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A Solar Grand Plan

By 2050 solar power could end U.S. dependence on foreign oil and slash greenhouse gas emissions

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High prices for gasoline and home heating oil are here to stay. The U.S. is at war in the Middle East at least in part to protect its foreign oil interests. And as China, India and other nations rapidly increase their demand for fossil fuels, future fighting over energy looms large. In the meantime, power plants that burn coal, oil and natural gas, as well as vehicles everywhere, continue to pour millions of tons of pollutants and greenhouse gases into the atmosphere annually, threatening the planet.

Well-meaning scientists, engineers, economists and politicians have proposed various steps that could slightly reduce fossil-fuel use and emissions. These steps are not enough. The U.S. needs a bold plan to free itself from fossil fuels. Our analysis convinces us that a massive switch to solar power is the logical answer.

Solar energy's potential is off the chart. The energy in sunlight striking the earth for 40 minutes is equivalent to global energy consumption for a year. The U.S. is lucky to be endowed with a vast resource; at least 250,000 square miles of land in the Southwest alone are suitable for constructing solar power plants, and that land receives more than 4,500 quadrillion British thermal units (Btu) of solar radiation a year. Converting only 2.5 percent of that radiation into electricity would match the nation's total energy consumption in 2006.

To convert the country to solar power, huge tracts of land would have to be covered with photovoltaic panels and solar heating troughs. A direct-current (DC) transmission backbone would also have to be erected to send that energy efficiently across the nation.

The technology is ready. On the following pages we present a grand plan that could provide 69 percent of the U.S.'s electricity and 35 percent of its total energy (which includes transportation) with solar power by 2050. We project that this energy could be sold to consumers at rates equivalent to today's rates for conventional power sources, about five cents per kilowatt-hour (kWh). If wind, biomass and geothermal sources were also developed, renewable energy could provide 100 percent of the nation's electricity and 90 percent of its energy by 2100.

The federal government would have to invest more than $400 billion over the next 40 years to complete the 2050 plan. That investment is substantial, but the payoff is greater. Solar plants consume little or no fuel, saving billions of dollars year after year. The infrastructure would displace 300 large coal-fired power plants and 300 more large natural gas plants and all the fuels they consume. The plan would effectively eliminate all imported oil, fundamentally cutting U.S. trade deficits and easing political tension in the Middle East and elsewhere. Because solar technologies are almost pollution-free, the plan would also reduce greenhouse gas emissions from power plants by 1.7 billion tons a year, and another 1.9 billion tons from gasoline vehicles would be displaced by plug-in hybrids refueled by the solar power grid. In 2050 U.S. carbon dioxide emissions would be 62 percent below 2005 levels, putting a major brake on global warming.

Photovoltaic Farms
In the past few years the cost to produce photovoltaic cells and modules has dropped significantly, opening the way for large-scale deployment. Various cell types exist, but the least expensive modules today are thin films made of cadmium telluride. To provide electricity at six cents per kWh by 2020, cadmium telluride modules would have to convert electricity with 14 percent efficiency, and systems would have to be installed at $1.20 per watt of capacity. Current modules have 10 percent efficiency and an installed system cost of about $4 per watt. Progress is clearly needed, but the technology is advancing quickly; commercial efficiencies have risen from 9 to 10 percent in the past 12 months. It is worth noting, too, that as modules improve, rooftop photovoltaics will become more cost-competitive for homeowners, reducing daytime electricity demand.

In our plan, by 2050 photovoltaic technology would provide almost 3,000 gigawatts (GW), or billions of watts, of power. Some 30,000 square miles of photovoltaic arrays would have to be erected. Although this area may sound enormous, installations already in place indicate that the land required for each gigawatt-hour of solar energy produced in the Southwest is less than that needed for a coal-powered plant when factoring in land for coal mining. Studies by the National Renewable Energy Laboratory in Golden, Colo., show that more than enough land in the Southwest is available without requiring use of environmentally sensitive areas, population centers or difficult terrain. Jack Lavelle, a spokesperson for Arizona's Department of Water Conservation, has noted that more than 80 percent of his state's land is not privately owned and that Arizona is very interested in developing its solar potential. The benign nature of photovoltaic plants (including no water consumption) should keep environmental concerns to a minimum.

The main progress required, then, is to raise module efficiency to 14 percent. Although the efficiencies of commercial modules will never reach those of solar cells in the laboratory, cadmium telluride cells at the National Renewable Energy Laboratory are now up to 16.5 percent and rising. At least one manufacturer, First Solar in Perrysburg, Ohio, increased module efficiency from 6 to 10 percent from 2005 to 2007 and is reaching for 11.5 percent by 2010.

Pressurized Caverns
The great limiting factor of solar power, of course, is that it generates little electricity when skies are cloudy and none at night. Excess power must therefore be produced during sunny hours and stored for use during dark hours. Most energy storage systems such as batteries are expensive or inefficient.

Compressed-air energy storage has emerged as a successful alternative. Electricity from photovoltaic plants compresses air and pumps it into vacant underground caverns, abandoned mines, aquifers and depleted natural gas wells. The pressurized air is released on demand to turn a turbine that generates electricity, aided by burning small amounts of natural gas. Compressed-air energy storage plants have been operating reliably in Huntorf, Germany, since 1978 and in McIntosh, Ala., since 1991. The turbines burn only 40 percent of the natural gas they would if they were fueled by natural gas alone, and better heat recovery technology would lower that figure to 30 percent.

Studies by the Electric Power Research Institute in Palo Alto, Calif., indicate that the cost of compressed-air energy storage today is about half that of lead-acid batteries. The research indicates that these facilities would add three or four cents per kWh to photovoltaic generation, bringing the total 2020 cost to eight or nine cents per kWh.

Electricity from photovoltaic farms in the Southwest would be sent over high-voltage DC transmission lines to compressed-air storage facilities throughout the country, where turbines would generate electricity year-round. The key is to find adequate sites. Mapping by the natural gas industry and the Electric Power Research Institute shows that suitable geologic formations exist in 75 percent of the country, often close to metropolitan areas. Indeed, a compressed-air energy storage system would look similar to the U.S. natural gas storage system. The industry stores eight trillion cubic feet of gas in 400 underground reservoirs. By 2050 our plan would require 535 billion cubic feet of storage, with air pressurized at 1,100 pounds per square inch. Although development will be a challenge, plenty of reservoirs are available, and it would be reasonable for the natural gas industry to invest in such a network.

Hot Salt
Another technology that would supply perhaps one fifth of the solar energy in our vision is known as concentrated solar power. In this design, long, metallic mirrors focus sunlight onto a pipe filled with fluid, heating the fluid like a huge magnifying glass might. The hot fluid runs through a heat exchanger, producing steam that turns a turbine.

For energy storage, the pipes run into a large, insulated tank filled with molten salt, which retains heat efficiently. Heat is extracted at night, creating steam. The molten salt does slowly cool, however, so the energy stored must be tapped within a day.

Nine concentrated solar power plants with a total capacity of 354 megawatts (MW) have been generating electricity reliably for years in the U.S. A new 64-MW plant in Nevada came online in March 2007. These plants, however, do not have heat storage. The first commercial installation to incorporate it—a 50-MW plant with seven hours of molten salt storage—is being constructed in Spain, and others are being designed around the world. For our plan, 16 hours of storage would be needed so that electricity could be generated 24 hours a day.

Existing plants prove that concentrated solar power is practical, but costs must decrease. Economies of scale and continued research would help. In 2006 a report by the Solar Task Force of the Western Governors' Association concluded that concentrated solar power could provide electricity at 10 cents per kWh or less by 2015 if 4 GW of plants were constructed. Finding ways to boost the temperature of heat exchanger fluids would raise operating efficiency, too. Engineers are also investigating how to use molten salt itself as the heat-transfer fluid, reducing heat losses as well as capital costs. Salt is corrosive, however, so more resilient piping systems are needed.

Concentrated solar power and photovoltaics represent two different technology paths. Neither is fully developed, so our plan brings them both to large-scale deployment by 2020, giving them time to mature. Various combinations of solar technologies might also evolve to meet demand economically. As installations expand, engineers and accountants can evaluate the pros and cons, and investors may decide to support one technology more than another.

Direct Current, Too

The geography of solar power is obviously different from the nation's current supply scheme. Today coal, oil, natural gas and nuclear power plants dot the landscape, built relatively close to where power is needed. Most of the country's solar generation would stand in the Southwest. The existing system of alternating-current (AC) power lines is not robust enough to carry power from these centers to consumers everywhere and would lose too much energy over long hauls. A new high-voltage, direct-current (HVDC) power transmission backbone would have to be built.

Studies by Oak Ridge National Laboratory indicate that long-distance HVDC lines lose far less energy than AC lines do over equivalent spans. The backbone would radiate from the Southwest toward the nation's borders. The lines would terminate at converter stations where the power would be switched to AC and sent along existing regional transmission lines that supply customers.

The AC system is also simply out of capacity, leading to noted shortages in California and other regions; DC lines are cheaper to build and require less land area than equivalent AC lines. About 500 miles of HVDC lines operate in the U.S. today and have proved reliable and efficient. No major technical advances seem to be needed, but more experience would help refine operations. The Southwest Power Pool of Texas is designing an integrated system of DC and AC transmission to enable development of 10 GW of wind power in western Texas. And TransCanada, Inc., is proposing 2,200 miles of HVDC lines to carry wind energy from Montana and Wyoming south to Las Vegas and beyond.

Stage One: Present to 2020

We have given considerable thought to how the solar grand plan can be deployed. We foresee two distinct stages. The first, from now until 2020, must make solar competitive at the mass-production level. This stage will require the government to guarantee 30-year loans, agree to purchase power and provide price-support subsidies. The annual aid package would rise steadily from 2011 to 2020. At that time, the solar technologies would compete on their own merits. The cumulative subsidy would total $420 billion (we will explain later how to pay this bill).

About 84 GW of photovoltaics and concentrated solar power plants would be built by 2020. In parallel, the DC transmission system would be laid. It would expand via existing rights-of-way along interstate highway corridors, minimizing land-acquisition and regulatory hurdles. This backbone would reach major markets in Phoenix, Las Vegas, Los Angeles and San Diego to the west and San Antonio, Dallas, Houston, New Orleans, Birmingham, Ala., Tampa, Fla., and Atlanta to the east.

Building 1.5 GW of photovoltaics and 1.5 GW of concentrated solar power annually in the first five years would stimulate many manufacturers to scale up. In the next five years, annual construction would rise to 5 GW apiece, helping firms optimize production lines. As a result, solar electricity would fall toward six cents per kWh. This implementation schedule is realistic; more than 5 GW of nuclear power plants were built in the U.S. each year from 1972 to 1987. What is more, solar systems can be manufactured and installed at much faster rates than conventional power plants because of their straightforward design and relative lack of environmental and safety complications.

Stage Two: 2020 to 2050

It is paramount that major market incentives remain in effect through 2020, to set the stage for self-sustained growth thereafter. In extending our model to 2050, we have been conservative. We do not include any technological or cost improvements beyond 2020. We also assume that energy demand will grow nationally by 1 percent a year. In this scenario, by 2050 solar power plants will supply 69 percent of U.S. electricity and 35 percent of total U.S. energy. This quantity includes enough to supply all the electricity consumed by 344 million plug-in hybrid vehicles, which would displace their gasoline counterparts, key to reducing dependence on foreign oil and to mitigating greenhouse gas emissions. Some three million new domestic jobs—notably in manufacturing solar components—would be created, which is several times the number of U.S. jobs that would be lost in the then dwindling fossil-fuel industries.

The huge reduction in imported oil would lower trade balance payments by $300 billion a year, assuming a crude oil price of $60 a barrel (average prices were higher in 2007). Once solar power plants are installed, they must be maintained and repaired, but the price of sunlight is forever free, duplicating those fuel savings year after year. Moreover, the solar investment would enhance national energy security, reduce financial burdens on the military, and greatly decrease the societal costs of pollution and global warming, from human health problems to the ruining of coastlines and farmlands.

Ironically, the solar grand plan would lower energy consumption. Even with 1 percent annual growth in demand, the 100 quadrillion Btu consumed in 2006 would fall to 93 quadrillion Btu by 2050. This unusual offset arises because a good deal of energy is consumed to extract and process fossil fuels, and more is wasted in burning them and controlling their emissions.

To meet the 2050 projection, 46,000 square miles of land would be needed for photovoltaic and concentrated solar power installations. That area is large, and yet it covers just 19 percent of the suitable Southwest land. Most of that land is barren; there is no competing use value. And the land will not be polluted. We have assumed that only 10 percent of the solar capacity in 2050 will come from distributed photovoltaic installations—those on rooftops or commercial lots throughout the country. But as prices drop, these applications could play a bigger role.

2050 and Beyond
Although it is not possible to project with any exactitude 50 or more years into the future, as an exercise to demonstrate the full potential of solar energy we constructed a scenario for 2100. By that time, based on our plan, total energy demand (including transportation) is projected to be 140 quadrillion Btu, with seven times today's electric generating capacity.

To be conservative, again, we estimated how much solar plant capacity would be needed under the historical worst-case solar radiation conditions for the Southwest, which occurred during the winter of 1982–1983 and in 1992 and 1993 following the Mount Pinatubo eruption, according to National Solar Radiation Data Base records from 1961 to 2005. And again, we did not assume any further technological and cost improvements beyond 2020, even though it is nearly certain that in 80 years ongoing research would improve solar efficiency, cost and storage.

Under these assumptions, U.S. energy demand could be fulfilled with the following capacities: 2.9 terawatts (TW) of photovoltaic power going directly to the grid and another 7.5 TW dedicated to compressed-air storage; 2.3 TW of concentrated solar power plants; and 1.3 TW of distributed photovoltaic installations. Supply would be rounded out with 1 TW of wind farms, 0.2 TW of geothermal power plants and 0.25 TW of biomass-based production for fuels. The model includes 0.5 TW of geothermal heat pumps for direct building heating and cooling. The solar systems would require 165,000 square miles of land, still less than the suitable available area in the Southwest.

In 2100 this renewable portfolio could generate 100 percent of all U.S. electricity and more than 90 percent of total U.S. energy. In the spring and summer, the solar infrastructure would produce enough hydrogen to meet more than 90 percent of all transportation fuel demand and would replace the small natural gas supply used to aid compressed-air turbines. Adding 48 billion gallons of biofuel would cover the rest of transportation energy. Energy-related carbon dioxide emissions would be reduced 92 percent below 2005 levels.

Who Pays?
Our model is not an austerity plan, because it includes a 1 percent annual increase in demand, which would sustain lifestyles similar to those today with expected efficiency improvements in energy generation and use. Perhaps the biggest question is how to pay for a $420-billion overhaul of the nation's energy infrastructure. One of the most common ideas is a carbon tax. The International Energy Agency suggests that a carbon tax of $40 to $90 per ton of coal will be required to induce electricity generators to adopt carbon capture and storage systems to reduce carbon dioxide emissions. This tax is equivalent to raising the price of electricity by one to two cents per kWh. But our plan is less expensive. The $420 billion could be generated with a carbon tax of 0.5 cent per kWh. Given that electricity today generally sells for six to 10 cents per kWh, adding 0.5 cent per kWh seems reasonable.

Congress could establish the financial incentives by adopting a national renewable energy plan. Consider the U.S. Farm Price Support program, which has been justified in terms of national security. A solar price support program would secure the nation's energy future, vital to the country's long-term health. Subsidies would be gradually deployed from 2011 to 2020. With a standard 30-year payoff interval, the subsidies would end from 2041 to 2050. The HVDC transmission companies would not have to be subsidized, because they would finance construction of lines and converter stations just as they now finance AC lines, earning revenues by delivering electricity.

Although $420 billion is substantial, the annual expense would be less than the current U.S. Farm Price Support program. It is also less than the tax subsidies that have been levied to build the country's high-speed telecommunications infrastructure over the past 35 years. And it frees the U.S. from policy and budget issues driven by international energy conflicts.

Without subsidies, the solar grand plan is impossible. Other countries have reached similar conclusions: Japan is already building a large, subsidized solar infrastructure, and Germany has embarked on a nationwide program. Although the investment is high, it is important to remember that the energy source, sunlight, is free. There are no annual fuel or pollution-control costs like those for coal, oil or nuclear power, and only a slight cost for natural gas in compressed-air systems, although hydrogen or biofuels could displace that, too. When fuel savings are factored in, the cost of solar would be a bargain in coming decades. But we cannot wait until then to begin scaling up.

Critics have raised other concerns, such as whether material constraints could stifle large-scale installation. With rapid deployment, temporary shortages are possible. But several types of cells exist that use different material combinations. Better processing and recycling are also reducing the amount of materials that cells require. And in the long term, old solar cells can largely be recycled into new solar cells, changing our energy supply picture from depletable fuels to recyclable materials.

The greatest obstacle to implementing a renewable U.S. energy system is not technology or money, however. It is the lack of public awareness that solar power is a practical alternative—and one that can fuel transportation as well. Forward-looking thinkers should try to inspire U.S. citizens, and their political and scientific leaders, about solar power's incredible potential. Once Americans realize that potential, we believe the desire for energy self-sufficiency and the need to reduce carbon dioxide emissions will prompt them to adopt a national solar plan.