Officials at the U.S. Department of Energy are working to kindle support for a crash program to transform solar energy from a bit player into the world's leading power source

Is It Time to Shoot for the Sun?

Ask most Americans about their energy concerns, and you're likely to get an earful about gasoline prices. Ask Nate Lewis, and you'll hear about terawatts. Lewis, a chemist at the California Institute of Technology in Pasadena, is on a mission to get policymakers to face the need for sources of clean energy. He points out that humans today collectively consume the equivalent of a steady 13 terawatts (TW)—that's 13 trillion watts—of power. Eighty-five percent of that comes from fossil fuels that belch carbon dioxide, the primary greenhouse gas, into the atmosphere. Now, with CO_2 levels at their highest point in 125,000 years, our planet is in the middle of a global experiment.

To slow the buildup of those gases, people will have to replace most, if not all, of those 13 TW with carbon-free energy sources. And that's the easy part. Thanks to global population growth and economic development, most energy experts predict we will need somewhere around an additional 30 TW by 2050. Coming up with that power in a way that doesn't trigger catastrophic changes in Earth's climate, Lewis says, "is unarguably the greatest technological challenge this country will face in the next 50 years."

Clearly, there are no easy answers. But one question Lewis and plenty of other high-profile scientists are asking is whether it's time to launch a major research initiative on solar energy. In April, Lewis and physicist George Crabtree of Argonne National Laboratory in Illinois co-chaired a U.S. Department of Energy (DOE) workshop designed to explore the emerging potential for basic research in solar energy, from novel photovoltaics to systems for using sunlight to generate chemical fuels. Last week, the pair released their report on the Web (www.sc.doe.gov/bes/reports/list.html), and the hard copy is due out soon.

The report outlines research priorities for improving solar power. It doesn't say how much money is needed to reach those goals, but DOE officials have floated funding numbers of about $50 million a year. That's up from the $10 million to $13 million a year now being spent on basic solar energy research. But given the scale of the challenge in transforming the energy landscape, other researchers and politicians are calling for far more.

Fields of gold. Solar power is the most promising renewable energy source.

It is too early to say whether the money or the political support will fall in line. But it is clear that support for a renewed push for solar energy research is building among scientists. Last month, Lewis previewed his upcoming report for members of DOE's Basic Energy Sciences Advisory Committee (BESAC), which regularly must weigh its support for facilities that include x-ray synchrotrons, neutron sources, nanoscience centers, and core research budgets. Despite a painfully lean budget outlook at DOE, support for a solar research program "is nearly unanimous," says Samuel Stupp, a BESAC member and chemist at Northwestern University in Evanston, Illinois.

Why? Terawatts. Even if a cheap, abundant, carbon-free energy source were to appear overnight, Lewis and others point out, it would still be a Herculean task to install the new systems fast enough just to keep up with rising energy demand—let alone to replace oil, natural gas, and coal. Generating 10 TW of energy—about 1/3 of the projected new demand by 2050—would require 10,000 nuclear power plants, each capable of churning out a gigawatt of power, enough to light a small city. "That means opening one nuclear reactor every other day for the next 50 years," Lewis says. Mind you, there hasn't been a new nuclear plant built in the United States since 1973, and concerns about high up-front capital costs, waste disposal, corporate liability, nuclear proliferation, and terrorism make it unlikely that will change in any meaningful way soon.

Other energy alternatives have their drawbacks as well. Fusion reactors have the theoretical potential to provide massive amounts of cheap power—but not soon. Last month, Japan, Europe, China, Russia, South Korea, and the United States agreed to build a new experimental fusion reactor in France at a projected cost of $5 billion (*Science*, 1 July, p. 28). But even if the facility meets proponents' grandest expectations, it will still provide a sustained fusion reaction for at most 500 seconds, a far cry from the continuous operation needed to yield large amounts of power. "Will it work? We don't know. But we think it's worth the investment," says Ray Orbach, who directs DOE's Office of Science.

There is, of course, a grab bag of renewable energy options as well. Chief among them is wind energy. The technology already produces electricity for $0.05 a kilowatt-hour, making it cheaper than all but natural gas and coal plants. Still, scale is a problem. If wind turbines were installed wherever wind is plentiful and the costs reasonable, they still would generate only 2 to 6 TW of power, according to recent estimates from the Intergovernmental Panel on Climate Change and the European Wind Energy Association. (A new estimate from researchers at Stanford University ups the figure to 72 TW, a much

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higher number based on wind potential at 80 meters off the ground—the height of modern wind turbine hubs—where wind speeds are typically stronger. But that estimate extrapolates global wind potential from point measurements, Lewis says.) In any case, it's clear that wind energy is a critical renewable resource that will be pursued. But if the earlier predictions of wind energy potential are correct, it's no panacea.

Biomass, geothermal, and energy from ocean waves also have potential. But biomass's potential is limited by the need to use arable land to grow food; geothermal energy's potential is limited by high drilling costs; and ocean power has been stalled in part by high construction costs. Shunting CO_2 from power plants underground before it can escape into the atmosphere holds vast promise (*Science*, 13 August 2004, p. 962). But large-scale demonstrations have only recently begun and haven't confirmed that CO_2 will remain underground for hundreds to thousands of years without leaking out. "We absolutely need to be doing this. But it may not technically work," Lewis says. Finally, conservation programs have the potential to squeeze a lot more mileage out of existing energy sources. But by themselves they don't solve the CO_2 problem.

So what is the world to do? Right now the solution is clear: The United States is currently opening natural gas plants at the rate of about one every 3.5 days. A stroll through Beijing makes it clear that China is pursuing coal just as fast. Fossil fuel use shows no signs of slowing (see figure, p. 550).

Handwringing geologists have been warning for years that worldwide oil production is likely to peak sometime between now and 2040, driving oil prices through the roof. The critical issue for climate, however, is not when production of a fossil fuel peaks, but its global capacity. At the 1998 level of energy use, there is still at least an estimated half a century worth of oil available, 2 centuries of natural gas, and a whopping 2 millennia worth of coal. The upshot is that we will run into serious climate problems long before we run out of fossil fuels.

What's left? Solar. Photovoltaic panels currently turn sunlight into 3 gigawatts of electricity. The business is growing at 40% a year and is already a \$7.5 billion industry. But impressive as it is, that's still a drop in the bucket of humanity's total energy use. "You have to use a logarithmic scale to see it" graphed next to fossil fuels, Lewis says.

What solar does have going for it is, well, the sun. Our star puts out 3.8×10^{23} kilowatt-hours of energy every hour. Of that, 170,000 TW strike Earth every moment,

Solar Report Sets the Agenda

If they are ever to supply a major part of the world's energy needs, solar cells must become both much cheaper and more efficient at converting sunlight to electricity. Meeting those somewhat contradictory goals will not be easy. But recent trends in the industry offer hope.

In fact, the efficiency of solar cells has risen steadily over the past 4 decades. And as manufacturing levels have risen, the price of installed solar panels has dropped dramatically—particularly in Japan, where increasing sales slashed solar power prices an average of 7% a year between 1992 and 2003, according to the International Energy Agency. Still, prices must drop another 10- to 100-fold to make solar not just competitive with other electric sources but cheap enough to be used to generate transportation fuel and home heating. In hopes of bringing about those and related changes, the new Department of Energy report identifies 13 priorities for solar energy research. Among them:

Flex time. Reel-to-reel manufacturing could slash the cost of plastic cells.

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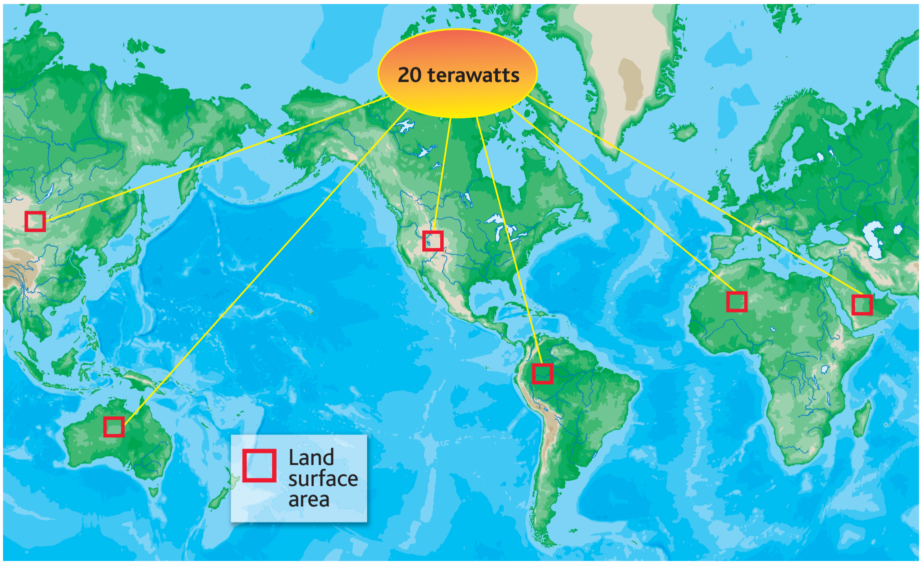
Revolutionary photovoltaic designs
Standard solar panels can turn at most one-third of the energy in the photons that strike them into electric current. Some of those photons have too little energy to excite electrons in the solar cells, and others have extra energy that just generates heat. Recent lab studies indicate that it may be possible to capture some of the high-energy strays using nano-sized lead-based particles that generate more than one electron from an incoming photon. But the technique has yet to be demonstrated in a working solar cell.

"Plastic" cells
Solar cells made from organic materials, including cheap high-volume polymers, have the potential to drastically reduce the cost of solar electricity. But current versions suffer from low efficiency, as most convert less than 2% of solar energy into electricity. New materials and device designs could change that equation.

Nanotechnology
Although crystalline solar cells can reach efficiencies of about 30%, producing the crystalline silicon in the first place is energy intensive and expensive. Solar cell makers have begun using cheap chemical manufacturing techniques to create nano-sized semiconductor crystals and incorporating these into solar cells. These cells are typically far cheaper to make, but for now the efficiency is stuck at about 10% or less. Researchers might be able to boost that efficiency if they can find ways to organize those nanoparticles to ferry excited electrons out of the cells.

From air and water to fuel
Sunlight can be used to split water molecules into oxygen and hydrogen gas, which can be stored, transported through pipelines, and used either to fuel vehicles or to generate electricity. But here too efficiency is a problem. The catalysts used to split water absorb only a couple of percent of the energy in sunlight that hits them, and in many cases they are unstable in practical settings. That could change if researchers could find new high-efficiency, stable catalysts to do the job. Equally promising is to find high-efficiency catalysts capable of using solar energy to convert carbon dioxide from the air into energy-rich hydrocarbon fuels.

Solar concentrators
Large banks of reflectors that concentrate large amounts of sunlight on a single photovoltaic already produce the lowest-cost solar electricity. Researchers are also looking at related designs to split water to create hydrogen gas, or to strip hydrogen gas from fossil fuels, while sequestering the carbon. To be most efficient, such reactors must concentrate enough sunlight to reach 2000 kelvin. But such high temperatures cause heat shocks that break down the ceramic materials in the chemical reactors. New heat-resistant ceramics could help lower the cost of sunlight-derived fuels. –R.F.S.



Global need. This map shows the amount of land needed to generate 20 TW with 10% efficient solar cells.

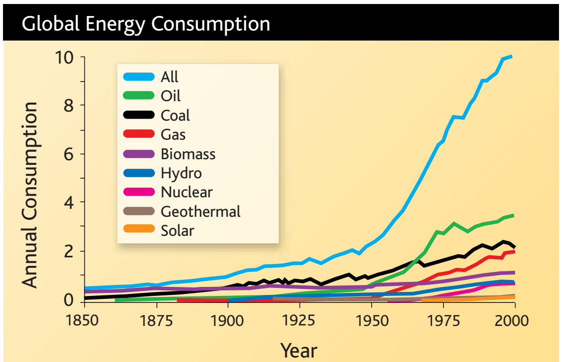
nearly one-third of which are reflected back into space. The bottom line is that every hour, Earth's surface receives more energy from the sun than humans use in a year.

Collecting even a tiny fraction of that energy won't be easy. To harvest 20 TW with solar panels that are 10% efficient at turning sunlight to electricity—a number well within the range of current technology—would require covering about 0.16% of Earth's land surface with solar panels. Covering all 70 million detached homes in the United States with solar panels would produce only 0.25 TW of electricity, just 1/10 of the electric power consumed in the country in the year 2000. That means land will need to be dedicated for solar farms, setting up land use battles that will likely raise environmental concerns, such as destroying habitat for species where the farms are sited.

Solar energy advocates acknowledge that a global solar energy grid would face plenty of other challenges as well. Chief among them: transporting and storing the energy. If massive solar farms are plunked down in the middle of deserts and other sparsely populated areas, governments will have to build an electrical infrastructure to transport the power to urban centers. That is certainly doable, but expensive.

A tougher knot is storing energy from the sun. Because electricity cannot be stored directly, it must be converted to some other form of potential energy for storage, such as the electrochemical energy of a battery or the kinetic energy of a flywheel. The massive scale of global electric use makes both of those forms of energy storage unlikely. Another possibility is using the electricity to pump water uphill to reservoirs, where it can later be released to regenerate electricity. Electricity can also be used to generate hydrogen gas or other chemical fuels, which can then be delivered via pipelines to where they are needed or used directly as transportation fuels. But that too requires building a new expensive infrastructure that isn't incorporated in solar energy's already high cost.

The issue of cost may be solar energy's biggest hurdle. Even without the extra infrastructure, harvesting power from the sun



remains one of the most expensive renewable technologies on the market and far more expensive than the competition. In his BESAC presentation last month, Lewis noted that electricity derived from photovoltaics typically costs \$0.25 to \$0.50 per kilowatt-hour. By contrast, wind power costs \$0.05 to \$0.07, natural gas costs \$0.025 to \$0.05, and coal \$0.01 to \$0.04. What is more, electricity makes up only about 10% of the world's energy use. Globally, most energy goes toward heating homes, something that can usually be done more cheaply than with electricity generated from fossil fuels. As a result, says Lewis, "solar energy needs to be 50-fold lower in cost than fossil fuel electricity to make electric heat cheap enough to compete."

If all this has a familiar ring to it, that's because many of the same arguments and alternatives have been discussed before. In the wake of the oil shocks of the 1970s, the Carter Administration directed billions of dollars to alternative energy research. The big differences now are the threat of climate change and the current huge budget deficits in the United States. Some of the cost numbers have changed, but the gap between solar energy's potential and what is needed for it to be practical on a massive scale remains wide. The April DOE meeting explored many ideas to bridge that gap, including creating plastic solar cells and making use of advances in nanotechnology (see sidebar, p. 549).

That wealth of potentially new technologies makes this "an excellent time to put a lot of emphasis on solar energy research," says Walter Kohn, a BESAC member and chemist at the University of California, Santa Barbara. Some of these ideas do currently receive modest funding, enough to support a handful of individual investigator-driven labs. But Richard Smalley, a chemist at Rice University in Houston, Texas, who advocates renewed support for alternative-energy research, notes that unless research progresses far more rapidly to solve the current energy conundrum by 2020, there is essentially no way to have large amounts of clean-energy technology in place by 2050. "That means the basic enabling breakthroughs have to be made now," Smalley says.

Of course a major sticking point is money. At the April meeting, DOE officials started talking about funding a new solar energy research initiative at about \$50 million a year, according to Mary Gress, who manages DOE's photochemistry and radiation research. Lewis is reluctant to say how much money is needed but asks rhetorically whether \$50 million a year is enough to transform the biggest industry in the world. Clearly, others don't think so. "I don't see any answer that will change it short of an Apollo-level program," Smalley says.

For the past few years, Smalley has been advocating a \$0.05-a-gallon gasoline tax to fund \$10 billion a year in alternative energy research, which encompasses more than just solar research. A few members of Congress have recently pushed for that level of funding for alternative energy R&D. But so far such measures have failed to win broad support. Even coming up with \$50 million a year in new money will be difficult, given growing pressure to reduce the current \$333-billion-a-year deficit. "With the budget outlook the way it is, it'll be pretty hard," says Patricia Dehmer, associate director of science in DOE's Office of Basic Energy Sciences. Asked whether a solar

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energy research initiative has a shot at receiving backing by the Administration, Joel Parriott, who helps the White House Office of Management and Budget oversee the budget for DOE's Office of Science, says that "it's too early to tell." He adds that the Administration has already set its energy policy priorities as increasing oil drilling in Alaska's Arctic National Wildlife Refuge, clean coal, and hydrogen. However, he says, "that doesn't mean there isn't room for new things."

With Congress close to passing an energy bill that focuses on tax breaks for oil exploration and hybrid cars, it doesn't look as if a big push on solar energy will be one of those "new things" anytime soon. But Dehmer notes that progress on energy issues happens slowly. "I'm trying to lay the groundwork for a commitment on the scale of a major scientific user facility," she says.

At least compared with DOE's earlier push for progress in hydrogen technology, many researchers expect that a push on solar energy research will be a far easier sell. "With hydrogen it was a lot more controversial," Stupp says. "There are scientific issues that are really serious [in getting hydrogen technology to work]. With solar, it's an idea that makes sense in a practical way and is a great source of discovery." If that research and discovery doesn't happen, Lewis says he's worried about what the alternative will bring: "Is this something at which we can afford to fail?"

–ROBERT F. SERVICE

Reproductive Biology

A Powerful First *KiSS-1*

Puberty researchers are finding that the protein kisspeptin and its receptor are central to this sexual maturation

Both anticipated and dreaded, puberty is rarely fun. From swelling breasts and sprouting hair to cracking voices and unexpected urges, this transition is almost always awkward, especially if puberty comes earlier or later than normal. It is a rare teenager who has not wondered, "Why is this happening to me?"

Are you ready? A protein called kisspeptin helps trigger the flood of hormones that marks puberty.

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The body's awakening into sexual maturity is no less puzzling for developmental biologists and endocrinologists. And they have an equally straightforward question: How does the body know when, exactly, to unleash the cascade of hormones that change face, voice, height, bone structure, and sexual organs into those of a fertile adult? The emerging answer, it seems, could have come from a teenage romance novel: Puberty starts with a kind of kiss.

Recent studies have shown that a protein called kisspeptin is a key trigger of the complex chain of physiological reactions that readies the body for sexual maturity. Without this signal, people, as well as mice and other mammals, stay in a preteen limbo and never fully grow up. Discovering the involvement of kisspeptin and its receptor, a protein called GPR54, in puberty "is a major breakthrough in reproductive physiology," says Manuel Tena-Sempere of the University of Cordoba in Spain. Indeed, the duo was one of the most-discussed topics at a recent meeting on the control and onset of puberty.*

Scientists hope the two proteins might help them solve long-standing puzzles about the start of puberty, such as how the body revives the hormone production that is prevalent in fetal and newborn development but then mysteriously disappears during childhood, and how puberty might be influenced by nutrition and other metabolic factors. Preliminary evidence suggests, moreover, that the protein pair may even play a lifelong role in regulating sex hormones and reproduction.

The topic is more than academic. For some children, puberty doesn't happen at the right time: Girls who start to develop breasts and pubic hair as young as 6 years old, and boys at 17 who still sing soprano often end up at the pediatrician's office looking for answers. Although the physical consequences of being an early or late bloomer remain unclear, the social consequences can be significant. Boys who develop late may face brutal taunting because of their small stature and underdeveloped muscles. And early-developing girls "have higher rates of depression, substance abuse, and teenage pregnancies," Pierre-André Michaud, a specialist in adolescent medicine at the University of Lausanne in Switzerland, said at the meeting. Consequently, physicians are eager to understand how puberty is controlled and whether they can, or should, safely delay or accelerate it in certain cases.

KiSS-1-ng partner

It was GPR54, not kisspeptin, that appeared first as a player in puberty. The initial clue was a 20-year-old man in Paris who had undeveloped testes, sparse pubic hair, and the bone maturity of a 15-year-old; such lack of sexual development is called idiopathic hypogonadotropic hypogonadism (IHH). Doctors soon discovered that the man was not the only one in his family to fail to complete puberty: Three of his four brothers were similarly affected, and one of his two sisters had experienced only a single menstrual period in her life—at age 16. All had abnormally low levels of sex hormones.

It turned out that the parents of this family were first cousins and, as a team led by Nicolas de Roux of INSERM in Paris reported in 2003, both mother and father carried a mutation in one copy of their *GPR54* gene. The affected children had all inherited two mutated copies of the gene. Other researchers had shown that GPR54 acts as a receptor for kisspeptin, so de Roux and his colleagues suggested that the molecular embrace between the two proteins might be a player in the first steps of puberty.

* 6th Puberty Conference, Evian, France, 26–28 May.