worthy biological projects would be competing with biofuels for the same limited land area, particularly in the tropics: biological sequestration by forestation, biodiversity preservation, and human crops.

Fertilizing ocean plankton with iron in regions poor in that nutrient will take carbon dioxide out of the atmosphere, but in a short time the organic detritus would oxidize back to CO₂ in the water column and diffuse back to the surface.

A low-tech biotechnology that could play a useful role exploits agricultural residues—the roughly one-quarter of farm productivity that normally rots on the ground. A continuous carbon sink could be created, if agricultural waste were seasonally collected and sunk to the deep regions of the sea. A demonstration project can prove whether **deep-sixing agricultural residues to sequester CO₂ emitted by natural gas power plants produces more carbon-neutral power than burning these residues directly as biofuels.**

Most of the CO₂ released to the atmosphere is eventually absorbed by the oceans, making them more acidic. Unrestrained burning of fossil fuels will make the ocean more acid than it has been for millions of years, potentially harming coral reefs, plankton, and other marine organisms. It has been suggested that acceleration of natural carbonate mineral weathering reactions at coastal power plants could neutralize this acidity while sequestering carbon in the ocean. A demonstration project can **prove whether accelerated carbonate mineral weathering can save the coral reefs and store carbon safely in the ocean.**

The DOE zero-emission plant and related demonstrations could be very useful for characterizing costs of different designs, and the best separation and sequestration technologies. Still, sequestration is likely to be a transitional technology to a long-term solution.

FISSION AND FUSION

Nuclear fission can contribute fundamentally to global climate stability. And modular gas-cooled reactor designs that may be immune to loss-of-coolant or criticality accidents have gone a long way toward addressing safety concerns. But the issues of nuclear waste disposal and diversion to weapons remain to be resolved.

Perhaps more important in controlling greenhouse emissions is the problem of fueling. Our studies indicate that today's power plants, which burn the uranium-235 isotope without recycling the fuel, would use up the world's surface supply of high-grade uranium in six to 30 years if it were burned at the rate of 10 TW.

Possible solutions to this bring their own problems. Low-grade ores face serious environmental and cost issues. Massive flow rates are needed for seawater extrac-

tion of U-235 at the required scale, regardless of cost. And commercial breeding of fissile fuels—required for fission to be a major player in climate change mitigation—isn't being done anywhere to our knowledge, and hasn't been demonstrated at the necessary speed or scale. Indeed, the issue for global warming isn't breeding, as such, but our ability to breed fast enough. A research laboratory must demonstrate that **breeding fuel at the theoretical factors of 60 (transmuting U-238 into plutonium) or 180 (turning thorium into U-233) can happen quickly enough** to make fission viable in the long term.

This will require drastic shifts in technology and substantial research and development. One concept worth developing is **the fusion-fission hybrid breeder**, a potential neutron source based on already-paid-for tokamak technology that was advocated by Andrei Sakharov



Private companies such as PowerSat Corp. have proposed erecting large rectifying antennas in order to collect microwave energy that is beamed from orbiting power stations.

as the best near-term fusion application.

The first thermonuclear explosions in the 1950s released energy powerfully from nuclear reactions of hydrogen isotopes. But harnessing fusion as a primary power source has proven elusive. Containing hundred million-degree plasmas (either in vacuum chambers with complex toroidal magnetic fields or as inertially expanding laser-heated pellets) long enough—or even getting them that hot in the first place without detonating fission bombs—has been the problem.

The critical demonstration now is a **“burning plasma experiment” that produces net fusion power and self-heating by hot alpha particles.** The Fusion Energy Sciences Act of 2001 calls on the DOE to develop a plan to build this, but many questions still remain, not the least of which is whether researchers have been using the right fuel. Up to now, deuterium-tritium mixtures similar to H-bomb fuels have been the most common choice, but others may be more promising. **Exper-**



To avoid severe warming of the planet, we will need to produce an enormous amount of emission-free power by the middle of this century.

iments with alternate mixtures such as deuterium-helium-3 could lead to systems converting fusion-generated charged particles' energy directly to electricity. One problem: Helium-3 is rare on earth, which means that a potential Persian Gulf may lie on the surface of the moon or the gas giant outer planet atmospheres, where the isotope is more plentiful.

SOLAR POWER FROM ORBIT

Space offers another source of energy. Satellites in orbit can have simultaneous lines of sight to the sun and to any place on Earth, and are exposed to roughly eight times the average solar flux as Earth's surface. This means they can collect solar energy in large photovoltaic arrays and beam that power via microwaves through clouds to rectifying antennas on the surface. A constellation of solar power satellites could supply the planet's energy needs.

Such solar power satellites, proposed by Peter Glaser in the 1970s, have recently been re-examined by NASA in its "Fresh Look Study" and by a committee of the U.S. National Research Council. Space solar power is feasible with near-term technology; and there are several promising approaches to overcoming the high-launch-cost barrier. Demonstrating this technology with **an equatorial satellite collecting solar power in PV arrays and beaming electricity to tropical developing nations** could likely be accomplished on decadal time scales, comparable in time to the Apollo program and to DOE's estimates of the time to demonstrate a zero-emission, coal-fired pilot power plant.

This would be an excellent opportunity for collaboration between spacefaring countries and developing nations that would build the ground-based rectifying antennas, power conditioning, and connection to local users. The UN Intergovernmental Panel on Climate

Change should endorse such tests as a concrete step to reduced CO₂ emissions by developing nations that have few options other than burning fossil fuels.

"We choose to go to the moon in this decade, and to do the other things, not because they are easy, but because they are hard," President Kennedy said, in explaining why he was dedicating the nation to a moon landing. Stabilizing fossil fuel greenhouse emissions by transforming the global energy system will not be easy, any more than developing nuclear weapons during the Manhattan Project or going to the moon during the Apollo program were easy. The amounts of emission-free power needed by mid-century are orders of magnitude higher than anything we have been able to accomplish with new energy sources in the last 50 years.

But that's no reason not to try to do it.

A broad potential spectrum of energy technologies needs urgent investigation to develop options capable of stabilizing CO₂ levels before they drastically change the climate.

Rather than ignore the overwhelming evidence that burning carbon-based fuels is generating global warming, the engineering community should embrace the opportunity to develop carbon-emission-free global energy systems. For technology optimists like us, global warming (and the related issue of energy security) are grand challenges. These are technology problems, and if the engineering community addresses them successfully, as we believe it can, the result will be entirely new industries and economic growth in this century. Indeed, only engineers can ensure that civilization as we know it can survive the 21st century and beyond. ■

Further details about the technologies discussed in this article can be found in the paper, "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science*, Vol. 298, Nov. 1, 2002, pp. 981-987. Hoffert, Caldeira, and Benford were the lead authors of that paper.