Weisz replies: It is good to see PHYSICS TODAY dedicating space to discussions about the role of fundamental physical laws in providing and constraining the growth of human civilization. The letters clearly point to the importance of recognizing the vital dependence of human civilization on both the constraining physical laws of nature and the lifestyle choices of human individuals and populations. Broad discussion may be the only effective way to generate insights that can drive remedial actions in social behavior, technology development, sound policy, and honest politics.

My study translated customary numerical energy units into broadly understandable parameters—for example, human lifetimes. Karo Michaelian notes that the average American consumes 10^8 kcal/yr of source energy, be it solar, fossil, or nuclear, in formal numerical units. As a similar illustration, that figure is about 100 times a human's own source energy intake—as food at 2700–3000 kcal/day from solar energy—which is about 10^6 kcal/yr. That person's added energy availability is therefore comparable to that of 100 human helpers. Since a person's biological ability to translate food-energy intake into work energy is 10–15% while external technological work efficiency may well average above 30%, current energy consumption may be considered to be equivalent to the use of some 200–300 "slaves" per capita.

Russell Seitz says that I propose "650 000 km^2 of photovoltaics in 11 nations alone." On the contrary, my table of data for 11 nations illustrates that the required photovoltaic-cell areas for many countries would be an impossibly large fraction of their total available land areas! Yet for other countries—the US and Australia, for example—the use of photovoltaics for major national energy use appears quite feasible, although it would constitute a large enterprise, or "macroengineering," as Seitz refers to it. Unfortunately, any methodology that will supply energy commensurate with current growth in population and per capita demand will involve macroefforts in technological innovation and social adaptation.

I do not dismiss wind energy as James Van Vechten says. On the contrary, I point out that "wind energy provides a significant potential resource contribution." Numerical estimates of the contribution of wind farms must be adjusted for energy losses in transmission, storage, or conversion technologies. Added energy cost accommodations are necessary because of the very large diurnal and weather-related swings in any solar-derived energy productivity. This is noted and illustrated for solar cells by the shift of the blue area (the nominal productivity at the generation site) to the yellow area (the net contribution) quantified in figure 5 of the original article (PHYSICS TODAY, July 2004, page 47).

Van Vechten is clearly searching for a fuel that may be easier and safer to handle than hydrogen. In the context of examining the serious problem of source-energy supply and demand for society, we must recognize that the multiple processes in generating guanidine and its starting materials will consume still greater amounts of existing source energies than will hydrogen production. Many ideas concerning energy technologies are interesting but need a net energy analysis that embraces the positive and negative contributions of all steps of the new system.

Many good ideas regarding social behavior, such as conservation, population control, and peaceful cooperation between providers and consumers, must be appraised in terms of what is accomplishable in a time frame shorter than the rate of source-energy starvation.

All of the letters and comments appear to agree on the magnitude of the evolving energy supply problem and on the mutual involvement of basic scientific arithmetic and human behavior. The challenge is comparable to the Manhattan Project, as noted by Arthur Smith, but is even larger in magnitude, the requirement of broad scientific understanding and social skills, and the necessity for international participation. Such effort must be guided and sustained by longer-range wisdom, policy, and activity than characterize the lifetime of political appointments. The major task lies in the arena of public understanding: basic education.

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Bartlett replies: Physicists acknowledge that population growth is a major cause of our energy problems. Why then do they offer all manner of diversionary suggestions but avoid addressing population growth limitation as a solution? Karo Michaelian suggests that "perhaps more important than population growth is individual energy consumption." Reducing per capita annual consumption of energy is an important initial step. Reducing it in the US by 1% each year would be a real achievement. But US population growth is about 1.2% per year, so the achievement would not lower total consumption. Our national goal must be to reduce the total annual consumption of nonrenewable energy for many coming years.[1]

Michaelian points out that annual per capita energy consumption in the US is 10 times that in developing nations. That fact emphasizes the importance of stopping US population growth, a course of action Michaelian seeks to avoid. How can we ask other countries to stop their population growth unless we are willing to set an example and stop our own?

It would be wrong to ask that "illiterate farmers in developing nations give up their natural desire for children." In accord with Brian Tinsley's call that "women receive education and job training so that they have an attractive alternative" to bearing children, I think we in the US should increase our support for domestic and foreign aid programs in education, economic opportunity, family planning, and maternal health, with the global goal that every child is a wanted child. That aid would cost much less than a war.

The population division of the United Nations, in a report released 24 February 2005, states that "by 2050 the world population is expected to reach 9.1 billion . . . and would still be adding 34 million persons annually." So it is difficult to imagine that the solution suggested by Michaelian would be a happy one with the population growing for another 250 years to almost 9 billion people and with individuals in the developed world consuming energy at twice the rate of those in the developing world.

Social workers and politicians have mostly failed to address the population problem, so it follows that we scientists have the professional obligation to call attention to the fact that population growth is the most important problem humans face. By failing to do this, we are propagating a silent lie.

Michaelian observes that we are a long way from dissipating the energy