LETTERS

Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 6 months or issues of general interest. They can be submitted by e-mail (science_letters@aaas.org), the Web (www.letter2science.org), or regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.

Planning for Future Energy Resources

WE AGREE WITH M. I. HOFFERT *ET AL.* ("Advanced technology paths to global climate stability: energy for a greenhouse planet," Review, 1 Nov., p. 981) that stabilizing atmospheric CO_2 concentrations at 550 parts per million (ppm) or below will require investment in energy research and development well in excess of current levels. However, their conclusion—that known technological options are not up to the task—suffers from two shortcomings related to how much decarbonization is required and how soon we need it. First, they do not consider uncertainty in future energy demand, basing their analysis on a single reference scenario (*1*). In contrast, the most recent Intergovernmental Panel on Climate Change (IPCC) report on emissions scenarios (*2*) foresees a wide range of plausible development paths leading to global primary power demand of anywhere from 20 to 50 TW by 2050. Relative to these scenarios, as quantified by six different integrated assessment modeling teams, stabilizing at 550 ppm may not require any additional energy from carbon-free technologies over the next 50 years beyond that produced by known technologies for reasons unrelated to climate change. Or it could require that additional zero-carbon generating capacity deliver nearly 600 TW-years of energy over that same period. Policy responses to climate change should be robust across this wide range of uncertainty.

Second, we doubt whether the development and implementation of the radically new technologies such as fusion or solar power satellites advocated in the article are feasible within the time horizon necessary for CO_2 stabilization. The process from invention, to demonstration projects, to significant market shares typically takes between five and seven decades (*3*). Fundamentally new technologies that have not been demonstrated to be feasible even on a laboratory scale today would therefore likely come much too late to contribute to the emissions reductions necessary by 2050, particularly for stabilization at 450 ppmv or below (*4*). We believe that the appropriate mix of investments must include an initial focus on technologies with proven feasibility if we are to embark on a path to stabilization. At the same time, we should begin to explore new energy sources that might then be available in the long term to finish the job.

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2. N. Nakicenovic *et al.*, *Special Report on Emissions Scenarios* (Cambridge Univ. Press, Cambridge, 2000).
3. A. Grübler, *Technology and Global Change* (Cambridge Univ. Press, Cambridge, 1998).
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THE REVIEW BY M. I. HOFFERT *ET AL.* ("Advanced technology paths to global climate stability: energy for a greenhouse planet," 1 Nov., p. 981) discusses a wide range of advanced technology solutions to achieving global climate stability. Their treatment of nuclear energy, however, is completely inadequate. Nuclear electric power and, with a small extension, nuclear process heat are the only alternatives among those considered that have been tested at a commercial scale. Because noncarbon alternatives to nuclear energy are not yet proven on a commercial scale, a wide range of options for sustainably applying nuclear technology must receive increasing attention.

> "[I]t would be foolhardy not to assess a broad spectrum of advanced energy sources, converters, and enabling technologies."
> —*HOFFERT* ET AL.

In the short term, there is no fuel resource problem. Even a trebling of capacity to meet the Kyoto accords is possible with uranium fuel at reasonable cost for 50 years. Beyond this, W. C. Sailor *et al.* (*1*) estimated that one-third of a postulated (high) 900 EJ/year primary energy demand in a 2050 world could be met by nuclear fission. To meet this level of demand, either cheaper fuel must be found, an increased cost must be accepted, or fuel must be bred from ^{238}U or ^{232}Th.

Breeding plutonium from ^{238}U would extend the uranium resource base by a factor of about 70; higher-cost uranium resources would then become feasible, extending that resource for 1000 years.

Although Hoffert *et al.* state that "breeder reactors are needed for fission to significantly displace CO_2 emissions by 2050," the need for a breeder reactor is less immediate than was perceived in the 1970s. The decrease in the price of raw uranium presently makes breeding uncompetitive and reduces the need for a rapid expansion, so that even more safe and economic reactor designs with a lower breeding ratio can now be considered. Moreover, reprocessing and recycling of spent fuel can dramatically reduce the heat load and radiotoxicity of the long-lived actinides sent to any waste repository. "Waste form modification," therefore, is being reconsidered for improved repository performance independently of perceived uranium resource issues.

Contrary to what Hoffert *et al*. state, breeding as well as reprocessing has not been illegal since the Reagan administration.

Hoffert *et al*. raise concerns about nuclear energy but do not describe how these concerns are being addressed. Indeed, major accidents have occurred at the Windscale, Chernobyl, and Three-Mile Island nuclear power plants. Much has been learned and applied from these events. Analyses of these few serious accidents have improved operational safety, which was already high.

Nuclear fission technology is indeed deeply rooted in the bomb-making military. Materials generated as a byproduct of commercial nuclear power might lead to undesirable proliferation of nuclear weapons. Proliferation-resistant commercial fuel cycles are being explored, although no nuclear weapons proliferation has been attributable directly to a commercial power plant or the attendant fuel cycle. Inefficiencies and public concerns led to cost increases between 1973 and 1990; however, since 1990, the economics of nuclear power have improved significantly. Several avenues should now be developed simultaneously: (i) further developing low-cost uranium and (ii) improving the economic and environmental characteristics of various breeder technologies. Fossil-coal and fissile-uranium share one common feature—they do not have a resource problem on the time horizon of 500 years. It is the environmental issues, in their broadest sense, that are likely to determine the choice.

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Reference
1. W. C. Sailor, D. Bodansky, C. Braun, S. Fetter, B. van der Zwaan, *Science* **288**, 1177 (2000).

WE DISAGREE WITH M. I. HOFFERT *ET AL.*'S ("Advanced technology paths to global climate stability: energy for a greenhouse planet," Reviews, 1 Nov., p. 981) characterization of the IPCC Third Assessment Report's conclusion that "known technological options could achieve a broad range of atmospheric stabilization levels, such as 550 ppm, 450 ppm or below over the next hundred years or more" (*1*, *2*, p. 8), as "a misperception of technological readiness." First, Hoffert *et al.* analyze (and dismiss) individual technologies in isolation and do not consider their full combined potential. Absent detailed argumentation at the energy system level, background reports (*3*, *4*) suggest that their critique rests on pessimistic assessments of the availability and efficiency of renewable energy. The IPCC evaluated a broad array of demand and supply studies, not just individual supply-side technologies (*5*). Most of these studies are much less pessimistic than Hoffert *et al.* about biomass, solar energy, efficiency, and fossil fuel decarbonization. Second, the authors imply that technologies not technically feasible today (nuclear fusion and space solar power) are needed to stabilize concentrations. But their development and diffusion may require more than 50 years, too long for timely carbon stabilization at acceptable levels. None of the studies assessed by the IPCC assumed penetration rates of new technologies higher than historical experience. Third, Hoffert *et al.* ignore the IPCC conclusion that no simple technological fix exists and that a portfolio of available technologies must be evaluated "in combination with associated socio-economic and institutional changes" (*5*). Fourth, they ignore possible carbon emissions reductions unrelated to energy services, such as options in the area of land-use changes.

We agree that carbon stabilization at low levels will be difficult and not cost-free. We agree that enhanced R&D and investment in conventional and new technologies is necessary. But we stand by the IPCC conclusion that today's technically feasible technologies including energy efficiency improvements could stabilize carbon concentrations if further developed and deployed, and if complemented by necessary nonenergy initiatives and associated socio-economic and institutional changes.

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References and Notes

1. "Known" refers to "technologies that exist in operation or pilot plant stage today. It does not include any new technologies that will require drastic technological breakthroughs" (*2*, p. 8).
2. B. Metz, O. Davidson, R. Swart, J. Pan, Eds., *Climate Change 2001* (Cambridge Univ. Press, Cambridge, 2001).
3. H. D. Lightfoot, C. Green, *Report No. 2002-5* (McGill University, Montreal, Canada, 2002).
4. H. D. Lightfoot, C. Green, *Report No. 2002-9* (McGill University, Montreal, Canada, 2002).
5. T. Morita *et al.*, in *Climate Change 2001*, B. Metz, O. Davidson, R. Swart, J. Pan, Eds. (Cambridge Univ. Press, Cambridge, 2001).

dEbates!

Discussion of the Hoffert *et al.* Review continues online in Science's dEbates.

Response

EXISTING TECHNOLOGIES CAN CONTRIBUTE to global warming mitigation. However, projected levels of emission-free power needed later this century to stabilize climate change appear to be so unprecedented (*1*, *2*) that it would be foolhardy not to assess a broad spectrum of advanced energy sources, converters, and enabling technologies.

The IPCC Special Report on Emission Scenarios (SRES) projects 40 energy scenarios (*3*). Unfortunately, no reliable theory exists to assess their probabilities. Our 33 TW primary power in 2050 is close to the midcentury mean of the SRES range. Unlike SRES, we specify a range of concentration targets and compute CO_2 emission–free power required as a function of time. We recently extended our analysis to global warming targets, including climate sensitivity uncertainty effects (*4*). For example, a 2°C warming target (which can still produce adverse climate impacts) requires non–CO_2-emitting primary power in the 10 to 30 TW range by 2050.

The crux of our disagreement with the IPCC Mitigation Panel is whether "known technologies"—which they define as already existing "in operation or as pilot plants"—can generate such massive emission-free power. Remarkably, their definition excludes fossil-fueled zero emission plants (ZEPs), with CO_2 sequestered. DOE just announced plans to build the first ZEP pilot plant by 2010–15 (*5*).

O'Neill *et al.* say that fusion and solar power satellites are not feasible because the process "from invention, to demonstration projects, to significant market shares typically takes between five and seven decades." Fusion power reactors may be unlikely before the latter half of the 21st century, but a fission path employing fusion-fission hybrid breeders based on paid-for tokamak technology (advocated by Andrei Sakharov) could come online earlier (*2*, *6*). Contrary to O'Neill *et al.* and Swart *et al.*, both the NASA "Fresh Look Study" and recent U.S. National Research Council assessments find space solar power feasible on decadal time scales (*7*). Leisurely market penetration times may apply to classic fuel substitutions, but not, historically, to technologies accelerated by government research: Gas turbines, commercial aircraft, spaceflight, radar, lasers, integrated circuits, satellite telecommunications, personal computers, fiber optics, cell phones, and the Internet all developed faster (*8*).

What about demand? Our 10 to 30 TW emission-free requirement by 2050 assumes ~2%/year growth in primary power demand: ~3%/year GDP growth (for some measure of equity for developing nations) less ~1%/year from declining E/GDP (energy per unit of GDP). The latter is where efficiency improvements come in (*9*, *10*). We realize there are many efficiency improvements possible. The question is whether they add up to >1%/year (*11*).

We agree with Krakowski and Wilson that fission can contribute fundamentally to global climate stability. Today, anxieties over waste disposal and diversion to weapons are evident in Nevada's opposition to a spent nuclear fuel repository in Yucca Mountain and the Pentagon's deployment of long-range bombers capable of destroying North Korea's Yongbyon reactor complex. These issues may indeed be amenable to technical solutions (*12*). But, as indicated above, holding global warming to <2°C requires 10 to 30 TW emission-free power in 50 years for plausible economic growth, regardless of power sources. W. C. Sailor and colleagues independently recognized this by putting ~10 TW from fission by 2050 in their nuclear scenario (*13*).

Although it is no longer technically illegal in the United States, commercial breeding of fissile fuels is not being done anywhere today to our knowledge (the United States, France, Japan, and Germany have suspended their commercial breeder reactor programs). Continued ^{235}U burning at 10 TW rates will require finding major new high-grade uranium deposits to prevent rapid exhaustion (*2*). Low-grade ores face serious environmental and cost issues. Our finding of massive flow rates needed for seawater extraction of ^{235}U surprised us. And we are nowhere near able to breed on the scale needed to realize theoretical factors of 60 (^{238}U $\rightarrow$ plutonium) or 180 (Th $\rightarrow$ ^{233}U) increase in fissionable fuels. The issue for global warming is not breeding, as such, but our ability to breed fast enough. This will require drastic shifts in technology and substantial research and development.

We are astonished at continued confident forecasts by Swart *et al.* that "existing" technology can accomplish the mitigation job ahead, while they discount or ignore technologies they deem too advanced. Expert predictions of technological readiness are notoriously unreliable (*14*). The near-term maturity of highly desired technologies is commonly overestimated (ballistic missile defense, cancer cures, controlled fusion), even as promising innovations perceived as too futuristic are often underestimated (*8*, *15–17*).

Market penetration rates of new technologies are not physical constants. They can be strongly impacted by targeted research and development, by ideology, and by economic incentives. Apollo 11 landed on the Moon less than a decade after the program started. We are confident that the world's engineers and scientists can rise to the even greater challenge of stabilizing global warming. But it does not advance the mitigation cause to gloss over technical hurdles or to say that the technology problem is already solved.

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2. M. I. Hoffert *et al.*, *Science* **298**, 981 (2002).
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Scenarios (Cambridge Univ. Press, New York, 2000).
4. K. Caldeira, A. K. Jain, M. I. Hoffert, *Science* **299**, 2052 (2003).
5. Department of Energy, Vision 21: Power Plant of the Future (available at www.fe.doe.gov/coal_power/vision21/index.shtml).
6. T. K. Fowler, *The Fusion Quest* (Johns Hopkins, Baltimore, MD, 1997), p. 195.
7. Committee for the Assessment of NASA's Space Solar Power Investment Strategy, Aeronautics and Space Engineering Board, National Research Council, *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy* (National Academy Press, Washington, DC, 2001).
8. M. I. Hoffert, S. D. Potter, in R. G. Watts, Ed., *Engineering Response to Global Climate Change*, (Lewis Publishers, Boca Raton, FL, 1997), pp. 205–259.
9. A. B. Lovins *et al.*, *Least-Cost Energy: Solving the CO_2 Problem* (Rocky Mountain Institute, Snowmass, CO, 1989).
10. H. D. Lightfoot, C. Green, Energy Intensity Decline Implications for Stabilization of Atmospheric CO_2 Content (Report 2001-7, McGill Centre for Climate and Global Change Research, Montreal, Canada, 2001).
11. Large carbon emission reductions over the 21st century from "efficiency" improvements reflected in E/GDP declines as high as 2%/year (a factor of 7.2 by 2100) have been proposed (*3*, *9*). However, the average global energy intensity decline over the 20th century was <1%/year, and some analyses of the combined potential from sectoral change and engineering efficiency improvements suggest that 1%/year may be an upper limit (*2*, *10*).
12. R. Krakowski, R. Wilson, in *Innovative Energy Strategies for CO_2 Stabilization*, R. G. Watts, Ed. (Cambridge Univ. Press, Cambridge, 2002), pp. 211–323.
13. W. C. Sailor, D. Bodansky, C. Braun, S. Fetter, B. van der Zwaan, *Science* **288**, 1177 (2000).
14. A. C. Clarke, *Profiles of the Future: An Inquiry Into the Limits of the Possible* (Holt, Rinehart & Winston, New York, 1982).
15. D. Walter, *Today Then: America's Best Minds Look 100 Years into the Future on the Occasion of the 1893 World's Columbian Exposition* (America & World Geographic Pub., St. Helena, MT, 1992).
16. J. Verne, *Paris in the Twentieth Century*, translated by R. Howard (Random House, New York, 1996).
17. This "lost novel" by Jules Verne (*16*) written in the 1860s was rejected for publication in its time because it pictured a future too strange to be credible. In this work, Verne imagined a future in the 1960s where people traveled by subway and in gas-driven cars, where they communicated by fax and telephone, where they used computers, and where "electric concerts" provided entertainment. In this world, everyone could read, but no one read books. It was a society dominated by money where destitute homeless people roamed the streets. Strange indeed.

CORRECTIONS AND CLARIFICATIONS

Technical Comments: Response to a Comment on "No major schizophrenia locus detected on chromosome 1q in a large multicenter sample" by D. F. Levinson (20 Dec., www.sciencemag.org/cgi/content/full/298/5602/2277a). In further discussion after publication, the authors of the Technical Comment (A. S. Bassett *et al.*) and the Response (Levinson *et al.*) have concluded that there was an error in the Response. The empirical *P* values reported by L. M. Brzustowicz *et al*. [*Science* **288**, 678 (2000)] were incorrectly interpreted in the Response as pointwise (uncorrected) values, but they were actually corrected for multiple testing, as described by F. Bonnet-Brilhault *et al*. [*Eur. J. Hum. Genet.* **7**, 247 (1999)] and C. R. Cloninger *et al*. [*Am. J. Med. Genet.* **81**, 275 (1998)]. The genome-wide *P* value for linkage to schizophrenia on proximal 1q in the Canadian sample was 0.0002 to 0.00002, a highly significant result. The Response also noted that significant linkage had not been reported in the largest family in the Brzustowicz *et al.* sample. As a point of clarification, the Z_{max} in this family at D1S1679 was 2.98 under a recessive model of inheritance, considering individuals with schizophrenia or schizoaffective disorder as affected. Single-family lod scores were not presented in the original publication because of space limitations.

TECHINICAL COMMENT ABSTRACTS

COMMENT ON "Arsenic Mobility and Groundwater Extraction in Bangladesh" (I)

Pradeep K. Aggarwal, Ashish R. Basu, Kshitij M. Kulkarni

Harvey *et al.* (Reports, 22 November 2002, p. 1602) concluded that irrigation pumping caused an influx of labile, carbon-laden recharge water in Bangladesh aquifers. In contrast, we present groundwater tritium data indicating similar vertical flow times in pre- and postirrigation pumping periods, and long-term water level records showing consistent seasonal fluctuations over a 30-year period.

Full text at www.sciencemag.org/cgi/content/full/300/5619/584b

COMMENT ON "Arsenic Mobility and Groundwater Extraction in Bangladesh" (II)

Alexander van Geen, Yan Zheng, Martin Stute, Kazi Matin Ahmed

Harvey *et al.* (Reports, 22 November 2002, p. 1602) claimed that elevated groundwater arsenic levels in Bangladesh are linked to water pumping for irrigation. This does not appear to be supported by their data and other data indicating high arsenic concentrations in groundwater recharged well before the onset of massive irrigation in the region.

Full text at www.sciencemag.org/cgi/content/full/300/5619/584c

RESPONSE TO COMMENTS ON "Arsenic Mobility and Groundwater Extraction in Bangladesh"

C. F. Harvey, C. Swartz, A. B. M. Badruzzaman, N. Keon-Blute, W. Yu, M. A. Ali, J. Jay, R. Beckie, V. Niedan, D. Brabander, P. Oates, K. Ashfaque, S. Islam, H. Hemond, M. F. Ahmed

Hydraulic and geochemical data indicate that groundwater flow, and hence pumping, influence arsenic concentrations at our site. These data contradict the van Geen *et al*. claim that arsenic is mobilized in stagnant water and the Aggarwal *et al*. claim that flow is unaffected by pumping. Their contrasting regional generalizations, crafted with selected data from the same set, contain serious inconsistencies and ignore basic hydrologic processes.

Full text at www.sciencemag.org/cgi/content/full/300/5619/584d