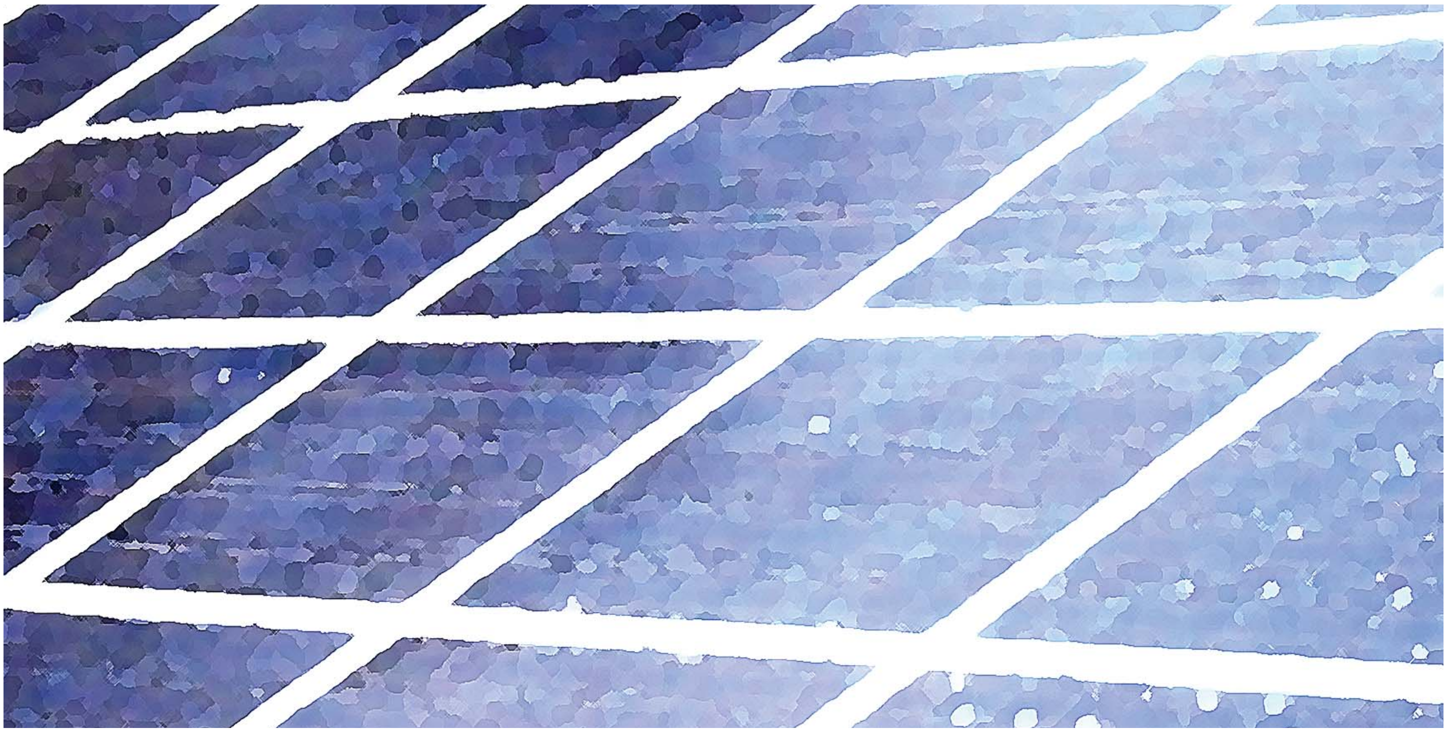
ELECTRIC POWER
RESEARCH INSTITUTE



An EPRI Technology Innovation White Paper

Solar Photovoltaics
Expanding Electric Generation Options

December 2007

Executive Summary

EPRI and others have demonstrated that a broad portfolio of cost-competitive supply technologies will be needed to satisfy the world's rising demands for energy while meeting climate policy and other societal objectives. Solar energy is a particularly attractive renewable energy option because it is well distributed and abundant over most of the earth's surface.

Photovoltaic (PV) conversion of solar energy directly to electricity is a proven power generation technology whose present-day application is constrained primarily by its relatively high first cost. Nonetheless, remote, off-grid PV installations have been economical for more than 20 years, and grid-connected PV deployment is growing extremely fast—most rapidly on the rooftops of residential and commercial buildings served by conventional electricity infrastructure, but larger-scale applications, in the form of ground-mounted PV plants feeding power directly to the grid, are also increasing modestly. At the end of 2006, installed PV capacity since 1991 totaled more than 7 GW (7,000 megawatts) worldwide. By 2011, annual PV deployment is projected to be about 8 GW—with 90% targeted for grid-connected applications—and global installed capacity at that time is expected to be about 33 GW.

PV cost has declined for decades in response to steady advances in conversion efficiency and manufacturing experience. Evolutionary progress with today's technologies will continue for some years to come, new technologies are expected, and revolutionary breakthroughs are anticipated. Political, social, economic, and technical drivers virtually guarantee continued worldwide growth in PV deployment. The remaining barriers are such that the question is no longer if PV will join today's mainstream energy technologies, but when.

The majority of PV applications over the next 10 years will continue to be in residential and commercial buildings as their desirability grows in consumers' eyes. Distribution utilities are first likely to be affected at the retail level: PV deployed on rooftops and integrated into building designs and other systems will drive changes in distributed supply technology, delivery infrastructure, and consumer behavior in the next decade.

At the wholesale level, PV plants on land dedicated for power production are projected to begin finding broad application after 2020, and they will likely compete with all other generation options before mid-century. However, between now and 2030, PV generation will not likely account for more than a few percent of total electricity needs.

Contents

This White Paper, prepared under the direction of Tom Key, was written by Brian Fies, Terry Peterson, and Chris Powicki, with graphic design by Elizabeth Hooper.

Successful integration of PV into the distribution grid will require modernization to enable the power control and communications functions needed for energy management and market access. At the transmission level, grid operations and markets will need to account for higher PV penetration. The pace of technology cost reductions and efficiency gains will largely define the timing of substantial PV deployment. Market entry generally will occur fastest in regions and countries with the best solar resources, the most favorable policy environments and largest incentives, and the highest electricity prices. In all areas, the remote grid and residential and commercial building applications are expected to be economic before central PV plants compete at the wholesale level. PV will play in more markets over time as public-private investments in research and development (R&D) and commercialization yield fruit.

Given the rates of PV technology advancement and deployment, the following intriguing scenarios—and the challenges and opportunities they imply—need to be considered in evaluating and planning for the future role of solar energy in the power industry:

- In 10 to 15 years at a retail level, building-integrated and other innovative PV deployment options erode markets served by conventional electricity infrastructure and precipitate novel consumer wants and needs that make new demands on the distribution system.
- By mid-century at a wholesale level, PV technologies compete with fossil, nuclear, and other renewable generation options by offering daytime energy independent of fuel price volatility and with low operations and maintenance costs.

The time to prepare for eventualities like these is now, as they offer the potential for major change, risk, and reward. For utilities and other participants in retail markets, new business models and technologies are needed to transform residential, commercial, and other distributed PV applications into grid assets. At the wholesale level, the biggest business opportunities may lie in planning for large-scale PV deployment and in supporting the development of future hardware and systems that enable successful grid integration.

Timely solutions to grid integration issues will work both to accelerate overall PV use and to greatly increase its specific value to the utility industry. Furthermore, the availability of cost-effective energy storage and/or advanced power electronics and control technology to address intermittency issues would not only simplify grid operation but also enable PV and several other renewable generation options to make greater contributions in addressing energy security, affordability, environmental protection, and climate change issues.

On behalf of the electricity enterprise, EPRI is committed to assessing PV developments and markets, testing and evaluating promising PV technologies, and communicating findings to enable informed and proactive responses by electric utilities and other stakeholders. In addition, EPRI is initiating work to directly address intermittency issues and to develop technologies for effectively integrating distributed PV with building electrical systems and grid communications and control systems.

Central-Station PV: 4-MW Solarpark Geiseltalsee (Credit: BP plc)

Introduction

Photovoltaic (PV) cells convert solar energy into electricity in a solid-state process that consumes no fuels during operation and emits no byproducts. The PV effect was noticed in the laboratory over 150 years ago, but modern PV began with the invention of the silicon solar cell by Bell Laboratory in 1954. The U.S. space program drove R&D in the 1960s, while the energy crisis in the 1970s stimulated the first wave of private sector activity, when many major oil companies made investments. Sunlight-to-electricity conversion efficiencies improved, costs dropped, and government support evolved from R&D funding and early demonstrations to tax credits and other financial incentives enabling development and deployment of commercial products.

In the early 1980s, U.S. government support for PV withered as petroleum prices fell, and all but a few oil companies lost interest. Despite a bruising business climate, worldwide installed PV capacity grew at a consistent and healthy average of over 20% per year through the late 1990s driven in large part by off-grid applications and steady improvement in PV performance and cost: Between 1980 and 2000, the efficiency of commercial modules nearly doubled while their cost dropped by 80%. In recent years, favorable policies and subsidies in nations such as Germany, Japan, Spain, and the United States have stimulated the grid-connected PV market prodigiously, with annual growth averaging 41% for the past 5 years (Figure 1). Total cumulative installed PV capacity exceeded 5 GW (5,000 MW) in 2005 and 7 GW in 2006 and will approach 10 GW by the end of 2007—extraordinary expansion for an industry that just passed the 1-GW milestone in 1999.

The burgeoning PV market is also a maturing one. Profits are being taken worldwide through a value chain that encompasses component suppliers, device manufacturers, system integrators, vendors, and installers. Large energy and electronics corporations—including some that dropped PV programs a few years earlier—are making significant investments in PV R&D and commercialization. Venture capital is flowing to aggressive newcomers, albeit predominantly for later-stage developments. Meanwhile, the manufacturing cost of PV is steadily falling, its conversion efficiency is increasing, building-integrated and other innovative applications are growing, and advanced PV concepts and materials offering the potential for revolutionary breakthroughs are being explored.

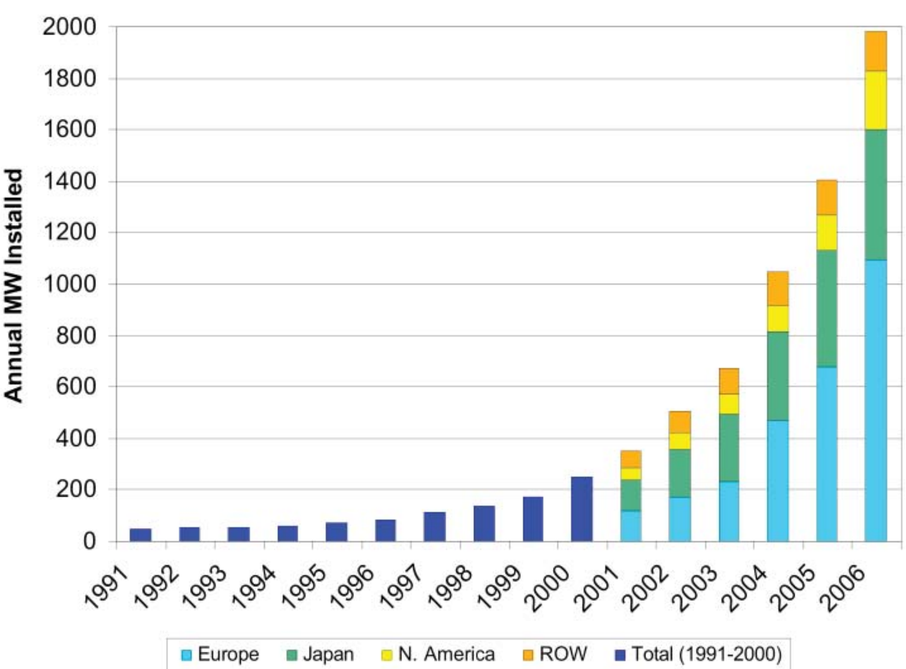


Figure 1
Global PV Installations by Year, 1991-2006. Data for the years 1991-2000 are expressed as worldwide totals, while other data specify where the PV was deployed. (Data source: Navigant Consulting PV Service Practice)

Given all these positive developments, many solar advocates are saying that the time has come for PV to be taken seriously as a grid-connected supply option. This has been said before—more than once—but now the optimism appears more real-

Distributed PV: Japan

Japanese policies have emphasized distributed rather than centralized solar power production, as illustrated by residential developments in Sapporo, a designated "Solar City."

Sapporo established a goal of reducing per-capita carbon dioxide emissions in 2012 by 10% compared to 1990 levels. The city has active programs to increase public awareness, stimulate citizen initiatives, provide incentives, and host clean energy installations. Distributed PV is a major emphasis. Local schools are hosting five 10-kW demonstration projects, and a suburban residential complex with 500 homes will be equipped with 1,500 kW of rooftop PV when completed in 2008.

Many other "Solar Cities" have instituted similar goals and programs, including Copenhagen, Denmark; Barcelona, Spain; Qingdao, China; Adelaide, Australia; Freiburg, Germany; and Portland, Oregon.

Distributed PV in Sapporo (Credit: IEA-PVPS)

istic. In the industrialized world, security and climate change concerns are focusing attention on solar energy as a globally available, inexhaustible, and emissions-free resource. Interest in minimizing the adverse impacts of energy production and use is being expressed politically, as officials act to support clean energy, and individually, as consumers deploy PV to increase self-sufficiency and promote energy sustainability. Meanwhile, in developing and underdeveloped nations, PV represents a "leapfrog" technology for delivering electric energy to improve quality of life and support economic development.

In brief, continuing improvements in PV cost-performance characteristics—combined with global socioeconomic considerations, energy security issues, climate change factors, and popular demand—virtually guarantee a growing role for PV in the carbon-constrained future. From EPRI's perspective, whether PV will become a meaningful contributor to the global energy supply portfolio is not the question. When and how PV deployment will change the grid, as well as the retail and wholesale energy markets, are critical questions. And where these changes will lead the electricity industry and society is an issue best addressed before transformative effects begin to happen.

This *White Paper* reviews the status of PV technology and markets, the potential for evolutionary and revolutionary technology advances, the issues and opportunities facing the industry, and priorities for future PV research, development, demonstration, and deployment.

Utility-Scale PV: Germany

Due to the structure of its incentive policies, Germany is a world leader in centralized PV deployment, with several megawatt-scale plants in operation or development.

The 10-MW Bavaria Solarpark, dedicated in June 2005, includes ground-mounted PV systems at three sites: the 6.3-MW Solarpark Mühlhausen, the 1.9-MW Solarpark Günching, and the 1.9-MW Solarpark Minihof. All together, the three projects comprise 57,600 solar panels over 62 acres of land. Cumulatively, they make up the largest PV plant in the world.

The Bürstadt Plant in Bürstadt is a 5-MW installation incorporating building-integrated and roof-mounted PV systems. It was completed in February 2005. Solarpark Leipziger in Espenhain is a 5-MW system built in August 2004. The facility has both stand-alone and grid-connected PV elements. The Solarpark Geiseltalsee/Merseburg employs 25,000 mono- and polycrystalline modules to generate 4 MW of electricity.

Central-Station PV: 6.3-MW Solarpark Mühlhausen (Credit: SunPower)

Technology Overview

PV technology relies on materials that produce electric currents when exposed to light, including semiconductors such as silicon as well as other substances. It is distinct from the other major solar electric generation option—known as solar thermal electric—that employs lenses or mirrors to focus solar energy on a heat transfer medium and converts heat energy into electricity via a conventional electromechanical generator.

Theoretically, solar PV could satisfy global electricity demand thousands of times over, yet its potential remains unrealized because its current performance renders it more expensive than conventional sources. The performance of PV cells and modules is judged by two fundamental criteria: *efficiency* and *cost*.

At noon on a clear day almost anywhere on Earth, light strikes surfaces directly facing the sun with a power density of approximately 1000 watts (1 kW) per square meter. *Efficiency* is the percentage of the incoming power that a PV device converts into electricity. Different PV materials absorb different colors of light, which correspond to different photon energies. For example, blue photons are nearly twice as energetic as red photons. The lowest-energy photons that a semiconductor can absorb define its energy bandgap. Photons with energies lower than the bandgap pass through the PV cell, while higher-energy photons are absorbed and some of their energy contributes to the solar cell's electrical output.

Cost depends on perspective. When comparing technologies, the PV industry often uses the cost of manufacturing a representative solar module as a fair baseline for comparison. When considering PV applications, utilities and power producers typically compare the levelized cost of electricity generated by PV to that of other generation technologies, while consumers often evaluate the installed cost of a PV system and its projected output over time in light of the retail cost of electricity. In this paper, units of cost will be defined when necessary to avoid ambiguity.

An ideal PV technology would demonstrate both low cost and high efficiency. However, both conditions need not be fully satisfied simultaneously for commercial application. For example, moderately low-efficiency PV can find vast markets if it is sufficiently inexpensive, while high-cost, high-efficiency cells are useful for certain applications.

Cost and efficiency are not the only parameters by which PV is compared to other generation options. PV offers unmatched modularity and siting flexibility—the same technology can power hand-held calculators, rooftop installations, and central-station plants. When operating, PV produces no air emissions or greenhouse gases, no liquid or solid wastes, and no noise. Despite often-recurring notions to the contrary, land use concerns for most PV installations also are minimal. In most current applications, PV is installed on a building's rooftop, a parking structure, or already disturbed land. Building-integrated PV (BIPV) is incorporated directly into roofing, siding, or glass work. Only multi-megawatt PV installations demand large areas of dedicated land, amounting to 5 to 10 acres (2 to 4 hectares) per megawatt of capacity. Impacts on native plant and wildlife can be avoided or minimized with proper project planning and management—for example, many sites suited for central-station installations consist of desert terrain of little use for alternative development.

Another frequent misperception relates to PV's energy payback period—a measure of how long a power generator must operate before it produces more energy than was required to manufacture it. Researchers at the U.S. National Renewable Energy Laboratory (NREL) estimate energy payback periods of 4 years for systems using today's commercial crystalline silicon modules, 3 years for existing thin-film modules, 2 years for future multi-crystalline modules, and 1 year for future thin-film modules. Assuming a module lifetime of 30 years, this means that 87% to 97% of a PV system's output will be pollution- and emissions-free electricity.

PV has relatively minimal environmental impact, but it is not completely benign. Most notably, potentially toxic or flammable materials are handled during manufacturing. These resemble the hazards encountered in the semiconductor industry, and the PV industry has taken advantage of many of the approaches employed there to reduce potential hazards.

State of Technology

At present, commercial PV technologies may be sorted into three main categories. *Crystalline silicon* sliced from ingots was the first PV type invented and is the most familiar and mature. Traditional flat-plate crystalline PV devices are single-junction solar cells, meaning they are made of two semiconductor layers joined at a p-n junction, across which flow electrons liberated by sunlight exposure. Multi-junction devices consist of two or more single-junction cells, each having differing bandgap energies, stacked together to absorb more wavelengths of the solar spectrum. The best conversion efficiencies for crystalline silicon cells achieved in the laboratory to date are approximately 24% in non-concentrated sunlight—roughly three-fourths of the corresponding theoretical limit. Commercially available single-junction modules have efficiencies ranging from about 10% for non-branded products to 18% or 19% for premium-cell modules from top manufacturers. However, crystalline silicon PV remains expensive to manufacture and appears to present limited prospects for breakthrough cost reduction.

Thin-film PV is a less mature development but is capturing a growing share of PV markets. It offers more scaleable and more automated manufacturing and, through processes such as vapor deposition that produce thinner semiconductor layers and less waste, more efficient use of materials. Also, thin films can be integrated with a wide variety of useful substrates, such as plastic and glass, that make them suitable for BIPV applications that serve double duty as both power sources and structural components. The performance of the most advanced commercially available thin-film PV technologies today—including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium-gallium diselenide (CIGS)—significantly trails that of crystalline silicon, both in absolute terms and relative to their theoretical limits. In the laboratory, the efficiency of small thin-film cells has exceeded 13%, 16%, and 19% for a-Si, CdTe, and CIGS, respectively. Based on the corresponding history with crystalline silicon PV, commercial thin-film products are expected to improve markedly as manufacturers gain production experience and the technology matures.

Concentrator PV (CPV), in which sunlight is focused onto a PV cell by mirrors or lenses to generate more power per unit of cell surface area, was an early favorite of electric utilities and was the centerpiece of EPRI's solar power technology development efforts for more

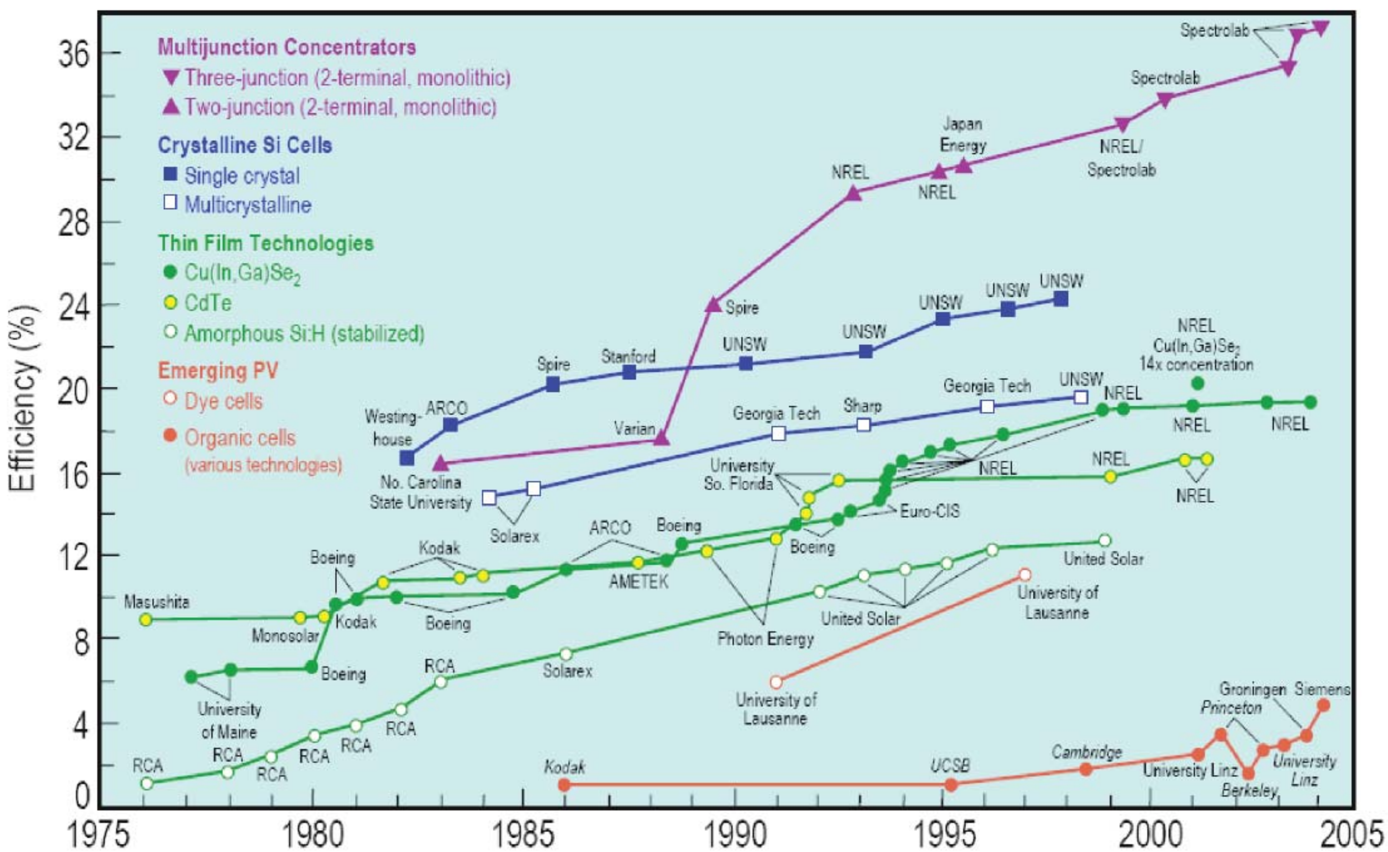


Figure 2
World-Record Conversion Efficiencies for Various PV Technologies *(Source: U.S. Department of Energy National Center for Photovoltaics)*

than 15 years from the 1970s to 1990s. CPV's main attraction is that it can leverage modest cell production volumes to much larger-scale systems using relatively simple and inexpensive optical concentration. Another attractive feature is that CPV systems can provide higher conversion efficiencies than conventional flat-plate systems—more than 30% (also roughly three-fourths of the theoretical limit) for multijunction devices incorporating epitaxial layers of Group III-V compounds, such as gallium-aluminum arsenide and gallium-indium antimonide, grown on crystalline substrates.

Despite these advantages, CPV has been slow to gain a commercial foothold because it is not well suited to the very small installations that have been the mainstream of the PV market. Today, CPV is benefiting from growing interest in larger central-station solar plants, especially in the western United States, Spain, Australia, and South Africa. The future of very large-scale CPV depends on engineering development and commercial production experience.

In addition to these commercial and near-commercial technologies, many emerging PV concepts are under development. Figure 2 shows record-setting PV efficiencies, sorted by technology type, over time. The most efficient PV devices are currently multi-junction concentrator systems, followed by crystalline silicon cells, thin-film technologies, and then emerging technologies such as dye-sensitized and organic solar cells. The ultimate theoretical efficiencies of conventional crystalline silicon and thin-film PV are constrained by fundamental physical limits. Advanced concepts, often collectively called *third-generation PV*, have the potential to transcend some of those limits and convert light to electricity with efficiencies four or five times those possible with earlier designs. Despite their long-term promise, they are the subject of so-far modest R&D efforts by governments, universities, and industry around the world.

Breakthrough Possibilities

The entire PV industry is making steady, evolutionary progress in using increasingly automated processes to produce ever-thinner cells in greater volumes with higher efficiencies and lower costs. Advances in PV materials and manufacturing will continue to incrementally improve the technology's cost-competitiveness and gradually expand its markets without the need for game-changing scientific breakthroughs. If true breakthroughs are made—the type that exploit new understanding of physics and material science to shatter old limits of efficiency and cost—the current solar power evolution could become a more rapidly paced revolution.

Defined in 1961, the Shockley-Queisser Limit established that a single-junction solar cell without sunlight concentration (operating at "one sun") has a maximum theoretical efficiency of about 31%. Similarly, a single-junction cell operating under a peak obtainable solar concentration of about 50,000 suns has a maximum theoretical efficiency of about 41%. Multi-junction devices can exceed these maxima by capturing more of

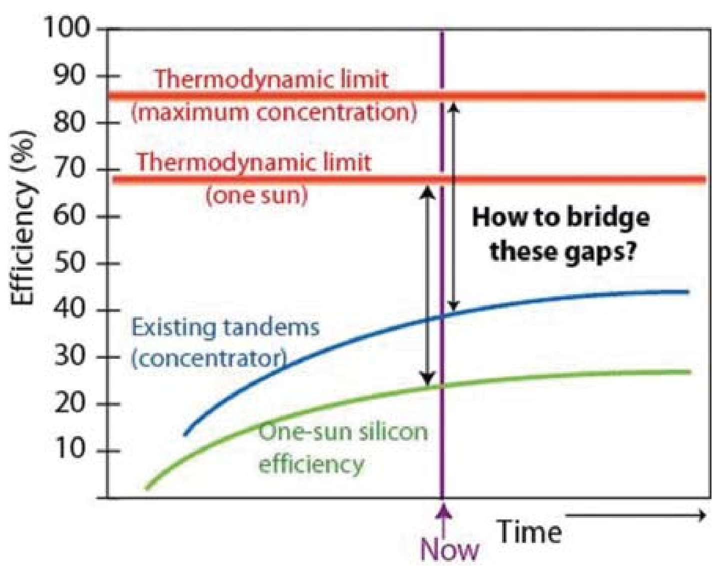


Figure 3
Grand Challenges: Narrowing the Gap Between Existing and Theoretical PV Efficiency (Source: U.S. Department of Energy)

the solar spectrum. Emerging PV materials and concepts show potential to significantly exceed the Shockley-Queisser Limit and approach the true thermodynamic limits of 68% for PV under one sun and 87% for PV under maximum solar concentration (Figure 3). Table 1 compares the theoretical limits to the best actual results obtained to date, further illustrating how much opportunity remains to improve the performance of all PV types.

Approximate Theoretical Limit Efficiency		Approximate Best Experimental Performance to Date	
Thermodynamic (concentrator)	87%	n/a	
Thermodynamic (1 sun)	68%	n/a	
Six-junction	58%	n/a	
Hot carrier	54%	n/a	
Triple-junction concentrator	64%	44%	III-V alloys, monolithic stack
Triple-junction (1 sun)	49%	15%	Thin-film amorphous silicon alloys
Double-junction concentrator	56%	30%	III-V alloys, monolithic stack
Double-junction (1 sun)	43%	12%	Thin-film amorphous silicon alloys
Shockley-Queisser single-junction (46,200 suns)	41%	30%	Crystalline silicon (500 suns)
Shockley-Queisser single-junction (1 sun)	31%	24% 20% 12% 6%	Crystalline silicon Thin multicrystalline silicon Dye-sensitized cell Organic cell

Table 1
Theoretical PV Efficiency vs. Experimental PV Performance *Data show the potential magnitude of future improvements in performance across device configurations.*

When efficiency and cost are plotted on a graph, PV technologies tend to fall in three clusters, often called "generations," as indicated in Figure 4. These generations generally correspond to the age and maturity of the technologies as well. First-generation PV technologies, comprising more than 90% of today's commercial investments, are the traditional, wafered crystalline silicon devices descended from the original Bell Labs solar cells. Second-generation technologies, just now emerging into the PV business mainstream, employ low-cost, low-energy-intensity manufacturing techniques such as thin-film vapor deposition and electroplating. They are less fully developed than first-generation devices, with potentially lower cost but also lower efficiencies constrained in principle by the Shockley-Queisser Limit and in practice by their immaturity. Third-generation technologies are potentially low-cost devices that for the most part exist only in general concept, have seen limited R&D investment, but can in principle exceed the Shockley-Queisser Limit by employing multi-junction layering or novel materials and techniques. Leading concepts include multiple exciton generation, optical frequency shifting, multiple energy level, and hot-carrier devices. These concepts likely will be enabled by organic materials, carbon nanotubes, and other nanofabrication technologies.

Multiple exciton generation (MEG) cells overcome a central limitation of existing PV technology—the one-to-one relationship between an absorbed photon and a generated electron-hole pair. They exploit the phenomenon of impact ionization, which converts one high-energy photon into multiple electron-hole pairs and, thus increased current. This process has been observed for decades in bulk semiconductor crystals, where it occurs with relatively low efficiency. According to recent experimental reports, multiple electron-hole pairs can be produced much more efficiently in nano-sized (quantum dot) semiconductors. NREL found that quantum dots can produce as many as three electrons from each

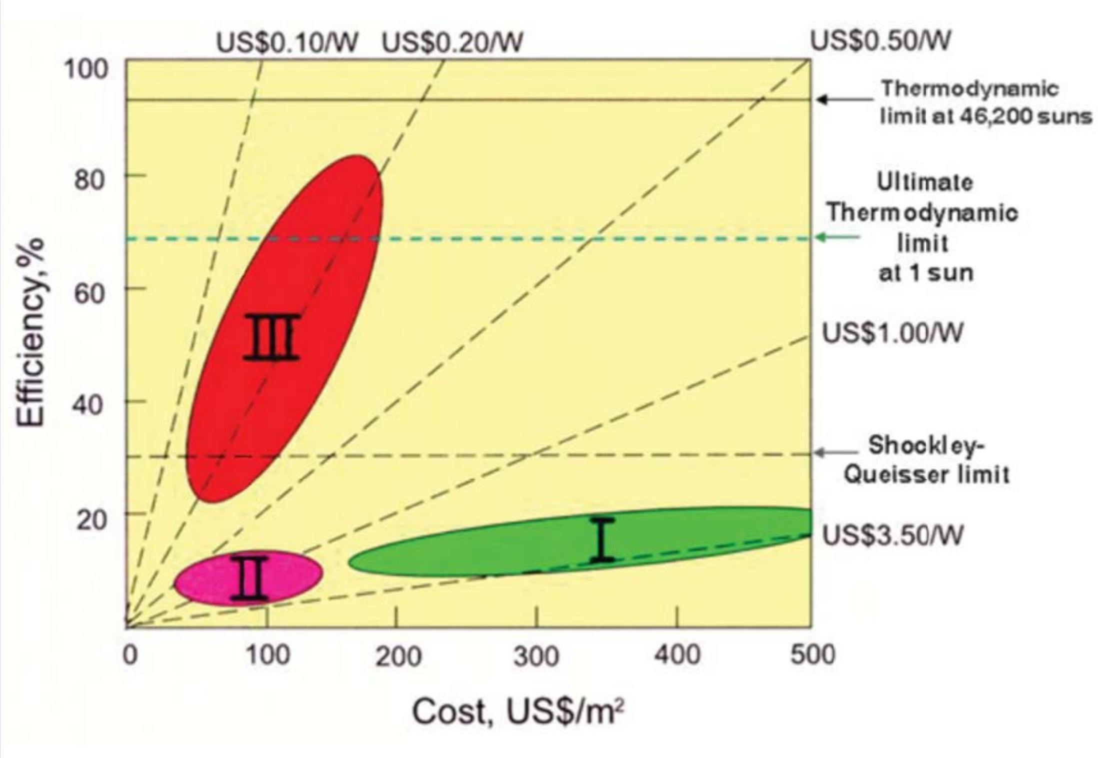


Figure 4
Efficiency vs. Cost Relations Schematically Define Three Generations of PV Technologies: First-Generation Crystalline Silicon, Second-Generation Thin Film, and Third-Generation Concepts (Source: University of New South Wales)

photon of sunlight and could theoretically convert more than 65% of the sun's energy into electricity.

Optical frequency shifting involves transforming the solar spectrum to maintain its overall power density within a much narrower range of photon energies, enabling increased energy capture. Approaches include both up and down conversion, which involve creating a single high-energy photon from two lower-energy photons or creating two lower-energy photons from a single higher energy photon, respectively; as well as thermophotonics, which employs an auxiliary device to combine thermal and optical energy inputs. A central feature is that the solar spectrum is transformed by coatings or other elements not part of the actual PV cell, providing a pathway toward substantially improving the efficiency of existing PV technologies.

In *multiple energy level solar cells*, the mismatch between the incident energy of the solar spectrum and a single bandgap is accommodated by introducing additional energy levels such that photons of different energies may be efficiently absorbed. Multiple energy level solar cells can be designed either with localized energy levels, called quantum wells, or with continuous intra-bandgap minibands, also called intermediate bands. Both designs have a fundamental similarity in that they include multiple energy barriers for light-excited electrons to surmount when harvesting the photon energy.

Hot carrier solar cells utilize selective energy contacts to extract light-generated hot carriers (electrons and holes) from semiconductor regions before their excess energy is converted to heat. This allows higher efficiency devices—up to a thermodynamic limit of 66% at one-sun intensity—by reducing the thermalization losses in single-junction solar cells. To benefit from this approach, hot carriers must escape through the energy-selective contacts before losing their energy to heat via various inelastic scattering processes. Specific materials show slower carrier cooling and hold the promise for realizing such hot carrier solar cells.

Organic solar cells relying on carbon-based materials were first discovered in the 1980s. Early work demonstrated the concept of organic PV, although energy conversion efficiencies were very low. During the past decade, refinements in the chemical composition of the cells, cell physics, and device engineering have led to individual demonstration cells with more than 5% conversion efficiency. Very inexpensive, lightweight, flexible, large-area, plastic-like PV cells appear possible, but their efficiency potential is not well established.

Carbon nanotubes are cylindrical carbon molecules with exceptional strength, a typical diameter on the order of a few nanometers, and unique electrical characteristics. Since 2005, researchers have been growing microscopic nanotube towers coated with semiconductor material atop silicon wafers and exploring other novel device configurations. It's too early for certainty, but such structures and associated nanofabrication techniques may provide the added manufacturing flexibility needed to realize one of the third-generation concepts in a commercializable device.

These third-generation PV device and materials concepts are not the only ones being explored today, and others are all but certain to emerge. Assessing how evolutionary and revolutionary advances might affect the electricity enterprise and society requires detailed consideration of

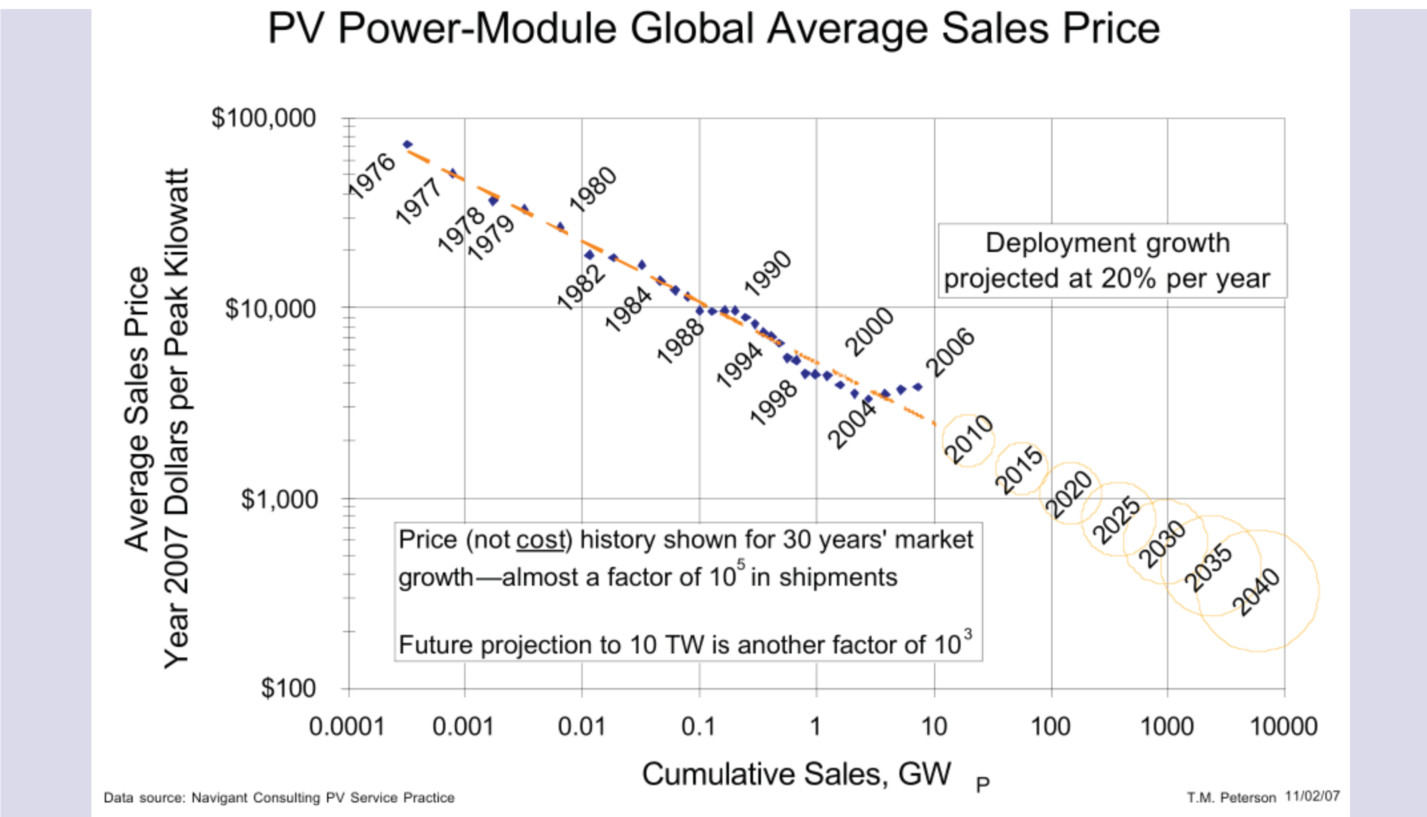


Figure 5
Worldwide PV Module Price Experience and Extrapolation to 10 TW (Data source: Navigant Consulting PV Service Practice)

the role of technology and other factors in shaping PV economics. This is one objective of the "High Efficiency PV" project recently begun by Electricité de France, EPRI, and others to explore and make more tangible the potential of several third-generation PV concepts.

System Economics

As noted previously, PV costs are looked at in different ways depending on perspective. PV industry experience since the 1970s shows a history of steady decline in the price of modules driven by continuous innovation, as summarized in Figure 5. Note that the scales of both axes are logarithmic. The relationship between average sales price and cumulative sales, which roughly mirrors the underlying declining-cost picture, is similar to that seen with most manufactured goods. The figure also shows the recent temporary stagnation in the price of crystalline silicon devices resulting from a combination of a polysilicon feedstock shortage and subsidy-superheated market demands in Europe and California.

Prices began easing in late 2006 and are likely to return toward the historic trend as additional polysilicon capacity comes on line and thin-film module producers implement aggressive expansion campaigns. Typical system prices in 2007 range from about $6,000 to $10,000/kW of installed "peak dc" nameplate capacity, depending inversely on size (the actual peak ac output of grid-connected systems is usually 70% to 80% of the dc rating). Going forward, Figure 5 projects a plausible future of ongoing evolutionary innovation and market expansion to a dramatic scale. Such a future is not guaranteed, of course, but in light of PV's past 30 years of technology and market progress it does appear reasonable.

As with every supply option, the price of the energy conversion system is only one component in calculating the levelized cost of energy (LCOE). PV modules account for about 50% of the typical up-front cost of an installed system, with the balance associated with items such as power conditioners, wiring, support structures, and labor. So far, balance-of-system costs have declined in parallel with module costs.

For all PV applications, resource availability is critical: The better the solar resource, the greater the system output, and the lower the LCOE. As seen in Figure 6, the available sunlight on a 24-hour average varies only from about 125 to 300 W/m^2 throughout most of the populated parts of the Earth. Utility, energy, environmental, and climate policies also strongly influence PV's attractiveness by directly or indirectly improving PV's LCOE relative to other generation options.

Several aspects of PV economics are foreign to the normal procedures used by utility planners and other industry practitioners focused on adding and operating capacity to serve load. On the positive side, PV uses a fuel that is free, it imposes no environmental control or waste management costs, and it has extremely low O&M costs—generally less than 2% of the total cost of a PV system over its lifetime. On the negative side, it generates electricity when the sun shines rather than when dispatched, and its output varies with unpredictable weather conditions superimposed over daily and seasonal cycles. This means that the initial capital investment for PV comprises almost the full cost of 20 to 30 years' worth of output, but an installation's nameplate capacity cannot be counted on at any particular instant.

These conditions present a conundrum to traditional system planning and operations, where high premiums are attached to predictability, reliability, and overall least cost. However, with PV's LCOE several times greater than that of competing generation options, its lack of dispatchability is not what has historically constrained supply-side PV applications. For consumers, the higher retail value of PV-delivered power has made justification easier, although the primary economic consideration for these purchasers typically has been system affordability rather than cost-effectiveness.

Because of the front-loaded nature of PV costs, the LCOE of a solar plant is dramatically impacted by financing terms: the cost of money. This means that the least-cost approach to solar generation involves choosing the right "ownership model"—in other words, arranging for the plant to be owned by the entity with the lowest financing costs and tax impacts.

Different ownership arrangements can easily produce 25% differences in the LCOE. For smaller PV systems, often the least-cost approach means cash or mortgage financing obtained by a property owner; for large-scale systems, it may indicate either independent power producer (IPP) or utility ownership, depending upon geopolitical site location. Incentive structures are also important in influencing PV deployment. Typically, residents prefer incentives that reduce up-front costs, while commercial entities favor credits distributed over a system's lifetime.

Some solutions to the mismatch between PV's characteristics and standard industry planning and operations are now appearing, including power purchase agreements (PPAs), feed-in tariffs, net-metering interconnection policies, RPS requirements, and voluntary green power purchasing programs. A common characteristic of these solutions is that both the system performance risk and the economic benefits belong to PV system owners—consumers or IPPs—and not to traditional utilities or distribution companies. Moreover, these behind-the-

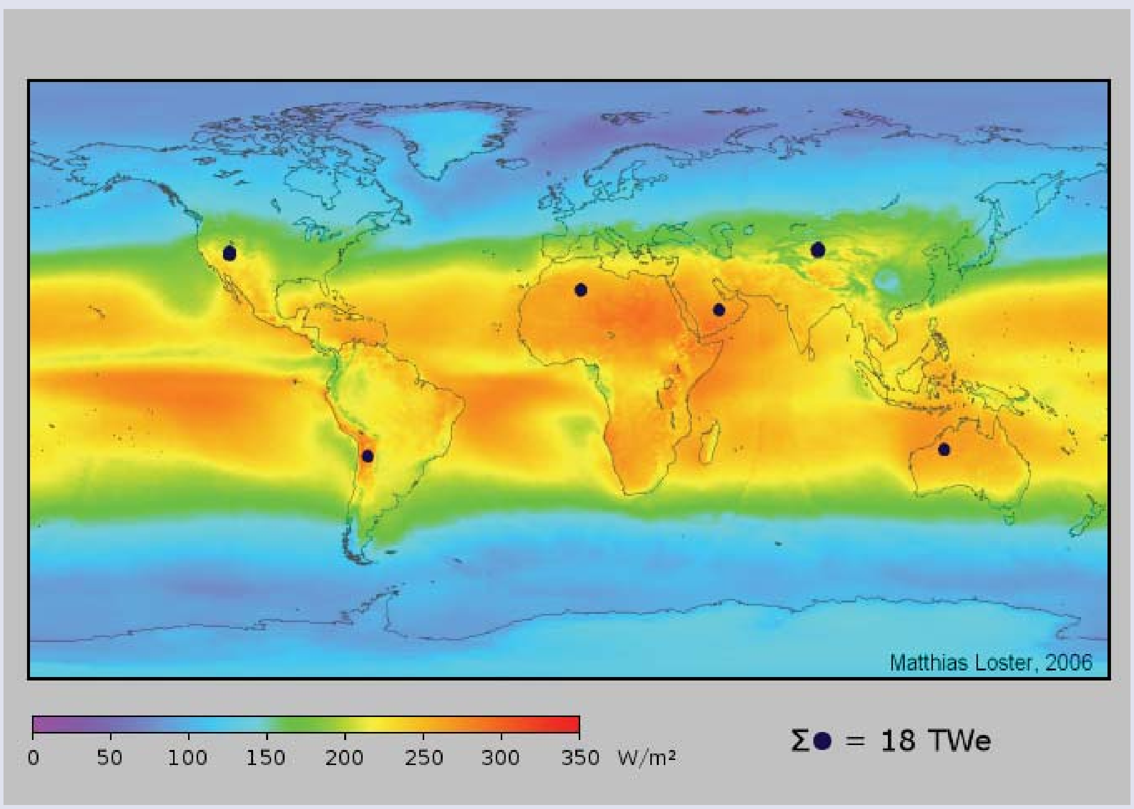


Figure 6
24-Hour Daily Average Worldwide Insolation, 1991-1993 (Source: M. Loster, U.C. Berkeley, www.ez2c.de/ml/solar_land_area/)

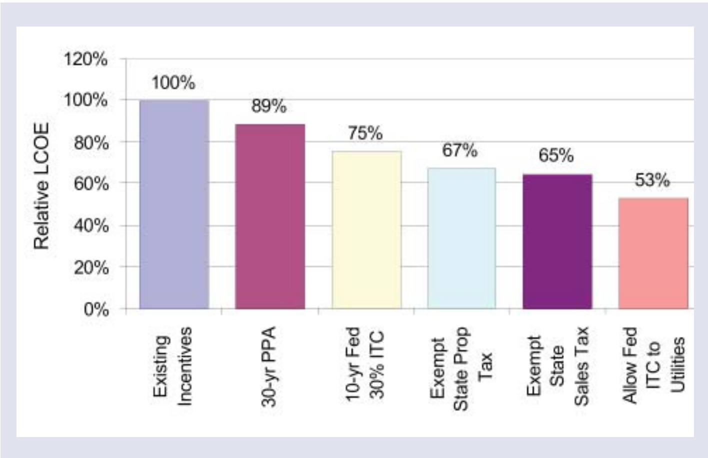


Figure 7
Cumulative Effects of Proposed Federal and State Incentives on Solar LCOE (Source: Western Governors' Association CDEAC Solar Task Force Report, http://www.westgov.org/wga/initiatives/cdeac/solar.htm)

meter applications tend to reduce retail sales and, under conventional rate structures, revenues. This explains why traditional industry players evidently need new business models before they can embrace significant amounts of PV generation in their portfolios.

Meanwhile, installed PV capacity is growing, and approaches for encouraging additional deployment are being evaluated. For example, in 2005, the Western Governors' Association's Clean and Diversified Energy Advisory Committee formed a Solar Task Force to analyze the feasibility of adding large amounts of solar generation to the western U.S. power grid and the policy means to encourage that to happen. The Task Force found that 8 GW of solar power generation, combining all types, could reasonably be deployed by 2015 if a package of Federal and State incentives was implemented to cut the owners' effective cost and, therefore, the LCOE, nearly in half, as shown in Figure 7. The key recommended Federal actions were to extend the recently implemented 30% investment tax credit (ITC) for solar systems from its present 2-year term to 10 years and to allow utility companies to access this credit.

Case Study: Residential PV

The effects of different parameters on PV LCOE are best illustrated by example. A grid-connected behind-the-meter system is considered here because that is the application experiencing the highest growth at present—and it is the one where PV will likely have its greatest impact over the next 20 years.

Table 2 characterizes a "typical" 5-kW_{dc} rooftop installation in Fresno, California, based on published data for PV systems installed in the State during 2007 and assuming a 20-year simple payback. (This is not usually judged a suitable economic metric for businesses but is often invoked by consumers when weighing investment decisions.) To recoup an up-front cash investment, the projected output over 20 years has an equivalent retail LCOE of 32¢/kWh, not considering any of the available State or Federal incentives. Subtracting the current Federal investment tax credit and the estimated California Solar Initiative (CSI) Expected Performance-Based Buydown (EPBB) payment from the capital cost reduces this figure to 24¢/kWh. If mortgage-based financing is employed over a 20-year period, the after-tax equivalent retail LCOE is 37¢/kWh for the first year of this system's output and 45¢/kWh (before tax deductions) over the loan's lifetime.

The comparison point for these LCOE figures is not the busbar generation cost, often quoted as in the range of 3 to 5¢/kWh, but the retail electricity rate for residents, which currently ranges from 12 to 36¢/kWh in California, depending upon usage. Even with State and Federal incentives and tax-deductible financing, PV installations currently supply only nominally competitive electricity. Nonetheless, consumer demand has spurred installation of about 25,000 PV systems totaling over 200 MW in California in the past few years. Future retail power prices are uncertain, but they seem likely to increase for a variety of reasons. Accordingly, a PV system that appears nominally competitive at today's rates may well

5-kW$_{dc}$ (3.75 kW$_{ac}$) Residential PV System in Fresno CA		
Annual Energy Output kWh	7,335	EPBB calculator*
Total Capital Expenditure	$47,000.00	Based on 2007 CA installation experience
Annual O&M	$18.34	Estimate at 0.25 cents/kWh
Total 20-year Cost	$47,366.75	
20-yr simple payback retail LCOE	$0.32	Total cost/total output in kWh for 20 years
Reduce costs via a Federal & State Incentives		
$2,000-Capped 30% Fed. ITC	$2,000.00	
CSI EPBB ("$2.33/W" this site)	$9,803.00	EPBB calculator*
Net Cost	$35,563.75	
20-yr simple payback retail LCOE	$0.24	Net cost/total output in kWh for 20 years
Consider Tax-Deductible Financing		
Effective tax rate	25%	
Annual interest rate	7%	
Loan lifetime (years)	20	
Present Value	$35,197.00	
Monthly Payment	$274.41	Loan + O&M
LCOE for 20-year 7% loan	$0.45	Annual payments/annual output in kWh
First-year after-tax retail LCOE	$0.37	(1st-year payments - tax rate * 1st-year interest)/annual output in kWh
* <http://www.csi-epbb.com/Default.aspx>		

Table 2
Cost of a Typical Residential PV System in Fresno, California These costs are based on published experience and available incentives for 2007.

seem to be a comparative bargain by the end of its lifetime.

The example shown in Table 2 offers other important insights on PV economics. First, the simple-payback equivalent LCOE for fixed financing and incentive assumptions is essentially inversely proportional to local insolation. Thus, at today's system price, ignoring State-to-State incentive differences, the cost of PV electricity varies with location based on resource availability, as shown for some selected sites in Figure 8. Setting aside Federal and State incentives and assuming an up-front cash investment, equivalent retail LCOE values vary from a low in El Paso, Texas, of 90% of the Fresno baseline to a high in Seattle, Washington, of 167%. This variation between States is comparable to that caused by the effects of subsidies, which means that PV ownership in a relatively low-resource State with strong incentives, such as New Jersey or New York, may actually be more attractive than in a higher-resource State with weaker incentives, such as Utah or Colorado. Furthermore, this variation is less than that in regional U.S. electricity rates, which range over a factor of 4. The implication here is that a PV "bargain" in one region can appear very expensive in another.

Second, the simple-payback LCOE for fixed financing and incentive assumptions is essentially inversely proportional to the initial capital expenditure. Accordingly, future behind-the-meter PV deployments will offer more attractive economics: Extrapolating from the projection of evolutionary technological progress in Figure 5, the 20-year cash payback retail LCOE for a 5-kW_{dc} system in Fresno decreases from 32¢/kWh today to 18¢/kWh if purchased in 2015 and 7¢/kWh if purchased in 2030. These may indeed appear to be attractive costs in those times.

By the same token, BIPV systems, which can take credit not only for electric outputs but also for replacing one or more structural building components, will likely have become cost-effective as well. This may launch a much more vigorous wave of these installations than seen today, where they are limited primarily to cases involving a building owner's desire to project a green image.

Third, the relationship between capital costs and LCOE has implications for future central-station PV deployment. At present, busbar-connected PV systems are not cost-effective by a wide margin because of today's high PV module price. Multi-megawatt PV systems are only being deployed where policies place a special premium on solar generation and, even then, solar thermal electric technology is capturing the bigger installations and a larger market share due to more favorable economics and performance characteristics.

However, the evolutionary technological progress shown in Figure 5 implies that the gap between the LCOE of central-station PV and other generation options will narrow over time, to the point where large-scale PV projects may also become cost-competitive generators in many locations by about 2030.

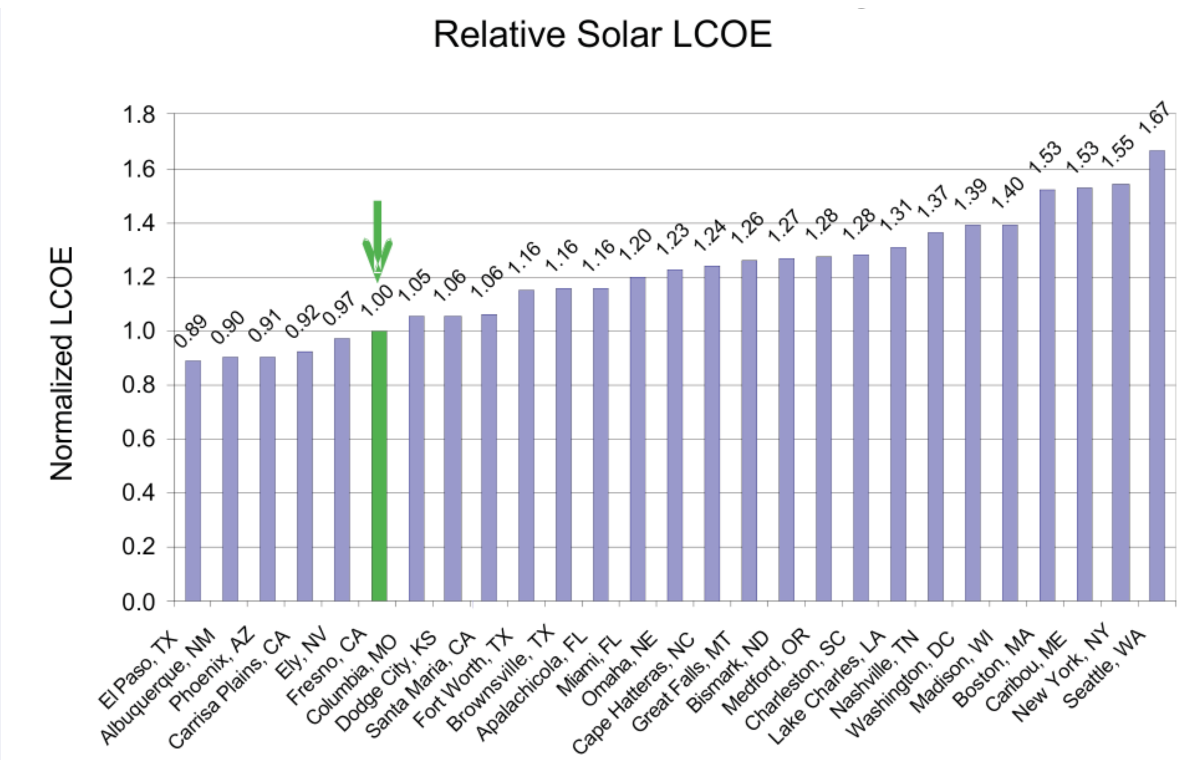


Figure 8
Relative Cost of PV Electricity in the United States Due to Resource Variability This figure does not account for the effects of State subsidies and average temperature differences.

Concentrator PV: Arizona, Spain & Australia

Since 1995, Arizona Public Service (APS) and Amonix have been installing Amonix CPV systems, with more than 600 kW presently operating on a daily basis. They have reported total installed costs of $6/W, which is comparable to installed costs for large flat-plate PV systems. As the technology matures, APS expects the cost of the Amonix CPV system to drop to perhaps $3/W or less.

Amonix recently announced a joint venture with Guascor, which has built a 10-MW/yr assembly plant in Spain. This market is made possible by Spain's new feed-in tariffs and long-term contracts that attract investors wanting to maximize the kilowatt-hours generated for their invested project dollars.

Solar Systems Pty Ltd. of Australia has spent more than 15 years developing several generation of CPV prototypes leading up to a 154-MW project being built in northwestern Victoria. A proprietary Heliostat CPV system will use fields of sun-tracking mirrors to focus sunlight on high-efficiency solar cells mounted 40 meters high. The first stage of the project is due to be completed in 2010, with full commissioning in 2013.

Concentrator PV in Arizona (Credit: Amonix)

Market Status & Outlook

PV markets have grown rapidly and changed dramatically in recent years driven by technological progress and a supportive policy environment.

As recently as 15 years ago, PV was used almost exclusively to generate power in high-cost, off-grid applications not served by conventional electricity supply and delivery infrastructure. Now, it is far more commonly used in grid-connected applications, with literally millions of kilowatt-scale distributed installations on the rooftops of homes and businesses offsetting the retail cost of grid electricity and a far smaller number of megawatt-scale central-station projects supplying power to the grid.

Figure 9 displays this dramatic transformation: The number of new remote, off-grid applications continues to increase worldwide, but their growth rate and capacity have been enormously outstripped by those of grid-connected PV since 2000. In 2006, off-grid applications—though still maintaining a worldwide compound annual growth rate (CAGR) of about 16%—accounted for approximately one-eighth as many shipped megawatts as grid-connected applications, which had a CAGR of approximately 50%. This trend is projected to continue.

The shift in PV applications is paralleled by a shift in markets. Two primary end-use markets for PV systems exist in the United States, and a third is emerging.

Buyers of grid-independent systems represented the largest market segment prior to 2000. This segment continues to grow steadily, with existing and new PV systems powering off-grid homes, ranches, farms, and facilities, as well as communications installations, environmental measurement and monitoring sites, security systems, signs, and other equipment located in remote locations. Buyers of consumer electronics, outdoor lighting systems, and other products that incorporate small PV cells may also be considered participants in this segment, with the manufacturers of these devices serving as middlemen between PV producers and consumers.

Buyers of grid-connected, behind-the-meter PV systems now represent the largest and fastest growing market segment. As in off-grid applications, these systems are most commonly deployed in rooftop installations and less frequently as ground-mounted arrays, while building-integrated applications are beginning to appear.

Residential and commercial consumers, and, to a lesser extent, industrial consumers participate in both the off-grid and grid-connected markets. Government agencies have historically been significant PV consumers. The U.S. Department of Defense, for example, has been installing both grid-independent and grid-connected PV systems at military facilities since at least 1976, with annual capacity additions usually totaling a few megawatts per year, much of it in the form of PV-battery-engine hybrid systems that range in size to over 100 kW. Additional agencies at the Federal, State, and lower levels have also been deploying PV systems to serve specific off-grid applications, to support R&D, and, more recently, to comply with new procurement policies mandating increased reliance on renewable energy sources.

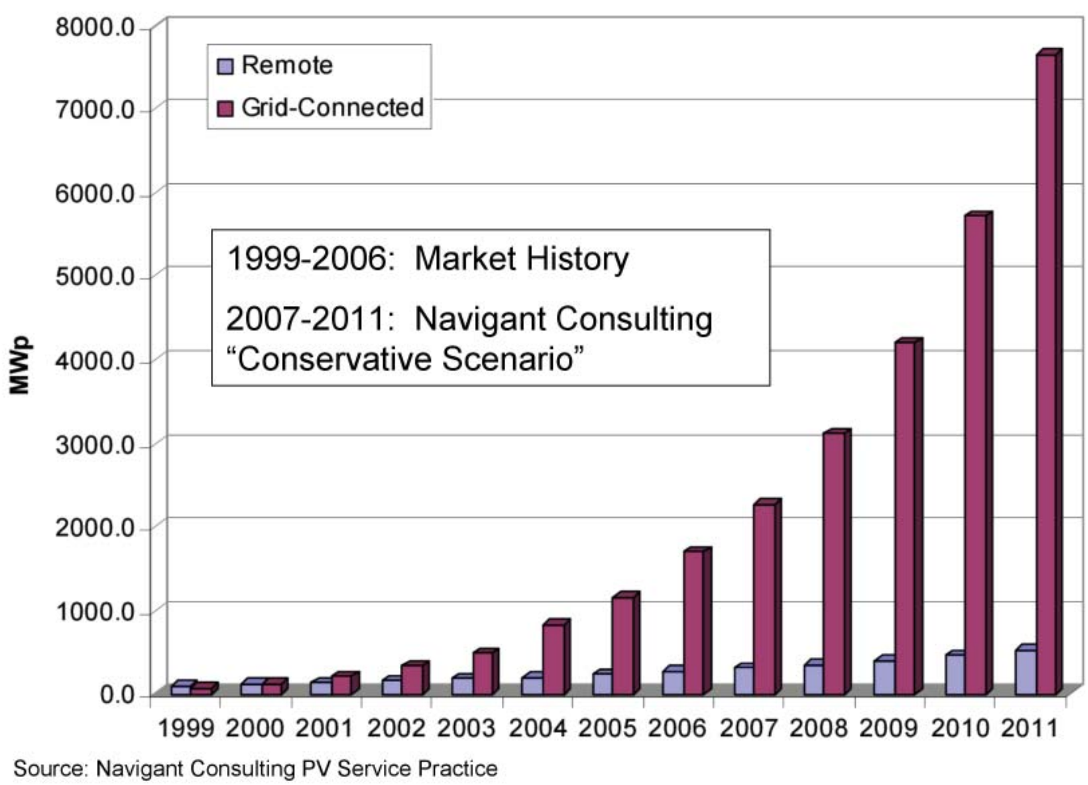


Figure 9
Proportion of Grid-Connected vs. Off-Grid PV Applications Worldwide, 1999-2011 (Source: Navigant Consulting PV Service Practice)

Buyers of grid-connected, supply-side PV systems represent the third major PV market. In the United States, large-scale investments by utilities and IPPs have been few and far between. The main examples to date have been deployments of a handful of megawatts made patently for demonstration purposes, such as the 4-MW Sacramento Municipal Utility District installation at Rancho Seco, California, and Tucson Electric Company's 6-MW field in Springerville, Arizona. However,

Building-Integrated PV: New York City

Reconstruction of New York's Stillwell Avenue subway station provided an opportunity to integrate amorphous silicon thin-film PV into a semi-opaque roof canopy that, upon its completion in 2005, was one of the largest BIPV structures in the world.

The canopy roof provides the station with electricity as well as shade. Some 2,800 thin-film modules covering 76,000 square feet (7,060 m^2) generate approximately 210 kW while permitting 20% to 25% of daylight to pass through. During summer, the system provides approximately two-thirds of the station's power needs (not related to powering the trains). Its annual output is about 250,000 kWh.

Planning and design took more than four years, and the station's design process was done in conjunction with an educational component that included a large-scale industry workshop involving several major PV companies. The station was designed to invoke the historic architecture of nearby Coney Island and provide passengers with a grand sense of arrival, elegance, and civic pride.

Building-Integrated PV in New York City (Credit: Schott AG)

State RPS mandates, such as California's requirement that 20% of electricity come from renewable sources by 2017, have spawned several announcements of utility PPAs with prospective builders of PV plants, indicating that capacity in the dozens of megawatts may come on line in the next few years.

Markets similar to those in the United States exist internationally, with their relative magnitude and importance varying in individual countries depending on domestic circumstances. For example, PV programs in Japan have encouraged residents and businesses to install many tens of thousands of grid-connected rooftop systems with capacities of a few kilowatts. Incentive structures in Germany have stimulated similar residential-scale installations, as well as some deployments of large-scale PV parks with nameplate capacities of several megawatts. In the developing world, off-grid PV is commonly employed to deliver the benefits of electricity to remote areas.

Wherever PV has flourished, it has done so with government support: Policies such as those adopted in Japan, Germany, Spain, and California over the past decade or so have nurtured PV and built these regions into world leaders. Subsidies, rebates, and tax credits help make PV more affordable for consumers and close the cost gap between PV and alternative generation technologies. Net metering provisions, feed-in tariffs, and other policies provide consumers and power producers with additional incentives to site and own grid-connected PV systems and to supply power to local grids under a variety of credit and compensation plans. Interconnection policies, building codes, and safety standards encourage and facilitate these applications, rather than present barriers. Air and climate policies are increasing the cost of fossil generation, and Renewable Portfolio Standards are requiring electricity providers to procure a growing portion of their supply from clean and renewable resources.

Figure 10 displays the tangible effect that these favorable policies have had on overall PV market expansion. The figure shows that in the decade preceding the regional subsidies in Japan, Germany, and California, average annual shipment growth was a respectable 15%, primarily in off-grid applications. But during the period 1999 to 2006, when those three regions had implemented substantial subsidies for grid-tied systems, that growth rate spurted to 41%, representing continued strong growth in the off-grid market plus extremely rapid growth in grid-connected applications.

Experiences in Japan and Germany further illustrate the strong influence of policies on market evolution. In the mid 1990s, the Japanese government implemented net-metering policies and a generous rebate program to encourage the grid-connected PV applications offering

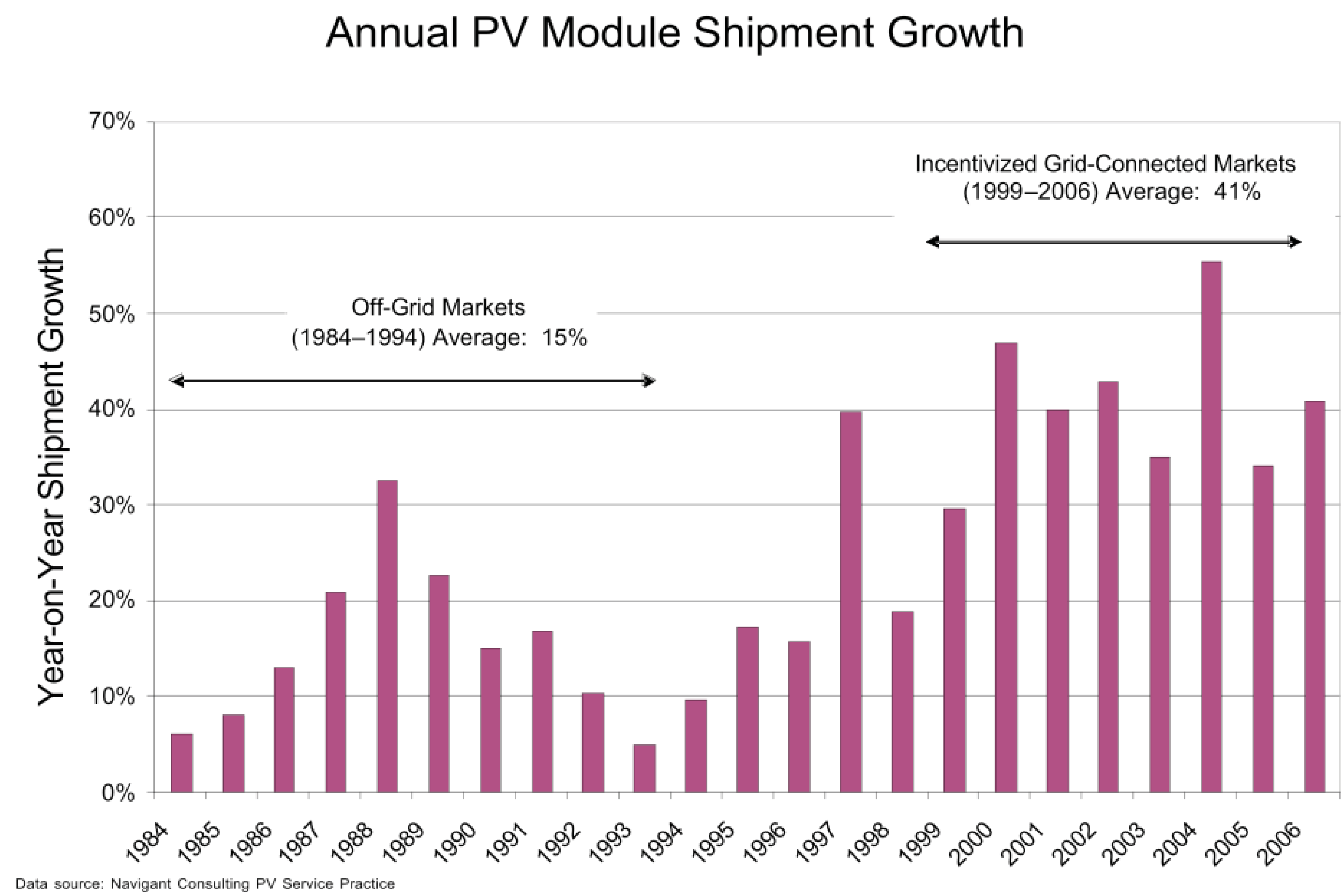


Figure 10
Effects of Policies on PV Market Growth Before incentives took effect for grid-tied systems in Japan, Germany, and California, annual PV module shipments grew at 15% on average, mainly in off-grid applications. Subsidies boosted average annual growth to 41% overall. (Data source: Navigant Consulting PV Service Practice)

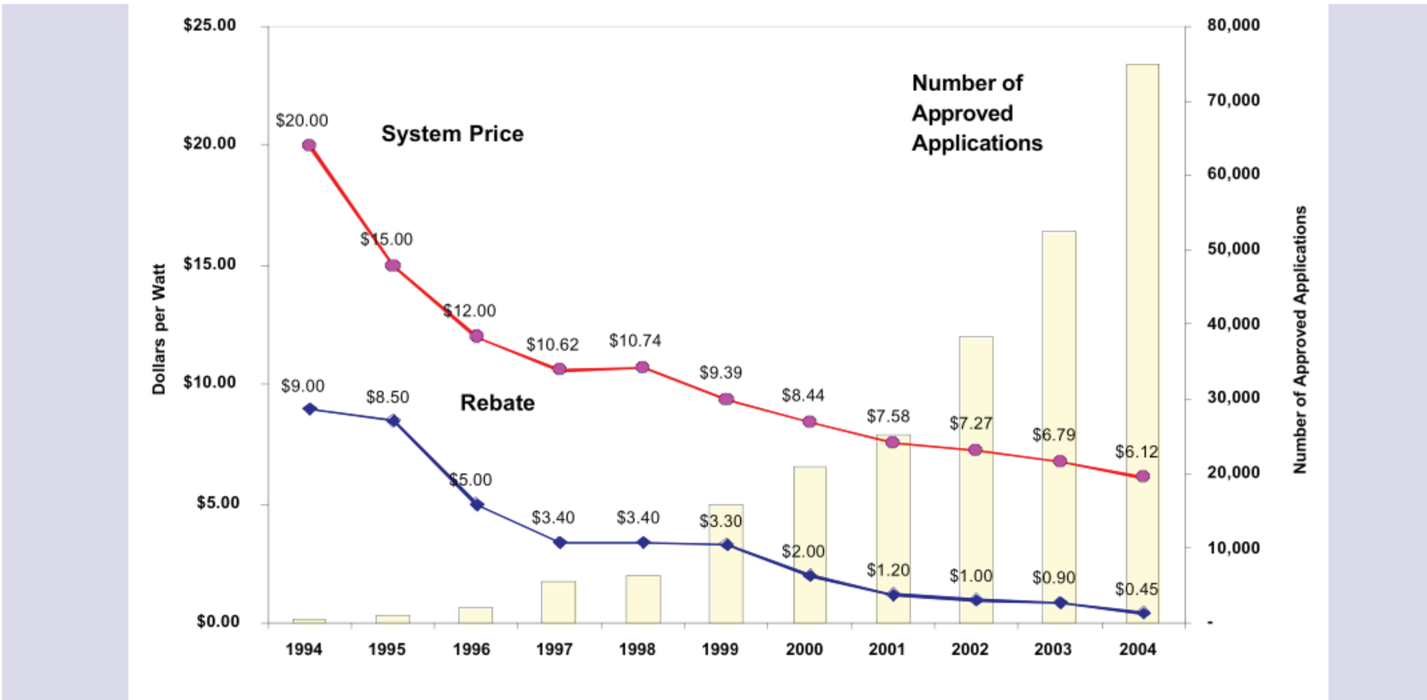


Figure 11
Japanese PV Program Rebates and Participation, 1994-2004 (Source: California Energy Commission)

consumers maximum advantage in light of high-priced retail power. Over time, rebates on capital expenditures declined and customer participation increased gradually, system prices fell substantially, and the net cost to the customer remained about the same, as shown in Figure 11. Despite a dearth of incentives after 2004, Japan's PV market continues to grow, albeit more slowly.

In contrast to Japan's capital cost rebate program, Germany's production-based incentive programs are based on the actual energy produced over a 20-year period and are paid through a national utility feed-in tariff, similar to a long-term electricity sales agreement. Because the value of the feed-in tariff (roughly 50¢/kWh) is high enough to repay PV system construction costs, it has stimulated entrepreneurial groups to form joint ventures that have financed multi-megawatt PV farms.

Industry observers agree that the extremely rapid current worldwide growth in PV deployment likely cannot be sustained over the next few years without continued public support through tax incentives, rebates, and other subsidies. However, as suggested previously (Figure 5), PV prices may decrease by the 2015 to 2025 time-frame to a point that such financial support is no longer needed for further market growth.

Technology Prospectus

The latter part of this century will see energy supply, delivery, and use systems that could be as profoundly different from today's as today's are from those of 50, 75, and 100 years ago. PV's role in that future is impossible to predict because the technology has only recently begun appearing in significant commercial quantities and has yet to find a routine place in mainstream settings. Early experience, however, indicates that its unique modularity and other characteristics have the potential for innovations that may transform the energy industry. PV is as different from other power generation technologies as transistors are from vacuum tubes. Consider how the cellular phones that have leap-frogged landlines in developing countries, transformed personal and business communications in the developed world, and created consumer wants and needs being met by new industry players and a seemingly continuous stream of innovations.

Assuming the continued evolutionary progress projected in Figure 5, PV deployment in distributed grid-connected applications is clearly heading in the direction of causing landscape changes in the retail electricity sector. Major scientific breakthroughs may accelerate the growth of these PV applications at the retail level, shake up wholesale electricity markets, and enable unforeseen innovations spanning the energy sector. These effects would not happen overnight, but PV will almost certainly change the way significant quantifies of electricity are supplied, delivered, and used.

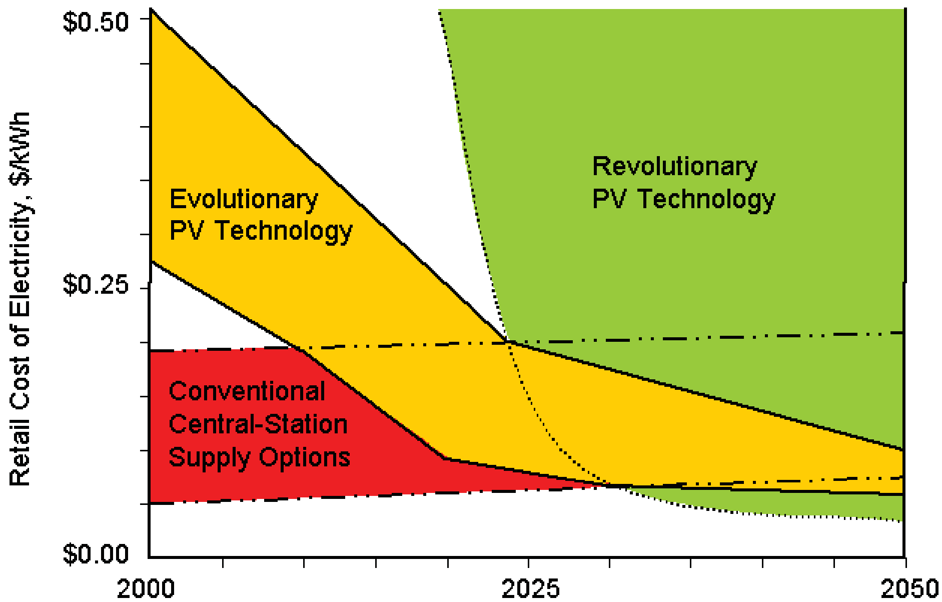


Figure 12
Projections of Technological Progress This schematic representation shows cost relationships between conventional power sources and likely evolutionary PV development as well as the possible impacts of revolutionary developments. Achieving the benefits of the leading edge depicted for revolutionary innovations will require an aggressive, sustained R&D effort.

Among the third-generation PV concepts, it is far too early to predict the fate of any individual approach because they have not been experimentally verified. Nevertheless, scientific breakthroughs and successful commercialization of any emerging third-generation PV concepts could produce a three-fold to five-fold increase in commercial module efficiency and a dramatic improvement in PV's deployment potential. Although impossible to forecast confidently, breakthroughs enabling market-competitive busbar electricity from PV technology are clearly possible by 2025 or 2030.

Given the relatively short history of PV science, it is also reasonable to anticipate the discovery of additional, yet-unimagined PV technologies in coming years. However, the laws of thermodynamics appear to limit the performance impacts of such speculative technologies to the same realm as those currently envisioned. Therefore, the main benefit of additional breakthroughs would likely be in accelerating the time to market for super-high-efficiency PV products.

Figure 12 compares schematically the range of potential PV costs in evolutionary and revolutionary scenarios with the retail cost of conventional power in the United States, extrapolating from current cost estimates. The bands indicate the range of projected costs depending on resource availability, on whether PV's continuing evolution proceeds in more or less accelerated fashion, and on whether or not aggressive R&D investments are made to pursue PV's revolutionary technology potential. These cost estimates are obviously speculative, and their likely error margin increases dramatically beyond a few years' time. Nevertheless, the depicted timeframes for the implied innovations and the relative scales of their cost impacts are plausible. So too are the following projections for market penetration:

- About 2010, evolutionary technology is a behind-the-meter solution in regions with high-quality solar resources, generous incentives, and/or high retail prices.
- From around 2015 to 2025, evolutionary technology drives innovations in retail electricity supply markets.
- From around 2020 to 2030, evolutionary technology is competitive with solar thermal electric and conventional central-station generation options.
- About 2025, revolutionary PV technology begins making inroads in current PV applications.
- After 2030, revolutionary PV technology is least-cost supplier with unforeseen versatility.

Issues & Opportunities

The expected advances in PV technology—even at the lower end of current projections—create challenges and opportunities for utilities, distribution companies, power producers, and other electricity industry stakeholders. Issues and turning points will arise at different times in different locations depending on resource availability, policy environment, and other market conditions.

Public sentiment and growing attention to environmental impacts and life-cycle costs are likely to increase PV's attractiveness as a distributed resource and to accelerate the expansion in grid-connected applications. Already, growing numbers of residents, businesses, institutions, and governments around the world are setting aside conventional economic metrics and installing PV systems to support energy independence, demonstrate a commitment to renewable energy, and reduce their carbon footprint. Going green is capturing not only public imagination but also entrepreneurial attention and venture capital investment as awareness of the inherent business opportunities grows. These developments are creating a political situation conducive to more substantive action on energy issues and a business environment likely to foster innovation. As PV costs continue to come down and applications expand, retail electricity markets may see major transformations as consumers grow more comfortable with the notion of buying and selling energy in electricity markets. This phenomenon could parallel that of cell-phone proliferation, with most consumers continuing to rely on conventional infrastructure until marginal cost-performance improvements or unforeseen applications lead to relatively sudden jumps in market penetration.

Such transformations could impact traditional retail electricity sales as effectively negative loads, but behind-the-meter PV systems can also create opportunities for utilities and other market participants that adopt new business models to leverage these new grid assets. Distributed PV may represent a significant component in demand-side management (DSM), grid reinforcement, portfolio diversification, and carbon management strategies. Already, some companies are packaging end-use efficiency measures with PV installations to deliver an economically and environmentally preferred option for serving load growth and helping consumers manage bills. The relative match between PV output and air conditioning needs could be exploited to meet peak demand cost competitively. Direct-current microgrids employing PV may more efficiently serve some loads. PV deployment could be encouraged as a hedge against volatile fuel prices. It also could provide a carbon-free generating option in the face of market-based climate policies. New markets could allow grid resources (generation and load) associated with sunny, low-demand conditions in one area to be traded against ramping down fossil generation, retaining impoundment water, or meeting peak loads in others. Distributed PV could be used to power plug-in hybrid electric vehicles as both new loads and mobile storage systems. Additional opportunities will surely arise from unanticipated directions.

Beyond the foreseeable aspects of technological advance and market evolution, the expected revolutionary breakthroughs in PV technology will likely extend its impacts to wholesale supply markets. Most importantly,

Tracking PV: Portugal

In March 2007, GE Energy Services, PowerLight, and Catavento commissioned an 11-MW solar power plant in Serpa, Portugal. The station's 52,000 modules cover 150 acres (60 hectares) and employ the SunPower® single-axis tracking system to keep the PV panels pointing toward the sun, increasing their daily electricity output by up to 35%. The project cost approximately $150 million.

Portugal relies heavily on imported fossil fuels and has implemented aggressive incentives for renewable energy installations. A key component of Portugal's "Energy Efficiency and Endogenous Energies" (E4) program is a feed-in tariff of $0.317 to $0.444/kWh for both ground-mounted and rooftop solar power systems with a 15-year power purchase guarantee. Adopted in 2001, the E4 program is expected to provide 4,400 MW of renewable energy by 2010, 150 MW of it in the form of PV.

Central-Station Tracking PV in Portugal (Credit: SunPower)

forecasted substantial improvements in cost-performance characteristics could position central-station PV deployment as a cost-competitive non-emitting generation alternative, shifting the dispatch order for current units and eroding the market share of competing options for new capacity additions. The biggest business opportunities may lie in planning for this scenario and, possibly, in securing a stakehold by supporting the development of future proprietary hardware.

The cost structure of PV technologies does not contain a single dominant factor whose elimination or substantial reduction would render their capital-equipment investments competitive with more conventional generation options on a widespread basis. Rather, there is a complex of factors, ranging in both degree of leverage and time-scale of effectiveness, which must all be addressed to achieve the goal of cost-competitive, globally significant PV power generation. For PV to proliferate and achieve its potential, incentives must remain in place, remaining policy and market barriers to deployment must be cleared, and major R&D investments must be made to reduce the costs of crystalline silicon, thin film, and CPV technologies and advance third-generation concepts.

Market-transforming policy measures have the most immediate effect by encouraging otherwise uneconomical early deployments and thereby accelerating "learning curve" advances where costs are reduced as production volume is increased. However, the cost reductions associated with manufacturing efficiencies and improved economies of scale are often incremental. Thus, policy incentives offer relatively little leverage on PV costs. They also entail the risk of retarding price declines by overstimulating market growth and pushing demand ahead of supply, as has happened with crystalline silicon PV over the past couple of years.

Improving the efficiency of PV cells and modules is the most effective route to increased cost-competitiveness. More power can be generated per unit of module area, and the required scale of nearly every system component can be reduced. Thus, even incremental efficiency gains affect total cost in a more-than-linear fashion. Improved efficiency also offers the promise of major cost reductions because breakthroughs would allow several times more energy to be harvested per unit of module area.

For the near and intermediate term, continued policy incentives and aggressive R&D—especially in manufacturing—are critical to continue the evolution of existing PV technologies, modules, and integrated systems for distributed generation. In an era of enduring public awareness of energy and environmental issues, it seems likely that third-generation PV concepts can sustain a critical mass of public R&D support over the next quarter century, the likely time required to advance those offering the greatest commercial potential. Already, smart, adaptive businesses as well as entrepreneurs are being attracted to the opportunities presented by investing in PV technology to respond to and anticipate tightening RPS and emissions requirements.

Favorable long-term outcomes may be effectively accelerated by a focused R&D program dedicated to identifying the easiest routes to terawatt-scale deployment of PV devices offering efficiencies greater than 50%. The complexity of the tasks required to bring the technology from concept to commercial reality—in terms of highly efficient and cost-competitive devices—makes the development timeframe unavoidably long, measured by the decade rather than year or month. Coordinated efforts by public and private stakeholders will be required to share in the costs and technology risks associated with meeting society's long-term needs for clean generation.

Grid-Connected PV in California

Technical issues beyond module cost and performance also must be addressed. EPRI, in collaboration with many others, has been studying the potential impacts of PV and other intermittent generation sources on grid operations over the past 30 years. Results indicate that today's distribution networks, which were not designed to accommodate numerous small-scale, intermittent generating units, can operate with moderate levels of PV penetration (nominally at least 10% to 15% of local loads) without negative effects. The full range of grid impacts at much higher penetration levels is not yet well understood, but PV-ready and PV-enabled systems clearly will require automated controls and sophisticated communications hardware that are not in place and may not even exist today. Besides new hardware, these grids will need novel operational strategies, new analytical tools, and forecasting methods like those developed for wind power. Field data from experimental trials and large-scale applications will be needed to assess deployment options and determine the business potential of aggregating distributed and central-station PV with wind, hydro, DSM, plug-in hybrids, and other technologies. Delivering output from central-station PV systems deployed in remote areas to serve loads elsewhere will necessitate transmission system expansion, along with equitable rules for cost allocation. Lower-cost, higher-performance storage systems will help transform intermittent sources such as PV into more valuable grid assets.

Collaborative R&D Responses

EPRI recently formed a Solar Electric Interest Group (SEIG) to bring utility, industry, technology, and other experts together to explore common interests, issues, opportunities, and challenges relating to solar power. The SEIG supports peer interaction and discussion regarding current PV technologies, applications, and market developments, as well as roles for PV in meeting RPS requirements and other business needs. SEIG participants also benefit from early access to results from solar energy R&D being performed by EPRI and others.

A couple projects funded through EPRI's Technology Innovation Program are pursuing novel near-term PV applications. In an ongoing demonstration, PV is being used to power advanced wireless sensors deployed for online monitoring of aging substation components. Specifications for a nanotechnology-enabled lithium-ion battery energy storage system are currently being developed to support 2008 demonstration of a dispatchable rooftop PV system offering both consumer and grid benefits.

The Renewable Systems Interconnection (RSI) study, a comprehensive project launched by the U.S. DOE in early 2007 in conjunction with EPRI and other stakeholders, addresses technical and analytical issues associated with supporting widespread PV deployment at the distribution level and, eventually, on the transmission system. Initial results appear consistent with earlier studies indicating minimal grid effects for penetration of intermittent PV systems at 15% or 20% of total regional capacity and for much higher penetration levels if PV systems are served by storage technology. RSI work also addresses the state of the art and R&D needs relating to operational and planning tools, storage and interconnection technologies, and business models. Findings are to be published in a series of 2008 reports.

To assist the industry in understanding, monitoring, and accelerating development of third-generation PV technology, EPRI launched the "High-Efficiency PV Research Project" in early 2007 in collaboration with Electricité de France (EDF) and others. Initial effort focuses on modeling and experiments to evaluate advanced materials and structures for their capacity to achieve conversion efficiencies exceeding 40%. This work will build on worldwide R&D activities, including the $21.7 million DOE program announced in November 2007 to support basic research and pre-commercial development for third-generation concepts, with the goal being to produce prototype devices and manufacturing processes by 2015. The EPRI-EDF project will evaluate progress under this program and others to support creation of a technical roadmap defining the further R&D required to bring a preferred PV device concept to market.

Clearly, PV technology is headed for increasing relevance to, and significant impacts on, the electric sector. Utilities and other businesses that attentively track its progress are most likely to be successful in addressing the challenges it will create and benefiting from the opportunities it will bring. Substantial and sustained R&D commitments to advance all aspects of the technology—from PV modules and auxiliary hardware to their interconnection with grid operations, power markets, and business systems—are yet needed to establish PV as a globally significant contributor to the world's portfolio of low- and non-emitting generation options. EPRI is committed to being on the forefront of PV development and application and to highlighting emerging issues and transferring key findings to utilities and other stakeholders.

EPRI Contact

Tom Key, Technical Leader, Renewables & Hydro
tkey@epri.com
865.218.8082

EPRI Resources

Solar Electric Interest Group (www.epri.com/SEIG)

Recent Publications

High-Efficiency Photovoltaic Research Project (1015473), 2007

Renewable Energy Technical Assessment Guide— TAG-RE: 2006 (1012722), 2007

Program on Technology Innovation: Strategizing a New Approach to EPRI's Solar Electric Research (1014603), 2006

Solar Electric Interest Group (1014470), 2006

Other Resources

U.S. National Renewable Energy Laboratory Photovoltaics Research (www.nrel.gov/pv)

U.S. Department of Energy Solar Energy Technologies Program (www.eere.energy.gov/solar)

Solar Electric Power Association (www.solarelectricpower.org)

Solar Energy Industries Association (www.seia.org)

European Photovoltaic Industry Association (www.epia.org)

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

1016279 December 2007

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com