

# Sunpower<sup>i</sup>

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In 1952 the Truman administration issued *Resources for Freedom*,<sup>ii</sup> an assessment of America's fuel and material needs. Noting that "efforts made to date to harness solar energy [have been] infinitesimal," the report found that an aggressive solar program "could make an immense contribution to the welfare of the free world." *Resources for Freedom* urged that the United States build 13 million solar-heated homes by the mid-1970s.

In 1980 the Carter administration produced *A New Prosperity*,<sup>iii</sup> a collaborative effort by several national laboratories and leading universities. In elaborate detail, this volume described technologies and policies that would dramatically increase America's overall energy efficiency and permit the nation to obtain 28 percent of its total energy needs from renewable sources by 2000.

Over the past half-century, dozens of such reports by disinterested experts have described the potential of solar technologies to meet a large fraction of the nation's, and the world's, energy needs within a relatively short time frame.<sup>iv</sup> None of their goals—often mistakenly characterized as forecasts or predictions—have been realized.

Fifty years after the issuance of *Resources for Freedom*, efforts to harness solar energy remain insignificant in terms of global energy markets. Thus a skeptic might reasonably ask: If solar energy is so attractive and sensible, why has it always been ignored? Were all those reports just plain wrong?

Actually, most of the enthusiastic reports and studies were right on the money.<sup>v</sup> The efficiency and reliability of solar energy technology improved as projected. Prices fell sharply, as expected, as production levels climbed and began to achieve efficiencies of mass production. Hydrogen and fuel cells have emerged as an attractive solution to the problem of storing sunlight for times (night, for example) when the sun isn't shining or for applications (powering an automobile, for example) for which incident sunlight is inappropriate. The resource base is enormous, and at least in comparison with other energy sources, sunlight is rather equitably distributed around the world.

In a nutshell, the problems have been rooted in: (1) bad politics; (2) bad pricing; (3) the Japanese economic downturn; (4) applied technology's "valley of death"; and (5) the failure of solar advocates to capitalize on their strongest asset—nearly universal public support.

## **Direct from the Sun to Everyone**

Our sun is one of a family of stars that astronomers call yellow dwarfs. Powering it are several kinds of fusion reactions that "burn" 11 billion pounds of hydrogen a second.

This fusion has been continuing reliably for the past 4 or 5 billion years<sup>vi</sup> and is expected to continue for another 4 or 5 billion.<sup>vii</sup>

The earth's surface receives, on average, 160 watts per square meter of energy from the sun. Human energy use equals about one ten-thousandth of the solar influx. No country uses as much energy as is contained in the sunlight that strikes its buildings. The sunlight that fell on roads in the United States last year contained roughly as much energy as in all the fossil fuel consumed last year in the world.

The awesome flow of sunlight to the earth powers the hydrological cycle and creates the wind and the weather. Sunlight provides the foundation of the biosphere; green plants bottle up sunlight in energy-rich bonds, using hydrogen from water and carbon extracted from carbon dioxide. That bottled-up energy is the currency of all life.<sup>viii</sup>

Photovoltaic cells, commonly called solar cells, are an extremely attractive energy option.<sup>ix</sup> Inherently modular, they gain no important advantages (other than ease of maintenance) from being clustered in large concentrations. Easily integrated into roofs, walls, and windows, they have no moving parts to break. Solar cells produce no acid rain, no greenhouse gases, no radioactive waste, no bomb-grade materials. They simply lie there and produce electricity when the sun shines, the amount of electricity varying with the duration and intensity of the sunlight.<sup>x</sup>

Solar electricity can be used on-site, stored in a battery, fed into an electrical grid, or used to split water into hydrogen and oxygen. In recent years, solar-hydrogen strategies have attracted increasing attention because hydrogen can easily be stored and transported, and it offers the promise of abundant, convenient power in a world otherwise constrained by threats of climate change.<sup>xi</sup> Hydrogen fuel cells generate electricity at very high conversion efficiencies and emit zero pollution.<sup>xii</sup>

Whereas many nations have no oil, coal, natural gas, or uranium, all nations have at least some sunshine, and most have quite a bit. Hence, low-cost solar energy could be a powerful force for abating global tensions and reducing balance-of-trade deficits. Moreover, some nations with intense year-round insolation (solar radiation) are sparsely populated. Those areas, including deserts in North Africa, the Middle East, and the American Southwest, could become net solar-hydrogen producers, exporting clean fuel to regions less richly blessed with sunshine.

That, in any event, has long been the idea.<sup>xiii</sup> However,

Between the idea  
And the reality  
Between the motion  
And the act  
Falls the shadow<sup>xiv</sup>

The shadow, in this case, has been a national political culture that, from Teapot Dome to the Price-Anderson Act, from “depletion allowances” for the world’s wealthiest industry to exemptions from air pollution regulations for old coal power plants, has consistently fed the fat cats and stacked the deck against solar energy.

### **The Politics of Energy**

Dwight Eisenhower, elected president in 1952 not long after the issuance of *Resources for Freedom*, ignored Truman’s solar proposal in favor of his own massive “Atoms for Peace” initiative. Throughout the Eisenhower years, only a fraction of 1 percent of federal energy research funding went to renewable energy sources.

Ronald Reagan, elected president in 1980, before *A New Prosperity* was issued, actually tried to suppress the Carter administration’s comprehensive, optimistic report. (Representative Richard Ottinger thwarted this censorship by publishing the entire report in the Congressional Record.) In its first few months, the Reagan administration fired most of the staff of the federal Solar Energy Research Institute, slashed funding for renewable energy R& D, and eliminated all programs to commercialize the fruits of past federal solar research. And, just to rub salt in the wounds, Reagan removed the solar panels from the roof of the White House.

The politics surrounding energy are arguably the highest-stake politics in America, and the players are among the richest and most powerful segments of the economy. In 1997, the world consumed 5.2 billion tons of coal, 26.4 billion barrels of oil, and 81.7 trillion cubic feet of natural gas. Twenty giant companies marketed about half of all this fuel. When their common interests are threatened, these companies can coalesce into an essentially unstoppable, global force. What they have in common is a desire to see the market for fossil fuels grow every year into the indefinite future.<sup>xv</sup>

Energy transitions are never easy. Those prospering in the status quo will always oppose any change that will cause them to lose an advantage. New technologies generally require either a stealth strategy or a powerful sponsor.

In the late 19th century, the infant oil industry sneaked up on the coal industry by making kerosene—a product that competed not with coal but with a whale oil, a product already in eclipse.<sup>xvi</sup> By the time the automobile industry provided a market for gasoline, the oil industry had grown strong enough to consolidate and expand.

Natural gas fell under the protective wing of the oil industry (most gas was initially a byproduct of oil production) until gas had developed a gigantic market of its own.

The nuclear industry was developed under contract to the military to propel submarines long distances with little sound. Commercial reactors were basically bigger versions of the naval reactors, and (with strong lobbying by General Electric, Westinghouse, the utility industry, and the U.S. Navy) have been extremely generously subsidized over the past half-century.

By comparison, solar, wind, biomass, geothermal power, and (until very recently) hydrogen fuel cells have always been cottage industries. Lacking powerful sponsors, they have never had the political muscle to advance and defend their long-term interests inside the Beltway.<sup>xvii</sup>

### **Pricing**

The price of energy is largely determined by public and private policies, here and abroad. The price of oil, for example, reflects the cost of finding it, pumping it, transporting it, storing it, marketing it—but does not begin to reflect *all* the costs associated with this fuel. American taxpayers maintain a permanent fleet in the Persian Gulf purely to police the oil lanes, but the cost of this fleet is not reflected in taxpayers' gasoline bills. Ancient coal-fired power plants, grandfathered under the Clean Air Act of 1970, continue to spew out pollutants that cause acid rain, harm human health, and contribute to global climate change. Even power plants equipped with new pollution-control technologies cause external damage that, if internalized, could double the price of power.<sup>xviii</sup> For older power plants without pollution controls, the costs of environmental damage can be vastly higher. None of these costs are reflected in the price of electricity from coal.

Sunlight (unlike fossil fuels) is a flow, not a stock. The world will have exactly the same amount of sunlight tomorrow, regardless of how much we harness today. But every barrel of oil we burn today is a barrel that will not be available for our children and grandchildren. Economists agree that this future interest should be represented, as a “futures rent,” in the price of any depleting resource, but it is not. Indeed, for most of the modern era the U.S. oil industry has been awarded just the opposite, an oil-depletion allowance!<sup>xix</sup>

Nuclear power has been subsidized by a government that underwrote all its R&D and that has assumed responsibility for safeguarding nuclear waste for eternity. The price does not encompass the enormous costs associated with an effective global institution that would actually stop the proliferation of nuclear weapons. In this era of mounting terrorism, perhaps the most telling nuclear distortion is that provided by the federal Price-Anderson Act, which places a ceiling on the potential liability of nuclear power plant owners for the astronomical damage that accidents or sabotage could cause. If the owners were forced to insure themselves, like those in every other industry, to cover a worst-case accident, the nuclear industry would disappear in a heartbeat.

### **The Japanese Economic Collapse**

The hope of many solar advocates has long been that Japan would begin the mass production of solar cells, driving down the cost and launching an era of accelerating growth. Japan's oil and nuclear industries do not have the iron grip on politics that those industries have in the United States, and Japan's giant, innovative electronics industry has had a long-term interest in photovoltaics. Moreover, Japanese firms have successful

marketing and service operations in regions of the Third World with no electrical grids, regions that hold particular promise for decentralized solar development.

## Top Global PV Producers, 2000

Company	Country	MW
Sharp	Japan	50.4
Kyocera	Japan	42.0
BP Solar	UK	41.9
Siemens Solar	Germany	28.0
Astropower	US	18.0
Sanyo	Japan	17.0
Photowatt	France	14.0
ASE GmbH	Germany	14.0
Mitsubishi	Japan	12.0
<b>Total</b>		<b>235.3</b>

Source: Paul Maycock, PV Energy Systems Inc.

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Much as Japanese innovation in automobile fuel efficiency and pollution control has egged on Detroit to greater progress in these areas, so might a serious push by the Japanese on solar cells inspire a major American response. However, the deep economic recession that has gripped Japan for the past 10 years has caused its companies to dramatically scale back or shelve such plans.

Japan is nevertheless the world's largest producer of solar cells, and its output is increasing faster than any other country's. The 128 megawatts it delivered in 2000 is nearly as much as the United States (75 MW) and the European Union (61 MW) combined. The Japanese solar electric industry grew 63 percent in 1999 and an additional 60 percent in 2000. But total production in Japan still remains too small to achieve the needed efficiencies of scale for a solar revolution—it would be too small even if it were all consolidated into one factory! Most studies agree that getting prices down by another factor of 4 with existing technologies will require a major manufacturing facility capable of producing enough panels each year to generate 250 to 500 megawatts.<sup>xx</sup>

### World Production of PV Systems

	Peak Megawatts									
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Japan	19.9	18.8	16.7	16.5	16.4	21.2	35.0	49.0	80.0	128.6
US	17.1	18.1	22.4	25.6	34.7	38.8	51.0	53.7	60.8	74.9
Europe	13.4	16.4	16.5	21.7	20.1	18.8	30.4	33.5	40.0	60.7
Others	5.0	4.6	4.4	5.6	6.3	9.7	9.4	18.7	20.5	23.4
Total	55.4	57.9	60.1	69.4	77.6	88.6	125.8	154.9	201.3	287.6

Source: Paul Maycock, PV Energy Systems Inc.

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### **The Valley of Death**

R&D is conventionally divided into three categories: basic research, applied research, and product development. Liberals and conservatives are in wide agreement that the federal government (through the National Science Foundation, the National Institutes of Health, the Department of Energy, the National Oceanographic and Atmospheric Administration, and other agencies) plays an important, legitimate role in basic research in all the scientific disciplines. Similarly, there is wide ideological agreement that private enterprise does a better job of assessing consumer tastes and designing commercial products.

However, the middle step, applied research, is the scene of endless battles between left and right. A 1998 House Science Committee report described the “widening and deepening . . . valley of death” between federally funded long-range basic research and industry-funded near-term product development.<sup>xxi</sup> Large corporate R&D units—such as Bell Labs, Sarnoff, Xerox PARC, and the IBM Watson Center—are in eclipse as a result of changes in their sponsoring companies and in the nature of the marketplace.

The Defense Advanced Research Projects Agency (DARPA) has done a generally excellent job supporting applied research for the armed forces. Liberals tend to think the government should play a similar bridging role for civilian technologies, whereas conservatives strongly oppose such “tinkering” with the market.

Buttressing the conservatives is the fact that government funding is often politicized and that applied research has sometimes been spent on corporate welfare, pork, and monuments to political vanity. Liberals reply that it makes no sense to push back the frontiers of knowledge with taxpayer dollars only to let breakthroughs gather dust on the shelf while other countries race past us exploiting our scientific discoveries.

When the Clinton administration took office, it promptly tripled the budget of the Advanced Technology Program (ATP) of the Department of Commerce, with plans to

build it into a civilian DARPA. In 1995, when Republicans captured both houses of Congress, they targeted ATP for complete elimination. The ensuing stalemate left the program in limbo for six years. The Bush administration now seeks again to eliminate it.

The federal government has a long history of supporting applied-research projects that later transform society. In 1798, the government contracted with Eli Whitney to produce interchangeable musket parts, thereby establishing the foundation for the machine tool industry. A few decades later, Congress appropriated funds to demonstrate the feasibility of Samuel Morse's telegraph. The government also played a key role in making possible transistors and computers, hybrid seeds, countless drugs, and the jet engine.

The federal government spent 25 years developing Arpanet, precursor to the Internet, for defense research purposes. Such a lengthy gestation of a system with no obvious market could never have taken place under purely private sponsorship, particularly today.

Perhaps the best analogy to the role the government could play for solar cells is the role that it played in commercializing integrated circuits. In 1961, Texas Instruments began producing integrated circuits for small, specialized applications. The earliest versions were very expensive: They cost \$100 but replaced just a couple dollars' worth of larger electronics, perhaps two transistors and three resistors. There was essentially no market for such devices in the private sector. Other electronics companies sneered at them.

But the American military recognized the potential importance of small, lightweight, low-power integrated circuits. The Department of Defense began to purchase integrated circuits in large quantities. Following a predictable "learning curve" (see the accompanying article by Robert Williams), the price fell dramatically. As the price fell, numerous private market niches opened up.

### **Sales of Integrated Circuits**

Year	Unit Price	Military Percentage
1962	\$50.00	100%
1963	\$31.60	94%
1964	\$18.50	85%
1965	\$ 8.33	72%
1966	\$ 5.05	53%
1967	\$ 3.32	43%
1968	\$ 2.33	37%

In just six years, the price of integrated circuits plummeted 95 percent and an enormous commercial market developed.

In 1971, Intel introduced the first central processing unit (CPU). The early CPUs were not immediately transformational. They were too simple to power anything beyond a calculator. However, those calculators rapidly got more and more sophisticated. By the

mid-1970s, microprocessors were performing computations for devices we can recognize as small computers. The processing power of CPUs has continued to double every eighteen months (as famously predicted by the chairman of Intel, Gordon Moore), a doubling accompanied by falling costs; this led directly to the information revolution.

Integrated circuits are now dirt cheap and CPUs are ubiquitous in our homes, cars, and workplaces. But if the government had not purchased huge quantities of chips before they were cheap enough for commercial applications, the technology might never have become cost-effective. The information revolution would have been delayed, perhaps indefinitely.

To date, no solar “Intel” or “Texas Instruments” has emerged.

Existing energy-savvy enterprises that might be expected to pioneer the next generation of energy technologies—ExxonMobil, Texaco, Shell, BP, General Electric—have gigantic investments tied to the existing energy infrastructure. As competitors on the global economic stage, they want to recover their costs and maximize their profits from their existing commitments. Even the few companies that have expressed a strong interest in solar technologies, notably Shell and BP, anticipate a transition that will require *at least* 50 years. A “solar Intel” that began eating their lunch would change those attitudes overnight.

To greater and lesser degrees, the energy industry is behaving in the classic pattern of a mainstream business confronting a potentially “disruptive technology.”<sup>xxii</sup> Manufacturers of carbon paper did not make the transition into xerography. Manufacturers of quill pens did not make ballpoint pens; ballpoint pen manufacturers in turn did not make typewriters; typewriter manufacturers failed to switch to personal computers.

Substantial funding will be necessary to carry solar electric and hydrogen technologies through the valley of death. If the source of support is not to be the federal government, society needs to find another one. At various times, transient hopes have been placed in federally funded but regionally controlled solar commercialization offices, in the utility-sponsored Electric Power Research Institute, and in state efforts (the Florida Solar Energy Center and a variety of short-lived California institutions, for example). To date, none has managed to assemble even a small fraction of the necessary resources. It may, in fact, be necessary for several states to pool resources—always a difficult task for states—if they are to achieve critical mass. Nevertheless, state initiatives in places like California, Texas, Florida, Arizona, and Minnesota are beginning to display creativity and vitality that have been missing from Washington, D.C., for more than 20 years.

### **Public Support**

In a much quoted line, Abraham Lincoln once said, “Public sentiment is everything. With public sentiment, nothing can fail; without it, nothing can succeed.” But Lincoln lived in a different era.

For the last several decades, the American public has proclaimed clearly, consistently, and by overwhelming margins, that it favors solar energy above all other sources. Once again, in a November 2001 Gallup Poll, 90 percent of the respondents supported investments in solar, wind, and fuel cells, and expressed grave misgivings about deepening America's dependence on fossil fuels. In the highly contentious field of energy policy, the steadfast public enthusiasm enjoyed by solar energy—unlike the attitudes toward oil, coal, and nuclear power—is remarkable. Considering that solar energy has remained the neglected stepchild of national energy policy, this widespread, enduring public loyalty is a powerful testament to its attractiveness.

The reason for such popularity is not hard to plumb. Energy analysts tend to view energy sources as interchangeable, with the only important variable being price. However, they are *not* neutral and interchangeable. Some contribute to global climate change; solar energy is carbon neutral. Some are necessarily centralized; solar electricity and fuel cells lend themselves to distributed applications. Some are exceedingly vulnerable to terrorists or natural disasters; solar-hydrogen options are inherently resilient. Some will exacerbate the gap between the world's rich and poor; solar will narrow it. Some produce large volumes of pollution; solar and hydrogen produce none. Some inherently dangerous sources can be safely permitted to grow unchecked only under very authoritarian regimes; solar energy is not one of them. In the long run, such considerations may well prove far more important than the cent-per-kilowatt-hour differences that currently dominate and limit thinking about energy.

With the world's most prestigious scientific bodies expressing public alarm over climate change; with tensions mounting over America's dependence on Middle Eastern oil; and with concern rising over the nation's imbalance of payments for petroleum imports in this period of economic weakness, it is surprising that no leader has emerged to channel this vast public support into a powerful solar constituency.

For less than the cost of waging the war in Afghanistan for three months, the United States government could launch a solar revolution. However, this has been true for at least 20 years, through Republican and Democratic administrations—and no such revolution has taken place.

Given the distribution of money and power in America today—and in the absence of fundamental campaign finance reform—a bold federal solar initiative may simply not be possible under ordinary conditions. The most promising opportunity might be in the heat of some future energy crisis, when a populist outpouring might be briefly powerful enough to trump any interest group. Until there is such a crisis, we must advance down the field with smaller steps. In football terms, we should grind out yardage however we can, while remaining prepared to toss the long ball when the opportunity presents itself.

In the search for cheap, clever, easy innovations that will help solar cells steadily acquire an increasing market share, it is hard to improve upon Robert William's astute observations and smart suggestions in the accompanying article.

- Thirty states have now adopted net metering, allowing solar owners to sell surplus electricity to the utility when the sun is shining—effectively “running their meters backward.” All states should pass such laws.
- All renewable portfolio standards should include a special *tranche* allocated exclusively to photovoltaics. Otherwise, the portfolio standard will award all its benefits to one or two technologies that just happen to be further along their learning curves.
- The Global Environment Facility should ensure that solar cells are the technology of choice for many international energy projects, especially in places without existing transmission grids.
- Green-power marketers should offer a specific *solar* option so that customers who are willing to pay a premium have an opportunity to assure that their utility bills are helping to underwrite new solar electricity-generating capacity.

These and other nurturing public policies can, together, assure a 20 to 30 percent annual growth rate in installed solar electricity capacity.

At some point, as demand grows, a major company will build a solar factory of sufficient scale to produce dramatically lower manufacturing costs. Sometime later, a second, competitive firm will build a similar facility, and then perhaps a third.

Until supply dramatically exceeds demand, prices will likely remain “sticky”—high enough to assure adequate returns to old plants and very large profits to the more recent facilities. But at some point, inventory will accumulate to the point where a manufacturer will decide to drop its prices in order to grow its market share, and the dam will burst. Ultimately, prices will fall to the marginal cost of the most productive facility. New entrants will be spurred to find ways to drive their costs still lower, producing the sort of accelerating innovation that is commonplace in the electronics industry but almost unheard of in the energy field. In the ordinary course of things, this will likely happen sometime in 20 to 40 years.

This is the rational, cost-effective path of solar development. It would keep alive a wide variety of alternative materials and manufacturing processes until the winners emerge. It is the course (coupled with a strong federal procurement role) that I strongly advocated 25 years ago.

Today, however, I fear such incremental business-as-usual may simply not be fast enough to avert calamity.

Since 1975 we have had an additional quarter-century of CO<sub>2</sub> emissions accumulating in the earth’s atmosphere. The clear, persuasive evidence of climate change has silenced virtually all doubters. For another quarter-century we have been depleting the world’s petroleum reserves: burning complex hydrocarbons in low-mileage vehicles instead of

preserving them for far higher purposes centuries hence. The remaining oil supply is ever more concentrated in unstable hands.

We have spent the last quarter-century building a global industrial base designed to run on fuels that we soon must stop burning. We have spent that quarter-century constructing buildings and communities that are oriented neither to capture incident sunlight nor to escape the shadows of taller buildings to the south that block solar access.<sup>xxiii</sup>

In short, the world has spent the last quarter-century heading—at an accelerating rate—in the wrong direction.

We soon need to get serious about solar energy. Serious, in the sense that America got serious after Pearl Harbor—when we converted our industries into the arsenal of democracy, and simply produced as many ships and planes and tanks as it took to win the war. Serious, in the sense that America got serious after Sputnik, and engaged many of the finest scientific minds of a generation in a quest to explore the frontiers of space.

It is impossible to predict what event might so galvanize the body politic that America might get serious about solar energy. A spectacular terrorist act, such as blowing up an urban nuclear power plant or a liquefied natural gas (LNG) terminal, or simply sinking a couple of oil tankers to block the Strait of Hormuz, might serve. One can imagine dozens of events that could create a climate in which a popular solar initiative could become unstoppable. But no detailed solar mobilization plan—vetted for technical, legal, and environmental obstacles—currently exists.

Past opportunities for dramatic change have been squandered. Caught unprepared by energy emergencies, presidents have proposed costly, half-baked initiatives like Project Independence and the Synthetic Fuels Corporation—assembled overnight, and showing it. Proponents of solar energy have never had their act together when these crises hit.

A high-powered task force should be given the charter of mapping out a mobilization plan for what President Carter once called “the moral equivalent of war.” This plan could be swiftly executed when the next full-blown energy crisis hits.

The plan would include detailed engineering designs for several types of facilities capable of manufacturing photovoltaic modules at a price of less than \$1 per watt. The plan would involve an aggressive manufacturing strategy for hydrogen generators, pipelines, and fuel cells. It would address questions of site selection and permitting, infrastructure, resource availability, job training, and all the other myriad details involved if a multi-billion-dollar commitment is to succeed.

The plan would calculate how much everything would cost, and it would suggest how everything should be financed. It would include a strategy to assimilate these new industries as rapidly as possible into the civilian economy. The plan would have to be updated every year or two, as conditions change and technology advances. It is crucial that the plan be current and actionable.

Sooner or later, as everyone knows, another energy crisis will present us with another opportunity. Let's be ready to make the solar energy investments that can make energy crises a thing of the past.

### Endnotes

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<sup>i</sup> Humankind can, and doubtless will, turn to a variety of attractive energy sources in the near future. These include solar heating and architecture, wind, biomass, geothermal power, natural gas, and perhaps others. This article will focus on solar photovoltaic electricity and solar-hydrogen fuel-cell options, because direct sunlight offers the world's single largest untapped source of high-quality, sustainable, geographically dispersed, environmentally benign energy. Moreover, in the author's view, these quantum solar processes have suffered from the greatest single market failure in the energy sector, and they are most in need of the sort of boost that other energy sources have received during the past century.

<sup>ii</sup> President's Materials Commission, *Resources for Freedom*, Washington, D.C., June 1952.

<sup>iii</sup> Solar Energy Research Institute, *A New Prosperity*, Brick House Publishing, Andover, Mass., 1981.

<sup>iv</sup> For example, a superb survey of the field was prepared for the United Nations Conference on Environment and Development, held in June 1992 in Rio de Janeiro. The 1,100-plus page study concluded that, with proper policies in place, renewable sources could account for three-fifths of the world's electricity and two-fifths of the world's fuels by 2050 *at no additional cost*. See T. B. Johansson, H. Kelly, A. K. N. Reddy, and R. H. Williams, eds., *Renewable Energy: Sources for Fuels and Electricity*, Island Press, Washington, D.C., 1993.

<sup>v</sup> In *Winner, Loser, or Innocent Victim: Has Renewable Energy Performed As Expected?* (J. McVeigh, D. Burtraw, J. Darmstadter, and K. Palmer. Research Report No. 7, Resources for the Future, Washington, D.C., April 1999) four distinguished energy economists conclude that the costs of renewable energy technologies have fallen about as fast as early proponents predicted. "This is remarkable," they write, "given that renewable technologies have not significantly penetrated the market, nor . . . [achieved] economies of scale in production, as many analysts anticipated when forming their cost projections" (p. 5). The RFF team notes that during the first Bush administration federal spending on research, development, and demonstration for renewables was about one-tenth the spending for carbon fuels. And even those latter funds, of course, pale next to the tax loopholes, below-cost leases, military subsidies, and other government assistance given to keep the oil flowing. If renewable energy sources had enjoyed support comparable to the rich subsidies and other tangible benefits enjoyed by carbon fuels over the past two decades, the solar energy revolution now might be comparable in scope and impact to the information revolution. (*Winner, Loser, or Innocent Victim* is available on the Web at [www.repp.org](http://www.repp.org).)

<sup>vi</sup> Although the sun is reliable, it has myriad fluctuations, such as solar flares and coronal eruptions. The best studied of these changes is the regular variation in the number of sun spots and associated events, which rises from a minimum to a maximum and falls back again to a minimum about every 11 years. This pattern has been observed since the mid-1800s. Other variations take place over other intervals. Still, evidence from geology and paleontology, wrung through mathematical simulations of climate, suggests that the sun has been remarkably well behaved throughout the past 3 or 4 billion years.

<sup>vii</sup> Humans have been carefully studying the sun for only a few centuries, and for only a few decades with the tools of modern astrophysics. Thus it may seem an act of intellectual arrogance to predict developments billions of years in the future. But reasoning from the size of the sun, its hydrogen content and distribution, and the life cycles of other similarly sized stars, scientists are in near agreement about the order of magnitude of these time periods. In 4 to 5 billion years, the outer regions of the sun will expand into a type of star called a red giant, engulfing Mercury and Venus and frying Earth. Later, the sun will contract into a white dwarf about the size of Earth. Finally, when its last fusion reaction has taken place, the sun will cease

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emanating energy and become a black dwarf. Assuming that *Homo sapiens* (or, more likely, our evolutionary progeny) have found sufficient wisdom to design social and economic systems that permit them to survive, and even flourish, at that distant time, we will hopefully have long since found another friendly sun with a habitable planet somewhere among the stars. Meanwhile, the sun can likely meet most of our energy needs for billions of years.

<sup>viii</sup> The processes by which heterotrophic organisms convert this stored sunlight to work are astonishingly intense. Energy output per unit of mass by respiring bacteria can reach up to 500 million times that of the sun itself. (Of course, only an infinitesimal portion of the sun's mass is fusing at any particular moment. Still, the comparison is arresting.) See V. Smil, *Energies: An Illustrated Guide to the Biosphere and Civilization*, MIT Press, Cambridge, Mass., 1999.

<sup>ix</sup> For a clear, non-technical history of this technology, see J. Perlin, *From Space to Earth: The Story of Solar Electricity*, AATEC Publications, Ann Arbor, Mich., 1999. For the more scientifically inclined nonspecialist, a good review of the current state of the art can be found in M. Green, "Photovoltaic physics and devices," in J. Gordon, ed., for the International Solar Energy Society, *Solar Energy: The State of the Art*, James & James, London, 2001. For those who are now ready to incorporate this technology into their own homes, the essential book remains S. J. Strong, *The Solar Electric House: Energy for the Environmentally-Responsible, Energy-Independent Home*, Chelsea Green Publishing, White River Junction, Vt., 1993.

<sup>x</sup> When sunlight hits a substance, it is absorbed. The incoming photons transfer their energy to electrons in the atoms of the sunlit material. As long as an electron remains excited by this extra energy, a pair of electrical charges—one negative and one positive—exist. The negative charge is the electron itself, and the positive charge is the place, or "hole," where the electron used to be. In semiconductors, electrons remain excited for about one-millionth of a second. (In metals, the pairs endure for only a trillionth of a second.) If nothing is done with the excited electrons, they return to their ground state and release the energy, simply warming the host material. However, if we separate the positive and negative charges and collect them, we generate electricity. Many different materials can be used to create solar cells. Most commercial cells are still made of silicon, doped with phosphorus and boron to form positive-negative junctions, although much effort also has gone into cells made of gallium arsenide, cadmium telluride, cadmium sulfide–copper sulfide, etc. Much of the research to date has been in efforts to increase the efficiency and durability in such materials while driving down the cost.

<sup>xi</sup> The holy grail of the solar-hydrogen economy is a photoelectrochemical process that would efficiently split water directly. Although support for this research has been trivial and erratic, much progress has been made in boosting efficiencies and reducing costs.

<sup>xii</sup> The first serious suggestion (that I am aware of) to power a whole nation using fuel cells running on hydrogen from renewable energy sources was made in a 1923 lecture at Cambridge University by the distinguished British scientist J. B. S. Haldane. Perhaps the most striking recent fuel-cell vision, notable in part for its unlikely source, is a January 7, 2002, press release by General Motors for its "AUTOmomy" fuel-cell-powered concept car, which (like a Boeing 777) would be controlled electronically rather than mechanically. "AUTOmomy is not simply a new chapter in automotive history. It is volume two, with the first hundred years of the automobile being volume one. The 20th century was the century of the internal combustion engine. The 21st century will be the century of the fuel cell. . . . With a hydrogen economy, we have a major opportunity for sustainable economic development, which respects the environment and creates the path to non-petroleum and renewable energy sources." GM envisions the vehicle serving as a clean, quiet back-up power source for the driver's home.

<sup>xiii</sup> D. Hayes, *Rays of Hope: The Transition to the Post-Petroleum World*, W. W. Norton, New York, 1977.

<sup>xiv</sup> T. S. Eliot, "The Hollow Men," *Collected Poems 1909–1935*, Harcourt, Brace and Company, New York, 1936).

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<sup>xv</sup> D. Yergin. *The Prize: The Epic Quest for Oil, Money, and Power*, Simon and Schuster, New York, 1991.

<sup>xvi</sup> Today, the largest market for kerosene is for jet fuel. In a sense, a part of the solar photovoltaic market grew in a kerosene-like stealth mode. The Japanese first produced amorphous silicon photovoltaics for “solar watches” and “solar calculators,” where they competed against small batteries—probably the most expensive form of commercial energy.

<sup>xvii</sup> For a brief moment in the Carter administration, following the price shocks that accompanied the Iran-Iraq war, a wave of public demand led to a serious federal R&D effort in renewable energy as well as the creation of four regional commercialization centers and several tax benefits for renewable resources. After four years of extraordinary progress, which stimulated corresponding efforts in several other countries, the Reagan administration abruptly dismantled the whole enterprise, claiming that it was inappropriate for government to “tinker” with the energy marketplace.

<sup>xviii</sup> A. Rabl and J. V. Spadaro, “The cost of pollution and the benefit of solar energy,” in Jeffrey Gordon, ed., for the International Solar Energy Society, *Solar Energy: The State of the Art*, James & James, London, 2001).

<sup>xix</sup> The oil industry won decades of enormous, mysterious tax breaks by focusing legions of lobbyists on the arcane rituals of the House Ways and Means Committee and the Senate Finance Committee. (Can anyone who doesn’t work on K Street explain the rationale for intangible drilling cost write-offs?)

<sup>xx</sup> T.M. Bruton et al., “Multi-Megawatt Upscaling of Silicon and Thin-Film Solar Cell and Module Manufacturing - MUSIC FM,” Eur. Conf. Renewable Energy Development, Venice, Italy, 22-25 November 1995. ; KPMG Bureau voor Economische Argumentatie, *Solar Energy: From Perennial Promise to Competitive Alternative*, Project Number 2562, Hoofddorp, Netherlands, 1999.

<sup>xxi</sup> House Committee on Science, *Unlocking Our Future: Toward a New National Science Policy*, September 24, 1998 ([www.house.gov/science/science\\_policy\\_report.htm](http://www.house.gov/science/science_policy_report.htm))

<sup>xxii</sup> Disruptive technologies, by definition, bring to the market a different value proposition. Generally, disruptive technologies *underperform* established products in mainstream markets, but they have other features that a few new customers value. C. M. Christensen, *The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail*, Harvard Business School Press, Boston, 1997. Christensen argues persuasively that major firms, and even whole industries, are often undermined by disruptive technologies, not because of bad management, or in spite of good management, but because of good management! “Precisely *because* these firms listened to their customers, invested aggressively in new technologies that would provide their customers more and better products of the sort they wanted, and because they carefully studied market trends and systematically allocated investment capital to innovations that promised the best returns, they lost their positions of leadership” (p. xii)

<sup>xxiii</sup> Every state should have been regulating against this for the past 20 years, but none has. See G. B. Hayes, *Solar Access Law: Protecting Access to Sunlight for Solar Energy Systems*, Environmental Law Institute/Ballinger Publishing, Cambridge, Mass., 1979).