The Energy Challenge

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SPECIAL ISSUE

THE ENERGY CHALLENGE

Energy lies at the very heart of physics. We study the nature of energy, its various manifestations, its transformation from one form to another, and its transfer from one place to another.

As a commodity, energy is also central to many economic and environmental issues. Primarily under the guise of electricity or combustibles, energy is hardly given a second thought. But the global consumption of energy is staggering, as hinted by this issue's cover. Without doubt, such usage also has a large effect on the environment. The US Department of Energy (DOE) projects[1] that the world's total energy consumption will rise by 59% between 1999 and 2020, from 382 to 607 quads. (A quad is one quadrillion, or 10^{15}, Btu, about 10^{18} joules, approximately 3×10^{11} kilowatt hours.) The same report predicts a 20-year increase of carbon dioxide emissions by a similar 60%, from 6.09 to 9.76 billion metric tons equivalent of carbon, and a population increase from 6.0 to 7.5 billion people. Most of the growth in all three areas will take place in rapidly developing parts of the world.

Finding the supply to meet this demand will be a Herculean task, yet that is just one part of the energy challenge. Global needs must be met in environmentally sound ways, and the energy must be used with great efficiency. In the face of global warming and geopolitical realities, it is clear that technological leaps, strong policies, and large investments will be required.

Human development and energy

Industrialized nations have found that more energy can often mean more wealth. Often, but not always. If a nation's population grows, the additional energy may simply be used to keep more citizens at the same (or even lower) standard of living. If, however, more efficient ways are found to both provide and use the additional energy, then there is some chance of actually improving the standard of living.

The United Nations compiles annual statistics about human development and the environment in 174 countries.[2] The statistics relate to energy use, life expectancy, nutrition and health, income and poverty, education, CO_2 emissions, and so on. Three of the indicators are combined to calculate a Human Development Index (HDI). Those indicators are: longevity, as measured by life expectancy; educational attainment, as measured by a combination of adult literacy (two-thirds weight) and the combined primary, secondary, and tertiary enrollment ratio (one-third weight); and standard of living, as measured by a discounted gross domestic product (GDP) per capita. The UN's HDI is considered by many to be a fair measure of basic human well-being.

Alan Pasternak of Lawrence Livermore National Laboratory recently looked at energy usage in the 60 most populous countries for which the UN had an HDI; those nations contain 90% of Earth's population.[3] He found a correlation between electricity consumption and the HDI (see the figure). His analysis showed that the HDI reached a high plateau when a nation's people consumed about 4000 kWh of electricity annually per capita, a value unchanged between 1980 and these 1997 data. The correlation is not perfect; in the end, each country's situation is unique. Still, Pasternak concludes that reaching the goal of basic human well-being in poor countries will require "significantly greater global consumption of electricity and primary energy than do projections for 2020 by the DOE and others." If the world agrees to that goal, working to solve the energy challenge is even more imperative.

We have been speaking in global generalities, but no consideration of the global energy challenge can ignore the presence and impact of the US. In 1999, with less than 5% of the world's population, the US generated 30% of the world's GDP, consumed 25% of the world's energy, and emitted 25% of the world's CO_2. Of the 97 quads consumed in the US in 1999, about 80 came from oil, natural gas, and coal—fossil fuels. The articles that follow in this special issue give both international and uniquely US perspectives.

Indispensable science and technology

A 1996 President's Committee [now Council] of Advisors on Science and Technology (PCAST) report to President Bill Clinton said, "Adequate and reliable supplies of affordable energy, obtained in environmentally sustainable ways, are essential to economic prosperity, environmental quality, and political stability around the world; and energy-supply and energy-efficiency technologies represent a multihundred-billion dollar per year global market."[4]

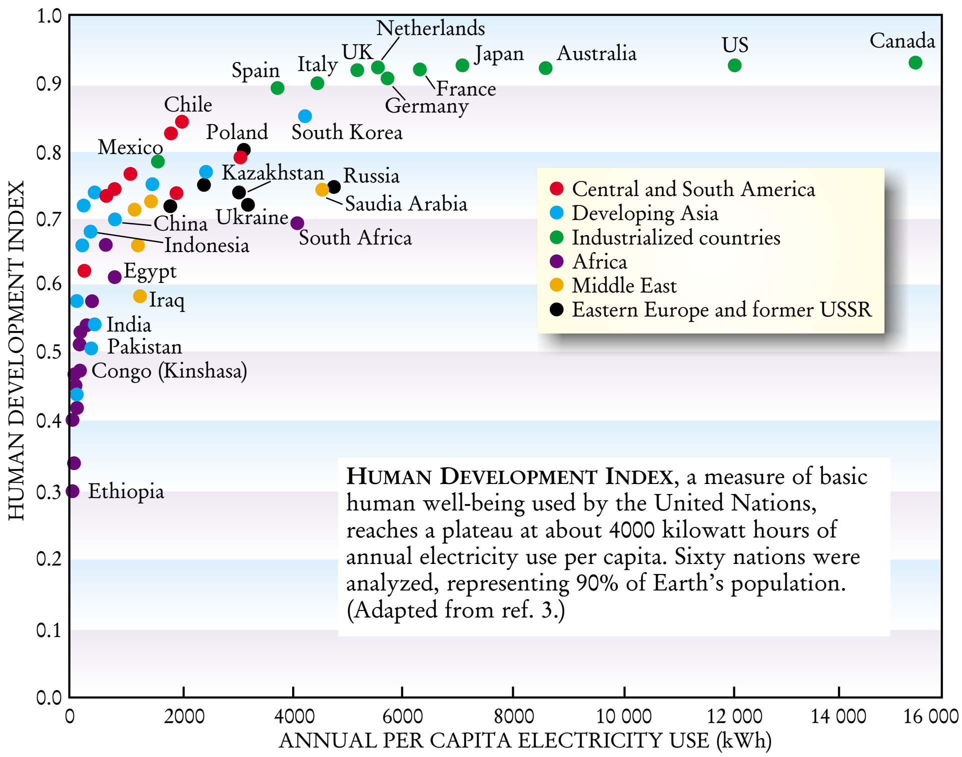
Some of those technologies are discussed in this special issue. However, they should not be viewed in isolation; each is just one element in the overall energy picture. Many of the most promising technologies address several objectives simultaneously.

Fusion is notably absent in this special issue. It offers great potential for abundant, clean energy, but its practical implementation still lies decades in the future. A number of scientific and engineering issues still must be resolved, even before economic realities can be addressed. PHYSICS TODAY will continue to follow the progress of fusion's march toward maturity.

In "Meeting Energy Challenges: Technology and Policy," beginning on page 40, Ernest Moniz and Melanie Kenderdine provide an in-depth look at the complex web of issues that permeate the energy challenge and note where technologies can contribute to long-term solutions. They point out that, with the proper support from policymakers, a host of approaches could help meet economic, security, and environmental imperatives.

Fossil fuels provide about 85% of the world's energy, and myriad technological developments and challenges relevant to fossil-fuel industries are worthy of our attention. For example, there is much physics involved in resource extraction, processing, transportation, and combustion and other end uses. Roughly half of the electricity used in the US comes from coal, with its attendant environmental impacts. Sulfur dioxide emissions have been reduced, but clean-coal and gasification technologies can take us much further. We focus here on oil and gas exploration.

The importance of oil to transportation and other energy-consuming sectors can hardly be overstated, and natural gas is often found in the same reservoirs as oil. In "Physics in Oil Exploration" (page 48), Brian Clark and Robert Kleinberg look at the physics and geology of petroleum formations and discuss many of the physics-based



Human Development Index, a measure of basic human well-being used by the United Nations, reaches a plateau at about 4000 kilowatt hours of annual electricity use per capita. Sixty nations were analyzed, representing 90% of Earth's population. (Adapted from ref. 3.)

technologies used to locate oil and gas. The surprising development of extended-reach horizontal drilling allows a single, relatively small facility to extract petroleum reserves from kilometers away, often avoiding the need for multiple wells.

With virtually the entire existing energy-related infrastructure designed for fossil fuels, it seems certain that the world will continue to rely heavily on hydrocarbon combustion for the foreseeable future. Because we cannot ignore the long-term impacts of continued hydrocarbon combustion, however, we must develop alternative energy sources. A major difficulty in finding long-term energy solutions is the prevalence of short-term vision in both the corporate and political sectors. The scientific community need not be similarly constrained. The remaining three articles in this issue look at some of the most promising alternatives to fossil fuels.

In "New Designs for the Nuclear Renaissance" (page 54), Gail Marcus and Alan Levin give a brief history of the age of nuclear energy. They take us from the first halting steps to the power plants currently on the drawing boards. Great strides have been made in improving safety, efficiency, nonproliferation, and cost. Some of the newest designs even allow for greatly reduced radioactive waste streams and the production of hydrogen for fuel. There is little doubt that nuclear energy can be a major component of hydrocarbon-free energy production, if public and political concerns can be adequately addressed.

Related Readings in Physics Today

The Statistical Physics of Sedimentary Rock, by Po-zen Wong, December 1988, page 24.

Fuel Cells: Energy Conversion for the Next Century, by Sivan Kartha and Patrick Grimes, November 1994, page 54.

Industrial Ecology: Minimizing the Impact of Industrial Waste, by Robert Frosch, November 1994, page 63.

Power Applications of High-Temperature Superconductors, by Gloria Lubkin, March 1996, page 48.

Build the International Thermonuclear Experimental Reactor? by Andrew Sessler, Thomas Stix; and Marshall Rosenbluth, June 1996, page 21.

Special Issue: Radioactive Waste, with guest editor John Ahearne, June 1997.

Technologies to Reduce Carbon Dioxide Emissions in the Next Decade, by Arthur Rosenfeld, Tina Kaarsberg, and Joseph Romm, November 2000, page 29.

Solid Acids Show Potential for Fuel Cell Electrolytes, July 2001, page 22.

Magnetically Confined Fusion Breaks a Pressure Barrier, September 2001, page 18.

Samuel Baldwin looks closely at "Renewable Energy: Progress and Prospects" (page 62). He notes that, since the 1973–74 oil embargo, significant technical and market advances for renewables have occurred. For example, the cost of electricity from both solar photovoltaic and wind systems has come down by an order of magnitude, and the capacities of both those systems have increased. Integrated bioenergy refineries, producing high-value chemicals, fuel, and power, also offer great potential to offset oil use and to generate jobs and income in rural areas.

"Hydrogen: The Fuel of the Future?" (page 69) by Joan Ogden is perhaps the most forward-looking of our articles, and offers one of the most promising long-term solutions to energy-related environmental and supply problems. Hydrogen can be burned efficiently, emitting only low levels of nitrogen oxides. It can also be used in a fuel cell with even greater efficiency and emit only water. Its widespread use, however, still requires answers to a number of technical, economic, and infrastructure questions.

The global energy challenge is daunting. It has many aspects: technical, environmental, economic, social, and political. Each of those aspects has many parts, there are numerous feedback loops within and between them, and they look different when viewed nationally or internationally. Though daunting, the challenge can be met. Future generations will appreciate our efforts.

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References

1. The report is available at http://www.eia.doe.gov/oiaf/ ieo
2. United Nations Development Programme (UNDP), *Human Development Report, 1999,* Oxford U. Press, New York (1999).
3. A. Pasternak, *Global Energy Futures and Human Development: A Framework for Analysis*, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773 (October 2000).
4. J. P. Holdren, S. F. Baldwin, *Annual Review of Energy and the Environment* **26**, 391 (2001).