oped countries. In fact the frequent news reports of famines and local wars imply that unsustainable growth is occurring that will result in the Malthusian scenario in which population stability is achieved only with a high death rate to balance the high birth rate.

The error in the second model is that the present situation need not perpetuate itself. Provided globalization continues and productive capacity and resource control shift from the minority to the majority, the Malthusian scenario for the majority could be avoided. This option would also require that women worldwide be given access to family planning technology. It is also essential that women receive education and job training so that they have an attractive alternative in life to that of continual childbearing.

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Readers who responded in the November 2004 issue of PHYSICS TODAY to the earlier articles on energy and population seem to fall into two main categories: those who believe the population problem is already solved through declining birth rates and those who believe the energy problem is already solved because we have nuclear power and continuing energy efficiency improvements. Both views are falsely optimistic and minimize the tremendous technology development problem we face: to provide sufficient energy for a prosperous world in the 21st century and beyond.

Even with the most dramatic conceivable drop in birth rate, the only way population will decrease sufficiently in coming decades is with a correspondingly dramatic increase in death rate. I am surprised so many physicists seem willing to accept that option.

Nuclear energy has four basic obstacles that may prevent it from ever being scaled up by the factor of 20 to 50 needed to address world energy needs: cost, incompetence, corruption, and waste. No breeder reactor, a technology necessary for nuclear fission to be a long-term solution, has ever been successful in the marketplace. Because each plant has such enormous energy content, staff incompetence, even at reactors billed as inherently safe, can lead to much more serious disasters than for other energy sources. A world filled with breeder reactors would necessarily include large-scale traffic in plutonium; just one criminal in the supply chain could trigger a nuclear catastrophe. And the long-lived accumulative character of nuclear waste justifiably frightens many educated members of the public. Billions of dollars have been spent on nuclear energy research, with little progress on resolving any of these issues at the scale that would be needed.

Energy efficiency improvements can only slightly mitigate the continued growth in world energy demand as developing countries advance. The energy problem we face is immense: In coming decades, trillions of dollars of energy infrastructure will need to be replaced with alternatives of some sort. All the renewable energy options face cost issues, both in production and in transmission and storage, that put them beyond large-scale deployment, at least until significant research investment brings those costs lower. The problem is on the scale of the cold war, but policymakers and the general public are not treating it as such. It is past time that the US Secretary of Energy should be given the same respect, and a comparable budget, as the Secretary of Defense, and be charged with resolving this critical problem for the nation.

Chemistry Nobel laureate Richard Smalley has been speaking on the energy problem around the country; I heard him recently at Brookhaven National Laboratory. His specific suggestion is a "nickel and dime" solution: a gasoline tax of $0.05/gallon and perhaps similar carbon taxes on other fossil fuels, to raise about $10 billion per year for alternative energy research. That's the scale we need, not the miserly $80 million solar energy gets in the current US budget. And physicists and engineers must energetically tackle the critical problems, just as they did 60 years ago for the Manhattan Project. Every year of delay in developing these alternatives further threatens the future well-being of humanity.

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Paul Weisz considers transforming America's energy economy using approximately 1000 square meters of solar cells per capita. That amounts to macroengineering; covering roughly 2.7% of the nation's area would alter radiative equilibrium and could effect climate change.

Earth's albedo is modest, but efficient solar cells reflect even less solar energy than the land they shade, a radiative forcing that can amount to hundreds of watts per square meter. Many cell designs also retard nighttime cooling. Weisz proposes 650 000 km^2 of photovoltaics in 11 nations alone. Add the rest, and the total is millions. Multiplying hundreds of watts per square meter over millions of square kilometers yields approximately 10^{14} W, rivaling the present anthropogenic CO_2 forcing.

This dark side of solar power competes with local efforts, like Los Angeles's Cool Cities Initiative, to limit the heat island effect of simmering expanses of asphalt by making sunlit surfaces lighter, not darker. Pale paving and roofing grow attractively cheaper as oil, electricity, and asphalt prices rise. Few Americans can swing a mortgage on 1000 m^2 of silicon, but whitewash is universally affordable. Even Senator John Kerry parks his sport utility vehicle on a brilliant white-shell Nantucket driveway, admirably offsetting the albedo deficit of the solar cells atop his yacht.

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In his comments, Paul Weisz concludes that our best hope is for solar cells and advanced nuclear energy. He dismisses wind energy with the assertion that "energy losses due to transmission, supply, and demand fluctuation or conversion to other energies will reduce the actual contribution" from his estimated maximum potential of 3–22 quads of energy per year, which is much less than the 100 Q required to sustain the US lifestyle. I find Weisz's statement illogical because the solar cells and nuclear sources will also require transmission, supply-to-load matching, storage, and conversion. More wind farms are being built than any other electricity-generation facilities because they are now the lowest-cost option. In its last quarterly report, Florida Power and Light noted that its profits from wind energy are enough to cover its losses from nuclear energy. Given that 2% of all solar energy reaching Earth is converted to wind energy,[1] the maximum potential at 30% conversion efficiency is 22 000 Q/yr.

Weisz also dismisses agricultural fuel production on the ground that agriculture currently provides barely more energy than it consumes. However, present agriculture is not trying to be sustainable but to maximize profits given cheap fossil fuel. Agriculture provided sustainable fuels—dung, oils, and wood—for millennia until the energy revolution. We should try to devise innovations to make biomass production sustainable again when fossil fuels are no longer cheap.

Consider urea as a fuel made from air, water, and electricity alone. Produced artificially on a scale of 120 million tonnes per year and also produced biologically, urea is noncorrosive, nonexplosive, essentially nontoxic, and almost nonflammable. Unfortunately, its energy per unit mass is not as great as some authorities require. The Bush administration's FreedomCAR Fuel Initiative set the target at 3.0 kWh/kg. One can do some engineering to recover waste heat from the fuel cell or the combustion engine to drive endothermic reactions needed to extract hydrogen from urea. Still, careful analysis shows that such recovery could provide only about 2.5 kWh/kg.

The key to sustainable energy is to develop a practical fuel system. I assert that the best sustainable fuel is guanidine, CN_3H_5, which provides 4 kWh/kg, or mixtures of guanidine and urea. I propose a combination wherein wind provides the majority of the energy and agriculture and aquaculture provide the carbon, hydrogen, nitrogen, and heat needed to package the energy as guanidine. If guanidine proves to be a practical fuel, then its relatively simple transportation would also solve the transmission, supply-to-load matching, and storage problems for any solar cell or advanced nuclear sources that do arise.

Although a molecule of guanidine contains only five hydrogen atoms, it can effectively store nine by extracting hydrogen from the water recovered from the exhaust. Guanidine is not as safe as urea because it easily reacts with water to form ammonia, but it ships in green containers, an indication that it is in the safest category for transportation. Economic processes for its mass production appear simple.[2]

To get the energy, consider wind. The best sites for wind farms are mostly over water and far from large consumption sites. However, for guanidine production, the wind farms can be located in the best sites.

The hydrogen for the fuel likely will come from water by electrolysis. This is efficient if the water is at high temperature and in the supercritical state. One will want to convert H_2 promptly to NH_3 via the high-temperature Haber process, then to urea and then to guanidine by moderate pressure–temperature processes.[2] Wind generators (and solar cells) do not produce much heat. The fuel-producing unit that converts electrical energy in excess of what can be sold immediately into guanidine will need hot N_2, hot CO_2, and hot H_2O.

A simple way to supply these hot gases is to burn organic material. It seems obvious that practical production of guanidine–urea fuels will find symbiosis with agricultural and aquacultural production of biomass fuel.

References

1. See http://www.windpower.com, a website of the Danish wind industry.
2. K. J. Shaver, "Guanidine or Melamine Process," US Patent 3,108,999 (29 October 1963).

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