Mobilizing the nation's resources
to develop reliable and affordable
solar energy technoloigies

Solar Energy Technologies Program

Multi-Year Program Plan 2007–2011

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

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Solar Energy Technologies: Program Manager's Outlook

Welcome to this Solar Energy Technologies Multi-Year Program Plan 2007–2011 for the U.S. Department of Energy (DOE). This document's purpose is to delineate what the Solar Energy Technologies Program is attempting to accomplish, the activities it is pursuing to meet its goals, and how it will track its progress.

Solar energy is one of the most ubiquitous primary energy sources on earth. However, this solar energy must be harnessed and converted into other forms, such as electricity and heat, to do useful work. And it must be provided at a cost competitive with more conventional energy sources.

Realizing the sun's energy potential by developing more efficient, reliable, and less costly solar energy technologies and systems is the mission of our Solar Program. Improvements in solar technologies over the last three decades have yielded substantial early market successes for several solar energy market segments—and these successes are due in large part to the leadership and support of the DOE applied program. This Multi-Year Program Plan (MYPP) presents a comprehensive strategy that can yield even greater technological and economic successes for solar energy in even broader energy markets.

This document has been designed to meet the guidance and tenets set forth in the Government Performance Results Act (GPRA) and the President's Management Agenda, to make government more accountable to its constituents. To that end, DOE has asked us to use a prescribed format that will inform you about not just what we do—but also, why we have selected to focus on certain aspects of solar energy, and how we plan to measure and evaluate our progress along the way.

This 2007–2011 MYPP extends the work set out in our very first such plan, the Multi-Year Technical Plan 2003–2007. In this current edition, we have implemented the use of our systems-driven approach to guide us through difficult programmatic options and to make sound decisions considering limited resources.

In general, the Solar Program has moved from a technology-based program aimed at improving technology performance toward a more goal-oriented program looking to produce cost-effective solar energy systems. Using the analytical tools from our systems-driven approach, we have determined the cost drivers for each solar energy system within a specific target market. We have defined technical improvement opportunities (TIOs) that clearly identify the specific aspects of solar energy systems that will aid us in achieving our levelized cost of energy goals. We believe this will sharpen the Solar Program's focus in working with industry and get more cost-effective solar systems to the marketplace sooner.

The Solar Program's MYPP is organized into four sections. Section 1 provides a Program Overview, an historical context and market overview for solar technologies and markets, and an attempt to tell you the "why" of the Solar Program. The chapter provides an external (i.e., business or public) perspective on the history of solar energy, as well as an internal (i.e., DOE or government) perspective of the three decades of progress of solar energy. Furthermore, we have created a Program Performance and Accountability Framework to describe the specific goals and metrics for which the Solar Program will be accountable.

Section 2 presents the Critical Functions, a review of our tools and techniques that provide a rationale for the Solar Program. This chapter describes the systems-driven approach as a four-step implementation process and presents how the Solar Program has implemented this process. Additionally, we identify the specific target market prices, today's benchmarks, and the programmatic goals for the short-term (2011) and long-term (2020) for each solar technology and market. The benefits for the Solar Program, in terms of both macroeconomic and strategic importance to the nation, are spelled out in this chapter. Finally, a series of planning, analysis, and management tasks are defined to ensure that the Solar Program is continually being managed for performance and results. This chapter essentially answers the "why" and "how" programmatic questions in greater detail.

Section 3 presents the Technical Research Plan, the "what" of the Solar Program, as it describes the technical context and elements for each of the three main solar technologies: photovoltaics, concentrating solar power, and solar heating and lighting. For each of these technologies, which is within a subprogram of the Solar Program, the section highlights the following:

- Specific market and program histories for each technology
- Market-driven goals for each technology (benchmarked using a reference solar energy system) and each market segment
- Technical barriers and the strategies for overcoming them
- Tasks to implement programmatic strategies
- Key milestones and decision points to evaluate program progress and accomplishments.

Thus, this chapter represents a concise review of the specific implementation elements for the Solar Program over the next 5 years.

Section 4 presents Program Administration, describing how DOE administers the Solar Program and manages all of the program elements. Included in this section are elements of organization structure, accountability, financial management, environmental health and safety, and communications and outreach activities.

We hope you will find this document readable, informative, and insightful as to the activities we have chosen to focus on in our solar energy program. Our activities are constantly being reviewed and evaluated in light of national policies, market changes, and technology progress. As always, we welcome your comments and suggestions on both this Multi-Year Program Plan and our Solar Program's activities.

Thank you for your interest and we look forward to working with you to make affordable solar energy a reality for all!

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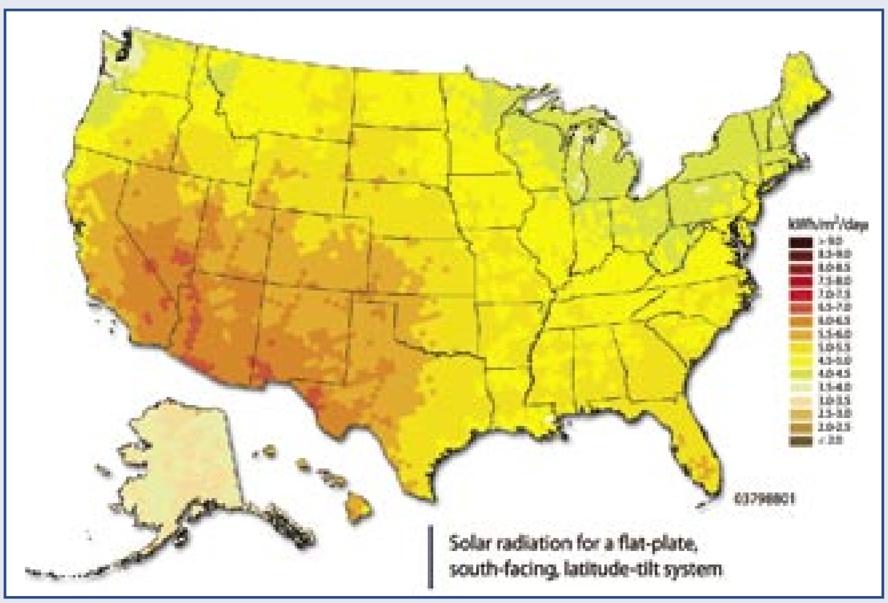
1.1 External Assessment and Market Overview

Solar energy is one of the most ubiquitous primary energy sources on earth. Throughout most of history, humans have depended on this energy derived from the sun for cooking and warmth. However, since the Industrial Revolution, we have relied on fossil fuels to power our machines developed for performing work, as well as for providing mobility and comfort. Unfortunately, these fossil fuels are finite and their extensive use appears to have significant, though uncertain, environmental consequences. For these reasons, we now look back to our heritage—and the potential for harnessing the sun's energy—to find a critical path forward and a major contributor to power our ever-growing high-technology society.

To supply significant amounts of energy to meet the needs of the modern age, solar energy must be collected and efficiently converted to more useable forms, such as heat or electricity, required for most applications. As illustrated in Fig. 1.1-1, solar energy is abundant across most of the United States, although most intense in the Desert Southwest.

Solar technologies can effectively power a substantial portion of America's residential, commercial, and industrial sectors. If every single-family home in America had a 3 kilowatt (kW) photovoltaic system on its roof, these combined homes could generate more than 420 billion kilowatt-hours (kWh) of electricity—more than 35% of the entire residential electricity demand for the United States. If every single-family home also had a 6-m^2 solar water heater, an additional 255 billion kWh of energy demand could be displaced. Considering an alternative scenario, it is estimated that a land mass of about 13,456 square miles—less than 0.5% of the U.S. mainland land mass, or about 25% of the area currently used for the nation's highway/roadway system—could provide as much electricity as presently consumed in the United States. The key to tapping into this vast, indigenous resource is in developing cost-effective solar energy systems that can harness the sun's energy and turn that energy into useable forms of work. In essence, this is the rationale and purpose for the U.S. Department of Energy's Solar Energy Technologies Program (or Solar Program).



Solar radiation for a flat-plate, south-facing, latitude-tilt system

Solar Energy: Available Across the Entire Nation

Annually, the average solar resource across the United States is 1,800 kilowatt-hours per square meter (kWh/m^2). The most intense resource is in the Desert Southwest, at 2,300 kWh/m^2. However, this is only about 25% higher than the nation's average. Interestingly, solar energy can actually be more cost effective in New York than in Arizona because electricity prices may be 50% higher in New York than in Arizona.

The U.S. Department of Energy (DOE), recognizing this potential, has supported the development of solar energy for the past three decades. This support through the DOE Solar Program has delivered more than 30 years of success in improving energy technologies that provide both thermal energy (i.e., solar water heating) and electric power (i.e., concentrating solar power and photovoltaics). Improved solar technologies, due in large part to the leadership and support of the DOE program, have yielded substantial early market successes for several market segments.

Residential Solar Water Heating Market

Solar water heating (SWH) was used extensively in parts of the United States between the late 1800s and WWII, but the industry declined due to copper shortages during WWII and the rise of low-cost, widely available natural gas and electricity after WWII. During the energy crises of the 1970s, SWH markets experienced rapid growth, fueled by federal and state tax credits. Poorly designed incentives and a lack of standards led to sales of some expensive, poorly performing systems installed by inexperienced and sometimes unscrupulous firms. These problems hurt the reputation of the entire solar industry. When federal tax credits lapsed in 1985, the industry experienced a severe contraction. To help overcome some of these problems, DOE supported the establishing of the Solar Rating and Certification Corporation (SRCC) to test and certify the performance of solar collectors and systems. The SRCC, coupled with the shakeout of marginal producers, helped to reduce a major barrier to solar water heating—namely, reliability—and significant progress was also made in reducing costs. The SWH firms remaining today have high-quality products and good service records, although market penetration is very low in most of the United States. Areas with high electricity costs, significant solar radiation, and state incentives (e.g., Hawaii, Florida) have achieved substantial market penetration. Internationally, solar water heating is expanding rapidly in countries that have offered subsidies, have less-developed energy infrastructure, or both. SWH systems have achieved significant installation rates in countries as diverse as Israel, Turkey, and China.

Today, an estimated 6,000 solar domestic water heaters (for a total area of 25,000 m^2) are sold in the United States each year, with more than half the sales in Hawaii. By comparison, SWH is widely used in Germany, Israel, China, the Mediterranean countries, and elsewhere. For example, about 80,000 solar water heaters were sold and installed in Germany in 2003 due to an aggressive government policy on solar energy technologies. In the United States, pool

Solar Water Heating: Success Around the World

The energy conservation, environmental, and national security benefits of solar water heaters are recognized and appreciated around the world, as shown in the following table:

	Glazed Solar Thermal Area, Installed in 1999 (m^2)	% of total
China	4,000,000	43.3
India	2,000,000	21.6
Japan	1,000,000	10.8
Europe	890,000	9.6
South Korea	500,000	5.4
Turkey	430,000	4.7
Israel	400,000	4.3
USA	25,000	0.3
	9,245,000	**100.0**

Emerging economies such as China and India rely on solar water heaters to free up valuable electricity and fossil fuels for more productive commercial and industrial uses, while still meeting the demands of their growing economies. Nations with geographically or politically constrained access to energy (e.g., Japan, Israel) consider solar water heaters as integral components of their energy or national security policies. European consumers and nations appreciate the environmental benefits conferred by solar water heaters.[1]

[1] U.S. Department of Energy, with representatives of the solar water heating industry. *A 20-Year Industry Plan for Water Heating Technology: Solar and Efficient Water Heating, A Technology Roadmap, 2005.*

heating has maintained a strong, commercial market presence, with 750,000 m^2 of collectors being installed each year. Thus, many solar businesses have depended on the pool heating business for their livelihood. The key to stimulating these SWH markets has been policy incentives, as shown by data from overseas markets. The federal tax credit recently enacted by the Energy Policy Act of 2005 (EPAct 2005) should lead to stronger sales in the United States.[2]

Wholesale Electric Power Markets Using Concentrating Solar Power

Concentrating solar power (CSP) technology was established around the turn of the century, most notably by John Ericsson's work on solar-powered engines and reflectors. None of this work, however, led to a commercial product. Beginning in the 1970s, power plants using troughs, dishes, and towers were demonstrated in the United States and elsewhere, mostly supported by government funding.

CSP troughs have had the most commercial success, with the Solar Electric Generating Stations (SEGS) projects in California reaching a capacity of 354 megawatts (MW). The first plant, SEGS-1, was completed in 1985, and all nine plants continue to operate today. SEGS-1 also hosted a short-term test of thermal storage that proved the concept of extending the versatility and increasing the capacity factor of the plants.[3] Although the SEGS plants are still operating, the trough industry suffered a major setback in 1991 when Luz, the developer of SEGS, declared bankruptcy due to financial issues involving changes in tax laws and problems negotiating power purchase contracts for the SEGS plants.

A recent renewal of CSP commercial activity has occurred in the United States and Spain, with U.S. plants under construction in Arizona (1 MW) and Nevada (65 MW). In the interim, the CSP industry has continued to build a small number of parabolic trough systems serving thermal loads such as domestic water heating for commercial and institutional applications. Significant progress has also been made on reducing both component costs and operating and maintenance (O&M) expenses associated with trough plants. Larger plants with larger power blocks will further reduce costs. Advanced thermal storage, using molten salt, has been demonstrated and can be used to provide the dispatchable power desired by the electric power industry. Cost of power from a new trough plant built today is estimated to be 12–14¢/kWh.

Solar power towers were developed through a number of system configurations using various working fluids, including water/steam, air, sodium, and molten nitrate salts. The 10 MW Solar One power tower (a water/steam system) and its successor, Solar Two (a 10 MW molten salt system with thermal storage), demonstrated the technical feasibility of generating power 24 hours per day and established the feasibility and value of thermal storage. The 10 MW size was never expected to be a viable commercial-scale plant and, in fact, did not validate economic feasibility. And after successful experimentation, Solar Two was retired. The substantial investment needed to build a commercial-scale plant of 50–100 MW has been an obstacle to commercialization, and at this time, there are no plans for a U.S. plant. Spain is likely to be the first site of a commercial plant.

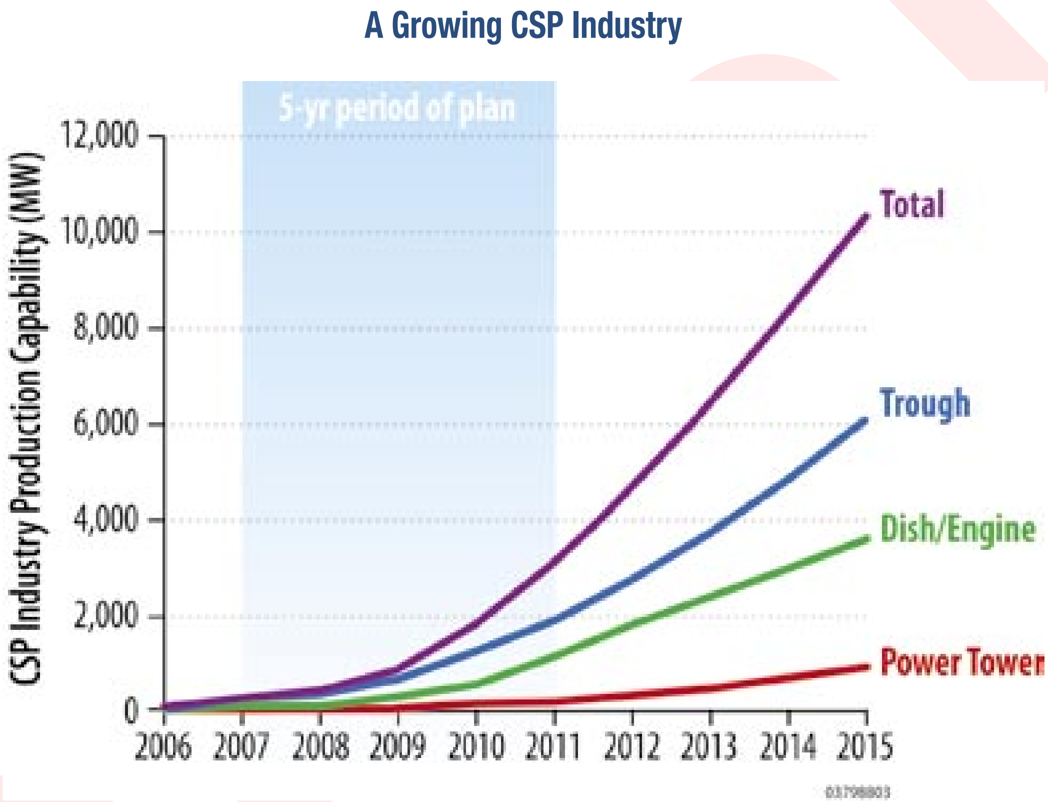
Since the late 1970s, dish/engine technologies have seen several demonstrations and pre-commercial deployments, but as of yet, no significant market deployment has occurred. A prototype six-dish, 150-kW, small-scale power plant has been built with private funds and is now operating at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories. The prototype-plant experience successfully reduced the capital cost of these systems. A major objective of these systems is to gain operational experience to improve reliability and reduce O&M costs. In August 2005, Edison International, a subsidiary of Southern California Edison (SCE), Rosemead, CA, and Stirling Energy Systems (SES) of Phoenix, AZ, announced the signing of a 20-year power purchase agreement to develop a 500-MW dish/Stirling power plant. The plant, which includes an option to increase the size to 850 MW, is to be located 70 miles northeast of Los Angeles near Victorville, CA. Initially, SES will build a 1-MW test facility using 40 of the company's

[2] The Energy Policy Act of 2005, signed into law on August 8, 2005, establishes a 30% residential tax credit for PV and solar water heaters, to be capped at $2,000/system during the period of 1/1/06 through 12/31/07.

[3] Thermal storage is not currently in use at SEGS-1.

37-foot-diameter dish assemblies. Subsequently, an array comprising 20,000 dishes will be constructed during a 4-year period. The agreement is subject to the review by and approval of the California Public Utilities Commission.

CSP markets are being driven by new policy incentives and technology improvements, with resulting renewed worldwide market interest. The Western Governors' Association has a 1,000-MW CSP initiative that is expected to lead to additional market growth in the United States. Meanwhile, favorable power purchase agreements are leading to commercial projects in Spain, and European suppliers are competing with American suppliers for these markets.



The production capability of the CSP industry is estimated to grow significantly through 2015. This estimate represents a cumulative 10.3 gigawatts (GW) of additional peak capacity.[4]

Solar Electric Power Markets Using Photovoltaic Technologies

The first efficient crystalline-silicon solar cell was demonstrated in 1955 by Bell Labs and later improved to provide power for satellite applications. In these space applications, however, cost was not a primary issue, and although early research on PV technology provided major technical advances, the technology was much too expensive for terrestrial energy markets. When the DOE solar research and development (R&D) program began during the 1970s, solar electricity costs were roughly $2/kWh and PV technology was mainly a power source for satellites and high-value remote applications (e.g., powering navigation lights and warning horns on oil platforms, and cathodic protection for natural gas production in remote areas).

[4] *Draft WGA Solar Task Force—Central Solar Working Group Report,* August 9, 2005. The dish curve includes both the dish/engine and CSP manufacturing capability.

Improved PV efficiencies and lower costs have caused the PV market to expand rapidly to include utility, distributed generation, and building-integrated applications. Also, PV is often the power source of choice for remote applications, based on cost and proven reliability. However, in 2000, a major milestone occurred when grid-connected PV applications decisively surpassed sales for remote applications. Looking at the big picture, in 1976, annual worldwide PV shipments totaled 0.32 MW. But by 2004, annual worldwide PV shipments surpassed 1000 MW for the first time, and annual growth hit a staggering 60%.

PV markets have emerged in five key segments, each of which has its own unique characteristics, as summarized in the following:

- **Grid-Connected Distributed Power: Commercial and Residential—**This market provides electricity for primary use in commercial and residential buildings. It has experienced accelerated growth since the 1990s and is currently the fastest-growing market segment for solar energy. Significant growth potential is forecasted for this segment.
- **Grid-Connected Central Power—**This market for large-scale solar power plants feeds into the utility grid and provides electricity for communities, cities, or both. Driven by federal subsidies in the early 1980s, utility-scale solar plants experienced rapid growth that eventually fell off. In terms of technology, considerable overlap exists today between “utility-scale” and “commercial-scale” solar systems, especially for PV power plants. Significant growth potential exists, but achieving this potential will require significant cost reductions in all aspects of PV systems.
- **Remote Power: Habitation—**This secondary medium-value market is driven by the need to provide electricity with higher reliability in areas where access to power from transmission lines is prohibitively expensive. International markets such as in India and China are likely to grow quickly. However, institutional and political barriers must be overcome to realize this market potential.
- **Remote Industrial Power—**Applications such as cellular telephone repeater stations, emergency call boxes, highway sign boards, and other industrial applications currently represent the highest value for solar PV applications, and solar is the dominant power supply of choice for most of these applications. Moderate growth potential continues to be forecasted for these segments as market saturation nears.
- **Consumer Products—**This early high-value market for PV technologies provided electricity for low-power devices including watches, calculators, toys, lights, and other consumer products. These markets grew significantly during the 1970s and 1980s and have achieved saturation. Limited growth potential exists for this market segment.

As shown in Fig. 1.1-1, the global PV market is expected to grow rapidly during the next couple of years, reaching a production level of roughly 6 GW by 2010. The grid-connected residential and commercial market sectors are expected to be the primary drivers of growth globally during the next 5–10 years. Most analysts have similar expectations for the United States—with California leading the way, followed by New Jersey and other states that have aggressive solar programs. As noted in the recent U.S. PV Industry Roadmap, the domestic PV industry is expected to parallel the growth in the global PV industry during the next 5–10 years.[5]

[5] *U.S. PV Industry Roadmap Through 2030 and Beyond.* September 2004.

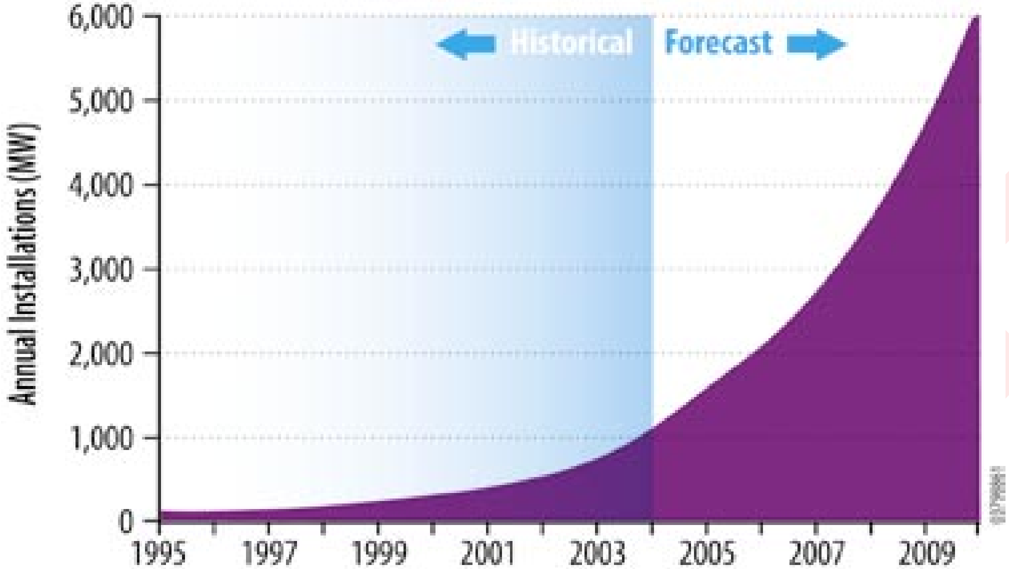


Fig. 1.1-1 Global PV market forecast.
Historical data (1995–2004) from Strategies Unlimited. 2005. "Photovoltaic Manufacturer Shipments 2004/2005" Report PM-57 (April). Projected data (2005–2010) from M. Rogol and B. Fisher. 2005. "Sun Screen II: Investment Opportunities in Solar Power." CLSA (July).

The technical potential[6] for distributed PV in the United States is very large. For example, a recent analysis by Navigant Consulting and Clean Power Research estimated the technical potential for PV on residential and commercial rooftops to be 540 GW in 2003.[7] This technical potential is expected to grow over the next 20 years due to growth in new constructions and increased power density (i.e., higher-efficiency PV cells) to 1,000 GW in 2025. Even if the PV industry's very high annual growth rates in excess of 30% experienced over the past decade can be sustained over the next 10–20 years, there will still be significant room for the PV industry to grow. For example, the U.S. PV Industry Roadmap projects a cumulative installed capacity of 36 GW of PV by 2020 under its "Roadmap" scenario, which includes expanded R&D investments, as well as aggressive federal policies. This capacity is less than 5% of the technical potential for PV.

Although the prospects for growth in the PV industry are significant, many factors could influence how rapidly U.S. markets expand. First is the need to realize a significant reduction in the cost of PV systems via R&D, manufacturing improvements, and reduced installation costs. Second, the volatile nature of fossil fuel prices, coupled with increasing concerns over environmental impact from the burning of hydrocarbons, will lower the economic hurdle that solar technologies need to clear. Third, reducing institutional barriers, including the lack of interconnection standards for distributed energy and allowing net-metering provisions, will open market opportunities. Finally, progressive clean energy policies in state and federal legislation will jump-start and accelerate emerging solar markets.

Thus, despite significant progress over the past three decades, much research, development, demonstration, and deployment work remains. While industry's R&D investments have led to significant product and technology improvements, the federal government has also played an important role in helping to bring the solar industry to where it is today. And it will also play an important role in helping solar energy achieve its potential, working with industry to capture market opportunities, and ultimately, enabling solar energy to deliver significant benefits to our society and nation.

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6 Technical potential for distributed PV on buildings takes into account material and structural compatabililty, as well as shading and orientation limitations.

7 M. Chaudhari, L. Frantzis, and T. E. Hoff. *PV Grid Connected Market Potential in 2010 under a Cost Breakthrough Scenario.* Navigant Consulting and Clean Power Research (Study for the Energy Foundation). September 2004.

1.2 Internal Assessment and Program History

Under the Solar Energy Research Act of 1974, predecessors to the Solar Program began conducting solar research in response to the first “energy crisis” that resulted from the Arab oil embargo. Skyrocketing oil prices shocked America and encouraged a search for energy independence and new domestic energy sources. Solar energy was considered a strong alternative to traditional fossil fuels in several markets, and federal involvement focused on rapidly developing and demonstrating solar technologies, coupled with federal and state tax credits to spur deployment. Federal and university laboratories pursued a wide range of solar technologies, and facilities such as Sandia National Laboratories’ National Solar Thermal Test Facility were constructed. In 1977, the Solar Energy Research Institute (SERI) began operation as a laboratory dedicated to renewable energy R&D. In 1991, SERI was designated a national laboratory and subsequently renamed the National Renewable Energy Laboratory (NREL).

A major strength of the Solar Program has been a consistent and balanced R&D portfolio, with continuing research support for near-, mid-, and long-term technologies aimed at reducing cost and increasing performance and reliability. The total funding appropriated for solar research since DOE was established has been $5.8 billion.[8] Of that total, $2.7 billion has been spent on photovoltaics research, $1.7 billion on concentrating solar power research, and $0.8 billion for solar heating and lighting and other buildings-related research.[9] The remainder ($0.6 billion) was spent on solar-related technology transfer, international efforts, and other activities.[10]

In the early 1970s, a “gold rush” mentality was evident in the push to demonstrate the feasibility of solar technologies. When energy prices moderated in the 1980s, the technical feasibility of the technologies was proven, but the cost of the solar option remained too high. At this point, the DOE program focused on sustained technological improvements, maintaining its efforts to improve the technology base via R&D, while waiting for conventional energy costs to rise to where solar technologies could be competitive. These patient efforts paid dividends by capturing substantial high-value markets, and solar energy technologies are poised to capture an increasing portion of conventional energy markets.

The Photovoltaics Subprogram embarked on a program to improve the fundamental materials science and engineering physics of PV cells and modules to achieve greater conversion efficiencies. Furthermore, a parallel public/private partnership to reduce the cost of cell and module manufacturing successfully drove down the costs of these components. In the early 1990s, the program worked with the electric utility industry to demonstrate various applications of PV systems via the Utility Photovoltaics Group. All these activities helped to drive down the costs of the technologies and achieve high-value market penetration. Today, the DOE PV effort focuses on further reducing the overall systems costs (including inverters and balance of systems) and rapidly expanding the market acceptance of solar electric technologies.

In the 1980s, the Concentrating Solar Power Subprogram focused on demonstration projects, culminating in the early 1990s with the construction of the Solar One and Solar Two plants. A parallel R&D effort evaluated several innovative solar-collector concepts (e.g., bowls). One technology emerging from this evaluation was the dish/Stirling system as the preferred low-cost option relative to Brayton and organic Rankine dish/engine options. Due to budget considerations during the last decade, the subprogram focused its efforts away from the higher capital-cost tower technology and continues to work on reducing the costs of both the CSP trough and dish/engine technologies.

Solar water-heating efforts evolved from the first-generation systems of the 1970s, which had mixed success in the marketplace. The DOE program focused on standards and certification for improving reliability, worked on improved

[8] *U.S. Department of Energy: FY 2002–FY 2006 Congressional Budget Request.* Office of Management, Budget and Evaluation. *U.S. Department of Energy: FY 1978–FY 2001 Power and Delivery Sector–Historical Budget by Line Item.* Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. 2001.

[9] Ibid.

[10] Ibid.

materials for longer-life systems, and worked with the industry to better understand the water-heating market. Currently, the R&D efforts focus on active systems that can operate in freezing climates and on passive systems that are lower cost by eliminating copper and other expensive materials.

These R&D strategies have resulted in the Solar Program significantly lowering the cost of solar technologies (with continued lowering of costs projected, as shown in Fig. 1.2-1). However, the magnitude of the U.S. solar market forecasted in the 1970s and early 1980s has yet to materialize, primarily because fossil fuel prices have never approached the levels predicted at that time. R&D alone cannot sufficiently lower the cost of solar technologies to enable them to compete with fossil fuels. Deployment is also an integral part of cost reduction. Today, DOE and the states are partners in moving solar technology into energy markets—with DOE providing the R&D, and the states providing the incentives for deployment through renewable portfolio standards and other market mechanisms. Additionally, EPAct 2005 leverages the states' initiatives by providing tax credit incentives.

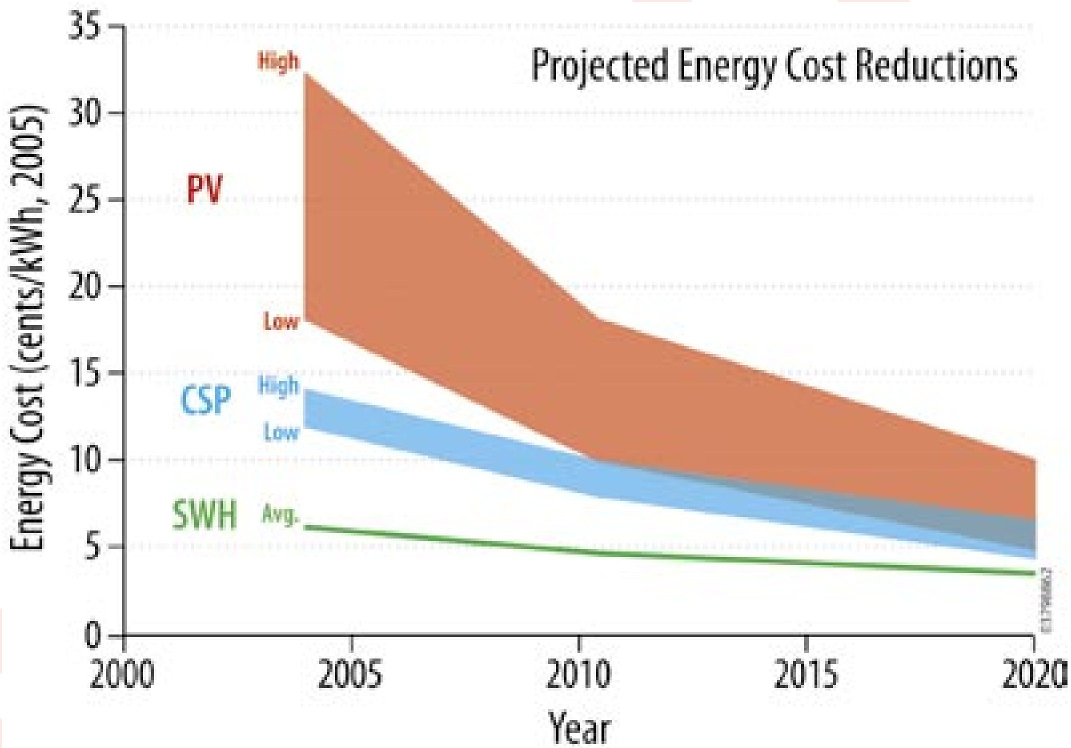

Fig. 1.2-1 Solar technologies cost curves.

1.3 Program Justification and Federal Role

Despite fluctuating budgets and differing national energy strategies, the Solar Program has pursued scientific progress resulting in the emergence of more cost-effective solar energy technologies. Solar energy continues to get the highest marks in the public's consciousness, as it remains the most popular choice in surveys about where the United States should obtain its energy in the future. Thus, despite its drawbacks of intermittency and higher cost, solar energy remains for many the "holy grail," holding out the vision that we can obtain all of our nation's energy needs from the sun.

A primary goal of the Bush Administration's National Energy Policy of 2001 is adding diversity to our nation's energy supply. Although solar energy is the largest renewable resource available in the United States, it provides very little of the 7% of the renewable energy currently produced (where hydropower is the predominant form of renewable energy).

Solar energy is available in all regions of the country and can provide significant amounts of energy in New York and Minnesota, as well as Texas and California. The distributed nature of solar energy promotes national security, as solar technology will be placed on the roofs of homes and office buildings throughout the country, in addition to powering central-generation plants much smaller than fossil or nuclear power plants. The increased use of solar energy will yield a cleaner environment and reduce the amount of greenhouse gases emitted to the atmosphere. Using more solar energy lessens the need for imported fuels, thereby reducing the country's trade deficit, and it creates thousands of jobs needed in the United States for manufacturing, installation, operating, and servicing the technology. The National Energy Policy envisions a future energy portfolio that provides a cleaner environment, stronger economy, and sufficient supply of energy for the country's future. The Solar Program is developing technology that will harness a renewable energy supply that meets all three of those goals.

In summary, the federal case for research and development of solar energy are clear and compelling. The reasons to continue R&D in solar energy technologies include:

1. Solar energy represents an opportunity for diversifying our primary energy requirements to meet our future electricity demand. Solar energy can strengthen our national security (in terms of domestic energy production) and energy security (in terms of diversification, decentralization and price stability).
2. Solar technologies will create jobs in high-tech manufacturing, installation, and operation of solar power plants and systems.
3. Realizing solar energy's potential will take a concerted R&D effort via a public/private partnership to reduce the cost of solar energy systems and to maximize solar energy's impact over the next 20 years.
4. Only the federal government can provide the leadership and continuity to assemble the necessary equipment, test facilities, talent, and staff to keep the technologies progressing toward the Solar Program's goals and for positioning solar technologies to meet the demands of more-competitive energy markets.

The DOE Solar Program responds to these needs by providing core scientific, engineering, and technical facilities, while engaging industry and its expertise in technology commercialization and bringing new products to the marketplace.

1.4 Solar Energy Technologies: Program Performance and Accountability Framework

The Solar Program Performance and Accountability Framework (PPAF) explains the strategic context of the Solar Program by providing a framework matrix divided into two halves. The first half is driven by the program's mission and includes performance goals and outputs for which the DOE program is specifically accountable. The second half is driven by the program vision and outlines the strategic goals and expected outcomes of the program if it is successful in achieving its goals and outputs, recognizing that this future depends on market and other factors for which the program is not accountable. Figure 1.4-1 provides the specifics of the PPAF.

Mission The mission of the Solar Energy Technology Program (Solar Program) is to improve America's security, environmental quality, and economic prosperity through public-private partnerships that bring reliable and affordable solar energy technologies to the marketplace.	**Vision** Millions of homes and commercial buildings across the nation use solar technology to provide all or much of their energy needs. Solar power plants in Sun Belt states generate electricity for local needs and export to other states. Solar-driven thermochemical and photolytic processes produce hydrogen to meet fuel and chemical needs.
Performance Goals for 2011 • 16.5% commercial US c-Si modules ($1.60/W production cost) • 13% thin-film modules capable of US commercial production • 14.2% efficient CSP trough/receivers (LCOE 9–11¢/kWh) • Low-cost SWH collectors operable in freezing climate (LCOE at 5–6¢/kWh_{eq})	**Strategic Goals** Improve performance of solar energy systems and reduce development, production, and installation costs to competitive levels, thereby accelerating both large-scale usage across the Nation and to make a significant contribution (GWh) to a clean, reliable and flexible U.S. energy supply.
Outputs Nested milestones from MYPP	

Outcomes (¢/kWh or eq.)	2011	2020
PV (30-yr user cost)	13–22	5–10
CSP (large-scale plants)	8–10	3.5–6
SHW (freezing climates)	5–6	n/a

Fig. 1.4-1 Program Performance and Accountability Framework (PPAF).

	Photovoltaics	Concentrating Solar Power	Solar Heating and Lighting
2006	Conduct a thorough PV portfolio review and prioritize activities necessary to achieve PV Subprogram goals. Go/no-go decision points.		
2007		Field validate improved reliability of trough receiver with thermal efficiency greater than 78%.	
2008	For all PV technologies and system configurations receiving support from the Solar Program, demonstrate and document (through SDA analysis) the relative levels of risk of achieving their respective 2011 performance, cost, and reliability targets. Go/no-go decision points, or revised strategies.	Assess dish/engine systems.	Complete fabrication of collector and/or system full-scale prototypes (for cold-climate SWH systems).
2009		Demonstrate field performance of advanced trough receiver with overall thermal efficiency > 82%.	
2010		• Assess trough systems. • Demonstrate 1000-hour MTBI and 4000-hour MTBF.	Complete fabrication of collector and/or system full-scale prototypes (for combined heating and cooling systems).
2011	• Develop new high-tech pre-commercial inverter design for a commercial and utility application, demonstrating 96% overall performance and 15-year lifetime. • Verify c-Si direct module manufacturing cost of $1.60/Wp ($260/m² at 16.0% efficiency). • Demonstrate factory integrated PV systems for commercial applications capable of producing electrical energy at $0.11/kWh.		

Fig. 1.4-2 Major Solar Program outputs for 2006–2011 representing key milestones that will lead successfully achieving performance goals.

1.5 Solar Program Approach

The future of solar energy technologies rests on developing a portfolio of technologies that can address America's energy needs—technologies that increase and diversify domestic energy supply, while having little or no effect on the environment. Their future is driven by the price trends of oil and gas impacting traditional energy markets, continued technology and market development that brings down their costs and improves their performance, and their ability to provide value to customers and contribute to both electric system and individual customer energy reliability as distributed energy technologies.

The DOE Solar Program is central to ensuring continued technological progress so that solar energy is in a position to capture its greatest share of energy market segments. The overall goal of the Solar Program is to develop technology and help reduce market barriers to the point where the cost of solar energy becomes competitive in relevant energy markets—principally in the buildings and power-plant markets. The program's strategic and performance goals are specifically targeted to achieve market competitiveness in these two segments.

Despite consistently improving solar technology development and systems engineering, one must recognize that achieving the Solar Program's strategic goals is subject to significant risk factors that include:

- Costs of critical materials such as silicon or glass
- Labor costs and the costs of manufacturing, especially in the United States
- Currency exchange rates that affect our ability to compete with products manufactured overseas
- Price and availability of alternative technologies and conventional fuels
- International R&D and deployment efforts, many of which currently exceed U.S. efforts
- Financial incentives and other policies from both federal and state governments
- Interest rates and inflation
- State and local regulation, including codes and standards for buildings and communities
- Market participant withdrawal or entry.

In summary, the DOE Solar Program has completed this plan that represents a market- and performance-based program of technology and systems improvements with specific targets that will result in solar energy technologies being market competitive.

2.0 Program Critical Functions

This section overviews the Solar Program's functional structure, as well as the critical functions, which include portfolio decision-making, performance measurement, analytical processes, program evaluation, and expected program benefits. These critical functions are supported by the Solar Program's administrative structure, which is described in Section 4.0.

2.1 Program Structure

The R&D activities of the Solar Energy Technologies Program encompass three areas, as shown in Fig. 2.1-1, and the organizational structure includes three teams. The first team, Photovoltaics, is the largest of the R&D areas and includes key activities in Fundamental Research, Advanced Materials and Devices, and Technology Development. The Solar Thermal team includes two subprogram areas, Concentrating Solar Power and Solar Heating and Lighting. The third team is the Systems Integration and Coordination (SINC) team, which includes both program administration functions, as well as program planning and analysis functions.

Fig. 2.1-1 Solar Program organization.

2.2 Portfolio Decision-Making Process

The Solar Program follows a multi-step planning process based on the “systems-driven approach” (SDA). The purpose of SDA is to ensure that all technical targets for R&D funded by the Solar Program are determined from a common market perspective and set of national goals. Figure 2.2-1 shows the key steps in the portfolio decision-making process.

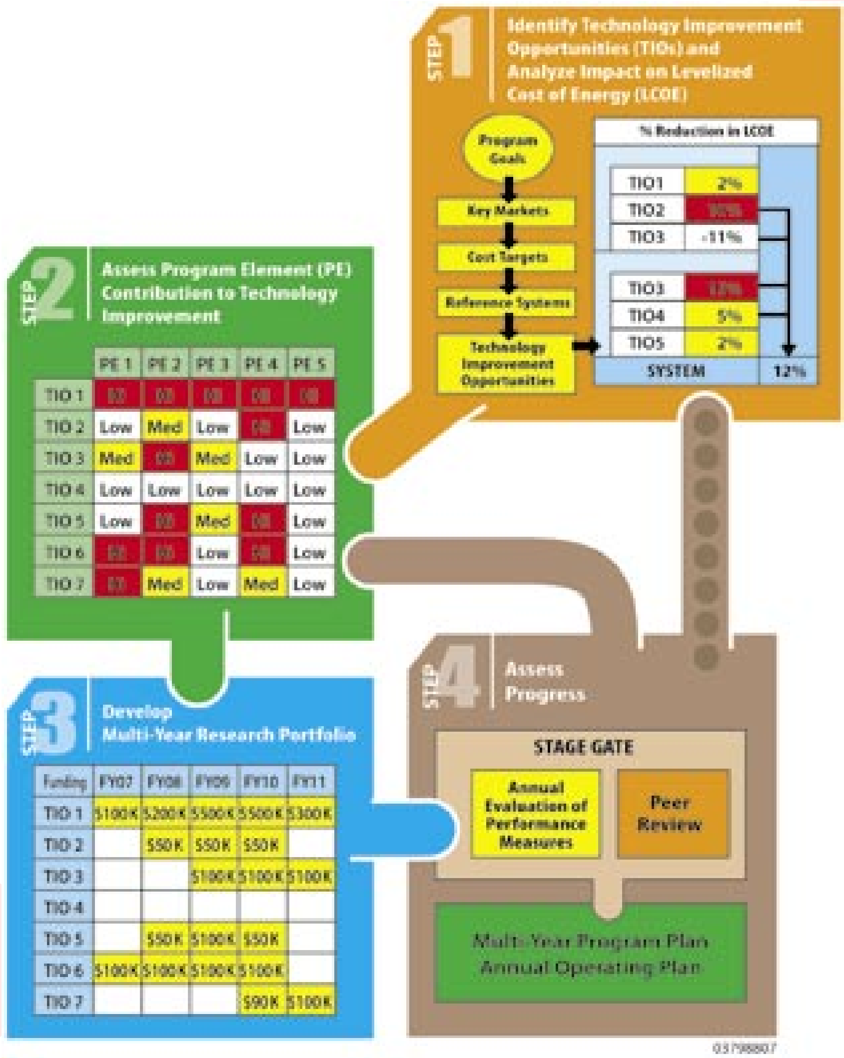

Fig. 2.2-1 Portfolio decision-making process.

Step 1—Identify Technology Improvement Opportunities and Analyze Impact on Levelized Cost of Energy

The Solar Program goals, as identified in Strategic Goals within the Program Performance and Accountability Framework (see Sec. 1.4), are to improve performance and reduce cost to enable large-scale usage of solar energy technologies. Markets with potential for large-scale deployment have been identified, and competitive cost targets have been established, as described in Sec. 2.3. Reference systems for each technology area have also been identified and are described in Sec. 3.1.5 for PV, 3.2.5 for CSP, and 3.3.5 for Solar Heating and Lighting (SHL). The reference systems provide a basis for analyzing the current state of technology for each application / technology combination and permit the use of Solar Program analytical tools in evaluating technology improvement opportunities. The reference systems also provide a benchmark against which future progress will be measured.

Technical improvement opportunities (TIOs) are identified for each reference system at the system, subsystem, component, and sub-component level. Each TIO is characterized by a set of key metrics, such as performance, cost, O&M, and reliability. For each reference system, a set of benchmark values for the metrics provides a quantitative representation of the current state of technology. Projected values of the metrics represent potential improvements based on Solar Program R&D efforts. The relative impact of each TIO on the reference system's levelized cost of energy (LCOE) is determined by calculating the LCOE using both the benchmark and projected values and comparing each TIO's contribution to changes in the LCOE. Current values of these metrics are derived from benchmarked data or engineering estimates. A variety of methods, including detailed modeling, engineering estimates, and consensus discussion, are used to identify possible improvements that are realistic to accomplish both within the timeframe of the Multi-Year Program Plan and based on reasonable assumptions for budget allocations.[1]

System analysis tools and methods described in Sec. 2.3 are used for the LCOE calculations. LCOE has been chosen as the *primary* system-level metric because it combines all the elements of system cost and performance into a single metric: ¢/kWh or equivalent.

Step 2—Assess Research Activity Contribution to Technology Improvement

Achieving a target for a particular TIO will often require support from a variety of program elements, where the word "element" is intended to include the terms "activity, project, agreement, and contract," as used in EERE's Corporate Planning System (CPS). Solar Program planners use the matrix shown in Fig. 2.2-1 to prioritize program elements in terms of the level of support provided to critical TIOs. Solar Program elements that contribute little to achieving technical targets, such as PE5 in the example in Fig. 2.2-1, are terminated. Those elements contributing the most are given the highest funding and management priority.

Step 3—Develop Multi-Year Research Portfolio

Having developed a prioritized list of program elements, program planners then formulate the Solar Program's research plan over the planning horizon, as illustrated in step 3 of Fig. 2.2-1. Planners must identify the set(s) of TIOs and associated program elements that will lead to achieving Solar Program goals. However, before dedicating Solar Program resources to any particular research effort, planners must also consider the following:

- Related research efforts under way with funding outside the Solar Program
- Technology advances that will occur with market growth
- Risk associated with various development paths
- Appropriate roles for federally funded R&D.

Step 4—Assess Progress

The state of the technology is benchmarked, and progress on all Solar Program elements is reviewed periodically, as discussed in Sec. 2.4. Information from these assessments provides feedback to the Solar Program planning process.

2.3 Program Analysis

The Solar Program carries out a wide range of analytical activities coordinated through the SDA to program planning. This analysis provides the tools and information for evaluating TIOs based on their ability to contribute to Solar Program technical and economic targets. The analysis includes cost and performance analysis to identify and evaluate the TIOs, and market analysis to set the technical and economic targets and to identify key markets.

For cost and performance analysis, an integrated model for systems analysis—the Solar Advisor Model (see Fig. 2.3-1)—is being developed that will permit analysis of all Solar Program technologies using a common modeling platform.

[1] This Multi-Year Program Plan was prepared assuming level budgets of $70 million for PV, $12 million for CSP, and $3 million for SHL.

The model allows analysts to investigate the impact of variations in performance, cost, and financial parameters on key figures of merit. The model is intended for use by DOE, laboratory management, and research staff in applying the SDA to program planning. The model may also be used by members of the solar industry to inform their internal R&D direction and to estimate systems cost and performance.

The Solar Advisor Model (Fig. 2.3-1) consists of four modules: (1) a user interface module for selecting and providing input data on the system configuration and operating environment, (2) a system performance module that simulates the hour-by-hour output of the selected system for the lifetime of a project, (3) a cost input module for providing simple or detailed cost inputs for system components, and (4) a financial analysis module for calculating system economics. The model integrates data from each module to calculate and display results, including such figures of merit as energy production, cost flows, and LCOE.

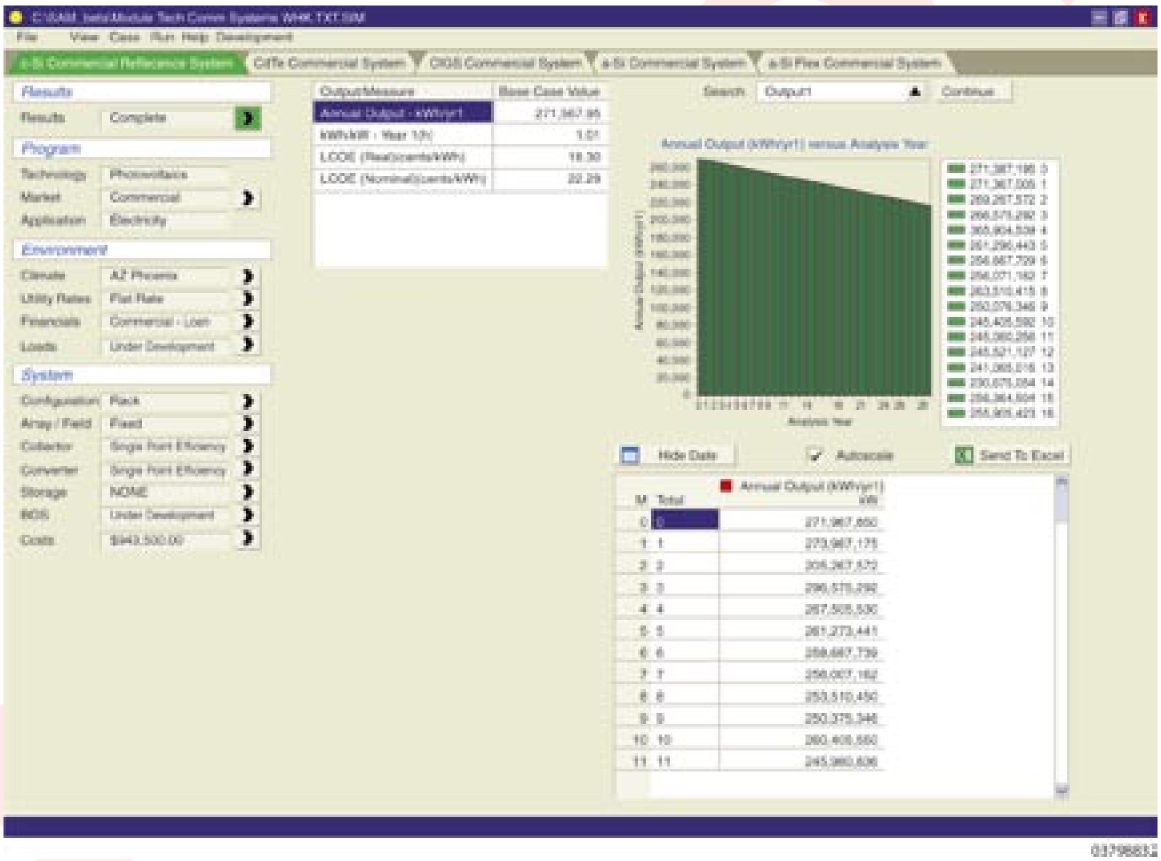

Fig. 2.3-1 The Solar Advisor Model user interface.

Solar Advisor was used to prepare the PV Subprogram section of this Multi-Year Program Plan. Existing spreadsheet-based cost and performance models were used for the CSP and SHL Subprograms sections. Future versions of Solar Advisor will integrate these CSP and SHL models into the common modeling platform.

Market analysis within the Solar Program focuses on three key areas: improving the understanding of long-term market potential for solar technologies, reviewing the Solar Program's technical and economic targets, and carrying out detailed value analysis of solar technologies. In developing long-term market penetration projections for solar technologies, the Solar Program is examining both the system and policy drivers of solar technologies in various markets in both the short- and long-term, as well as improving the analytical basis for projecting the Solar Program's economic and environmental benefits. For this analysis, the Solar Program uses existing models, including the Energy

Information Administration's (EIA's) National Energy Modeling System (NEMS), MARKAL, and other models. The Solar Program is also developing new models for market analysis to support the SDA.

The Solar Program's market analysis has identified the following markets as key to achieving a significant solar contribution to U.S. energy supply[2]:

- Electricity and hot water for residential and commercial applications (point of use on the customer side of the meter)
- Utility-scale electricity (tied to the electrical transmission and distribution system on the utility side of the meter).

The Solar Program's economic targets (see Table 2.3-1) were determined based on analyzing the key markets and were set based on assessing what the cost of energy needs to be for solar technologies to be competitive in these markets. The current market price range for dispatchable utility power (5.6–7.6 ¢/kWh) is based on the LCOE of new combined-cycle gas turbines (CCGTs) in the Southwest United States.[3] The EIA projects that the cost of new CCGTs will remain fairly constant (in real terms) through 2025.[4] Given that the Southwest has exceptional solar resources, combined with solar's time-production profile, this is a reasonable target market, i.e., to meet intermediate and peaking capacity/generation needs in the Southwest. The value of solar is affected by its intermittent nature. So solar energy plants without storage may not be eligible for capacity payments. Nondispatchable power has a current market price of about 4 ¢/kWh.

The target residential price range (8–10 ¢/kWh) and commercial price range (6–8 ¢/kWh) are based on current retail electricity prices. The full range of retail electricity prices is considerably wider: 5.8–16.7 ¢/kWh in the residential sector and 5.4–15.0 ¢/kWh in the commercial sector.[5] The narrower ranges chosen here reflect the fact that electricity prices are, on average, higher in the residential sector than in the commercial sector, and most electricity prices fall within a much narrower price band. The EIA's *Annual Energy Outlook (2005)* projects that electricity prices will remain fairly constant (in real terms) through 2025.

Table 2.3-1 Solar Market Cost Targets

Market Sector	Current U.S. Market Price Range (¢/kWh)	Technology	Cost (¢/kWh) Benchmark 2005	Target 2011	Target 2020
Utility	4.0–7.6	CSP	12–14	8–10	3.5–6
		PV	13–22	10–15	5–7
Commercial*	5.4–15.0	PV	16–22	9–12	6–8
Residential	5.8–16.7	PV	23–32	13–18	8–10
		SWH**	11–12	5–6	5–6

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* In many commercial applications, utility costs are tax deductible. In these cases, the cost of solar energy should be compared to the effective price, considering tax effects.
** SWH cost targets are for saved energy in freezing-climate applications for water heating (2005 and 2011) and space heating (2020).

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2 In the past, off-grid applications of PV have provided the high-value markets that have consumed most of the PV module production, worldwide and in the United States. The last few years have seen rapid growth of grid-connected PV applications, especially in the developed countries. These markets offer opportunities for widespread replication of system designs and applications. Off-grid applications remain an important part of the PV marketplace, and continued advances in PV modules will benefit these markets. However, at the system level, the multiplicity of off-grid applications and small market sizes, especially in the United States, do not suggest opportunities for high-impact use of Solar Program resources in achieving our goal of a significant contribution to U.S. energy supply. Additionally, solar hybrid lighting for commercial applications is of interest to the Solar Program.

3 The LEC for an advanced combined-cycle plant is currently 5.6 ¢/kWh at a capacity factor of 50% and 7.6 ¢/kWh at a capacity factor of 25%, under the following assumptions: Plant Size = 400 MWe, Heat Rate = 6422 Btu/kWh, Capital Cost = $599/kWe, Fixed O&M = $10.34/kWyr, Variable O&M = 2.07 mil/kWh, Burner Tip Gas Price = $5/MMBtu, 20-year Internal Rate of Return @ 12%, 15-year Debt @ 6%.

4 EIA's *Annual Energy Outlook (2005)*.

5 EIA, *Electric Power Monthly,* January 2005.

Table 2.3-2 lists the financial assumptions used to calculate the LCOE values presented in this Multi-Year Program Plan. The financial assumptions are typical values for a project using fully commercialized solar technology in 2005. These assumptions were used in the analysis of each reference system to provide a consistent basis for comparing the impact of different TIOs on LCOE. By comparing the LCOE of a reference system calculated using different technology improvement scenarios under the same financial assumptions, the relative value of each TIO was determined. LCOE is very sensitive to variations in the financial parameters, so for calculations of an absolute LCOE value for specific projects, it is critical to use financial assumptions that reflect actual project costs. However, in the analysis for this plan, it was more critical that the financial assumptions be consistent across reference systems so that the relative LCOE values reflected the relative value of different R&D options.

Note that many incentives, including federal tax credits, are currently available. These incentives were not considered when calculating LCOE from solar systems in this plan because of the following:

- State and local incentives vary from place to place
- Federal credits are scheduled to end in 2007, which is before the 2011 target for this plan.

Table 2.3-2 Financial Assumptions

Application	Residential	Commercial	Utility PV/CSP
General			
TMY* Reference Location	Phoenix	Phoenix	Phoenix/Barstow
Analysis Period (years)	30	30	30
Inflation Rate (%)	2.5	2.5	2.5
Real Discount Rate (%)	5.5	5.5	7.5
Taxes and Insurance			
Federal Tax (%/year)	28	35	35
State Tax (%/year)	7	7	8
Property Tax (%/year)	0	0	0
Insurance (%/year)	0	0	0/0.5
Financing	Residential Mortgage	Commercial Loan	Independent Power Producer
Debt (% Installed Cost)**	100	50	60
Term (years)	30	15	20
Rate (%/year)	6	6	6
Minimum Debt Service Coverage Ratio (%)			1.4
Equity (% Installed Cost)**			40
Internal Rate of Return (%)			15
Permanent Federal Investment Tax Credit (%)			10
Depreciation	n/a	MACRS***	MACRS***

*Typical Meteorological Year (TMY)
**Debt/Equity Ratio optimized to minimize LCOE
***Modified Accelerated Cost Recovery System (MACRS)

2.4 Program Performance Measurement and Assessment

Preparation of this Multi-Year Program plan is the first application of the systems-driven approach to Solar Program planning and optimization. A key part of the SDA is benchmarking, which establishes the current state of the progress and verifies progress. Benchmark data also provides validated input to the SDA models and is used to validate model output. Data collection spans all elements of life-cycle cost, including component and system performance, as well as cost of components, system design, installation, permitting, O&M, financing, and so forth. Analysis of the data provides the basis for cost and performance models.

The Stage Gate model,[6] shown in Fig. 2.4-1, complements the reference system / TIO approach, and the Solar Program will begin using Stage Gate as a program management tool during FY 2006. Under this tool, commitment of funding on a project is low at the start and increases as more work is done and confidence increases (through the Gate reviews) that the project will ultimately be successful. Initial efforts, such as exploratory research, focus on the most critical and uncertain elements early in the life of a project, thereby minimizing spending. Background studies, done to increasing levels of detail throughout the project, examine the potential for the technology, who will use it, its expected economics, and the anticipated effort to develop. These studies allow Gate Keepers (i.e., reviewers along the development path) to make the best judgment calls regarding spending increasing sums of money on the best projects. The expectation is that projects with significant technical and market problems are weeded out from the Solar Program's portfolio sooner rather than later. Therefore, the "big" spending is reserved for those projects that have the greatest potential for success.

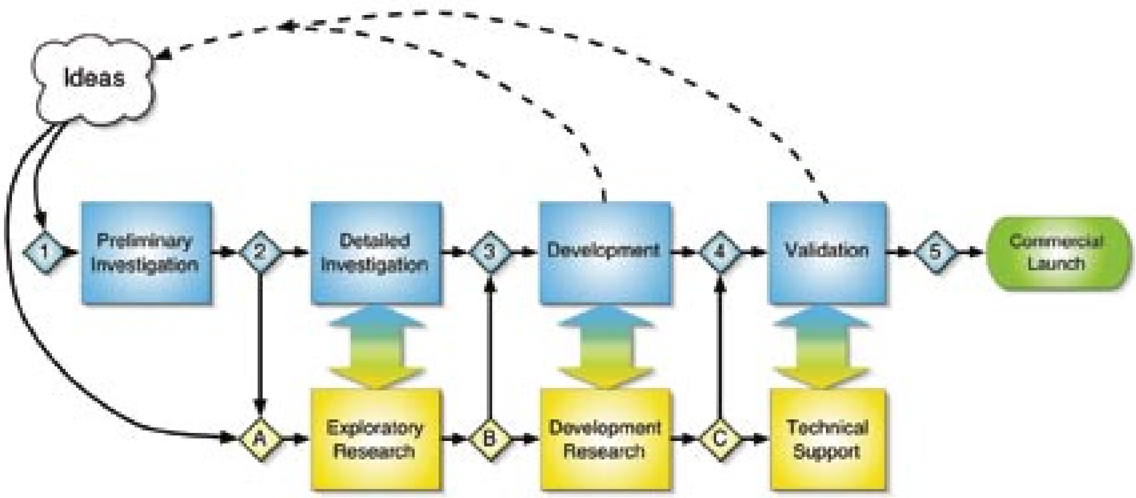

Fig. 2.4-1 The Stage Gate model.

Examples of Stage Gate-like program management are already found throughout the Solar Program, with projects moving through phases (or stages) and technologies being phased out (or "off ramped"). The SDA model will be used as part of the formal evaluation of the impact of program elements on Solar Program goals, particularly at Stage Gates. Frequent benchmarking of performance and critical analysis of the likelihood of achieving research goals will support the new emphasis on portfolio risk management in EERE. Stage Gate places a priority on early identification of the potential commercial impact of applied research. The use of LCOE as a primary metric helps to ensure that research is targeted to improve the commercial impact of our research.

The following review meetings support Solar Program performance measurement and assessment:

- State Gate Reviews: When the Stage Gate process is formalized within the Solar Program, gate reviews of program elements will be scheduled at the completion of each stage. The schedule for the reviews will depend on the length of the stage. For example, multi-phase research subcontracts will have gate reviews at the completion of each phase.

[6] EERE RDD&D Decision Process—Standard Model, July, 2004

- Semiannual Program Reviews: DOE and national laboratory program managers review the status, progress, budgets, and issues for the entire Solar Program at least twice each year. Additional review meetings are scheduled as needed for program elements requiring more intense scrutiny. Findings from these secondary meetings are communicated to Solar Program managers for key decision-making.
- Annual Solar Program Reviews: All program elements are reviewed in a conference setting, including paper and poster sessions. The Review is planned and implemented according to the EERE Peer Review Guidance.
- Peer Reviews: These reviews are intended to provide periodic independent review and confirmation of the technical quality and merit of program elements. Each technical program element is reviewed at least biannually, and a programmatic peer review is scheduled to evaluate the Solar Program portfolio balance and objectives. Solar program peer reviews are typically held every other year at the start of the fiscal year in conjunction with the annual Solar Program Review. Each Peer Review panel comprises independent reviewers whose eligibility is in accordance with OMB guidelines, as well as the EERE Peer Review Guidance.

2.5 Program Benefits

The Solar Program's benefits are examined on an ongoing basis through EERE's Government Performance and Results Act (GPRA) Benefits Analysis Team effort, and Solar Program-specific analysis activities.[7] Solar energy can directly benefit the nation by substantially contributing toward meeting three national challenges—air quality, energy reliability and security, and economic development. Our nation's economic health and security increasingly depends on reliable, clean, abundant, and affordable energy. Energy consumption in the United States is projected to increase by about 34% between 2003 and 2025.[8] Solar energy systems have the versatility to provide clean electricity and energy systems for grid-connected distributed power, centralized power generation, grid-independent power, water and space heating, and industrial process heating. Solar energy has enormous potential as a supplement or alternative to fossil fuels for serving energy markets in both the United States and developing nations.

Economic Benefits

The solar industry continues to grow steadily as costs for solar systems decline. During the last decade, the market for solar energy from photovoltaics grew at an average annual rate of 33%. The solar industry estimates that growth rates above 30% annually can be sustained over the next decade (with targeted policies and R&D), and then after 2015 growth rates are likely to become more moderate. This level of market growth would result in a U.S. solar industry that could employ 250,000 people by 2030.[9] With technological innovations lowering costs and increased market growth leading to new jobs and export opportunities, solar energy can become a major high-technology growth industry that contributes significantly to our country's economic growth while concurrently serving to improve our trade balance.

Energy Security and Reliability

Domestic solar energy will increase the nation's energy supply and provide expanded opportunities to enhance the reliability of our energy infrastructure, thus creating a more stable environment for economic growth. The distributed, modular characteristics of solar energy offer tremendous flexibility for both grid-connected and off-grid electricity applications. Distributed energy technologies are expected to supply an increasing share of the electricity market to improve power quality and reliability. Power outages and disturbances currently cost the United States economy an estimated $100 billion per year.[10] Solar energy can play a significant role in helping to reduce these costs.[11]

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[7] EERE 2005 Government Performance Results Act Reports.

[8] Energy Information Administration. *Annual Energy Outlook 2005.*

[9] *U.S. PV Industry Roadmap Through 2030 and Beyond.* September 2004.

[10] C.W. Gellings and K.Yeager, "Transforming the Electric Infrastructure," *Physics Today,* December 2004; and K. Hamachi LaCommare and J.H. Eto, "Understanding the Cost of Power Interruptions to U.S. Electricity Consumers, http://certs.lbl.gov/certs_p_reliability.html).

[11] R. Perez et al., 2005. Solution to the Summer Blackouts? *Solar Today.* July/August, pp.32–35.

Solar energy systems can be distributed to generate power at the point of use, decreasing the need for vulnerable and costly power lines. Solar energy systems are already the technology of choice for remote and portable power markets. Solar energy is available during peak daylight hours when electricity use (and price) is at its highest level, thereby easing the burden on current peak-load energy production. Thus, the use of solar energy enhances the security of our national energy supply because sunlight—as an indigenous resource—can be harvested for use in commercial and industrial heating and for electricity production, avoiding the need for fossil fuels in these applications. It will indirectly reduce our need for fossil fuel imports, allowing U.S. supplies of oil and natural gas to meet the demands of transportation and other markets. By reducing our reliance on imported oil and avoiding volatile fossil-fuel markets, solar energy can improve the U.S. trade balance and minimize the effects of world energy price shocks.

Clean Energy

The advancement of solar energy provides the United States with an opportunity to lead the world to a clean energy future. Solar energy is harnessed by a diverse mixture of technologies that can meet the environmental challenges of today while safeguarding the future. Solar energy produces no pollution, while harnessing the inexhaustible resource of sunlight. Solar energy systems can reduce the impact of global warming and other environmental externalities by reducing fossil-fueled consumption and related pollution (i.e., nitrogen oxide, sulfur dioxide, carbon dioxide, and particulates). In addition to providing broad environmental benefits, taking advantage of solar energy will help to reduce the adverse health-related impacts, particularly on the elderly and children, of burning fossil fuels.

Beyond electricity production, solar energy can be integrated into building designs to provide heat and light. Current applications of solar water heating have already lowered energy bills for millions of homes worldwide. In addition to cheap and reliable energy, Americans are demanding clean, environmentally friendly energy that does not contribute to pollution or global warming. Future research into innovative solar-energy concepts will further reduce energy consumption in buildings—leading to zero net-energy use—while increasing the role of solar energy in our nation's energy supply.

GPRA Benefits Estimates

The FY 2006 GPRA Benefits Analysis[12] projected that if the Solar Program's technology targets and market expectations are met, the result would be an estimated 13 GW of electric capacity additions, $1.8 billion in energy expenditure savings annually, and 7.6 million metric tons of carbon savings annually by 2025, rising to 62 GW of electric capacity additions, $2.3 billion in energy system cost savings annually, and 36 million metric tons of carbon savings annually by 2050. Although these numbers are substantial, the assumptions and methods underlying the GPRA06 modeling efforts have a significant impact on the estimated benefits, and these results could vary significantly if external factors, such as future energy prices, differ from the "baseline case" assumed for the GPRA06 analysis. In addition, possible changes in public policy and disruptions in the energy system that may affect estimated benefits are not modeled. The benefits estimates reported in GPRA06 thus do not reflect potential additional consumer demand for solar energy due to factors such as increased reliability of service, provision of emergency power backup, and/or improvements in load management capabilities. As a result, the benefits reported in GPRA06 likely understate the demand for solar energy.

2.6 Relationship to Other EERE, DOE, and Federal Programs

The Solar Program collaborates with other programs within EERE, other federal agencies, and state, local, and international organizations (see Table 2.6-1). The purpose of these collaborations is to support activities that align with Solar Program goals and add value to Solar Program activities.

[12]EERE. 2005 (March). *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs FY 2006 Budget Request.* NREL/TP 620-37931.

Table 2.6-1 Solar Program Coordination with Other EERE Programs

EERE Program	Activity
Building Technologies	Advanced water-heating technologies (joint workshop) and Zero Energy Buildings
Distributed Energy Program and Office of Electricity Delivery and Energy Reliability Federal Energy Management Program	Collaboration on interconnection standards and power conditioning (joint workshop) Technical assistance in application of solar energy technologies
FreedomCAR and Vehicle Technologies Program	Identification of cross-cutting power electronics requirements
Hydrogen, Fuel Cells and Infrastructure Technologies Program	Solar Hydrogen Workshop and solar production of hydrogen
Weatherization and Intergovernmental Programs	Promotion of solar energy deployment through state and local organizations and implementation of international energy agreements

The Solar Program also coordinates its activities with other offices within DOE and with other government agencies, including the following:

- The Small Business Innovative Research/Small Business Technology Transfer Research (SBIR/STTR) Programs stimulate opportunities and innovation through research grants in solar and other technologies.
- DOE's Office of Science supports critical research in materials and fundamental sciences that improve solar energy technology.
- The Department of Homeland Security's Federal Emergency Management Agency has worked to accelerate the commercialization of solar products for homeland security and disaster relief applications.
- The Departments of Defense, Interior, and Agriculture have been supportive in using solar energy in federal facilities and through the Rural Utility Services.
- The National Aeronautics and Space Administration (NASA) is a large user of PV cells for space power and collaborates with DOE on R&D activities.
- Housing and Urban Development entered into a collaborative effort to educate appraisers and buyers of homes on the merits of residential solar energy systems.
- U.S. Agency for International Development (USAID) has partnered with the Solar Program through interagency agreements to collaborate on solar energy deployment and market-preparation activities.

2.7 Program Planning, Management, and Analysis Tasks

The activities identified here are carried out by the SINC team in their role to effectively plan, administer, manage, review, and control the Solar Program. The activities fall into five program areas as follows:

1. Development and implementation of a systems analysis framework
2. Benchmarking for validating the analyses
3. Analysis of the technical activities and their potential impact on the important metrics for solar systems
4. Program planning and implementation functions, especially including preparation of multi-year program plans, annual operating plans, program reviews, and biannual management reviews
5. Program management and administrative functions, including budget preparation, budget execution, financial management, and information systems management.

Substantial progress was made during the initial development and application of modeling efforts supporting the SDA; this work is summarized in Sec. 2.3 and is explicitly described in multiple sections of Sec. 3. Substantial additional efforts remain to be able to provide a fully integrated and validated tool for Solar Program-wide planning and prioritization. For all three categories (i.e., analysis, benchmarking, and modeling), documentation of the work effort is becoming a significant activity. A guide for using the analysis approach is being developed, benchmarking progress is being published, and the extensive analysis efforts supporting the development of program planning efforts are being documented.

2.7.1 Systems Analysis Framework

The major focus will be to further develop the analytical model(s) used to estimate impacts of technology-specific R&D efforts and to establish standard frameworks for collecting and assessing performance and cost data within the technology programs. Existing simulation and modeling tools were assessed, and gaps among existing tools were identified. Future efforts will focus on developing improved capabilities and on filling in the gaps, specifically:

- Analytic approaches for troughs, dishes, and SWH will be integrated within the current models to ensure consistency between analyses of multiple technologies.
- Improvements in PV modeling, particularly as regards cost issues and building-integrated technologies, will also be made to better simulate the range of system capabilities that exist within this technology and to assess the robustness of our approaches.
- Risk and associated uncertainty analysis capabilities will also be added to provide the capabilities to identify the impact of multiple approaches to achieving technical goals and to assess how additional activities can reduce the existing risk of meeting the goals.

2.7.2 Benchmarking and Validation

With the recent development of reference systems for each of the solar technologies, a framework now exists for evaluating the cost, performance, and reliability of fielded systems. The benchmarking data developed to date have been effectively used to establish the current ranges of the parameters used for the reference systems. As anticipated, a wide variation exists in the quality and quantity of the data available to support these reference system evaluations. For example, there is a wide variation in the costs identified for installing residential PV systems. Such gaps will be filled by additional data gathering and assessment. Needed technical efforts include the following:

- Updates of the baseline data for the reference systems will be provided regularly through data collection undertaken by the technology programs. These updates are essential to demonstrate and document progress toward meeting the Solar Program's long-term goals for each technology.
- Emphasis will be on field data that can assess system-integration impacts, manufacturing costs, installation costs, and other indirect costs for multiple types of systems.
- Best practices (including practices in Germany and Japan) for residential PV system installation will be developed to more firmly establish targets for supporting technical R&D.
- Benchmark data will be obtained on new CSP trough and dish deployment efforts to better quantify many of the cost elements, especially those related to O&M, where demonstrated reliability improvements are the key to reducing costs.

2.7.3 Analysis and Impact Assessments

A primary activity within the systems-driven approach is developing and evaluating technical and economic targets for the systems considered in the Solar Program. The targets reflect market requirements, assessments of out-year technology costs, and related estimates of penetration into existing and new markets. Measures of success (e.g., LCOE, payback, first cost) are identified within market sectors, and targets are set that align the solar activities with national energy goals. Principal analysis activities include the following:

- Updates of analyses that assess progress toward the goals are an ongoing requirement.
- Analysis applications will focus on determining better evaluation approaches of market penetration, assessing technology tradeoff impacts, assessing policy impacts on markets and technology development, and evaluating the impact of improvements in lower-tier TIOs.
- GPRA-type evaluations are also a continual part of the analysis efforts.
- Assessments of the potential economic and technical impacts of CSP for electricity or hydrogen production are a requirement in the recently passed Energy Policy Act.
- Stage Gate evaluations that will be integral to major Solar Program decisions will require substantial analysis support to be certain that the impact of technology pathways and progress are appropriately factored into the decisions.

2.7.4 Program Planning and Implementation

These activities serve to set the direction and course of the Solar Program, including both long-term and short-term planning. Principal activities are the following:

- The Multi-Year Program Plan is prepared every two years for consistency with national energy policy, directions from DOE management, analysis of market trends, and an evaluation of technology progress made by both the solar program and the industry.
- Each year, an annual operating plan is prepared that sets the priorities and is based on the framework of the Multi-Year Program Plan. This becomes the baseline—for financial planning, progress milestones, and contractual commitments—used to execute the Solar Program for a given fiscal year.
- Solar Program evaluation occurs at least twice each year with thorough semi-annual management review meetings and a thorough Program Review.
- Peer reviews are carried out about every two years to evaluate the scientific quality of the individual Solar Program elements.

2.7.5 Program Management and Administration

The budget is prepared and the finances managed through these efforts, with the major focus of these activities being to:

- Prepare and defend an annual Solar Program budget based on the program planning priorities
- Execute and manage the financial affairs of the Solar Program once a budget has been passed by Congress
- Work with Solar Program contractors and laboratories to input programmatic and financial information from the AOP into the DOE's CPS database.

These functions are critical to creating a baseline with which to review and evaluate both technical and managerial annual performance.

2.8 Milestones and Decision Points

Milestone	Due Date
Program Planning Activities	
• Multi-Year Program Plan	September 2007, 2009, 2011
• Annual Operating Plan	October 2007, 2008, 2009, 2010, 2011
• Semi-Annual AOP Reviews	Nov & April 2007, 2008, 2009, 2010, 2011
• Annual Solar Program Review	Nov 2006, 2007, 2008, 2009, 2010, 2011
• Peer Reviews	November 2007, 2009, 2011
Program Management and Administration Activities	
• Update Solar Program CPS input	November 2007, 2008, 2009, 2010, 2011
Systems Analysis & Benchmarking Activities	
• Release updated versions of Solar Advisor Model for Program-wide use	Periodic
• Publish detailed analyses documenting progress of all solar technologies in meeting 2011 goals	September 2011
• Publish interim analyses documenting progress of all solar technologies toward meeting 2011 goals	Annual
• Publish analyses supporting Stage Gate assessment of dish/engine technology	August 2008
• Publish analyses supporting Stage Gate assessment of trough technology	August 2011
• Publish analyses supporting Stage Gate assessment of system engineering (including building-integrated PV) impacts in PV technology	As needed
• Publish analyses supporting Stage Gate assessment of advanced PV technologies	As needed
Congressionally Mandated Reporting Activities	
• Publish Congressionally mandated assessment of potential impact of CSP technology	February 2007
• Publish Congressionally mandated report on economic and technical potential of CSP for electricity or hydrogen production	August 2010

Decision Points

2011 will be a critical time for the Solar Program. At that point, the Solar Program will determine the progress made by each technology toward meeting its 2011 target goals, assess changes in the market that impact the Solar Program needs and priorities, and make the decisions necessary to establish specific Solar Program directions for reaching 2020 goals. This effort will rely heavily on supporting Stage Gate evaluations of the individual technologies (see Sec. 3) and will be the basis for prioritizing activity that will lead to the greatest potential for success in achieving the 2020 goals.

3.0 Technology Research Plan

This section presents the technical plan for the major R&D areas in the Solar Program. A separate technical plan will be provided for each subprogram: Sec. 3.1 Photovoltaics, Sec. 3.2 Concentrating Solar Power, and Sec. 3.3 Solar Heating and Lighting. The details of each subprogram element will be examined with markets, program history, goals, approaches, reference systems, challenges and barriers, milestones, and decision points.

3.1 Photovoltaics

3.1.1 PV Industry and Market Overview

Photovoltaic panels produce direct-current (DC) electricity directly from absorbed photons from sunlight. Power PV panels typically come in one of two forms: flat-plate PV panels, which use sunlight directly to produce electricity, and concentrating PV (CPV) panels, which use concentrated sunlight to produce electricity. Flat-plate PV panels are typically manufactured in units (modules) that range from 5 to 300 watts-peak (Wp) of output. CPV modules are larger and range from 500 Wp to 40 kWp. Although a number of applications use the direct current from the modules, the fastest-growing markets for PV use panels that are integrated into systems with power-conditioning equipment that converts the DC electricity from the panels to alternating current (AC). These systems are then interconnected to the utility grid and are referred to as grid-tied systems. The modularity of PV has opened a wide variety of markets for this technology, with residential grid-tied, commercial grid-tied, and central power generation being the market foci for Solar Program planning purposes.

The PV industry has been expanding very rapidly during the past decade. Global PV production increased from about 60 MW in 1994 to just over 1 GW in 2004 (see Fig. 3.1.1-1 for a breakdown of recent PV shipments by country/region, and Fig. 3.1.1-2 for a breakdown in market share of each module technology). These numbers translate into an average annual growth of 33% for the past decade. During this period, the most rapidly growing PV markets were for grid-connected PV systems installed on residential and commercial buildings. In essence, during the past decade, the PV marketplace has gone through a dramatic shift in emphasis from remote industrial and remote home systems (accounting for 60% of the market in 1994) to grid-tied systems (accounting for 80% of systems in 2004). The PV industry is expected to continue its rapid expansion over the next decade, with a continuing shift toward grid-tied markets.[1] Much of this growth has been driven by PV-targeted subsidies in Germany, Japan, and a number of U.S. states (e.g., California, Arizona, New Jersey). A consequence of this rapid growth has been the emergence of a solar-grade silicon supply shortage. (Solar-grade silicon is a key input for crystalline PV cells/modules, the dominant PV technology in the marketplace today.) This supply shortage, which is believed to be temporary with new supplies coming on line throughout 2006 and 2007, has created a short-lasting opportunity for thin-film PV and concentrator technologies, which do not use polysilicon feedstock, to accelerate their move from the laboratory into manufacturing and large-scale production.

[1] U.S. *PV Industry Roadmap 2004*, Strategies Unlimited 2005; *SunScreen* Report 2004

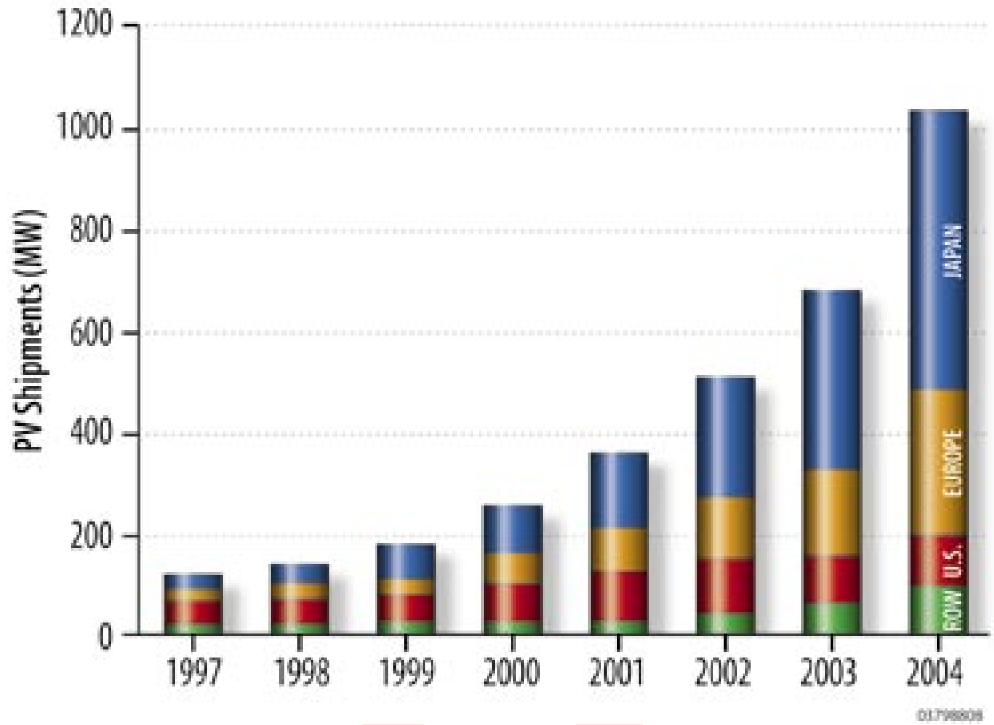

Fig. 3.1.1-1 Worldwide PV shipments with regional breakdown, where ROW is "Rest of World." (Strategies Unlimited, 2005)

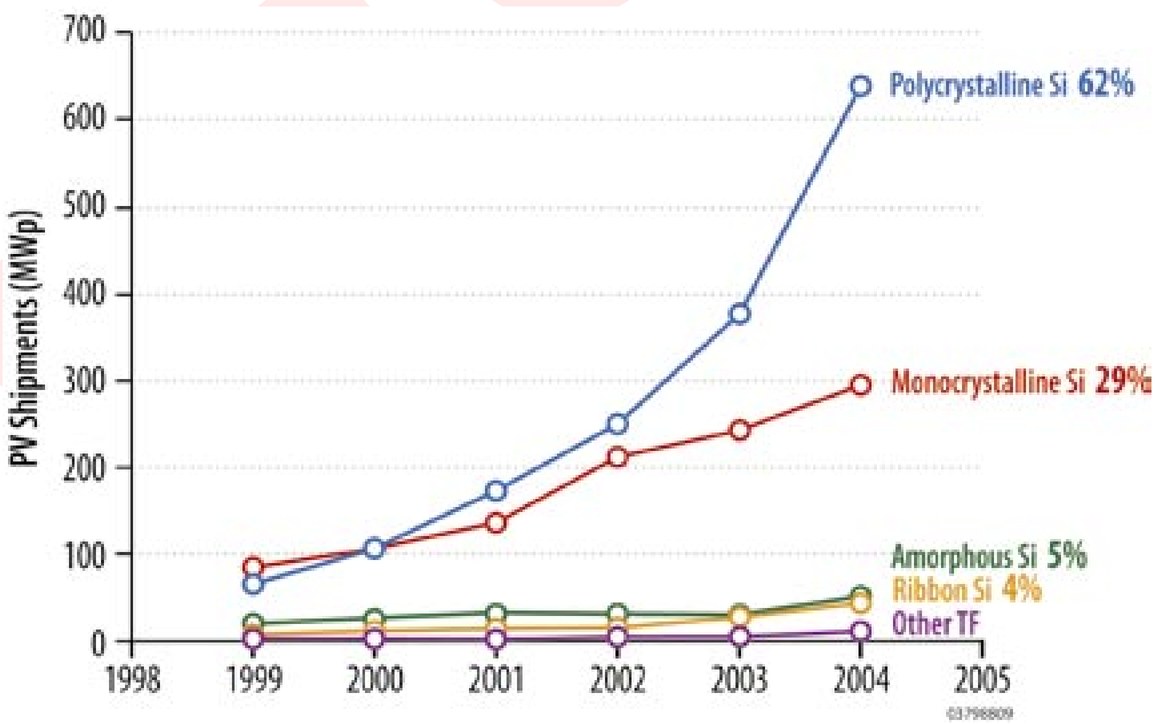

Fig. 3.1.1-2 Historic and current market share of crystalline and thin-film PV technologies. (Strategies Unlimited, 2005)

PV Module Technologies

The photovoltaic module forms the heart of the PV system from the perspective of performance, cost, and reliability. The module represents 50%–55% of the overall installed cost of a PV system. Because of the significance of the module's impact on system performance, cost, and reliability, the Solar Program's R&D investment emphasis has historically been on exploring a variety of pathways to increase module performance, reduce costs, and increase reliability.

Current commercially available module technology can be broadly grouped into three categories:

1. Wafer-based silicon (single- and multicrystalline)
2. Thin film (polycrystalline cadmium telluride [CdTe], copper indium gallium diselenide [CIGS], and amorphous Si [a-Si])
3. Concentrating PV (single-crystalline Si and III-V multijunction cells).

To further accelerate the adoption of PV technologies into the marketplace, the PV industry, in partnership with the Solar Program, has invested in R&D to affect performance, cost, and reliability improvements in all three module technology categories. A brief introduction to each of these module technologies is given below.

Wafer-Based Crystalline Si. Wafer-based Si is based on the concept of fabricating discrete solar cells from silicon wafers that have been sawn from a silicon boule or ingot, or cut from a thinly grown multicrystalline sheet. The cells are then electrically interconnected to form a module.

Historically and currently, wafer-based crystalline-silicon (c-Si) technologies have held the majority of the market for PV modules, with more than 90% market share in 2004. As volumes of c-Si product sales have grown and the technology's performance has advanced, c-Si technologies have continued to show steady improvement in cost that have tracked along a 20% learning curve in price reductions. Although volume effects work together with technology improvements to decrease the price of c-Si modules, recent scholarship[2] strongly suggests that technology improvements have made the most significant contribution to price reductions in PV module technology. Many of these technological advances can be traced directly to very successful Solar Program/industry initiatives and partnerships.

Thin Films. Thin-film technologies are designed to minimize semiconductor material costs by using thin layers—about 1 to 2 micrometers in thickness. Thin films also offer potential cost advantages by using large substrates (several square meters or even continuous sheets), more automation, and simpler cell interconnect schemes. They can also be made in a variety of forms, both flexible and rigid.

In 2004, thin-film technologies as a category (including CdTe, CIGS, and a-Si) held slightly less than 10% of the worldwide market, but have continued to grow along with the market as a whole. Although this level of market share has been fairly constant over the last several years, in 2004 several thin-film manufacturers gained increased traction in the market, bringing them closer to the kinds of volume production that will help realize the cost potential of these technologies. Over the long term (2020), it is anticipated that the manufacturing costs of thin films could be significantly lower than those of c-Si technologies. The key to thin film's ability to gain additional market share is in realizing these manufacturing cost advantages, while closing the gap between production and laboratory cell efficiencies and achieving competitive reliability.

The difference between laboratory best-cell efficiencies and those of commercial thin-film modules (about 1 m^2 in area) is based on several challenges, including: processes that can be uniform over large areas at reasonable speeds; processes where control can be maintained to achieve high yields; the introduction of lower-cost processes, where possible; a proper cell interconnect and module packaging design; the assurance of intrinsic cell stability; and the assurance of outdoor reliability of an encapsulated module. These are technically and financially challenging goals and objectives.

[2] G. Nemet, 2005. "Technical Change in Photovoltaics and the Applicability of the Learning Curve Model." Draft Paper, IIASA, UC-Berkeley.

Concentrating PV. The fundamental distinction between concentrator and flat-plate PV technologies is the amount of sunlight concentrated on the solar cells within each module. It is common to refer to the standard solar irradiance at the Earth's surface—1 kW/m^2—as "one sun"; in CPV, light is focused on the cell up to 1000-suns concentration. Because the CPV array relies on focusing direct sunlight onto the cell, the system's array tracks the sun throughout the day to maintain the sun's focus on the cell.

Although CPV technologies held a very small portion of market share in 2004 (less than 1%), the technology's potential lies in the ability to use relatively small areas of high-efficiency solar cells by collecting the light that falls on a large area and focusing that light onto the cells using inexpensive polymer lenses. Although the balance of the module's material (other than cells) is relatively inexpensive plastics and steel, this approach also requires more sophisticated gears and tracking than other PV systems, which introduces additional costs and O&M considerations. Improvements in trackers and support structures made in the concentrating solar thermal program activities also positively impact CPV applications.

Current CPV systems employ high-efficiency c-Si technologies and are beginning to use III-V multijunction cells. Although there is still little market penetration for CPV, serious interest is being shown by utilities in the Desert Southwest as a technology with the potential to be competitive in the utility power market. One of the keys to future competitiveness for CPV is the ability to increase the efficiency of the small-area cells. In this area, the Solar Program and its industrial partners continue to lead the world with laboratory cells with efficiencies approaching 40%.

Inverters, Balance of Systems, Systems Engineering and Integration

The inverter, which converts the DC electricity from a PV array to the AC of common use and is the basic controller for the entire PV system, is generally the second-highest initial hardware cost component in a PV system, behind the array itself. Inverters often reflect the highest ongoing maintenance costs of PV systems due to the complexity of the electronic componentry, software, and thermal management. The Solar Program is actively engaged in pursuing ways to reduce overall system levelized cost of energy (LCOE) and improve reliability through improved inverters. The Solar Program has conducted two multi-day workshops with participants from industry, academia, and the laboratories, employing a systems-driven approach to identify and prioritize technical improvement opportunities (TIOs) for future-generation inverters in PV systems. Over the time frame of this Multi-Year Program Plan, as PV grows further into mainstream markets, inverters will likely become more intricate system command, control, and communications devices.

The rest of the balance of systems (BOS) includes mounting hardware, wiring and cable housing, disconnects, fuses, and all other non-module or inverter parts of the PV system. Through improved design and full system integration from the module to the output, opportunities exist to standardize and reduce the complexity and cost of other BOS components, with the added benefit of reducing installation costs and improving overall system performance and reliability.

Systems engineering and integration involves the combining of PV components into an optimized and functional system. For the most part, the integration is currently done on-site during an installation. In terms of the activities and costs involved, this includes design and engineering, site preparation, installation, permitting and interconnects, inspection, and commissioning. This is a very important component of the overall system price. Using SDA analyses, new approaches such as standardized designs, factory integration of systems, new building-integrated concepts, and improved interchangeability of components are being developed to streamline much of these integral costs. These modified designs will be significant advances over the reference systems (discussed below) in the target market sectors, and the resultant cost and performance improvements will cut across all TIOs.

3.1.2 PV Subprogram History / Background

The development of terrestrial PV began in response to the oil crises of the early 1970s. The Solar Program, funded through DOE since 1977, has been instrumental in discovering new materials, devices, and fabrication approaches, improving device and module efficiencies and reliability, and lowering module and system costs. Among the key advances resulting from the research are the discovery of innovative silicon sheet or ribbon growth approaches, aimed at reducing the silicon waste and slicing costs associated with silicon ingots, and the discovery and advancement of thin-film technologies aimed at significant reductions in module costs. These technologies are currently among the first new technologies being commercialized, with U.S. laboratories and companies holding a significant competitive edge worldwide. Another area that owes its genesis to the DOE research program is high-efficiency multijunction concentrator cells. U.S. laboratories and industry are also the world leaders in this area.

One of the most significant trends over the past 30 years—one that is undeniably one of the best measures of the success of PV research—is the continuous improvement of solar cell efficiencies for all technologies over the years (Fig. 3.1.2-1). With few exceptions, these leading laboratory-scale devices have resulted from DOE-supported research. Although these results are clearly important, significant gaps still remain between the best performances and the theoretically predicted values for each solar cell technology. Furthermore, the efficiencies of commercial (or even the best prototype) modules are only 50%–65% of these "champion" solar cells. Closing these gaps is the focus and challenge of ongoing and future research, and it is one of the primary technical efforts of the Solar Program.

Fig. 3.1.2-1 Historical laboratory cell efficiencies, compared with 2005 module efficiencies.

The DOE-supported research efforts have also resulted in improvements in a second significant metric, the manufacturing cost of PV modules. These achievements are reflected in the marketplace, where PV module prices have followed an historical trend along a so-called "20% learning curve." That is, for every doubling of the total cumulative production of PV modules worldwide, the price has dropped by about 20%. This trend has led to a price drop from about \$80/Wp in 1976 to \$3.50/Wp in 2005 (both expressed in 2005 dollars).

A third significant metric is the improvement in module reliability, as reflected in the product warranties offered by manufacturers. Today, most crystalline-silicon module manufacturers offer warranties of 25 years, typically guaranteeing that the power output of the module will not decrease by more than 20% over this period. These warranties are the result of 30 years of R&D progress, accelerated tests to identify failure mechanisms, and decades of experience from fielded systems. Research is ongoing to improve the reliability of thin-film modules and concentrator systems. These efforts are a significant part of the Solar Program. Finally, the most important trend for the PV industry is the rapid growth of PV markets, as described above, with the average annual growth rate worldwide exceeding 43% over the past 5 years.[3]

The overall direction of the DOE PV Subprogram has shifted periodically as a result of the research advances (and some failures) and the investments and research needs of the private sector. The first decade of research (1975–1984) focused mainly on c-Si technology, from feedstock to modules, and applications development. From the many approaches for silicon ribbon growth, edge-defined film-fed growth (EFG) emerged as a leading contender. This technology and the String Ribbon™ approach, developed in the mid-1980s, are the current leaders in commercial ribbon production and are both U.S.-based. The PV Design Assistance Center was developed during this period to assist adopters of new terrestrial PV systems in design and applications. In addition, modeling tools were developed, such as PVFORM, to help these early adopters both size their systems and determine the overall energy production potential.

The next decade of research (1985–1994) resulted in several thin-film technologies showing significant promise, with three technologies demonstrating greater than 10% efficiency in the laboratory. The leading contenders became hydrogenated amorphous silicon (a-Si:H), copper indium diselenide, and cadmium telluride. Initial successes in high-efficiency c-Si and III-V multijunctions were also made during this period. The first commercial thin-film modules (mostly a-Si:H) were made during this period. Manufacturing R&D for modules—and later, for all system components—became a major government/industry partnership initiative in 1990. As the industry grew and matured over this period, the PV Subprogram led the development of key codes and standards for PV systems in several applications, and held regular industry workshops on systems performance and reliability. This was also a period of program technical support and oversight of large, early deployment efforts, such as "PV for Utility-Scale Applications" (PVUSA), to show the technical feasibility of PV systems.

The most recent decade was highlighted with continuing increases in laboratory thin-film efficiencies (19.5% in CIS and 16.5% in CdTe), as well as significant increases in multijunction III-V efficiencies resulting from the DOE High-Performance PV project initiated in 2001. The current record is 39% at 236-suns concentration. Crystalline-silicon production, driven mostly by the incentive programs overseas, has increased significantly. Manufacturing costs have continued to decrease, in great part resulting from the DOE PV Manufacturing R&D program. Thin-film technologies have recently entered the marketplace and are in a period of strong growth, which highlights the success of the Solar Program's Thin-Film PV Partnership project. Developing a multi-parameter performance model, which contains more than 170 fully characterized commercial PV modules, has dramatically improved the ability of designers and integrators to predict energy production. This period has also seen growth of building-integrated PV components and systems, improved inverters through the High-Reliability Inverter Initiative, and technical assistance to important domestic partners such as the states, the Federal Energy Management Program, and several international partners, as well. The Solar Program has also engaged in significant barrier removal by developing installer certification programs, hardware certification specifications, and interconnection standards.

Critical to the success of PV technologies in the marketplace has been DOE's role in advancing module efficiencies, costs, and reliability; inverter performance, reliability, and cost; and improvements in BOS. The remainder of this document delineates the Solar Program's role in these critical areas for providing the scientific research and discovery that are the foundations for PV to become energy significant in this century.

3.1.3 PV Strategic and Performance Goals

The following goals and objectives are planned for five-year 2007–2011 period and are based on the long-term goal that PV will be market-competitive with fossil-fuel-generated electricity within a 15-year time frame (2020).

Long-Term Goals

From the beginning of the PV Subprogram in the 1970s through the mid-1990s, one of the long-term visions was to be competitive in central-generation applications. These central-generation calculations were the original source of the PV Subprogram's historical "6 ¢/kWh" target. More recently, with rapidly expanding residential and commercial markets

[3] Refer to Fig. 1.1-1, PV Cost and Manufacturing Trends.

(i.e., distributed grid-tied markets), the PV Subprogram has broadened its goals and has set a range of market-specific targets.[4] As shown in Table 3.1.3-1, the PV Subprogram has defined targets for three key market segments: residential, commercial, and utility-scale markets.[5] The target ranges in Table 3.1.3-1 are based on our assessment of what PV technology needs to achieve to be competitive in each of these markets.

Table 3.1.3-1 Long-Term Targets for Levelized PV Energy Cost and Installed System Price by Market Segment

	Current U.S. Market Price Range (¢/kWh)	Target for PV LCOE in 2011 (¢/kWh)	Target for PV LCOE in 2020 (¢/kWh)	Required 2020 Installed PV System Price ($/Wp with $0.01/kwh O&M)
Residential	25–32	13–18	8–10	2.25–3.00
Commercial	18–22	9–12	6–8	2.00–2.75
Utility	15–22	10–15	5–7	1.50–2.25

The target utility price range (5–7 ¢/kWh in 2020) is based on the LCOE of new combined-cycle gas turbines (CCGTs) in the Southwest.[6] The EIA's *Annual Energy Outlook 2005* projects that the cost of new CCGTs will remain fairly constant (in real terms) through 2025. Given that the Southwest has exceptional solar resources, combined with solar's time-production profile, this is a reasonable target market, i.e., to meet intermediate and peaking capacity/generation needs in the Southwest. However, because PV is not firm (without storage), it may only get part of the capacity credit.[7] Over the next 10–15 years, as PV begins to penetrate the utility market (as the cost of PV systems decline), the advantages of being highly coincident with peak demand in key target markets,[8] as well as being clean, easy to permit, site, and build quickly in relatively small increments, will make PV more valuable from a systems perspective. In the long term (beyond 2020), to achieve widespread use, i.e., beyond 5%–10% of total electricity generation capacity, PV will need to be integrated with storage, building energy management techniques, hydrogen production, or other complementary technologies/approaches to help address intermittency.

Five-Year Performance Objectives

To work toward its 2020 targets, the PV Subprogram will partner with the PV industry over the course of this Multi-Year Program Plan (2007–2011) to conduct the R&D necessary, and to implement the progress into commercially available products that result in the following:

- 16%-efficient crystalline-silicon module that can be produced at a direct manufacturing cost of $260/m^2 ($1.60/Wp)
- 10%-efficient CdTe module that can be produced at a direct manufacturing cost of $90/m^2 ($0.90/Wp)
- 12%-efficient CIGS module that can be produced at a direct manufacturing cost of $170/m^2 ($1.40/Wp)

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[4] The Solar Program's most recent Multi-Year Technical Plan (2004) included long-term targets for utility-scale applications (5–7 ¢/kWh) and residential applications (8–10 ¢/kWh). Here, a long-term target for the commercial sector (6–8 ¢/kWh) is also included.

[5] The move to a range of market-specific targets increases the need to develop consistent and transparent methods of translating installed system price (in $/kW) into levelized energy cost (in ¢/kWh). The Solar Program is developing the tools and methods to be consistent and transparent with its systems-driven approach.

[6] The levelized energy cost for
under the following assumptions: Plant Size = 400 MWe, Heat Rate = 6422 Btu/kWh, Capital Cost = $599/kWe, Fixed O&M = $10.34/kWyr, Variable O&M = 2.07 mil/kWh, Burner Tip Gas Price = $5/MMBtu, 20-Year Internal Rate of Return @ 12%, 15-Year Debt @ 6%.

[7] The effective load carrying capacity of PV systems (i.e., the amount of capacity a PV system can be relied on to displace when added to an existing system) has been estimated at 50%–70% in locations with good insolation and summer peaks driven by air conditioning (Perez et al., 1996. *Photovoltaics Can Add Capacity to the Utility Grid.* National Renewable Energy Laboratory, Golden, CO).

[8] Key target markets include areas with high effective load carrying capacity, such as southern California. Some areas, such as parts of Florida, where annual peak demands are driven more by winter`

- 8%-efficient a-Si module that can be produced at a direct manufacturing cost of \$90/m^2 (\$1.15/Wp)
- 25%-efficient concentrator module that can be integrated into a fully installed system at a systems level price of \$250/m^2 (\$3.00/Wp)
- 95%-efficient inverter that has a 10-year lifetime
- Systems manufacturing and integration techniques and tools to achieve levelized energy cost targets in the utility (\$0.10–\$0.15/kWh), commercial (\$0.09–\$0.12/kWh), and residential (\$0.13–\$0.18/kWh) sectors.

3.1.4 PV Approach

The primary R&D pathways in the PV Subprogram are aimed at increasing performance, reducing costs, and enhancing reliability of fielded PV systems in all markets serviced by the technology, with an emphasis on residential, commercial, and utility markets. To develop higher-performing, lower-cost, higher-reliability PV components and systems, the PV Subprogram partners with industry and universities in a Stage Gate process (see Sec. 2.4) of R&D phases:

1. Preliminary Investigation—This area in the PV Subprogram has historically been dominated by R&D in novel PV absorber materials and cell structures. Significant effort in this area has targeted building, maintaining, and expanding the science base and fundamental understanding of materials and device physics for optimum PV performance. In the future, Stage 1 will apply to all new concepts within the PV Subprogram, from absorbers and cells to modules, inverters, and BOS, all the way through novel system integration concepts.
2. Detailed Investigation—Upon proof of concept in Stage 1, the PV Subprogram engages university and industry partners to expand the knowledge base of a new material/device/component/system to ensure that there is commercial interest and that the concept addresses a viable market need.
3. Development—Second-generation prototypes are developed and industry is supported in the development of pilot manufacturing processes.
4. Testing and Validation—This stage involves engaging industrial partners with full-scale manufacturing to field commercially viable products and to continue to implement R&D progress into manufacturing lines to reduce the timeline for program-supported R&D to reach products in the marketplace, as well as to implement the improvements necessary to reach the Solar Program's PV LCOE targets.

In moving from one phase to the next, progress is evaluated, compared to strategic goals and performance targets, and a decision is made regarding moving on to the next phase of effort, discontinuing the effort, or redirecting the work to a new direction dictated by the results.

R&D is generally managed in the PV Subprogram at the component level, with appropriate activities targeted to optimizing systems integration. Specifically, module research in the PV Subprogram focuses on improving absorber materials and device structures to enhance cell and module performance, as well as discovering new materials that will constitute next-generation PV technologies. Materials R&D is also conducted to reduce costs and improve reliability of fielded modules. Additionally, the PV Subprogram supports work on novel material concepts that will form the basis of the next generation of PV technologies. Numerous manufacturing R&D partnerships are maintained by the PV Subprogram to facilitate and accelerate the implementation of R&D progress into module manufacturing lines, while reducing the cost per square meter required to produce high-performing, reliable modules. Inverter R&D improves the DC-to-AC conversion efficiency, while improving inverter reliability and lifetime. Inverter software R&D is also explored to improve the PV array utilization under a variety of illumination and thermal conditions (e.g., maximum power-point tracking). Further inverter and BOS R&D focuses on integrating system control, diagnostic, and communications features, to better position PV as a source of distributed generation in a variety of applications. The PV Subprogram also provides industry support in the areas of BOS design and specification, as well as overall systems integration and installation. These activities include assessing fielded systems, troubleshooting, and benchmarking performance and reliability.

3.1.5 PV Reference System Descriptions

Due to the modularity of PV technology, systems can be configured to provide value in a variety of market sectors. Therefore, as part of this market-based, systems-driven approach, reference systems have been defined that provide the basis for trade-off studies of different technology development pathways and their resultant impacts of system-level parameters. Some key characteristics of these reference systems are shown in Table 3.1.5-1 for the key markets identified above, as well as an off-grid market reference system. Note that reference systems are meant to describe typical systems and not necessarily price or performance leaders. Further, detailed information is provided on reference systems in Appendix A.

Figure 3.1.5-1 is a graphical representation of a PV system with common terms illustrated.

Table 3.1.5-1 Characteristics of PV Reference Systems

Parameter	Residential	Commercial	Utility-scale, flat-plate	Utility-scale, concentrating PV	Residential Island (off-grid)
Array size	4 kWpdc	150 kWpdc	10 MWpdc	10 MWpdc (constructed of 40-kW modules)	1.2 kWpdc
Inverter size (kW)	4	150	150	160	2.4
Mounting characteristics	Roof-mount retrofit	Flat roof-mount, no penetrations	Ground, one-axis tracking, N-S	Ground, two-axis tracking	Ground, self-contained sled
Tilt	Latitude minus 15°	15°	Horizontal	N/A	Latitude

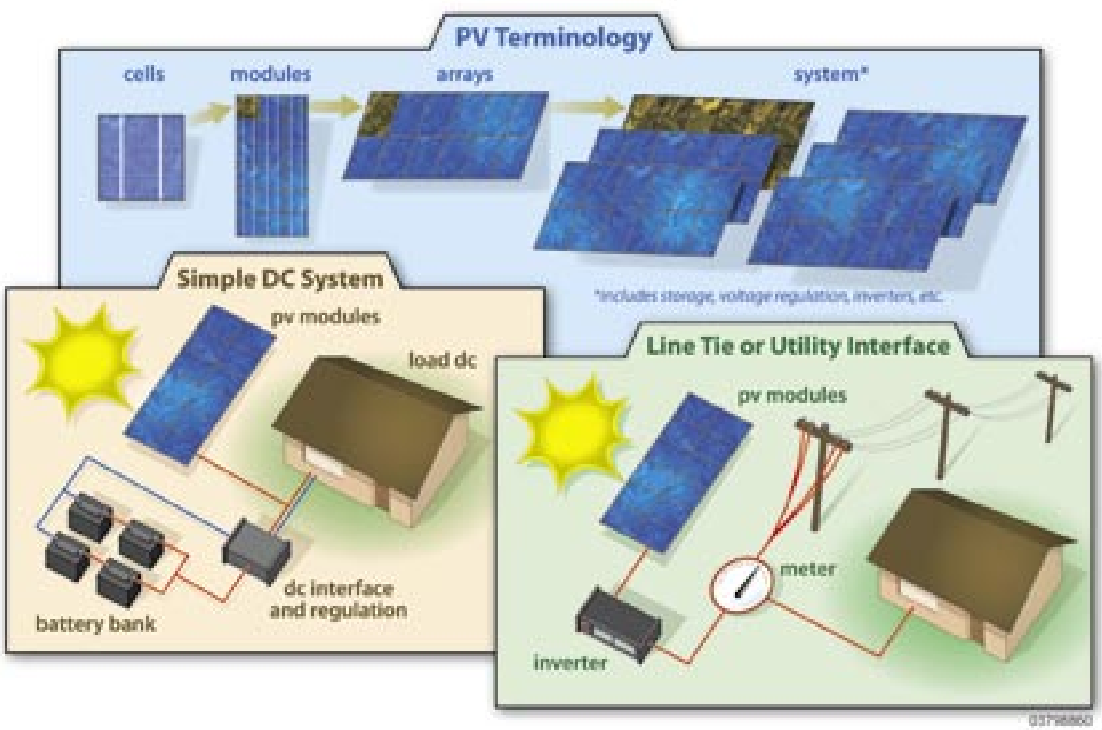

Fig. 3.1.5-1 Graphical representation of a PV system with common terms illustrated.

3.1.6 PV Technical (Non-Market) Challenges/Barriers and Goals

Analysis of the reference system leads to identifying technical improvement opportunities (TIOs) to overcome barriers related to cost, performance, and reliability. Figure 3.1.6-1 shows the TIOs at two high levels, starting at Tier 1 and further divided in Tier 2. This figure also shows the impacts of these TIOs on key metrics as determined by systems modeling that will be described below. Analyses of the impacts of different TIOs on overall cost of the energy produced were conducted in some cases at additional levels of detail.

Numerical values in these analyses are determined to reflect today's "best practice" values and "best estimates" for future years, such as 2011 and 2020. These metrics are then aggregated to determine overall performance, cost, and reliability projections for PV systems of the future. The Solar Advisor Model (SAM) allows parametric sensitivity studies around these and other Tier 1 variables to determine overall LCOE and a variety of other outputs for market-based comparisons. A brief overview discussion of the Tier 1 TIOs follows.

TIOs		Metrics			
TIER 1 TIOs	TIER 2 TIOs	Performance Efficiency	Cost	O&M	Reliability
Modules	Module				
	Absorber				
	Cells and Contacts				
	Interconnects				
	Packaging				
	Manufacturing				
Inverter & BOS	Inverter				
	Inverter Software				
	Inverter Components/Design				
	Inverter Packaging/Manufacturing				
	Inverter Integration				
	Other BOS				
Systems Engineering & Integration	System Engr. & Integration				
	System Manufacturing/Assembly				
	Installation & Maintenance				
Deployment Facilitation					

Fig. 3.1.6-1 List of TIOs and associated metrics. Shading indicates degree of impact each TIO has on each metric and overall system LCOE for the residential reference system: red (dark) is high; yellow (light) is medium; no shading is low.

During the last two to three years, the Solar Program has focused much effort on collecting and analyzing data related to the performance and costs of PV systems in the field, as well as on developing new analytical tools to determine the relative merits of different technology pathways. This section highlights the results of these efforts by discussing future performance, cost, and reliability targets for the different components and subcomponents within the technologies. These targets are determined by investigating the individual and cumulative impacts of technological advances within the different market sectors under study. One important caveat: although great effort has been made to ensure the quality of data and assumptions used in these analyses, perhaps more important than the specific numbers portrayed here are the *relative* improvements shown.

PV Modules

LCOE calculations were done at the Tier 1 level for modules by exploring different values for metrics in the commercial reference system, based on a variety of module technology enhancements, and across several module technologies. This was done using the newly developed SAM, which consists of three major software components that combine a set of user inputs to calculate key metrics of merit, including the LCOE of the system. Based on the user's inputs, these components calculate the performance of the system over its life, the total cost to install and maintain the system, and the cost of financing the procurement of the system. It should be noted that, in addition to uncertainties related to inputs, the development of SAM is still under way. And *full* validation of all performance, cost, and financial models has not taken place, although considerable preliminary validation of all aspects of SAM ensures that the outputs generated and shown in this section fall in reasonable and expected ranges. Further, many assumptions have been made in how to approach the modeling of different system sizes and technologies. To reiterate, although the LCOE numbers produced by SAM and shown below are in the expected range, the focus of the reader should be on relative comparisons and not on absolute values.

The results of Tier 1 module analyses are shown in Table 3.1.6-1. To conduct these analyses for each module technology, a 2005 base case was configured in SAM using the 2005 benchmarked values for module efficiency, cost, lifetime, and reliability. (Additional considerations for lifetime and reliability will be given below.) From these values, coupled with other assumptions (detailed in Appendix A), the baseline LCOE was calculated. From each module technology's baseline, each parameter was changed from its 2005 base value to its 2011 target value, one parameter at a time, to isolate that parameter's impact on the LCOE. In all cases, the BOS parameters were kept at their 2005 levels (see Table 3.1.6-3). These impacts are shown in Table 3.1.6-1 in terms of the LCOE value, as well as the percentage change in LCOE when changing that parameter's value to the 2011 target.

Science and Technology Facility—

A new type of research facility will support a new way of doing research on several of the technologies highlighted in the President's National Energy Policy, including the development of next-generation energy technologies such as hydrogen and fuel cells. Construction began in the fall of 2004 on the new Science and Technology Facility (S&TF), located at the National Renewable Energy Laboratory in Golden, CO. Completion of the facility is expected in the summer of 2006.

The S&TF was designed specifically to reduce barriers and time delays associated with transferring technology from research and development to industry. The centerpiece of the building will be the Process Development and Integration Laboratory (PDIL), specifically designed to accommodate a new class of c-Si and thin-film PV processing and characterization tools.

The PDIL will allow researchers to pass samples between equipment in a controlled way, avoiding contamination from the air. The PDIL also will allow a scientist to integrate control systems and databases in such a way that someone who is growing a sample can see results of a measurement and vice versa. The S&TF will also include nine advanced material synthesis, characterization and general support laboratories.

Table 3.1.6-1 Impacts of Tier 1 Module Metrics on LCOE for Commercial PV Reference System

	Units	2005 Benchmark	2011 Projected Value	Resulting LCOE (¢/kWh)	LCOE Reduction (as % '05 Benchmark)
Crystalline Silicon *(2005 Commercial Baseline: 18.3 ¢/kWh)*					
Efficiency	%	13.5	16.0	15.8	13.7
Price	\$/m^2 (\$/Wp)	473 (3.50)	352 (2.20)	15.1	17.5
Lifetime*	Years	30	35	17.6	3.8
Reliability		1 failure/ 4,200 mod years	1 failure/ 5,000 mod year	18.2	0.5
Performance	%/yr degradation	1.0	1.0	18.3	0.0
CdTe *(2005 Commercial Baseline: 19.9 ¢/kWh)***					
Efficiency	%	8.5	10.0	17.2	13.6
Price	\$/m^2 (\$/Wp)	213 (2.50)	133 (1.33)	16.9	15.1
Lifetime	Years	30	35	19.2	3.3
Reliability		Not available			
Performance	%/yr degradation	2.0	1.5	18.9	5.0
CIGS *(2005 Commercial Baseline: 22.2 ¢/kWh)***					
Efficiency	%	9.5	12.0	18.0	18.9
Price	\$/m^2 (\$/Wp)	333 (3.50)	240** (2.00)	18.2	18.0
Lifetime	Years	30	35	21.5	3.2
Reliability		Not available			
Performance	%/yr degradation	2.0%	1.5	21.2	4.5
a-Si - Glass *(2005 Commercial Baseline: 21.7 ¢/kWh)***					
Efficiency	%	6.5	8.0	18.0	17.1
Price	\$/m^2 (\$/Wp)	215 (3.30)	124 (1.55)	19.4	10.6
Lifetime	Years	30	35	21.0	3.2
Reliability		Not available			
Performance	%/yr degradation	1.5%	1	20.7	4.6
a-Si - Flexible *(2005 Commercial Baseline: 20.3 ¢/kWh)***					
Efficiency	%	6.5	8.0	16.9	16.7
Price	\$/m^2 (\$/Wp)	215 (3.30)	124 (1.55)	15.6	23.2
Lifetime	Years	30	35	19.5	3.9
Reliability		Not available			
Performance	%/yr degradation	1.5	1	19.3	4.9

*Of the module technologies shown in the table, only c-Si technologies have sufficient field data to support an established lifetime assumption of 30 years in 2005. Impacts of uncertainties in lifetimes for other technologies are discussed later in this section.

**For reference baseline and target numbers, see "Terawatt Challenge for Thin-Film PV," NREL Report TP-520-38350."

The general conclusion of these sensitivity studies is that achieving targets in module performance and cost have the greatest impact on LCOE. As noted above, the Solar Program has historically placed an emphasis on R&D in these areas.

To assess the overall impact of improving the key module metrics from 2005 values to the 2011 projections, initial studies (which will continue to be updated and validated) were conducted by inputting all 2011 values for efficiency, cost, lifetime, and reliability into SAM to calculate the overall change in LCOE. The results of the 2011 module projections on LCOE are shown in Fig. 3.1.6-2. In these studies, all inverter, BOS, and financing assumptions were maintained at their 2005 levels so module impacts could be isolated. (For these reasons, the LCOE seen in Fig. 3.1.6-2 for c-Si will not match the LCOE seen in Fig. 3.1.6-6 for c-Si. In that case, module and BOS components were set to 2011 targets. Financing assumptions were held constant in all cases.) The orange line is the 2005 LCOE for the c-Si reference system.

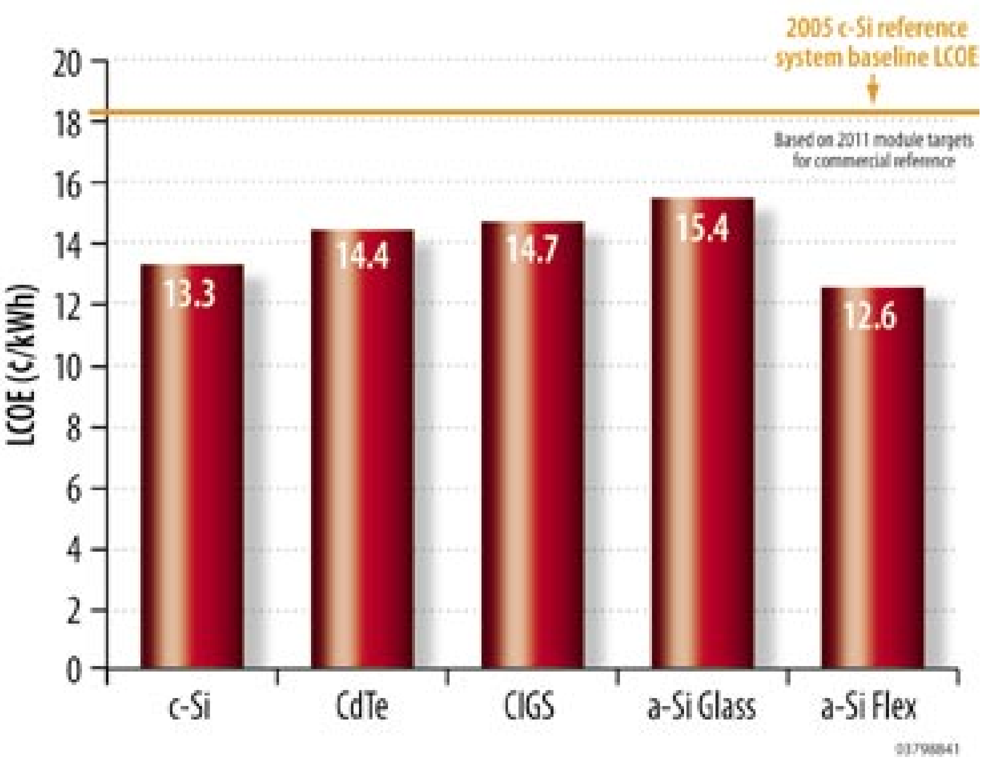

Fig. 3.1.6-2 LCOE values for different module technologies based on 2011 targets for key module metrics with BOS parameters left at their 2005 levels.

In all the above SAM studies, module lifetime was set at 30 years for each technology's 2005 benchmark. For c-Si modules, sufficient field data exist to substantiate this number. Thin-film modules, however, have not been commercially deployed for a sufficient time for data to be collected that would support a 30-year lifetime assertion. Because of this inexperience in fielded thin-film module lifetimes and the associated uncertainty (commercial warranties are usually 20 years versus 25 years for c-Si), the studies were conducted using 30-year 2005 lifetimes and 35-year 2011 lifetimes to allow for a more direct comparison on efficiency and cost between thin films and c-Si modules. Figure 3.1.6-3 shows the LCOE sensitivity to module lifetime for a thin-film system.

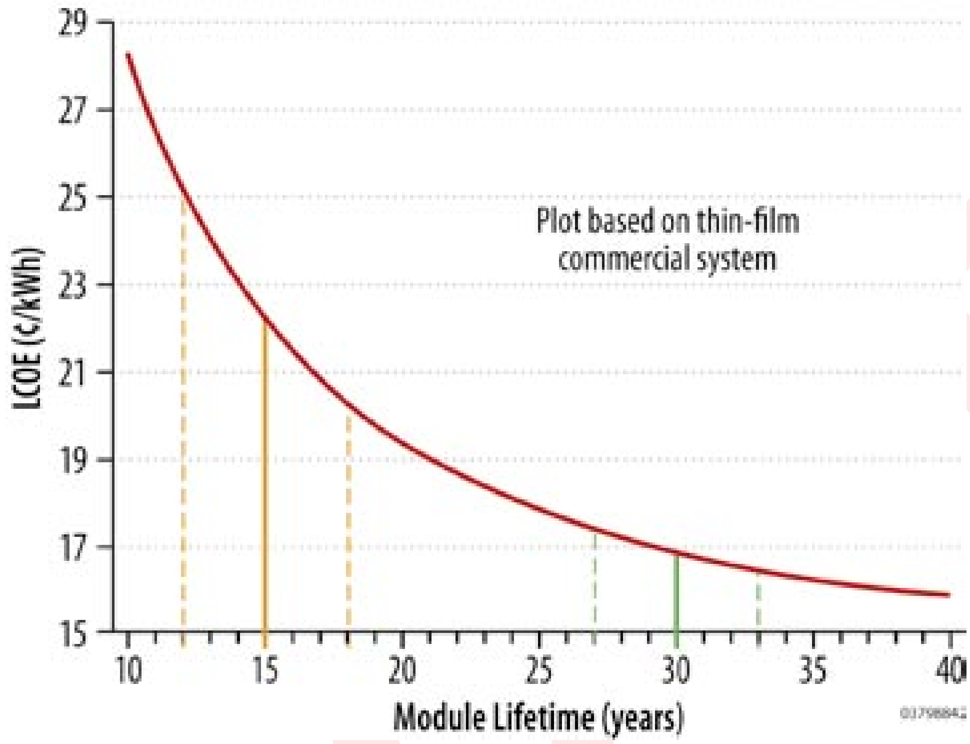

Fig. 3.1.6-3 Impact of module lifetime on LCOE.

Figue 3.1.6-3 shows the very significant importance of module lifetime with respect to LCOE. As noted, the uncertainty in module lifetimes introduces significant uncertainty in the LCOE calculations. Although uncertainties in the module lifetime have small impacts for longer lifetimes (at a 30-year lifetime, ±3 years results in a 0.9 ¢/kWh span), uncertainties in lifetime are more important for shorter lifetimes (at a 15-year lifetime, ±3 years results in a 4.9 ¢/kWh span). This indicates that an important activity for the Solar Program is to work with the thin-film industry and systems installers to better understand thin-film reliability and lifetime. In addition, any new module designs for either thin film or c-Si should be carefully evaluated through accelerated life testing to ensure that lifetime and reliability are not compromised.

In addition to the Tier 1 sensitivity studies shown in the table above for commercial rooftop systems, selected analysis was also conducted at the Tier 2 level. As an example of how the SDA is being employed to explore this level of detail, Fig. 3.1.6-4 shows the results of an analysis that explores the contributions of the materials, labor, and other cost improvements for the discrete elements of c-Si module production. When modeled at the Tier 1 level, improvements in module price based on 2011 targets resulted in decreasing the LCOE from the baseline of 18.3 ¢/kWh to 15.1 ¢/kWh—a 3.2 ¢/kWh reduction. The contribution from each c-Si element to the LCOE reduction was then calculated by looking at a breakdown of the Tier 2 target costs for 2011. The "Other" category shown includes manufacturing supplies, equipment maintenance, manufacturing spares, utilities associated with manufacturing, cost of manufacturing floor space, and equipment depreciation.

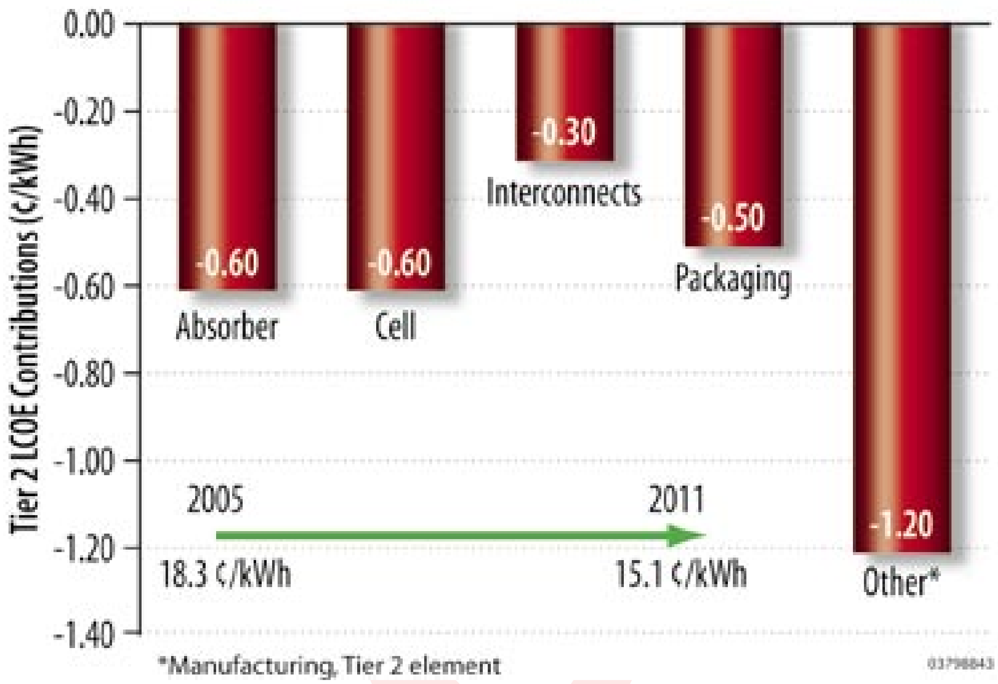

Fig. 3.1.6-4. Crystalline-silicon Tier 2 TIO contributions to 2011 target cost reductions.

PV Systems

As discussed above, TIOs were defined across the different components within the reference systems, all geared toward reducing the LCOE of these systems and thereby increasing opportunities for PV in these markets. The following charts and discussion show the cumulative merits of addressing these TIOs at the system level. These results have been obtained using the SAM and are intended to show relative impacts of technology improvements—more so than absolute numbers. In the module discussion above, different PV module technologies were assessed in various commercial configurations. In contrast, all the system-level analyses below were made based only on the 2005 reference systems, which use c-Si technology.

For each of the figures that follow (Figs. 3.1.6-5 through 3.1.6-9), each component's contribution to LCOE (as determined by SAM) is shown for a given reference system. The 2005 value is based on extensive benchmarking activities within the Solar Program, through which component and system-level parameters related to performance, cost, and reliability were determined from families of fielded systems. The 2011 values are based on projections of current trends in each technology area and verified through expert consensus. Values for 2020 come from the prior versions of the Solar Program Multi-Year Technical Plan and the latest Solar Energy Industries Association's PV industry roadmap.[10] These benchmarks and projections are summarized in Tables 3.1.6-2 to 3.1.6-6. A near-term decision point is planned to determine the most effective R&D portfolio for meeting the 2011 projections. Decision points are given in Sec. 3.1.9.

The component LCOE contributions in the following figures are broken into six categories—modules, inverter, BOS, installation, other costs, and O&M—with the addition of storage in the off-grid island case. BOS includes all hardware beyond the modules and inverters, including frames, fuses and disconnects, cables, and combiner boxes. Installation includes related labor and equipment costs to conduct the on-site installation. Other costs include design, engineering,

[10] *Our Solar Energy Future: The U.S. Photovoltaic Industry Roadmap Through 2030 and Beyond,* NREL/BR-520-36283, (2004).

site preparations, permitting and interconnects, and profits. O&M calculations are determined based on inverter lifetimes and as an annual percentage of overall installed system cost, based on benchmarking data available.

In all of the reference applications below, the greatest reductions in LCOE come through module improvements in performance and cost, and through modifications to the system-level component integration, thereby reducing installation and O&M costs and increasing overall reliability. This increase in systems integration is reflected in the relatively stable contribution of "other costs" to the system LCOEs over time. Although several components of this "other" category are reduced over time, the system engineering costs are increased, resulting in significant reductions in BOS, installation, and O&M contributions to LCOE. The types of activities to achieve these targets are defined in Sec. 3.1.8.

Table 3.1.6-2 2005 Benchmarked Parameters, 2011 and 2020 Projections for Modeling of 4-kW Residential Reference System

System Element	Units	2005	2011	2020
System Location		Phoenix		
System Size	kW	4	4.56	5.92
Module Price	$/Wdc	4.00	2.20	1.25
Conversion efficiency	%	13.5	16	20
Module size	Wpdc	100	118.5	148
Inverter Price	$/Wac	0.90	0.69	0.30
Inverter size	kW	4	4.74	5.92
DC-AC conversion efficiency	%	90	96	97
Inverter life/replacement	Years	5	10	20
Other BOS	$/Wdc	0.61	0.40	0.33
Installation	$/Wdc	1.66	0.57	0.42
Other/Indirect*	$/Wdc	1.30	1.14	1.00
INSTALLED SYSTEM PRICE	$/Wdc	8.47	5.00	3.30
Lifetime	Years	30	35	35
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O&M Cost (not including inverter replacement)	% installed price	0.5	0.3	0.2
LEVELIZED COST OF ENERGY (LCOE)	$/kWhac	0.32	0.15	0.09

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*For this and other tables presented below, the "Other/Indirect" category includes design, engineering, site-related costs, permitting, and profit.

2005 benchmark cost and performance values contained here are from detailed data on more than 200 residential PV systems installed between 2000 and 2005, with emphasis on those more recently installed; Web-based price information on more than 5000 installations in 2004 and 2005; and laboratory-based measurements and modeling. Out-year projections are based on the PV industry roadmap, earlier versions of this Multi-Year Plan, and input from engineers and scientists in the DOE Solar Program and in industry.

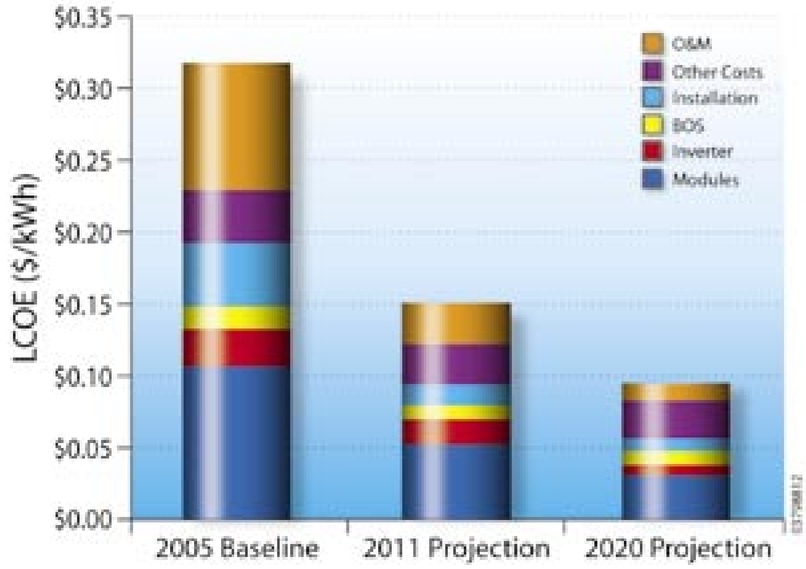
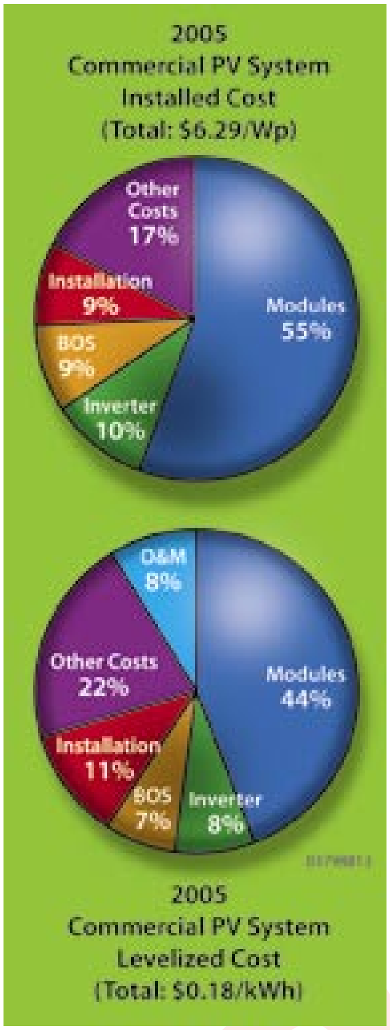


Fig. 3.1.6-5 Component contributions to LCOE for c-Si residential reference system – shown for 2005 benchmark and 2011/2020 projections.

Table 3.1.6-3 2005 Benchmarked Parameters, 2011 and 2020 Projections for Modeling of 150-kW Commercial Reference System

System Element	Units	2005	2011	2020
System Location		Phoenix		
System Size	kW	150	1.78	222
Module Price	$/Wdc	3.50	2.20	1.25
Conversion efficiency	%	13.5	16	20
Module size	Wpdc	150	178	222
Inverter Price	$/Wac	0.60	0.51	0.25
Inverter size	kW	150	178	222
DC-AC conversion efficiency	%	92	96	97
Inverter life/replacement	Years	10	15	20
Other BOS	$/Wdc	0.54	0.36	0.13
Installation	$/Wdc	0.55	0.17	0.08
Other/Indirect	$/Wdc	1.10	0.76	0.50
INSTALLED SYSTEM PRICE	$/Wdc	6.29	4.00	2.21
Lifetime	Years	30	35	35
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O&M Cost (not including inverter replacement)	% installed price	0.45	0.3	0.2
LEVELIZED COST OF ENERGY (LCOE)	$/kWhac	0.18	0.10	0.06

2005 benchmark cost and performance values contained here are from procurement documents, supplier information, and electric utility sources on about 30 installations; Web-based sources on more than 300 PV systems in several states across the United States; and laboratory-based measurements and modeling. Out-year projections are based on the PV industry roadmap, earlier versions of this Multi-Year Plan, and input from engineers and scientists in the DOE Solar Program and in industry.



PV System Metrics: Installed Cost vs. Levelized Cost of Energy

Applying DOE's systems-driven approach has led to identifying market-based metrics and targets for PV systems related to the "levelized cost of energy" (LCOE). In the past, when the dominant market for PV was remote applications, potential buyers (e.g., remote homeowners, telecommunications companies) would compare the installed cost of a PV system to other options, such as the cost of extending the electric grid.

However, as PV plays a greater role in mainstream markets, the market-based comparison needed is between the cost or value of the energy produced by PV systems and the cost of alternatives. Thus, given that electricity costs in the residential, commercial, and utility markets are based on cents per kilowatt-hour (¢/kWh) delivered, the same "performance-based" metric must be used for PV systems.

The LCOE of a PV system takes into account the installed cost of the system; all operation and maintenance (O&M) costs over the system lifetime, including replacements; and any related financial parameters and assumptions, such as loans, inflation, and discount rates. For many years, utility planners have determined LCOE from such parameters. Although the data requirements to determine LCOE are more rigorous than installed cost, the Solar Program is continually improving these LCOE estimates and projections with data obtained from partners and fielded systems.

The figures to the left looks at crystalline-silicon module technology and shows the component percentages of the total installed and levelized costs for the 2005 commercial reference system. A key conclusion is that achieving levelized cost targets depends on improving the entire system, rather than just one or two specific components. Note that O&M is not part of the installed cost of a system, so it is not shown in the upper plot. However, O&M is an important element in the overall LCOE of the system (lower plot).

Fig. 3.1.6-6 Component contributions to LCOE for c-Si commercial reference system – shown for 2005 benchmark and 2011/2020 projections.

Figures 3.1.6-7 and 3.1.6-8 show utility-scale systems using flat-plate and concentrating PV systems. From a program perspective, it is worth stating that much of the work going into modules and systems is synergistic across these application areas. Thus, although the utility sector is an important one and specific program goals are maintained, few Solar Program efforts are geared uniquely toward this sector.

As an illustration of the impacts of financing on LCOE, Figs. 3.1.6-7 and 3.1.6-8 show ranges of levelized costs for these systems under different financing schemes. The lower bar on these figures represents the direct cash, or non-financed, cost of energy, whereas the upper bar shows the costs under typical financing for independent power producers (assumptions shown in Appendix A). Direct utility financing falls between these two values.

Although a single-axis-tracked c-Si system has been chosen as the 2005 reference system based on a type of system commonly deployed, it is important to note that other systems configurations (e.g., fixed tilt, thin film) show considerable promise in meeting the Solar Program's long-term goals. These analyses will continue to be updated and reported over the course of this Multi-Year Program Plan.

Table 3.1.6-4 2005 Benchmarked Parameters, 2011 and 2020 Projections for Modeling of 10-MW Flat-Plate Utility Reference System

System Element	Units	2005	2011	2020
System Location			Phoenix	
System Size	MW	10	11.85	14.82
Module Price	$/Wdc	3.30	2.20	1.25
Conversion efficiency	%	13.5	16	20
Module size	Wpdc	150	178	222
Inverter Price	$/Wac	0.46	0.35	0.25
Inverter size	kW	150	178	222
DC-AC conversion efficiency	%	92	96	97
Inverter life/replacement	Years	10	15	20
Other BOS	$/Wdc	0.97	0.73	0.61
Installation	$/Wdc	0.27	0.16	0.10
Other/Indirect	$/Wdc	0.55	0.46	0.37
INSTALLED SYSTEM PRICE	$/Wdc	5.55	3.90	2.58
Lifetime	Years	30	35	35
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O&M Cost (not including inverter replacement)	% installed price	0.15	0.10	0.10
LEVELIZED COST OF ENERGY (LCOE)	$/kWhac	0.15–0.22	0.10–0.15	0.06–0.09

2005 benchmark cost and performance values contained here are from procurement documents, supplier information, and electric utility sources on about 30 installations; Web-based sources on more than 300 PV systems in several states across the United States; and laboratory-based measurements and modeling. Out-year projections are based on the PV industry roadmap, earlier versions of this Multi-Year Plan, and input from engineers and scientists in the DOE Solar Program and in industry.

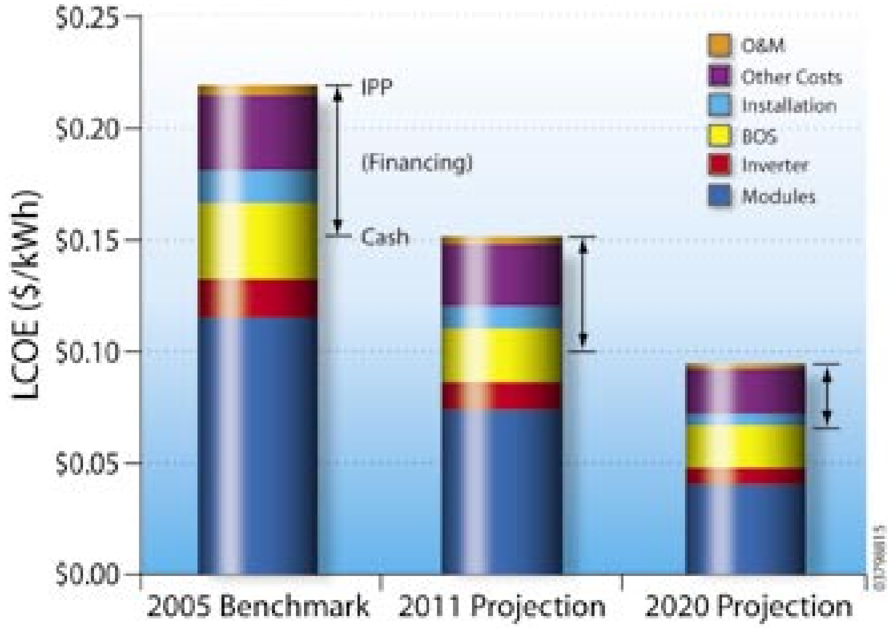


Fig. 3.1.6-7 Component and financing assumption contributions to LCOE for c-Si flat-plate utility reference system–shown for 2005 benchmark and 2011/2020 projections.

Table 3.1.6-5 2005 Benchmarked Parameters, 2011 and 2020 Projections for Modeling of 10-MW Concentrator Utility Reference System

System Element	Units	2005	2011	2020
System Location		Phoenix		
System Size	MW	10	12.5	16
Module Price	$/Wdc	4.13	3.00	1.56
Conversion efficiency	%	20	25	32
Module size	kWpdc	40	50	64
Inverter Price	$/Wac	0.46	0.35	0.25
Inverter size	kW	160	200	256
DC-AC conversion efficiency	%	92	96	97
Inverter life/replacement	Years	10	15	20
Other BOS	$/Wdc	0.70	0.53	0.44
Installation	$/Wdc	0.55	0.33	0.20
Other/Indirect	$/Wdc	0.11	0.09	0.07
INSTALLED SYSTEM PRICE	$/Wdc	5.95	4.30	2.52
Lifetime	Years	30	35	35
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O&M Cost (not including inverter replacement)	% installed price	0.85	0.60	0.24
LEVELIZED COST OF ENERGY (LCOE)	$/kWhac	0.15–0.27	0.10–0.15	0.06–0.11

2005 benchmark cost and performance values contained here are from utility and manufacturer analyses, and laboratory-based measurements and modeling. Out-year projections are based on earlier versions of this Multi-Year Plan and input from engineers and scientists in the DOE Solar Program and in industry.

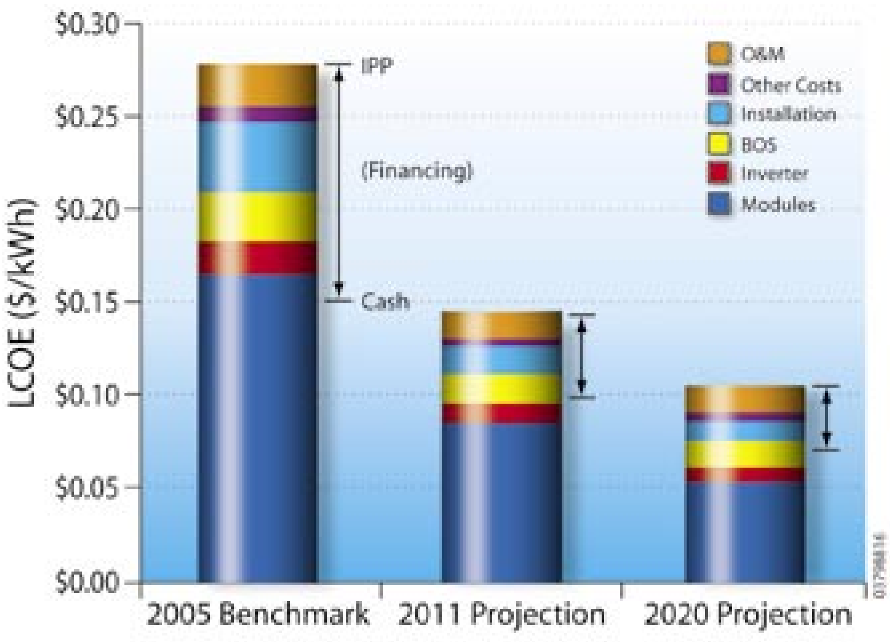


Fig. 3.1.6-8 Component and financing assumptions contributions to LCOE for c-Si CPV reference system – shown for 2005 benchmark and 2011/2020 projections.

Figure 3.1.6-9 shows the LCOE targets for an off-grid islanding system. Unlike the rest of the reference systems, where LCOE is dominated by the high initial cost of PV modules, today's off-grid systems have O&M as their largest cost contributor. This is due to both the complexity of the design (including storage and associated charge control) and the remoteness of many of these systems in the field, making access for even routine actions rather costly. Thus, technology improvements that lead to improved system reliability, and therefore reduced O&M, will have the greatest impact on reducing overall LCOE.

Table 3.1.6-6 2005 Benchmarked Parameters, 2011 and 2020 Projections for Modeling of 1.2-kW Off-Grid, Islanding Reference System

System Element	Units	2005	2011	2020
System Location		Phoenix		
System Size	kWdc	1.2	1.42	1.78
Module Price	$/Wdc	4.00	2.20	1.25
Conversion efficiency	%	13.5	16	20
Module size	Wpdc	100	114	148
Inverter Price	$/Wac	0.90	0.69	0.30
Inverter size	kWac	2.4	2.84	3.56
DC-AC conversion efficiency	%	90	96	97
Inverter life/replacement	Years	5	10	20
Other BOS	$/Wdc	0.61	0.50	0.40
Installation	$/Wdc	1.00	0.90	0.80
Storage	$/Wdc	1.49	1.49	1.49
Other/Indirect	$/Wdc	4.71	4.20	3.71
INSTALLED SYSTEM PRICE	$/Wdc	13.61	10.69	8.26
Lifetime	Years	30	35	35
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O&M Cost (not including inverter replacement)	% installed price	3.6	2.7	2.1
LEVELIZED COST OF ENERGY (LCOE)	$/kWhac	0.79	0.46	0.30

2005 benchmark cost and performance values contained here are from a sample set of more than 60 installed systems and laboratory-based measurements and modeling. Out-year projections are based on earlier versions of this Multi-Year Plan and input from engineers and scientists in the DOE Solar Program and in industry.

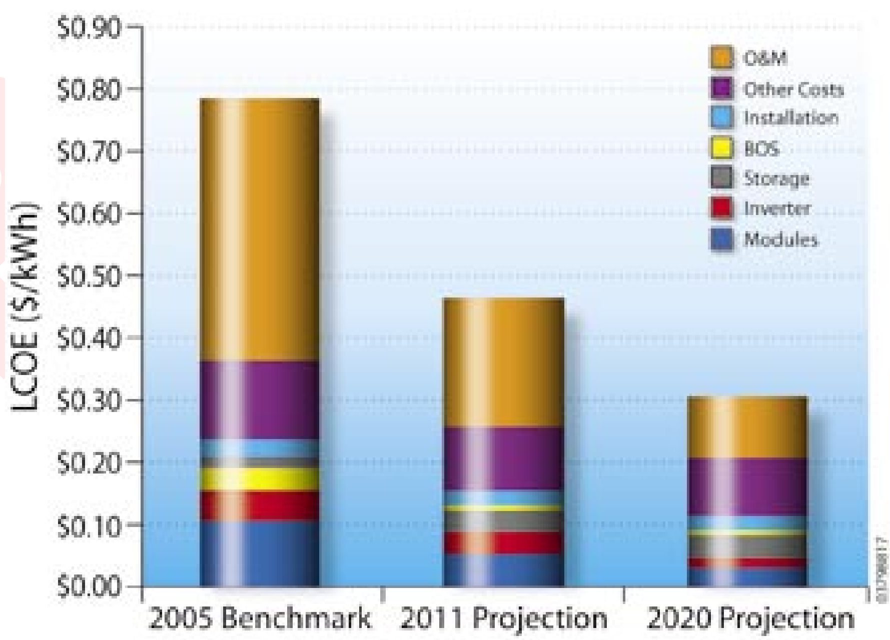


Fig. 3.1.6-9 Component contributions to LCOE for c-Si off-grid reference system – shown for 2005 benchmark and 2011/2020 projections.

We emphasize that of the four major elements that go into the LCOE calculations—performance, cost, lifetime, and financing—the Solar Program can influence performance, cost, and lifetime, but not financing. In establishing the default financial parameters for the modeling, reasonable mid-range assumptions were sought where no explicit guidance was available. Other assumptions, such as discount rate, were referenced to guidance from the Office of Management and Budget (OMB). Financial algorithms coded into SAM were taken from published works on the financing of renewable energy technologies.[11] All financial assumptions are given in the reference systems specification sheets in Appendix A.

The important consideration in making financial assumptions is that they remain fixed for case-to-case technology comparisons. To give the reader an idea of LCOE variations that can come from varying financial assumptions, Fig. 3.1.6-10 shows the effects on LCOE of choosing a variety of loan terms and amounts of the initial capital costs financed. As can be seen, the variation is significant from best case to worse case. The commercial reference case was calculated with 50% of the initial cost financed for 15 years.

The marked impacts of the financing parameters on the cost of energy to the end user are very consistent with intentions seen in market-based incentive programs where policies (e.g., tax-based incentives) are designed to reduce the cost of energy at current hardware performance and cost levels.

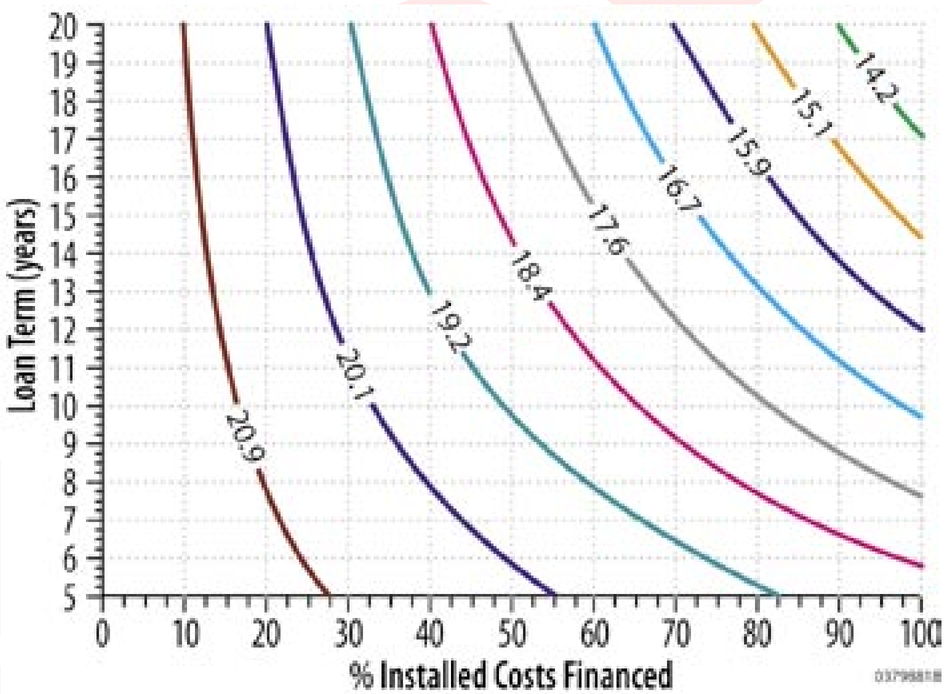


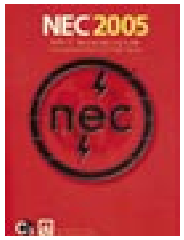
Fig. 3.1.6-10 LCOE as a function of different financed amounts and loan terms for the 2005 commercial reference system. The LCOE values given on the curves are in ¢/kWh.

3.1.7 PV Market Opportunities and Strategies for Overcoming Challenges

The main objectives of deployment facilitation are to provide technical support in assisting market growth and to retrieve technical performance, cost, and reliability information from fielded applications. This information is then fed back to researchers, providing direct, market-based data that can drive decisions throughout the Solar Program. Deployment facilitation activities are geared to produce an impact on overall market volume across the spectrum of market sectors,

[11] W. Short, D.J. Packey, and T. Holt, 1995, *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies,* NREL/TP-462-5173.

Codes and Standards: R&D Community and Industry Working Together



Standards organizations such as Underwriters Laboratories (UL) rely on industry input and new product results from R&D, benchmarking, and hardware analysis to keep safety standards up to date.

An example of one change pertinent to the PV industry is the use of blocking (series) diodes with multiple-string PV systems. The PV industry used to use blocking diodes in each string of a PV array to block back-fed fault currents from the other parallel strings. The use of blocking diodes has been discontinued because they represent a serious reliability shortcoming.

The result is that the National Electrical Code (NEC), currently written to allow blocking diodes, may require the use of huge cables if the blocking diodes are not used because multiple-string back-fed fault currents are probable. The alternative is ground-fault detection/interruption (GFDI) devices. The requirements for GFDI devices must be added to the 2008 NEC and to existing UL listing standards and related domestic and international systems standards.

including residential, commercial, industrial/utility, rural and off-grid, and international. The relevant metric for these activities is market size or volume, rather than the more directly measurable technical metrics defined for the other TIO areas.

The Solar Program meets these deployment facilitation opportunities in a variety of ways. For example, DOE's Million Solar Roofs (MSR) Initiative is a public/private technology deployment partnership aimed to overcome barriers to market entry for solar technologies and to facilitate the installation of residential, commercial, and industrial systems. Another example is DOE's Solar Decathlon, which brings college and university teams from around the world to compete in designing and building houses that demonstrate the benefits of solar technologies.

International partnerships also play a role in deployment facilitation because the majority of domestically produced solar products are currently shipped overseas, and international solar markets will continue to grow in the foreseeable future. Therefore, knowledge and information from solar activities outside of the United States provide business opportunities to U.S. solar companies in developed markets, such as Japan and Europe, and in developing markets as well, such as Spain, India, and China. The Solar Program also supports the International Energy Agency (IEA), specifically through the IEA Photovoltaic Power System Implementing Agreement. Activities include technical assistance, demonstration of the technical feasibility of new technologies and applications, training, development and promotion of norms and standards, and fostering business development, such as facilitation of joint-venture agreements between foreign and U.S. companies.

To facilitate continued market growth, it is of great importance to develop appropriate and reasonable codes, standards, and certification programs. The Solar Program focuses support on collaborative efforts with standards organizations, including the National Fire Protection Association (NFPA for the National Electrical Code [NEC]), the Institute for Electrical and Electronic Engineers (IEEE), the American Society for Testing Materials (ASTM), Underwriters Laboratories, and the International Electrotechnical Commission. Specific opportunities that will develop during the time frame of this plan include improved utility interconnection standards that include communications and controls for grid stabilization, a standardized communications protocol for inverters and system controllers, hardware certifications to improve consumer confidence and ultimately help define future TIOs, and standardized practices for certification of PV system designers and practitioners, assuring up-to-date knowledge on advances in technology, safety, or interconnect practices.

3.1.8 PV Technical Tasks

The PV Subprogram, as indicated in the Annual Operating Plan for FY 2005, covers a diverse set of activities that span the range of TIOs. TIO improvements often rely on the extensive laboratory and field measurement activities that accurately assess and characterize the performance of systems and components. During the period of this plan, periodic progress assessments and portfolio reviews will be held to ensure that, within available budgets, the PV Subprogram portfolio is balanced in a manner most likely to result in achieving the Solar Program 2011 targets. Upon conducting these assessments, PV Subprogram activities will be prioritized in terms of their relative importance on the metrics shown earlier in this section. Additionally, Stage Gate decision criteria will be further established and refined to evaluate the merits of continuing down certain pathways and to build in go/no-go decision points.

PV Modules (Tier-1 TIO)

The use of the SDA and SAM has shown that, across all module technologies, the key metrics for the module TIO that drive competitiveness are efficiency/performance, manufacturing cost per square meter, and reliability/lifetime. A brief discussion is given below of the activities planned by the Solar Program to address the 2011 targets for these metrics, for each module technology.

Wafer-Based Crystalline Silicon. Although the price of c-Si modules has come down 85% since 1980 (in real terms), an in-depth analysis of the TIOs shown in Fig. 3.1.6-1 indicates that a number of R&D pathways still exist for continued improvements in performance and cost. The results of these analyses, which are shown in Sec. 3.1.6, reveal several key findings, among the most significant of which concerns c-Si module technologies' ability to meet long-term Solar Program goals for competitiveness in key markets. Conventional wisdom has long held that c-Si manufacturing costs would make it difficult for this technology to ever reach full competitiveness in retail or wholesale electricity markets. However, when the performance potential of c-Si technologies is included in a whole-system evaluation, the higher long-term manufacturing cost projections are largely offset by efficiency potential of c-Si.

The emphasis for improvements in c-Si technology will continue to be on increasing laboratory and production cell efficiencies, while reducing the manufacturing costs per square meter. Efforts to address these metrics will be conducted both at the laboratories and through subcontracted R&D with universities (including DOE's University Center of Excellence in Silicon) and the PV industry. Internal laboratory efforts will focus on the absorber and cells/contacts Tier 2 TIOs, while subcontracted R&D will cover the full range of Tier 2 TIOs—absorbers, cells/contacts, interconnects, packaging, and manufacturing. Internal and external efforts will be led and coordinated by the Solar Program's Crystalline Silicon Project (c-Si Project) and the PV Manufacturing R&D Project. Work will be divided into two high-level areas—efforts on currently produced technologies to address the 2011 targets for commercially available c-Si modules, and efforts on novel materials and devices intended to address Solar Program targets for 2020 and beyond.

Examples of specific activities to address c-Si performance and costs are shown below. Note that although c-Si has amassed a very strong reliability record in the field and has not been named as a specific R&D focus, vigilance will be required to ensure this level of reliability is maintained as new module designs and materials are incorporated into fielded products.

Crystalline-silicon activities are given below.

Absorber (Tier-2 TIO)

- Research improved impurity and defect engineering.
- Move toward thinner, larger-area wafers with more-efficient feedstock utilization.
- Develop new hydrogen passivation techniques.
- Develop novel methods for growing thin c-Si on foreign substrates.

Cells and Contacts (Tier-2 TIO)

- Develop lower-cost cell processes that result in higher-efficiency devices.
- Develop novel cell-contacting schemes.
- Develop novel device structures such at HIT (heterojunction with intrinsic thin layer) cells.

Interconnects (Tier-2 TIO)

- Pursue innovations to improve manufacturability of cells and interconnects.

Packaging (Tier-2 TIO)

- Pursue innovations to reduce optical losses.
- Develop encapsulation materials that reduce module cost and maintain reliability.
- Continue to refine accelerated life testing that predictably replicates failures seen in the field.

Manufacturing (Tier-2 TIO)

- Maintain current partnerships, and form new ones, to accelerate the implementation of R&D progress into commercially available products.
- Implement fully the Science and Technology Facility (S&TF) tool suites to facilitate laboratory/industry interaction in developing manufacturing technologies and accelerating technology transfer to industry.
- Develop and implement in-line diagnostics.

The c-Si Project will coordinate these activities while strengthening collaborations between DOE laboratories, universities, and industry. To ensure this interaction, the c-Si Project has formed an external working group composed of industry and university leaders in c-Si R&D. The working group will assemble to exchange the latest information and R&D results, while informing the c-Si Project on desired future directions.

Thin Films. The technical aspects of the plan for thin-film R&D focus on the three key TIO metrics: module efficiency, module area cost, and module reliability. As in c-Si, efforts to address these metrics will be conducted both at the laboratories and through subcontracted R&D with universities (including DOE's University of Excellence in Thin Films) and the PV industry. Internal laboratory efforts will focus on the absorber and cells/contacts Tier 2 TIOs, while subcontracted R&D will cover the full range of Tier 2 TIOs—absorbers, cells/contacts, interconnects, packaging, and manufacturing. Internal and external efforts will be led and coordinated by the Solar Program's Thin-Film PV Partnership and the PV Manufacturing R&D Project.

Examples of specific, key activities to address thin-film performance, cost, and reliability are shown below.

Absorber (Tier-2 TIO)

- Reduce semiconductor layer thicknesses and increase photon absorption, reduce feedstock consumption, and decrease energy input and capital costs.

Cell and Contact (Tier-2 TIO)

- Develop novel cell structures and processes to improve cell performance at lower potential manufacturing costs.
- Engage in efforts to transfer laboratory cell performance to production modules.

Interconnects (Tier-2 TIO)

- Pursue innovations in module design leading to reduced active-area losses through edge and interconnect scribes.

Packaging (Tier-2 TIO)

- Develop technology-specific accelerated life tests that accurately replicate observed field failures.
- Develop and evaluate lower-cost, more-reliable packaging materials.

Manufacturing (Tier-2 TIO)

- Improve semiconductor materials utilization in manufacturing.
- Develop and employ improved, in situ production process controls and in-line diagnostics.

These R&D efforts will be conducted within the framework of the Thin-Film PV Partnership national teams in each of the thin-film technology areas.

High-Performance Multijunction Thin Films. To leverage advances in thin-film technologies, the Solar Program is investigating the development of higher-performance devices that take advantage of tandem or multijunction solar cells. Polycrystalline thin-film tandem cells include combining high- and low-bandgap single junctions to make a device that is able to use more of the solar spectrum in generating electrons. Although no commercially available modules exist using this approach, these materials are a good example of the investment the Solar Program makes to develop next-generation PV devices. Activities in this area are given below and will be managed by the Solar Program's High-Performance PV Project.

Absorber (Tier-2 TIO)

- Continue to develop high-bandgap alloys based on I-III-VI2 and II-VI compounds and other novel materials that can be used for the top cell in high-performance devices.
- Continue to develop low-bandgap CIS and its alloys, thin silicon, and other novel approaches as the bottom cell in high-performance devices.

Cells and Contacts (Tier-2 TIO)

- Develop methods for integrating the thin-film tunnel junction (interconnect) with the top cell both optically and electrically.
- Continue to develop monolithic and stacked device structures.
- Develop p-type transparent conducting oxides (TCOs) for an interconnect of the tandem structure with process compatibility for manufacture.

Concentrator PV. In terms of megawatts deployed, CPV is the least mature of the PV module technologies, yet this technology faces the same key challenges as flat-plate modules. As with flat-plate modules, the key activities leading to competitiveness for CPV will center on increasing efficiency/performance, reducing the manufacturing cost per unit area, and ensuring the reliability of fielded products. Internal laboratory efforts on CPV will focus on the absorber and cells/contacts (increased cell efficiencies) Tier 2 TIOs, while subcontracted R&D will cover the full range of Tier 2 TIOs—absorbers, cells/contacts, interconnects, packaging, and manufacturing.

Examples of specific, key activities to address CPV performance, cost, and reliability are shown below.

Absorber (Tier-2 TIO)

- Continue to explore improved high-efficiency absorber materials.

Cells and Contacts (Tier-2 TIO)

- Continue to aggressively improve laboratory cells to greater than 40% efficiency.

Packaging (Tier-2 TIO)

- Improve performance of optical systems.
- Develop novel thermal-management systems.

Manufacturing (Tier-2 TIO)

- Transition from high-efficiency c-Si cells to higher-efficiency III-V multijunction solar cells.
- Work with industry to improve systems integration.

The Solar Program will work closely with CPV industry partners and interested utilities to coordinate these activities and ensure that key TIOs are addressed.

Future Generation. At present, three non-conventional PV technologies are receiving R&D attention: organic solar cells, dye-sensitized solar cells, and third-generation concepts including those based on nanostructured materials. The key activities leading to competitiveness for the future-generation technologies will center on increasing efficiency/performance, lowering cost, manufacturing, and reliability of future products. Internal laboratory efforts on future-generation technologies will focus on the absorber and cells/contacts (increased cell efficiencies) Tier 2 TIOs, while subcontracted R&D will cover the full range of Tier 2 TIOs—absorbers, cells/contacts, manufacturing, and reliability. This activity is supported under the High-Performance PV Project.

Examples of specific, key activities to address future-generation performance, cost, manufacturing, and reliability are shown below.

Absorber (Tier-2 TIO)

- Continue to identify and explore materials and concepts of organic solar cells, dye solar cells, and future-generation cells toward 10%, 20%, and over 50% efficiencies, respectively.

Cells and Contacts (Tier-2 TIO)

- Continue to aggressively improve materials and incorporate into devices.

Manufacturing (Tier-2 TIO)

- Assess and verify durability and reliability of future-generation solar cells.
- Identify commercialization pathways for promising new technologies via university/industrial partnerships.

The Solar Program will work closely with future-generation industry partners and interested utilities to coordinate these activities and ensure that key TIOs are addressed.

Inverters and BOS (Tier-1 TIO)

In the area of inverters and balance of systems, the Solar Program has the opportunity to lead a transition over the next 5 years from a component-based manufacturing paradigm to an integrated systems manufacturing approach. The discussion below applies across all reference systems, which are generally in two size categories: residential/off-grid islanding and commercial/utility. As a reference, the document High-Tech Inverter, Balance-of-Systems, and Systems R&D: A Five-Year Strategy, derived from a series of workshops with industry, academic, and laboratory participants, will provide the SDA guidance and prioritization for this transition phase.

Inverter Software (Tier-2 TIO)

- Develop “smart” diagnostic algorithms to report reasons for degradation or failures and predict impending problems due to overstressed components.
- Further automate inverter set-up functions to reduce installation time and errors, and facilitate component interchangeability without system redesign.
- Develop real-time current-voltage curve tracing capability, allowing an inverter to match its maximum-power-point tracking (MPPT) algorithm to the true physical characteristics of the PV array to which it is connected.

Inverter Components/Design (Tier-2 TIO)

- Incorporate emerging new componentry, such as room-temperature superconductors, silicon carbide switching devices, advanced magnetics, and longer-lived capacitors; advanced surge suppression; improved modeling and design optimization; and the development of fully integrated circuitry—new micro-chips to simplify designs, improve reliability, and reduce losses.
- Employ modeling, simulation, and prototype hardware development to completely redesign inverters for high-volume manufacturing with higher efficiencies and greater reliabilities. New algorithms for switching modulation, management of islanding, and interactions among parallel inverters for microgrid control will be developed and analyzed.

Inverter Packaging/Manufacturing (Tier-2 TIO)

- Develop new active and passive heat-rejection and thermal-management designs using air and liquid. Analyze new designs using finite-element simulations, infrared imaging, and other laboratory measurements.
- Develop integrated interconnect switches to reduce system componentry.

Inverter Integration (Tier-2 TIO)

- Use the advantages of various types of communications systems, including spread-spectrum and power-line carriers. Assess and develop data acquisition and communication requirements.
- Work with standard-setting bodies (i.e., UL, IEEE, IEC, CEC) to develop communications protocols, integrated communications capabilities, proper codes and standards for inverter and system-level functionality, system-level controls for the overall PV system, and third-party certification of inverters and PV systems.

Other BOS (Tier-2 TIO)

- Introduce system-level integration into building energy management by developing “smart” controllers and breakers, providing load management, including prioritization of critical loads; enhanced safety; and opportunities to include storage in building energy systems. These smart controllers can also be the hub for system-level data acquisition and performance monitoring.
- Develop advanced array structures for building-integrated and other applications to minimize connections and associated labor, using snap-together elements, jacks for retrofits to existing roofs, and advanced materials such as polymers, synthetics, or composites.
- Develop efficient, flexible DC-to-AC conversion, making any arbitrary PV array and inverter connection possible, and allowing easy expansion of systems and interchange of any components within a system.

Systems Engineering and Integration (Tier-1 TIO)

During the five-year time frame of this plan, the Solar Program will work with industry partners to develop a new systems-manufacturing paradigm for PV systems, facilitating more factory integration and standardization, and less field integration of systems. This approach spans all PV market sectors and applies to all reference systems listed in this document.

System Manufacturing and Assembly (Tier-2 TIO)

- Develop standardized specifications and test procedures for system components and integration in the context of high-volume manufacturing.
- Develop integrated, system-level diagnostics in the context of Quality Assurance/Quality Control programs.
- Design optimized surge suppression throughout the system to improve overall system reliability and increase lifetimes.

Installation and Maintenance (Tier-2 TIO)

- Collaborate with utilities to develop uniform interconnection processes, hardware, and controls that meet utility requirements and state-level regulations.
- Conduct in-depth analysis to improve knowledge of all costs related to O&M of fielded PV systems in all market sectors.
- Grow the training and certification programs for technical personnel, and hand off nationally certified or industry-approved programs to the private sector.

Deployment Facilitation (Tier-1 TIO)

- Provide technical support and guidance to DOE-led initiatives, such as Million Solar Roofs, Solar Decathlon, and international commitments, designed to increase acceptance of PV technologies through outreach, communications, and increasing consumer confidence in the technologies.
- Provide feedback and data to the technology R&D activities related to market acceptance, functionality, reliability, performance, and cost of fielded PV systems in a variety of domestic and international applications.
- Support the development of and continued critical coordination of new and revised codes, standards, and certifications to better ensure safety and performance, and to help build consumer confidence and acceptance in the marketplace.

3.1.9 PV Milestones and Decision Points

Milestone Points	Due Date	Applicable TIOs (Level 1)	Metric
Achieve 16%-efficient production c-Si module	2011	Module	Efficiency
Verify c-Si direct module manufacturing cost of $1.60/Wp ($260/m^2 at 16.0% efficiency)	2011	Module	Cost
Achieve 10%-efficient production CdTe module	2011	Module	Efficiency
Verify CdTe direct module manufacturing cost of $0.90/Wp ($90/m^2 at 10% efficiency)	2011	Module	Cost
Demonstrate, through accelerated life testing, a 20-year line for production CIGS modules	2011	Module	Reliability
Achieve 12%-efficient production CIGS module	2011	Module	Efficiency
Verify CIGS direct module manufacturing cost of $1.00/Wp ($120/m^2 at 12% efficiency)	2011	Module	Cost
Demonstrate, through accelerated life testing, a 20-year life for production CIGS modules	2011	Module	Reliability
Achieve 8%-efficient production a-Si module	2011	Module	Efficiency
Verity a-Si direct module manufacturing cost of $1.05/Wp ($85/m^2 at 8% efficiency)	2011	Module	Cost
Demonstrate, through accelerated life testing, a 20-year life for production a-Si modules	2011	Module	Reliability
Achieve 25%-efficient point-focus concentrator module	2011	Module	Efficiency
Demonstrate a 41%-efficient multijunction cell for CPV applications	2009	Module	Efficiency
Demonstrate a 20% thin-film polycrystalline tandem cell	2011	Module	Efficiency
Verify $3.00/Wp ($250/m2 at 25% efficiency) for a fully installed concentrator module	2011	Module	Cost
Determine and document R&D pathways, through theory/modeling, that can achieve a >50% efficient cell	2011	Module	Efficiency
Identify and document commercialization pathways for promising new future-generation technologies via university/industry partnerships	2009	Module	Efficiency, Cost
Develop new high-tech pre-commercial inverter design for a residential application, demonstrating 96% overall performance and 10-year lifetime	2010	Inverter/BOS	Performance, Reliability
Develop new high-tech pre-commercial inverter design for a commercial and utility application, demonstrating 96% overall performance and 15-year lifetime	2010	Inverter/BOS	Performance, Reliability
Develop requirements for integrated PV system "smart" diagnostics and control	2010	Inverter/BOS	Cost, Performance, Reliability
Determine priority PV system configurations for government-listed procurements and for hardware certification programs	2008	Systems Integration	
Extend SAM capabilities as a predictive energy model based on future commercial technologies in modules, inverters, BOS, and systems configurations	2009	Systems Integration	Cost, Performance
Complete field analysis, retrieval, and lab analysis of thin-film and next-generation PV systems and components operating in extreme climates	2008	Deployment Facilitation	Performance, Reliability
Introduce voluntary PV systems certification program, based on thorough benchmarking analysis of system performance, cost, and reliability, and supporting government-listed (and tribal) procurements of PV systems for remote, grid-connected, and micro-grid applications	2010	Deployment Facilitation	Cost, Reliability
Demonstrate factory-integrated residential PV systems capable of producing electrical energy at $0.15/kWh	2011	Systems Integration	Cost, Reliability
Demonstrate factory-integrated PV systems for commercial applications capable of producing electrical energy at $0.10/kWh	2011	Systems Integration	Cost, Reliability
Demonstrate off-grid islanding PV systems capable of producing electricity at $0.46/kWh	2011	Systems Integration	Cost, Reliability
Recommend technical and policy options for rapidly emerging PV markets abroad (e.g., China, India, Spain) that affect production of and investment in U.S. PV products	2008	Deployment Facilitation	Volume

Decision Points

Using the Stage Gate process and systems-driven analysis tools, the PV Subprogram will assess the progress made toward achieving technical goals. Key decision points are given below.

Decision Points	Date
Conduct a thorough PV portfolio review and prioritize activities necessary to achieve PV Subprogram goals. Go/no-go decision points.	2006
Conduct a thorough PV progress assessment and portfolio review, and prioritize activities necessary to achieve PV Subprogram goals. Go/no-go decision points.	2008
Conduct a thorough PV progress assessment and portfolio review, and prioritize activities necessary to achieve PV Subprogram goals. Go/no-go decision points.	2010
For all module technologies receiving support from the Solar Program, demonstrate and document (through SDA analysis) the relative levels of risk of achieving their respective 2011 performance, cost, and reliability targets. Go/no-go decision points, or revised strategies.	2008
Determine and document whether further field-performance assessments are needed of thin-film and next-generation PV systems and components operating in extreme climates	2007
Determine and document whether additional lessons learned from international deployments are of value to U.S. industry	2007