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Retrospective Benefit-Cost Evaluation of DOE Investment in Photovoltaic Energy Systems

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EXECUTIVE SUMMARY

This study is a retrospective analysis of net benefits accruing from the U.S. Department of Energy's (DOE) investment in photovoltaic (PV) technology development. The study employed a technology cluster approach. That is, benefits measured for a subset of technologies in a meaningful cluster, or portfolio, of technologies were compared to the total investment in the cluster to provide a lower bound measure of return for the entire cluster.[1]

The technologies selected for analysis were PV module technologies. PV modules are encapsulated sets of solid-state solar cells that convert solar energy into electricity. They are perhaps most recognizable as the flat-plate solar panels mounted on roof-tops, affixed to signal posts, or assembled in large arrays that compose solar farms. PV modules are usually characterized by the material technologies that compose the cells. These may be crystalline silicon (c-Si) or "thin films" of semiconductor material, particularly cadmium telluride (CdTe), copper indium diselenide (CIS), and amorphous silicon (a-Si).

PV technologies have benefited from long-term DOE investment that has supported core cell and module technology R&D, manufacturing process development, and the technology infrastructure supporting that R&D. Between 1975 and 2008, the period of analysis for this study, researchers in industry, academia, and DOE's national laboratories received financial and technical support to hasten the development and market introduction of higher quality, longer lived, and lower cost PV modules.

The core of PV systems are the modules, and given this central role, and in light of the magnitude of DOE's investment, the extent to which DOE enabled, accelerated, or supported module R&D constituted a research question of keen interest.

Photovoltaic Energy Systems is one of the four thrusts within the Solar Energy Technology Program (SETP) in DOE's Office of Energy Efficiency and Renewable Energy (EERE). Photovoltaic Energy Systems received the largest portion of DOE's budget for solar energy between 1975 and 2008. Over this period, total appropriations from Congress to DOE for solar energy were $4,089 million in nominal terms, or $7,438 million in real, inflation-adjusted terms (2008$). Photovoltaic Energy Systems accounted for over half of these funds: $2,309 million in nominal terms, or $3,710 million in real terms (2008$).

ES.1 DOE Technology Development Initiatives in Photovoltaic Energy Systems, 1975−2008

The PV technologies reviewed in this report were developed with DOE funding or cost share under four initiatives. Each initiative represented a 10-year or longer commitment on the part of DOE to provide

[1] The economic analysis included in this study values DOE's contributions to PV technology development. Its purpose was not to compare total public and private investment in photovoltaics relative to all benefits accruing from photovoltaics to determine whether PV systems have, through 2008, been socially advantageous. (To be "socially advantageous", the sum of all discounted costs and benefits accruing over time is positive.) Such an analysis has great merit, however the purpose of this evaluation was to value and report measures of return on DOE's investment in technology development. All arguments, costs, and benefits presented in this analysis are those relevant to quantifying DOE's contributions alone.

funding and technical expertise to researchers seeking to develop novel commercial technologies that exploit solar energy:

- **Flat-Plate Solar Array Project (1975–1985)**, which was the first major terrestrial PV technology development initiative sponsored by the Federal government. The project aggressively targeted core technical barriers so as to move photovoltaics from niche, off-grid applications to the mainstream. Technologies for silicon refining, encapsulants, automated module assembly, technology infrastructure, greater energy conversion efficiencies, silicon ingot growth, and silicon ribbon growth were developed. Industry experts interviewed for this study universally regarded the Flat-Plate Solar Array Project (FSA) period as foundational to the terrestrial PV industry.

  In 1975, the U.S. PV industry produced 0.4 megawatts (MW) at an average production cost per watt of $83.86 (2008$). Each module produced had no warranty, was expected to have a useful life of two to three years, and was largely "unimpressive" (Christensen, 1985; Green, 2005). When FSA ended in 1985, 7.8 MW was produced (+2000%) at a production cost per watt of $9.40 (−82%), and 10-year warranties were offered.

- **PV Manufacturing Technology Project (1991–2008)**, which targeted manufacturing operations to enable PV companies to accelerate decreases in production costs and increases in production capacity. PV Manufacturing Technology Project (PVMaT) furthered low-cost PV module production via R&D into advanced manufacturing technologies for cell production and module assembly. Funded companies included AstroPower (GE), BP Solar, Evergreen, First Solar, Global Solar, SolarWorld USA, SunPower, and Uni-Solar.

  In 1991, the U.S. PV industry produced 17.5 MW at a production cost per watt of $6.93 (2008$). In 2008, 1,022.6 MW (+>5,700%) was produced at a production cost per watt of $1.92 (−72%).

- **Thin-Film PV Partnerships (1994–2008)**, under which thin-film technologies were vastly improved, yielding thin-film PV modules that are produced today in greater numbers by U.S. manufacturers than c-Si modules. Through the 1980s and into the early1990s, the National Renewable Energy Laboratory (NREL) sponsored research that aimed to increase efficiency and reduce instability for a-Si, CdTe, and CIS PV technologies.[2] U.S. PV companies reported receiving significant applied research funding beginning in 1988 under TFP's predecessor programs.

  Thin films advanced dramatically during the past two decades, increasing from about 4% of all U.S. production in 1995 to over 60% in 2008. Steep production increases since 2005 are due to the success of major recipients of DOE funding funder TFP, including First Solar (CdTe), Global Solar (CIS/CIGS), and Uni-Solar (a-Si).

- **Measurement, Characterization, and Reliability R&D (1975–present)**, under which the technology infrastructure for module cell and reliability (including the Outdoor Testing Facility), device performance, surface analysis, electro-optical characterization, and analytical microscopy was developed, provided an infrastructure that enabled industry, government, and university researchers to achieve their research objectives under the above three initiatives.

[2] Thin films provided an alternative that held the possibility of overcoming some of the limitations inherent in c-Si, but a significant amount of research would have been required to develop thin films into a viable technology alternative. This R&D constituted an investment with high technical and financial risk that few technology companies or investors were willing to make without outside support. DOE funded nearly all of the materials characterization work for thin films, and all interviewees stated that thin-film companies were heavily reliant on TFP and its predecessor initiatives for R&D funding.

Technology infrastructure work for PV began in 1975 during FSA's block purchase program, which required NASA's Jet Propulsion Laboratory (JPL) and its contractors not only to design performance specifications but also to develop core measurement and characterization methods and standards for performance measurement. Since that time, the infrastructure supporting the PV industry has grown and become established, with private certifications, warranties, and Underwriters' Laboratories and International Electro-technical Commission standards.

ES.2 Study Objectives and Methodology

The objective was to compare DOE's investment to four important measures of benefit:

- **Economic benefits** are increases in the value of goods and services in the economy. Technological advancement is one way to increase economic benefits by improving the performance of existing goods and services and/or reducing their cost and by developing novel goods and services that provide new capabilities and experiences. Resource savings, such as labor, capital, or materials expended are often significant sources of economic benefit.
- **Environmental benefits** are avoided air pollutant emissions and associated avoided adverse health effects.
- **Energy security benefits** are reduced risks to the national energy infrastructure, increases in energy independence, and decreased exposure to exogenous (non-U.S.) volatility in fossil-fuel trade. Energy security benefits are inherently difficult to quantify and compare across projects. The physical units of avoided fossil fuel consumption were converted into barrels of oil equivalent units (BOE).
- **Knowledge benefits** are derived from historical knowledge-tracing studies that review the creation and dissemination of explicit knowledge as codified in patents, publications, relational networks, and tacit knowledge.

Benefits were measured relative to the "next best technology alternative," which refers to the counterfactual state of PV module technologies that would exist in the absence of DOE funding, cost share, technical expertise, and technology infrastructure support. The approach included conducting primary and secondary research on technology advances in photovoltaics funded or cofounded by DOE and ascertaining how, when, and if those advances would have progressed without DOE financial and technical support.[3] Counterfactual PV technology development timelines and cost curves were developed to quantify dollar-denominated benefits.

The study was retrospective in that only benefits and costs through 2008 were included in the analysis. As a result, the measures of economic return calculated are conservative because historical DOE-funded R&D activities will continue to generate benefits well into the future.

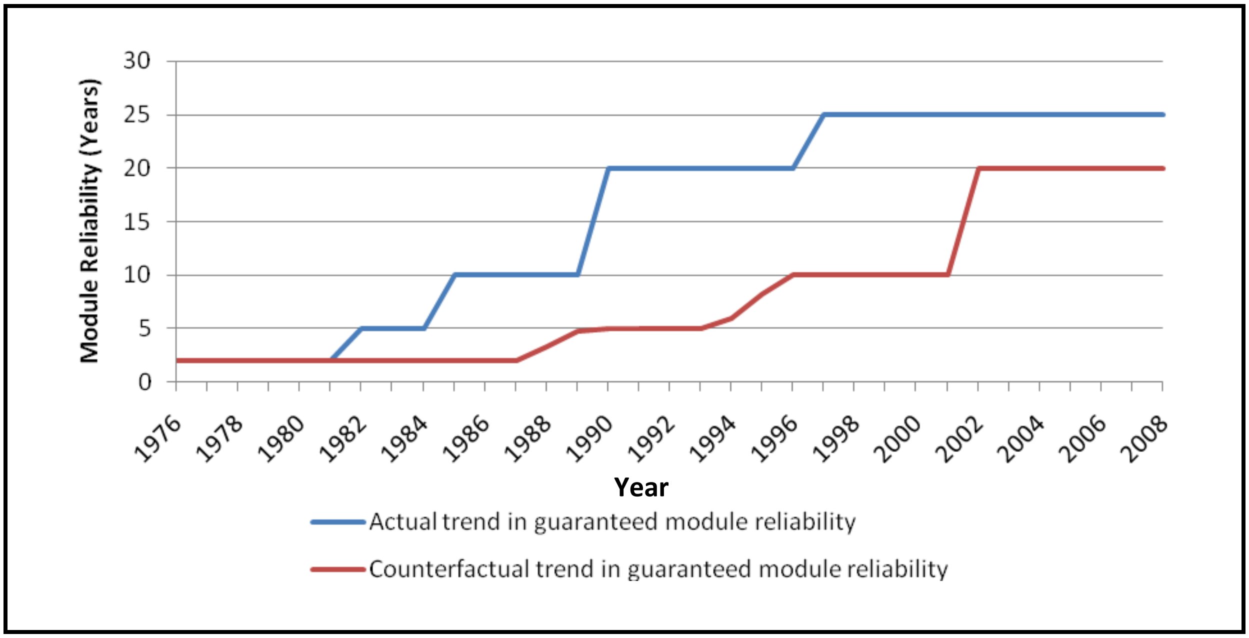
[3] Research questions focused on program additionality, and the authors' explained to all interviewees that their responses should reflect such a focus. All counterfactual production cost per watt data (i.e., insights into how those historical cost data would be different) were provided by PV companies under the assumption that DOE technical expertise and cost sharing were not available and companies' progress continued in its absence. Thus, attribution of economic benefit to DOE was implicit in this analysis.

ES.3 Summary Economic Analysis Results

Interviews with PV company representatives, academic experts, and scientists at DOE's national laboratories combined with economic analysis results comparing actual with counterfactual technical progress indicate that DOE has substantially accelerated the development of high-quality, lower-cost PV modules.

The acceleration effect was estimated to be 12 years, which implies that the progress made over the 10 years of the FSA program would have instead taken 22 years. Figure ES-1 illustrates this effect's impact on guaranteed PV module reliability. Shifting technology development places the introduction of a 5-year warranty in 1990 instead of 1982, and the introduction of the 20-year warranty in 2002 instead of 1990.

Figure ES-1. Actual and Counterfactual Reliability Curves



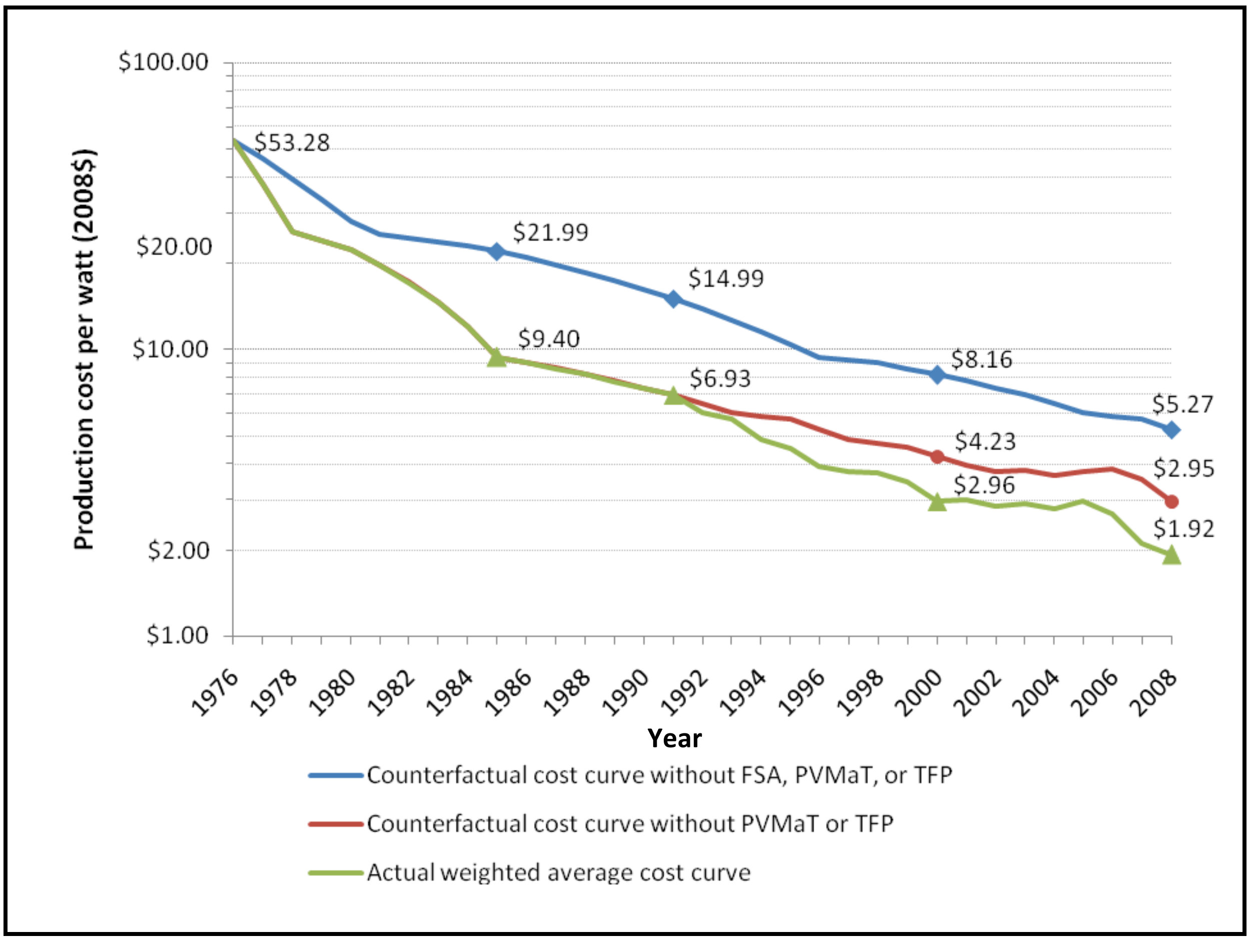
Source: Christensen (1985); Green (2005); Authors' calculations.

The weighted average counterfactual production cost per watt curves depicted in Figure ES-2 were developed by aggregating company-specific responses to how their technology portfolios and manufacturing operations would have developed in the absence of DOE cost sharing. Production cost per watt reductions were greatly accelerated because of FSA, and technologies developed under PVMaT and TFP further hastened these reductions.

Figure ES-2 presents three curves:

- The green curve is the *actual* weighted average production cost per watt curve against which progress in the absence of DOE and its resources was measured. In 2008 dollars, cost per watt was $9.40 in 1985, $6.93 in 1991, $2.96 in 2000, and $1.92 in 2008.
- The blue curve is the *counterfactual* production cost per watt curve that presents the aggregate progress in the absence of DOE involvement, as determined by expert interviewees' assessment of DOE's impact. In the absence of DOE cost sharing, technical expertise, and technology infrastructure, industry progress would have proceeded at a slower pace. As shown in Figure ES-2, PV module production cost per watt would have been higher. The weighted average cost per watt would have been $5.27 in 2008 rather than $1.92.

Figure ES-2. Actual and Counterfactual PV Module Production Cost per Watt Curves (2008$)



Source: Friedman et al. (2005); EIA (2008); IEA (2009); Authors' calculations.

- The red curve beginning in 1991 illustrates the effect of PVMaT and TFP. If PVMaT and TFP had not followed FSA, then beginning in 1991 the cost per watt would have diverged from the green path to the red path. Costs would have been as much as 66% higher, the rate of progress would have been lower, and the weighted average cost would have been $2.95 in 2008 rather than $1.92.

- In 2008, the difference between the actual and counterfactual cost was $3.35 per watt, of which $2.32 was associated with the acceleration effect from FSA and $1.03 was associated with PVMaT and TFP technology.

In all, $18,734.8 million (2008$) in economic benefits over the period from 1975 to 2008 were quantified, encompassing

- $11,319 million in benefits for PV systems installed in the United States between 1976 and 2008. These benefits included cost savings as well as increases in PV modules' guaranteed useful life.
- $6,773 million in production cost savings for PV companies producing modules destined for non-U.S. markets.
- $630 million from the development of advanced silicon refining processes.
- $12 million from accelerated adoption of wire saw technology by the semiconductor industry for slicing silicon ingots into wafers.

ES.4 Summary Environmental Health, Greenhouse Gas, and Energy Security Results

The Co-Benefits Risk Assessment (COBRA) model was used to calculate the health benefits of reductions in air pollutants resulting from using PV systems rather than the next best technology alternative for electricity production.[4] Grid-connected centralized systems, such as utility systems, were compared to natural gas peaking units. Grid-connected decentralized systems, such as systems installed at residences, were compared to a weighted-average (by region) fossil fuel portfolio. Off-grid systems were compared to diesel engines.

Table ES-1 shows estimated total greenhouse gas (GHG) emissions avoided. About 6.8 million tons of CO_2 emissions were avoided, with approximately 1.1 million tons of those emissions attributable to DOE. Although fossil fuel combustion releases much smaller amounts of CH_4 and N_2O than CO_2, these GHGs are not trivial because they are approximately 21 times and 310 times, respectively, more effective at trapping heat in the atmosphere than CO_2 (EPA, 2009b).

[4] The COBRA model was developed by the U.S. Environmental Protection Agency (EPA) to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies. At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint.

Table ES-1. Estimated Avoided GHG Emissions, 1976–2008

	Total Avoided Emissions			Approximate Attribution to DOE		
	CO_2 (tons)	CH_4 (tons)	N_2O (tons)	CO_2 (tons)	CH_4 (tons)	N_2O (tons)
On-grid centralized	202,694	7	3	32,152	1	<1
On-grid distributed	2,346,139	83	33	372,154	13	5
Off-grid	4,266,270	42	548	658,167	6	84
Total	**6,815,103**	**132**	**583**	**1,062,473**	**21**	**90**

Source: Authors' calculations.

Environmental health benefits from avoided adverse health incidences were estimated to be $237 million for 1976 to 2008, of which approximately $39.8 million could be attributed to DOE.[5] Although total benefits were monetized using the COBRA model, specific attribution was unable to be resolved because of challenges associated with isolating technology effects from demand-side public policies. Thus, only a lower bound approximation of environmental health benefits was calculated. Therefore, these benefits were excluded from the measures of economic return.

Terrestrial photovoltaics were originally funded by the U.S. government as a response to disruptions to the nation's energy supply in the 1970s. Photovoltaics represent a secure domestic source of energy in the face of threats to energy supply and provide clean energy to avoid long-run security risks from GHG emissions and climate change.

Because of its distributed nature, photovoltaics hold additional energy security benefits. In the United States, 95% of PV systems are distributed throughout small-scale on- and off-grid applications, making it less vulnerable to threats to the power supply than central power infrastructure.

Energy security benefits are presented quantitatively in barrel of oil equivalents (BOE). One BOE represents the energy released by burning a barrel of oil, or 1,700 kWh. In 2008, PV systems produced over 1.8 billion kWh, or 1.1 million BOE. Between 1976 to 2008, PV replaced an estimated 4.8 million BOE, of which approximately 0.8 million can be attributed to DOE.[6]

ES.5 Summary Knowledge Benefits Results

The knowledge benefits analysis was prepared by Rosalie Ruegg, TIA Consulting, Inc., and Patrick Thomas, 1790 Analytics. The principal conclusions were the following:

[5] Including benefits for 2009 to 2033, assuming a useful life for a PV system of 25 years, increases total benefits before discounting by over $900 million. Thus, retrospective and future environmental benefits for the installed base of PV systems as of 2008 are between $1.1 billion and $1.2 billion. Including benefits projected for 2009 to 2033, approximately $246.7 million in environmental benefits may be attributed to DOE activities.

[6] Including benefits for 2009 to 2033, assuming a useful life of 25 years, increases security benefits by 24.9 million BOEs. Thus, retrospective and future benefits for the installed base as of 2008 are estimated at 29.7 million BOEs. An additional 5.7 million BOEs can be attributed to DOE from the 2008 PV infrastructure extended out to 2033, amounting to a total of 6.5 million BOEs in benefits.

- DOE funding of solar PV research generated knowledge embodied in, among other things, an estimated 274 patent families in photovoltaics (where each patent family contains all patents based on the same invention) and more than 900 publications. These patents and publications provide a knowledge foundation on which further innovations in solar energy have built, as well as innovations in the semiconductor industry more generally.
- All of the eight top U.S. solar PV producers are closely linked to earlier DOE-attributed PV patents, among them ECD (Uni-Solar), BP Solar, Global Solar, and SunPower.
- Nine of 10 of the leading companies worldwide in solar energy patenting are closely linked to earlier DOE-attributed PV patents, among them Boeing, Canon, ExxonMobil, and, again, Uni-Solar and BP Solar. Of the more than 1,800 solar energy patent families of these 10 leading companies, 30% are linked to the earlier DOE-attributed PV patents.
- DOE-attributed PV patent families were identified as among those highly cited by others, including patents describing thin-film PV devices that increase light absorption; patents describing solar cells constructed from multiple layers of amorphous silicon; patents describing processing techniques for producing PV cells and module assembly; patents describing large-area, thin-film cells formed from copper indium diselenide (CIS); recent patents describing nanowires, useful in a variety of energy conversion applications, and light harvesting rods for regenerative solar cells, among others.
- Citing the DOE-attributed PV publications, as well as patents by companies outside the solar energy industry, suggests an interest in the results of DOE-funded PV research that crosses industry areas. Citing the publications by a number of foreign national laboratories suggests interest in the DOE-funded PV research by counterpart institutions abroad.

ES.6 Measures of Return on DOE's Investment in Photovoltaic Energy Systems

Net of DOE investment costs of $3,710 million (2008$) in Photovoltaic Energy Systems, the total quantified net economic benefit accruing from DOE's contributions to technology development was $15,025 million, corresponding to an internal rate of return of 17% over the 33-year period of analysis (Table ES-2).

Applying a discount rate of 7% yields a net present value (NPV) of $1,459 million and a benefit-cost ratio (BCR) of 1.83, indicating that for every $1 invested, $1.83 in benefits accrued. Applying a 3% social discount increases the NPV to $5,725 million and the BCR to 3.24.

To review long-term influences, this study also reorganized economic benefit results by initiative:

- FSA ran from 1975 to 1985, cost DOE $535 million, and continues to generate economic benefits, which through 2008 amounted to $15,673 million. Applying the 7% social discount rate provides a BCR of 7.12 and an NPV of $2,435 million. The internal rate of return (IRR) was 37%.
- PVMaT and TFP ran from 1988 to 2008, cost DOE $495 million, and also continue to generate economic benefits, which through 2008 amounted to $3,061 million. Applying the 7% social discount rate provides a BCR of 3.35 and an NPV of $637 million. The IRR was 24%.

That the IRRs of FSA and PVMaT/TFP were individually greater than the cluster IRR of 17% results from including costs for activities for which benefits estimation was not undertaken. It is also important to note that benefits for FSA accrued over the entire 33-year period of analysis. Results for PVMaT and TFP reflect more recent investments, and economic returns from DOE's investment in thin-film PV in particular are only now beginning to accrue.

Table ES-2. Measures of Economic Return for Photovoltaic Energy Systems

Measure	Photovoltaic Energy Systems Cluster	FSA (1975–1985)	PVMaT (1991–2008) TFP (1988–2008)
Period of Net Benefits Accrual	*1975–2008*	*1975–2008*	*1988–2008*
Total benefits (million 2008$)	$18,734.8	$15,673.3	$3,061.5
Total costs (million 2008$)	$3,709.9	$535.0	$495.0
Net benefits (million 2008$)	$15,024.9	$15,138.3	$2,556.6
Internal rate of return	17%	37%	24%
NPV at 7% (million 2008$)	$1,458.9	$2,435.1	$636.9
Benefit-to-cost ratio at 7%	1.83	7.12	3.35
NPV at 3% (million 2008$)	$5,724.7	$6,592.8	$1,409.9
Benefit-to-cost ratio at 3%	3.24	15.07	4.76

Source: Authors' calculations.

A complete summary of findings from evaluations of economic, environmental, energy security, and knowledge benefits is included in Table ES-3. In addition to these quantitative measures, interviews with industry, academic, and public-sector scientists and business leaders revealed that FSA, PVMaT, and TFP were critical to PV technology development. Most experts interviewed for this analysis concluded that without these programs not only would the state of photovoltaics be significantly poorer, but many U.S. companies, which employ thousands of people, would not exist.

Table ES-3. Summary Cost-Benefit Analysis Results, 1975–2008

	Quantified Benefit	Minimum Attribution to DOE	Unit of Measure
Economic Benefits			
Net economic benefits	$15,024.9	$15,024.9	Million, 2008$
Public rate of return		17%	
Net present value at 7% [Base year = 1975]		$1,458.9	Million, 2008$
Net present value at 3% [Base year = 1975]		$5,724.7	Million, 2008$
Benefit-to-cost ratio at 7%		1.83	
Benefit-to-cost ratio at 3%		3.24	
Environmental Health Benefits			
Monetized via COBRA	$237.23	$39.80	Million, 2008$
Avoided mortality[a]	32.65	5.48	Deaths
Avoided infant mortality[a]	0.07	0.01	Deaths
Avoided chronic bronchitis	21.98	3.69	Cases
Avoided nonfatal heart attacks	51.03	8.57	Attacks
Avoided resp. hospital admissions.	7.63	1.28	Admissions
Avoided CDV hospital admissions	15.88	2.67	Admissions
Avoided acute bronchitis	54.87	9.20	Cases
Avoided upper respiratory symptoms	490.69	82.29	Episodes
Avoided lower respiratory symptoms	650.84	109.15	Episodes
Avoided asthma ER visits	29.52	4.99	Visits
Avoided MRAD	27,036.52	4,535.47	Incidences
Avoided work loss days	685.87	123.00	Days
Emissions Benefits			
Avoided carbon dioxide emissions (CO_2)	6,815,103	1,062,473	Tons
Avoided methane emissions (CH_4)	132	21	Tons
Avoided nitrous oxide emissions (N_2O)	583	90	Tons
Avoided particulate matter emissions (PM)	1,232	207	Tons
Avoided sulfur dioxide emissions (SO_2)	2,634	463	Tons
Avoided ammonia emissions (NH_3)	16	3	Tons
Avoided volatile organic compounds emissions (VOCs)	1,090	181	Tons
Energy Security Benefits			
Equivalent avoided petroleum consumption	4,790,478	827,189	Barrels of oil equivalent
Knowledge Benefits			
DOE-attributed patent families in photovoltaics		274	Patent families
DOE publications in photovoltaics		900	Publications
Percentage of leading U.S. PV company patents linked to DOE		30%	

[a] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

1. INTRODUCTION

This study is a retrospective analysis of net benefits accruing from the U.S. Department of Energy's (DOE) investment in photovoltaic (PV) technology development. The study employed a technology cluster approach. That is, benefits measured for a subset of technologies in a meaningful cluster, or portfolio, of technologies were compared to the total investment in the cluster to provide a lower bound measure of return for the entire cluster.

The technologies selected for analysis were photovoltaic (PV) module technologies. PV modules are encapsulated sets of solid-state cells that convert solar energy into electricity. They are perhaps most recognizable as the flat-plate solar panels mounted on roof-tops, affixed to signal posts, or assembled in large arrays that compose solar farms. PV modules are usually characterized by the material technologies that compose the cells. These may be crystalline silicon (c-Si) or "thin films" of semiconductor material such as cadmium telluride (CdTe) or copper indium diselenide (CIS).

PV technologies have benefited from long-term DOE investment in core cell and module technology R&D, manufacturing process development, and the technology infrastructure enabling that R&D. Between 1975 and 2008, the period of analysis for this study, researchers from industry, academia, and DOE's national laboratories received financial and technical support to hasten the development and market introduction of higher quality, longer lived, and lower cost PV modules.

There has been a national solar energy imperative since the beginning of the Organization of Petroleum Exporting Countries (OPEC) oil embargo in 1973, which led to an immediate concern about energy security in the United States. Coincidentally, the National Science Foundation and the National Aeronautics and Space Administration (NASA) had been planning a conference to lay out funding and develop a plan for terrestrial PV development. At the time, the domestic PV industry was in its infancy and technical expertise was concentrated at NASA's Jet Propulsion Laboratory (JPL) which developed photovoltaics for space applications. Referred to as the Cherry Hill Conference, this conference was held just one week after the oil embargo began, giving it great national significance.

The Cherry Hill Conference established technology goals for terrestrial photovoltaics and marked the beginning of the National Photovoltaics Program. The following year, after the creation of the Energy Research and Development Administration (ERDA, the precursor to DOE),[7] the Solar Energy Research, Development, and Demonstration Act called for research and commercialization programs and established the Solar Energy Research Institute (now the National Renewable Energy Laboratory [NREL]), which began operation in 1977. In the years that followed DOE deployed long-term, sustained R&D initiatives that were responses to technical barriers or technology opportunities for terrestrial photovoltaics.

[7] ERDA became a cabinet-level department with the Department of Energy Organization Act of 1977. The Act was passed as a way to combine federal energy programs into a single department. DOE was formed to address energy shortages and foreign dependence through renewable energy and energy efficiency initiatives.

Three of these initiatives are of particular focus in this analysis:

- The Flat-Plate Solar Array Project (FSA) (1975–1985), which was funded by ERDA and DOE but managed by JPL in order to transfer JPL's rich space-based PV expertise to the nascent terrestrial PV industry and the Solar Energy Research Institute;
- The Photovoltaic Manufacturing Technology Project (PVMaT) (1991–2008), which was later renamed the Photovoltaic Manufacturing Research and Development Program and aimed to develop manufacturing technology for low-cost module production; and
- The Thin-Film PV Partnerships Program (TFP) (1994–2008), which was preceded by the Amorphous Silicon and Polycrystalline Thin-Film programs dating to the 1970s and aimed to develop thin-film PV technologies.

The technology cluster was Photovoltaic Energy Systems, which is one of the four thrusts within the DOE Solar Energy Technology Program (SETP) in the Office of Energy Efficiency and Renewable Energy (EERE).[8] During part of the period covered in this study, the National Center for Photovoltaics (NCPV) coordinated DOE's strategy for photovoltaics. Solar PV projects are conducted by DOE, its national laboratories (particularly NREL in Golden, Colorado, and Sandia National Laboratory (SNL) in Albuquerque, New Mexico), university research centers, nonprofit centers of excellence, and solar energy technology companies.[9] Historically, and as will be reviewed in this report, many of the projects yielding viable PV technologies were collaborations between private-sector, government, and academic researchers.

1.1 Overview of Objectives and Approach

The objective of this analysis was to estimate net economic and other benefits attributable to DOE investment in Photovoltaic Energy Systems and to calculate measures of return. A cost-benefit analysis employing a technology cluster approach enabled the study to find a technology focus, and thereby balance the importance of being comprehensive with a manageable scope and an allotted period of performance.

The economic analysis included in this study values DOE's contributions to PV technology development. Its purpose was not to compare total public and private investment in photovoltaics relative to all benefits accruing from photovoltaics to determine whether PV systems have, through 2008, been socially advantageous. (To be "socially advantageous", the sum of all discounted costs and benefits accruing over time is positive). Such an analysis has great merit, however the purpose of this evaluation was to value and report measures of return on DOE's investment in technology development. All arguments, costs, and benefits presented in this analysis are those relevant to quantifying DOE's contributions to technology development alone.

[8] SETP supports the development of technology to harness energy from the sun, an abundant renewable energy source. SETP focuses on four thrusts: photovoltaics, concentrating solar power, systems integration, and market transformation.

[9] In addition to NREL and SNL, other key participants in the NCPV at present are Brookhaven National Laboratory, the Georgia Institute of Technology, the Institute for Energy Conversion at the University of Delaware, DOE's Southeast Regional Experiment Station, and DOE's Southwest Technology Development Institute.

Four categories of benefits were studied: economic, environmental health and greenhouse gas (GHG) emissions, energy security, and knowledge benefits. Evaluating the benefits of DOE's contributions to technology development across these four categories provides a more comprehensive review along important program evaluation dimensions than would result from a pure economic cost-benefit study alone.[10]

Benefits were measured relative to the "next best technology alternative." The next best alternative refers to the state of PV module technologies in the absence of DOE funding or cost share, technical expertise, and technology infrastructure support. The approach included conducting primary and secondary research on technology advances in photovoltaics funded or cofounded by DOE and ascertaining how, when, or if those advances would have been made in the absence of DOE's support.

The following research questions were of interest:

- To what extent has DOE produced economic benefits (resource savings and other positive economic effects) relative to the next best alternative?
- To what extent has DOE promoted environmental benefits and enhanced energy security by providing alternative energy sources and energy efficiency and by protecting existing resources?
- To what extent has DOE cultivated a knowledge-base for photovoltaics that may be leveraged by researchers to further PV R&D, and to what extent has funded research formed a technology base supporting private-sector intellectual property?
- Would today's commercialized PV module technologies likely have happened at the same time, with the same scope and scale, and with the same extent of deployment without DOE's Photovoltaic Energy Systems thrust?
- To what extent do benefits attributable to DOE/EERE involvement exceed DOE/EERE expenditures for Photovoltaic Energy Systems?

To address the economic questions, counterfactual PV technology development timelines and cost curves were developed to quantify dollar-denominated benefits. Where benefits could not be quantified, they were treated qualitatively in discussions that substantiate this study's findings. Findings from evaluations of knowledge, environmental, and energy security benefits complete the review and complement the findings from the economic analysis.

There are four notable attributes to analyzing PV module technologies with and without DOE support when compared to an alternate approach of measuring benefits relative to a portfolio of fossil-fuel, nuclear, or other renewable energy technologies:

- PV modules would have developed without DOE (albeit with some delay), given that the domestic PV industry was in its infancy in the mid-1970s, and several PV development programs

[10] Although the current study is the first independent retrospective economics study of photovoltaics funded by DOE, this work greatly benefited from earlier JPL, NREL, SNL, and other scholarly evaluations of the technical significance of DOE program activity. The purpose of this study was not to replicate technical program reviews, but rather to contribute to the knowledge base by independently measuring the extent to which technical impacts were matched by economic and other quantitative benefits.

were underway abroad. Most notable among international initiatives was the Sunshine Project, which the Japanese government created in response to the 1973 oil crisis.

- A focus on PV modules alone made the technology focus manageable and economic modeling relevant to quantifying the additionality contributed by DOE. Segmenting the contributions of modules from the benefits of whole PV systems, which would have been then compared to a portfolio of non-PV systems, would have required more assumptions and analytical steps, adding greater uncertainty and reducing the accuracy of finding.
- Lines of inquiry explored with industry and academic experts were specific, narrow in scope, and aligned with the technology development projects for which companies and universities received the majority of their DOE cost share.
- Attribution to DOE was implicit in the approach. One of the most challenging aspects of benefit-cost analyses is measuring program additionality—the proportion of quantified benefits attributable to the DOE investment. By comparing actual technology development with alternative technology development without DOE support, the study avoided the step of apportioning attribution among stakeholders.

The study was retrospective in that only benefits and costs through 2008 were included in the analysis. As a result, the measures of economic return calculated are a lower bound because historical DOE-funded R&D activities will continue to generate benefits well into the future.

1.2 Selection of Photovoltaic Energy Systems as the Technology Cluster

Photovoltaic Energy Systems received the largest portion of ERDA's and DOE's budget for solar energy initiatives between 1975 and 2008. Over this period, total appropriations from Congress for solar energy were $4,089 million in nominal terms, or $7,438 million in real terms (2008$). Photovoltaic Energy Systems accounted for over half of these funds: $2,309 million in nominal terms, or $3,710 million in real terms.[11]

Within the Photovoltaic Energy Systems cluster, the technologies of focus were those that supported the development of c-Si and thin-film modules, including R&D for solar cells, module manufacturing, and technology infrastructure. FSA, PVMaT, and TFP were technology initiatives that represented 10+ year commitments on the part of DOE to provide cost share and technical expertise to U.S. companies seeking to develop novel commercial PV technologies. The core of PV systems are the modules, and given this central role, the extent to which DOE enabled, accelerated, or supported module R&D constituted a research question of keen interest.

A large body of engineering and public policy literature has rigorously assessed technical progress in photovoltaics and the role of DOE in supporting that progress. Many recent works, including those by Komp (2001), Green (2005, 2009), Swanson (2006), and Osterwald and McMahon (2009), continue to highlight the significance of the 1975–1985 FSA project on the development of solar technologies.

[11] EERE budget analysts provided historical data on Congressional appropriations for Photovoltaic Energy Systems and for all solar energy programs, which included CSP and other non-PV technologies. ERDA funding for NASA and NSF in the amount of $600,000 for FY1975 were also included. See also Table F-3 in Appendix F.

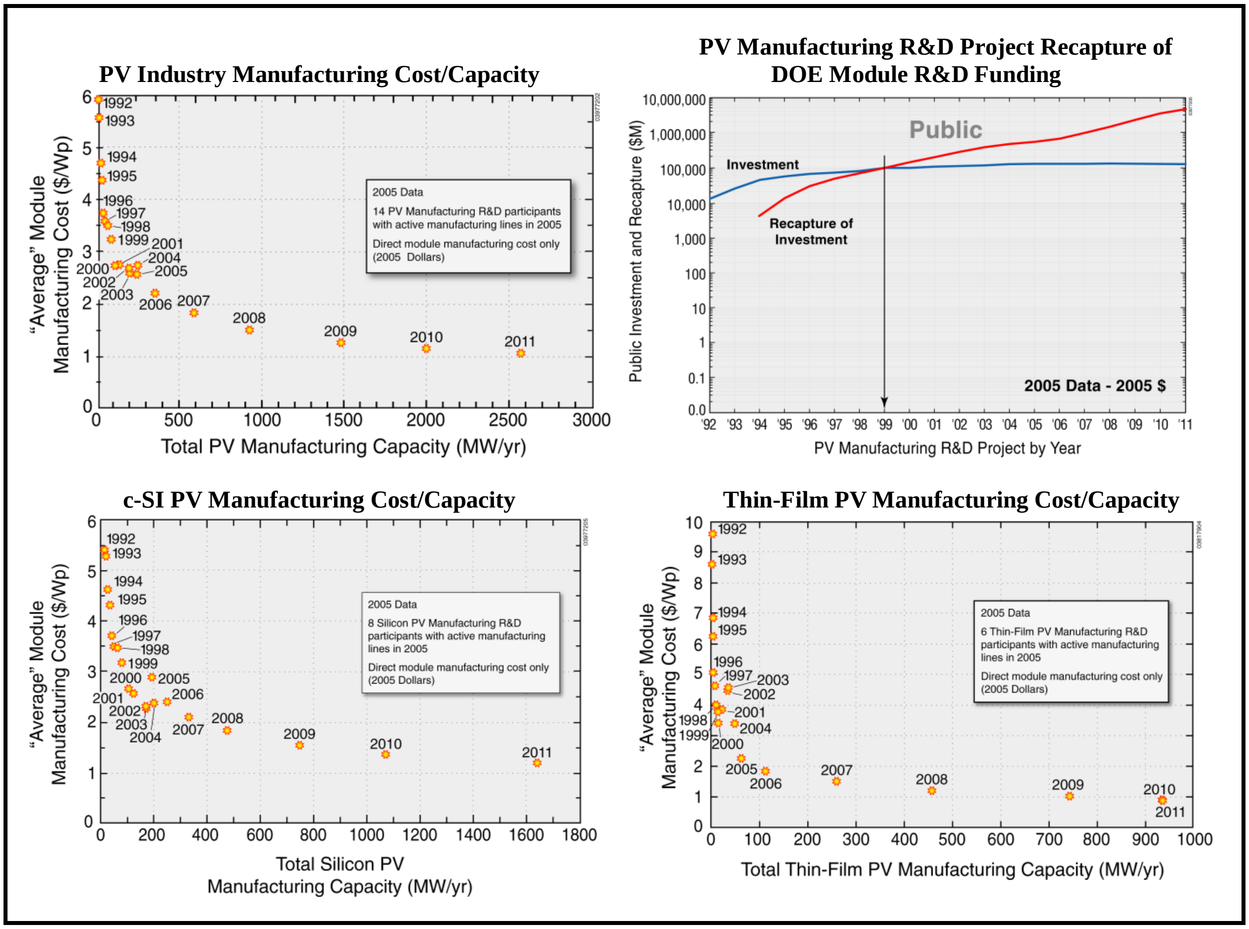
DOE program reviews and technical reports for PVMaT and TFP highlighted the challenges PV companies faced in further developing core PV technology, operational efficiency, and economies of scale in manufacturing. These challenges inhibited sector and technology development. NREL, in particular, offered several prospective analyses of program goals and strategies (Surek, 1992; Mitchell et al., 1992; Witt et al., 1993), as well as retrospective assessments and case studies of technical progress and best practices to guide future endeavors (Witt et al., 2001; Margolis, 2002; Margolis et al., 2006).

NREL, SNL, and DOE jointly performed two internal quantitative analyses of investment recovery on the DOE and private investment in PVMaT (Witt et al., 2001; Friedman et al., 2005).[12] Figure 1-1 presents historical results from these analyses through 2005 and the authors' best forecasts through 2011. Witt et al. (2001) found that the public investment in PVMaT was recouped in 1997, and the industry investment was recouped in 1999.[13] Friedman et al. (2005) calculated that, between 1992 and 2005, the average module manufacturing cost fell 54%, production capacity increased 18.5 fold, and progress ratios were 87% for c-Si companies and 81% for thin-films companies. These results suggested that economic benefits might be significant and should be quantified.

[12] These two studies are akin to engineering cost recovery analyses or payback analyses. They differ fundamentally from the current work in that they did not measure benefits relative to counterfactual technology or market development in the absence of the initiatives being reviewed. Witt et al. (2001) collected data on direct manufacturing cost per watt, production volumes, and production capacity from program participants. Year-on-year cost reductions were monitored, and program participants were asked to assign the proportion of annual cost savings passed to consumers via reduced prices or retained as increased profits. Cumulative cost savings estimates were compared with cumulative industry and public costs to gauge the timing of DOE investment recovery. The second study (Friedman et al., 2005) updated the results of Witt et al. (2001) with historical data from 2001 to 2005.

[13] The cost-per-watt results from Friedman et al. (2005) formed the baseline manufacturing costs per watt for 1992–2005 employed in our economic analysis The baseline scenario presented in Section 5 also provides data points for 1974–1991 and 2006–2008. The current work conducted extensive interviews with industry, government, and academia to assess how industry progress would be different without DOE's investment. Two recent papers, one by Nemet (2006) and one by van der Zwaan and Rabl (2004), address the rapid rate of learning and highlight the challenges of decoupling technology advancement and learning by doing from the influence of production scale, materials prices, and capital expenditures, for example. Thus, we proceeded duly cautioned about the interplay between technology development and production scale.

Figure 1-1. Results from 2005 DOE Investment Recovery Analysis



Source: Friedman et al. (2005).

1.3 Report Organization

The remainder of this report is organized as follows:

- Chapter 2, Background Information on Photovoltaics, offers a brief primer on PV technologies and terminology for readers without a background in photovoltaics.
- Chapter 3, Evaluated PV Module Technologies and DOE Technology Development Initiatives, reviews technologies, technical accomplishments, and the history and rationale for DOE technology development activity.
- Chapter 4, Methodology Overview and Economic Analysis Framework, describes the methods used in our analysis.
- Chapter 5, Economic Analysis Results, provides our assumptions, estimation procedures, and findings from the economic analysis.
- Chapter 6, Environmental Health, Greenhouse Gas, and Energy Security Benefits, describes the use of the Co-Benefits Risk Assessment (COBRA) model to estimate health effects from photovoltaics and presents the results as well as energy security and other environmental benefits.

- Chapter 7, Knowledge Linkages and Benefits, presents summary knowledge benefits linkages based on patent and citation analysis.
- Chapter 8, Summary Results and Concluding Remarks, presents the conclusions of the study.

2. BACKGROUND INFORMATION ON PHOTOVOLTAICS

For readers without a technical background in PV technologies, this chapter provides a primer on photovoltaics, different PV materials technologies, and important terms and concepts. This material is not comprehensive; rather the intent is to offer sufficient background information to enable the reader to follow the technical and economic impact discussions that compose the balance of the report. Readers with a technical background may choose to skip this chapter.

Photovoltaics is the conversion of sunlight into electricity by a semiconductor device. The term "semiconductor" refers to inorganic substances composed of metalloid elements (e.g., silicon, copper, germanium) that are prized for their electrical conductivity. The PV effect was first explored scientifically in the nineteenth century, but it remained a curiosity until the mid-twentieth century, when U.S. government funding catalyzed substantial applied research in photovoltaics to develop power supplies for space applications. Put simply, photons of light of sufficient energy will excite electrons in a semiconductor into a conductive state, causing electricity to flow within the material. The amount of energy required to excite electrons in the semiconductor substance into a conductive state is known as the "band gap." Each semiconductor material has a unique band gap.

2.1 Crystalline Silicon (c-Si)

There are two broad materials categories that differentiate commercial PV modules reviewed in this chapter: c-Si and thin films.[14] Early solar cells used c-Si as the semiconductor material, and c-Si remains a leading technology today. All types of c-Si cells begin with a polycrystalline silicon, or polysilicon, feedstock. Solar-grade polysilicon must be very pure, because contaminants will affect its electrical properties. Although silicon is an abundant resource, purifying silicon for use in semiconductor devices is expensive and energy consuming (Komp, 2001). The majority of polysilicon used in the solar and electronics industry is manufactured by refining inexpensive metallurgical-grade silicon into a gaseous silicon compound that is then deposited as polysilicon in a reactor. C-Si technologies include single-crystalline silicon (sc-Si), cast multicrystalline silicon (mc-Si), and ribbon multicrystalline silicon (ribbon-Si).

2.1.1 Single-Crystalline Silicon (sc-Si)

Functional sc-Si solar cells were first demonstrated at Bell Laboratories in 1954. Since then, sc-Si cells have been drastically improved, with solar energy conversion efficiency increasing from 6% in 1954 to 25% in 2009 (NREL, 2009e). As of this writing, leading U.S. producers of sc-Si modules are California-based SunPower, whose production facilities are located in the Philippines, and SolarWorld, which is a multinational company headquartered in Germany that acquired successor companies to Arco Solar, one of the first U.S. PV companies. SolarWorld USA has production facilities in California and Oregon (*PV News*, 2009).

[14] Other materials are being investigated for PV applications, including organic materials, however this research is still in its infancy and no technologies have reached large-scale commercialization.

Sc-Si cells are made from single crystals of silicon, which improves cell performance, but the trade-off is the costly process of growing large single crystals using the Czochralski (Cz) process. In this process, a seed crystal known as a puller is dipped in molten polysilicon and removed slowly, pulling out a round crystal ingot as the silicon solidifies on the seed.

Round sc-Si wafers are cut from the ingot with a wire saw. Before the development of wire saws, internal diameter saws were used in a wasteful process that cut wafers one at a time. As much as half of the purified silicon was kerf loss, which is the silicon equivalent of sawdust. Wire saws, which were first successfully adopted by Solarex (now BP Solar) under PVMaT, have now been adopted throughout the semiconductor industry for their ability to slice larger ingots, cut thinner wafers, produce less waste, and slice multiple wafers at a time (Komp, 2001). Round wafers may be trimmed into approximately rectangular shapes to allow a given area of module to contain a greater area of solar cells.

2.1.2 Cast Multicrystalline Silicon (mc-Si)

Lower grade silicon, such as silicon recycled from the electronics industry, can be cast into a block, forming mc-Si. Although mc-Si cells are typically less efficient than sc-Si cells, they can use a less expensive feedstock and avoid the energy-intensive crystal-pulling step. The ingots formed are rectangular, making the trimming process unnecessary. If the crystal grains are large enough and the boundaries are perpendicular to the front of the cell, mc-Si silicon cells can be as efficient as sc-Si cells (Komp, 2001). Like sc-Si, mc-Si blocks must be sliced into wafers. Mc-Si silicon cells have seen significant gains in efficiency since development. In 2009, Mitsubishi produced a record 18.9% efficient mc-Si cell (Mitsubishi, 2009). In 2008, BP Solar was the largest U.S. producer of mc-Si silicon devices (*PV News*, 2009).

2.1.3 Ribbon Multicrystalline Silicon (ribbon-Si)

Ribbon-Si is the term for the production of mc-Si wafers directly from molten polysilicon. This process avoids the costs of slicing individual silicon wafers faced by sc-Si and mc-Si manufacturers and uses silicon more efficiently by avoiding all kerf loss caused by the sawing process (Komp, 2001). In a ribbon growth system, a ribbon of crystalline silicon is grown and cut to size. Evergreen Solar, which uses the string ribbon method, and SCHOTT Solar, which uses the edge-fed growth method, are the largest manufacturers of ribbon-Si (*PV News*, 2009).

2.2 Thin Films

With good stability and comparatively high conversion of solar energy to electricity, c-Si accounted for nearly all PV module production until 2007, when thin-film manufacturing began to grow. Thin films consist of several layers of semiconductor deposited onto a glass, metal, or plastic substrate and sealed. Methods vary by thin-film type and manufacturer, but generally, thin-film cells require fewer manufacturing steps than c-Si cells. Thin-film cells also require smaller amounts of expensive semiconductor materials than c-Si cells and are often flexible and lightweight. The trade-off is that thin films do not have the solar energy conversion efficiency of c-Si cells. There are three established thin-film technologies: amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS).[15]

2.2.1 Thin Film: Amorphous Silicon (a-Si)

A-Si, a noncrystalline alloy of silicon and hydrogen, was first explored for use in solar cells in the 1960s, and a-Si consumer products were on the market by the 1980s, making it the first commercially available thin film (Goetzberger et al., 2003). A-Si was initially used in small products such as calculators, but has since become suitable for larger applications. Energy Conversion Devices (ECD), Energy Photovoltaics, Iowa Thin Film Technologies, Solarex Corporation (BP Solar), and Utility Power Group all received PVMaT contracts for improving a-Si manufacturing and modules. In 2009, Uni-Solar (a wholly owned subsidiary of Energy Conversion Devices) is the largest U.S. manufacturer of a-Si modules.

A-Si faces one key limitation: it becomes unstable when initially exposed to sunlight, a phenomenon known as the Staebler-Wronski effect. During the first few hundred hours under sunlight, the conversion efficiency of a-Si decreases. This is likely due to an increase in the defect density during light soaking. Steady state may be reached after about 1,000 hours. Researchers have had some success in reducing efficiency loss by using multiple junctions, each with a thinner absorber layer, but the Staebler-Wronski effect is observed in most a-Si modules, complicating the prediction of performance in the field.

2.2.2 Thin Film: Cadmium Telluride (CdTe)

The origins of CdTe thin films began with the development of a 6% efficient copper telluride (Cu_2Te) cell in the early 1960s (Goetzberger et al., 2003). By the 1970s, Cu_2Te, which faced problems related to the diffusion of copper into other layers of the cell, was replaced with CdTe, the same n-type semiconductor used in cells today. Laboratory efficiencies of over 16% have been reached (NREL, 2009e).

CdTe is a material well suited for use in photovoltaics based on its band gap, high electron mobility, and natural p-type doping (NREL, 2009g). CdTe is relatively easier to deposit and produce at a large scale, and it can be produced many different ways (Komp, 2001). Several companies explored the use of CdTe for PV modules during TFP, including Golden Photon and Solar Cells Inc. (now First Solar). First Solar (2009), the largest CdTe producer and the largest module producer in the world by volume in 2009, manufactured 10.7% efficient CdTe modules at less than $1.00 per watt in 2009 (2008$).

2.2.3 Thin Film: Copper Indium Diselenide (CIS)

CIS was investigated for use in PV cells in 1974 but did not reach commercialization until 1998 because of problems with low yields and poor reproducibility of initial results (Rau and Schock, 2001). CIS improved rapidly in the decades after its initial use, with laboratory efficiency tripling from 6% to greater than 19% from 1974 to 2005 (NREL, 2009e). In 2005, NREL achieved efficiency levels in the laboratory of greater than 19%, making CIS the most efficient thin-film technology to date (NREL, 2009e). Although CIS performs very well in the laboratory, commercialization has been difficult. The top

[15] Early research explored other potentially viable thin-film materials such as zinc phosphide (Zn_3P_2) and cadmium selenide (CdSe), but these candidate technologies were demonstrated not to be suitable.

modules on the market are only 11 to 13% efficient. Many manufacturers produce a variant of CIS known as copper indium gallium diselenide (CIGS). In this report, we refer to all CIS-type cells as CIS for simplicity.

Despite the benefits of less semiconductive material and fewer production processes than c-Si, CIS faces several obstacles. Indium is very rare, which could restrict future production volumes. CIS is also difficult to produce with high-throughput manufacturing because of its complexity as a semiconductor. This reduces yield and increases the cost of producing CIS modules.

Global Solar Energy, Inc., ITN Energy Systems, and Shell Solar Industries all received PVMaT contracts for improving CIS technology. Shell Solar (now SolarWorld USA) went into CIS production for several years before ceasing production in 2005. Global Solar, which manufactures CIGS on a flexible substrate, is the largest U.S. producer, producing 7 MW in 2008. Global Solar has achieved a relatively inexpensive roll-to-roll manufacturing process that produces efficient, lightweight modules (Britt and Wendt, 2002).

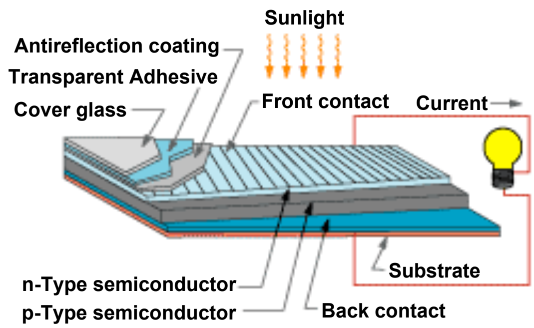
2.3 Components of a PV Energy System

A PV system provides electricity via modules that produce direct-current electricity. This section describes how PV modules in conjunction with other technologies are assembled to create a PV energy system. A complete installed system is necessary to convert electrical power generated by the PV module into a form consumers can use. The following example is for a typical c-Si system, which is composed of cells, modules, and balance of systems.

2.3.1 Example c-Si PV Cell

A solar cell is the semiconductor device that converts solar energy into electrical power. To make a c-Si cell, silicon wafers must be cleaned, doped, and sometimes textured before use. A metal back contact, often containing aluminum, is added to the back of the cell, and the front contact is attached to the front of the cell in a grid-like pattern. The lines on the front contact, which is generally attached through vacuum evaporation or screen printing, must be very thin to limit the amount of sunlight that is prevented from reaching the cell. (Front contacts pose a number of technical issues, and some manufacturers have adopted alternatives such as a buried contact approach.) Silicon reflects about 35% of the light striking it (Komp, 2001); therefore, an antireflective coating, such as silicon nitride or titanium dioxide, is usually applied. Figure 2-1 displays an example of a complete PV cell.

Figure 2-1. Diagram of a PV Cell

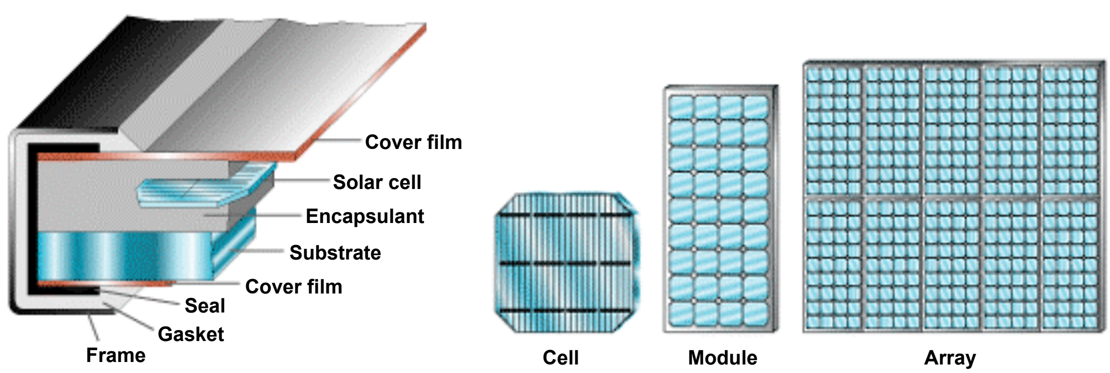


Source: EERE (2009a).

2.3.2 Example c-Si PV Module

In a PV module, a group of PV cells are wired together and are sealed by a polymer encapsulant for protection from the elements. Failure of encapsulants poses a number of technical problems. Electrical connections must be especially well sealed to prevent corrosion. If the thermal expansion of an encapsulant differs from that of the cells, the cells may crack or the encapsulant may come unsealed. Discoloration is also often a problem in encapsulants: prolonged exposure to sunlight can cause the encapsulant to darken and reduce the amount of light reaching the cell. Ethylene vinyl acetate (EVA) was developed during FSA as an alternative to silicon rubber, which had a tendency to degrade. The encapsulated cells are then attached to an aluminum frame with a backsheet of Mylar or Tedlar. A layer of tempered glass or plastic is then added on top of the module (see Figure 2-2). A collection of PV modules is referred to as an array.

Figure 2-2. Diagram of a PV Module



Source: EERE (2009a).

2.3.3 Example Balance of System Components

Balance of system (BOS) refers to the components of a PV system that convert the electrical output from PV modules into electricity in a usable format. Depending on the type of system, BOS components include batteries, inverters, wiring, mounting, and other items. Although this analysis focuses on PV modules alone, it is important to include a brief discussion of BOS components, because these items can account for as much as half of the total cost of the system (SNL, 2009).

Power conditioners such as inverters are needed when electricity from a grid-connected solar panel is converted to alternating-current electricity. In a standalone system, batteries are used to store electricity for use when sufficient sunlight is unavailable. Ascension Technology, Omnion Power Engineering Corporation, Solar Design Associates, Trace Engineering Company, and Xantrex Technology all received PVMaT contracts for research on various BOS components.

2.4 Frequently Used Metrics and Terminology for PV Modules and Systems

Several technical metrics are used when discussing PV technologies and the economics of PV. The following metrics are used extensively throughout this report:

- Efficiency (specifically, conversion efficiency),
- Power,
- Installed cost per watt,
- Production cost per watt,
- Reliability, and
- Levelized cost of electricity (LCOE).

For PV cells, **efficiency** is defined as the ratio of electric power generated by the solar cell to the amount of incident solar power. If a solar cell illuminated by 100 W of solar power generates 15 W of power, the cell's solar energy conversion efficiency is 15%. In this report, the terms "efficiency" or "efficient" without a modifier always refer to the solar energy conversion efficiency. When referring to manufacturing or costs, this report specifically uses the term "operational efficiency."

Power is the rate at which energy is supplied by the PV cell or module. The amount of power contained in the solar spectrum hitting a given area is not uniform across the globe. Therefore, standard test conditions of 1 kW/m^2 at 25°C were established to allow researchers and companies to communicate performance measurements comparably. Thus, all power ratings for solar cells and modules are reported subject to conditions that have been artificially defined, not what they will experience in the field.

The **installed cost per watt** of a PV energy system refers to the sum of all module, BOS, installation, and other costs divided by the power rating of the system. This study quantitatively evaluates only the PV module component of the system. The common metric for reviewing manufacturing costs for PV modules is the **production cost per watt**. Production cost per watt captures increases in conversion efficiency and increases in operational efficiency of production systems. As cell technology improves, so does the cell's efficiency rating, which lowers the materials cost per watt and increases the power rating of a module. Improvements in manufacturing technology also place downward pressure on production cost per watt.

PV systems are solid-state energy systems that have long lives. The minimum guaranteed lifetime for modules is 25 years, with the expectation that most modules will convert solar energy into electrical current for additional years. This concept is referred to as **reliability**. The total installed cost of a system is considered along with the system's lifetime and power rating to yield the **LCOE**.

The LCOE is usually presented as dollars per kilowatt-hour ($/kWh). The total energy produced is calculated by power multiplied by time and is reported by power producers as kilowatt-hours. The amount of energy in kilowatt-hours produced in a year by an electricity generator is the capacity in kilowatts multiplied by the number of hours in a year adjusted by a capacity factor to adjust for periods of nonoperation, or in the case of solar power, for when the sun is not shining at its peak. In the United States, PV modules, on average, have a capacity factor of 18%. Thus, 1 watt-peak (Wp) module can be expected to produce 1.58 kWh per year. Wp is a measure of power output under standard reporting conditions. Although the cost per kilowatt-hour can be estimated by taking into account the cost per watt, the lifespan of the module, and the number of hours of available sunlight per day, the calculation result provides only a rough approximation.

3. PV MODULE TECHNOLOGIES AND DOE TECHNOLOGY DEVELOPMENT INITIATIVES

This chapter reviews technology outcomes from each technology development initiative as well as pertinent components of the PV technology infrastructure:

- Flat-Plate Solar Array Project (1975–1985), under which technologies for silicon refining, encapsulants, automated module assembly, technology infrastructure, greater energy conversion efficiencies, silicon ingot, and ribbon growth were developed.
- PV Manufacturing Technology Project (1991–2008), under which advanced manufacturing technologies for cell production and module assembly were developed to hasten cost reductions and improve efficiency, quality, and reliability.
- Thin-Film PV Partnerships (1994–2008), under which thin-film technologies were vastly improved, yielding thin-film PV modules that are produced today in greater numbers by U.S. manufacturers than c-Si modules. Also included in the TFP review are the predecessor Amorphous Silicon and Polycrystalline Thin-Film projects that later merged to form TFP and ran from 1988 to 1994.
- Measurement, characterization, and reliability R&D (1975–present), under which the technology infrastructure for module cell and reliability (including the Outdoor Testing Facility), device performance, surface analysis, electro-optical characterization, and analytical microscopy was developed . This provided an infrastructure that enabled industry, government, and university researchers to achieve their research objectives under the above three initiatives.

Each initiative was a broad technology response to the technical barriers and technology needs present at the time the initiative was launched, and each built on the technology base developed by its predecessor. FSA aggressively targeted core reliability, quality, and efficiency barriers to move photovoltaics from niche off-grid applications to the mainstream. Industry experts interviewed for this study universally regarded the FSA period as foundational to the modern terrestrial PV industry.

In 1975, the U.S. PV industry produced 0.4 MW at a production cost per watt of $83.86 (2008$). Each module produced had no warranty and was expected to have a useful life of 2 to 3 years. When FSA officially ended in 1985, 7.8 MW (+2,000%) was produced at a production cost per watt of $9.40 (−82%), and 10-year warranties were offered (Table 3-1).

End-year FSA milestones were largely the results of technology developed by 1983 and 1984, and industry progress slowed during most of the 1980s after Federal funding for technology development was reduced. PVMaT was launched in 1991 to reinvigorate progress by developing manufacturing technologies. Despite progress under FSA, many production processes remained manual. Further, FSA had identified thin films as a viable alternative to c-Si, but little commercialization progress had been made. TFP would focus on bringing thin films technologies to commercialization, and PVMaT would develop the manufacturing technology to increase operational efficiencies through process development and automation.

Table 3-1. U.S. PV Industry Progress, 1976–2008

Year	Module Production (MW)			Production Cost ($/W)	Reliability (Years)	Notable Technology Outcomes
	c-Si	Thin Films	Total			
1974	0.19	0.00	0.19	$114.44	2	
1975	0.37	0.00	0.37	$83.86	2	
1976	0.80	0.00	0.80	$53.28	2	**Flat-Plate Solar Array Project** • Block Purchases I-V • EVA for encapsulants • UCC silicon refining process • Silicon ingot growth • Silicon ribbon growth • Automated module assembly • Design and test methods for durability, performance, and safety • Laboratory cells reaching 22% efficiency • 10-year module warranties
1977	1.22	0.00	1.22	$37.60	2	
1978	1.65	0.00	1.65	$25.64	2	
1979	2.07	0.00	2.07	$23.93	2	
1980	2.50	0.00	2.50	$22.22	2	
1981	4.46	0.00	4.46	$19.65	2	
1982	5.05	0.00	5.05	$17.09	5	
1983	5.63	0.00	5.63	$14.53	5	
1984	6.22	0.05	6.27	$11.96	5	
1985	7.30	0.50	7.80	$9.40	10	
1986	6.40	0.85	7.25	$8.99	10	
1987	7.45	1.40	8.85	$8.58	10	
1988	9.70	1.85	11.55	$8.16	10	
1989	12.95	1.45	14.40	$7.75	10	
1990	13.78	1.37	15.15	$7.34	20	
1991	16.48	1.00	17.48	$6.93	20	**Thin-Film PV Partnerships** • National teams • Basic research in a-Si, CdTe, and CIS • a-Si modules (ECD/Uni-Solar) • CdTe modules (First Solar [Solar Cells Inc.]) • CIS/CIGS modules (Global Solar) **PV Manufacturing Technology Project** • Wire saw technology adoption for silicon ingot wafering • Automated cell and module assembly processes • In-line diagnostics and monitoring • High-efficiency c-Si cells • Cost reductions from $6.93 per watt in 1991 to $1.92 per watt in 2008 • 25-year module warranties • Funded AstroPower (GE), BP Solar (Solarex), Evergreen, First Solar, Global Solar, SCHOTT Solar, SolarWorld USA (Arco/Siemens/ Shell), SunPower, Uni-Solar
1992	16.95	1.65	18.60	$6.00	20	
1993	20.91	1.53	22.44	$5.69	20	
1994	24.31	1.95	26.26	$4.84	20	
1995	33.30	1.66	34.96	$4.53	20	
1996	37.35	2.46	39.81	$3.93	20	
1997	48.00	3.10	51.10	$3.77	25	
1998	48.10	5.80	53.90	$3.71	25	
1999	53.80	7.00	60.80	$3.45	25	
2000	66.00	9.00	75.00	$2.96	25	
2001	86.70	13.80	100.50	$3.00	25	
2002	109.40	18.20	127.60	$2.85	25	
2003	86.82	15.80	102.62	$2.91	25	
2004	115.20	23.50	138.70	$2.80	25	
2005	133.60	44.50	178.10	$2.96	25	
2006	175.30	92.50	267.80	$2.67	25	
2007	189.20	263.00	452.20	$2.11	25	
2008	379.90	642.70	1,022.60	$1.92	25	

Sources: Christensen (1985); *PV News* (Maycock, 1986–2004; *PV News*, 2005–2009); EIA and IEA (EIA, 2008; IEA, 2009); Friedman et al., 2005; Green (2005).

In 1991, the U.S. PV industry produced 17.5 MW at a production cost per watt of $6.93 (2008$). In 2008, 1,022.6 MW (+>5700%) was produced at a production cost per watt of $1.92 (−72%). Over 60% of 2008's production volume was in thin film PV modules.

Throughout this report, use of the initiative's name is synonymous to the portfolio of technologies developed during the initiatives' time frame. If readers require additional technical detail about the technologies presented in this chapter, comprehensive technical reports can be found on the Web sites of DOE/EERE, NREL, and SNL.

3.1 Technologies Developed during the Flat-Plate Solar Array Project (FSA)

Commercially available PV modules in the early to mid-1970s had low efficiency ratings in the range of 4.8 to 6.5%, were priced between $80 and $150 per watt (2008$), had no warranty, and were largely unimpressive (Christensen, 1985; Green, 2005). The Cherry Hill Conference called for developing the entire technology base that would bring PV from a curiosity or niche market application into the mainstream and ultimately into grid-connected systems.

The Massachusetts Institute of Technology's Energy Laboratory supplied DOE with an assessment of the nascent terrestrial PV industry and provided the public policy analysis framework for guiding public investment in PV (Linden et al., 1977). *The Solar Photovoltaics Industry: The Status and Evolution of the Technology and the Institutions* explored the interplay between technology development, production, and public policy to overcome market failures and technical obstacles. The report identified the primary market failures that were inhibiting the development of terrestrial photovoltaics:

- **Incorrect energy prices** that do not account for deleterious environmental or human health impacts associated with fossil fuel consumption and combustion
- **Production uncertainties** concerning prices, availability, quality, reliability, production volumes, and the ready supply of renewable and fossil fuel technology alternatives
- **Technological uncertainties**, particularly with respect to development costs, time, and R&D performance
- **Interdependencies of production and technology development**, which are the confluence of uncertainties, indivisibilities, and externalities that impede market function through asymmetries in information and poor convergence of expectations
- **Indivisibilities and inability to appropriate returns from technology development**, so that, despite photovoltaics being in the national interest, the costs of developing and maturing the technology may preclude private-sector innovation if returns from innovation cannot be appropriated as profits within a suitable time horizon
- **Imperfections in financial markets** attributable to the chasm between internal sources of funding and the risk-reward profile that influences private equity financing
- **Non-competitive market structures** that may inhibit new, competing sector development

In response, the funding for photovoltaics in the early years addressed both the supply side and the demand side of technology development. Industry, university, and government researchers established two major goals that drove FSA's mission to lower costs, increase efficiency, and increase reliability. The first was to demonstrate technologies that, if scaled to commercial production levels, could achieve a module production price of $1.62/Wp (2008$) with a 10% efficiency and 20-year lifetime. The second was to mass produce this technology.[16]

DOE funded applied research within the industry to improve c-Si module design and production technology and acted as the primary purchaser of these products. These purchased PV products were then tested by FSA researchers, and companies used test results to improve their products. Funding was from ERDA (later, DOE), but JPL was selected to manage the project, given its extensive expertise in developing photovoltaics for space applications. Previous spaceflight projects provided JPL staff with invaluable experience in reliability testing and technical skills that were not available elsewhere.[17] ERDA planned the launch of the Solar Energy Research Institute and the development of programs at SNL. Contracting with JPL offered an opportunity to transfer expertise between Federal programs and to the nascent PV industry.

FSA was originally organized in five sections: silicon material refinement, sc-Si sheet formation, automated module assembly, encapsulation, and large-scale production.[18] In 1982, a high-efficiency cell task was added. In addition to these technical tasks, FSA included a project analysis and integration area to integrate the other project areas, provide economic analyses, and assess technical progress. Periodic economic analyses were used to judge the potential of current technical options and cancel unpromising pathways. For reference, Table A-1 in Appendix A lists the contractors that contributed to the body of technology developed during FSA as well as each contractor's technology focus.

Despite frequent redirections and funding cuts due to shifting national priorities, FSA had achieved many of its objectives when it ended (Christensen, 1985):

- Module prices were reduced by a factor of 15, and efficiencies for modules in commercial production increased from about 5% to 10%.
- Reliability improvements sparked by testing at FSA allowed companies to offer at least 10-year warranties on modules, whereas before FSA, warranties were nonexistent in the PV industry. Researchers had studied existing terrestrial PV systems and found that many of these systems

[16] In 1981, the commercial readiness goal was dropped. In 1983, the technology readiness goal shifted from a module cost per watt-peak to a system cost per kilowatt-hour to reflect what would be required for competitive PV power in a central grid.

[17] The U.S. government's initial interest in developing PV technology was for space applications, with solar cells used to power a backup radio transmitter in the Vanguard I satellite in 1958 (Margolis, 2002). PV technology, although expensive, did not represent a large portion of the costs associated with NASA's programs, and early R&D at JPL focused on improving the technology for space applications without great regard to its cost. In 1970, the average cost of space PV modules was about $150 per watt (1970$) (Margolis, 2002).

[18] Extensive technical information on FSA is available from JPL. A summary of the project was prepared by Christensen (1985), but this analysis relied most heavily on the *Flat-Plate Solar Array Project Final Report,* which documented achievements, described processes, and conveyed program rationale and the policy and market context in which decisions were made. The volumes of that report were as follows: Volume I: Executive Summary (Callaghan & McDonald, 1986), Volume II: Silicon Material (Lutwack, 1986), Volume III: Silicon Sheet: Wafers and Ribbons (Briglio et al., 1986), Volume IV: High-Efficiency Solar Cells (Leipold et al., 1986), Volume V: Process Development (Gallagher et al., 1986), Volume VI: Engineering Science and Reliability (Ross and Smokler, 1986), Volume VII: Module Encapsulation (Cuddihy et al., 1986), and Volume VIII: Project Analysis and Integration (McGuire & Henry, 1986).

failed within a year of installation and that no warranties were offered. Causes of module failure were rapidly understood and addressed through R&D collaboration between industry and government. Reliability technology was transferred efficiently to industry, and by the early 1980s, c-Si module manufacturers had converged on a module design that is essentially the same as it is today. One industry veteran noted that the PV industry stated that PV module "failure rates [before FSA] were horrendous" and "this early work was the best and has stood the test of time."

- Polysilicon research led to the development of an effective, low-cost purification process.
- Important innovations in manufacturing automation and silicon ribbon growth were invented.
- Core industry standards were established. Underwriters' Laboratories (UL) standards and International Electrotechnical Commission standards are traceable to FSA.

3.1.1 Silicon Material Refinement

Abundant polysilicon feedstock is necessary for large-scale c-Si PV production, and the cost of polysilicon is a significant contributor to the total cost of c-Si PV modules. Solar-grade silicon must be very pure and requires an expensive refining process. To realize their cost goals, FSA funded R&D for many technologies that had the potential to lower the cost of polysilicon feedstock relative to the existing manufacturing process involving silicon deposited in a Siemens-type reactor from trichlorosilane gas.

FSA funded 11 different contractors, each with a unique vision for polysilicon production processes. The most successful was the silane-to-silicon process at Union Carbide Corporation (UCC) using fluidized-bed reactors. The UCC process uses silane gas as opposed to trichlorosilane as a feedstock to deposit polycrystalline silicon using the Siemens process. Advantages of the UCC process include "a lower deposition-reaction temperature, a higher conversion efficiency, and lower environmental and corrosion problems" (Lutwack, 1986). Union Carbide demonstrated the ability to produce purified polysilicon from metallurgical-grade silicon at lower costs (Christensen, 1985).

3.1.2 Silicon Sheet Formation: Wafers and Ribbons

FSA explored three categories of sheet formation: ingot growth with subsequent wafering, ribbon growth, and silicon coating on a substrate.[4]

In researching the first category, researchers were successful in reducing cost and increasing yield in the Cz ingot growth process. However, ingots must be sliced into wafers for use in PV cells, and the wafering process can be time consuming and expensive, wasting large amounts of valuable polysilicon feedstock material. To address this problem, FSA evaluated several different wafering technologies, none of which met speed and yield goals.[5]

Five ribbon growth methods were examined. High-throughput growth and multiple ribbon growth were achieved with ribbon growth using the edge-defined film-fed growth method (EFG). Mobil Solar

[4] None of the silicon coating methods, the third category of sheet formation, met cost, yield, or performance goals for the project.
[5] This technical challenge would later be overcome during PVMaT when researchers successfully adopted wire saw technologies.

demonstrated EFG's performance during FSA. This technology has since been acquired by SCHOTT Solar, a major U.S. PV producer and is in commercial production.

3.1.3 High-Efficiency Solar Cells

The 1983 DOE Five-Year Plan set a goal of 15% efficiency for low-cost modules, which would require production cells with over 17% efficiency. High-efficiency research at FSA focused on reducing bulk losses in the silicon, reducing surface losses, improving design and production, and improving modeling and measurements to reach this goal. Conversion efficiency increased greatly during the years of the task, with laboratory cells reaching 22% efficiency (Christensen, 1985).

3.1.4 Encapsulants

FSA explored encapsulant materials and processes to identify an encapsulant that could provide 20-year module life at a low cost. The most significant accomplishment of this task was the development of improved ethylene vinyl acetate (EVA) suitable for mass module production. Prior to using EVA as a laminating material, modules used a polyvinyl butyral encapsulant or silicon rubber, both of which faced problems with exposure to the elements. EVA was commercialized through FSA and remains the standard encapsulant in modules 25 years later.

3.1.5 Process Development and Automated Module Assembly

More than 140 processes were developed and transferred between industry and government partners, including those for cell surface treatment, junction formation, metallization, and module fabrication (Christensen, 1985). Modules on the market in 1975 suffered from labor-intensive processes, high materials costs, and low cell-packing factors (Gallagher et al., 1986). The process development thrust under FSA was formed to decrease the cost of module production through automation and development of manufacturing technologies. More than 75 contracts were issued in two groups: low-cost processes and high-efficiency cell processes. Research in this area led to the successful demonstration of robotic module assembly and resulted in many new processes and equipment (Table 3-2).

Table 3-2. Summary Accomplishments under FSA's Process Development Area

Surface Preparation	**Metallization**
Technological and economic feasibility studies of automated surface preparation Test patterns for process development and monitoring tools Industry-standard texturizing process Spin drying Silicon nitride as a multipurpose cell coating	Thick-film screenable cost-effective processes using Ag, AgAI, Cu, and MOD AgBi Reliable plating systems using Pd and Ni followed by solder build-up by immersion or Cu plating to provide conductivity MOD films for low-temperature contact systems Generic fabrication systems for MOD films
Junction Formation	**Module Fabrication**
Large-area, large-volume gaseous diffusion processes Spin-on, spray-on, and meniscus coating processes Simultaneous front and back junction-forming processes using liquid dopant and RTP NMA ion implementation of front and back junctions	Fully automated interconnect soldering equipment Fully automated ultrasonic bonding equipment

Source: Gallagher et al. (1986).

3.1.6 Large-Scale Production (Block Purchase Program)

During FSA, JPL, via its large-scale production thrust, was responsible for procuring and testing modules from large production runs, and tested more than 150 different module designs (Christensen, 1985). Through its block purchase program, JPL purchased and tested a series of five block purchases of modules, offering feedback to manufacturers. Manufacturers would attempt to fix the problems identified by JPL, perform R&D to overcome shortcomings, and submit modules for the next round of testing. Testing began with very primitive modules, which performed poorly and degraded quickly with exposure to the elements.

Modules improved so drastically from Block I (1976) to Block V (1984) that the modules evaluated in Block V were not significantly different from those used today. Module prices fell from $152/W in 1974 to $12.50/W in 1985 (2008$). Block I modules had an average lifetime of under 3 years with no warranty. Block V modules offered 10-year warranties, and the expected useful life of a module produced in 1985 was around 30 years.

As part of the qualification and testing process for block purchases, this work also established the technology infrastructure for efficiency measurement, materials characterization, and reliability testing, including the following:

- Design and test methods for performance, environmental durability, and safety;
- Materials characterization and optimization methods;
- Module fabrication methods and system designs for durability, safety, and performance;
- Robust reliability physics and test methods and equipment; and
- Reference materials and U.S. and international PV standards.

3.1.7 DOE Expenditures for FSA

The actual, nominal-dollar investment in FSA between 1975 and 1985 was $228 million (Christensen, 1985). Annual expenditure data were adjusted to 2008 dollars, and in inflation-adjusted terms, the total investment was $535 million (Table 3-3).

Table 3-3. DOE Expenditures for FSA

Fiscal Year	Nominal ($ thousand)	Deflator	Real 2008$ ($ thousand)
1975	600	0.31	1,939
1976	11,700	0.33	35,765
1977	30,900	0.35	88,796
1978	31,800	0.37	85,390
1979	32,900	0.40	81,559
1980	30,500	0.44	69,291
1981	28,600	0.48	59,409
1982	16,700	0.51	32,694
1983	13,600	0.53	25,613
1984	15,000	0.55	27,227
1985	15,500	0.57	27,307
Total	**227,800**		**534,990**

Source: Christensen, 1985; GDP Implicit Price Deflator (2005 = 100) from U.S. DoC (2009).

3.2 Technology Developed during the Photovoltaic Manufacturing Technology (PVMaT) Project

Whereas FSA aimed to rapidly develop technologies throughout the PV module value chain, PVMaT targeted manufacturing technologies that would enable PV companies to accelerate decreases in production costs and increases in capacity.[21] Despite all the gains from technologies developed under FSA, much assembly was still performed by hand and technical challenges involving crystal growth, wafer slicing, deposition, encapsulation, and other issues made it difficult for companies to reduce costs or increase capacity.

PVMaT was also created in part as a response to the falling U.S. share of the global PV market, which had dropped significantly in years since the last block purchase under FSA in 1984 (Mitchell et al., 1998). The United States, once the world's only major producer of PV systems, saw a significant growth in competition from Japan during the 1980s. Although U.S. government funding for PV R&D had declined during the 1980s, Japanese government funding was much higher than it was in the 1970s. PVMaT was

[21] In 2000, PVMaT was renamed the PV Manufacturing R&D Project to reflect changes in PV manufacturing technology needs; however, it was still commonly referred to as PVMaT, which is the name used in this report for simplicity.

envisioned as a way to ensure that the United States would remain a major competitor in the global PV market. A strong domestic PV industry could lead to job creation and correct trade imbalances while providing a source of renewable energy and increasing energy independence (Mitchell et al., 1998).

PVMaT's goals were to:

- Improve module manufacturing processes and equipment;[22]
- Reduce the cost of manufacturing PV modules, BOS components, and integrated systems;
- Improve module performance and reliability; and
- Increase U.S. PV manufacturing capacity (Mitchell et al.,1998).

DOE generated financial leverage for emergent PV companies through cost-sharing plans to accelerate manufacturing technologies and products in ways that otherwise might not have occurred or would have taken longer to materialize. PVMaT was technology neutral: all PV companies with viable strategies for improving their production technologies were invited to submit proposals for funding. Successful proposers would receive DOE cost-sharing up to 50% of the total project cost and preferential access to NREL and SNL technology experts.[23]

PVMaT was conducted in 11 phases between 1991 and 2008 (Table 3-4). Each phase was an R&D response to technical challenges facing the industry at the time a phase was conceived. Companies helped NREL identify the major technical issues the industry faced, and NREL developed a roadmap for the initiative. Projects were awarded by a panel of PV experts.[24] Although the largest portion of PVMaT contract funding went toward improving c-Si technologies, PVMaT also supported thin film companies in the scale-up of their manufacturing processes. All eight major U.S. producers of PV received PVMaT funding. Of those eight, seven were in the top 10 recipients of PVMaT funds from NREL. Table B-1 in Appendix B summarizes subcontractor funding by phase over the life of PVMaT.[25]

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[22] PVMaT originally focused on module manufacturing before expanding to include BOS components and system integration elements, but these accounted for less than 15% of total DOE funding for PVMaT.

[23] Cost-sharing levels differed by project phase. Overall industry cost sharing for all phases was about 48%. To encourage collaboration with universities, companies were allowed to waive the cost-sharing requirement up to a specified amount for contract funding used to conduct research at universities. Smaller companies were required to meet a lower cost-share percentage than larger companies.

[24] Panels generally included one representative each from NREL, DOE, and SNL, plus 10 or more other experts with varied PV experience and no conflict of interest (Margolis, 2002).

[25] Following the initial exploratory Phase 1 of PVMaT, 40 unique companies participated in the remaining 10 phases. However, many of these companies were acquired by other companies, and those 40 have since been consolidated into 26 current companies.

Table 3-4. PVMaT Phases

Phase	First Year	Research Focus	DOE Cost Share ($ thousands)	Company Cost Share ($ thousands)	Total ($ thousands)
1	1991	Problem identification	1,053	—	1,053
2A	1992	Problem solving: Process-specific manufacturing	30,738	21,316	52,055
2B	1993	Problem solving: Process-specific manufacturing	13,384	14,557	27,941
3A	1993	Problem solving: Teamed research on generic problems	2,220	752	2,972
4A1	1994	Product-driven PV systems and component technology	5,343	1,812	7,155
4A2	1994	Product-driven PV module manufacturing	14,349	10,167	24,516
5A1	1998	PV system and component technology	4,261	4,700	8,961
5A2	1998	PV module manufacturing technology	26,451	20,689	47,140
IDIP–1	2001	In-line diagnostics and intelligent processing: PV system and component technology	3,593	3,807	7,400
IDIP–2	2001	In-line diagnostics and intelligent processing: PV Module manufacturing technology	23,369	30,443	53,812
YDR-1	2003	Large-scale module and component yield, durability, and reliability	2,860	6,358	9,219
YDR-2	2003	Large-scale module and component yield, durability, and reliability	23,397	23,773	47,170
Total			**151,018**	**138,375**	**289,393**

Note: Dollars in presented in nominal terms. IDIP = in-line diagnostics and intelligent processing. YDR = yield, durability, and reliability. Dollar values presented exclude DOE program administration expenditures.

Source: NREL (2009b).

3.2.1 Summary Technical Accomplishments

Participating companies produced annual and final technical reports detailing the goals and accomplishments of their individual manufacturing R&D projects, which are discussed in detail in Appendix C. The following is a summary of notable accomplishments by phase, many of which occurred early in PVMaT between 1992 and 1996 (Margolis, 2002):

- **Phase 1** was an exploratory phase under which all U.S. PV companies were invited to receive planning grants of up to $50,000 to study and recommend ways in which their processes could be improved to meet PVMaT goals.
- **Phases 2A and 2B** focused on process-specific problem solving and was directly related to low-hanging fruit identified during Phase 1. One of the most significant accomplishments of Phase 2 was Solarex's successful adoption of the wire saw; a technology that reduced silicon waste and

increased wafer size and that would later be adopted across the semiconductor industry. Solarex (now BP Solar) had explored the use of wire saws before PVMaT but had been unable to obtain funding to successfully implement them in their production process (Margolis, 2002).

- **Phase 3A** emphasized teamed research for generic, industry-wide problems. Teams consisted of combinations of university and industry partners. Spire Corporation, with Solec International and University of Massachusetts automation specialists, developed improved automated cell assembly processes that had lower costs. Springborn, with other companies and universities acting as subcontractors, developed new EVA encapsulants that resolved discoloration and degradation issues.
- **Phases 4A1 and 4A2** focused on product-driven, full-system issues. Phase 4A was split into two parts to address system components (Phase 4A1) and module manufacturing (Phase 4A2) separately. Ascension Technology and ASE Americas' developed an alternating-current module. AstroPower also created the world's largest production silicon solar cell, a record efficiency 1 cm^2 cell, and a high-speed silicon-film production process (NREL, 2009d).
- **Phases 5A1 and 5A2** continued the R&D trajectory set by Phase 4. Crystal Systems Inc. successfully designed a process to convert metallurgical-grade silicon to solar-grade silicon, reducing the cost of solar-grade silicon to less than $10 per kilogram—a price much lower than the contract goal. In Phase 5A2, BP Solar created a fully automated high-throughput cell-processing system (NREL, 2009d).
- **Phases IDIP-1 and IDIP2** were designed to increase yield-of-module and BOS components through improved in-line diagnostics and monitoring. Sinton Consulting developed an in-line monitoring tool that allowed low-quality materials to be removed before becoming a cell. Evergreen Solar developed its string-ribbon silicon growth process and successfully moved a dual-ribbon growth system from R&D to production while drastically increasing throughput (NREL, 2009d).
- **Phase YDR** was intended to increase yield and reliability through better PV module manufacturing, packaging, and assembly. In 2006, the Solar America Initiative began. Some YDR contracts were completed; however, many YDR contracts were transformed into the new Technology Pathway Partnership project or discontinued before contract completion

Under PVMaT, Direct module manufacturing costs and total capacity among participants were collected annually to analyze the effects of PVMaT and monitor progress. Direct costs of module manufacturing fell from $6.00/Wp in 1992 to $2.92/Wp in 2005 (2008$) (NREL, 2009c). During the same period, capacity increased 18.5 times to 251 MW (Friedman et al., 2005).

3.2.2 DOE Expenditures for PVMaT

Total public expenditures for PVMaT were estimated to be $200.7 million (see Table 3-5). These expenditure data were assembled by reviewing project histories, annualizing by period of performance, and netting out project cancellations and funding adjustments. Program administration expenses were estimated to be 12% of DOE cost share amounts (Hulstrom, 2010).

Table 3-5. DOE Expenditures for PVMaT and TFP

	DOE Cost Share ($ thousands, nominal)			DOE Cost Share ($ thousands, 2008$)		
Year	**TFP**	**PVMaT**	**Deflator**	**TFP**	**PVMaT**	**Total**
1988	8,900		0.62	14,413		14,413
1989	11,400		0.64	17,790		17,790
1990	10,600		0.67	15,927		15,927
1991	7,800	1,179	0.69	11,318	1,711	13,029
1992	8,700	7,426	0.71	12,332	10,527	22,859
1993	9,200	12,777	0.72	12,759	17,720	30,479
1994	11,000	13,412	0.74	14,940	18,217	33,157
1995	12,400	11,904	0.75	16,498	15,838	32,336
1996	10,200	11,983	0.77	13,318	15,645	28,963
1997	11,480	9,825	0.78	14,729	12,606	27,334
1998	16,000	9,108	0.79	20,298	11,555	31,854
1999	14,958	12,930	0.80	18,701	16,166	34,868
2000	13,205	10,421	0.82	16,160	12,753	28,913
2001	18,958	8,416	0.84	22,687	10,072	32,760
2002	18,278	2,370	0.85	21,525	2,791	24,316
2003	12,495	11,457	0.87	14,405	13,209	27,613
2004	10,461	8,131	0.89	11,727	9,115	20,843
2005	9,086	6,088	0.92	9,857	6,605	16,461
2006	6,134	8,424	0.95	6,444	8,850	15,295
2007	6,068	9,259	0.98	6,198	9,457	15,655
2008	2,266	7,844	1.00	2,266	7,844	10,110
Total	**229,589**	**162,957**		**294,292**	**200,681**	**494,973**

Note: Dollar values include DOE program administration expenditures. Sources: Hulstrom (2010); Mitchell (2009); Ullal (2009); See also Section 3.3.3. GDP Implicit Price Deflator (2005=100) from U.S. DoC (2009).

3.3 Technology Developed during Thin-Film PV Partnerships (TFP)

Thin-Film PV Partnerships (TFP) ran from 1994 to 2008, although PV companies began receiving significant funding for thin film technology development beginning in 1988. FSA focused on c-Si technologies, but had identified two research pathways that were deemed to have the potential to offer low cost terrestrial PV technology: a-Si and polycrystalline thin films. Through the 1980s and early into the 1990s, NREL sponsored research that aimed to increase efficiency and reduce instability in a-Si devices. For polycrystalline thin films, NREL sponsored the Polycrystalline Thin Films Subcontract program which supported the development of CIS and CdTe. In 1994, the a-Si and polycrystalline thin films research programs were merged to form TFP.

When TFP was launched, c-Si was by far the leading PV technology. However, c-Si cells required large amounts of refined silicon material, and these cells' efficiency was limited by an imperfect band gap. Thin films provided an alternative that held the possibility of overcoming some of the limitations inherent in c-Si, but a significant amount of research would be required to develop thin films into a viable technology alternative. This R&D constituted an investment with high technical and financial risk that few technology companies or investors were willing to make without outside support. DOE funded nearly all of the materials characterization work for thin films, and all interviewees stated that thin-film companies were heavily reliant on TFP and its predecessor initiatives for funding.

DOE's goal was to further encourage development of thin-film technologies and move laboratory research to pilot production. As with PVMaT, cost sharing was an important aspect of TFP, although cost-sharing levels in TFP were lower to reflect earlier stage R&D.

3.3.1 National Teams

A national research team was formed for each critical area of R&D focus: a-Si photovoltaics; CdS/CdTe photovoltaics; CIS photovoltaics; environmental, safety, and health; and thin-film module reliability. Each team generally included about 40 people and was formed from a combination of university researchers, manufacturers, and NREL scientists (Zweibel, 2001):

- **Technology partners** were major U.S. companies attempting to make the transition to large-scale thin-film manufacturing, and they were allowed up to $1 million/year for a 3-year contract. Cost sharing was tiered based on firm size: 40% for large companies and 20% for smaller companies.
- **R&D partners** consisted of universities and smaller businesses that provided basic research support for technology partners. R&D partners were required to cost share at a lower level than technology partners: 20% for larger companies and 10% for smaller companies.

Team participation was a requirement for companies receiving contracts. A percentage of awarded contracts funds were dedicated to team research, while the remaining portion went to proprietary research. Teams helped universities, companies, and national laboratories stay up to date on technological issues, share knowledge, and reduce duplication of research. Core intellectual property development was retained by companies and university partners to incentivize commercialization of the technologies developed.

The a-Si team was the first of the teams to be formed. Originally a collaboration of NREL and the Electric Power Research Institute, NREL became the sole funder around 1999 (Von Roedern, 2003). A-Si technologies were severely limited by light-induced instability known as the Staebler-Wronski effect, which offered a common problem on which researchers could cooperate. When the team was formed, instability and triple-junction cells were identified as key issues. Three sub-teams focused on each part of the triple-junction cell, while a fourth addressed issues pertaining to the entire cell. In 2000, the a-Si team was reorganized to update the issues at hand. Research was grouped into development of higher deposition rates, alternative narrow-band gap materials, stability, and performance and integration (Von Roedern, 2003). The leading U.S. a-Si PV company in 2009 was ECD Uni-Solar.

A thin-film silicon team was formed in 2002 in conjunction with the a-Si team. The c-Si thin-film team was designed to explore light trapping, voltage issues, and high-rate deposition while focusing on addressing problems with low-temperature deposition on glass and high-temperature deposition on ceramic substrates. Thin-film silicon researchers collaborated with those from the a-Si team to explore thin-film silicon as a possible bottom layer in multi-junction a-Si.

The CIS team, formed in 1994, was aimed primarily at improving junctions and addressing problems with molybdenum and transients. The team was originally broadly divided into junction and absorber work. Initially, the CIS team mainly focused on company-specific problems, with sections of the team addressing different issues at individual companies. Although this organization was successful, the team was eventually transformed to become less company specific. The leading U.S. company funded under this team in 2009 was Global Solar.

The CdTe team, created in 1994, concentrated on improving front and back contacts, using thinner CdTe and stability testing. Sub-team topics included device physics, stability, and materials chemistry (Ullal et al., 2006). Unlike the original CIS team, the CdTe team was mainly focused on general research subjects but still allowed the option of focusing on a company-specific problem. For example, one group focused solely on a proprietary subject at First Solar, which was funded for many years under TFP and was the leading CdTe company in 2009.

The environmental, safety, and health team, organized during the early 1990s, was formed to research better methods of module recycling, waste disposal, and materials usage to protect workers, the public, and the environment while seeking U.S. Environmental Protection Agency (EPA) toxicity certification for CdTe and CIS modules. Managers from NREL, DOE, and Brookhaven National Laboratory, which had previously hosted similar PV safety research, helped researchers address these topics. Key issues included proper use and disposal of cadmium and selenium.

The thin-film module reliability team focused on improving thin-film reliability to offer 30 years of outdoor service. Team members researched important degradation mechanisms and instability problems. Key issues included moisture ingress and encapsulant and backsheet adhesion.

3.3.2 Summary Technical Accomplishments

TFP funded hundreds of subcontracts for more than 100 different companies and universities. NREL shares seven R&D 100 Awards, awards given annually by R&D magazine, with industry partners for work done under TFP (NREL, 2009a):

- 1984, Boeing, for the first very thin films of a viable material (CIS)
- 1991, Golden Photon, for the first large-area CdTe devices

- 1998, Uni-Solar, for flexible, waterproof PV roof shingles using triple-junction a-Si
- 1999, Siemens Solar, for the first large-area CIS modules
- 2002, BP Solar, for a semitransparent module that can be used in place of glass
- 2003, First Solar, for the world's first polycrystalline thin-films mass production method, a high-rate module deposition process that can produce one CdTe module per minute
- 2004, Global Solar, for lightweight, flexible CIS modules that can be easily folded and carried

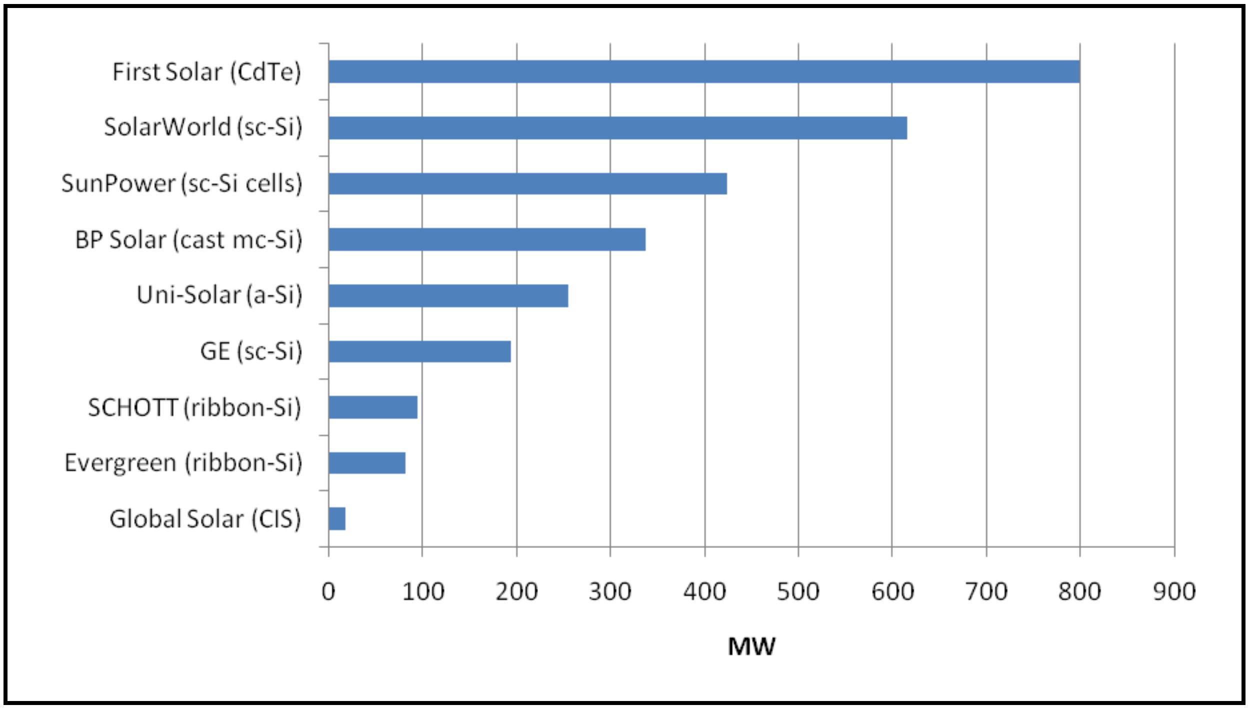
Thin films advanced dramatically during the past two decades, going from about 4% of all U.S. PV production in 1995 to over 60% in 2008. The steep production increase since 2005 is largely due to the success of CdTe at First Solar, the largest U.S. PV producer and a major recipient of DOE funding for CdTe technology R&D.

Because TFP centered on earlier stage R&D than PVMaT, research had a much broader focus. During the early years of TFP, many contracts focused on exploring different thin-film materials and eliminating those that proved to be unsuitable for PV. Although the benefits of these contracts are more difficult to quantify than for the PVMaT contracts, which often directly reduced manufacturing costs, they nonetheless played a valuable role in accelerating the development of the thin-film industry by guiding companies to the best technological options.

Uni-Solar and BP Solar both brought their multi-junction a-Si modules to production through support from the partnership. Although BP Solar has since discontinued its a-Si production line, Uni-Solar is now the second largest U.S. producer and is the largest producer of a-Si. CIS laboratory cell efficiencies increased drastically under TFP (Margolis, 2002). The leading U.S. producer of CIS, Global Solar, also received support from TFP.

Thin-film production by U.S. companies surpassed c-Si production in 2007 (Maycock, 1999–2004; *PV News*, 2005–2009). Figure 3-1 shows the largest U.S. PV producers with cumulative production from 1973 to 2008. Total U.S. PV production reached 1,023 MW in 2008, up more than 50% from just 452 MW in 2007. U.S. production of thin film surpassed U.S. production of c-Si in 2007, largely due to the success of First Solar, which produces thin-film modules with a CdTe semiconductor.

Figure 3-1. Cumulative Production by U.S. Module Producers, 1976–2008



Sources: Maycock, 1986–2004; *PV News*, 2005–2009.

3.3.3 DOE Expenditures for TFP

Total DOE expenditures for TFP were estimated to be $294.3 million (Table 3-5). In general, company cost shares were approximately 30% to 33% of DOE expenses (Hulstrom, 2010). Though annual TFP cost data from annual reports were only available for 2004 through 2008, data for 1988 through 2003 were obtained from Photovoltaics Energy Systems annual reports, NREL annual reports, or budget justification documents.[11] In addition, PV companies reported receiving extensive technical assistance and measurement, characterization, and reliability support from SNL and NREL beyond that provided directly by PVMaT and TFP managers and technical officers. The DOE cost for these activities was not included. TFP was, in part, a merger of the Amorphous Silicon and Polycrystalline Thin Films projects, which each contained basic research projects dating as early as 1978. Companies reported that significant funding and momentum for applied research and commercialization did not begin until fiscal year 1988.

The data presented included funding for centers of excellence and university research, which contributed research that was essential to technology commercialization by thin-film PV companies. Interviewees stated that one of the most significant sources of benefit under TFP was the research and knowledge exchange between university researchers and commercializing companies. Thus, full program funding, not just funding for commercialization partners, was included in the net benefits calculations.

[11] Sources for TFP were Summers (1991, 1995, 1996) for 1988 to 1995; Office of Energy Research (1997–1999) for 1996 to 1998; Office of Science (2000–2004) for 1999 to 2004; EERE (2005–2009) for 2004 to 2008.

3.4 Technology Infrastructure: Measurement, Characterization, Performance, and Reliability R&D and Testing

Measurement, characterization, and reliability testing ensures quality and safety in the PV industry. Technology infrastructure work for PV began in 1975 during FSA's block purchase program, which required JPL and its contractors not only to design performance specifications but also to develop core measurement and characterization methods and standards for performance measurement. In the words of one researcher: "all metrology and standardization had to be [developed] from scratch."

Since that time, the infrastructure supporting the PV industry has grown and become established, with private certifications, warranties, and UL and International Electrotechnical Commission (IEC) standards. The nexus of this infrastructure is provided by NREL, which maintains and furthers measurement and characterization science and whose certifications and measurements support the PV industry, standards bodies (i.e., UL, IEEE, IEC), investors, and consumers.

3.4.1 Measurement and Characterization (M&C)

The M&C Division at NREL is tasked by the DOE to provide routine and specialized measurements and characterization support for DOE-sponsored research. In executing this mandate, M&C provided industry and university research teams funded under PVMaT and TFP with technical assistance to complement these teams' core technical foci. M&C has established much of the technology infrastructure for thin films, particularly CIS, CIGS, CdTe, and a-Si, while furthering metrology for c-Si developed during FSA. M&C also conducts collaborative R&D to further understanding and build the knowledge base of photovoltaics. Four complementary research groups provide specialized expertise and develop techniques and diagnostics: Cell and Module Performance, Analytical Microscopy, Surface Analysis, and Electro-Optical (E-O) Characterization.

Cell and Module Performance

Standardized measurement specifications are necessary for proper comparison between cells and modules produced by different, and often competing, companies. The Cell and Module Performance laboratory is an independent testing facility for verifying device and module performance. The performance group also provides reference cells and develops hardware, software, and techniques for emerging PV technologies.

To provide a standard of measurement, NREL offered PV manufacturers reference cell calibrations to enable them to evaluate the performance of their own cells and modules and to attest to their quality. A reference cell is a standard PV cell with known properties providing a calibration value that relates the cell's short-circuit current to the total irradiance corrected for temperature and solar spectrum. Researchers use these cells to establish traceability to primary reference standards and to ensure accurate calibration of research instruments in R&D facilities and online diagnostic and quality control equipment in production facilities.

Without a central agency providing reference cells, individual PV manufacturers would either develop their own reference cells or pay a private enterprise to provide them. If companies did not use reference cells, manufacturers would not be providing comparable product information, and some beneficial transactions would not take place because of imperfect information. In the case where a market existed for reference cells, multiple reference-cell companies would replicate the technology infrastructure to compete in the market. The cost of this replicated infrastructure represents a cost to society. In addition, there would be a risk that reference-cell manufacturers would use different standards of evaluating their cells, and the industry would be burdened by maintaining the infrastructure to compare their products to multiple standards.

Analytical Microscopy

Analytical microscopy examines PV materials at the atomic level to provide insights into materials- and device-related R&D challenges. Using a variety of tools,[27] the Analytical Microscopy group analyses topography, structural properties, and material composition; assesses conductivity and doping; and performs imaging studies at high magnification. Facilities in large R&D centers may have some of these capabilities, but smaller start-up laboratories often do not, and even those facilities that do have them may not have the technical skills or experience to investigate phenomena and interpret results with the same level of rigor as NREL specialists. PV modules are solid-state devices, and detailed assessment of crystallography, microstructure, defects, materials composition, and topography are imperative for improving module performance and cell efficiency (NREL, 2009f).

The Analytical Microscopy group assisted PVMaT and TFP companies by analyzing solar cells and materials to understand the fundamental properties of materials and identify material or microstructure defects that impede performance. Comparing research cells with those from production lines also assisted with process development and optimization: materials defects present in production cells but not in research cells might rapidly point to issues in processing environment conditions or production equipment that otherwise might only be resolved through trial and error processes.

Surface Analysis

Surface analysis examines the surfaces and interfaces of PV material. These areas are often critically important to the electrical properties of the material as well as how devices are constructed. Surface properties and the outermost micrometers of a layer of material often control the electrical, chemical, and mechanical properties of a device or one of the device's layers. Surface analysis is particularly important for thin-films PV in which different materials' layers are deposited one on the other to compose a device. Researchers at NREL study impurities and grain boundaries, mapping and gathering information to better understand the material (NREL, 2009f). This information is valuable in failure analyses and for assessing how defects and artifacts in materials influence efficiency.

The Surface Analysis group specializes in developing and applying techniques that probe the elements composing each material layer, assessing the depths of each layer, and providing insights into how compositions, layer depth, or processing conditions could be optimized to improve cell performance. The

[27] Data are acquired through advanced imaging studies using transmission electron microscopy (TEM), scanning electronic microscopy (SEM), scanning probe microscopy (SPM), dual-beam focused-ion-beam instruments, and related techniques.

group designed and built the Surface Analysis Cluster Tool, which collects deposition, processing, and analysis tools in one instrumentation suite that operates in a vacuum. The benefit of this tool is to enable researchers to perform studies at each step in processing. In so doing, PV companies and researchers have an opportunity to acquire feedback on their materials, device composition and assembly, and processing conditions to improve products and automated production equipment.

Electro-Optical Characterization

E-O builds on Surface Analysis and Analytical Microscopy to improve our understanding of how electrical and optical properties of PV materials can help manufacturers resolve problems, improve efficiency and reliability, and reduce costs (NREL, 2009f). E-O characterization explores device performance and the relationship between performance and the materials composing the device. The E-O characterization group uses optical techniques, electrical studies, and other metrological approaches to measure the electrical and optical properties of materials and devices. M&C's E-O group provided companies with strategies for improving their process conditions, quality assurance procedures, and ultimately their products. NREL studies band gaps, material doping, defect levels, minority-carrier lifetimes, surface and bulk recombination, reflectance, and other aspects of materials and devices. Many of these techniques use optical probes that allow for two-dimensional maps, or images, of material properties across the surface. These techniques also lend themselves to contactless, and thus less expensive, measurement techniques that can be used in developing in-line diagnostics for the PV industry.

3.4.2 Performance and Reliability

The expected lifetime of a PV module is a fundamental component of the calculation of the LCOE, and the goal of reliability testing and R&D is to develop technologies for extending this lifetime and provide an infrastructure for performance monitoring. Exposed to the elements, modules' performance degrades in the face of a variety of environmental factors, including moisture ingress, corrosion, yellowing or soiling, general deterioration, damage from wind or hail, and delamination of encapsulants. Before reliability testing for PV modules began, no module manufacturers offered warranties. Today, warranties of 25 years are standard.

The focus of Performance and Reliability R&D at NREL is to improve PV technology by testing modules and systems for performance, stressing them both in the field and with accelerated testing equipment, to find solutions to improve PV reliability. NREL researchers test modules under normal conditions at the Outdoor Test Facility (OTF) and under accelerated field conditions at indoor laboratories.

The OTF is used to examine the effects of everyday weather. At the OTF, researchers examine the electrical performance, stability, and long-term reliability of modules under normal and accelerated outdoor conditions. Accelerated testing allows researchers to assess the long-term reliability of PV modules over only a few months. Modules must pass a series of tests that place them under extreme heat, humidity, and ultraviolet light exposure to mimic long-term stresses.

Test results are provided to module producers, but generalized knowledge, techniques, and diagnostics are published to advance module reliability more broadly. Reliability engineers research and extensively publish on a range of reliability issues including corrosion, delamination, moisture ingress, light-induced cell degradation, cell and film layer integrity, interconnects, thermal fatigue, and many other issues for which technology solutions must be developed to maintain the advancement of module technologies.[28]

3.5 Other Technology Development Areas in Photovoltaic Energy Systems

A technology focus on PV modules in this study's quantitative assessments by definition excluded other significant areas of technology development. A large body of technology developed by DOE, SNL, NREL, and researchers at other national labs, universities, and private companies was not included in this review. Chapter 2 highlighted the importance of BOS components, including inverters and other system components, that are required to convert the electrical current developed by modules into current usable by devices powered by electricity. Other notable areas excluded are technology infrastructure, R&D, and standards for systems reliability and deployment. These technologies and technology infrastructure are critical aspects of the national PV technology portfolio without which the economic benefits quantified in this analysis could not be appropriated by consumers.

[28] These reliability concerns were extracted from a lengthy list of issues, relevant citations and references, and failure prioritization maintained by NREL's Sarah Kurtz. The source document is available online at http://www.nrel.gov/pv/performance_reliability/pdfs/failure_references.pdf.

4. STUDY METHODOLOGY AND ECONOMIC ANALYSIS FRAMEWORK

This chapter describes the benefit-cost analysis approach to valuing the contributions of DOE to developing PV module technologies, with a particular emphasis on the economic analysis framework.[29] The economic analysis is given extensive treatment in this chapter to ensure that readers have the necessary understanding of the theory, assumptions, and procedures used to calculate economic benefits presented in Chapter 5. Approaches for evaluating knowledge, environmental, and security benefits are presented in greatest detail in their respective results discussions to streamline report presentation.

4.1 Categories of Benefits

The four categories of benefits are defined as follows:

- **Economic benefits** are increases in the value of goods and services in the economy. Technological advancement is one way to increase economic benefits. Economic benefits accrue by improving the performance of existing goods and services and/or reducing their cost, and by developing novel goods and services that provide new capabilities and experiences.[30] Resource savings, such as labor, capital, or materials expended are often significant sources of economic benefit.
- **Environmental benefits** are changes in the physical units of fossil-fuel energy consumed and are focused primarily on changes in air emissions. Environmental health benefits were estimated by monetizing the benefits of avoided adverse health incidences associated with changes in the physical units of fossil-fuel energy consumed.
- **Energy security benefits** are reduced risks to the national energy infrastructure, increases in energy independence, and decreased exposure to exogenous (non-U.S.) volatility in fossil-fuel trade. Energy security benefits are inherently difficult to quantify and compare across projects. Per EERE guidance, in this analysis energy security benefits were presented by converting kWh generation from PV systems into barrels of oil equivalent units.
- **Knowledge benefits** are derived from historical knowledge-tracing studies that review the creation and dissemination of explicit knowledge as codified in patents, publications, relational networks, and tacit knowledge.

4.2 Conceptual Approach to Economic Benefit-Cost Analysis

DOE helped the U.S. PV industry in the development, scale-up, and maturation of core PV technologies and manufacturing processes. Benefits accrued directly to PV module producers in the form of increases in product quality, operational efficiency, reliability, and reductions in production costs.

Following methodologies pioneered by Griliches (1958) and Mansfield et al. (1977), economic benefits were quantified by comparing actual technological progress to counterfactual scenarios under which DOE

[29] The economic analysis follows EERE evaluation guidelines set forth in the draft *Guidelines for Conducting Retrospective Benefit-Cost Studies* (Ruegg and Jordan, 2009).

[30] Sales revenue (i.e., unit volume multiplied by price) is not considered an economic benefit, because prices facilitate the exchange of resources between demanders and suppliers. Profits may accrue to the innovator as a private benefit, but no resource savings are associated with profits.

technical expertise, technology infrastructure, and financial support were not available and PV module companies pursued their technology R&D strategies without DOE support. Our approach was to conduct primary and secondary research on technology advances in photovoltaics funded or co-funded by DOE and ascertain how, when, or if those advances would have been made in the absence of DOE's programs. This process defined the next best alternative against which economic benefits were measured and, definitional to this approach, established attribution to DOE.

Where technical accomplishments may have economic impacts outside the PV market, such as the accelerated adoption of wire saw technology in the semiconductor industry or processes for refining high-grade silicon, these externalities were also included in the quantitative analysis.

4.2.1 Economic Benefits Relative to the Next Best Technology Alternative

Economic benefits are measured relative to the next best technology alternative, or defender technology, that consumers would adopt if the novel technology were not available. The next best alternative for c-Si modules was modules produced in the absence or delayed introduction of the efficiency gains, manufacturing technologies, technology infrastructure, and other gains presented in Chapter 3.

Companies' rates of progress, as measured by year-on-year production cost reductions, would have been lower. For example, in discussing how their production costs would have been different without PVMaT, the most common comment made by interviewees was that PVMaT enabled firms to work on issues of long-term importance. In a start-up environment, firms often put off long-term goals to focus on near-term ones that are of immediate concern for keeping the business going. Ultimately, these long-term projects are critical to the maturation and sustainability of a company.

The next best alternative for thin-films modules was the counterfactual c-Si modules produced in any given year. A-Si, CdTe, and CIS/CIGS modules would not have emerged as commercial products before 2008. TFP was characterized as "fundamentally enabling," and academic and industry researchers alike doubted whether thin films would have been viable without DOE support. One principal scientist posited that "[t]here were too many problems, progress was at times too slow, and it took so much time to get there [commercialization] that it is hard to see how thin films would have made it to the marketplace without DOE." Where there were, in actuality, labor and materials savings relative to c-Si modules, these would not have accrued.[31]

Thus, both thin-film and c-Si modules were compared against the same alternative: counterfactual c-Si modules. Key specifications for counterfactual modules *in any given year* are presented in Chapter 5.

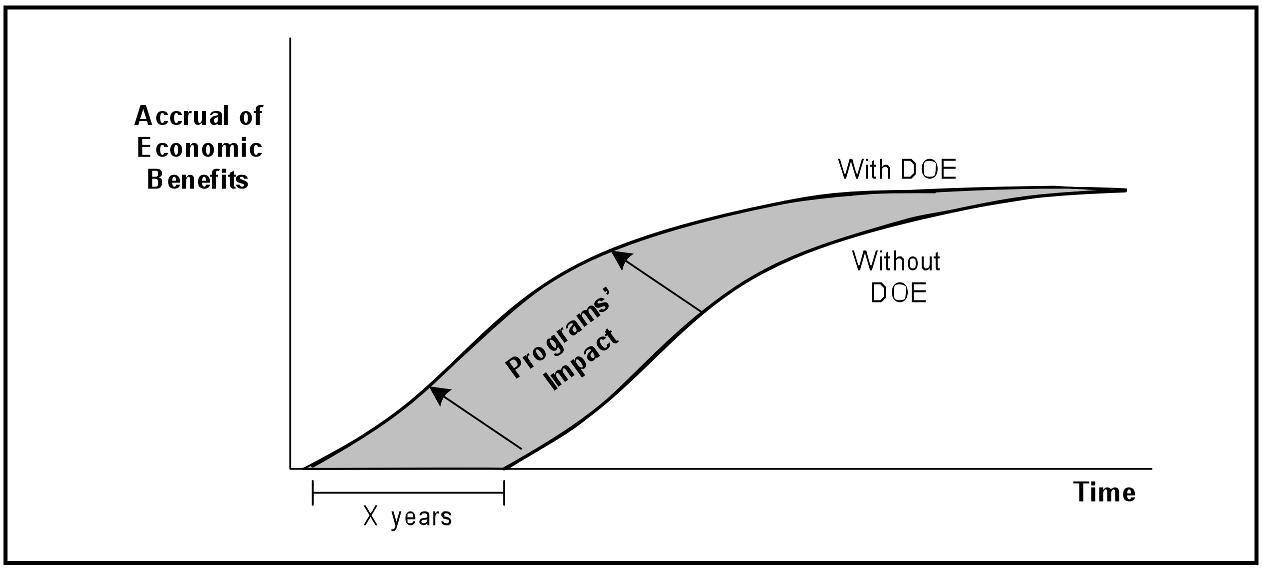
[31] First Solar is often offered by the industry as a success story, but even this financially successful firm relied on TFP funding from its start in 1991, even after it received private equity financing in 1999. Commercial production at First Solar did not commence until 2003, more than 12 years after the company's founding.

4.2.2 Economic Benefits from Technology Acceleration

Studying when technology milestones would have been met in the absence of DOE is a technology acceleration analysis. Not only may initiatives lead to innovations that would not have been developed in their absence, they also broaden R&D programs, which in turn accelerate the accrual of benefits for society. Having a more cost-effective process today, rather than tomorrow, offers both a resource-saving and time value of money impact. In the case of PV modules, superior technology performance and lower costs, and earlier accrual of these benefits, combined to amplify economic benefits.

When acceleration benefits are being estimated, the actual streams of costs and benefits are arrayed as a time series (Figure 4-1). The counterfactual expenditures and benefits that would have occurred in the absence of funding are subtracted from these actual cash flows to create the net impact of DOE support, both on an annual basis and across the entire time period. Because of the time value of money, the early accrual of economic benefits is a significant source of benefit in itself.

Figure 4-1. Illustration of the Acceleration of Economic Benefits



Source: RTI.

Technology acceleration was a critical area of analysis particularly because of the foundational role of FSA. Before the early 1980s, PV modules were vastly inferior to modules that emerged just a few years later during FSA's block purchases. Developing superior modules to meet FSA specifications enabled the PV industry to move from supplying modules for off-grid niche market applications to on-grid residential and utility applications. One interviewee likened the breadth of technology developed during the FSA period to a recipe book for a PV industry: cell, module, and systems technologies; requirements for technology infrastructure; and processing and production automation technologies were all dramatically improved. In the absence of FSA's effect on the terrestrial PV industry, PV modules would likely have improved at a far slower rate along all relevant dimensions.[32]

4.2.3 Economic Benefits from Technology Infrastructure

As the term "infrastructure" implies, the technology infrastructure of an industry refers to the tools, methods, and data that enable or support R&D, products, and services (Tassey, 1997). These tools, methods, and data are considered infrastructural because they are not necessarily products themselves; rather, they support or embody processes and components that make many advanced technology products and services possible. Many elements of the technology infrastructure are unseen or are taken as a given because they are deeply embedded in or underlie research methodologies and instruments.

Although some researchers may not notice their presence, gaps in the technology infrastructure are often readily apparent to other researchers because they hamper productivity and collaboration, and thus present additional obstacles to technology development. For example, techniques that control process quality or verify the accurate calibration of laboratory instruments are part of the technology infrastructure, as are standardized reference materials and data that researchers use to increase their confidence and assurance of the accuracy and precision of their work. More visible components of this infrastructure include certification programs, analytical instruments, and advanced software systems and algorithms.

Early in FSA, it became apparent to program leaders that the absence of a coordinated technology infrastructure for PV represented a significant barrier to technology and industry development (Linden et al., 1977; Christensen, 1985). Improvements in this infrastructure can have numerous potential economic impacts, including the following:

- Cost reductions:
  - lower labor and materials costs for developing and producing PV modules
  - lower transaction costs associated with marketing new products and meeting reliability, investor, and warranty requirements
  - avoided R&D expenditures by individual researchers or companies on measurement, characterization, and reliability testing and infrastructure

[32] Because there was no U.S. substitute project for FSA, contemporary programs funded by other national governments were reviewed for a next best alternative but none were found. In 1974, following the 1973 oil price shocks, Japan created an energy R&D program called the Sunshine Project, which was intended to support PV, coal gasification and liquefaction, geothermal, and hydrogen technologies. The project was organized by the Agency of Industrial Science and Technology within the Ministry of International Trade and Industry. Much of the PV funding from the Sunshine Project was directed toward developing a-Si and c-Si, including research on low-cost silicon feedstock material. Japanese a-Si companies had produced a-Si mostly for small applications, such as watches and calculators, before improving cells for large-scale use. With the Sunshine Project, Japan began to pursue the development of grid-connected rooftop PV systems, leveraging technology outcomes and best practices published by JPL and discussed widely in the global PV technical community. Large plots of land needed for array fields are rare and expensive in Japan because of its mountainous topography, and the imperative for the Sunshine Project was to facilitate grid-connected, distributed power, which today accounts for the majority of PV applications in Japan (Kurokawa & Ikki, 2001). The Sunshine Project was replaced by the New Sunshine Project in 1993. The New Sunshine Project shifted from the earlier focus on R&D to emphasize commercialization. Experts believe that while the Sunshine Project was important, it benefitted greatly from FSA and therefore should not have been a considered a substitute for FSA.

- Accelerated time to market:
  - shorter time between development and production
- Quality improvements:
  - detection of potential failures earlier in R&D and production cycles
  - improved and more reliable product performance and product life

Increasing research output per dollar of input, shrinking development times, and avoiding needless research in the upstream portion of the product supply chain hasten the introduction of new products and the benefits these products offer consumers over their predecessors.

Technology infrastructure supporting PV technology development was included in this analysis because measurement, characterization, and reliability testing and expertise were provided by NREL to PV companies. These research divisions were cited by funded PV technologies as being important to accelerated achievement of technology goals and are reflected in reliability gains' cost-per-watt reductions.

4.2.4 Technical and Economic Impact Metrics

Technical and economic impact metric pairs are used to operationalize economic models that calculate benefits. A technical impact metric conveys the benefit of a new technology in terms of physical units, such as number of labor hours saved or amount of raw materials saved, relative to the next best alternative. An economic impact metric, such as wage rates or cost of materials per ton, monetizes that technical benefit. The product of technical and economic impact metrics is then applied to the relevant quantity of output to derive total economic benefit.

The data required for this analysis included:

- Production cost per watt for each company,
- Guaranteed PV module reliability measured in years,
- Annual volume of PV modules produced (in megawatts) for each company, and
- Annual volume of PV modules installed in the United States (in megawatts).[33]

The breadth of technology developed and reviewed in Chapter 3 presented the challenge of how best to collect data to inform technical and economic impact metrics and then aggregate across technologies and companies. The solution was to use the common PV industry progress measure: production cost per watt.

PV companies and DOE's technology and policy strategists all placed great emphasis on driving down the production cost per watt for modules, which accounts for a significant portion of the total installed cost of a PV system. Gains in efficiency, technologies from process development R&D, yield gains, and

[33] Technologies that benefited non-PV stakeholders were quantified using stakeholder-specific technical and economic impact metrics, such as the volume and cost of materials saved using a new production technology.

other technical impact metrics all influence the production cost per watt. This progress measure has been used and commonly reported since the late 1970s. Actual and counterfactual production cost per watt and production quantity data were aggregated across all funded PV companies. To the best of their ability, interviewees isolated technology effects from the addition of new production lines or similar capacity increases.

A second technical metric of interest was reliability, as measured by the guaranteed life of a PV module, which is not captured by production cost per watt. Gains in reliability benefit consumers directly by lowering the annualized module cost and thus the LCOE. The technical impact metric was lifetime measured in years, and the economic metric was the change in the annualized module cost, which also incorporated decreases in the production cost per watt. The economic results section includes the formula for calculating this benefit.

Actual PV module quantity output was used as the quantity basis for calculating total economic benefits. Using historical production data enabled the capture of economic benefits from technology development for every unit of production and every unit installed.[34] Innovation both increased the megawatt rating of PV modules and, through income and substitution effects, increased module demand. A significant positive attribute of using historical production data is that this analysis did not change the timing of total PV system investments or public costs associated with demand-side policies, thereby isolating economic impacts attributable to technology development only.

4.2.5 Treatment of Demand-Side Policies, Rebates, and Financial Incentives

The market for PV systems is global and driven by public policy initiatives (Jennings et al., 2008; Wiser et al., 2009). Feed-in tariffs, renewable energy portfolio standards, tax credits, and rebates create a demand-side pull that accelerate the accumulation of PV installations. Federal, state, local, and foreign governments and authorities' public policies have sustained a market for photovoltaics.[35] In the absence of demand-side policies, and without regard to externalities, grid-connected PV systems would not be cost-competitive with fossil-fuel or other energy sources during this study's period of analysis.

German, Spanish, and Japanese policies, as well as those in many other countries, were critical in supporting the push for scale in R&D and manufacturing and accelerating the accumulation of installed PV systems. Germany, which enacted a feed-in tariff in 2004, increased its solar capacity by more than a factor of 5 by 2008 despite relatively low sunshine levels. Japan, which surpassed U.S. installations in the late 1990s and continued to grow steadily into the 2000s, is now experiencing a decreasing growth rate

[34] Technologies whose development was funded and supported by DOE under these programs and that were adopted outside of the PV industry were also included in our analysis. The approach to quantifying benefits was conceptually the same.

[35] Wiser et al. (2009) reviewed the installed cost of 363 MW of grid-connected residential and nonresidential PV systems from 1998 to 2007. The authors reviewed installed cost reductions from gains in nonmodule PV system components and reviewed how wide-ranging and intermittent federal, state, and local rebates and incentives influenced the installed cost over time. Jennings et al. (2008) reviewed the rapid introduction of private equity financing (venture capital) into the PV space from 2000 to 2007. In their introduction, the authors highlight the more than 20-year role of public-sector financing in supporting the industry and improving the risk profile to the point where professional investment groups were willing to invest. Both Wiser et al. (2009) and Jennings et al. (2008) underscore the historical importance of demand-side incentives for building the market for and demand for PV systems.

after a key incentive program was phased out in 2005. In Spain, which in 2007 enacted a feed-in tariff and a building code that requires newly constructed or renovated commercial buildings to generate a portion of their electricity from photovoltaics, PV installations more than quadrupled from 2007 to 2008.

In the United States, many state and local governments, nonprofits, and utilities also offer incentives for photovoltaics, including loans, rebates, and commercial and residential tax credits. Several states also mandate renewable portfolio standards. In California, which had more installed PV capacity in 2008 than any other state, more than 50 non-Federal financial incentives are available for photovoltaics, compared to fewer than 10 in most states. Each of the 10 states with the highest PV capacity in 2008 has a renewable portfolio standard. Half of these 10 states are among the 18 states that offer both personal and corporate tax credits (NC Solar Center, 2009).[36]

This analysis left U.S. and international, state, and local demand-side policies unchanged (Table 4-1), thereby calculating actual accrual of economic benefit of DOE's technology development additionality for every unit produced and/or installed. Technology availability likely influenced policy design and funding requirements, but incorporating counterfactual policy analyses would have diluted the analytic focus from valuing the contributions of DOE technology development programs to that of the contributions and roles of all public and private stakeholders in growing the installed base of PV systems overall.

[36] As demonstrated by the high PV capacity in states like New York, New Jersey, and Connecticut, which have far more PV than sunnier areas such as Florida, Georgia, South Carolina, and much of the Southwest, financial incentives can be a stronger force for driving demand for photovoltaics than a sunny climate. For a more comprehensive list of state and federal incentives, visit the Web site of the Database of State Incentives for Renewables and Efficiency, http://www.dsireusa.org.

Table 4-1. Sampling of Federal Incentives for Photovoltaics

Year	Initiative
1978	Department of Energy Act of 1978 allocated $13 million for PV systems in Federal facilities
	National Energy Conservation Policy Act of 1978 authorized $98 million for the Federal Photovoltaic Utilization Program
	Energy Tax Act of 1978 created a 10% business tax credit for photovoltaics
	Public Utility Regulatory Policies Act of 1978 required utilities to purchase from small renewable energy producers
1980	Crude Oil Windfall Profit Tax of 1980 created a 40% residential energy tax credit that could be used for photovoltaics and raised the business tax credit to 15%
1981	Economic Recovery Act of 1981 authorized accelerated depreciation of PV equipment
1986	Tax Reform Act of 1986 reinstated the business credit for photovoltaics at 15%, dropping to 12% in 1987 and 10% in 1988
1988	Technical and Miscellaneous Revenue Act of 1988 extended the PV business credit through 1989
1989	Omnibus Budget Reconciliation Act of 1989 extended the PV business credit through 1990
1990	Omnibus Budget Reconciliation Act of 1990 extended the PV business credit through 1991
1991	Omnibus Budget Reconciliation Act of 1991 extended the PV business credit through 1992
1992	Energy Policy Act of 1992 permanently established a 10% PV business credit and formed the Renewable Energy Production Incentive offering 1.5 cents per kilowatt-hour (kWh)
2005	Energy Policy Act of 2005 raised the business tax credit to 30%

Source: Margolis (2002) and Database of State Incentives for Renewables and Efficiency (NC Solar Center, 2009).

The effect of demand-side policies on measures of economic return is indeterminate. Certainly, international policies have stronger effects than U.S. policies—60% of PV production by U.S. companies is destined for international markets—which encourage economies of scale in manufacturing, thereby lowering production cost per watt. Setting aside international policy considerations, adjusting the timing and introduction of demand-side policies would shift the timing, frequency, and/or occurrence of public and private investment decisions in the PV industry, non-DOE public-sector subsidies and other outlays, and the rate of system installation accumulation. In turn, the accrual of economic benefits detailed in this analysis as well as environmental health, greenhouse gas, energy security, and other benefits would be affected.

Although such a study has great merit, focusing on the technology variables isolated DOE's impact on technology development, which was the principal objective of this analysis. Subsequent demand-side policy studies can leverage from the results from this study's economic analysis of DOE's effect on technology development.

4.2.6 Attribution of Benefits to DOE

The determination of attribution of economic benefits is frequently one of the main sources of uncertainty in a benefit-cost analysis. Issues often stem from obtaining multiple lines of evidence and the extent to which that evidence comes from unbiased, independent sources. Data collection may present challenges, such as lost or nonexistent records, key people who cannot be found or choose not to respond to inquiries, and industry concerns about sharing proprietary data. Yet, because this study focuses on estimating the return on DOE's investment, it is important to identify DOE's role in realizing the benefits described above. This is also sometimes referred to as "program additionality."

A DOE R&D program might have any of a number of effects on technology development, although not all are relevant to all technologies, such as:

- Accelerating technology entry into the marketplace, such as by speeding the R&D effort (which is then carried forward), by reducing the risk of failure and enhancing the attraction of other funding for development and commercialization, and by increasing market awareness;
- Improving the performance characteristics of the technology, such as by increasing the scale or scope of the R&D effort to take on more technical challenges;
- Changing the cost of a technology, such as by encouraging collaborative R&D activities among organizations to avoid investment redundancy and by providing specialized facilities and services needed by an entire industry to make advances; and
- Increasing market size, such as by reducing barriers to market adoption through information, training, and standards and certification activities, and by increasing the access of U.S. companies to growing global markets.

In this study, the challenge posed by attribution was avoided because research questions focused on program additionality and interviewees understood that their responses should reflect such a focus. All counterfactual production cost per watt data (i.e., insights into how those historical cost data would be different) were provided by PV companies under the assumption that DOE technical expertise and cost sharing were not available and companies' progress continued in its absence. Thus, attribution of economic benefit to DOE was implicit in the approach.

4.2.7 Measures of Economic Return

Economic performance measures permit DOE stakeholders to objectively review, assess, and compare program cluster performance in a manner similar to investment analysis. In economic assessments, such as this one, in which all benefit streams may not be quantified, it is important to note that the performance measures that are calculated are likely to be conservative. It is also important to provide an account of other important effects, which may include measures using other nonmonetary quantitative units or qualitative assessments.

Further, the impact measures for each of the benefit categories were derived from retrospective analysis. This means that innovations included in the study have been deployed commercially or are under deployment by the time of the study. Benefits beyond 2008 were not included in the analysis. Performing the study retrospectively reduces the technical and market uncertainties that typically characterize prospective benefit-cost analyses of advanced technologies. It also makes the analysis results conservative when future benefits are likely to accrue or when much of the investment is in technology infrastructure, human capital, and technology development with significant enduring value.

Cluster and individual technology benefits and costs are presented as time series of annual cash flows. Cluster costs represent the total DOE investment in solar PV, and individual technology costs represent the DOE investment just in that technology. Project benefits represent cash inflows and are typically positive. Benefits may be negative if technology adoption costs exceed technology usage benefits in the same year. Each year in the time series has a net economic benefit amount represented by net cash flows.

Once the share of net economic and environmental benefits attributable to the programs was estimated, the share compared to technology cluster expenditures to develop measures of economic performance. Three measures were calculated:

- **Net Present Value (NPV):** Two discount rates were set—7% and 3%—levels specified by Circular A-94 of the Office of Management and Budget (OMB),[37] in accordance with OMB Circular A-4. Any program cluster or individual project that yields a positive NPV when analyzed using OMB's real discount rate is socially advantageous. A negative NPV would indicate that the costs to society outweigh the benefits, and an NPV equal to zero would indicate a breakeven point.[38]

  Per EERE guidance, costs are assumed to accrue at the beginning of a period and benefits are assumed to accrue at the end. This has the effect of discounting benefits one additional period.

- **Benefit-to-Cost Ratio (BCR):** The BCR calculated in this analysis is the ratio of the NPV of benefits to the NPV of costs, which accounts for differences in the timing of cash flows. Because benefits and costs occur at different time periods, both are expressed in present-value terms before the ratio is calculated. Essentially, a BCR greater than 1 indicates that quantified benefits outweigh the calculated costs. A BCR less than 1 indicates that costs exceed benefits, and a BCR equal to 1 means that the project breaks even.

[37] For federal economic evaluations, the Office of Management and Budget (OMB) issues directives on discounting and discount rates for different types of evaluations. Circular A-94, issued in 1992, directs the use of a 7% real discount rate for federal benefit-cost analysis. More recent guidance is provided by Circular A-4, issued in 2003, which pertains to benefit-cost analysis used as a tool for regulatory analysis. It notes that Circular A-94 stated that a real discount rate of 7% should be used in benefit-cost analysis as an estimate of the average before-tax rate of return to private capital in the U.S. economy. This rate is an approximation of the opportunity cost of capital. Circular A-4 further notes that OMB found in a subsequent analysis that the average rate of return to capital remained near 7%. It also points out that Circular A-94 recommends using other discount rates to show the sensitivity of the estimates to the discount rate assumption, and notes that the average real rate of return on long-term government debt has averaged about 3%. A-94 requires the use of both a 7% and a 3% real discount rate for a benefit-cost analysis conducted for regulatory purposes. When regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services), a lower discount rate is appropriate, and OMB suggests a 3% real rate of time preference. For the purpose of discounting constant dollar cash flows in this study, both rates are used—a 7% and a 3% real discount rate—even though the purpose is not regulatory.

[38] Commenting on the 7% real discount rate, OMB (2003, p. 33) observed: "The 7 percent [real] rate is an estimate of the average before-tax rate of return to private capital in the U.S. economy. It is a broad measure that reflects the returns to real estate and small business capital as well as corporate capital. It approximates the opportunity cost of capital, and it is the appropriate discount rate whenever the main effect of a regulation is to displace or alter the use of capital in the private sector. OMB revised Circular A-94 in 1992 after extensive internal review and public comment."

- **Internal Rate of Return (IRR):** The IRR on an investment is interpreted as the percentage yield on an R&D investment. In mathematical terms, the IRR is the discount rate that sets the NPV equal to zero or results in a BCR of 1. The IRR's value can be compared with conventional rates of return for comparable or alternative investments.[39]

4.3 Approach to Environmental Health and Emissions Benefits Estimation

Emissions changes associated with gains in module technologies were approximated by comparing observed weighted average conversion efficiencies with counterfactual efficiencies. Greenhouse gas emissions and energy security benefits are the physical units of emissions changes. The Co-Benefits Risk Assessment (COBRA) model provides estimates of health effect impacts and the economic value of these impacts resulting from changes in the physical units of emitted pollutants. See also Appendix D.

The COBRA model was developed by the U.S. Environmental Protection Agency (EPA) to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies. At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint.

4.4 Approach to Energy Security Benefits Estimation

Solar energy represents a secure domestic source of energy in the face of threats to energy supply and provides clean energy to avoid long-run security risks from GHG emissions and climate change. Although national security benefits are difficult to monetize, they represent an important advantage of renewable energy. Because of its distributed nature, PV holds additional energy security benefits. In the United States, 95% of PV is distributed throughout small-scale on- and off-grid applications, making it less vulnerable to threats to the power supply than central power infrastructure. Per EERE direction, energy security benefits are presented quantitatively in barrel of oil equivalents (BOE). A BOE represents the energy released by burning a barrel of oil, or 1,700 kWh.

4.5 Approach to Knowledge Benefits Estimation

Knowledge benefits were calculated using bibliometric evaluation methods, particularly patent analysis. Bibliometric methods of evaluation are useful in historical tracing studies, such as the source study, *Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power from Solar Energy, 2010*, which traces from DOE's solar PV R&D to downstream renewable power generation. Bibliometric methods can be used to provide objectively derived quantitative measures of linkages from publication and patent outputs of the R&D program to other publications and patents outside the program. The related

[39] Risk-free capital investments such as government bonds can be expected to yield rates of return under 5% in real terms, while equities seldom return more than 10% over an extended period of time. In academic studies of the diffusion of new technologies, however, real rates of return of 100% or more have been found for significant advances with broad social benefits (Tassey, 2003).

analyses can indicate that knowledge has been created, who created it, the extent to which it is being disseminated and used (or at least referenced) by others, and by whom. See also Appendix E.

4.6 Primary Data Collection

In addition to reviews and synthesis of technical impact data from the science and engineering literature, primary data were collected via semi-structured interviews to quantify the role DOE played in furthering PV technology. Interviews were conducted with representatives of:

- PV companies and other recipients of DOE cost shares;
- Scientists, engineers, and policy analysts with DOE national laboratories;
- Academics and university-based researchers;
- Solar energy trade associations;
- Retired company executives and government experts from DOE, NASA, and other agencies, which was important for reviewing the state of technology between 1970 and 1985;
- Venture capital and technology consulting groups; and
- Investor-owned electric utilities.

Discussion topics included technologies developed under FSA, PVMaT, and TFP; the role and significance of DOE and DOE cost sharing; counterfactual technology development and technical progress; U.S. and non-U.S. innovation policies for photovoltaics; and technology infrastructure. All interviewees' responses, especially those receiving DOE cost-share, were compared with extent technical literature, market analyses, and reviews of non-U.S. programs.

This study respected the sensitive nature of the information provided by participants. Candid assessments of technology development were needed to quantify economic benefits and determine attribution to DOE. Interviews were confidential, as were the names and affiliations of private-sector participants. Participants were informed that their comments, as well as any supporting data or documentation, would only be presented in the aggregate. Therefore, firm-specific responses to questions about counterfactual technology development and reductions in production cost per watt over time were confidential. All cost data are weighted averages calculated using firm-specific production, baseline production cost per watt, and counterfactual production cost per watt data. These data will not be disclosed; only aggregated and weighted average results are presented herein.

5. ECONOMIC ANALYSIS RESULTS

This chapter presents the economic analysis of DOE's role in PV module technology development. Benefits were calculated pursuant to the methodology detailed in Chapter 4, which reviewed the process for determining what constituted economic benefits, defined the next best alternative against which benefits were measured, and presented attribution to DOE.

This chapter begins by reviewing baseline (actual) data on PV modules and then presents the economic model that compared that baseline data with data on counterfactual technology progress collected from interviews with subject matter experts. The difference between actual and counterfactual production cost per watt and reliability constituted the majority of quantified economic benefits. Benefits were also calculated for technology spillovers into the semiconductor industry, specifically for the UCC silicon refining process and accelerated adoption of wire saw technology. This chapter concludes by comparing quantified economic benefits with the entire DOE investment in Photovoltaic Energy Systems.

All dollar values in this chapter are in real terms (2008$), unless otherwise specified.

5.1 Baseline Data on PV Modules

Myriad market research reports offer what are, at times, conflicting values for any given year for four key variables imperative to this analysis: (1) production quantity, (2) production cost per watt, (3) guaranteed module reliability, and (4) PV installations in the United States. Definitions, assumptions, and data sources for these variables, whose values are presented in tables and figures in sections 5.3 through 5.6, are provided in the following discussion.

5.1.1 PV Module Production Quantity

Company-level production data (MW) for all DOE-funded companies for 1974 to 2008 were summed by year to generate an aggregate industry production quantity time series.[40] Data sources were:

- **1974 to 1985**: FSA reports (Christensen, 1985);
- **1986 to 2004**: *PV News* (Maycock, 1986–2004; *PV News*, 2005–2009; Watts et al., 1984) (see also Margolis [2002]); and
- **2005 to 2008**: Energy Information Administration (EIA) and International Energy Agency (IEA) (EIA, 2008; IEA, 2009).

5.1.2 PV Module Production Cost per Watt

The weighted-average production cost per watt of c-Si and thin-film companies receiving DOE cost share was a critical economic impact metric. Recall from chapter 4 that production cost per watt captures improvements in conversion efficiency, quality, and operational efficiency from advanced manufacturing

[40] Production quantity included domestic and overseas production by companies receiving DOE cost share whose technology can be attributed directly to U.S.-based R&D.

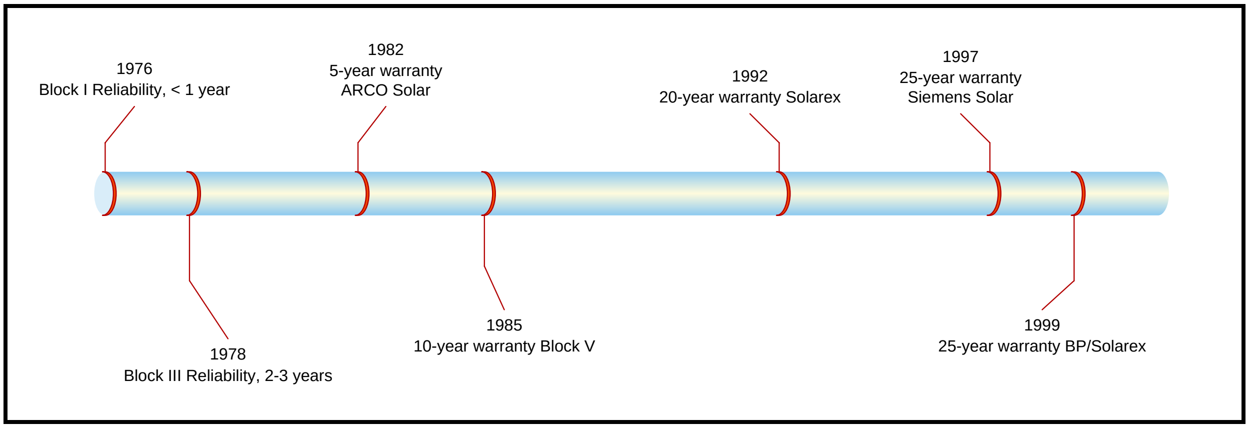
technologies, as well as the influence of the PV technology infrastructure.[2] The following data sources and estimation procedures were used:

- **1990 to 2005:** NREL collected production cost per watt as part of its program monitoring activity (Friedman et al., 2005). NREL's data collection protocols were reviewed and found to be consistent with data needs for this analysis.[3] These data were compared with pricing data from EIA and IEA reports, which provided average module price by technology for 1992 to 2007, to estimate gross margins (EIA, 2008; IEA, 2009). The gross margin was estimated to be approximately 25% in the 1990s.
- **1974 to 1989:** Data were estimated by subtracting the estimated gross margin from average price data reported by EIA or presented in FSA reports. Any missing years were linearly interpolated using the 1992 EIA average module price as the final data point.
- **2006 to 2008:** Data were provided by companies or estimated by financial reports.

5.1.3 Guaranteed PV Module Lifetime (Reliability)

The actual trend in guaranteed module lifetime was the baseline module reliability. Although module lifetimes may extend beyond the guaranteed period, guaranteed lifetime was the baseline, given that the producer incurs a financial consequence if that performance standard is not met. In 1982, Arco Solar (now SolarWorld USA) offered the first module warranty of 5 years.[4] At the close of FSA, 10-year warranties were offered, and modules were expected to last for 20 years. In the early 1990s, Solarex (now BP Solar) offered the first 20-year warranty. By the late 1990s, 25-year warranties had become standard (Figure 5-1).

Figure 5-1. Timeline of PV Warranty Introduction (Guaranteed Reliability)



Sources: Christensen (1985); Green (2005).

[2] The production cost advantages of thin film over c-Si can be viewed in light of the production cost per watt. See chapter 3.
[3] Friedman et al. (2005) adjusted dollar values to real terms using the consumer price index. This analysis corrected the inflation adjustment by reverting values back to nominal terms and then adjusting for inflation using the BEA national income production accounts.
[4] Modules produced from 1976 to 1981, years in which no warranties existed, were assumed to have had a module lifetime of 2 years.

5.1.4 U.S. PV Installations

Although U.S. companies are major players in the global market, the domestic market for photovoltaics is not as large as that in other countries. The United States ranked fourth in the world for PV installations in 2008, behind Germany, Spain, and Japan.[44] In the United States, California is the leading state in PV capacity and accounted for more than 60% of grid-connected PV installations (IEA, 2009).

The following were the data sources and estimation procedures for installations in the United States:

- **1974 to 1984:** Little international trade in photovoltaics occurred, and all production for 1976 to 1981 was assumed to be installed domestically. Installations for 1981 through 1984 were estimated net of exports via simple regression based on EIA data for 1985 to 1992.
- **1985 to 1992:** Estimated installations were from EIA (2008).
- **1993 to 2008:** The annual change in installed photovoltaics in the United States was derived from IEA market analyses (2009).

Although modules produced by foreign manufacturers are installed in the United States, these modules must have met the cost and reliability specifications established by DOE and U.S. producers and expected by U.S. consumers. In light of the fact that foreign producers relied on FSA technology in the public domain and technology infrastructure supplied by DOE for their R&D and manufacturing processes, it was therefore reasonable for benefits calculations to include total U.S. installations and not just installations of U.S.-produced PV. This is referred to in economics as induced innovation.

5.2 Economic Models for Quantifying Economic Benefits

Great care was taken during primary data collection to elicit the impact that DOE cost sharing, technical expertise, and technology infrastructure had on firm-level production cost per watt and overall trends in module reliability. This study used two models for quantifying economic benefits. One quantified production cost savings alone for units that were not installed in the United States. The other quantified benefits for installations in the United States, which included both production cost savings and reliability benefits. Two models ensured that reliability gains accruing to non-U.S. consumers were not included in the measures of economic return.

For modules installed in the United States, the combined effect of simultaneous increases in reliability and reductions in cost yielded an amplified economic benefit greater than if one of these benefits occurred and the other did not. To monetize the benefits of improved reliability, a baseline annualized module cost was developed using the production cost per watt time series and the reliability curve, as shown in the following equation:

[44] The United States led the world in PV installations until surpassed by Japan in 1997 and Germany in 2001. Spain joined the top PV producers after increasing total installation by a factor of 23 between 2006 and 2008. The United States had 1,169 MW of accumulated installations in 2008. Germany led with 5,340 MW, followed by Spain (3,354 MW) and Japan (2,144 MW) (IEA, 2009).

$$AC = \frac{C}{\sum_{t=0}^{T} \frac{1}{(1+r)^t}} \tag{5.1}$$

Where:

AC	=	annualized PV module cost (2008$)
C	=	PV module cost (2008$)[45]
T	=	PV module lifetime (years)
r	=	discount rate

This equation represents the annualized cost of a PV module that factors into the PV system purchase decision. Because this calculation is sensitive to the discount rate applied, to calculate measures of economic return, separate curves for each social discount rate of interest must be calculated.

A model to account for both a change in production cost and a change in expected lifetime was developed. Benefits were calculated using the following equation to compare the *baseline (actual)* module cost and reliability to the *counterfactual* module cost and reliability for the quantity installed in the United States:

$$Q_{US} \times \left(\frac{C_c}{\sum_{t=0}^{T_c} \frac{1}{(1+r)^t}} - \frac{C_b}{\sum_{t=0}^{T_b} \frac{1}{(1+r)^t}} \right) \times \sum_{t=0}^{T_b} \frac{1}{(1+r)^t} \tag{5.2}$$

Where:

Q_{US}	=	quantity of modules installed in the United States in any given year (W)
C_c	=	counterfactual module production cost per watt ($/W)
C_b	=	actual module production cost per watt ($/W)
T_c	=	counterfactual module reliability (years)
T_b	=	actual module reliability (years)
r	=	discount rate

Because reliability for modules installed outside the United States is excluded, economic benefits are quantified simply as

$$Q_{Non-US} \times (C_c - C_b) \tag{5.3}$$

Where:

Q_{Non-US}	=	quantity of modules produced in any given year for the non-U.S. market (W)
C_c	=	counterfactual module production cost per watt ($/W)
C_b	=	actual module production cost per watt ($/W)

[45] PV module cost was production cost per watt multiplied by production quantity in megawatts. Production cost per watt was used to monetize reliability gains instead of price per watt because historical pricing data include profit, which is a transfer of wealth between parties and not an economic benefit.

5.3 Economic Benefits Attributable to DOE of Higher Quality, Lower Cost PV Modules

Economic analysis results of DOE's contributions to PV modules are presented in the following order:

- Technology acceleration and counterfactual module reliability;
- Technology acceleration and counterfactual production cost per watt;
- Actual and counterfactual industry progress ratios;
- Total economic benefits of higher quality, lower cost PV modules separated by (1) cost savings and reliability benefits for modules installed in the United States and (2) cost savings for modules destined for non-U.S. markets; and
- Assessment of benefits of technology infrastructure.

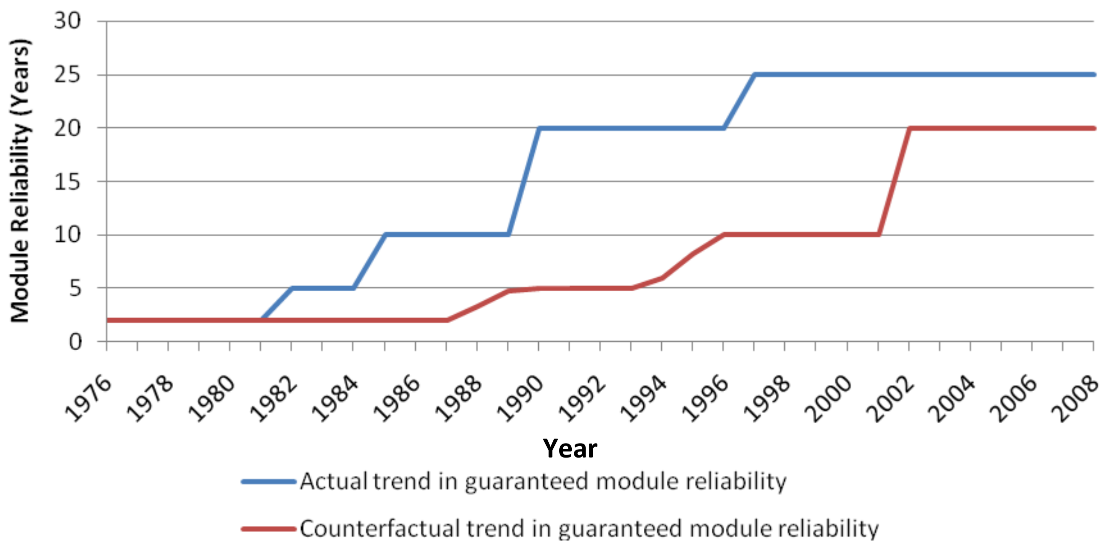
5.3.1 Technology Acceleration and Counterfactual PV Module Reliability

Between 1975 and 1985, FSA supported and integrated R&D efforts across every aspect of the terrestrial PV industry, from cell and module process improvements and engineering improvements to the incorporation of PV standards into the national electric code. During interviews experts often referred to the suite of technologies described in section 3.1 and noted as evidence the extent to which those technologies are still embodied in commercial products.

Most experts estimated FSA's acceleration effect on cost reductions and reliability improvements to be between 10 and 15 years, with a whole-year average of 12 years.[46] A 12-year acceleration implies that the progress made over the 10 years of the FSA program would have instead taken 22 years. Figure 5-2 illustrates this effect's impact on guaranteed PV module reliability. Shifting milestones back 12 years places the introduction of the 5-year warranty in 1990 instead of 1982, and the introduction of the 20-year warranty in 2002 instead of 1990. Twenty-five year warranties would not have been introduced within the period of analysis.

[46] The average period of technology acceleration was the average of responses provided by researchers active between 1975 and 1990. Responses such as "at least 10 years" or "10 to 15 years" were converted to lower bound or midpoint estimates, respectively. Some experts were unable to provide an estimate but stated that the acceleration effect was "significant" or "fundamental." The whole-year mean of responses was 12 years. In follow-up interviews, we reviewed with interviewees the effect their estimates would have on reliability milestones and costs.

Figure 5-2. Actual and Counterfactual Reliability Curves



Sources: Authors' calculations. See also section 5.1.

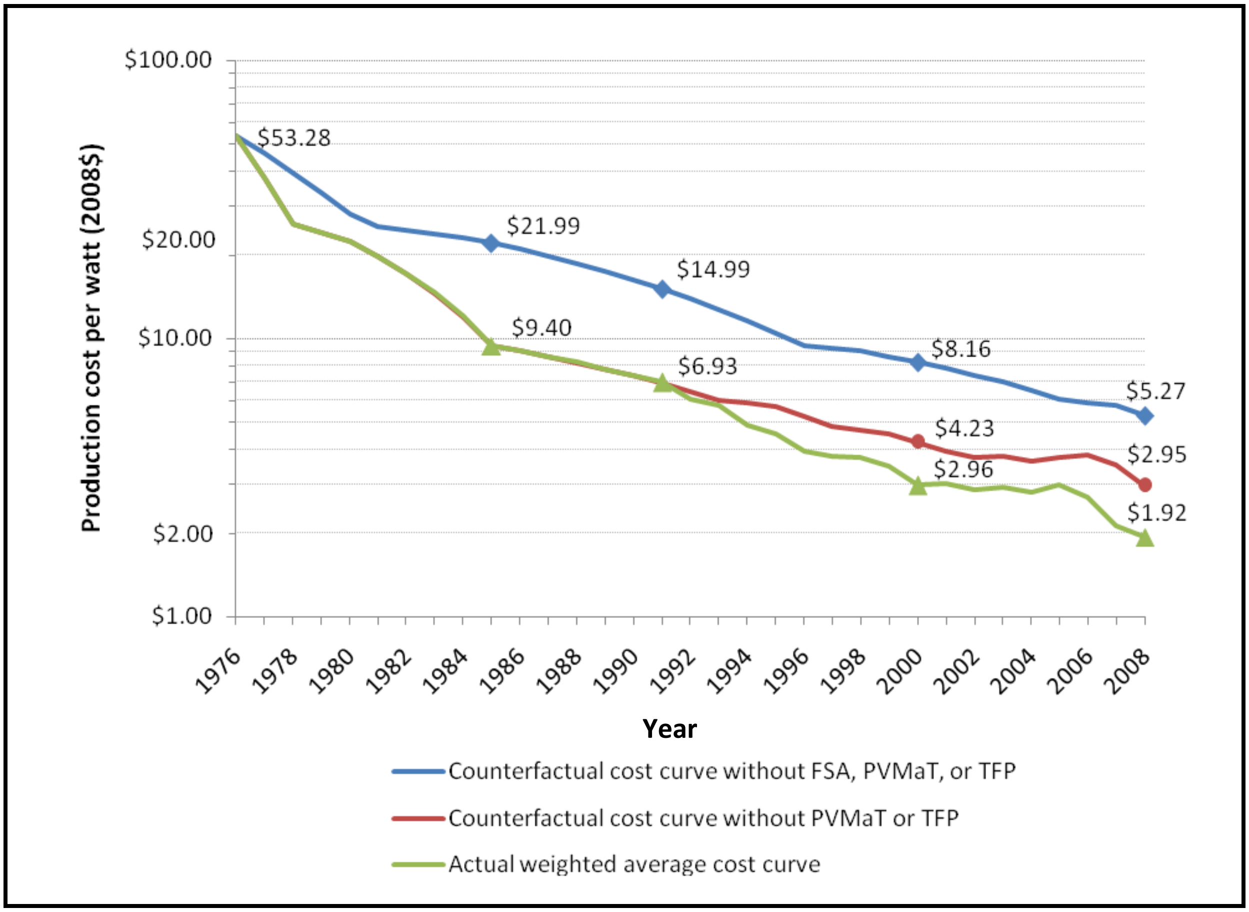
5.3.2 Counterfactual PV Module Production Cost per Watt

The production-weighted average counterfactual production cost per watt curves depicted in Figure 5-3 were developed by aggregating company-specific responses to how their technology portfolios and manufacturing operations would have developed in the absence of DOE cost sharing. Production cost per watt reductions (2008$) were greatly accelerated because of FSA, and technologies developed under PVMaT and TFP further hastened these reductions. Figure 5-3 presents three curves:

- The green curve is the actual weighted average production cost per watt curve against which progress in the absence of DOE and its resources was measured. In 2008 dollars, cost per watt was $9.40 in 1985, $6.93 in 1991, $2.96 in 2000, and $1.92 in 2008.
- The blue curve is the counterfactual, weighted average production cost per watt curve that presents the aggregate progress in the absence of DOE involvement, as determined by expert interviewees' assessment of DOE's impact. In the absence of DOE cost sharing, technical expertise, and technology infrastructure, industry progress would have proceeded at a slower pace. Note that in 1985, the last year of FSA, the cost per watt would have been $21.99, rather than $9.40. In 2008, it would have been $5.27, rather than $1.92—a difference of $3.35 per watt.
- The red curve beginning in 1991 illustrates the effect of PVMaT and TFP. If PVMaT and TFP had not followed FSA, then beginning in 1991 the cost per watt would have diverged from the green path to the red path. Costs would have been as much as 66% higher, the rate of progress would have been lower, and the weighted average cost would have been $2.95 in 2008 rather than $1.92.
- In 2008, the difference between the actual and counterfactual cost was $3.35 per watt, of which $2.32 was associated with the acceleration effect from FSA and $1.03 was associated with PVMaT and TFP technology.

This gap in and the differences between DOE initiatives combined with the start-up of new PV companies translated into experts suggesting DOE's influence be segmented by initiative: FSA and PVMaT/TFP combined.[8] The last block purchase under FSA was in 1984, and the project ended in 1985. Recall that PVMaT and TFP, which ran largely concurrently, did not ramp up significantly until 1992 to 1994. This segmentation also enables benefits to be separated between FSA's foundational research into all aspects of photovoltaics and those from targeted R&D into manufacturing systems (PVMaT) and thin films (TFP and PVMaT).

Figure 5-3. Actual and Counterfactual PV Module Production Cost per Watt Curves (2008$)



Sources: Authors' calculations. See also section 5.1.

[8] For analysis purposes, PVMaT and TFP were combined for two reasons. First, only a few U.S. PV companies participated in these programs and have PV module production and cumulative installations for which economic benefits were quantified. Combining the programs precluded disclosure of individually identifiable results. Second, many companies received funding under both programs, and although they were able to assign technical impacts between programs, the interplay between economic impacts from the two programs and the rapid scale-up of the thin-film sector was such that gains from PVMaT and TFP individually could not be distinguished meaningfully.

Table 5-1 presents the data from Figure 5-3 in tabular format as well as with the percentage increase of counterfactual over actual production cost per watt to document interviewees' aggregate responses. Note that in the case of PVMaT and TFP alone, cost per watt would have been in the range of approximately 20% to 60% over the actual cost between 1994 to 2005. The difference is greatest for 2007 and 2008 as thin-film technologies entered the market in large numbers, because of these technologies' production cost advantages over c-Si, despite the lower average energy conversion efficiency.

5.3.3 Counterfactual Industry Progress Ratios

The concept of the experience curve has played an important role in the development of R&D policy for photovoltaics (van der Zwaan & Rabl, 2004; Nemet, 2006).[48] A logical extension of the analysis of the difference between actual and counterfactual production cost per watt is to compare the implied progress ratios from the weighted-average cost curves, given the cumulative production of PV companies receiving DOE cost share.

The progress ratio is equal to the percentage an item cost to produce following a doubling of production. For instance, if an item costs $10 to produce after a total of five have been made and $8 to produce after 10 have been made, the progress ratio between these two periods would be 80%, or a 20% reduction in cost. This can be calculated as:

$$PR = 2^{\ln\frac{C_t}{C_o} / \ln\frac{Q_t}{Q_o}}$$

Where C_0 is the cost in the base time period, C_t is the cost in time t, Q_0 is the cumulative quantity produced in the base time period, and Q_t is the cumulative quantity produced in time t. In addition, the "learning ratio" is the percentage reduction due to a doubling of production and is equal to one minus the progress ratio.

$$LR = 1 - PR$$

[48] Indeed, this observation that costs tend to fall by a certain percentage with every doubling of cumulative production volumes was central to the original push for the FSA project (Christensen, 1985). Despite module prices being prohibitively high at the time of the 1973 Cherry Hill Conference sponsored by NSF, the nascent terrestrial PV industry had many doublings of production ahead of it if it were to exponentially lower the cost of photovoltaics to one competitive with fossil-fuel energies. The experience curve concept has particularly been used to justify or support demand-side subsidies to "buy down" the cost of photovoltaics. This study, however, focused on how the federal government's investment in supply-side R&D has accelerated cost reductions.

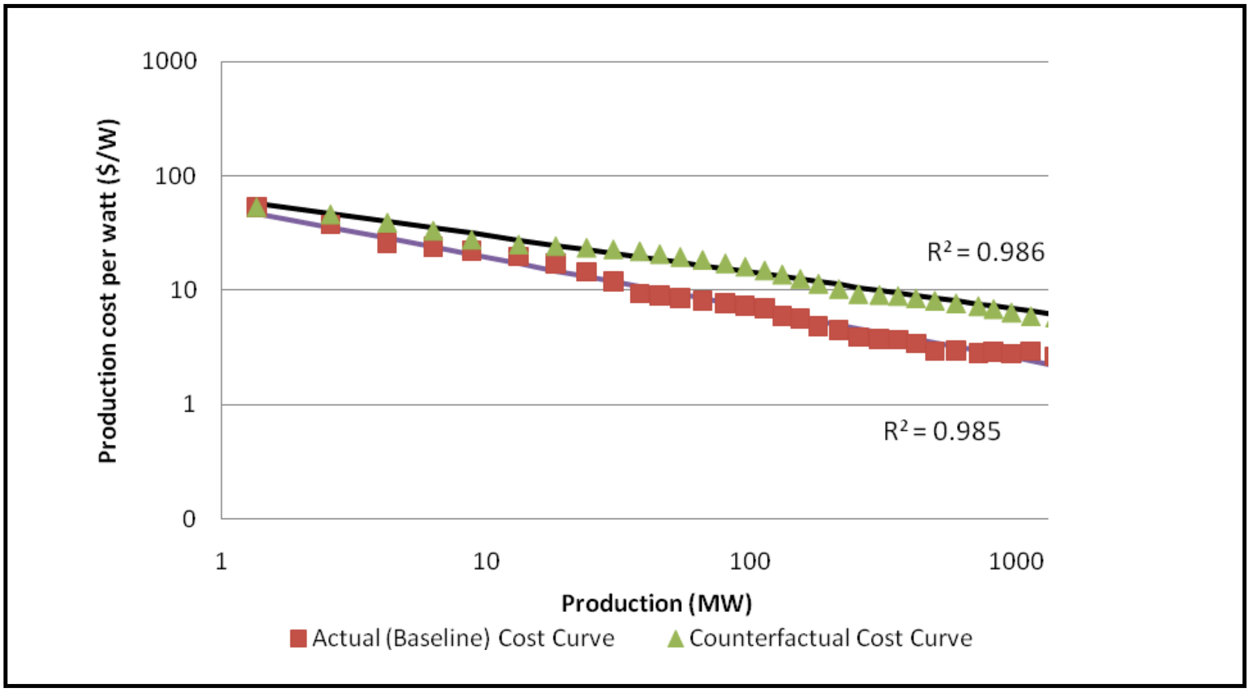
Table 5-1. Actual and Counterfactual Weighted-Average Production Cost per Watt (2008$)

Year	Actual Production Cost per Watt ($/W)	Counterfactual Cost without FSA and PVMaT/TFP ($/W)	% Increase over Baseline	Counterfactual Cost without PVMaT/TFP ($/W)	% Increase over Baseline
1974	$114.44	$114.44	—	—	—
1975	$83.86	$83.86	—	—	—
1976	$53.28	$53.28	—	—	—
1977	$37.60	$46.15	23%	—	—
1978	$25.64	$39.03	52%	—	—
1979	$23.93	$33.25	39%	—	—
1980	$22.22	$27.81	25%	—	—
1981	$19.65	$25.17	28%	—	—
1982	$17.09	$24.39	43%	—	—
1983	$14.53	$23.62	63%	—	—
1984	$11.96	$22.84	91%	—	—
1985	$9.40	$21.99	134%	—	—
1986	$8.99	$20.82	132%	—	—
1987	$8.58	$19.65	129%	—	—
1988	$8.16	$18.49	126%	—	—
1989	$7.75	$17.32	123%	—	—
1990	$7.34	$16.16	120%	$7.34	—
1991	$6.93	$14.99	116%	$6.93	—
1992	$6.00	$13.83	131%	$6.46	8%
1993	$5.69	$12.66	122%	$6.00	5%
1994	$4.84	$11.50	138%	$5.85	21%
1995	$4.53	$10.33	128%	$5.69	26%
1996	$3.93	$9.36	138%	$5.27	34%
1997	$3.77	$9.18	143%	$4.84	28%
1998	$3.71	$8.99	142%	$4.68	26%
1999	$3.45	$8.58	148%	$4.53	31%
2000	$2.96	$8.16	176%	$4.23	43%
2001	$3.00	$7.75	159%	$3.93	31%
2002	$2.85	$7.34	158%	$3.73	31%
2003	$2.91	$6.93	138%	$3.77	30%
2004	$2.80	$6.46	131%	$3.63	30%
2005	$2.96	$6.00	102%	$3.76	27%
2006	$2.67	$5.85	119%	$3.81	43%
2007	$2.11	$5.69	170%	$3.50	66%
2008	$1.92	$5.27	174%	$2.95	54%

Sources: Authors' calculations. See also section 5.1.

Using the year 1976 as the base year and 2008 as the final year, we estimate the actual learning ratio to be 0.26, while the counterfactual learning ratio is estimated to be 0.19 (Figure 5-4). Both of these learning ratios are within the range of values estimated by previous studies, and the actual learning ratio of 0.26 is identical to that estimated by Maycock in 2002, which was the source of company production data in MW but not production cost data (see also Nemet, 2006). The implication of the counterfactual learning ratio is that the U.S. industry would still need to double 4.8 more times to achieve the estimated actual production costs of 2008, given technology gains.

Figure 5-4. Actual and Counterfactual PV Industry Progress Ratios



Source: Authors' calculations.

5.3.4 Total Economic Benefits from Higher Quality, Lower Cost Modules

Total economic benefits attributable to DOE from technology acceleration and development, as reflected by reductions in production cost per watt and gains in reliability presented in the preceding sections, are estimated to have been $18,093 million between 1976 and 2008 in real terms (2008$).[49]

[49] Benefits were calculated for PV companies individually: each firm's counterfactual cost per watt less actual cost per watt and then multiplied by their production volume yielded company-specific benefits. Benefits were then summed and assembled into a time series. Future analyses leveraging this work should take heed of the following. Accommodated within the analysis, but withheld from all tables are data on firm acceleration. Multiple companies indicated that they would not have existed in the absence of DOE funding, and others stated that not only were their cost-per-watt reductions accelerated, but their entire company's development was accelerated as well. Responses on company development acceleration ranged from 1 to 5 years. For the purpose of calculating economic benefits and assembling the counterfactual cost-per-watt curve, these companies' production quantity and costs were delayed by the acceleration period and remaining companies' data were used to create the curve. Thus, the difference between the counterfactual cost per watt and baseline curves differs from the implied average cost-per-watt benefit.

For PV modules installed in the United States between 1976 and 2008, the DOE-supported technology offset what would otherwise be higher production costs per watt and lower guaranteed module lifetime. The simultaneous accrual of production cost reductions and reliability gains generated benefits of $11,320 million (Table 5-2), a figure that would have been lower had only cost savings or only reliability gains been achieved.

Note in particular the period between 1985 and 1987. Although annual installations only ranged in the upper 5 MW, benefits were estimated to be over $500 million (2008$) in each year. The influence is attributable to accelerated cost reductions and reliability gains achieved under FSA. Whereas consumers were installing modules in 1984 with a 10-year guaranteed lifetime, in the absence of FSA those modules would only have a two year expected lifetime. A module installed 10 years later in 1994 had a 20-year expected lifetime. This is an empirical result of the acceleration effect. Study participants indicated a 12-year acceleration of the industry along all major measures of progress under FSA. The 1986 cost per watt was delayed until 1998, and without PVMaT or TFP, the rate of progress for 1998 to 2008 would have corresponded roughly to actual progress for the late 1980s and early 1990s.

Larger annual economic benefits began to accrue in 2003 as the volume of photovoltaics installed in the United States every year increased from 63 MW in 2003 to 338 MW in 2008. Legacy impacts attributable to foundational technologies developed under FSA were combined with the introduction of thin-film technologies, which offer lower materials costs to producers at the expense of energy conversion efficiency, and operational efficiency achieved through the introduction of advanced manufacturing technologies. The difference in guaranteed reliability for these years was 5 years, but increasingly large volumes of photovoltaics installed multiplied by accelerated introduction of cost per watt indicate that DOE’s role in technology development increasingly delivered value to consumers. That value was estimated at $1,574 million in 2008 alone.

Table 5-2. Economic Benefits from PV Modules Installed in the United States (2008$)

Year	Annual U.S. PV Installed (MW)	Actual		Counterfactual		Incremental Change		Economic Benefit ($ million)
		Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)	
1976	0.8	$53.28	2	$53.28	2	—	—	—
1977	1.2	$37.60	2	$46.15	2	$8.55	—	10.5
1978	1.6	$25.64	2	$39.03	2	$13.39	—	22.1
1979	2.1	$23.93	2	$33.25	2	$9.32	—	19.3
1980	2.5	$22.22	2	$27.81	2	$5.59	—	14.0
1981	4.5	$19.65	2	$25.17	2	$5.52	—	24.6
1982	5.0	$17.09	5	$24.39	2	$7.30	3	221.4
1983	5.2	$14.53	5	$23.62	2	$9.09	3	231.7
1984	5.4	$11.96	5	$22.84	2	$10.88	3	242.1
1985	5.5	$9.40	10	$21.99	2	$12.59	8	555.3

(continued)

(Table 5-2 continued)

Year	Annual U.S. PV Installed (MW)	Actual		Counterfactual		Incremental Change		Economic Benefit ($ million)
		Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)	
1986	5.7	$8.99	10	$20.82	2	$11.83	8	540.5
1987	5.8	$8.58	10	$19.65	2	$11.07	8	524.1
1988	6.0	$8.16	10	$18.49	3	$10.33	7	280.9
1989	6.2	$7.75	10	$17.32	5	$9.57	5	178.0
1990	6.3	$7.34	20	$16.16	5	$8.82	15	362.2
1991	6.5	$6.93	20	$14.99	5	$8.06	15	343.8
1992	6.6	$6.00	20	$13.83	5	$7.83	15	327.5
1993	6.8	$5.69	20	$12.66	5	$6.97	15	305.7
1994	7.5	$4.84	20	$11.50	6	$6.66	14	255.6
1995	9.0	$4.53	20	$10.33	8	$5.80	12	186.6
1996	9.7	$3.93	20	$9.36	10	$5.43	10	143.5
1997	11.7	$3.77	25	$9.18	10	$5.41	15	224.2
1998	11.9	$3.71	25	$8.99	10	$5.28	15	223.3
1999	17.2	$3.45	25	$8.58	10	$5.13	15	309.4
2000	21.5	$2.96	25	$8.16	10	$5.20	15	375.3
2001	29.0	$3.00	25	$7.75	10	$4.75	15	475.1
2002	44.4	$2.85	25	$7.34	20	$4.49	5	281.0
2003	63.0	$2.91	25	$6.93	20	$4.02	5	362.2
2004	100.8	$2.80	25	$6.46	20	$3.66	5	532.2
2005	103.0	$2.96	25	$6.00	20	$3.04	5	466.6
2006	145.0	$2.67	25	$5.85	20	$3.18	5	672.0
2007	206.5	$2.11	25	$5.69	20	$3.58	5	1,034.8
2008	338.0	$1.92	25	$5.27	20	$3.35	5	1,574.1
Total								**11,319.5**

Sources: Authors’ calculations. See also section 5.1.

The rightmost columns in Table 5-2 present the discounted time series of economic benefits. Reliability analyses are sensitive to discount rates, as the economic model in Section 5.2 indicates. This is because when consumers purchase a module today, they are looking at the LCOE they expect to lock in over the lifetime of their module. Because modules are a sunk cost for consumers, the reliability benefit is part of the investment decision and can, therefore, be treated as a one-time gain that distributes noncash benefits over time. To calculate measures of return accurately, the same discount rates for LCOE assessments must be used as for the measures of return.

PV companies receiving DOE cost shares produced a large volume of modules destined for non-U.S. markets. Accordingly, the analysis only valued benefits from production cost savings accruing to producers, excluding the reliability benefits accruing to non-U.S. consumers. Multiplying the annual cost difference by the subset of production volume yields $6,773 million over the period from 1976 to 2008 (Table 5-3).

Economic benefits from technology infrastructure are a subset of total economic benefits of $18,093 million. Although these benefits are captured in the counterfactual production cost per watt assessment, evidence emerged during interviews that provided insights into the value of technology infrastructure.[50]

- One company indicated that surface analysis techniques developed at NREL enabled the company to optimize a production process in such a way as to increase efficiency by a full percentage point, which corresponds to an increase in the output rating of the module and as much as a 10% reduction in materials cost.
- Another company estimated NREL technical assistance during a critical phase of PVMaT was worth $100,000 to $300,000. Its R&D did not have the same depth of expertise as NREL in SEMS and FTIR, and the exchange between the two organizations transferred best practices and insights into data interpretation that has been of enduring value.
- Cell efficiency measurement and reliability testing were two areas cited by a third organization as particularly valuable. The infrastructure provided by NREL and SNL equated to a reduction in capital expenditures on laboratory facilities and instrumentation and the measurements and characterizations were of higher quality than what the company's R&D staff would have been able to provide. The company believes it accrued the equivalent of 400 person hours per year over a 10-year period. Assuming a direct labor rate of $44 per hour[51] and a multiplier of 2 to 3 to account for fringe benefits, indirect technical expenses, and administration, the benefit received could be valued between $35,000 and $52,000 per year, or $350,000 to $530,000 for the company over 10 years before accounting for capital and materials expenses.

Table 5-3. Economic Benefits of PV Modules Destined to Non-U.S. Markets (2008$)

Year	Economic Benefit of U.S. Installations ($ million)	Economic Benefits of Modules Destined for Non-U.S. Markets			Total Module Technology Economic Benefits ($ million)
		Production (MW)	Incremental Cost Savings Benefits ($/W)	Economic Benefits ($ million)	
1976	—	0.00	0.00	—	—
1977	10.5	0.00	8.55	—	10.5
1978	22.1	0.00	13.39	—	22.1
1979	19.3	0.00	9.32	—	19.3
1980	14.0	0.00	5.59	—	14.0
1981	24.6	0.00	5.52	—	24.6
1982	221.4	0.00	7.30	—	221.4
1983	231.7	0.43	9.09	3.9	235.5
1984	242.1	0.90	10.88	9.8	251.9

(continued)

[50] Technical assistance provided by NREL and SNL to companies funded under PVMaT and TFP is subject to nondisclosure requirements and/or cooperative research and development agreements.

[51] According to the Bureau of Labor Statistics Occupational Employment Statistics, the mean wage for 2008 for "17-2199: engineers, all other" in the semiconductor and other electronic component manufacturing industry was $43.59 (see http://www.bls.gov/oes/2008/may/naics4_334400.htm).

(Table 5-3 continued)

Year	Economic Benefit of U.S. Installations ($ million)	Economic Benefits of Modules Destined for Non-U.S. Markets			Total Module Technology Economic Benefits ($ million)
		Production (MW)	Incremental Cost Savings Benefits ($/W)	Economic Benefits ($ million)	
1985	555.3	2.28	12.59	28.6	583.9
1986	540.5	1.57	11.83	18.5	559.1
1987	524.1	3.01	11.08	33.3	557.4
1988	280.9	5.55	10.33	57.3	338.2
1989	178.0	8.24	9.57	78.9	256.9
1990	362.2	8.83	8.82	77.9	440.0
1991	343.8	11.00	8.07	88.7	432.5
1992	327.5	11.96	7.83	93.7	421.2
1993	305.7	15.64	6.97	109.0	414.7
1994	255.6	18.76	6.66	124.9	380.5
1995	186.6	25.96	5.80	150.7	337.2
1996	143.5	30.11	5.44	163.6	307.2
1997	224.2	39.40	5.40	212.8	437.1
1998	223.3	42.00	5.28	221.7	445.0
1999	309.4	43.60	5.12	223.3	532.7
2000	375.3	53.50	5.21	278.6	653.9
2001	475.1	71.50	4.75	340.0	815.1
2002	281.0	83.20	4.49	373.9	654.8
2003	362.2	39.62	4.02	159.2	521.4
2004	532.2	37.90	3.66	138.9	671.1
2005	466.6	75.10	3.04	227.7	694.3
2006	672.0	122.80	3.18	389.7	1,061.7
2007	1,034.8	245.70	3.58	881.4	1,916.2
2008	1,574.1	684.60	3.35	2,287.0	3,861.1
Total	**11,319.5**			**6,773.0**	**18,092.5**

Sources: Authors' calculations. See also section 5.1.

5.4 Economic Benefits of UCC Polysilicon Production Method

The FSA project's silicon material initiative's goal was to generate polycrystalline silicon feedstock at a reduced cost to the traditional trichlorosilane Siemens process. FSA contractors explored several different processes; however, only the process developed by UCC was deployed for commercial production. The UCC process uses silane gas as opposed to trichlorosilane as a feedstock to deposit polycrystalline silicon using the Siemens process. Advantages of the UCC process include "a lower deposition-reaction temperature, a higher conversion efficiency, and lower environmental and corrosion problems" (Lutwack, 1986).

Detailed engineering analyses at the time indicated that the UCC process was less expensive by $8.53/kg (2008$) (Yaws et al., 1986). For the purposes of this analysis, it was assumed that, although many of the production costs may have fluctuated over time, this cost difference has remained constant.[52]

Table 5-4 presents data on plant production capacity based on the UCC process, estimated annual output, and the cost savings accruing from using this novel silicon refining process from 1985 to 2008. The first commercial facility implementing the UCC process went into production in 1985 in Moses Lake, Washington, with a capacity of 1,000 MT. This capacity was expanded to 1,400 MT in 1987 and again to 2,100 MT in 1996 (Flynn and Bradford, 2006). In 1990, Kanetsu acquired the production facility from UCC and renamed it Advanced Silicon Materials Inc. (ASiMI). ASiMI constructed an additional facility with a capacity of 3,800 MT in Butte, Montana, that came into production in 1998. In 2002, the Renewable Energy Corporation (REC) developed a joint venture with ASiMI at the Moses Lake facility to form Solar Grade Silicon (SGS). In 2005, REC acquired the Butte, Montana, facility from ASiMI and began a debottlenecking project to increase polysilicon capacity by 1,000 MT. Maximum capacity for 2007 and 2008 was, therefore, 6,900 MT.

Capacity utilization rates between 2005 and 2008 averaged 89%. There was an oversupply of silicon in 2007, and the facilities operated at only 84% capacity that year. An average utilization rate of 90% was used to estimate production for 1985 to 2004 because actual production information was unavailable. Through the end of 2008, approximately 70,900 MT of polysilicon had been produced using the UCC process. This amounts to a total benefit of $630 million (2008$).

[52] Furthermore, this analysis ignores economic benefits of the large-scale silane gas production at these facilities relative to alternative technologies and is, thus, a conservative estimate of the total benefit to society of this technology.

Table 5-4. Economic Benefits from UCC Polycrystalline Silicon Production Process (2008$)

Year	Capacity (million tons)	Production (million tons)	Cost Savings per Kilogram ($/kg)	Economic Benefits ($ million)
1985	1,000	800	8.53	7.2
1986	1,000	800	8.53	7.2
1987	1,400	1,120	8.53	10.1
1988	1,400	1,120	8.53	10.1
1989	1,400	1,120	8.53	10.1
1990	1,400	1,120	8.53	10.1
1991	1,400	1,120	8.53	10.1
1992	1,400	1,120	8.53	10.1
1993	1,400	1,120	8.53	10.1
1994	1,400	1,120	8.53	10.1
1995	1,400	1,120	8.53	10.1
1996	2,100	1,680	8.53	15.2
1997	2,100	1,680	8.53	15.2
1998	5,900	4,720	8.53	42.8
1999	5,900	4,720	8.53	42.8
2000	5,900	4,720	8.53	42.8
2001	5,900	4,720	8.53	42.8
2002	5,900	4,720	8.53	42.8
2003	5,900	4,720	8.53	42.8
2004	5,900	4,720	8.53	42.8
2005	5,900	5,300	8.53	45.2
2006	5,900	5,555	8.53	47.4
2007	6,900	5,780	8.53	49.3
2008	6,900	6,171	8.53	52.6
Total				**630.1**

Sources: Flynn and Bradford, 2006; Authors' calculations.

5.5 Economic Benefits of Accelerated Introduction of Wire Saw Technology to the Semiconductor Industry

The wire saw is a less costly technology for slicing silicon ingots relative to the alternative defender technology, internal diameter saws. Wire saws are capable of cutting larger silicon ingots into smaller wafers with less kerf loss (wasted silicon) than internal diameter saws. In addition, they are capable of cutting an entire ingot into wafers at once. The development and adoption of wire saws for silicon slicing was driven primarily by the requirement for low-cost silicon wafers by the PV industry. Costs associated with slicing silicon are small relative to the value added by wafer manufacturers in the semiconductor industry. However, the need for inexpensive silicon wafers for photovoltaics compelled the industry and DOE to explore wire saws.

Wire saws were assessed in the 1970s and 1980s as part of FSA. Although beneficial for the reasons described above, these wire saws had high variable and maintenance costs and, thus, were not cost-effective. In the early 1990s, PVMaT enabled both Solarex and Siemens to assess contemporary wire saw machinery, and both companies successfully adopted wire saws in 1993. Solarex replaced all 24 of their internal diameter saws with a single wire saw and purchased several more wire saws. Solarex reported that the wire saws provided a savings of $0.13 per wafer.

Expert interviews have indicated that without DOE funding, wire saws would have eventually been adopted by the PV industry and subsequently the semiconductor industry. DOE funding accelerated the adoption of wire saws to the semiconductor industry by an estimated 3 years.[53] We assume that wire saw adoption in 200 mm wafer production followed an S-shaped adoption pattern in the semiconductor industry from 1994 to 1998. Based on an estimate of $0.13 saved per wafer, total economic benefits of wire saws were estimated to be $99.3 million (Table 5-5). Benefits attributable to DOE from accelerated introduction of this technology to the industry were estimated to be $12.2 million.

5.6 Benefit-Cost Analysis of Photovoltaic Energy Systems Cluster

This section presents the summary total of economic benefits, measures of economic performance, and sensitivity analysis for the technology cluster Photovoltaic Energy Systems.

5.6.1 Measures of Economic Return for the Technology Cluster

Total quantified economic benefits were compared to the total public investment in Photovoltaic Energy Systems to provide lower bound measures of economic return for the entire cluster. Recall from Chapter 1, that between 1975 and 2008 Congress had appropriated $7,438 million for solar energy, including $3,710 million for Photovoltaic Energy Systems (2008$).

Economic benefits were estimated to be $18,735 million, of which:

- $18,092 million accrued from higher quality, lower cost PV modules;
- $630 million accrued from the UCC polycrystalline silicon refinement process; and
- $12 million accrued from the accelerated adoption of wire saw technology by the semiconductor industry.

[53] Chip fabrication machines require a standard-sized silicon wafer. The semiconductor industry has gone through a number of standard wafer diameters. Because both the machines to produce wafers and to fabricate chips are expensive, wafers of a particular diameter will persist for many years. Although wire saws are required for 300 mm production and the per-wafer savings are included in the total benefits, this analysis did not study acceleration of the progression to 300 mm adoption.

Table 5-5. Economic Benefits from Accelerated Adoption of Wire Saws in the Semiconductor Industry (2008$)

Year	200 mm Wafers (million square inches)	300 mm Wafers (million square inches)	Cost Savings ($ million)	Cost Savings Under Delayed Introduction ($ million)	Economic Benefits of Accelerated Wire Saw Introduction ($ million)
1994	7,824,247	—	<0.0	—	<0.0
1995	17,640,493	—	0.4	—	0.4
1996	25,875,462	—	2.3	—	2.3
1997	33,658,636	9,127	3.8	0.1	3.7
1998	33,453,275	45,636	4.2	0.9	3.4
1999	41,462,347	456,357	5.3	3.7	1.6
2000	57,952,820	857,952	7.5	6.7	0.7
2001	47,171,377	1,168,275	6.1	6.1	—
2002	50,929,480	3,194,501	6.9	6.9	—
2003	59,000,160	4,034,199	8.0	8.0	—
2004	68,816,406	7,246,955	9.6	9.6	—
2005	66,085,107	12,221,250	9.9	9.9	—
2006	72,800,406	19,167,009	11.7	11.7	—
2007	69,001,231	28,339,791	12.3	12.3	—
2008	54,934,016	32,373,990	11.1	11.1	—
Total			**99.3**	**87.1**	**12.2**

Sources: SEMI (2009); Authors' calculations.

Thus, net of investment costs of $3,710 million, net economic benefits were $15,025 million in real terms (Table 5-6). The IRR was 17%. Also, applying a 7% discount rate yields a NPV of $1,459 million and BCR of 1.83.[54] Applying a 3% discount rate yields a NPV of $5,725 million and BCR of 3.24.

[54] Following Ruegg and Jordan (2009), costs are assumed to be incurred at the beginning of each year, but benefits are assumed to be realized at the end of each year. Thus, the time period for the discounting of benefits is one year longer than for costs.

Table 5-6. Lower Bound Net Economic Benefits from DOE Investment in Photovoltaic Energy Systems (2008$)

Year	Module Technology Benefits ($ million)	UCC Polysilicon Production Process ($ million)	Accelerated Adoption of Wire Saw Technology ($ million)	Total Benefits ($ million)	Total Costs, Photovoltaic Energy Systems ($ million)	Net Benefits ($ million)
1975	—	—	—	—	(1.9)	(1.9)
1976	—	—	—	—	(65.9)	(65.9)
1977	10.5	—	—	10.5	(170.7)	(160.2)
1978	22.1	—	—	22.1	(204.6)	(182.5)
1979	19.3	—	—	19.3	(294.5)	(275.2)
1980	14.0	—	—	14.0	(340.9)	(326.9)
1981	24.6	—	—	24.6	(314.9)	(290.3)
1982	221.4	—	—	221.4	(144.9)	76.6
1983	235.5	—	—	235.5	(109.1)	126.5
1984	251.9	—	—	251.9	(91.1)	160.8
1985	583.9	7.2	—	591.2	(96.3)	494.9
1986	559.1	7.2	—	566.3	(69.5)	496.9
1987	557.4	10.1	—	567.5	(67.4)	500.1
1988	338.2	10.1	—	348.4	(56.2)	292.2
1989	256.9	10.1	—	267.1	(54.8)	212.2
1990	440.0	10.1	—	450.2	(51.6)	398.6
1991	432.5	10.1	—	442.7	(66.8)	375.8
1992	421.2	10.1	—	431.3	(85.0)	346.3
1993	414.7	10.1	—	424.8	(90.0)	334.8
1994	380.5	10.1	<0.0	390.7	(101.7)	289.0
1995	337.2	10.1	0.4	347.8	(111.5)	236.3
1996	307.2	15.2	2.3	324.7	(80.0)	244.7
1997	437.1	15.2	3.7	456.0	(76.0)	380.0
1998	445.0	42.8	3.4	491.2	(82.1)	409.1
1999	532.7	42.8	1.6	577.0	(88.2)	488.8
2000	653.9	42.8	0.7	697.4	(79.0)	618.4
2001	815.1	42.8	—	857.8	(88.9)	768.9
2002	654.8	42.8	—	697.6	(77.1)	620.5
2003	521.4	42.8	—	564.2	(84.4)	479.7
2004	671.1	42.8	—	713.9	(81.3)	632.5
2005	694.3	45.2	—	739.5	(71.4)	668.0
2006	1,061.7	47.4	—	1,109.1	(34.0)	1,075.0
2007	1,916.2	49.3	—	1,965.5	(141.3)	1,824.1
2008	3,861.1	52.6	—	3,913.7	(136.7)	3,776.9
Total	**18,092.5**	**630.1**	**12.2**	**18,734.8**	**(3,709.9)**	**15,024.9**

Source: Authors' calculations.

5.6.2 Measures of Return for FSA and for PVMaT/TFP

To review long-term influences, this study also reorganized economic benefit results by initiative (Table 5-7):

- FSA ran from 1975 to 1985, cost DOE $535 million, and continues to generate economic benefits, which through 2008 amounted to $15,673 million. Applying the 7% social discount rate provides a BCR of 7.12 and an NPV of $2,435 million. The IRR was 37%.
- PVMaT and TFP ran from 1988 to 2008, cost DOE $495 million, and also continue to generate economic benefits, which through 2008 amounted to $3,061 million. Applying the 7% social discount rate provides a BCR of 3.35and an NPV of $637 million. The IRR was 24%.

Table 5-7. Lower Bound Measures of Economic Return for Photovoltaic Energy Systems

Measure	Photovoltaic Energy Systems Cluster	FSA (1975–1985)	PVMaT (1991–2008) TFP (1988–2008)
Period of Net Benefits Accrual	*1975–2008*	*1975–2008*	*1988–2008*
Total benefits (million 2008$)	$18,734.8	$15,673.3	$3,061.5
Total costs (million 2008$)	$3,709.9	$535.0	$495.0
Net benefits (million 2008$)	$15,024.9	$15,138.3	$2,556.6
Internal rate of return	17%	37%	24%
NPV at 7% (million 2008$)	$1,458.9	$2,435.1	$636.9
Benefit-to-cost ratio at 7%	1.83	7.12	3.35
NPV at 3% (million 2008$)	$5,724.7	$6,592.8	$1,409.9
Benefit-to-cost ratio at 3%	3.24	15.07	4.76

Source: Authors' calculations.

That the IRRs of FSA and PVMaT/TFP were individually greater than the cluster IRR of 17% results from including cluster costs for which no benefits were calculated in the time series of cash flows.

It is also important to note that benefits for FSA accrued over the entire 33-year period of analysis. Results for PVMaT and TFP reflect more recent investments, and economic returns from DOE's investment in thin-film PV in particular are only now beginning to accrue. Note that chapters 3 and 5 highlight that large-volume production of thin-film PV did not begin until 2003, but investment was sustained by DOE beginning in 1988. This constituted a nearly 15-year incubation period. Thus, it is expected that the annual public return on investment in PVMaT and TFP will exceed the 24% calculated for the 20-year period from 1988 to 2008.

5.6.3 Sensitivity Analysis on Measures of Economic Return for the Photovoltaic Energy Systems Cluster

Cash flow analyses are sensitive to the timing of cash flows, and this study spanned 33 years of DOE investment and identified a significant technology acceleration effect. The earlier a cash flow accrues in a series, the greater its influence on the measure. As such, a sensitivity analysis was performed on the measures of economic return by calculating how calculated values would change under alternative acceleration periods. FSA's technology acceleration effect had the most significant effect on the industry weighted-average counterfactual production cost per watt (see also Figure 5-2).

Recall from Section 5.3 that the average acceleration effect incorporated into the counterfactual cost per watt curve was 12 years. The distribution of experts' quantitative estimates was between 10 and 15 years. Therefore, the sensitive analysis calculated two alternative counterfactual cost curves: one for a 10-year acceleration effect and another for a 15-year effect. Appendix F contains tabular data for this sensitivity analysis, the summary results for which are presented in Table 5-8.

Table 5-8. Sensitivity Analysis of FSA Acceleration Effect on Economic Performance Measures

Measure	Results (12-year acceleration)	Under 10-Year FSA Acceleration Effect	Under 15-Year FSA Acceleration Effect
Total benefits (million 2008$)	$18,734.8	$14,389.8	$25,875.7
Total costs (million 2008$)	$3,709.9	$3,709.9	$3,709.9
Net benefits (million 2008$)	$15,026.8	$10,681.8	$22,167.7
Internal rate of return	17%	14%	20%
NPV at 7% (million 2008$; base year = 1975)	$1,458.9	$858.8	$2,394.6
Benefit-to-cost ratio at 7%	1.83	1.49	2.37
NPV at 3% (million 2008$; base year = 1975)	$5,724.7	$3,987.2	$8,531.5
Benefit-to-cost ratio at 3%	3.24	2.56	4.35

Source: Authors' calculations.

If the acceleration effect from FSA were 10 years rather than 12 years:

- Total benefits would have been $14,390 million and net benefits would have been $10,682 million.
- Applying a discount rate of 7%, the NPV becomes $859 million, which is 41% less than $1,459 million. Similarly the BCR would have been 1.49 instead of 1.83
- The IRR would have been 14%.

If the acceleration effect from FSA were 15 years rather than 12 years:

- Total benefits would have been $25,876 million and net benefits would have been $22,168 million.
- Applying a discount rate of 7%, the NPV becomes $2,395 million, which is 64% more than $1,459 million. Similarly the BCR would have been 2.37 instead of 1.83

- The IRR would have been 20%.

6. ENVIRONMENTAL EMISSIONS, HEALTH, AND ENERGY SECURITY BENEFITS

This chapter reviews estimates of environmental emissions, environmental health, and energy security benefits of on- and off-grid PV systems for 1976 through 2008. Electricity from PV systems, unlike fossil fuels and other sources of electricity, does not present environmental costs during energy generation. Yet, the module production process is energy intensive. Further, the more often PV modules fail, the more often they must be replaced and therefore the greater the environmental cost.

PV technology may present a risk to the environment at the end of its lifetime. Before FSA, modules often failed within a year. By the end of the project, companies were offering 10-year warranties. Today, modules generally have a guaranteed lifetime of 25 years. This improved reliability reduces the number of modules that must be disposed of and replaced.

At the end of their useful life PV modules are often disposed of in landfills because most can be safely thrown away. Recycling may not be the most cost-effective option for companies because modules contain a relatively small amount of semiconductor and are widely dispersed among customers (EERE, 2009b). Some companies agree to take back modules at the end of modules' lifetime for recycling. Longer lifetimes ensure that fewer modules will end up in landfills, even if they are not recycled.

6.1 Environmental Emissions Benefits

Environmental emissions benefits were estimated by comparing the reduction in air pollutant emissions from using PV systems as compared to the next best technology alternative. Electricity generation is a major source of greenhouse gas (GHG) and other air pollutant emissions. Solar energy, which serves as a substitute for GHG-producing energy sources such as natural gas, coal, and petroleum, does not release GHGs during energy production. The GHGs produced during electricity generation from fossil fuels are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Other GHGs, such as hydrofluorocarbons, perfluorcarbons, and sulfur hexafluoride, are not directly associated with fossil fuel combustion and are therefore not included in this analysis.

PV installations were segmented by (1) grid-connected centralized, (2) grid-connected decentralized, and (3) off-grid applications. Each segment was then compared to the most likely fuel choice for the application, excluding any solar technologies. The percentage change in emissions factors for electricity production, such as particulate matter (PM), nitrogen oxide (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), drove the model results (see Table 6-1 and Figure 6-1).

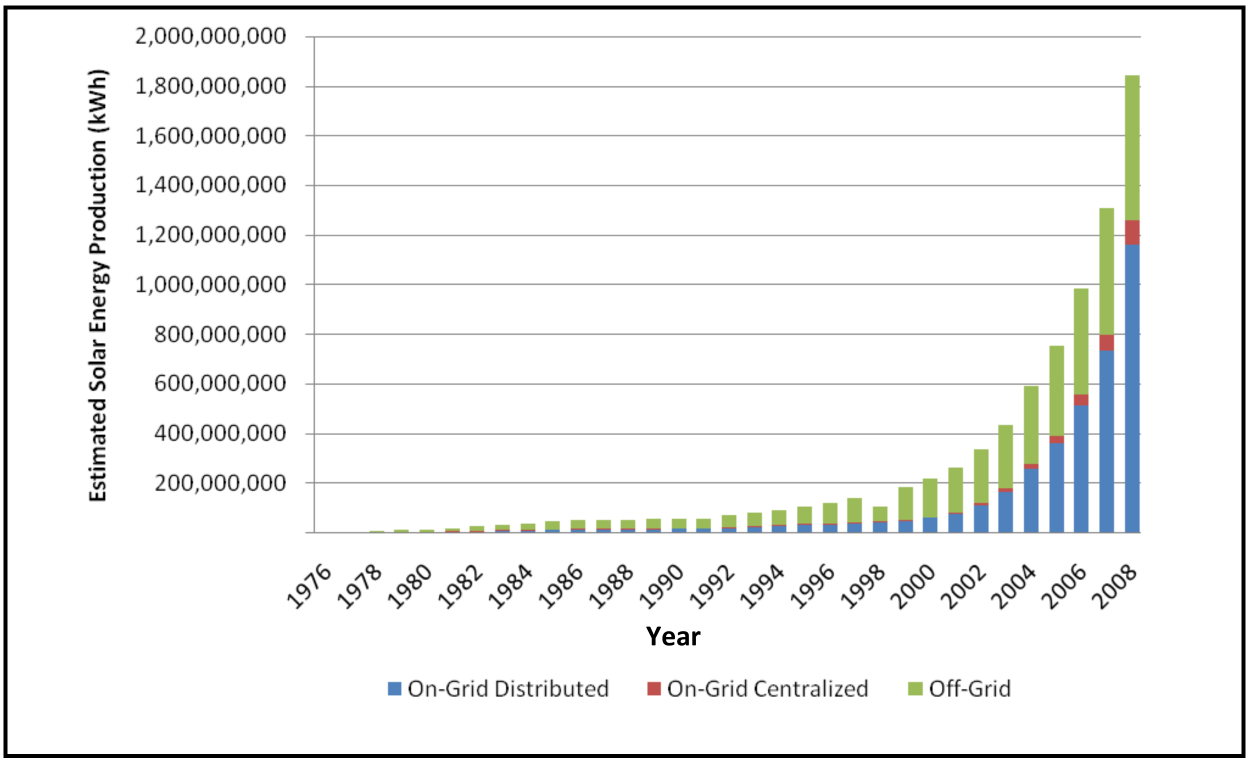
Table 6-1. Emissions Factors Underlying Environmental Health Effects (Avoided Emissions [lbs/kWh])

	CO_2	CH_4	N_2O	PM	SO_2	NO_x	NH_3	VOCs
On-grid distributed	1.226208	0.000041	0.000010	0.000094	0.001022	0.000495	0.000004	0.000016
On-grid centralized	1.160000	0.000075	0.000101	0.000016	0.000006	0.000162	0.000004	0.000013
Off-grid	2.150000	0.000021	0.000276	0.000522	0.000332	0.009694	0.000004	0.000526

Sources: EIA (2009a). See also http://www.epa.gov/ttn/chief/ap42/ch03/final/c03s04.pdf.

Grid-connected centralized applications are energy centers that are not associated with a particular customer and are primarily utility scale. The versatility and short ramp-up time of natural gas electricity generation units compare closely with PV systems, and these units are often used for peak hours, particularly during warmer months when air conditioning use increases electricity demand. Geothermal and wind power were not considered close substitutes, despite being renewable sources, because geothermal is considered base load, and the location profile favoring wind power may not align with that for solar. Thus, barring advances in storage technologies, PV electricity generation is limited to daytime conditions, and the nearest substitute for a PV system is a natural gas peaking unit.

Figure 6-1. Solar Energy Production (kWh)



Source: EIA (2009b).

The kilowatt-hours avoided for natural gas and internal combustion engines were multiplied by the emission factors for CO_2, CH_4, and N_2O available from the Energy Information Administration (EIA) (EIA, 2009a). For on-grid distributed applications, GHG emissions avoided were found by using the emissions factors specific to each region from EPA's eGRID and weighted by the kilowatt-hours of solar energy in each region (EPA, 2009a).

On-grid distributed applications refer to PV systems that are connected to the grid and used to provide power to a particular customer, such as a residential roof-mounted system. The power displaced by distributed PV systems depends on the fuel generation portfolio for each state. Current PV installations by state and the proportion of each fossil fuel type providing power in each state were reviewed (see Table 6-2). A weighted average kWh reduction was calculated for each fuel source: 80% of emissions reductions came from the avoided use of natural gas, 16% from coal, and 3% from petroleum.

Off-grid applications were compared to diesel-fired internal combustion engines. Many remote off-grid PV modules, such as those on street signs or remote sheds, can take the place of a diesel generator. Because diesel generators produce more emissions per kilowatt-hour than natural gas, off-grid solar produced much larger benefits than on-grid solar, despite producing fewer kilowatt-hours in 2008.

Table 6-2. Solar Energy Generation and Average Fossil Fuel Mix by State, 2008

State	Solar (kWh)	Coal	Natural Gas	Petroleum
California	688,718,789	2%	96%	2%
New Jersey	91,516,296	35%	64%	2%
Colorado	46,540,338	70%	29%	0%
Nevada	44,584,862	24%	76%	0%
Arizona	32,982,369	52%	48%	0%
New York	28,549,955	28%	61%	11%
Hawaii	17,599,288	15%	0%	85%
Connecticut	11,472,128	25%	66%	9%
Oregon	10,038,112	23%	77%	0%
North Carolina	6,127,159	94%	5%	1%
Other	62,835,975	68%	30%	2%
Weighed fuel use		16%	80%	3%

Source: EIA (2009b).

Table 6-3 shows estimated total GHG emissions avoided.[55] Although fossil fuel combustion releases much smaller amounts of CH_4 and N_2O than CO_2, these GHGs are not trivial because they are approximately 21 times and 310 times, respectively, more effective at trapping heat in the atmosphere than CO_2 (EPA, 2009b). Avoided GHG emissions attributable to DOE were approximated through an acceleration analysis of efficiency improvement. The percentage of benefits attributable to DOE was approximated using the ratio of the baseline to the counterfactual in each year.

Table 6-3. Estimated Avoided GHG Emissions, 1976–2008

	Total Avoided Emissions			Approximate Attribution to DOE		
	CO_2 (tons)	**CH_4 (tons)**	**N_2O (tons)**	**CO_2 (tons)**	**CH_4 (tons)**	**N_2O (tons)**
On-grid centralized	202,694	7	3	32,152	1	<1
On-grid distributed	2,346,139	83	33	372,154	13	5
Off-grid	4,266,270	42	548	658,167	6	84
Total	**6,815,103**	**132**	**583**	**1,062,473**	**21**	**90**

Source: COBRA estimates.

Figure 6-2 shows the actual (baseline) module efficiency and a projection of module efficiency with a 12-year delay (the counterfactual).

The EPA's Greenhouse Gas Equivalency Calculator converts GHG emissions to everyday terms (EPA, 2009c). Approximate equivalencies for total emissions avoided by PV in 2008 alone include the following:

- GHG emissions from 247,139 passenger vehicles,
- One year of CO_2 emissions from electricity use in 167,862 homes, or
- Carbon sequestered annually from 275,595 acres of pine or fir forest.

The use of PV also avoids other harmful non-GHG emissions released during electricity production from coal, natural gas, oil, and other combustibles. Emissions such as particulate matter (PM), ammonium (NH_3), and volatile organic compounds (VOCs) can have a negative impact on public health and the environment. Table 6-4 displays estimated emissions avoided and the amount of these which is attributable to DOE.

[55] Avoided emissions estimated for 2008 have been scaled back to estimate previous years based on on-grid and off-grid kilowatt-hours production in each year. Because detailed data were not available for all years, this estimate assumes a constant ratio of distributed to centralized on-grid PV for the years prior to 2008. Including benefits for 2009 to 2033, assuming a useful life of 25 years, increases total GHGs avoided by 800 tons CH_4, 2,100 tons N_2O, and 32,100,000 tons CO_2. Thus, retrospective and future avoided GHGs for the installed base as of 2008 are 900 tons CH_4, 2,700 tons N_2O, and 38,900,000 tons CO_2.

Figure 6-2. Actual and Counterfactual PV Module Efficiency

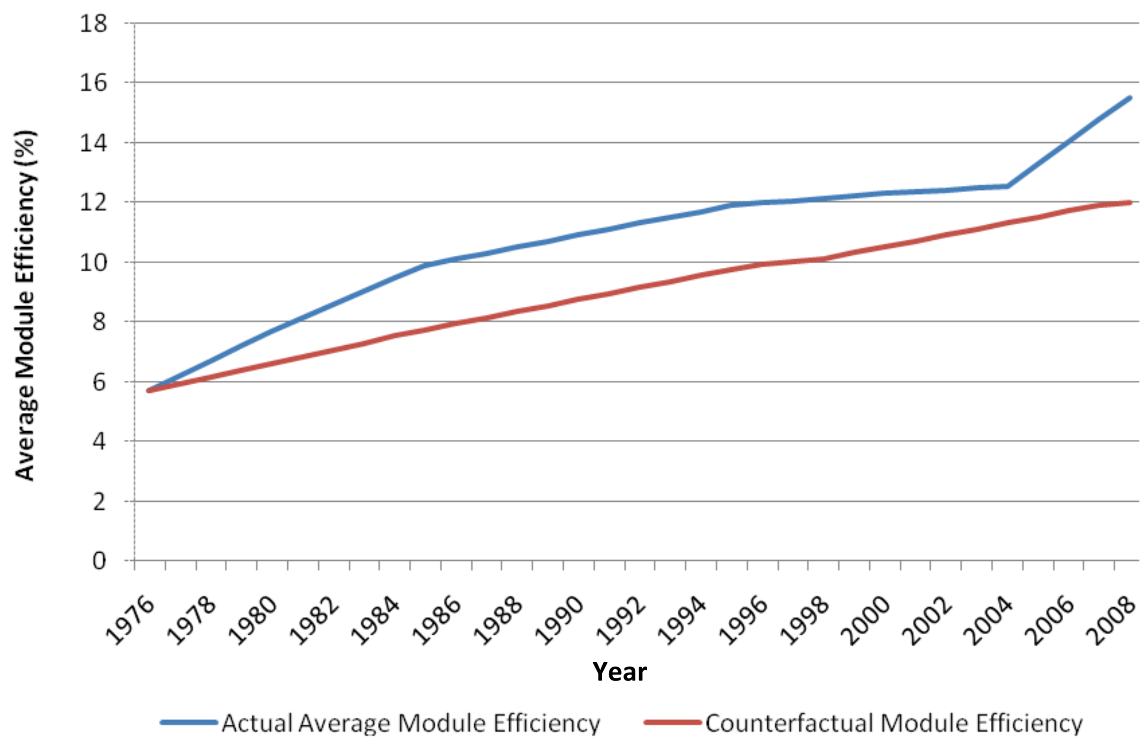


Table 6-4. Estimated Other Emissions, 1976–2008

	Total Avoided Emissions				Approximate Attribution to DOE			
	PM (tons)	SO_2 (tons)	NH_3 (tons)	VOCs (tons)	PM (tons)	SO_2 (tons)	NH_3 (tons)	VOCs (tons)
On-grid centralized	3	3	1	2	<1	<1	<1	<1
On-grid distributed	181	1,964	8	31	32	352	1	6
Off-grid	1,049	667	8	1,057	174	111	1	175
Total	**1,232**	**2,634**	**16**	**1,090**	**207**	**463**	**3**	**181**

Source: Authors' calculations.

6.2 Environmental Health Benefits

EPA's Co-Benefits Risk Assessment (COBRA) model was used to calculate the health benefits of reductions in air pollutants resulting from using PV systems. The COBRA model produces the incidence and cost of health effects. Incidence is defined as the change in number of health incidents relative to natural gas combustion.

According to COBRA, for 2008 alone, avoided adverse health incidents were estimated to be:

- On-grid centralized systems: $90,500 for 100.1 million kWh (Table 6-5)
- Grid-connected distributed systems: $11.8 million for 1,158.9 million kWh (Table 6-5)
- Off-grid systems: $28.7 million in 2008 for 583.4 million kWh (Table 6-6)

Thus, for 2008 alone, the total environmental health benefit from on-grid centralized PV ($0.09 million), on-grid distributed PV ($11.8 million), and off-grid PV ($28.7 million) was $40.6 million. Total benefits for 1976 to 2008 were $237 million.[56,57]

Table 6-5. Environmental Health Benefits for On-Grid Centralized and On-Grid Distributed PV Systems, 2008

	On-Grid Centralized		On-Grid Distributed	
Health Effect	**Incidence**	**Cost (2008$)**	**Incidence**	**Cost (2008$)**
Mortality	0.01	$82,967	1.63	$10,875,424
Infant mortality	<.01[a]	$109	<.01	$25,638
Chronic bronchitis	0.01	$3,153	1.01	$466,212
Nonfatal heart attacks	0.02	$1,592	2.51	$285,379
Resp. hospital admissions	<.01	$5	0.39	$4,211
CDV hospital admissions	0.01	$59	0.81	$21,524
Acute bronchitis	0.02	$0	2.42	$484
Upper respiratory symptoms	0.19	$0	21.6	$229
Lower respiratory symptoms	0.26	$0	28.63	$168
Asthma ER visits	0.01	$0	2.14	$190
MRAD	10.57	$382	1,220.18	$75,679
Work loss days	1.79	$54	205.04	$15,583
Asthma exacerbations	0.25	—[b]	27.68	—
Total health effects		**$90,495**		**$11,788,589**

[a] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study. COBRA rounds the incidence to zero from a very small value, but because the cost of mortality is high, even a very small value produces some cost.

[b] COBRA does not produce a value for asthma costs.

[56] Because of the linear relationship between benefits and kilowatt-hour generation, the benefits estimated for 2008 have been scaled back to estimate previous years based on kilowatt-hour production in each year. Because detailed data were not available for all years, this estimate assumes a constant ratio of distributed to centralized on-grid PV for the years prior to 2008 and a constant ratio of on-grid to off-grid PV before 1992.

[57] Including benefits for 2009 to 2033, assuming a useful life of 25 years, increases total benefits before discounting by over $900 million. Thus, retrospective and future environmental benefits for the installed base as of 2008 are between $1.1 billion and $1.2 billion.

Table 6-6. Environmental Health Benefits for Off-Grid PV Systems, 2008

Health Effect	Incidence	Cost
Mortality	3.95	$26,335,489
Infant mortality	0.01[a]	$70,695
Chronic bronchitis	2.7	$1,255,503
Nonfatal heart attacks	6.19	$713,669
Resp. hospital admissions.	0.92	$11,938
CDV hospital admissions	1.91	$54,230
Acute bronchitis	6.79	$2,433
Upper respiratory symptoms	60.74	$1,407
Lower respiratory symptoms	80.57	$1,149
Asthma ER visits	3.25	$787
MRAD	3,332.22	$211,984
Work loss days	562.36	$46,314
Asthma exacerbations	77.75	—[b]
Total health effects		**$28,718,032**

[a] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study. COBRA does not produce a value for asthma costs.

[b] COBRA does not produce a value for asthma costs.

From 1976 to 2008, $39.8 million in environmental benefits can be attributed to DOE through gains in efficiency (Table 6-7).[58] Although total benefits were monetized using the COBRA model, specific attribution was unable to be resolved because of challenges associated with isolating technology effects from demand-side public policies. Thus, only a lower bound estimate of environmental health benefit is presented. The exclusion of environmental health benefits has no material impact on the measures of economic return. Environmental health benefits were not included in the measures of economic return.

[58] Including benefits projected for 2009 to 2033, approximately $246.5 million in environmental benefits can be attributed to DOE activities.

Table 6-7. Estimated Environmental Health Benefits of PV Attributable to DOE (2008$)

Year	Estimated Baseline Efficiency (%)	Estimated Counterfactual Efficiency (%)	Percentage Difference	Total Environmental Health Benefits ($ million)	Approximate Benefits Attributable to DOE ($ million)
1976	5.7	5.7	0%	0.1	0.0
1977	6.2	5.9	4%	0.1	0.0
1978	6.7	6.2	8%	0.2	0.0
1979	7.2	6.4	11%	0.3	0.0
1980	7.7	6.6	14%	0.5	0.1
1981	8.1	6.8	16%	0.7	0.1
1982	8.6	7.1	18%	0.9	0.2
1983	9.0	7.3	19%	1.1	0.2
1984	9.5	7.5	21%	1.3	0.3
1985	9.9	7.7	22%	1.6	0.4
1986	10.1	7.9	21%	1.8	0.4
1987	10.3	8.1	21%	1.9	0.4
1988	10.5	8.3	21%	1.9	0.4
1989	10.7	8.5	20%	2.0	0.4
1990	10.9	8.7	20%	2.0	0.4
1991	11.1	8.9	19%	2.1	0.4
1992	11.3	9.1	19%	2.5	0.5
1993	11.5	9.3	19%	2.9	0.5
1994	11.7	9.5	18%	3.3	0.6
1995	11.9	9.7	18%	3.8	0.7
1996	12.0	9.9	17%	4.5	0.8
1997	12.1	10.0	17%	5.2	0.9
1998	12.1	10.1	17%	6.0	1.0
1999	12.2	10.3	16%	7.0	1.1
2000	12.3	10.5	15%	8.3	1.2
2001	12.4	10.7	13%	9.7	1.3
2002	12.4	10.9	12%	11.7	1.4
2003	12.5	11.1	11%	14.2	1.6
2004	12.5	11.3	10%	18.1	1.8
2005	13.3	11.5	13%	21.7	2.9
2006	14.0	11.7	17%	26.2	4.3
2007	14.8	11.9	19%	32.7	6.3
2008	15.5	12.0	23%	40.6	9.2
Total				**237.2**	**39.8**

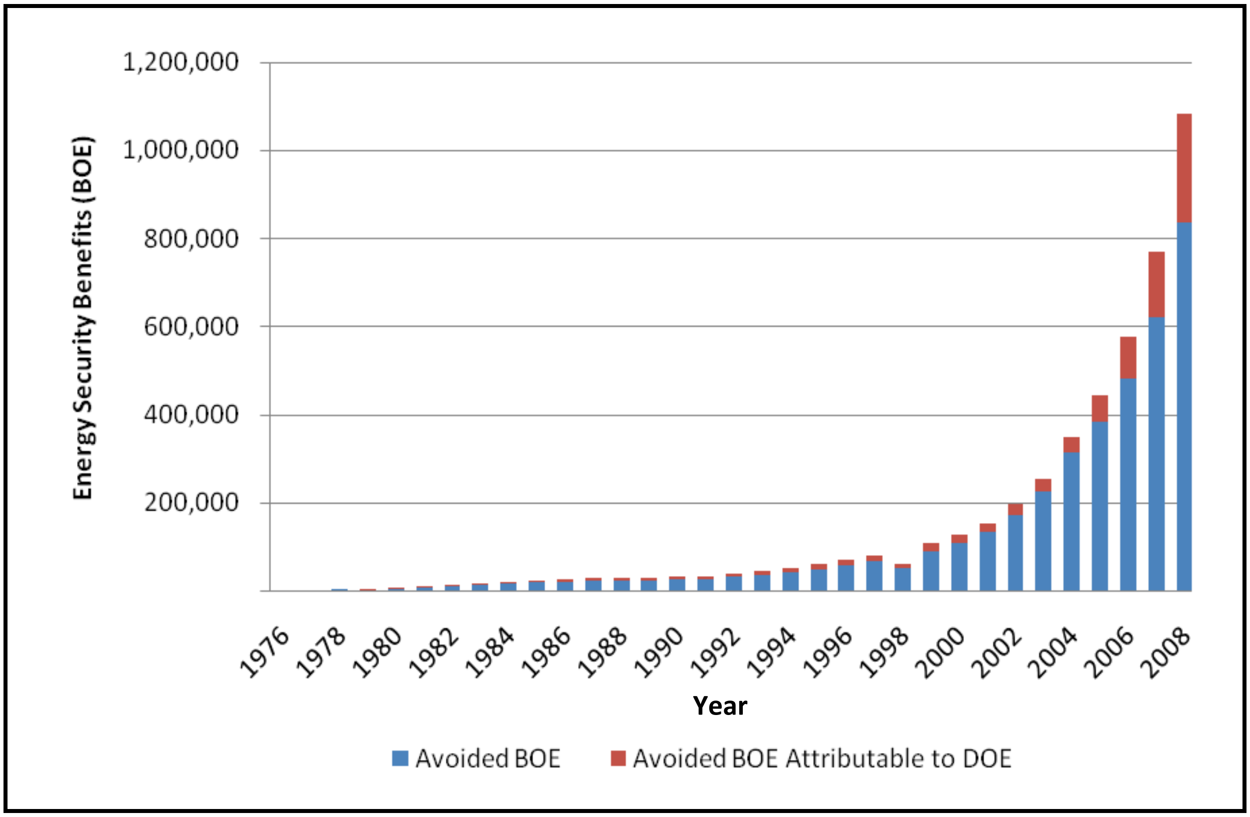
Source: Authors' calculations using COBRA.

6.3 Energy Security Benefits

Solar energy represents a secure domestic source of energy in the face of threats to energy supply and provides clean energy to avoid long-run security risks from GHG emissions and climate change. Although national security benefits are difficult to monetize, they represent an important advantage of renewable energy. Because of its distributed nature, PV holds additional energy security benefits. In the United States, 95% of PV is distributed throughout small-scale on- and off-grid applications, making it less vulnerable to threats to the power supply than central power infrastructure.

Energy security benefits are presented quantitatively in barrel of oil equivalents (BOE). A BOE represents the energy released by burning a barrel of oil, or 1,700 kWh. The majority of on-grid PV provides energy that would normally be supplied by natural gas peaking plants, although some distributed PV replaces energy from coal and petroleum. Off-grid PV replaces internal combustion engines. In 2008, PV energy produced over 1.8 billion kWh, or 1.1 million BOE. Between 1976 to 2008, PV replaced an estimated 4.8 million BOE, of which approximately 0.8 million can be attributed to DOE (Figure 6-3).[59]

Figure 6-3. Energy Security Benefits (BOE)



Source: Authors' calculations.

[59] Including benefits for 2009 to 2033, assuming a useful life of 25 years, increases security benefits by 24.9 million BOEs. Thus, retrospective and future benefits for the installed base as of 2008 are estimated at 29.7 million BOEs. An additional 5.7 million BOE can be attributed to DOE from the 2008 PV infrastructure extended out to 2033, amounting to a total of 6.5 million BOE in benefits

7. KNOWLEDGE LINKAGES AND BENEFITS[60]

This chapter presents an overview of DOE-funded or co-funded PV knowledge outputs as embodied in patents and publications, their dissemination, and evidence of their influence. The purpose of this knowledge benefit review is to identify and summarize DOE's contributions to the knowledge base in solar energy photovoltaics and notable PV technologies. Appendix E provides a summary of the methodology used for the featured patent and publication analyses.

Principal conclusions supported by the patent and publication citation analyses are that DOE-funded PV research has had a comparatively strong influence on the top U.S. PV producers, as well as the international companies that lead in solar energy patenting. The results also support the conclusion that DOE-funded PV research has had a strong influence on subsequent technology developments, extending beyond PV devices to semiconductor technologies in general.

The analysis identified a number of particularly influential DOE-attributed PV patent families. In particular, the analysis revealed the influence of early DOE-attributed patents related to a-Si and CIS devices on present-day commercialized technologies developed by leading companies. It showed DOE's influence on multiple generations of solar technology, from thin-film a-Si and CIS/CIGS devices to recent developments in nanoscale PV devices.

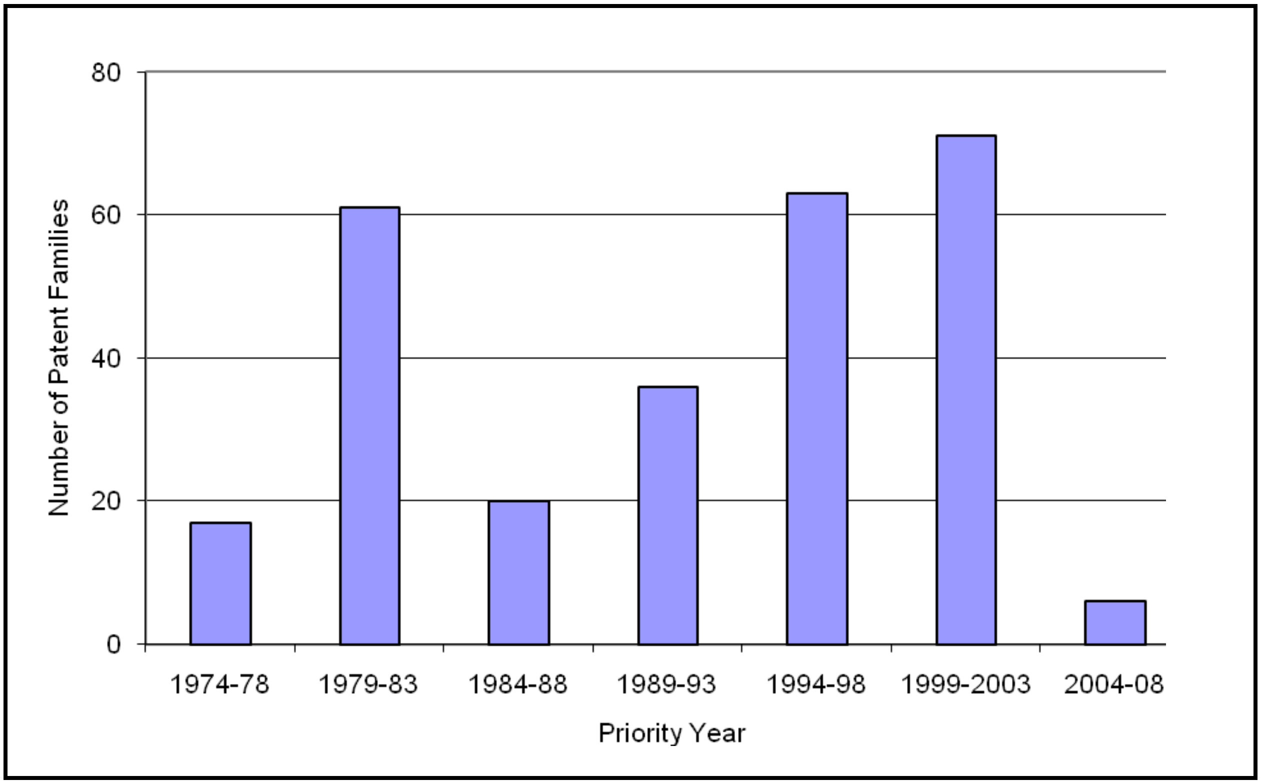
7.1 Trends in Knowledge Outputs Embodied in Patents

A patent family is the set of all patents and patent applications resulting from the same patented invention. The numbers of DOE-attributed PV patent families by 5-year periods, from 1974 through 2008, are shown in Figure 7-1. There are two distinct periods in which DOE-attributed patenting peaked, reflecting, at least in part, changing administrations and associated changing budgets for renewable energy. The first peak occurred between 1979 and 1983, a period during which approximately 60 DOE-attributed PV patent families originated. The second peak occurred from 1994 through 2003, when more than 130 originated. Thereafter, the number of DOE-attributed PV patent families declined significantly.

In total, an estimated 274 PV patent families are attributed to DOE-funded R&D during the period shown. These 274 families contain 343 U.S. patents, 75 European Patent Office (EPO) patents, and 113 patents filed with the World Intellectual Property Organization (WIPO). See Appendix E for information on how the patents were identified and patent families constructed.

[60] This chapter, prepared by Rosalie Ruegg and Patrick Thomas, is based on a larger historical tracing report also coauthored by Ruegg and Thomas (2010), entitled *Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power from Solar Energy*. For more details about the approach and findings, please consult Appendix E and the source report by Ruegg and Thomas from which this chapter is drawn.

Figure 7-1. Number of DOE-Attributed PV Patent Families by Priority Year



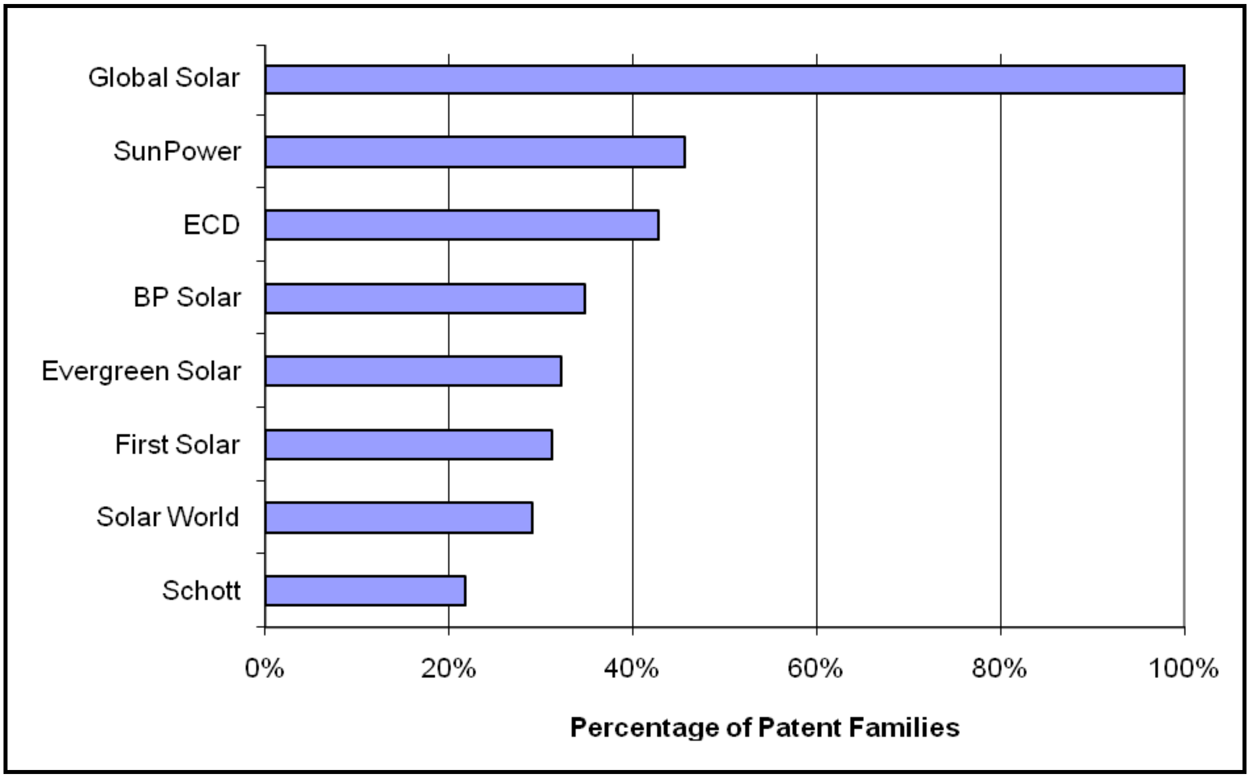
Note: The patent families are grouped by priority year (i.e., the year of the filing of the original patent within a patent family). See Appendix E for more on patent families.

Comparing DOE-attributed PV patents to the total of solar energy patents reveals that DOE-attributed PV patenting fell between 2004 and 2008, while total solar energy patents rose. The comparison also shows that the DOE-attributed PV patent portfolio comprises a small fraction of total patenting in solar energy. Between 1989 and 2003, the DOE-attributed PV patents comprised 3% to 4% of total solar energy patents, but only represented 0.2% since 2004. Despite DOE's small share of the total volume of patenting in this area, its influence on subsequent patenting efforts by both the top U.S. producers of PV and the leading companies in patenting of solar energy inventions worldwide appears substantial.

7.2 DOE-Attributed Knowledge Base Heavily Used by Companies in Solar Energy

The study used backward patent tracing (explained in Appendix E) in two ways to assess if, and the extent to which, the DOE-attributed PV patent set has provided a knowledge base upon which further innovations by the top U.S. PV producers and the leading international companies in solar energy patenting have built. Figure 7-2 shows the percentage of solar energy patent families of each of the top U.S. PV producers that are linked to earlier DOE-attributed PV patent families, a measure of the breadth of DOE's influence on these companies' technology. All of these companies have more than 20% of their solar energy patent families linked to earlier DOE-attributed PV patent families, three have more than 40%, and one (a small company with very few patents) has 100% of its patent families linked to the DOE set.

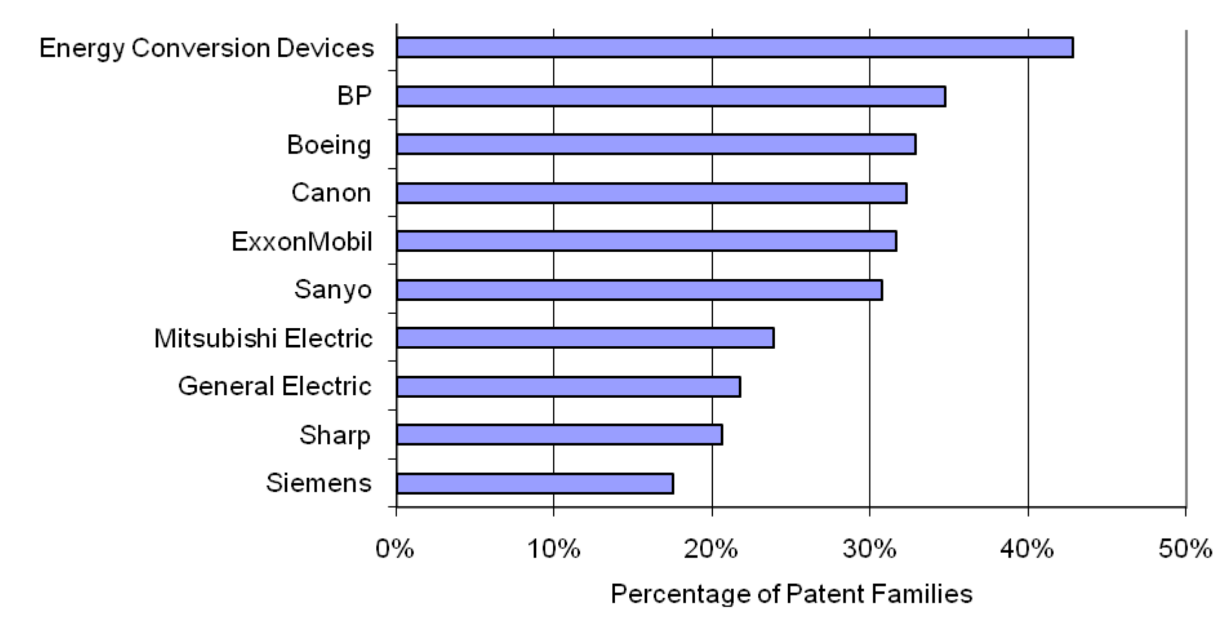
Figure 7-2. Top U.S. PV Producers by the Percentage of their Solar Energy Patent Families Linked to Earlier DOE-Attributed PV Patents



When the total number of links of the solar energy patents of each of these top U.S. PV producers back to the DOE-attributed patent set is considered, BP Solar has the most, followed by ECD and SunPower. When the average number of links to DOE per patent family is considered—a better measure of the depth of the influence—First Solar leads. First Solar has an average of over five links per solar patent family to earlier patents in the DOE set, followed closely by BP Solar, SunPower, and Schott, in that order. These findings suggest that much of U.S. companies' PV technologies are closely linked to DOE-funded research.

Next, Figure 7-3 shows the extent to which the leading companies worldwide in solar energy patenting have built on the knowledge base. It shows that 9 of the 10 leading companies in solar energy patenting have at least 20% of these linked to earlier DOE-attributed PV patent families. Six have more than 30%. ECD has more than 40% of its patent families linked to the earlier DOE set. Two companies, ECD and BP Solar, have sufficient patents and production of PV to put them on the lists in both Figures 7-2 and 7-3. Figure 7-3 suggests that DOE-funded PV research has influenced the development of solar energy technologies and companies more broadly than indicated by Figure 7-1.

Figure 7-3. Leading Companies in Solar Energy Patenting by the Percentage of their Solar Energy Patent Families Linked to Earlier DOE-Attributed PV Patents



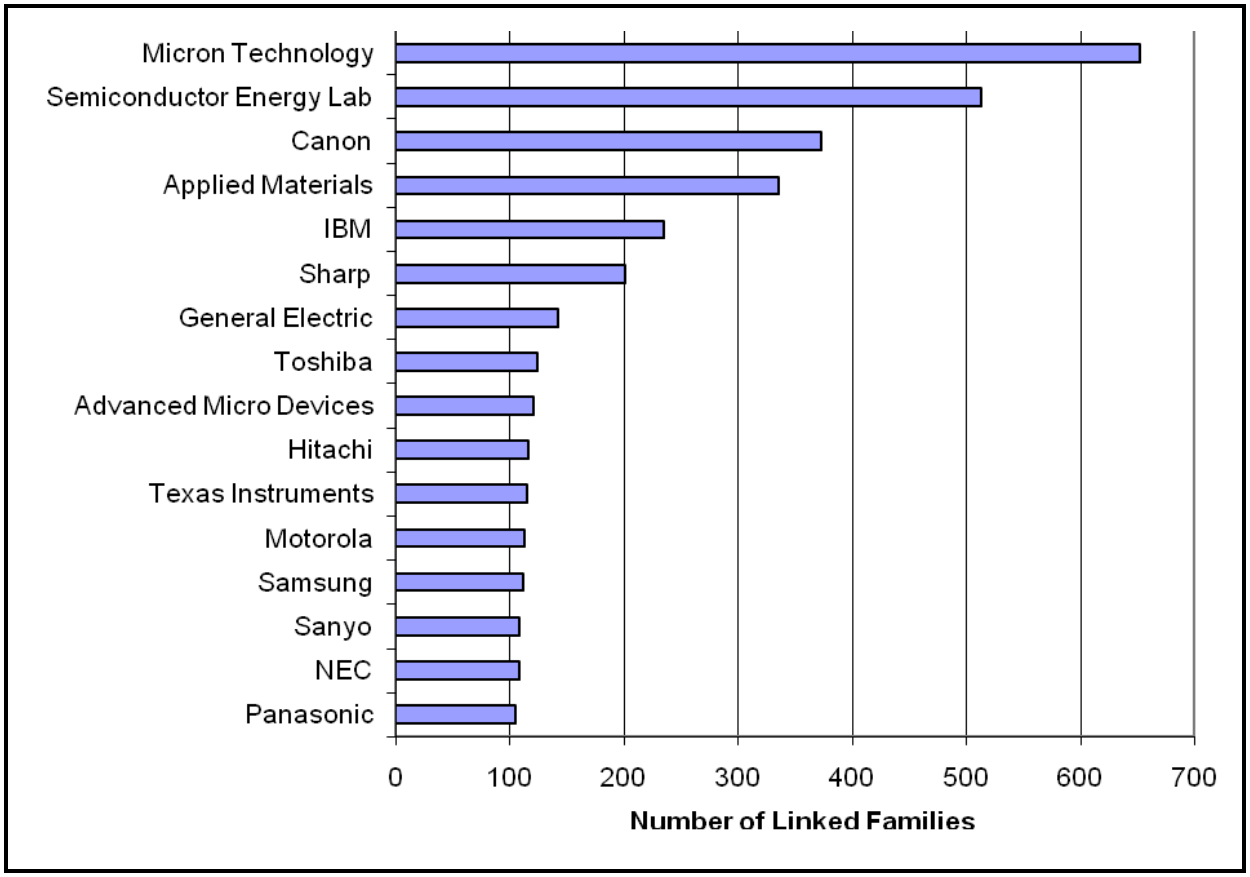
Note that some companies may not be major PV manufacturers, yet they have built formidable solar energy patent portfolios over time. Canon, for example, does not appear to be presently active in solar energy, but its solar energy patent portfolio covers a range of technologies including solar energy cells, modules, and roofing panels.

Comparing the influence of DOE-attributed PV research with the influence of research carried out by each of the leading companies (not shown) also found DOE to be ranked at the top, tied with two companies, ECD and BP Solar. Each had more than 500 of the total 1,812 solar patent families of the leading companies linked back to their earlier solar energy patents. But it should be noted, as shown in Figure 7-3, that the patent families of ECD and BP Solar are linked to earlier DOE-attributed PV patent families. Thus, in comparison with other organizations, DOE was found to be prominent in that it has formed part of the foundation for subsequent R&D outcomes by leading companies, despite having a small fraction of the total solar energy patent portfolio.

7.3 Strong Linkage from DOE-Attributed PV Patent Families to Developments in Semiconductor Technology beyond PV Devices

The forward patent tracing element of the study (explained in Appendix E) identified organizations from all industry sectors that had the largest number of their patent families linked to the earlier DOE-attributed PV families (Figure 7-4). This figure is dominated by companies with strong links to the semiconductor industry, notably Micron, Semiconductor Energy Lab, Applied Materials, and IBM, indicating that DOE-funded PV research has had an influence on subsequent developments in semiconductor technology beyond PV devices.

Figure 7-4. Organizations from All Industry Sectors with the Largest Number of Patent Families Linked to Earlier DOE-Attributed PV Patents



Additional evidence of the influence of the DOE-attributed PV patent families beyond solar energy to semiconductor technology more generally was acquired by identifying the International Patent Classifications (IPCs) with the largest number of patent families that cite DOE-attributed PV patents. The results are dominated by the IPC pertaining to semiconductor devices. Within this IPC, there is a specific subclass (H01L 31) directed to light-sensitive semiconductor devices, including PV cells.

To examine the influence of DOE-funded PV research on subsequent patents concerned with PV cells (those patents in H01L 31) versus non-PV semiconductor devices, the patents in IPC H01L were divided into two groups: those in H01L 31 and those in other subclasses of IPC H01L.

These results show that DOE-funded PV research is linked to subsequent developments both in PV research and in semiconductor technology more generally. In addition, the analysis found linkages to IPCs related to coating methods (C23C), measuring and testing (G01R and G01N), and crystal growth (C30B), among others, but the numbers of patents in these IPCs are small compared to the numbers in H01L31 and other H01L.

When a second generation of forward citation links was added to the IPC analysis, the number of links to the other semiconductor patents (H01L other) increased markedly relative to the number of links to light-sensitive devices (H01L31). This finding suggests that, over time, the influence of DOE PV research has spread extensively to the broader semiconductor device industry.

7.4 Notable Individual Patent Families

Whereas the prior results focused at the organizational level, the focus now shifts to results at the individual patent level. Notable DOE PV patents are those that are heavily cited by later patents or are linked to highly cited patents of other organizations.

7.4.1 DOE-Attributed PV Patent Families Linked to the Largest Number of Solar Energy Patent Families of Leading Companies

Identified by backward tracing, the DOE-attributed patent family linked to the most patent families of leading companies describes a solar cell constructed from multiple layers of a-Si (represented by anchor patent[61] U.S. #4,272,641) and resulting from DOE-funded research at GE. Other GE-assigned patent families resulting from DOE-funded research and cited by large numbers of subsequent solar energy patent families include the following:

- One describing processing techniques for producing a-SI cells (anchor patent U.S. #4,292,092),
- Another describing Schottky barriers for the cells (anchor patent U.S. #4,167,015), and
- Another describing the connection of such cells to produce solar batteries (anchor patent U.S. #4,316,049).

These represent older foundational technologies that have extensive links to subsequent developments made by leading companies in the solar energy industry.

Backward tracing also identified a series of DOE-attributed patent families in thin films resulting from DOE-funded research at the University of Delaware that are linked to a large number of subsequent patents of the leading companies. These include a patent describing a method for increasing the light absorption of thin-film solar cells while reducing the roughness of the electrical junction, which is designed to make the cell less susceptible to adverse environmental conditions (anchor patent U.S. #4,328,390). Backward tracing also identified multiple patents describing large-area, thin-film solar cells formed from chalcopyrite compounds such as copper indium diselenide (CIS) and resulting from DOE-funded research at Boeing. These latter two patents, U.S. #4,335,266 and U.S. #5,078,804, are linked to a large number of patent families of the leading companies.

[61] Each patent family in Figure 7-4 is represented by a single anchor patent (i.e., a single patent from the family that is generally the first patent issued and the priority filing, unless the priority filing were outside the U.S. Patent Office, the EPO, or the WPTO, such as a Japanese application).

7.4.2 High-Impact DOE-Attributed PV Patents—Taking into Account All Application Areas and All Citing Organizations

High-impact patents are defined as those cited by large numbers of subsequent patents, as measured by Citation Index (CI) values.[62] Forward tracing produced the results presented in Table 7-1, which lists the DOE-attributed PV patents that have the highest CI values. Among these are a number of recent patents. In fact, the patent with the highest CI value (U.S. #6,996,147) is a University of California (Lawrence Berkeley National Laboratory) patent issued in 2006 describing nanowires useful in a variety of energy conversion applications. This patent has already been cited 27 times more than expected, such that it appears to have had a particularly strong immediate impact on subsequent technological developments. Other recent highly cited patents include two patents assigned to North Carolina State University (U.S. #6,420,648 and U.S. #6,603,070) describing light harvesting rods for regenerative solar cells, as well as a Powerlight (now SunPower) patent (U.S. #6,534,703) describing a PV module assembly and mounting apparatus that allows for easier shipping and installation.

Among the older of the most highly cited patents are two patents filed in the late 1980s by Energy Conversion Devices. These patents (U.S. #4,775,425 and U.S. #4,891,330) describe thin-film PV devices incorporating band gap widening elements. These wider gaps increase the transparency of the layers of the PV device, allowing more light to enter, thereby increasing the efficiency of the device. The ‘425 patent has been cited by 137 subsequent patents, while the ‘330 patent has been cited by 173 subsequent patents—many more citations than expected for patents of this age and technology. This result suggests that the DOE-funded research that supported these patents has had a particularly strong impact on subsequent developments in photovoltaics.

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[62] The CI is a normalized measure derived by dividing the number of citations received by a patent by the mean number of citations received by peer patents from the same issue year and technology. For example, a CI of 10 means that the patent has been cited 10 times as frequently as expected, given its age and technology; a CI of 1 means it has been cited as frequently as expected. CI values are based on a single generation of citations.

Table 7-1. High-Impact DOE-Attributed PV Patent Families (Based on Citation Indices)

Patent	Issue Date	Number of Citations Received	Citation Index	Assignee	Title
6996147	2006	19	27.04	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated there from
4775425	1988	137	11.13	Energy Conversion Devices	P and n-type microcrystalline semiconductor alloy material including band gap widening elements, devices using same
4891330	1990	173	6.48	Energy Conversion Devices	Method of fabricating n-type and p-type microcrystalline semiconductor alloy material including band gap widening elements
4287473	1981	76	6.23	U.S. Dept. of Energy	Nondestructive method for detecting defects in photodetector and solar cell devices
5588995	1996	63	5.79	Midwest Research Institute	System for monitoring the growth of crystalline films on stationary substrates
4253882	1981	43	4.38	University of Delaware	Multiple gap photovoltaic device
4379020	1983	80	3.78	Massachusetts Institute of Technology	Polycrystalline semiconductor processing
5747967	1998	44	3.70	Midwest Research Institute	Apparatus and method for maximizing power delivered by a photovoltaic array
4272641	1981	34	3.46	General Electric	Tandem junction amorphous silicon solar cells
4292092	1981	67	3.44	General Electric	Laser processing technique for fabricating series connected and tandem junction series connected solar cells into a solar battery
4335266	1982	34	3.36	Boeing	Methods for forming thin film heterojunction solar cells from I-III-VI/2\chalcopyrite compounds, and solar cells produced thereby
6420648	2002	23	3.26	North Carolina State University	Light harvesting arrays
6268014	2001	18	3.22	Unassigned	Method for forming solar cell materials from particulars
6534703	2003	12	3.12	SunPower Corp	Multiposition PV assembly
6603070	2003	14	3.06	North Carolina State University	Convergent synthesis of multiporphyrin light-harvesting rods
4392451	1983	30	3.01	Boeing	Apparatus for forming thin film heterojunction solar cells employing materials selected from the class of I-III-VI/2\chalcopyrite compounds

To better pick up the diffusion of the DOE-attributed PV patents into other application areas, highly cited patents were examined, taking into account two generations of citations. To adjust (approximately) for time—since time is positively correlated with the number of citations and the CI is not used when there are multiple generations of citations—the patent families in the DOE-attributed set were divided into pre- and post-1990 groups. Further, the citing patents were divided into two groups: solar energy patent families that cite the DOE-attributed PV patents and all other patent families that cite the DOE-attributed PV patent families. Separating these linked patent families into two groups made it possible to determine which DOE patents have had a strong impact within solar technology and which have had a broader impact beyond.

Examples from the older group of DOE-attributed PV patents with a strong impact on subsequent generations of solar energy technology include those assigned to GE, Boeing, and the University of Delaware. These were already highlighted in the backward tracing analysis. An example from the older group of DOE-attributed PV patent families that has had a strong impact *beyond* solar technology is MIT's polycrystalline semiconductor processing patent family (U.S. #4,379,020 anchor). Of a total of 637 citations, 618 were by non-solar energy patents. Other examples of DOE-attributed PV patents with a strong impact beyond solar technology are Advanced Energy Fund’s metal organic chemical vapor deposition on silicon patent (U.S. #4,588,451), with 533 of 535 total citations by non-solar energy patents, and Energy Conversion Devices’ microcrystalline semiconductor alloy material patent (U.S. #4,775,425), with 451 of 474 total citations by non-solar energy patents. A great deal of the influence of these patent families is found in broader semiconductor applications.

Among the younger group of highly cited DOE-attributed PV patent families whose influence is mainly in solar energy are a series of patents describing CIGS devices. These CIGS patent families are assigned to a number of different organizations, including Midwest Research Institute/NREL (U.S. #5,356,839 anchor), Boeing (U.S. #5,078,804 and U.S. #5,141,564 anchors), and International Solar Electric Technology (U.S. #5,028,274 anchor). This suggests that DOE has funded technology related to CIGS devices in a number of different organizations, which has had a significant impact on subsequent developments in solar energy.

The younger group of highly cited DOE-attributed PV patent families also includes some that are linked to large numbers of subsequent patents from outside solar and PV technology. Four highly cited PV patent families assigned to Midwest Research Institute/NREL have had their major influence in non-solar energy applications. For example, the patent family (U.S. #5,304,509 anchor) describing a method for hydrogenation of silicon substrates to reduce defects is linked to 436 subsequent total patent families, all but three of which are mainly concerned with semiconductor fabrication techniques. Other highly cited NREL patents that are focused on the growth of thin films are also linked to large numbers of subsequent semiconductor patents. Furthermore, the highly cited LBNL nanowire patent family discussed earlier (U.S. #6,996,147 anchor) appears to be a high-impact patent family within the very active and rapidly developing nanotechnology industry.

7.4.3 High-Impact Patents of Other Organizations Linked to Earlier DOE-Attributed PV Patent Families

A few examples are given here of high-impact patents of the top U.S. PV producers, of the leading companies in patenting solar energy, and of others patenting in and outside the field of solar energy that are all linked back to the DOE PV set.

High-impact patents of the top U.S. PV producers that are linked to earlier DOE-attributed PV patent families include

- ECD patents describing the fabrication of thin-film solar cells (U.S. #4,419,533),
- SunPower patents for series-connected solar cells (U.S. #5,164,019) and PV assemblies (U.S. #6,534,703),
- BP patents detailing PV framing systems (U.S. #6,111,189) and thin-film solar cells (U.S. #4,915,745), and
- an Evergreen Solar patent (U.S. #6,353,042) describing a UV stabilizer for a solar cell.

High-impact patents of the leading companies in patenting of solar energy that are linked to the DOE set include

- a Canon patent (U.S. #6,682,990) describing a solar cell fabrication method that helps reduce damage to the substrate, which cites an earlier DOE-attributed Midwest Research Institute/NREL patent (U.S. #5,544,616) as prior art;
- another high-impact patent linked to the DOE set is Sharp's patent (U.S. #6,242,686) describing a pin junction photovoltaic device, which links back to an earlier DOE-attributed patent (U.S. #4,718,947), assigned to BP Solar (Solarex); and
- ECD's four high-impact patents that are linked to the DOE set. Three of these ECD patents are older, describing the fabrication of thin-film solar cells (e.g., U.S. #4,419,533 issued in 1983). The fourth patent issued in 2004 (U.S. #6,729,081) describes a self-adhesive PV module and appears to be closely related to ECD's UNI-SOLAR rooftop solar module products. The '081 patent is linked to a number of earlier DOE-attributed PV patent families, suggesting that DOE-funded research has helped form an important part of the foundation for this recent high-impact technology.

There are also high-impact patents in solar energy linked to earlier DOE-attributed PV patent families and owned by a wide range of organizations other than those identified previously. Among these other organizations are large corporations (e.g., Raytheon and NEC), smaller specialist solar energy companies (e.g., Nanosys), and universities (e.g., Princeton, Columbia, and École Polytechnique Fédérale de Lausanne (EPFL). In addition, several high-impact solar energy patents linked back to the DOE set are unassigned.[63] DOE's influence can be seen in developments in thin-film technology (e.g., U.S. #6,706,963 assigned to Konarka, and U.S. #6,340,788 assigned to Raytheon); in methods for connecting thin-film PV devices (e.g., U.S. #6,069,313 assigned to EPFL); in recent highly cited patents describing PV devices

[63] On a patent, there is a section for the inventor(s), and a section for the assignee. If the assignee section is left blank, the patent is "unassigned," and the patent rights revert to the inventor(s). Thus, unassigned patents are typically held by individual inventors, unless they have transferred their rights privately to someone else.

based on nanoscale compositions (e.g., U.S. #6,878,871 assigned to Nanosys, and U.S. #6,946,597 assigned to NanoSolar). These findings suggest that DOE research has had a broad impact on important developments in the solar energy industry beyond top U.S. PV producers or leading companies in solar energy patenting.

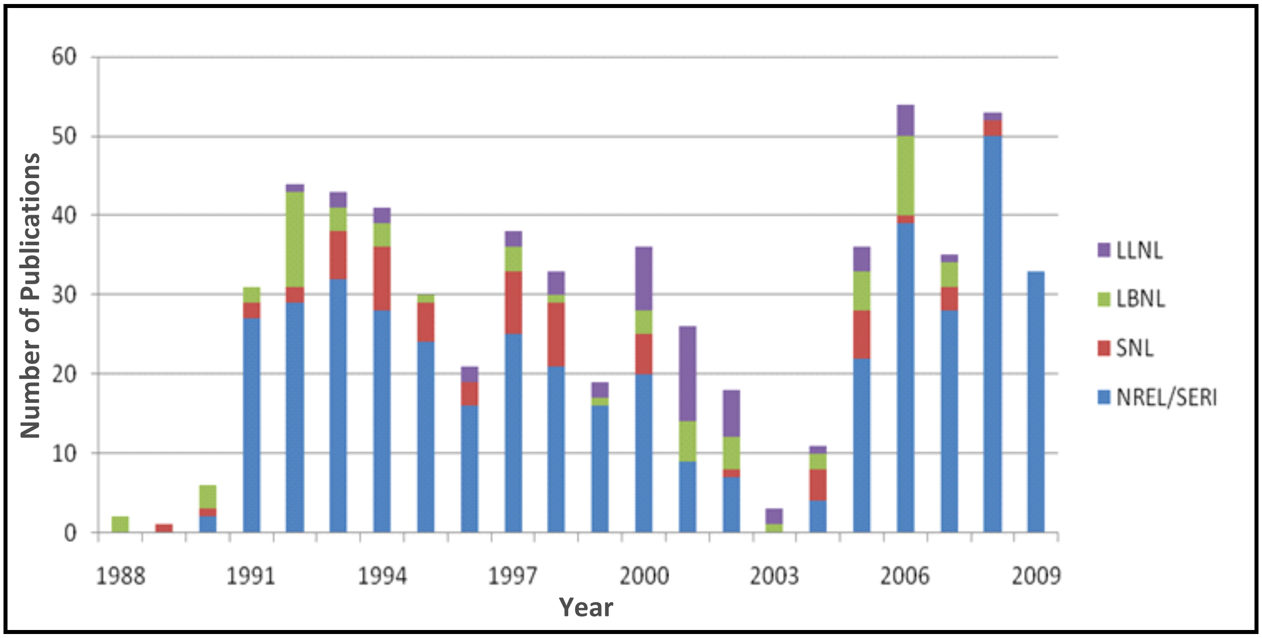
Finally, some high-impact patents outside solar and PV technology are linked to the earlier DOE-attributed PV patents. Most of these patents describe semiconductor manufacturing techniques, notably deposition of thin films (e.g., U.S. #6,342,277 assigned to ASM International, U.S. #6,176,992 assigned to Nutool, and U.S. #5,000,113 assigned to Applied Materials). Some of these patents describe technologies unrelated to semiconductors, such as organic LEDs (U.S. #5,707,745 assigned to University of Princeton) and image sensors (U.S. #6,407,381 assigned to Amkor). However, the main focus of the highly cited non-solar energy patents that trace back to DOE is on semiconductor device fabrication. This finding reinforces the conclusion that the main impact of DOE solar PV research beyond solar energy technology has been on technology outcomes in the semiconductor industry.

7.5 Publication Analysis

Publications present an alternative form of DOE-funded or co-funded PV knowledge output. A search of the DOE Office of Scientific and Technical Information (OSTI) database for all PV publications sponsored by DOE extending back to 1988 yielded a total of 924.[64] A year-by-year distribution of the output of DOE PV publications by the leading DOE publishers (i.e., NREL/SERI, SNL, SBNL, and LLNL) is shown in Figure 7-5. There are two notable peaks: the first in the early 1990s and the second after 2004. From the body of NREL/SERI publications, which represents the largest group of these DOE PV publications, random samples were drawn from technical reports (74% of the NREL/SERI publications) and conference papers (25%), the remainder comprising booklets, journal articles, theses, and miscellaneous. The random samples were used to analyze publication coauthoring and citing.

[64] The search of DOE's OSTI database was made for all fields containing "solar PV" or "solar photovoltaic" or "thin film" or "PVMaT." The result is highly likely an undercount, because not all DOE laboratory publications appear to be entered into the OSTI database, and some PV publications may not have contained any of these keywords. The OSTI database was used because it is reportedly the best central source of DOE publication data across DOE units. PV publications of organizations outside DOE were not included unless they had been entered in the OSTI database as DOE sponsored. Thus, early JPL/NASA publications in photovoltaics without DOE publication notation are not included.

Figure 7-5. DOE PV Publications for Selected Organizations, by Year and by Organization, 1976–2009



Note: Data for 2009 are incomplete.

For the technical reports, company authoring was prominent, with 52% of the sample authored by DOE-funded company researchers. Company affiliations of authors include Solarex, Utility Power Group, Ascension Technology, Trace Engineering, Mobil Solar Energy, Solar Design Associates, Springborn Laboratories, ECD, Navigant Consulting, GE Global Research, Siemens Solar Industries, Spire, ASE Americas, Advanced Energy Systems, Dow Corning, BP Solar, Navigant Consulting, Solarex, Photovoltaics International, AstroPower, and others.

The citation analysis showed that approximately 10% of the technical reports were cited more than five times. The organizational affiliation of those citing the technical reports the most were government organizations (55%). Affiliations also included universities (21%), companies (6%), and other organizations, particularly a number of foreign national laboratories, demonstrating interest in the research by counterpart institutions abroad. An example of one of the more heavily cited technical reports in the sample is Optimal Building-integrated Photovoltaic Applications, NREL/TP-472-20339, by Kiss and Company Architects, published in 1995.

The citation analysis of the sample of conference papers revealed that about 25% of them had been cited more than five times. Organizational affiliations of those citing the NREL conference papers are more heavily represented by companies than those citing the NREL technical reports. Citing companies include Tucson Electric Power Company, IBM, GM, Spectolab, Emcore Photovoltaics, Exxon, Solar Consulting Services, and Solexant, among others. The presence of citing companies outside the solar industry, such as IBM and GM, reinforces the findings of the patent analysis that interest in DOE's PV research crosses into other industry areas. An example of a heavily cited NREL conference paper from the sample is

Lattice-Mismatched Approaches for High-Performance III-V Photovoltaic Energy Converters, NREL/CP-520-37440, by M. W. Wanlass et al., published in 2005.

8. SUMMARY RESULTS AND CONCLUDING REMARKS

This study quantified economic benefits of gains in reliability and reductions in cost attributable to DOE from its long-term financial and technical support for PV module technology R&D. Our findings lead us to concur with, and provide measures of economic and other benefits to substantiate, findings in technical reports and policy studies that have concluded that DOE has had a significant impact on the state of PV module technology.

Lower bound measures of economic return were calculated for DOE's investment in Photovoltaic Energy Systems by comparing quantified benefits accruing from a subset of funded technologies developed by private-sector, university, and DOE researchers under FSA, PVMaT, and TFP. Between 1975 and 2008, DOE invested $3,710 million (2008$) in Photovoltaic Energy Systems (Table 8-1). The total economic benefit accruing from this investment was $18,735 million, corresponding to a return on DOE's investment of 17% over the 33-year period. Applying a discount rate of 7% yields a BCR of 1.83, indicating that for every $1 invested, $1.83 in benefits accrued. Applying a 3% social discount increases the BCR to 3.24.

In addition to these economic benefits, other measures of benefit through 2008 were estimated:

- $237.2 million in environmental health benefits from avoided adverse health incidences, with approximately $39.8 million of these benefits attributable to DOE.[65]
- 6.8 million tons of avoided CO_2 emissions, with approximately 1.1 million tons of avoided emissions attributable to DOE
- 4.8 million BOE in energy security benefits, with approximately 0.8 million of these attributable to DOE
- Knowledge benefits linking critical PV technology patents and publications at major U.S. and international PV companies to DOE-funded or cost-shared R&D activities.

In addition to these quantitative measures, interviews with industry, academic, and public-sector scientists and business leaders revealed that FSA, PVMaT, and TFP were critical to the development of PV companies. Experts concluded that without these programs not only would the state of photovoltaics be significantly poorer, but many U.S. companies, which employ thousands of people, would not exist.

[65]Most PV in the United States is installed in California, and environmental health and GHG emissions were compared with the likely next best alternative energy portfolio. For California, this portfolio would likely consist of natural gas and other renewable energy sources. However, as electricity generation from PV installations in markets characterized by comparatively high coal combustion increases, such as in North Carolina and New Jersey, environmental benefits and avoided GHG emissions per kilowatt-hour would exceed those for California. Environmental health benefits were not included in the measures of economic return.

Table 8-1. Summary Cost-Benefit Analysis Results, 1975–2008

	Quantified Benefit	Minimum Attribution to DOE	Unit of Measure
Economic Benefits			
Net economic benefits	$15,024.9	$15,024.9	Million, 2008$
Public rate of return		17%	
Net present value at 7% [Base year = 1975]		$1,458.9	Million, 2008$
Net present value at 3% [Base year = 1975]		$5,724.7	Million, 2008$
Benefit-to-cost ratio at 7%		1.83	
Benefit-to-cost ratio at 3%		3.24	
Environmental Health Benefits			
Monetized via COBRA	$237.23	$39.80	Million, 2008$
Avoided mortality[a]	32.65	5.48	Deaths
Avoided infant mortality[a]	0.07	0.01	Deaths
Avoided chronic bronchitis	21.98	3.69	Cases
Avoided nonfatal heart attacks	51.03	8.57	Attacks
Avoided resp. hospital admissions.	7.63	1.28	Admissions
Avoided CDV hospital admissions	15.88	2.67	Admissions
Avoided acute bronchitis	54.87	9.20	Cases
Avoided upper respiratory symptoms	490.69	82.29	Episodes
Avoided lower respiratory symptoms	650.84	109.15	Episodes
Avoided asthma ER visits	29.52	4.99	Visits
Avoided MRAD	27,036.52	4,535.47	Incidences
Avoided work loss days	685.87	123.00	Days
Greenhouse Gas Emissions Benefits			
Avoided carbon dioxide emissions (CO_2)	6,815,103	1,062,473	Tons
Avoided methane emissions (CH_4)	132	21	Tons
Avoided nitrous oxide emissions (N_2O)	583	90	Tons
Avoided particulate matter emissions (PM)	1,232	207	Tons
Avoided sulfur dioxide emissions (SO_2)	2,634	463	Tons
Avoided ammonia emissions (NH_3)	16	3	Tons
Avoided volatile organic compounds emissions (VOCs)	1,090	181	Tons
Energy Security Benefits			
Equivalent avoided petroleum consumption	4,790,478	827,189	Barrels of oil equivalent
Knowledge Benefits			
DOE-attributed patent families in photovoltaics		274	Patent families
DOE publications in photovoltaics		900	Publications
Percentage of leading U.S. PV company patents linked to DOE		30%	

[a] Researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

The PV industry has experienced phenomenal growth within the past few years, and U.S companies have fared well in the global market. Experts in the PV industry believes that JPL and NREL identified technical approaches worth supporting many years before venture capital companies did and noted that even today financiers rely on NREL's independent assessments when making investment decisions.[66]

The influence of DOE and the companies receiving cost shares is reflected in the scientific literature—factory automation for scale, encapsulants, thin-film PV, differential processing of ingots, measurement and characterization—all this research was enabled by DOE, which in turn reduced the LCOE, and in so doing supported demand-side policies in fueling the accumulation of installed clean, PV energy systems.

[66] Receipt of NREL funding via TFP and PVMaT is viewed as a stamp of approval that the technical focus of a company is worth funding, particularly because it was a competitive procurement. The fact that NREL was willing to invest in a technology gave investors confidence that investing in the company was worthwhile. NREL performed technology diligence with a rigor of which private investors were not capable; financiers look to NREL experts for validation of a start-up's approach and for confirmation of technical claims. NREL also provided stability for programs as they sought to launch technologies that were in the nation's interest.

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APPENDIX A:

FSA CONTRACTORS

Table A-1. FSA Contractors and Research Areas

Contractor	Device Research	Module Performance & Failure Analysis	Process Development	Project Analysis and Integration	Reliability and Engineering Science	Advanced Silicon Sheet	Silicon Materials
Aerochem Research Laboratories, Inc.							●
AIA Research Corp.					●		
Applied Solar Energy Corp.	●	●	●		●		
Arco Solar Inc.		●	●		●		●
Arizona State University							●
Astrosystems, Inc.						●	
Battelle Memorial Institute						●	●
Bechtel National, Inc.				●	●		
Bernd Ross Associates			●				
Burt Hill Kosar Rittelmann Associates					●		
C.T. Sah Associates	●						●
California Institute of Technology	●						●
Carnegie Mellon University					●		
Case Western Reserve University	●						
Chronar Corp.					●		
Clemson University					●		
Coors Porcelain Co.							●
Cornell University			●				●
Crystal Systems, Inc.						●	●
Dow Corning Corp.			●				●
Eagle-Picher Industries, Inc.						●	
Electrik, Inc.			●				
Endurex Corp.			●				
Energy Materials Corp.						●	●
General Electric Co.		●	●		●	●	
Gnostic Concepts, Inc.				●			
Hemlock Semiconductor Corp.							●
Honeywell, Inc.						●	
IBM Corp.						●	
IIT Research Institute					●		

Table A-1. FSA Contractors and Research Areas (continued)

Contractor	Device Research	Module Performance & Failure Analysis	Process Development	Project Analysis and Integration	Reliability and Engineering Science	Advanced Silicon Sheet	Silicon Materials
Illinois Toolworks, Inc.			●				
J.C. Schumacher Co.							●
Kayex Corp.							●
Kinetic Coatings, Inc.			●				
Kulicke & Soffa Industries			●				
Lamar University							●
Lockheed Missiles & Space Co.			●		●		
MZ International, Inc.		●					
Massachusetts Institute of Technology						●	●
Materials Research, Inc.	●						●
Mitre Corp.			●				
Mobil Solar Energy Corp.		●	●		●	●	
Monsanto Research Corp.							●
Motorola, Inc.	●	●	●		●	●	●
Nat'l Research for Geosciences Labs, Inc.					●		
North Carolina AT&T Foundation, Inc.	●						
North Carolina State University							●
Northrop Corp.							●
Oregon State University						●	
P.R. Hoffman (Norlin Industries)						●	
Pennsylvania State University	●						
Photowatt International, Inc.		●	●		●		
Polytechnic Institute of New York–Albany					●		
Purdue Research Foundation			●			●	
RCA Corp.		●	●			●	●
Research Triangle Institute	●						
Rockwell International Corp.			●		●	●	
Scanning Electron Analysis Laboratory			●				
Science Applications, Inc.			●				
Silicon Technology Corp.						●	
Siltec Corp.						●	
Solar Energy Research Institute						●	
Solar Power Corp.		●					

(continued)

Table A-1. FSA Contractors and Research Areas (continued)

Contractor	Device Research	Module Performance & Failure Analysis	Process Development	Project Analysis and Integration	Reliability and Engineering Science	Advanced Silicon Sheet	Silicon Materials
Solar Technology International			●				
Solarelectronics, Inc.							●
Solarex Corp.		●	●		●		●
Solavolt International					●		
Solec International			●				
Solenergy Corp.					●		
Sollos, Inc.			●				
Spectrolab, Inc.		●	●		●		●
Spire Corporation		●	●		●	●	
Springborn Labs, Inc.					●		
SRI International							●
Stanford University	●					●	
State University of New York—Albany							●
Superwave Technology, Inc.							●
Texas Instruments, Inc.			●			●	●
Texas Research & Engineering Institute							●
Aerospace Corp.					●		
Boeing Co.			●				
Theodore Barry & Associates			●				
Tracor MB Associates			●			●	
Tylan Corp.					●		
Underwriters Labs, Inc.					●		●
Union Carbide Corp.							●
University of California at Los Angeles	●					●	
University of California at Santa Barbara	●						
University of California at Santa Cruz						●	
University of Florida	●						
University of Illinois						●	
University of Kentucky			●				
University of Massachusetts			●				
University of Missouri						●	
University of Pennsylvania	●		●			●	

(continued)

Table A-1. FSA Contractors and Research Areas (continued)

Contractor	Device Research	Module Performance & Failure Analysis	Process Development	Project Analysis and Integration	Reliability and Engineering Science	Advanced Silicon Sheet	Silicon Materials
University of South Carolina						●	
University of Southern California	●		●			●	
University of Toronto					●		
University of Washington	●						
Varian Associates						●	
Washington University at Saint Louis							●
Westinghouse Electric Corp.	●		●		●	●	●
Wilkes College					●		
Wyle Laboratories					●		
Xerox Corp.			●				

APPENDIX B:

TECHNOLOGY DEVELOPED UNDER PVMAT, BY COMPANY

This appendix discusses nine major U.S. PV companies that received support from PVMaT.

Table B-1. PVMaT Subcontractor Funding by Phase (Excluding Phase 1)[a]

Current Co. Name	Company	Phase	NREL/DOE Cost Share	Company Cost Share	Total
Advanced Energy Systems, Inc.	AES*	Phase 4A1	$940,023	$294,563	$1,234,586
BP Solar International, LLC	Solarex	Phase 2A	$4,996,522	$4,996,522	$9,993,044
		Phase 2B	$3,177,822	$3,177,822	$6,355,644
		Phase 5A2	$2,988,807	$3,049,887	$6,038,694
	BP Solar	Phase IDIP-2	$2,969,471	$4,100,699	$7,070,170
		Phase YDR-2	$3,000,000	$2,903,752	$5,903,752
Crystal Systems, Inc.	Crystal Systems	Phase 5A1	$1,000,000	$411,378	$1,411,378
Dow Corning Corporation	Dow Corning Corp	Phase YDR-2	$2,453,426	$2,459,403	$4,912,829
Eco-Energy, Inc.	PV International	Phase 4A2	$3,462,349	$1,483,864	$4,946,213
Energy Conversion Devices, Inc.	ECD	Phase 2A	$4,978,748	$5,844,618	$10,823,366
		Phase 5A2	$3,000,000	$3,056,723	$6,056,723
		Phase IDIP-2	$3,000,000	$3,000,000	$6,000,000
Energy Photovoltaics, Inc.	EPV	Phase IDIP-2	$752,458	$752,458	$1,504,917
Evergreen Solar, Inc.	Evergreen Solar	Phase 4A1	$929,789	$232,448	$1,162,237
		Phase 5A2	$2,850,186	$1,221,508	$4,071,694
		Phase IDIP-2	$2,998,203	$2,998,203	$5,996,406
		Phase YDR-2	$3,000,000	$3,000,000	$6,000,000
First Solar, LLC	Solar Cells, Inc.	Phase 2B	$3,381,006	$3,813,806	$7,194,812
		Phase 5A2	$3,000,000	$1,382,538	$4,382,538
	First Solar	Phase YDR-2	$3,000,000	$3,146,518	$6,146,518
GE Energy (USA), LLC	AstroPower, Inc.	Phase 2A	$6,157,686	$2,639,007	$8,796,693
		Phase 4A2	$4,376,838	$3,084,870	$7,461,708
		Phase 5A2	$3,218,465	$3,336,633	$6,555,098
		Phase IDIP-2	$2,890,420	$5,917,067	$8,807,487
	GE Energy	Phase YDR-2	$3,000,000	$3,066,445	$6,066,445
Global Solar Energy, Inc.	Global Solar	Phase 5A2	$2,672,432	$1,001,065	$3,673,497
ITN Energy Systems, Inc.	ITN Energy	Phase IDIP-2	$1,965,478	$1,932,440	$3,897,918
Kyocera Solar	Golden Photon	Phase 2B	$4,825,171	$4,825,171	$9,650,342
	UPG	Phase 2A	$4,571,194	$93,290	$4,664,484
		Phase 4A1	$1,001,609	$250,401	$1,252,010
		Phase 5A1	$974,218	$628,816	$1,603,034
PowerFilm Solar	Iowa Thin Films	Phase 4A2	$2,697,490	$1,156,111	$3,853,601
S&C Electric Company	Omnion Power	Phase 4A1	$834,604	$363,839	$1,198,443
		Phase 5A1	$450,193	$192,940	$643,133
					(continued)

Table B-1. PVMaT Subcontractor Funding by Phase (Excluding Phase 1)[a] (continued)

Current Co. Name	Company	Phase	NREL/DOE Cost Share	Company Cost Share	Total
SCHOTT Solar, Inc.	Mobil	Phase 2A	$2,334,402	$2,168,547	$4,502,949
	ASE Americas	Phase 4A2	$1,256,000	$1,885,000	$3,141,000
		Phase 5A2	$2,846,241	$3,483,362	$6,329,603
	RWE Schott	Phase IDIP-2	$2,917,580	$3,686,369	$6,603,949
		Phase YDR-2	$2,983,991	$2,895,481	$5,879,472
	SES	Phase 4A1	$240,172	$60,043	$300,215
	Ascension	Phase 4A1	$486,006	$309,002	$795,008
		Phase 5A1	$637,773	$341,480	$979,253
	Schott Solar	Phase IDIP-1	$406,866	$461,838	$868,704
Shingleton Design, LLC	Shingleton Design	Phase YDR-1	$988,253	$2,156,000	$3,144,253
Sinton Consulting, Inc.	Sinton	Phase IDIP-2	$146,730	$146,730	$293,460
Solar Design Associates, Inc.	SDA	Phase 4A1	$717,197	$250,460	$967,657
SolarWorld	Siemens	Phase 2A	$4,999,915	$5,490,884	$10,490,799
		Phase 4A2	$2,556,684	$2,556,684	$5,113,367
		Phase 5A2	$2,997,624	$2,997,624	$5,995,248
	Shell Solar	Phase IDIP-2	$3,000,000	$5,352,669	$8,352,669
		Phase YDR-2	$3,000,000	$3,176,578	$6,176,578
Specialized Technology Resources, Inc.	Springborn	Phase 3A	$1,006,091	$448,325	$1,454,416
	STR	Phase IDIP-1	$901,859	$804,804	$1,706,663
Spire Corporation	Spire	Phase 3A	$1,213,996	$303,498	$1,517,494
		Phase 5A2	$2,876,792	$1,159,757	$4,036,549
		Phase IDIP-2	$2,728,427	$2,556,666	$5,285,093
SunPower Corporation	PowerLight	Phase 5A1	$1,198,716	$3,125,745	$4,324,461
		Phase IDIP-1	$1,190,150	$1,445,587	$2,635,737
		Phase YDR-1	$998,846	$3,328,936	$4,327,782
	SunPower Corp	Phase YDR-2	$2,959,948	$3,124,525	$6,084,473
Texas Instruments, Inc.	Texas Instruments	Phase 2B	$2,000,000	$2,740,655	$4,740,655
WorldWater & Solar Technologies Corp.	Entech	Phase 2A	$2,699,831	$83,499	$2,783,330
Xantrex Technology, Inc.	Trace	Phase 4A1	$193,289	$51,381	$244,670
	Xantrex	Phase IDIP-1	$1,094,490	$1,094,489	$2,188,979
		Phase YDR-1	$873,248	$873,250	$1,746,498
Total			**$149,965,725**	**$138,374,673**	**$288,340,398**

[a] Some contracts were cancelled in the final years of the program. These data do not reflect those changes.

Source: NREL (2009b).

BP Solar (Solarex)

Solarex was founded in 1973. In 1999, Solarex merged with BP Solar to become BP Solarex, which was renamed BP Solar in 2001 (BP Solar, 2009). Headquartered in Frederick, Maryland, BP Solar was the largest U.S. producer of mc-Si in 2008, with 20 MW of production. BP Solar was previously a leader in a-Si production before discontinuing its line in 2002.

BP Solar, together with Solarex, received over $18 million in DOE funds (Table B-1). In 1992, Solarex was issued the Phase 2A Large-Area Triple-Junction a-Si Alloy Production Scale-Up Project contract. According to Oswald and O'Dowd (1994), this project successfully:

- Increased efficiency of triple-junction a-Si cells by 3–6%,
- Developed front-contact deposition equipment for cost reduction,
- Created a low-cost zinc-oxide/aluminum back contact, and
- Reduced cost of producing 8% efficient tandem modules.

In 1993, Solarex received a second subcontract for Phase 2B Cast Polycrystalline Silicon Photovoltaic Cell and Module Manufacturing Technology Improvements, followed by BP Solar's 1998 Phase 5A2 Improvements in Polycrystalline Silicon PV Module Manufacturing Technology subcontract. During these phases, the company drastically increased cell efficiency, more than doubled capacity through assembly area improvements and wire saw implementation, increased productivity, and reduced cost (Wohlgemuth & Narayanan, 2002).

The 2001 Large-Scale PV Module Manufacturing Using Ultrathin Polycrystalline Silicon Solar Cells. According to Wohlgemuth and Narayanan (2002), contracts awarded to BP Solar resulted in:

- Increased ingot size leading, to yield improvements and reduced casting time;
- Completion of work on wire saws, reducing sawroom losses by 30%;
- Large-area c-Si cells that were 15% efficient;
- Implementation of low-cost bypass diodes for large-area PV modules and a cost-reduced junction box; and
- Development of a silicon nitride process in screen print facilities for increased efficiency.

BP Solar received their final subcontract, Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost, in 2005.

Evergreen Solar

Founded in 1994, Evergreen Solar uses a unique string ribbon silicon technology and is currently a major producer of c-Si modules, producing 27 MW in 2008. Evergreen Solar received four PVMaT contracts from 1994 to 2003, amounting to nearly $10 million in DOE funds (Table B-1). Beginning in 1994, Evergreen worked on the Advanced Polymer PV System subcontract to reduce costs and improve the quality of their modules. During this period, they successfully reduced module manufacturing costs by 20%, or $50/W, and created a new frameless module with a new backskin, encapsulant, and junction box, and began using the continuous lamination method (Hanoka, 1999).

In 1998, Evergreen received a second PVMaT subcontract for Continuous Automated Manufacturing of String Ribbon Silicon PV Modules. From 1998 to 2001, Evergreen increased run-length by 200%, cell efficiency by 5%, and factory yield by 20%, according to contract reports (Hanoka, 2001).

Evergreen's 2001 Innovative Approaches to Low-Cost Module Manufacturing of String Ribbon Si PV Modules subcontract led to the development of a dual-ribbon growth system that:

- Reduced manufacturing costs by cutting the use of some consumables by 50%,
- Increased cell efficiency to 14.6%, and
- Achieved wrap-around cell efficiency of 13.6%.

Evergreen also developed a production machine for contact printing, which led to a 3% gain in yield, a 0.3% efficiency improvement, and a 70% increase in throughput (Hanoka, 2004).

In 2003, Evergreen received a final subcontract for Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules. From 2005 to 2008, Evergreen designed a new ribbon-cutting device and improved yields in several steps for manufacturing thinner wafers (Felton, 2009).

First Solar (Solar Cells, Inc.)

Solar Cells, Inc., was founded in 1987 and was renamed First Solar in 1999. First Solar is headquartered in Arizona and maintained manufacturing facilities in Ohio, Malaysia, and Germany. It is currently the world's largest producer of CdTe modules, producing 504 MW in 2008 (Table 3-3). First Solar reached an important industry goal in 2008 when it successfully brought manufacturing costs below $1.00 per watt (First Solar, 2009).

First Solar and Solar Cells Inc. received three PVMaT contracts and $9.4 million from DOE (excluding the problem identification phase). The first, the Phase 2B High-Throughput Manufacturing of Thin Film CdTe Photovoltaic Modules subcontract, was awarded in 1993. Through this research,

- Best-demonstrated aperture area efficiency for production models went from under 4% in 1992 to over 8% in 1995,
- Module pass rate for the interim qualification test increased from under 10% before the start of the contract to 100% at the end of the second year, and
- Laser scribing process time was reduced by 90% through a new high-throughput system.

First Solar received the Phase 5A2 Specific PVMaT R&D in CdTe Product Manufacturing subcontract in 1998. According to Bohland et al. (2004), from 1998 to 2003, First Solar

- Increased module production yield by more than 90%,

- Improved the laser scribing system to reduce capital cost by 65%, and
- Developed a high-throughput lamination and potting process that could produce 30 modules per hour; by the end of the contract, throughput had increased to 60 modules per hour.

In 2003, First Solar began work on the Phase YDR Implementation of Reliable Manufacturing of Higher Efficiency First Solar Modules subcontract with the goal of increasing module efficiency by 2%.

GE Energy (AstroPower)

AstroPower was founded in 1983 and was acquired by GE Energy in 2004. AstroPower initially produced recycled semiconductor wafers to save costs. In the late 1980s, AstroPower began work on its proprietary Silicon-Film sheets, solar cells, and modules. In 1995, AstroPower received an R&D 100 Award for Silicon-Film, which was developed under PVMaT. AstroPower received a total of five PVMaT subcontracts after Phase 1, amounting to over $19 million in DOE funds.

From 1992 to 2001, AstroPower received a series of four subcontracts for improving Silicon-Film manufacturing and modules. The first subcontract resulted in the largest cell ever produced at that time, and surpassed production capacity goals. Gains in module power and reductions in cost per wafer came as a result of better silicon material use efficiency, an improved gettering sequence, and the use of larger sheets of wafer material (Collins et al., 1996).

The second subcontract, which ran from 1995 to 1998, reduced the cost of manufacturing modules by 13% while increasing the production capacity for Silicon-Film by 300% (Rand et al., 1998). In 1998, AstroPower received a third contract called Silicon-Film Solar Cells by a Flexible Manufacturing System. According to Rand (2002), from 1998 to 2001, AstroPower:

- Increased wafer generation capacity by 350% through continuous sheet manufacturing,
- Increased solar cell area by 80%, and
- Constructed a new high-throughput wafer-making system.

In their 2001 subcontract, AstroPower worked on high-volume manufacturing of Silicon-Film. This resulted in a 5% increase in power and a 15% increase in yield. Manufacturing costs were reduced significantly through a 50% decrease in feedstock usage due to improvements in impurity reduction techniques (Rand & Culik, 2005). In 2003, AstroPower received a subcontract for Phase YDR Solar Cell Design for Manufacturing, which was intended to reduce system cost and increase module efficiency to 11% in production.

Global Solar

Global Solar was founded in 1996 and is located in Tucson, Arizona. Global Solar produces CIGS on a flexible substrate and is the largest producer of CIGS in the United States, producing 7 MW in 2008 (Table 3-3). Global Solar received a 1998 Phase 5A2 PVMaT subcontract for reducing manufacturing costs and increasing throughput for CIGS. According to Britt and Wendt (2002), through this research, Global Solar successfully:

- Developed a high-speed, all-laser scribing process for CIS modules on polyimide substrates;
- Demonstrated inkjet printing with a speed of 30 cm/sec;
- Improved CIS evaporation sources;
- Implemented X-ray florescence in production roll coater;
- Developed a selenium delivery system to reduce selenium usage;
- Integrated the parallel-detector spectroscope ellipsometer into a production CIS deposition chamber; and
- Identified alternative, less expensive back-contact materials.

SolarWorld USA

SolarWorld is a descendant of Siemens Solar, Arco Solar, and Shell Solar. Arco Solar was founded in 1975. In 1990, Siemens purchased Arco's solar division (Margolis, 2002). Siemens Solar was later purchased by Shell Solar, which was then acquired by SolarWorld. SolarWorld is a major U.S. producer of c-Si, producing 85 MW in 2008. Shell and Siemens received a combined five subcontracts (excluding problem identification) amounting to over $16 million in DOE funds (Table B-1). In its technical reports submitted to NREL (Jester, 1995), SolarWorld attributed improvements in module cost, yield, and labor productivity during Phase 2A to:

- Improved crystal growth,
- Automated assembly,
- Higher electrical yield in cells,
- Larger modules and cells,
- A new junction box, and
- Completion of wire saw implementation.

According to Jester (1999), during Phase 4A2 of PVMaT:

- Breakage was reduced by investigation, leading to higher yields,
- Labor productivity was improved through automation,
- Wire saws were made thinner for better wafer production, and
- Larger modules were constructed with the same size cell.

Work in Phase 5A reduced costs through a new module design and a reduction in wafer thickness (Jester, 2002). In 2001, they received a PVMaT subcontract called PV Manufacturing-Integrated CIS Thin-Film Manufacturing Infrastructure, in which they implemented a new laser scribing system for reduced breakage and higher productivity (Tarrant & Gay, 2004). During Phase YDR of PVMaT, SolarWorld was issued another subcontract for manufacturing improvements in Cz-silicon module production. As of 2006, they had reduced wafer thickness by 20% for cost reduction, achieved a 14% efficient module, and identified a new backsheet (Jester, 2007).

SCHOTT Solar

SCHOTT Solar is a major sc-Si module producer specializing in EFG ribbon silicon. After a series of acquisitions, SCHOTT Solar represents several companies that participated in PVMAT, including RWE SCHOTT Solar, Mobil Solar, ASE Americas, Solar Electric Specialties, and Ascension Technologies. ASE was formed jointly by Mobil and Tyco in 1974. In 1994, ASE Gmbh acquired all of Mobil Solar's assets. RWE SCHOTT Solar was formed in 2002 as a joint venture between RWE Solar Gmbh, its subsidiary ASE Americas, and SCHOTT. RWE SCHOTT was fully purchased by SCHOTT to become SCHOTT Solar in 2005.

SCHOTT Solar and its predecessors received several PVMaT contracts for cell and module development, as well as contracts for improvements in balance of system components. DOE funding for these contracts amounted to over $14 million.

In 1992, Mobil Solar began work on the Mobil Solar Energy Corporation Thin EFG Octagons subcontract, in which they successfully reduced wafer thickness, increased cell efficiency, doubled laser cutting throughput, and increased EFG-octagon run length. These improvements led to a 13.4% reduction in wafer costs and a 5.2% reduction in module costs (Kalejs, 1994).

In 1994, ASE Americas received a Phase 4A2 subcontract for Market-Driven EFG Modules. According to Kardauskas and Kalejs (1999), from 1995 to 1999, ASE Americas:

- Reduced wafer thickness for an 8% reduction in silicon usage;
- Cut silicon-feedstock losses in half;
- Reduced cost by 6% through extended EFG crystal growth length;
- Implemented a computer-based manufacturing technique, yielding improvements in cell efficiency and 6.5% reduction in module costs; and
- Reduced module costs by 2.5% and total module manufacturing costs by 15%.

In 1998, ASE Americas was issued a second PVMaT contract for Phase 5A, Cost Reductions in High Volume EFG PV Module Manufacturing Line. According to Kalejs et al. (2002), through this subcontract, ASE Americas:

- Increased cell efficiencies by 0.5%,
- Reduced yield losers by more than half,
- Implemented a better encapsulant for 6% reductions in manufacturing costs, and
- Cut manufacturing costs by 30% overall, surpassing the program goal of 25%.

RWE SCHOTT Solar received a Phase IDIP-2 subcontract for EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing in 2001. According to Kalejs et al. (2005), accomplishments from this program include:

- A 25% increase in productivity per furnace,
- Laser area throughput increases of 35%, and
- Improved wafer strength and yields with thinner wafers.

In 2003, SCHOTT Solar was issued a Phase YDR subcontract for High Performance Multicrystalline Modules and Products. Research was initiated in 2006. Goals included development of a 17% efficient cell with EFG wafers and construction of a backplane interconnect cell design.

SunPower

SunPower, founded in 1988 and headquartered in Sunnyvale, California, is a major U.S. manufacturer of sc-Si modules. SunPower, which holds all of its manufacturing facilities in the Philippines, produced 237 MW in 2008. SunPower participated in Phase YDR of PVMaT. PowerLight, acquired by SunPower in 2006, also received three subcontracts for improvements to its PowerGuard roofing tiles. Together, the two companies received 3.4 million in DOE funds through PVMaT.

In 2003, SunPower received a PVMaT subcontract for Automated Manufacturing of High-Efficiency Modules. The project was aimed at producing low-cost modules with 30-year warranties and 50% higher energy production through:

- Thin wafer breakage reduction with improved automated handling,
- Lead-free interconnects,
- Automated soldering, and
- Alternative encapsulation methods and materials.

This project led to the production of the world's highest efficiency production PV module, with a total-area efficiency of 20.1%. According to subcontract reports (Rose et al., 2008), SunPower:

- Used antireflective-coated cover glass to increase efficiency;
- Developed a lead-free interconnect system with lower risk of fatigue failure;
- Selected an automated soldering technique for thin, back-contact cells; and
- Improved manufacturing to enable the use of 150-µm cells for cost reduction and increased efficiency.

Uni-Solar (ECD)

United Solar was founded in 1990 and is headquartered in Michigan. Uni-Solar is a subsidiary of ECD, and was the largest U.S. producer of a-Si in 2009, with 119 MW production. ECD received three subcontracts between 1992 and 2001 for improvement of their Continuous Roll-to-Roll a-Si Photovoltaic

Manufacturing Technology, amounting to $22.9 million in DOE funds (Table B-1). The first was intended to support production of a triple-junction module with 10.2% efficiency at a cost of $1.00/Wp, improve deposition techniques, and reduce material and labor costs. From 1992 to 1995, ECD successfully:

- Achieved production of dual-junction cells with a yield of 99.7%;
- Created the first roll-to-roll triple-junction, two-band-gap a-Si module, with 9.5% efficiency;
- Constructed a silver/zinc oxide (Ag/ZnO) back-reflector system with high subcell yield; and
- Constructed a low-cost deposition machine with higher throughput.
- In 1998, ECD received a second subcontract called Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy Manufacturing Technology with a final goal of 25 to 30% reduction in module cost and a 60% increase in manufacturing capacity. By 2001, ECD had met all program goals and, according to Izu (1996), had: Reduced production costs by $0.06/W and increased throughput with a new heating system; Demonstrated new pinch valve technology for a 10% increase in throughput; and Completed design and installation of second-generation sensors in a-Si pilot deposition machine.

During their final contract, Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production, ECD developed a comprehensive in-situ diagnostic system that reduced time between deposition and device characterization from 200 hours to 1 hour (Ellison, 2005).

APPENDIX C:

TECHNOLOGY AND R&D PARTNERS FOR THIN-FILM PV PARTNERSHIPS

Table C-1. TFP Technology and R&D Partners

Advanced Photovoltaic Systems	Iowa State University	SRI International
Aerochem	ITN Energy Systems, Inc.	Stanford University
AMETEK	Jet Propulsion Laboratory	State University of New York-Buffalo
SolarWorld USA (ARCO Solar, Shell Solar, Siemens Solar)	Lawrence Berkeley Laboratory	SumX Corporation
Argonne	Lawrence Livermore Laboratory	Syracuse University
AstroPower, Inc.	Lockheed Missiles and Space Company	Technion-Israel Institute of Technology
Battelle-Columbus Laboratories	Louisiana State University	Telic Corporation
Boeing	Martin Marietta	The University of Toledo
BP Solar (Solarex)	Materials Research Group, Inc. and ITN Energy Systems	Tulane University
Brookhaven National Laboratory	Minnesota Mining and Manufacturing Company	UHT Corporation
Brooklyn College of CUNY	Massachusetts Institute of Technology	University of Arizona
Brown University	Mobil Tyco Solar Energy Corporation	University of Arkansas
California Institue of Technology	Monosolar Inc	University of California, Los Angeles
Chronar Corporation	MV Systems, Inc.	University of Central Florida
Clarkson College	NanoSolar	University of Colorado
Colorado School of Mines	National Aeronautics & Space Administration	University of Delaware
Colorado State University	National Renewable Energy Laboratory	University of Florida
DayStar Technologies, Inc.	Naval Research Laboratory	University of Illinois
Duke University	Naval Weapons Center	University of North Carolina
EIC Corporation	National Institute of Standards & Technology	University of Oregon
Energy Conversion Devices, Inc. (Uni-Solar)	North Carolina A & T University Foundation	University of South Florida
Energy Photovoltaics, Inc.	North Carolina State University	University of Southern California
Exxon Research & Engineering Company	Pennsylvania State University	University of Texas at Arlington
First Solar, LLC (Solar Cells, Inc.)	Photon Energy	University of Texas at Austin
Florida Solar Energy Center	Plasma Physics	University of Toledo
Georgia Institute of Technology	Poly Solar	University of Utah
Glass Tech Solar	Princeton University	University of Washington
Global Solar Energy, LLC	Purdue University	Vactronics Laboratory Equipment
Golden Photon	Radiation Monitoring Devices	Virginia Institute of Technology
Gould Incorporated	RCA	Washington State University
Grumman Aerospace Corporation	Research Institute of Colorado	Washington University

(continued)

(Table C-1 continued)

Harvard University	Rockwell International Corporation	Wayne State University
Hughes Aircraft Company	Research Triangle Institute	Weizmann Institute of Science
IBM	Southern Methodist University	Westinghouse Electric Corporation
Institute of Gas Technology	Sperry Univac	World Industry Minerals
International Solar Electric Technology Inc.	Spire Corporation	Xerox Corporation
		Yeda R& D

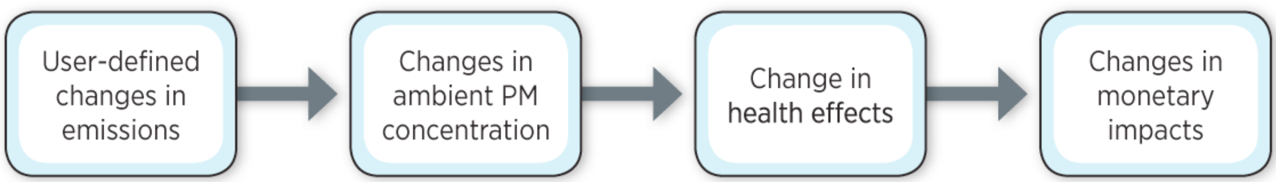
APPENDIX D:

SUMMARY OF THE CO-BENEFITS RISK ASSESSMENT (COBRA) MODEL[67]

The Co-Benefits Risk Assessment (COBRA) model provides estimates of health effect impacts and the economic value of these impacts resulting from emission changes. The COBRA model was developed by the U.S. Environmental Protection Agency (EPA) to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies.

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. Figure D-1 provides an overview of the modeling steps.

Figure D-1. COBRA Model Overview



Source: EPA (2006).

D.1 Changes in Emission → Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x) and identifies the economic sector from which the emissions are being reduced. These changes are in total tons of pollutants by sector for the U.S. economy for the chosen analysis year. The economic sectors chosen determine the underlying spatial distribution of emissions and hence the characteristics of the human population that is affected.[68] For example, emissions reductions due to the use of geothermal technology are typically applied to coal plants in electric utilities. Reductions due to the use of wind technology are applied to coal, oil, and natural gas plants in electric utilities. Emissions reductions due to improved efficiency of diesel engines are applied to both highway diesel engines and off-highway non-road diesel engines.

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average $PM_{2.5}$ concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by $PM_{2.5}$ species to this concentration from each emission source.

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67 This Appendix was prepared by Michael Gallaher, RTI International.

68 The COBRA model has a variety of spatial capabilities. However, for this study there was limited information on the specific location of pollution reductions. Thus, a national analysis was conducted where the national distribution of emissions by fuel type, by sector (e.g., special distribution of national coal emissions in the electricity sector) was used to determine the emission location as input to the S-R matrix.

This matrix provides quick but rough estimates of the impact of emission changes on ambient $PM_{2.5}$ levels as compared to the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2006).

D.2 Changes in Ambient PM Concentrations → Changes in Health Effects

The model then translates the changes in ambient PM concentration to changes in incidence of human health effects using a range of health impact functions and estimated baseline incidence rates for each health endpoint. The data used to estimate baseline incidence rates, and the health impact functions used vary across the different health endpoints. To be consistent with prior EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Regulatory Impact Analysis of the Clean Air Interstate Rule (U.S. EPA, 2005).[69]

The model provides (in the form of a table or map) changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario. The different health endpoints are included in Table D-1.

Each health effect is described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendices C of the COBRA user's manual (U.S. EPA, 2006) and Abt (2009).

Table D-1. Health Endpoints Included in COBRA

Health Effect	Description
Mortality	Number of deaths
Chronic bronchitis	Cases of chronic bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
Cardiovascular related hospital admissions	Number of cardiovascular-related hospitalizations
Acute bronchitis	Cases of acute bronchitis
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
Minor restricted activity days	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD).
Work days lost	Number of work days lost due to illness

[69] For a detailed discussion of studies used for health impact functions and unit values, see U.S. EPA (2005).

Mortality researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Chronic bronchitis is defined as a persistent wet cough and mucus in the lungs for at least three months for several consecutive years, and it affects approximate 5% of the population (Abt, 2009). A study by Abbey et al. (1995) found statistically significant relationships between $PM_{2.5}$ and PM_{10} and chronic bronchitis.

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks are modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earning.

Hospital admissions include two major categories: respiratory (such as pneumonia and asthma) and cardiovascular (such as heart failure, ischemic heart disease). Using detailed hospital admission and discharge records, Sheppard et al. (1999) investigated asthma hospital admissions associated with PM, carbon monoxide (CO), and ozone. Moolgavkar (2000 and 2003) and Ito (2003) also found a relationship between hospital admissions and PM. COBRA includes separate risk factors for hospital admissions for people aged 18 to 64 and aged 65 and older.

Acute bronchitis, defined as coughing, chest discomfort, slight fever, and extreme tiredness lasting for a number of days, was found by Dockery et al. (1996) to be related to sulfates, particulate acidity, and, to a lesser extent, PM. COBRA estimates the episodes of acute bronchitis in children aged 8 to 12 from pollution using the findings from Dockery et al.

Upper respiratory symptoms include episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes). Pope et al. (2002) found a relationship between PM and the incidence of a range of minor symptoms, including runny or stuffy nose; wet cough, and burning; aching or red eyes.

Lower respiratory symptoms in COBRA are based on Schwarz and Neas (2000) and focus primarily on children's exposure to pollution. Children were selected for the study based on indoor exposure to PM and other pollutants resulting from parental smoking and gas stoves. Episodes of lower respiratory symptoms are coughing, chest pain, phlegm, or wheezing.

Asthma related emergency room visits are primarily associated with children under the age of 18. Norris et al. (1999) found significant associations between asthma ER visits and PM and CO. To avoid double counting, hospitalization costs (discussed above) do not include the cost of admission to the emergency room.

Minor restricted activity days (MRAD) in COBRA were based on research by Ostro and Rothschild (1989). MRADs include days on which activity is reduced but not severely restricted (e.g., missing work or being confined to bed is too severe to be an MRAD). They estimated the incidence of MRADs for a national sample of the adult working population, aged 18 to 65, in metropolitan areas. Because this study is based on a "convenience" sample of nonelderly individuals, the impacts may be underestimated because the elderly are likely to be more susceptible to PM-related MRADs).

Work loss days were estimated by Ostro (1987) to be related to PM levels. Based on an annual national survey of people aged 18 to 65, Ostro found that two-week average PM levels were significantly linked to work loss days. However, the findings showed some variability across years.

D.3 Changes in Health Effects → Changes in Monetary Impacts

COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint. The per-unit monetary values are described Appendix F of the COBRA user's manual (U.S. EPA, 2006). Estimation of the monetary unit values vary by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life (VSL) estimates. Other endpoints such as hospital admissions use cost of illness (COI) units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering.

D.4 Limitations

It should be noted that COBRA does not incorporate effects of many pollutants, such as carbon emissions or mercury. This has two potential implications. First, other pollutants may cause or exacerbate health endpoints that are not included in COBRA. This would imply that reducing incidences of such health points are not captured. Second, pollutants other than those included in COBRA may also cause a higher number of incidences of the health effects that are part of the model. This is also not captured in this analysis. Thus, the economic value of health effects obtained from COBRA may be interpreted as a conservative estimate of the health benefits from reducing emissions.

APPENDIX E:

BIBLIOMETRIC METHODOLOGY USED IN THE SOLAR PV KNOWLEDGE BENEFITS CHAPTER [70]

This appendix provides a brief treatment of the bibliometric methods of evaluation—particularly patent analysis—used in the source report from which this appendix is derived. For additional information about these and other methods used in the source report, please refer to Ruegg and Thomas, *Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power from Solar Energy, 2010, in press*.

Bibliometric methods of evaluation tend to be useful in historical tracing studies, such as the source study, which traces from DOE's solar PV R&D to downstream renewable power generation. Bibliometric methods can be used to provide objectively derived, quantitative measures of linkages from publication and patent outputs of the R&D program to other publications and patents outside the program. The related analyses can indicate that knowledge has been created, who created it, the extent that it is being disseminated and used (or at least referenced) by others, and who is using or referencing it.

E.1 Why Patent Analysis?

When looking for connections from knowledge creation in a research program to commercialized technologies, patents are of particular interest because they are considered close to application. The use of patents as indicators of technology creation, and patent citation analysis as indicative of technology diffusion reflects a central role of patents in the innovation system. Patent citation analysis has been used extensively in the study of technological change.

In patent analysis, a reference from a patent to a previous patent is regarded as recognition that some aspect of the earlier patent has had an impact on the development of the later patent. In the patent analysis presented in this report, the idea is that the technologies represented by patents that cite DOE-supported patents have built in some way on the patents attributable to research funded by DOE.

Patent citation analysis also has been employed in other studies, as it is here, to evaluate the impact of particular patents on technological developments. This approach is based on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. Because they form the basis for many new innovations, they are cited frequently by later patents. Although it is not true to say that every highly cited patent is important or that every infrequently cited patent is unimportant, research studies have shown a correlation between the rate of citations of a patent and its technological importance.[71]

[70] This appendix was prepared by Rosalie Ruegg, TIA Consulting Inc. and Patrick Thomas, 1790 Analytics LLC.

[71] For background on using patent citation analysis, including a summary of validation studies supporting its use, see Breitzman and Mogee (2002). For a similar background on using paper citation analysis, see Chapter 3 of Thomas (1999).

E.2 "Prior Art"

A patent discloses to society how an invention is practiced, in return for the right during a limited period of time to exclude others from using the patented invention without the patent assignee's permission. The front page of a patent document contains a list of references to prior art. "Prior art" in patent law refers to all information that previously has been made available publicly such that it might be relevant to a patent's claim of originality and, hence, its validity. Prior art may be in the form of previous patents, or published items such as scientific papers, technical disclosures, and trade magazines.

Patent citation analysis centers on the links between generations of patents, and between patents and scientific papers, that are made by these prior art references. In basic terms, this type of analysis is based on the idea that the prior art referenced by patents has had some influence, however slight, on the development of these patents. The prior art is thus regarded as part of the foundation for the later invention.

E.3 Forward and Backward Patent Tracing

Two approaches to patent analysis are used in this study—forward tracing and backward tracing—paralleling the two perspectives of the broader historical tracing framework.

E.3.1 Forward Patent Tracing

The idea of forward tracing is to trace the influence of a given body of research on subsequent technological developments. In the context of the current analysis, forward tracing involves identifying all solar PV patents resulting from research programs funded by DOE and evaluating their influence on subsequent generations of technology. This tracing is not restricted to later solar PV patents, since the influence of a body of research may extend beyond its immediate technology.

E.3.2 Backward Patent Tracing

The idea of backward tracing is to start downstream of the DOE R&D program, with the program's intended area of influence, and determine if this area did, in fact, build on the earlier DOE-generated knowledge base embodied in patents attributed to DOE R&D. In the context of this project, the idea of backward patent tracing is to trace back from patents of two downstream groups: (1) leading U.S. solar PV producers and (2) leading companies in solar energy patenting worldwide to assess the extent to which each group links back to the DOE-attributed solar PV patents. Linkages of the first group provide an indication of the extent DOE-funded solar PV research has influenced subsequent solar PV technologies by leading U.S. producers. Linkages of the second group provide an indication of the broader influence of the DOE research on developments by leading companies worldwide in solar energy invention. Further, comparing the extent of the linkage in each case back to DOE with the linkages back to the patents of other organizations provides an indication of the relative importance of DOE's knowledge base to further advances in solar energy technologies in general and in solar PV technologies in particular.

E.4 Extensions of the Patent Citation Analysis

The simplest form of patent tracing is based on a single generation of citation links between U.S. patents. Such a study identifies U.S. patents that cite, or are cited by, a given set of U.S. patents as prior art. This study extends the patent analysis in three ways.

E.4.1 Extension to Patents Citing Publications

It extends the analysis to include patent citations of publications authored by DOE-funded researchers. The rationale for this extension is that DOE scientists may produce publications that are considered directly relevant to a technology's development. Adding prior art references to DOE-supported publications thus takes into account the influence of the research described in these publications on innovations captured in patents.

E.4.2 Extension to Multiple Generations of Citation Links

It extends the analysis by adding a second generation of citation links. This means that the study traces forward through two generations of citations, starting from DOE-attributed solar PV patents, and backward through two generations starting from the solar energy patents of leading innovative solar energy companies.

The idea behind adding this second generation of citations is that Federal agencies such as DOE often support scientific research that is more basic than applied. It may take time and multiple generations of research for this basic research to be used in an applied technology, such as that described in a patent. The impact of the basic research may not, therefore, be reflected in a study based on referencing a single generation of prior art. Introducing a second generation of citations provides greater access to these indirect links between basic and applied research and technology development.

One potential problem with adding a second generation of citations should be acknowledged. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The problem is that, if one uses enough generations of linkages, eventually almost every node in the network will be linked. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents and extends the network of prior art references far enough, eventually almost all patents will be linked to this starting set. Based on previous experience, using two generations of citation links is appropriate for tracing studies such as this. However, adding additional generations may bring in too many patents with little connection to the starting set.

E.4.3 Extension beyond the U.S. Patent System

The report looked beyond the U.S. patent system to include patents from the European Patent Office (EPO) and patent applications filed with the World Intellectual Property Organization (WIPO). The analysis thus allows for a wide variety of possible linkages between DOE-funded solar PV research and subsequent technological developments in and outside the United States.

E.5 Patent Data Sets for Analysis

The forward tracing starts from the set of solar PV patents attributed to DOE's R&D funding, while the backward tracing starts in turn from two sets: (1) the set of solar energy patents of the leading U.S. PV companies and (2) the set of solar energy patents of the leading companies in solar energy patenting (not restricted to U.S. companies). None of these three data sets were already compiled; they had to be constructed by the study.

E.5.1 Identifying the Set of DOE-Attributable Solar PV Patents for Forward Tracing

The set of DOE-attributable solar PV patents was constructed through a five-step process:

1. Construct an initial database of patents attributable to a Government Agency.
2. Filter the database to identify DOE-attributed patents related to solar PV.
3. Identify additional candidate DOE-attributed solar PV patents based on document review.
4. Narrow the candidate patent list through DOE expert review.
5. Add international and U.S. continuation or divisional patents related to patents in the candidate list.

These steps are described below.

Step 1: Construct an Initial Database of Patents Attributable to a Government Agency

Identifying patents funded by government agencies is often more difficult than identifying patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. To construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries, acquisitions, etc.

In contrast, a government agency such as DOE may fund research in a variety of organizations. For example, DOE operates a number of laboratories and research centers. Patents emerging from these laboratories and research centers may be assigned to DOE, or they may be assigned to the organization that manages the laboratories or research centers. For example, patents from Sandia National Laboratory may be assigned to Lockheed Martin, while Lawrence Livermore National Laboratory patents may be assigned to the University of California.

A further complication is that DOE does not only fund research in its own labs and research centers. It also funds research carried out by private companies and universities. If this research results in patented inventions, these patents are likely to be assigned to the company or university carrying out the research, rather than to DOE.

To identify patents resulting from DOE-funded advanced solar PV research, the study started with the following data sources to identify most of the population DOE-funded patents:

- ***OSTI Database***—The first source used was a database provided by DOE's Office of Scientific & Technical Information (OSTI) for use in DOE-related projects. This database contains information on research grants provided by DOE since its inception. It also links these grants to the organizations or DOE centers carrying out the research, the sponsor organization within DOE, and the U.S. patents that resulted from these DOE grants.

- ***Patents assigned to DOE***—The study identified a number of U.S. patents assigned to DOE that were not in the OSTI database because they have been issued since the latest version of that database. These patents were added to the list of DOE-attributed patents.

- ***Patents with DOE Government Interest***—A U.S. patent has on its front page a section entitled "Government Interest," which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. The study identified all patents that refer to "Department of Energy" or "DOE" in their Government Interest field, along with patents that refer to government contracts beginning with DE- or ENG-, since these abbreviations denote DOE grants. Patents in this set that were not already in the OSTI database and were not assigned to DOE were added to the list of DOE-attributed patents. The DOE patent database constructed from these three sources contains a total of 19,642 U.S. patents issued between January 1976 and March 2009.

Step 2: Filter the Database to Identify DOE-Attributed Patents Related to Solar PV

The study constructed and applied a patent filter to search within the above generated database to identify DOE-attributed patents related to solar photovoltaics. As a starting point for the filter, the study identified a set of U.S. Patent Office Classifications (POCs) and International Patent Classifications (IPCs) related to solar energy. The search was restricted to patents in these IPCs and POCs. Restricting the search by patent classification reduces the chance of including irrelevant patents. In addition, the study identified keywords and phrases related to solar and PV technology to focus the filter on solar photovoltaics. Patents identified by the filter were read and those deemed irrelevant were removed.

For more details on the construction of the patent filter, including the IPCs, POCs, and keywords used, see the source report by Ruegg and Thomas (in press).

Step 3: Identify Additional Candidate DOE-Attributed Solar PV Patents Based on Document Review

In addition to identifying DOE-attributed solar PV patents by applying the constructed solar PV patent filter to the compiled broader database of DOE-attributed patents, the study also identified DOE-attributed solar PV patents based on an analysis of DOE annual reports and other program documents. These documents identified some of the companies that were funded by DOE to develop solar energy technologies, for example, under the Photovoltaic Manufacturing Technology (PVMaT) program. The time periods during which these companies were funded and the technologies they were funded to develop were also identified. By matching companies, time periods and technologies, the study was able to identify a number of additional patents that had not been identified by the patent filter.

Patents identified from reviewing DOE documents were added to the DOE-attributed solar PV patent set from applying the solar PV patent filter to the broader database of DOE-attributed patents (as described above). The resulting combined list was considered by the study to be a candidate list, requiring validation by DOE experts in the field.

Step 4: Narrow the Candidate Patent List through DOE Expert Review

The list of candidate of solar PV patents identified by the study was sent to DOE for validation. DOE scientists and program managers—experts in the field—provided feedback to the study on which of the candidate patents should be included in the final set of DOE-attributed solar PV patents and which should be omitted. Candidate patents omitted included those concerned with technologies such as solar collectors, balance of system components, and also certain applications such as solar water heaters, because these were considered to be outside the scope of the analysis—the scope being PV module technologies. Some of the candidate patents identified on the basis of partial information found in DOE documents were ultimately omitted because of uncertainty regarding the degree of DOE attribution.

Based on the process outlined above, the study arrived at a final list of 331 solar PV U.S patents attributed to DOE-funded research.

Step 5: Add International and U.S. Continuation or Divisional Patents Related to Patents in the Candidate List

Finally, to take into account equivalents of each of these patents in the EPO and WIPO patent systems (i.e., patents filed in the EPO and WIPO patent systems that represent essentially the same invention as that covered by one of 331 identified U.S. patents), the study searched those patent systems. In addition, the study searched again the U.S. patent system for U.S. patents that are continuations, continuations-in-part, or divisionals of each of the 331 U.S. patents, again to take into account patents representing the same invention. In total, the patent searches yielded 343 U.S. patents (including the 331), 75 EPO patents, and 113 WIPO patents. The study then grouped these patents into 274 patent families based on matching priority documents. A list of these patents can be found in Appendix A of the source report by Ruegg and Thomas (in press).

E.5.2 Identifying the Top U.S. Solar PV Producers for Backward Tracing

The top eight U.S. solar PV producers, identified in Table 3-4 of this report, were used in the first element of the backward tracing. The cut-off was the top eight because below that point, the reported production output was rounded to zero. These eight companies are, in declining order of the number of their solar energy patent families, BP Solar (213 families), Energy Conversion Devices (United Solar) (166 families), SunPower (79 families), Solar World (55 families), Schott (46 families), Evergreen Solar (31 families), First Solar (16), and Global Solar (3). In total, these companies own 608 solar energy patent families, containing a total of 321 U.S. patents, 204 EPO patents, and 172 patent applications filed with the WIPO. Again, using this set of companies is to better assess the influence of DOE’s earlier solar PV research specifically on later technology developments by the top U.S. solar PV producers.

E.5.3 Identifying the Leading Companies in Solar Energy Patenting for Backward Tracing

To identify more broadly the influence of DOE’s earlier solar PV research on later solar energy technology development, leading companies in solar energy patenting were identified and used in the second element of the backward tracing. To identify such companies, the study first defined the universe of solar energy patents using a modified version of the patent filter employed to identify the DOE-attributed candidate solar PV patents. The narrower filter was used because of practical considerations. In defining the DOE solar PV patent set, candidate patents were read individually to determine their relevance. This process was possible because the number of patents involved was relatively small. The same process of reading individual patents was not practical when the patent set is drawn from the entire universe of patents, not just those patents attributed to research funded by DOE. The patent filter used to define the universe of solar energy patents thus had to avoid introducing large numbers of irrelevant patents, since these patents could not be removed by reading them individually. The patent filter used for this process is described in detail in the source report (Ruegg and Thomas, in press).

In total, using the patent filter, the study defined a solar energy universe containing 6,793 U.S. patents, 4,093 EPO patents, and 3,971 WIPO patents. These patents were grouped into 13,156 patent families.

The study then identified the top 10 companies with the largest number of patent families in this set, including patents assigned to subsidiaries, acquisitions etc. These companies in declining order of their number of solar energy patents are Canon (455); BP Solar—also included in the list of the top U.S. solar PV producers (213); Sanyo (202); Sharp (199); Energy Conversion Devices—also included in the list of the top U.S. solar PV producers (166); Siemens (137); General Electric (129); Boeing (128); ExxonMobil (95); and Mitsubishi Electric (88).

In total, these companies are responsible for 1,812 solar energy patent families, containing a total of 1,105 U.S. patents, 642 EPO patents, and 273 WIPO patents. These 1,812 solar energy patent families owned by these leading companies in solar energy patenting form the starting point for the second element of the backward tracing analysis. This element of the backward tracing is to assess the influence of DOE's solar PV research more broadly on later solar energy technology developments by international leaders in solar energy invention. There is some overlap in the two backward tracings, in that two companies, BP Solar and Energy Conversion Devices, are on both lists.

E.6 Constructing Patent Families Based on the "Priority Application"

Organizations often file for protection of their inventions across multiple patent systems. For example, a U.S. company may file to protect a given invention in the United States and also file for protection of this invention in other countries. Also, inventors may apply for a series of patents in the same country based on the same underlying invention. As a result, there may be multiple patent documents resulting from the same invention. In the case of this project, one or more U.S., EPO, and WIPO patents may result from a single invention.

To avoid counting the same inventions multiple times, it is necessary to construct patent families. A patent family contains all of the patents and patent applications that result from the same original patent application (named the priority application). A family may include patents/applications from multiple countries and also multiple patents/applications from the same country.

The source study constructed patent families for those patents attributed to DOE, for the top U.S. solar PV producers, for the leading companies in solar energy patenting, and also for all of the patents/applications linked through citations to DOE. To construct these patent families, the study matched the priority documents of the U.S., EPO, and WIPO patents/applications, to group them into the appropriate families. It used fuzzy matching algorithms to achieve this, along with a small amount of manual matching, since priority documents have different number formats in different patent systems. It should be noted that the priority document need not necessarily be a U.S., EPO, or WIPO application. For example, a Japanese patent application may result in U.S., EPO, and WIPO patents/applications that are grouped in the same patent family because they share the same Japanese priority document.

E.7 Publication Coauthoring and Citation Analyses

Past similar studies suggest that analyses of publications may offer additional insights into the creation and dissemination of knowledge from DOE's solar PV R&D. The volume of publications over time provides a rough indicator of the extent of publications as a knowledge output. Coauthoring of publications by DOE researchers with researchers from other organizations in solar photovoltaics indicates collaboration and, in some cases, linkages of DOE researchers with those involved in downstream technology development and commercialization. Organizational affiliations of those citing DOE solar PV publications indicate paths of knowledge flow.

The publication citation search is facilitated by using a publication citation database and search engine. For a long period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was the principal entity facilitating publication citation analysis. But today there are a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, that provide comprehensive coverage beyond the major journals, including, for example, conference proceedings, book chapters, dissertations, and research reports (Meho, 2007, p. 32). For this study's publication-to-publication citation analysis, conference papers and research reports were prominent, and Google Scholar was used because it included these kinds of publication in its search capability. A comparison of alternative publication search tools rated Google Scholar among the best (Meho, 2007).

APPENDIX F: SUPPLEMENTAL ANALYSIS TABLES

Table F-1. Economic Benefits from PV Systems Installed in the United States, by Social Discount Rate (2008$)

Year	Annual U.S. PV Installed (MW)	Actual		Counterfactual		Economic Benefit 0% SDR ($ million)	Economic Benefit 3% SDR ($ million)	Economic Benefit 7% SDR ($ million)
		Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)			
1976	0.8	$53.28	2	$53.28	2	—	—	—
1977	1.2	$37.60	2	$46.15	2	10.5	10.5	10.5
1978	1.6	$25.64	2	$39.03	2	22.1	22.1	22.1
1979	2.1	$23.93	2	$33.25	2	19.3	19.3	19.3
1980	2.5	$22.22	2	$27.81	2	14.0	14.0	14.0
1981	4.5	$19.65	2	$25.17	2	24.6	24.6	24.6
1982	5.0	$17.09	5	$24.39	2	221.4	208.3	192.9
1983	5.2	$14.53	5	$23.62	2	231.7	218.6	203.1
1984	5.4	$11.96	5	$22.84	2	242.1	229.1	213.7
1985	5.5	$9.40	10	$21.99	2	555.3	489.4	419.8
1986	5.7	$8.99	10	$20.82	2	540.5	476.4	408.6
1987	5.8	$8.58	10	$19.65	2	524.1	461.8	396.0
1988	6.0	$8.16	10	$18.49	3	280.9	251.1	219.1
1989	6.2	$7.75	10	$17.32	5	178.0	161.7	144.0
1990	6.3	$7.34	20	$16.16	5	362.2	285.4	217.5
1991	6.5	$6.93	20	$14.99	5	343.8	270.8	206.2
1992	6.6	$6.00	20	$13.83	5	327.5	258.5	197.4
1993	6.8	$5.69	20	$12.66	5	305.7	241.0	183.8
1994	7.5	$4.84	20	$11.50	6	255.6	203.9	157.8
1995	9.0	$4.53	20	$10.33	8	186.6	152.4	121.5
1996	9.7	$3.93	20	$9.36	10	143.5	120.3	98.9
1997	11.7	$3.77	25	$9.18	10	224.2	175.0	134.0
1998	11.9	$3.71	25	$8.99	10	223.3	174.2	133.3
1999	17.2	$3.45	25	$8.58	10	309.4	241.7	185.3
2000	21.5	$2.96	25	$8.16	10	375.3	294.8	227.7
2001	29.0	$3.00	25	$7.75	10	475.1	372.0	286.1
2002	44.4	$2.85	25	$7.34	20	281.0	255.1	232.1
2003	63.0	$2.91	25	$6.93	20	362.2	327.5	296.8
2004	100.8	$2.80	25	$6.46	20	532.2	480.4	434.5
2005	103.0	$2.96	25	$6.00	20	466.6	417.5	374.0
2006	145.0	$2.67	25	$5.85	20	672.0	604.6	544.9
2007	206.5	$2.11	25	$5.69	20	1,034.8	941.2	858.4
2008	338.0	$1.92	25	$5.27	20	1,574.1	1,432.5	1,307.1
Total						**11,319.5**	**9,835.5**	**8,484.8**

Sources: Authors' calculations. See also section 5.1.

Table F-2. Total PV Module Technology Benefits, by Social Discount Rate (2008$)

Year	Economic Benefits Non-U.S. Installations ($ million)	Total PV Module Technology Benefits 0% SDR ($ million)	Total PV Module Technology Benefits 3% SDR ($ million)	Total PV Module Technology Benefits 7% SDR ($ million)
1976	—	—	—	—
1977	—	10.5	10.5	10.5
1978	—	22.1	22.1	22.1
1979	—	19.3	19.3	19.3
1980	—	14.0	14.0	14.0
1981	—	24.6	24.6	24.6
1982	—	221.4	208.3	192.9
1983	3.9	235.5	222.4	207.0
1984	9.8	251.9	238.9	223.5
1985	28.6	583.9	518.1	448.5
1986	18.5	559.1	494.9	427.1
1987	33.3	557.4	495.2	429.3
1988	57.3	338.2	308.4	276.3
1989	78.9	256.9	240.6	222.8
1990	77.9	440.0	363.3	295.4
1991	88.7	432.5	359.5	294.9
1992	93.7	421.2	352.1	291.1
1993	109.0	414.7	350.0	292.7
1994	124.9	380.5	328.8	282.7
1995	150.7	337.2	303.1	272.1
1996	163.6	307.2	284.0	262.5
1997	212.8	437.1	387.8	346.8
1998	221.7	445.0	396.0	355.1
1999	223.3	532.7	465.0	408.7
2000	278.6	653.9	573.4	506.3
2001	340.0	815.1	712.0	626.0
2002	373.9	654.8	628.9	606.0
2003	159.2	521.4	486.7	456.0
2004	138.9	671.1	619.3	573.4
2005	227.7	694.3	645.1	601.6
2006	389.7	1,061.7	994.3	934.6
2007	881.4	1,916.2	1,822.6	1,739.8
2008	2,287.0	3,861.1	3,719.5	3,594.1
Total	**6,773.0**	**18,092.5**	**16,608.5**	**15,257.8**

Sources: Authors' calculations. See also section 5.1.

Table F-3. DOE Investment in Photovoltaic Energy Systems, 1975–2008

Year	Total, Photovoltaic Energy Systems (nominal millions)	Total, Solar Energy Program (nominal millions)	Deflator	Total, Photovoltaic Energy Systems (2008$ millions)	Total, Solar Energy (2008$ millions)
1975	0.60	0.60	0.31	1.94	1.94
1976	21.56	89.21	0.33	65.90	272.69
1977	59.40	248.31	0.35	170.69	713.57
1978	76.20	232.10	0.37	204.61	623.24
1979	118.80	324.10	0.40	294.50	803.44
1980	150.05	378.10	0.44	340.88	858.97
1981	151.60	363.17	0.48	314.91	754.39
1982	74.00	152.05	0.51	144.87	297.68
1983	57.92	118.96	0.53	109.07	224.04
1984	50.18	110.23	0.55	91.09	200.07
1985	54.65	97.73	0.57	96.28	172.18
1986	40.30	74.02	0.58	69.47	127.59
1987	40.25	46.15	0.60	67.43	77.30
1988	34.69	56.90	0.62	56.17	92.14
1989	35.15	52.26	0.64	54.85	81.56
1990	34.33	54.25	0.67	51.58	81.51
1991	46.07	67.09	0.69	66.85	97.35
1992	60.00	90.75	0.71	85.04	128.64
1993	64.90	94.81	0.72	90.00	131.49
1994	74.88	111.05	0.74	101.70	150.83
1995	83.84	118.50	0.75	111.54	157.66
1996	61.27	87.20	0.77	79.99	113.86
1997	59.21	83.41	0.78	75.97	107.02
1998	64.69	83.63	0.79	82.07	106.10
1999	70.56	90.91	0.80	88.22	113.66
2000	64.57	81.41	0.82	79.02	99.63
2001	74.26	91.69	0.84	88.87	109.73
2002	65.46	87.11	0.85	77.09	102.58
2003	73.25	82.33	0.87	84.44	94.91
2004	72.54	80.73	0.89	81.32	90.50
2005	65.84	75.73	0.92	71.43	82.15
2006	32.41	41.14	0.95	34.05	43.22
2007	138.37	157.03	0.98	141.33	160.38
2008	136.74	166.32	1.00	136.74	166.32
Total	**2,308.52**	**4,088.98**		**3,709.91**	**7,438.33**

Table F-4. Lower Bound Net Economic Benefits from DOE Investment in Photovoltaic Energy Systems, by Social Discount Rate (2008$)

Year	Total Economic Benefits 0% SDR ($ million)	Total Economic Benefits 3% SDR ($ million)	Total Economic Benefits 7% SDR ($ million)	Total Costs, Photovoltaic Energy Systems ($ million)	Net Economic Benefits 0% SDR ($ million)	Net Economic Benefits 3% SDR ($ million)	Net Economic Benefits 7% SDR ($ million)
1975	—	—	—	(1.9)	(1.9)	(1.9)	(1.9)
1976	—	—	—	(65.9)	(65.9)	(65.9)	(65.9)
1977	10.5	10.5	10.5	(170.7)	(160.2)	(160.2)	(160.2)
1978	22.1	22.1	22.1	(204.6)	(182.5)	(182.5)	(182.5)
1979	19.3	19.3	19.3	(294.5)	(275.2)	(275.2)	(275.2)
1980	14.0	14.0	14.0	(340.9)	(326.9)	(326.9)	(326.9)
1981	24.6	24.6	24.6	(314.9)	(290.3)	(290.3)	(290.3)
1982	221.4	208.3	192.9	(144.9)	76.6	63.4	48.0
1983	235.5	222.4	207.0	(109.1)	126.5	113.4	97.9
1984	251.9	238.9	223.5	(91.1)	160.8	147.8	132.4
1985	591.2	525.3	455.7	(96.3)	494.9	429.1	359.4
1986	566.3	502.2	434.4	(69.5)	496.9	432.7	364.9
1987	567.5	505.3	439.5	(67.4)	500.1	437.9	372.0
1988	348.4	318.5	286.5	(56.2)	292.2	262.3	230.3
1989	267.1	250.7	233.0	(54.8)	212.2	195.9	178.1
1990	450.2	373.4	305.5	(51.6)	398.6	321.9	253.9
1991	442.7	369.6	305.0	(66.8)	375.8	302.8	238.2
1992	431.3	362.3	301.3	(85.0)	346.3	277.3	216.2
1993	424.8	360.1	302.9	(90.0)	334.8	270.1	212.9
1994	390.7	339.0	292.9	(101.7)	289.0	237.3	191.2
1995	347.8	313.7	282.7	(111.5)	236.3	202.2	171.2
1996	324.7	301.5	280.1	(80.0)	244.7	221.5	200.1
1997	456.0	406.8	365.7	(76.0)	380.0	330.8	289.8
1998	491.2	442.1	401.2	(82.1)	409.1	360.0	319.2
1999	577.0	509.4	453.0	(88.2)	488.8	421.2	364.8
2000	697.4	616.9	549.8	(79.0)	618.4	537.9	470.8
2001	857.8	754.7	668.8	(88.9)	768.9	665.8	579.9
2002	697.6	671.7	648.7	(77.1)	620.5	594.6	571.6
2003	564.2	529.5	498.7	(84.4)	479.7	445.0	414.3
2004	713.9	662.0	616.2	(81.3)	632.5	580.7	534.8
2005	739.5	690.3	646.8	(71.4)	668.0	618.9	575.4
2006	1,109.1	1,041.6	981.9	(34.0)	1,075.0	1,007.6	947.9
2007	1,965.5	1,871.9	1,789.1	(141.3)	1,824.1	1,730.6	1,647.8
2008	3,913.7	3,772.1	3,646.8	(136.7)	3,776.9	3,635.3	3,510.0
Total	**18,734.8**	**17,250.8**	**15,900.0**	**(3,709.9)**	**15,024.9**	**13,540.9**	**12,190.1**

Source: Authors' calculations.

Table F-5. Economic Benefits Attributable to PVMaT and TFP (2008$)

Year	Actual Production Cost per Watt Benefit ($/W)	Total Quantity (MW)	Economic Benefits ($ millions)	Implied Average Production Cost per Watt Benefit ($/W)
1990	—	15.2	—	—
1991	—	17.5	—	—
1992	0.47	18.6	7.89	0.42
1993	0.30	22.4	6.30	0.28
1994	1.01	26.3	24.54	0.93
1995	1.17	35.0	38.85	1.11
1996	1.34	39.8	50.00	1.26
1997	1.06	51.1	50.99	1.00
1998	0.97	53.9	46.84	0.87
1999	1.07	60.8	57.82	0.95
2000	1.27	75.0	83.95	1.12
2001	0.93	100.5	80.62	0.80
2002	0.88	127.6	96.61	0.76
2003	0.86	102.6	75.01	0.73
2004	0.80	138.7	112.22	0.73
2005	0.84	178.1	165.74	1.01
2006	1.10	267.8	315.42	1.24
2007	1.12	452.2	672.30	1.23
2008	0.77	1,022.6	1,164.16	0.89
Total			**3,061.47**	

Sources: Christensen (1985); Maycock (1986–2004); *PV News* 2005-2009; Watts et al. (1984); EIA (2008); IEA (2009); authors' calculations.

Table F-6. Sensitivity Analysis: Net Economic Benefits of 10-Year FSA Technology Acceleration (2008$)

Year	Actual		Counterfactual		Total Economic Benefits ($ million)	Total Costs, Photovoltaic Energy Systems ($ million)	Net Economic Benefits ($ million)
	Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)			
1975						(1.9)	(1.9)
1976	$53.28	2	53.28	2		(65.9)	(65.9)
1977	$37.60	2	45.44	2	9.6	(170.7)	(161.1)
1978	$25.64	2	37.60	2	19.7	(204.6)	(184.9)
1979	$23.93	2	31.62	2	16.0	(294.5)	(278.6)
1980	$22.22	2	25.64	2	8.5	(340.9)	(332.3)
1981	$19.65	2	24.78	2	22.9	(314.9)	(292.0)
1982	$17.09	5	23.93	2	215.6	(144.9)	70.7
1983	$14.53	5	23.07	2	228.2	(109.1)	119.2
1984	$11.96	5	22.22	2	243.0	(91.1)	151.9
1985	$9.40	10	20.94	2	559.8	(96.3)	463.5
1986	$8.99	10	19.65	2	531.4	(69.5)	461.9
1987	$8.58	10	18.37	2	296.2	(67.4)	228.8
1988	$8.16	10	17.09	2	215.8	(56.2)	159.7
1989	$7.75	10	15.81	2	223.6	(54.8)	168.7
1990	$7.34	20	14.53	2	394.5	(51.6)	343.0
1991	$6.93	20	13.25	2	378.1	(66.8)	311.3
1992	$6.00	20	11.96	2	359.5	(85.0)	274.4
1993	$5.69	20	10.68	2	243.1	(90.0)	153.1
1994	$4.84	20	9.40	5	200.5	(101.7)	98.8
1995	$4.53	20	9.19	5	256.5	(111.5)	144.9
1996	$3.93	20	8.99	5	306.2	(80.0)	226.2
1997	$3.77	25	8.58	10	414.9	(76.0)	338.9
1998	$3.71	25	8.16	10	432.0	(82.1)	350.0
1999	$3.45	25	7.75	10	505.7	(88.2)	417.4
2000	$2.96	25	7.34	10	411.7	(79.0)	332.7
2001	$3.00	25	6.93	10	488.0	(88.9)	399.1
2002	$2.85	25	6.46	20	575.9	(77.1)	498.8
2003	$2.91	25	6.00	20	453.9	(84.4)	369.5
2004	$2.80	25	5.85	20	612.8	(81.3)	531.5
2005	$2.96	25	5.69	20	678.0	(71.4)	606.6
2006	$2.67	25	5.27	20	932.7	(34.0)	898.6
2007	$2.11	25	4.84	20	1,283.1	(141.3)	1,141.8
2008	$1.92	25	4.68	20	2,872.3	(136.7)	2,735.6
Total					**14,389.8**	**(3,709.9)**	**10,681.8**

Sources: Authors' calculations. See also section 5.1.

Table F-7. Sensitivity Analysis: Net Economic Benefits of 15-Year FSA Technology Acceleration (2008$)

Year	Actual		Counterfactual		Total Economic Benefits ($ million)	Total Costs, Photovoltaic Energy Systems ($ million)	Net Economic Benefits ($ million)
	Cost ($/W)	Reliability (Years)	Cost ($/W)	Reliability (Years)			
1975			83.86	2	—	(1.9)	—
1976	$53.28	2	53.28	2	—	(65.9)	(65.90)
1977	$37.60	2	47.01	2	11.5	(170.7)	(159.19)
1978	$25.64	2	40.74	2	24.9	(204.6)	(179.72)
1979	$23.93	2	35.21	2	23.4	(294.5)	(271.11)
1980	$22.22	2	30.42	2	20.5	(340.9)	(320.37)
1981	$19.65	2	25.64	2	26.7	(314.9)	(288.23)
1982	$17.09	5	24.95	2	228.5	(144.9)	83.62
1983	$14.53	5	24.27	2	244.3	(109.1)	135.24
1984	$11.96	5	23.59	2	262.6	(91.1)	171.50
1985	$9.40	10	22.90	2	618.6	(96.3)	522.29
1986	$8.99	10	22.22	2	608.3	(69.5)	538.79
1987	$8.58	10	21.19	2	617.1	(67.4)	549.68
1988	$8.16	10	20.17	2	633.0	(56.2)	576.82
1989	$7.75	10	19.14	2	509.9	(54.8)	455.02
1990	$7.34	20	18.12	2	661.6	(51.6)	610.05
1991	$6.93	20	17.09	2	520.1	(66.8)	453.26
1992	$6.00	20	16.07	2	517.5	(85.0)	432.44
1993	$5.69	20	15.04	2	526.7	(90.0)	436.67
1994	$4.84	20	14.01	5	566.5	(101.7)	464.78
1995	$4.53	20	12.99	5	657.1	(111.5)	545.55
1996	$3.93	20	11.96	5	685.6	(80.0)	605.58
1997	$3.77	25	10.94	10	714.2	(76.0)	638.19
1998	$3.71	25	9.91	10	590.3	(82.1)	508.22
1999	$3.45	25	9.32	10	641.3	(88.2)	553.05
2000	$2.96	25	9.15	10	803.5	(79.0)	724.44
2001	$3.00	25	8.99	10	1,035.8	(88.9)	946.97
2002	$2.85	25	8.58	20	1,345.0	(77.1)	1,267.95
2003	$2.91	25	8.16	20	1,353.4	(84.4)	1,268.97
2004	$2.80	25	7.75	20	1,902.0	(81.3)	1,820.65
2005	$2.96	25	7.34	20	1,013.3	(71.4)	941.88
2006	$2.67	25	6.93	20	1,438.0	(34.0)	1,403.99
2007	$2.11	25	6.46	20	2,351.9	(141.3)	2,210.57
2008	$1.92	25	6.00	20	4,722.8	(136.7)	4,586.02
Total					**25,875.7**	**(3,709.9)**	**22,167.68**

Sources: Authors' calculations. See also section 5.1.

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