

The road from old to new energy sources can be bumpy, but the transitions have gone pretty smoothly in the past. After millennia of dependence on wood, society added coal and gravity-driven water to the energy mix. Industrialization took off. Oil arrived, and transportation by land and air soared, with hardly a worry about where the next log or lump of coal was coming from, or what the explosive growth in energy production might be doing to the world.

Times have changed. The price of oil has been climbing, and ice is melting around both poles as the mercury in the global thermometer rises. Whether the next big energy transition will be as smooth as past ones will depend in large part on three sets of questions: When will world oil production peak? How sensitive is Earth's climate to the carbon dioxide we are pouring into the atmosphere by burning fossil fuels? And will alternative energy sources be available at reasonable costs? The answers rest on science and technology, but how society responds will be firmly in the realm of politics.

There is little disagreement that the world will soon be running short of oil. The debate is over how soon. Global demand for oil has been rising at 1% or 2% each year, and we are now sucking almost 1000 barrels of oil from the ground every second. Pessimists—mostly former oil company geologists—expect oil production to peak very soon. They point to American geologist M. King Hubbert's successful 1956 prediction of the 1970 peak in U.S. production. Using the same method involving records of past production and discoveries, they predict a world oil peak by the end of the decade. Optimists—mostly resource economists—argue that oil production depends more on economics and politics than on how much happens to be in the ground. Technological innovation will intervene, and production will continue to rise, they say. Even so, midcentury is about as far as anyone is willing to push the peak. That's still "soon" considering that the United States, for one, will need to begin replacing oil's 40% contribution to its energy consumption by then. And as concerns about climate change

intensify, the transition to nonfossil fuels could become even more urgent (see p. 100).

If oil supplies do peak soon or climate concerns prompt a major shift away from fossil fuels, plenty of alternative energy supplies are waiting in the wings. The sun bathes Earth's surface with 86,000 trillion watts, or terawatts, of energy at all times, about 6600 times the amount used by all humans on the planet each year. Wind, biomass, and nuclear power are also plentiful. And there is no shortage of opportunities for using energy more efficiently.

Of course, alternative energy sources have their issues. Nuclear fission supporters have never found a noncontroversial solution for disposing of long-lived radioactive wastes, and concerns over liability and capi-

tal costs are scaring utility companies off. Renewable energy sources are diffuse, making it difficult and expensive to corral enough power from them at cheap prices. So far, wind is leading the way with a global installed capacity of more than 40 billion watts, or gigawatts, providing electricity for about 4.5 cents per kilowatt hour.

That sounds good, but the scale of renewable energy is still very small when compared to fossil fuel use. In the United States, renewables account for just 6% of overall energy production. And, with global energy demand expected to grow from approximately 13 terawatts a year now to somewhere between 30 and 60 terawatts by the middle of this century, use of renewables

What Can Replace Cheap Oil—and When



will have to expand enormously to displace current sources and have a significant impact on the world's future energy needs.

What needs to happen for that to take place? Using energy more efficiently is likely to be the sine qua non of energy planning—not least to buy time for efficiency improvements in alternative energy. The cost of solar electric power modules has already dropped two orders of magnitude over the last 30 years. And most experts figure the price needs to drop 100-fold again before solar energy systems will be widely adopted. Advances in nanotechnology may help by providing novel semiconductor systems to boost the efficiency of solar energy collectors and perhaps produce chemical fuels directly from sunlight, CO₂, and water.

But whether these will come in time to avoid an energy crunch depends in part on how high a priority we give energy research and development. And it will require a global political consensus on what the science is telling us.

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The following six mathematics questions are drawn from a list of seven outstanding problems selected by the Clay Mathematics Institute. (The seventh problem is discussed on p. 96.) For more details, go to www.claymath.org/millennium.

Is there a simple test for determining whether an elliptic curve has an infinite number of rational solutions?

Equations of the form $y^2 = x^3 + ax + b$ are powerful mathematical tools. The Birch and Swinnerton-Dyer conjecture tells how to determine how many solutions they have in the realm of rational numbers—information that could solve a host of problems, if the conjecture is true.

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Can a Hodge cycle be written as a sum of algebraic cycles?

Two useful mathematical structures arose independently in geometry and in abstract algebra. The Hodge conjecture posits a surprising link between them, but the bridge remains to be built.