RETHINKING "HOBBITS"
What They Mean for Human Evolution

THE EVERYTHING TV
Get Ready for the Wide-Screen Web

SCIENTIFIC AMERICAN

November 2009 www.ScientificAmerican.com

The Long-Lost Siblings of OUR SUN
page 40

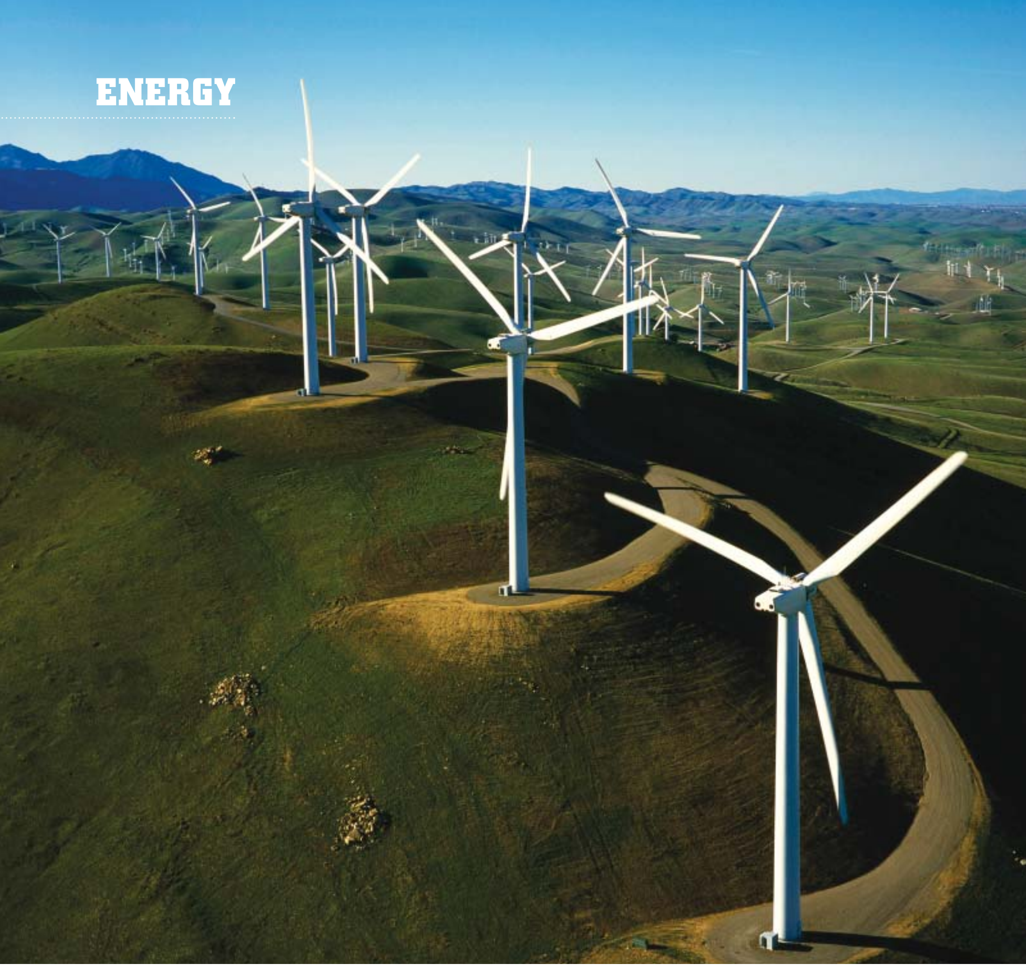
A Plan for a Sustainable Future

How to get all energy from wind, water and solar power by 2030

Chronic Pain
What Goes Wrong

Plus:
- **The Future of Cars**
- **Farms in Skyscrapers**

$5.99



JOHN LEE *Aurora Photos (wind farm)*; BILL HEINSOHN *Aurora Photos (dam)*

A PATH TO SUSTAINABLE ENERGY BY 2030

Wind, water and solar technologies can provide 100 percent of the world's energy, eliminating all fossil fuels. HERE'S HOW

By Mark Z. Jacobson and Mark A. Delucchi

In December leaders from around the world will meet in Copenhagen to try to agree on cutting back greenhouse gas emissions for decades to come. The most effective step to implement that goal would be a massive shift away from fossil fuels to clean, renewable energy sources. If leaders can have confidence that such a transformation is possible, they might commit to an historic agreement. We think they can.

A year ago former vice president Al Gore threw down a gauntlet: to repower America with 100 percent carbon-free electricity within 10 years. As the two of us started to evaluate the feasibility of such a change, we took on an even larger challenge: to determine how 100 percent of the world's energy, for *all* purposes, could be supplied by wind, water and solar resources, by as early as 2030. Our plan is presented here.

Scientists have been building to this moment for at least a decade, analyzing various pieces of the challenge. Most recently, a 2009 Stanford University study ranked energy systems according to their impacts on global warming, pollution, water supply, land use, wildlife and other concerns. The very best options were wind, solar, geothermal, tidal and hydroelectric power—all of which are driven by wind, water or sunlight (referred to as WWS). Nuclear power, coal with carbon capture, and ethanol were all poorer options, as were oil and natural gas. The study also found that battery-electric vehicles and hydrogen fuel-cell vehicles recharged by WWS options would largely eliminate pollution from the transportation sector.

Our plan calls for millions of wind turbines, water machines and solar installations. The numbers are large, but the scale is not an insurmountable hurdle; society has achieved massive

transformations before. During World War II, the U.S. retooled automobile factories to produce 300,000 aircraft, and other countries produced 486,000 more. In 1956 the U.S. began building the Interstate Highway System, which after 35 years extended for 47,000 miles, changing commerce and society.

Is it feasible to transform the world's energy systems? Could it be accomplished in two decades? The answers depend on the technologies chosen, the availability of critical materials, and economic and political factors.

Clean Technologies Only

Renewable energy comes from enticing sources: wind, which also produces waves; water, which includes hydroelectric, tidal and geothermal energy (water heated by hot underground rock); and sun, which includes photovoltaics and solar power plants that focus sunlight to heat a fluid that drives a turbine to generate electricity. Our plan includes only technologies that work or are close to working today on a large scale, rather than those that may exist 20 or 30 years from now.

To ensure that our system remains clean, we consider only technologies that have near-zero emissions of greenhouse gases and air pollutants over their entire life cycle, including construction, operation and decommissioning. For example, when burned in vehicles, even the most ecologically acceptable sources of ethanol create air pollution that will cause the same mortality level as when gasoline is burned. Nuclear power results in up to 25 times more carbon emissions than wind energy, when reactor construction and uranium refining and transport are considered. Carbon capture and sequestration technology can reduce carbon dioxide emissions from coal-fired power plants but will *increase* air pollutants and will extend all the other deleterious effects of coal mining, transport and processing, because more coal must be burned to power the capture and storage steps. Similarly, we consider only technologies that do not present significant waste disposal or terrorism risks.

In our plan, WWS will supply electric power for heating and transportation—industries that will have to revamp if the world has any hope of slowing climate change. We have assumed that most fossil-fuel heating (as well as ovens and stoves) can be replaced by electric systems and that most fossil-fuel transportation can be replaced by battery and fuel-cell vehicles. Hydrogen, produced by using WWS electricity to split water (electrolysis), would power fuel cells and be burned in airplanes and by industry.

HO/REUTERS/CORBIS (*solar panels*)

KEY CONCEPTS

- Supplies of wind and solar energy on accessible land dwarf the energy consumed by people around the globe.
- The authors' plan calls for 3.8 million large wind turbines, 90,000 solar plants, and numerous geothermal, tidal and rooftop photovoltaic installations worldwide.
- The cost of generating and transmitting power would be less than the projected cost per kilowatt-hour for fossil-fuel and nuclear power.
- Shortages of a few specialty materials, along with lack of political will, loom as the greatest obstacles.

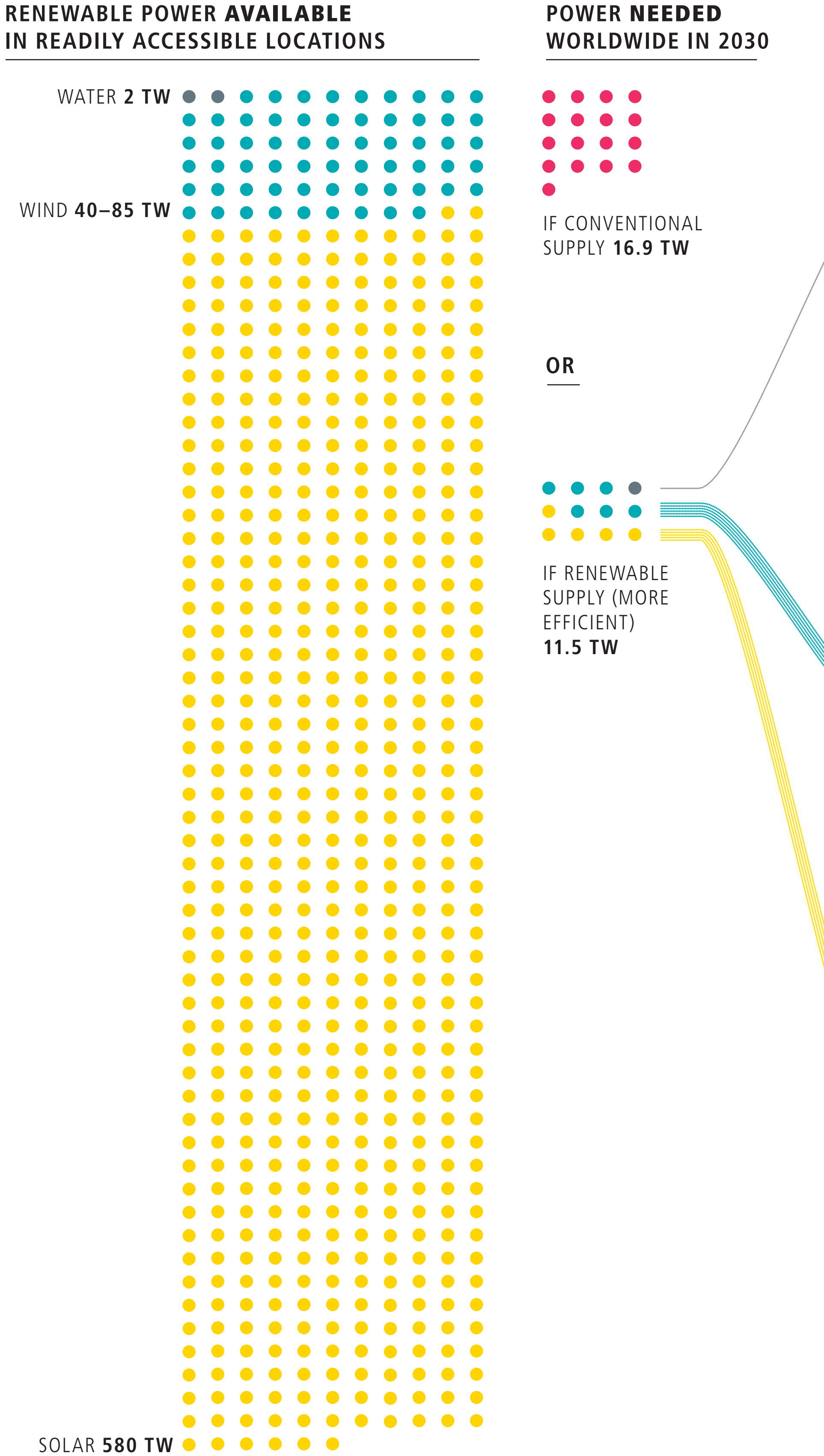
—The Editors

Plenty of Supply

Today the maximum power consumed worldwide at any given moment is about 12.5 trillion watts (terawatts, or TW), according to the U.S. Energy Information Administration. The agency projects that in 2030 the world will require 16.9 TW of power as global population and living standards rise, with about 2.8 TW in the U.S. The mix of sources is similar to today's, heavily dependent on fossil fuels. If, however, the planet were powered entirely by WWS, with no fossil-fuel or biomass combustion, an intriguing savings would occur. Global power demand would be only 11.5 TW, and U.S. demand would be 1.8 TW. That decline occurs because, in most cases, electrification is a more efficient way to use energy. For example, only 17 to 20 percent of the energy in gasoline is used to move a vehicle (the rest is wasted as heat), whereas 75 to 86 percent of the electricity delivered to an electric vehicle goes into motion.

Even if demand did rise to 16.9 TW, WWS sources could provide far more power. Detailed studies by us and others indicate that energy from the wind, worldwide, is about 1,700 TW. Solar, alone, offers 6,500 TW. Of course, wind and sun out in the open seas, over high mountains and across protected regions would not be available. If we subtract these and low-wind areas not likely to be developed, we are still left with 40 to 85 TW for wind and 580 TW for solar, each far beyond future human demand. Yet currently we generate only 0.02 TW of wind power and 0.008 TW of solar. These sources hold an incredible amount of untapped potential.

The other WWS technologies will help create a flexible range of options. Although all the sources can expand greatly, for practical reasons, wave power can be extracted only near coastal areas. Many geothermal sources are too deep to be tapped economically. And even though hydroelectric power now exceeds all other WWS sources, most of the suitable large reservoirs are already in use.



MW – MEGAWATT = 1 MILLION WATTS
GW – GIGAWATT = 1 BILLION WATTS
TW – TERAWATT = 1 TRILLION WATTS

The Editors welcome responses to this article. To comment and to see more detailed calculations, go to **www.ScientificAmerican.com/sustainable-energy**

RENEWABLE INSTALLATIONS REQUIRED WORLDWIDE

WATER **1.1 TW** (9% OF SUPPLY)

490,000
TIDAL TURBINES – 1 MW* – <1% IN PLACE
*size of unit

5,350
GEOTHERMAL PLANTS – 100 MW – 2% IN PLACE

900
HYDROELECTRIC PLANTS – 1,300 MW – 70% IN PLACE

WIND **5.8 TW** (51% OF SUPPLY)

3,800,000
WIND TURBINES – 5 MW – 1% IN PLACE

720,000
WAVE CONVERTERS* – 0.75 MW – <1% IN PLACE
*wind drives waves

SOLAR **4.6 TW** (40% OF SUPPLY)

1,700,000,000
ROOFTOP PHOTOVOLTAIC SYSTEMS* – 0.003 MW – <1% IN PLACE
*sized for a modest house; a commercial roof might have dozens of systems

49,000
CONCENTRATED SOLAR POWER PLANTS – 300 MW – <1% IN PLACE

40,000
PHOTOVOLTAIC POWER PLANTS – 300 MW – <1% IN PLACE

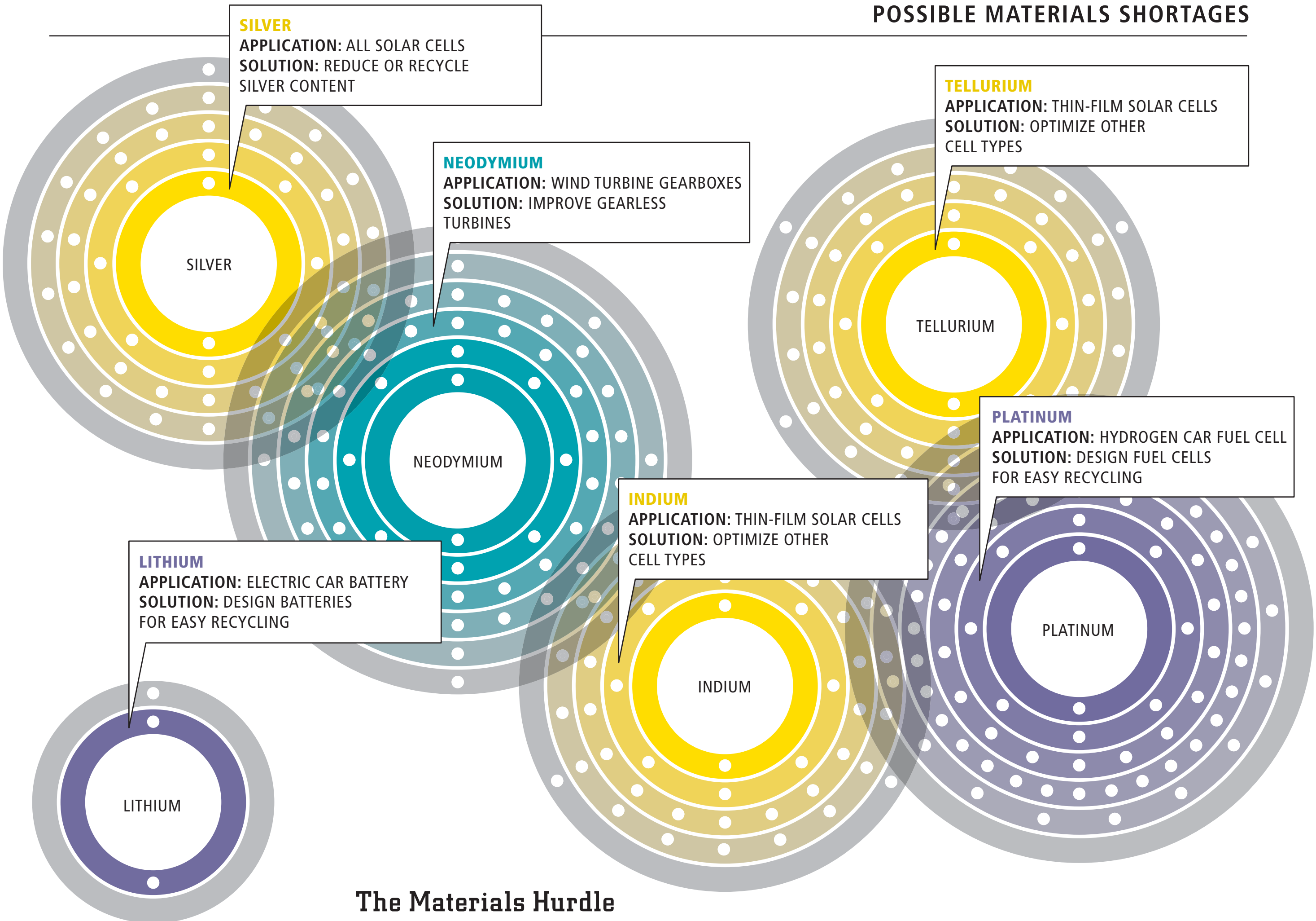
The Plan: Power Plants Required

Clearly, enough renewable energy exists. How, then, would we transition to a new infrastructure to provide the world with 11.5 TW? We have chosen a mix of technologies emphasizing wind and solar, with about 9 percent of demand met by mature water-related methods. (Other combinations of wind and solar could be as successful.)

Wind supplies 51 percent of the demand, provided by 3.8 million large wind turbines (each rated at five megawatts) worldwide. Although that quantity may sound enormous, it is interesting to note that the world manufactures 73 million cars and light trucks *every year.* Another 40 percent of the power comes from photovoltaics and concentrated solar plants, with about 30 percent of the photovoltaic output from rooftop panels on homes and commercial buildings. About 89,000 photovoltaic and concentrated solar power plants, averaging 300 megawatts apiece, would be needed. Our mix also includes 900 hydroelectric stations worldwide, 70 percent of which are already in place.

Only about 0.8 percent of the wind base is installed today. The worldwide footprint of the 3.8 million turbines would be less than 50 square kilometers (smaller than Manhattan). When the needed spacing between them is figured, they would occupy about 1 percent of the earth's land, but the empty space among turbines could be used for agriculture or ranching or as open land or ocean. The nonrooftop photovoltaics and concentrated solar plants would occupy about 0.33 percent of the planet's land. Building such an extensive infrastructure will take time. But so did the current power plant network. And remember that if we stick with fossil fuels, demand by 2030 will rise to 16.9 TW, requiring about 13,000 large new coal plants, which themselves would occupy a lot more land, as would the mining to supply them.

CATALOGTREE (*illustrations*); NICHOLAS EVELEIGH *Getty Images (plug)*



[THE AUTHORS]

Mark Z. Jacobson is professor of civil and environmental engineering at Stanford University and director of the Atmosphere/Energy Program there. He develops computer models to study the effects of energy technologies and their emissions on climate and air pollution. **Mark A. Delucchi** is a research scientist at the Institute of Transportation Studies at the University of California, Davis. He focuses on energy, environmental and economic analyses of advanced, sustainable transportation fuels, vehicles and systems.

The Materials Hurdle

The scale of the WWS infrastructure is not a barrier. But a few materials needed to build it could be scarce or subject to price manipulation.

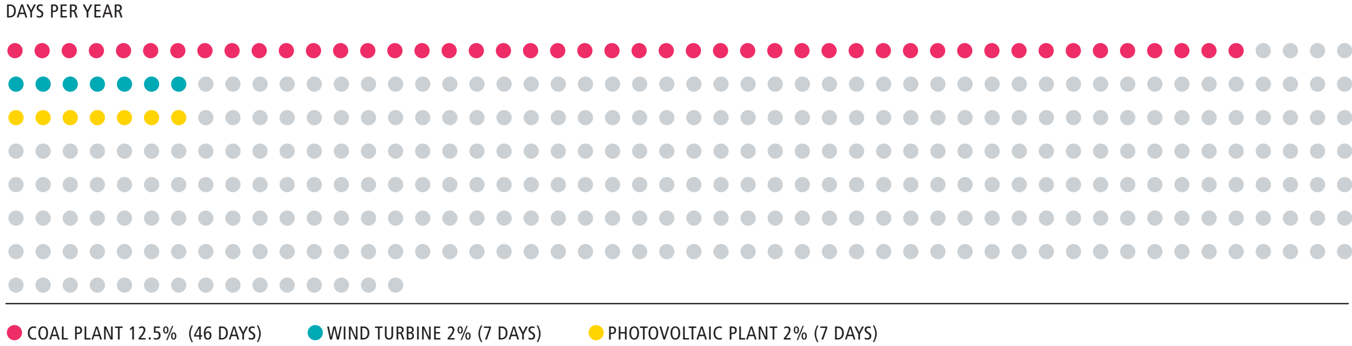
Enough concrete and steel exist for the millions of wind turbines, and both those commodities are fully recyclable. The most problematic materials may be rare-earth metals such as neodymium used in turbine gearboxes. Although the metals are not in short supply, the low-cost sources are concentrated in China, so countries such as the U.S. could be trading dependence on Middle Eastern oil for dependence on Far Eastern metals. Manufacturers are moving toward gearless turbines, however, so that limitation may become moot.

Photovoltaic cells rely on amorphous or crystalline silicon, cadmium telluride, or copper indium selenide and sulfide. Limited supplies of tellurium and indium could reduce the prospects for some types of thin-film solar cells, though not for all; the other types might be able to take up the slack. Large-scale production could be restricted by the silver that cells require, but finding ways to reduce the silver content could tackle that hurdle. Recycling parts from old cells could ameliorate material difficulties as well.

Three components could pose challenges for building millions of electric vehicles: rare-earth metals for electric motors, lithium for lithium-ion batteries and platinum for fuel cells. More than half the world's lithium reserves lie in Bolivia and Chile. That concentration, combined with rapidly growing demand, could raise prices significantly. More problematic is the claim by Meridian International Research that not enough economically recoverable lithium exists to build anywhere near the number of batteries needed in a global electric-vehicle economy. Recycling could change the equation, but the economics of recycling depend in part on whether batteries are made with easy recyclability in mind, an issue the industry is aware of. The long-term use of platinum also depends on recycling; current available reserves would sustain annual production of 20 million fuel-cell vehicles, along with existing industrial uses, for fewer than 100 years.

CATALOGTREE (*illustration*); COURTESY OF MARK Z. JACOBSON (*Jacobson*); COURTESY OF KAREN DELUCCHI (*Delucchi*)

AVERAGE DOWNTIME FOR ANNUAL MAINTENANCE



Smart Mix for Reliability

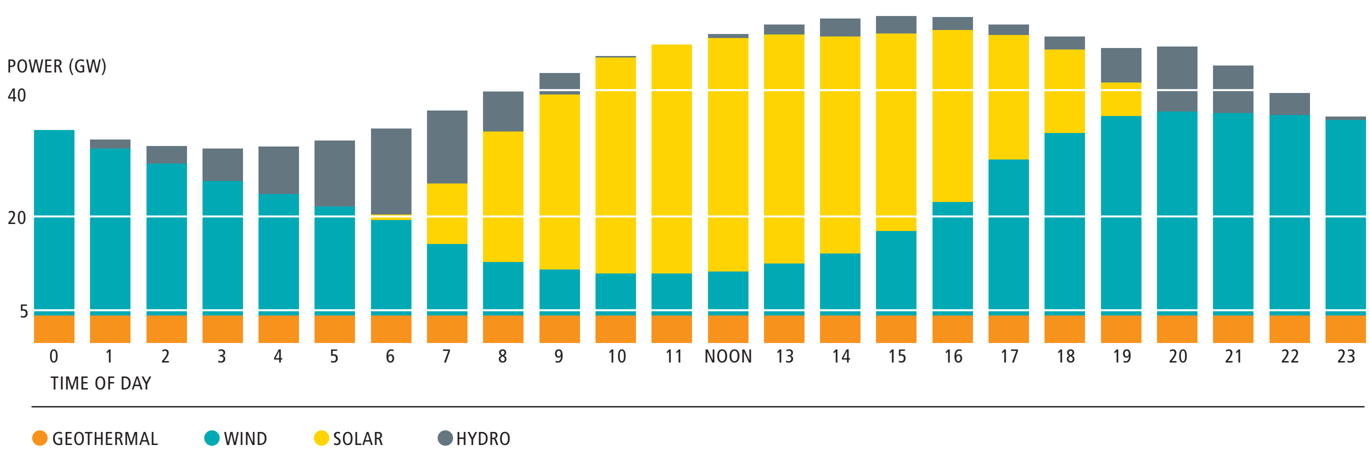
A new infrastructure must provide energy on demand at least as reliably as the existing infrastructure. WWS technologies generally suffer less downtime than traditional sources. The average U.S. coal plant is offline 12.5 percent of the year for scheduled and unscheduled maintenance. Modern wind turbines have a down time of less than 2 percent on land and less than 5 percent at sea. Photovoltaic systems are also at less than 2 percent. Moreover, when an individual wind, solar or wave device is down, only a small fraction of production is affected; when a coal, nuclear or natural gas plant goes offline, a large chunk of generation is lost.

The main WWS challenge is that the wind does not always blow and the sun does not always shine in a given location. Intermittency problems can be mitigated by a smart balance of sources, such as generating a base supply from steady geothermal or tidal power, relying on wind at night when it is often plentiful, using solar by day and turning to a reliable source such as hydroelectric that can be turned on and off quickly to smooth out supply or meet peak demand. For example, interconnecting wind farms that are only 100 to 200 miles apart can compensate for hours of zero power at any one farm should the wind not be blowing there. Also helpful is interconnecting geographically dispersed sources so they can back up one another, installing smart electric meters in homes that automatically recharge electric vehicles when demand is low and building facilities that store power for later use.

Because the wind often blows during stormy conditions when the sun does not shine and the sun often shines on calm days with little wind, combining wind and solar can go a long way toward meeting demand, especially when geothermal provides a steady base and hydroelectric can be called on to fill in the gaps.

▼ CALIFORNIA CASE STUDY: To show the power of combining resources, Graeme Hoste of Stanford University recently calculated how a mix of four renewable sources, in 2020, could generate 100 percent of California's electricity around the clock, on a typical July day. The hydroelectric capacity needed is already in place.

CLEAN ELECTRICITY 24/7



CATALOGTREE

As Cheap as Coal

The mix of WWS sources in our plan can reliably supply the residential, commercial, industrial and transportation sectors. The logical next question is whether the power would be affordable. For each technology, we calculated how much it would cost a producer to generate power and transmit it across the grid. We included the annualized cost of capital, land, operations, maintenance, energy storage to help offset intermittent supply, and transmission. Today the cost of wind, geothermal and hydroelectric are all less than seven cents a kilowatt-hour (¢/kWh); wave and solar are higher. But by 2020 and beyond wind, wave and hydro are expected to be 4¢/kWh or less.

For comparison, the average cost in the U.S. in 2007 of conventional power generation and transmission was about 7¢/kWh, and it is projected to be 8¢/kWh in 2020. Power from wind turbines, for example, already costs about the same or less than it does from a new coal or natural gas plant, and in the future wind power is expected to be the least costly of all options. The competitive cost of wind has made it the second-largest source of new electric power generation in the U.S. for the past three years, behind natural gas and ahead of coal.

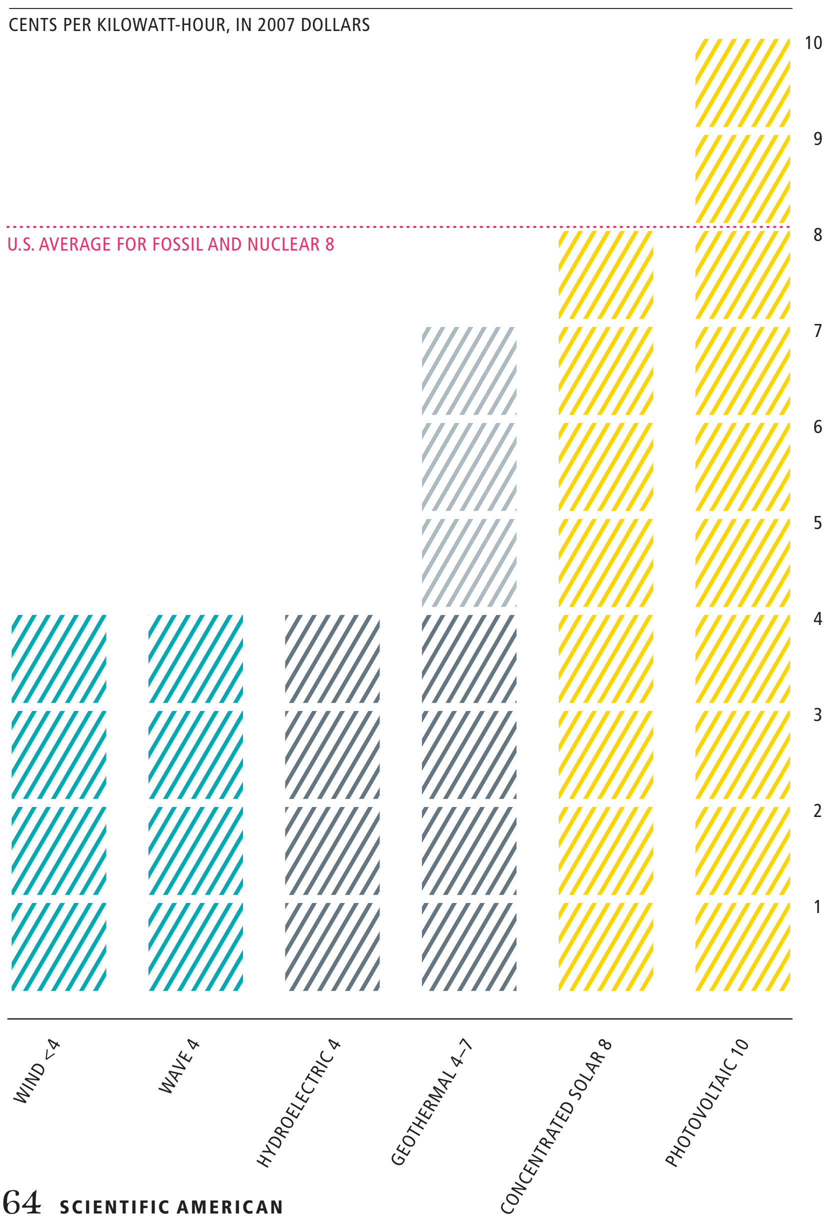
Solar power is relatively expensive now but should be competitive as early as 2020. A careful analysis by Vasilis Fthenakis of Brookhaven National Laboratory indicates that within 10 years, photovoltaic system costs could drop to about 10¢/kWh, including long-distance transmission and the cost of compressed-air storage of power for use at night. The same analysis estimates that concentrated solar power systems with enough thermal storage to generate electricity 24 hours a day in spring, summer and fall could deliver electricity at 10¢/kWh or less.

Transportation in a WWS world will be driven by batteries or fuel cells, so we should compare the economics of these electric vehicles with that of internal-combustion-engine vehicles. Detailed analyses by one of us (Delucchi) and Tim Lipman of the University of California, Berkeley, have indicated that mass-produced electric vehicles with advanced lithium-ion or nickel metal-hydride batteries could have a full lifetime cost per mile (including battery replacements) that is comparable with that of a gasoline vehicle, when gasoline sells for more than $2 a gallon.

When the so-called externality costs (the monetary value of damages to human health, the environment and climate) of fossil-fuel generation are taken into account, WWS technologies become even more cost-competitive.

Overall construction cost for a WWS system might be on the order of $100 trillion worldwide, over 20 years, not including transmission. But this is not money handed out by governments or consumers. It is investment that is paid back through the sale of electricity and energy. And again, relying on traditional sources would raise output from 12.5 to 16.9 TW, requiring thousands more of those plants, costing roughly $10 trillion, not to mention tens of trillions of dollars more in health, environmental and security costs. The WWS plan gives the world a new, clean, efficient energy system rather than an old, dirty, inefficient one.

COST TO GENERATE AND TRANSMIT POWER IN 2020



Political Will

Our analyses strongly suggest that the costs of WWS will become competitive with traditional sources. In the interim, however, certain forms of WWS power will be significantly more costly than fossil power. Some combination of WWS subsidies and carbon taxes would thus be needed for a time. A feed-in tariff (FIT) program to cover the difference between generation cost and wholesale electricity prices is especially effective at scaling-up new technologies. Combining FITs with a so-called declining clock auction, in which the right to sell power to the grid goes to the lowest bidders, provides continuing incentive for WWS developers to lower costs. As that happens, FITs can be phased out. FITs have been implemented in a number of European countries and a few U.S. states and have been quite successful in stimulating solar power in Germany.

Taxing fossil fuels or their use to reflect their environmental damages also makes sense. But at a minimum, existing subsidies for fossil energy, such as tax benefits for exploration and extraction, should be eliminated to level the playing field. Misguided promotion of alternatives that are less desirable than WWS power, such as farm and production subsidies for biofuels, should also be ended, because it delays deployment of cleaner systems. For their part, legislators crafting policy must find ways to resist lobbying by the entrenched energy industries.

Finally, each nation needs to be willing to invest in a robust, long-distance transmission system that can carry large quantities of WWS power from remote regions where it is often greatest—such as the Great Plains for wind and the desert Southwest for solar in the U.S.—to centers of consumption, typically cities. Reducing consumer demand during peak usage periods also requires a smart grid that gives generators and consumers much more control over electricity usage hour by hour.

A large-scale wind, water and solar energy system can reliably supply the world's needs, significantly benefiting climate, air quality, water quality, ecology and energy security. As we have shown, the obstacles are primarily political, not technical. A combination of feed-in tariffs plus incentives for providers to reduce costs, elimination of fossil subsidies and an intelligently expanded grid could be enough to ensure rapid deployment. Of course, changes in the real-world power and transportation industries will have to overcome sunk investments in existing infrastructure. But with sensible policies, nations could set a goal of generating 25 percent of their new energy supply with WWS sources in 10 to 15 years and almost 100 percent of new supply in 20 to 30 years. With extremely aggressive policies, all existing fossil-fuel capacity could theoretically be retired and replaced in the same period, but with more modest and likely policies full replacement may take 40 to 50 years. Either way, clear leadership is needed, or else nations will keep trying technologies promoted by industries rather than vetted by scientists.

A decade ago it was not clear that a global WWS system would be technically or economically feasible. Having shown that it is, we hope global leaders can figure out how to make WWS power politically feasible as well. They can start by committing to meaningful climate and renewable energy goals now. ■

▲ **COAL MINERS and other fossil-fuel workers, unions and lobbyists are likely to resist a transformation to clean energy; political leaders will have to champion the cause.**

JEFF GENTNER *AP Photo* (protesters); DON FARRALL *Getty Images* (coal)

MORE TO EXPLORE

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. S. Pacala and R. Socolow in *Science,* Vol. 305, pages 968–972; 2004.

Evaluation of Global Wind Power. Cristina L. Archer and Mark Z. Jacobson in *Journal of Geophysical Research—Atmospheres,* Vol. 110, D12110; June 30, 2005.

Going Completely Renewable: Is It Possible (Let Alone Desirable)? B. K. Sovacool and C. Watts in *The Electricity Journal,* Vol. 22, No. 4, pages 95–111; 2009.

Review of Solutions to Global Warming, Air Pollution, and Energy Security. M. Z. Jacobson in *Energy and Environmental Science,* Vol. 2, pages 148–173; 2009.

The Technical, Geographical, and Economic Feasibility for Solar Energy to Supply the Energy Needs of the U.S. V. Fthenakis, J. E. Mason and K. Zweibel in *Energy Policy,* Vol. 37, pages 387–399; 2009.