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Linkages from DOE's Solar Photovoltaic R&D to Commercial Renewable Power from Solar Energy

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This report uses bibliometric analysis to trace linkages of knowledge outputs from solar photovoltaic research and development (R&D) by the Solar Energy Technologies Program of the U.S. Department of Energy (DOE), to downstream innovations in renewable electricity generation and other areas. The report is prepared for DOE under Purchase Order No. 933589 of Sandia National Laboratories in Albuquerque, New Mexico. Sandia is operated by Sandia Corporation, a subsidiary of Lockheed Martin Corporation.

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Rosalie Ruegg of TIA Consulting, Inc. led the study and was joined by Patrick Thomas of 1790 Analytics LLC, as co-researcher and report co-author. Laura LaMonica of LaMonica Associates provided assistance with publication citation analysis.

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Any errors contained in this report remain solely the authors' responsibility.

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Executive Summary

Background

The U.S. Department of Energy's (DOE) Solar Photovoltaic R&D Subprogram promotes the development of cost-effective systems for directly converting solar energy into electricity for residential, commercial, and industrial applications.

Over the period 1975 to 2008, DOE spent more than $2.3 billion (nominal dollars) on R&D to advance photovoltaic (PV) technology. DOE established five major partnership initiatives with industry, funded university research, conducted research in the DOE national laboratories, provided analytical services and measurement characterizations to companies and other organizations, worked collaboratively with others in the field, and carried out activities to advance the development and deployment of PV technology. During this period of DOE's investment in PV research, production costs per watt of PV modules fell dramatically from more than $100 in the mid-1970s to between $1.00 and $2.00 per watt by 2008, while system reliability increased from just 2 years to more than 25 years over the same period. U.S. installed PV capacity rose from essentially none at the beginning of the period to approximately 1.1 gigawatts in 2008. (See Chapter 2.)

Study Purpose

This study was commissioned to assess the extent to which the knowledge outputs of R&D funded by the DOE Solar PV Subprogram are linked to downstream developments in commercial renewable power. A second purpose was to identify spillovers of the resulting knowledge to other areas of application. A third purpose was to lend support to a parallel benefit-cost study by contributing evidence of attribution of benefits to DOE. (See Chapter 1.)

Study Methods

Bibliometric methods—namely patent and publication analyses—are the primary tools used by this study to trace the creation and dissemination of knowledge outputs of DOE's photovoltaic R&D investment into downstream use. These tools are supplemented by review of documents and databases, and, to a limited extent, interview.

When looking for connections between knowledge creation in an applied research program and downstream commercial developments, patents are of particular interest because they are considered close to commercial application. Patent citation analysis provides objective, quantitative results, and has been used extensively in the study of technological change.

The study's patent analysis traces back from the solar innovations of leading companies in the industry to determine the extent they have built on earlier DOE-funded PV R&D. This part of the analysis is referred to as "backward patent tracing." The backward patent tracing is performed starting with two groups of company solar energy patents: (1) those of the top U.S. producers of PV, and (2) those of the leading company innovators in solar energy worldwide.

The study traces forward from solar PV innovations attributed to DOE to assess the broader influence of DOE-funded PV R&D on subsequent innovations both within and outside the field of solar energy. This part of the analysis is referred to as "forward patent tracing."

Both backward and forward patent tracing are performed at two levels: (1) the organizational level, and (2) the individual patent level. This approach provides both a comparative assessment of DOE's influence on other organizations and identifies noteworthy inventions. Using backward and forward tracing of patents at both the organizational and patent levels helps to determine the extent to which the results of DOE-funded PV research has been taken up by companies pursuing the commercialization of solar energy in general, and PV in particular, as well as by companies in other fields; and it helps to identify particularly influential patents attributed to DOE-funded PV R&D.

The study uses publications analysis to extend the assessment of explicit knowledge outputs attributable to DOE-funded PV R&D. An analysis of co-authoring shows the extent to which collaboration on authoring publications has been a path of knowledge dissemination. Citation analysis shows how frequently these publications have been referenced and who referenced them.

The study supplemented the bibliometric analysis with interviews and document review to assess other linkages between DOE and companies and universities. Other linkages included laboratory prototypes; test measurement and data characterizations; training of students and researchers; and increased public awareness of PV as an alternative energy resource. (See Chapter 3.)

Findings

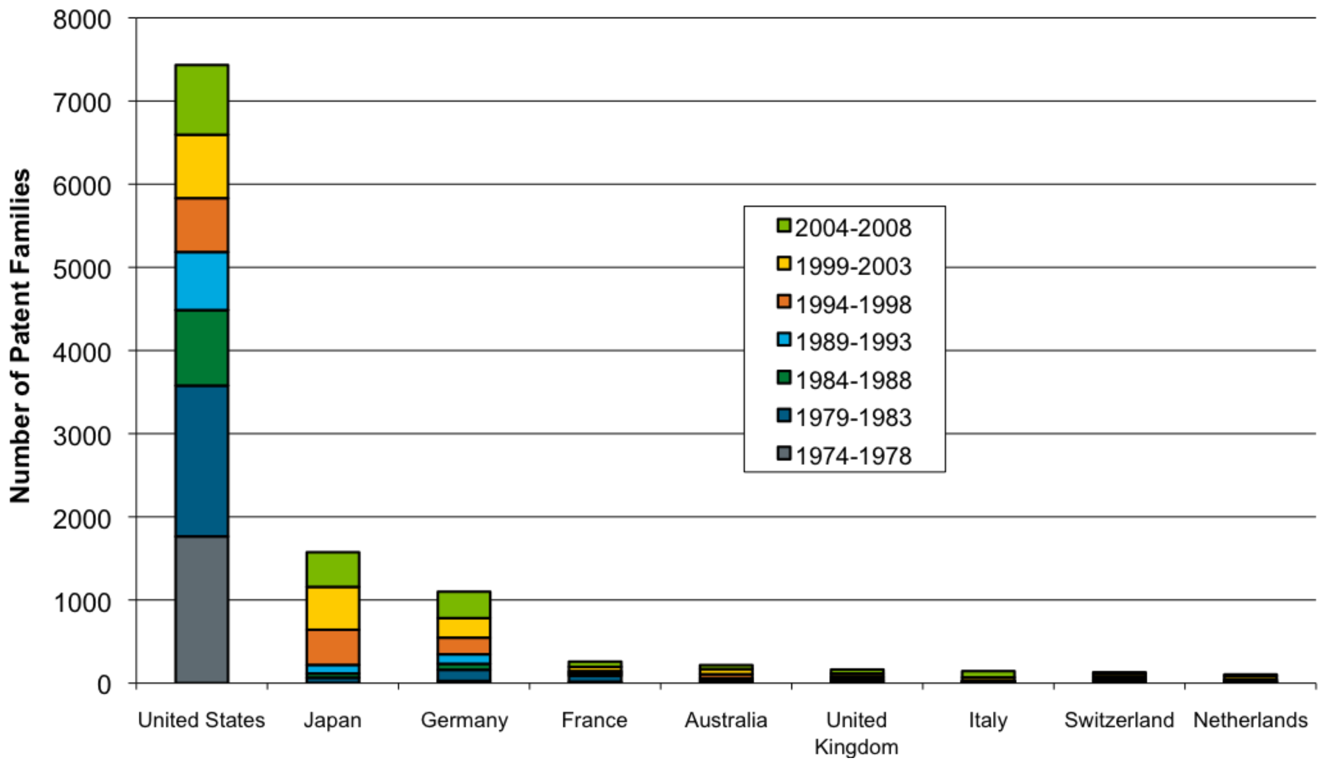
To reveal the extent to which the results of DOE's PV research have influenced technological and commercial advancements in solar PV, the study answers a detailed list of study questions. (See Chapter 3, Table 3-1). Here, for brevity, the questions are implied and the focus is on the answers.

An overview of patenting in solar PV and solar energy more broadly revealed the following:

- Among the knowledge outputs of DOE's Solar PV Subprogram are an estimated 274 patent families (where a patent family contains all patents based on the same invention).
- These 274 patent families attributed to DOE-funded PV R&D contain a total of 343 U.S. patents, 75 European Patent Office (EPO) patents, and 113 patent applications filed with the World Intellectual Property Organization (WIPO).
- The total population of solar energy patent families (inclusive of PV and other patents) is 13,156, of which 609 are assigned to the top eight U.S. producers of solar PV, and 1,812 to the 10 leading innovators in solar energy worldwide.
- Solar energy patenting in the United States has outstripped that in other countries in every five-year interval from 1974 through 2008, as shown by Figure ES-1.

- Most of the impact of DOE-attributed PV patents has been on subsequent technologies developed in the United States.

Figure ES-1. Number of Solar Energy Patent Families by Priority Year and Country of Priority Issue, 1974-2008



A principal conclusion of the backward patent analysis at the organizational level is that DOE's solar PV research has generated a knowledge base on which further innovations by leading commercial companies in solar energy in general, and solar PV in particular, have built. The following points provide evidence of DOE's role in generating an influential knowledge base:

- Patents of the top U.S. producers of solar PV are closely linked to earlier DOE-attributed PV patents. These top companies are Energy Conversion Devices (ECD) (and its subsidiary, Uni-Solar), Solar World, BP Solar, First Solar, Schott, Evergreen Solar, Global Solar, and SunPower. (See Section 4.2.1, especially Figures 4-9 through 4-12 for details.)
- Patents of nearly all of the leading innovators in solar energy worldwide are also closely linked to earlier DOE-attributed solar PV patents. These companies include Boeing, Canon, ExxonMobil, Sanyo, Sharp, Siemens, General Electric, Mitsubishi Electric and, again, ECD/Uni-Solar, and BP Solar. Of the more than 1,800 solar energy patent families of these 10 leading companies, 30% are linked to earlier DOE-attributed solar PV patents. (See Section 4.2.2, especially Figures 4-13 and 4-14 for details.)

A principal conclusion of the forward patent tracing analysis conducted at the organizational level is that DOE's solar PV research has influenced innovations beyond PV applications, such as in the broader semiconductor industry. The following points provide supporting evidence of DOE's broader influence:

- DOE-attributed PV patents are strongly linked to patents of organizations prominent in the semiconductor industry, notably Micron, Semiconductor Energy Lab, Applied Materials, and IBM. (See Section 4.3.1, especially Figure 4-15.)
- Over time, the influence of DOE research related to PV thin film technology has spread extensively to the broader semiconductor device industry, as indicated by a two-generation analysis of patenting. (See Section 4.3.1)
- While the influence of DOE-funded PV research is particularly strong on developments related to the design and manufacture of PV cells and other semiconductor devices, influence on other technology fields, such as nanotechnology, and to a lesser extent Light Emitting Diodes (LEDs), image sensors, coating methods, measuring and testing, and crystal growth is also noteworthy. (See Section 4.3.1, especially Figure 4-16, and also Section 4.4.5 and Tables 4-9, 4-10 and 4-11.)

At the individual patent level, the backward and forward patent tracing analyses provide multiple lines of evidence to identify noteworthy patents among the set attributed to DOE or linked to that set. Among the noteworthy patents are the following:

- BP Solar patents describing multi-junction solar cells formed from amorphous silicon and copper indium diselenide, and a PV module framing system for mounting on roof surfaces; First Solar patents describing PV arrays; SunPower patents describing photovoltaic roof shingle systems, as well as photovoltaic module frames; Sanyo patents describing two-sided weatherproof photovoltaic modules, and a thin film amorphous silicon photovoltaic device; a Canon patent describing a stacked PV device; a General Electric patent describing silicon thin-film, integrated solar cell, module, and methods of manufacturing; and a Boeing patent describing a solar tile and an associated fabrication method. These are noteworthy because they belong to the top U.S. producers of solar PV and leading innovators in solar energy worldwide and have the most citation links to earlier DOE-attributed PV patent families. (See Section 4.4.1, especially Tables 4-1 and 4-2.)
- ECD patents describing thin-film fabrication; SunPower patents for series connected solar cells and PV assemblies; BP patents detailing PV framing systems and thin-film cells; an Evergreen Solar patent describing a UV stabilizer for a solar cell; BP Solar patents describing PV framing systems; several Canon patents including one describing a solar cell fabrication method that helps to reduce damage to the substrate; three Sharp patents including one describing a pin junction PV device; four ECD patents variously describing fabrication of thin film cells and a self-adhesive PV module; an ExxonMobil patent describing a solar cell with two-dimensional hexagonal reflecting diffraction grating; as well as patents by Sanyo on a method of manufacturing polycrystalline semi-conductive film, several other BP solar patents, several Boeing patents, and one owned by Mitsubishi. These are noteworthy because they are high-impact patents of the top U.S. producers of solar PV and leading innovators in solar energy worldwide that are linked to

earlier DOE-attributed PV patent families. (See Section 4.4.2, especially Tables 4-3 and 4-4.)

- Highly cited patents outside solar energy—mainly concerning semiconductor device fabrication— are also among the noteworthy, including ASM International's patent describing sequential chemical vapor deposition; Princeton University's patent describing organic LEDs; and AmKor Technology's patent describing a wafer scale image sensor package. (See Section 4.4.3, especially Tables 4-5 and 4-6.)
- A number of DOE-attributed PV patent families are noteworthy. These include those linked strongly to patent families of leading innovators in solar energy worldwide, including patents describing a solar cell constructed from multiple layers of amorphous silicon, and those describing processing techniques for producing the cells, Schottky barriers for cells, and the connection of cells to produce solar batteries (assigned to General Electric); patents pertaining to thin film solar cells, including one describing a method for increasing the light absorption of thin film cells while reducing the roughness of the electrical junction (assigned to University of Delaware); and patents describing large area copper indium diselenide (CIS) thin film solar cells (assigned to Boeing). (See Section 4.4.4, especially Table 4-7.)
- Other noteworthy DOE-attributed PV patent families are those most highly cited overall—taking into account all organizations and fields—some of which have been previously mentioned as noteworthy based on other criteria. These include patents describing thin film PV devices that increase light absorption (assigned to ECD); a patent describing multiple layers of amorphous silicon (assigned to General Electric); patents describing chalcopyrite compounds for thin film cells (assigned to Boeing); patents describing the detection of defects in solar cells (assigned to DOE); a patent describing large grain amorphous films (assigned to MIT); a patent describing multiple gap PV devices (assigned to the University of Delaware); patents describing light harvesting rods for regenerative solar cells (assigned to NC State University); a patent describing a PV assembly and mounting apparatus for the module (assigned to SunPower); and a recent patent, which is the most highly cited given its age and technology area, describing nanowires, useful not only for PV but in a variety of energy conversion applications (assigned to the University of California based on work done at Lawrence Berkeley National Laboratory (LBNL)). (See Section 4.4.5, especially Table 4-9.)

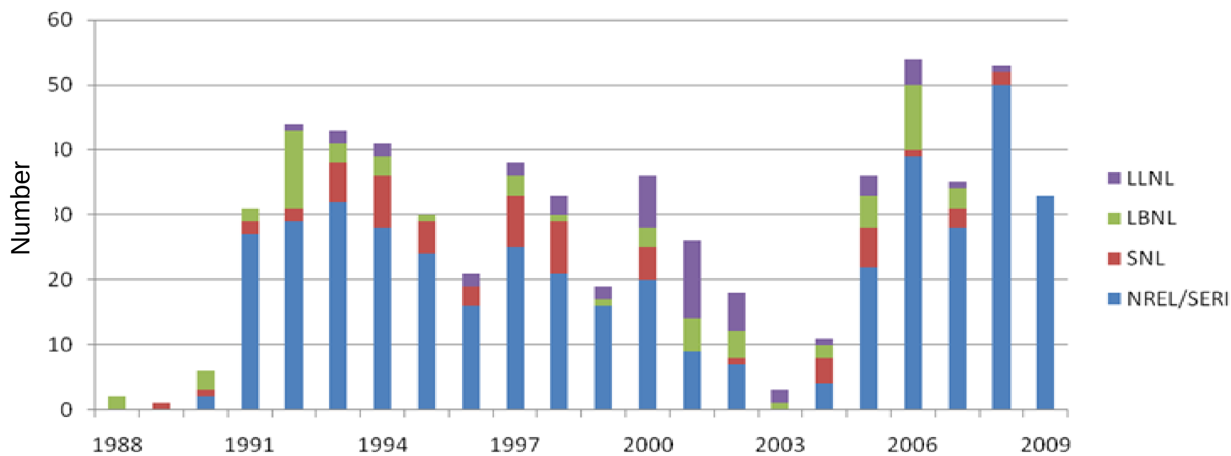
DOE solar PV publications, numbering more than 1,000 and comprising mainly technical reports and conference reports, have also provided a means of capturing and disseminating the results of DOE-funded PV research to organizations around the world.

Figure ES-2 shows the distribution of DOE-sponsored PV publications by year for DOE laboratories most active in solar energy research. The points that precede and follow the figure help to characterize dissemination of knowledge through DOE PV publications.

- An analysis of a random sample of NREL technical reports showed authoring by companies in PV research partnerships with DOE to be prominent. (See Section 5.4.1.)

- An analysis of a random sample of NREL conference reports showed authoring by NREL researchers only and co-authoring by NREL researchers with other DOE researchers to be prominent. (See Section 5.4.2.)
- Co-authoring by DOE researchers with outside researchers was not found to have provided an important path of knowledge dissemination in solar PV technology. (See Section 5.4.)
- Co-authoring among NREL researchers and by NREL researchers with other DOE researchers suggests collaborative PV research within NREL and DOE. (See Section 5.4.)

Figure ES-2. DOE Solar PV Publications, by Year and by Organization, 1988-2009



Note: Prior to 1988 there were few DOE publications on solar PV. Data for 2009 are incomplete. The organizations are DOE national laboratories, namely the National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute (SERI); Sandia National Laboratories (SNL); Lawrence Berkeley National Laboratory (LBNL); and Lawrence Livermore National Laboratory (LLNL).

- Publication citation analysis showed that close to 40% of both the samples of NREL technical reports and conference reports have been cited at least once, and a share of these reports were cited more than five times. (See Section 5.5.1.)
- Those citing NREL technical reports within the random sample were most frequently affiliated with government organizations, followed by universities, foreign and domestic national laboratories and institutes, and companies. (See Section 5.5.1.)
- Those citing NREL conference reports within the sample were frequently affiliated with government organizations and foreign national laboratories. Organizations in Spain, Singapore, Germany, the Netherlands, Japan, Austria, Italy, and China were among those citing the NREL conference reports. (See Section 5.5.2.)
- Companies were more often among those citing NREL conference reports than they were among those citing technical reports, despite the fact that companies authored many of the technical reports. (See Section 5.5.2.)

Beyond its linkages to downstream developments through the explicit knowledge outputs of solar PV patents and publications, the DOE Solar PV Subprogram has also achieved knowledge and technology transfer through a variety of other modes, such as the following:

- R&D partnerships with more than 160 companies have provided numerous direct linkages of DOE PV program staff to those positioned to further develop and commercialize the resulting technology advances. For example, First Solar, now a leader in solar PV, with more than $2 billion of revenue in 2009, credited its earlier DOE partnership as instrumental in achieving a breakthrough process. The company won an R&D 100 Award in 2003 for the development of the process that was at the heart of its high volume manufacturing line to lower the cost of PV modules. (See Section 6.1.)
- Discussions and talks presented by DOE staff to diverse audiences, provision of analytical services and measurement characterizations to companies, and collaborative research activities also have transferred the results of DOE-funded PV research to others. (See Section 6.1.)
- More than 100 of the patents for PV technologies developed in the NREL laboratory have been licensed to companies, or options have been arranged for their licensing. PrimeStar Solar, for example, obtained an agreement for the commercial scale-up of a highly efficient thin film cadmium telluride PV technology that was developed at NREL. (See Section 6.2.)
- DOE's funding of PV research at approximately 65 universities across the United States and its support of internships in PV research for undergraduate and graduate students have generated tacit knowledge outputs important to further scientific advancement. (See Section 6.3.)

I. Introduction

Shortly prior to the establishment of the U.S. Department of Energy (DOE) in 1977, its predecessor, the Energy Research and Development Administration (ERDA) issued a national plan that postulated that in the long-term (defined then as post-2000) solar electric energy might have wider applications and could be produced by a variety of methods, including by the use of photovoltaic (PV) technology. At the same time that the future potential of PV was forecasted, it was recognized that there were numerous technical problems that would have to be solved before low-cost, reliable components with long operational lives would make widespread applications of PV feasible. Among the challenges were to identify new materials; develop new approaches for fabricating and engineering components; determine thermodynamic cycles compatible with efficient energy conversion; and establish performance standards and test procedures.[1]

First ERDA, and then DOE made R&D investments aimed at advancing solar PV technology. The goal of the DOE research program in solar PV technology has been to find ways to produce electricity directly from the sun in a clean and cost-efficient manner, in order to foster the development of a robust U.S. PV industry capable of meeting a growing share of U.S. and world electricity demands.

Strategies used by DOE's Solar PV Subprogram to achieve its goals have included research to improve the materials used for PV cells and modules; development and automation of new manufacturing processes to fabricate PV cells and modules; and development of supporting technology infrastructure.

Through 2008, DOE had spent an estimated total of more than $2.3 billion (nominal dollars) to advance PV technology and demonstrate its use. This funding has resulted in numerous advances in PV knowledge and knowhow, and outputs including patents, publications, presentations, prototypes, demonstrations, test data, and trained and experienced researchers in the field.

Over the same three and a half decades of DOE's PV research, dramatic advances have been achieved in PV production. The production cost per watt for solar PV has fallen from over $100/Watt, to between $1-$2/Watt, PV system life has risen from 2 years to 25 years and longer, and cumulative installed PV capacity in the United States has increased from a negligible amount to approximately 1.1 GW in 2008. But are there identifiable and even measurable linkages between the outputs of DOE's PV research and the observed PV technology and commercial advances? This question motivates the evaluation study.

[1]Sandia National Laboratories (March 1977), and Argonne National Laboratory (1978).

1.1 Overview of the Evaluation Study

This study is responsive to congressional and administrative directives for evaluation of federal programs, as well as to the needs of DOE program managers. It assesses how the outputs of DOE-funded PV research have been disseminated and applied to downstream technical and commercial advances in PV and beyond. It uses bibliometric methods to trace from the explicit Program outputs of patents and publications to downstream innovation in PV, in solar energy more broadly, and to innovations in other areas. Bibliometric methods are supplemented by other methods in limited ways to extend the assessment to other important modes of DOE PV outputs, such as laboratory prototypes and human capital.

Identifying and documenting linkages reveal pathways through which the R&D results have been disseminated. Comparisons of DOE's knowledge outputs in the field of PV with those of other organizations help to show the relative importance of the role that DOE has played in advancing this form of renewable energy. Moreover, the study of linkages from knowledge outputs of DOE's R&D in solar PV to downstream developments reveals the extent to which this research has influenced solar technology and other fields. In addition, the results of the current study have lent support to a parallel benefit-cost study[2] by contributing evidence of attribution of benefits to DOE.

1.2 Report Organization

The report is presented in an executive summary, six chapters, and two appendices.

Chapter 2, "Background", provides contextual background for the study's analysis. It presents a brief primer on PV technologies; gives an overview of trends in PV performance, costs, and system life expectancies from the mid-1970s through 2008; briefly characterizes the U.S. and world PV markets; and presents a brief overview of the DOE Solar PV Subprogram. It identifies major solar PV funding initiatives by DOE, and shows annual budget data.

Chapter 3, "Evaluation Methodology", presents the bibliometric evaluation methodology featured in the study. It explains why patent analysis is particularly suitable for tracing knowledge outputs from a federal civilian applied research program to its downstream applications. It also describes other methodologies used in the study.

Chapter 4, "Patent Analysis", presents the results of patent analysis. Appendix A supplements Chapter 4 with details on construction of key patent and company data needed for the analysis, and Appendix B lists the individual patents traced in the study.

Chapter 5, "Publication Analysis", presents the results of the publication analysis. Random samples of technical reports and conference reports issued by the National Renewable Energy Laboratory (NREL) and its predecessor, the Solar Energy Research Institute (SERI), are

[2] For the referenced benefit-cost study of DOE's investment in Photovoltaic Energy Systems, including a lower-bound estimate of the rate of return on investment, see O'Connor, et al. (August 2010).

analyzed, both for co-authorship and for citations. These comprise the predominant types of DOE solar PV publications.

Chapter 6, "Other Effects", discusses other important modes of linkages from knowledge outputs of the DOE Solar PV Subprogram to those involved downstream in commercial power generation. Featured are DOE R&D partnerships with approximately 160 companies; licensing of DOE solar energy intellectual property to others; and DOE support of at least 65 universities across the nation to conduct research in PV, and related training of students and researchers.

A list of references and two appendices conclude the report.

2. Background

Among the notable events in the timeline of solar PV history are: the first recognition of the photovoltaic effect in 1839; the first use of solar panels on a spacecraft in 1958; the first time solar cell production for terrestrial use passed the 1 GW mark in 2004; and the first time the 40% efficiency barrier was broken in 2009.[3] To provide context for the study's tracing analysis, this chapter supplies background material. It provides a brief overview of PV technologies; gives an overview of trends in PV performance, costs, and system life expectancies; briefly characterizes the U.S. and world PV markets; and presents a brief overview of the DOE PV Subprogram.

2.1 About PV Devices

PV cells are electrical semiconductors. Traditionally, PV hardware consists of solid-state PV cells that are connected to form modules. The modules are connected to form arrays. The rest of the system, referred to as "balance of system" (BOS) components, typically includes electrical connections, mounting hardware, power-conditioning equipment, and energy storage.

From the outset, silicon was used to fabricate cells, using semiconductor fabrication methods. Types of silicon PV cells are (1) single-crystal silicon, (2) polycrystal silicon (also known as multicrystal silicon), (3) ribbon silicon, and (4) amorphous silicon (aSi) (also known as thin-film silicon).

Single-crystal PV cells are made from thin wafers sliced from purified, melted, crystallized silicon ingots. Polycrystalline silicon cells are made in a similar manner, but from a lower-cost silicon. Ribbon silicon cells are made by growing a ribbon from molten silicon rather than slicing wafers from an ingot, but ribbon silicon cells have a crystalline structure as do the previous two types. Amorphous or thin-film silicon cells, in contrast, do not have a crystalline structure, but rather are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal. The first three types of cells, with their crystalline structures, have higher efficiencies than the amorphous silicon cells, but the amorphous silicon (thin-film) cells are cheaper to produce. Of the crystalline structures, the single-crystal cells tend to cost more. In general, producing thin-film modules tends to require less energy and less overall production costs than conventional silicon wafers.

The types of materials used for making thin-film solar PV cells have broadened over time. Polycrystalline thin films are made from materials such as copper indium diselenide (CIS), copper indium gallium (di)selenide (CIGS), and cadmium telluride (CdTe). Single-crystalline thin films are made of gallium arsenide (GaAs). Compared with silicon, these other materials generally have higher efficiencies and also higher costs.

Recent revolutionary advances in microsolar technology are resulting in the production of PV particles, made of crystalline silicon. Fabricated using microelectronic and

[3] Raffaelle (2010).

microelectromechanical systems (MEMS), the tiny cells may be fastened to flexible substrates, such as fabric, and molded to unusual shapes. These and other advances in PV technology continue.

2.2 Trends in PV Costs and Reliability

PV technology has evolved over the past 35 years, changing from an exotic form of energy used mainly to provide power in space to one that is encountered in many land-based applications. These land-based applications range from powering electronic devices, to providing electricity where transmission lines are not available, to contributing grid-based electricity supply. Dramatic advances in the technology, characterized by falling production costs, rising collection efficiency, and greatly extended system life, have driven the wider-spread us of PV. At the same time, the United States has the largest exploitable solar resource of any of the industrialized countries in the world.

Table 2-1 tracks progress in terms of declines in PV production costs, increases in module production, and extensions in reliability. It is annotated with corresponding notable technology developments.

Table 2-1. U.S. PV Industry Progress, 1974–2008

Year	Module Production (MW)			Production Cost ($/W)	Reliability (Years)	
	c-Si	Thin Films	Total			Notable Technology Developments
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	**DOE's 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	

Table 2-1. (continued) U.S. PV Industry Progress, 1974–2008

Year	Module Production (MW)			Production Cost ($/W)	Reliability (Years)	
	c-Si	Thin Films	Total			**Notable Technology Developments**
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	**DOE's 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)
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	**DOE's 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 • Funding to AstroPower (GE), BP Solar (Solarex), Evergreen, First Solar, Global Solar, SCHOTT Solar, SolarWorld USA (Arco/Siemens/Shell), SunPower, Uni-Solar
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	

Source: O'Connor, et al. (2010), Table 3-1.

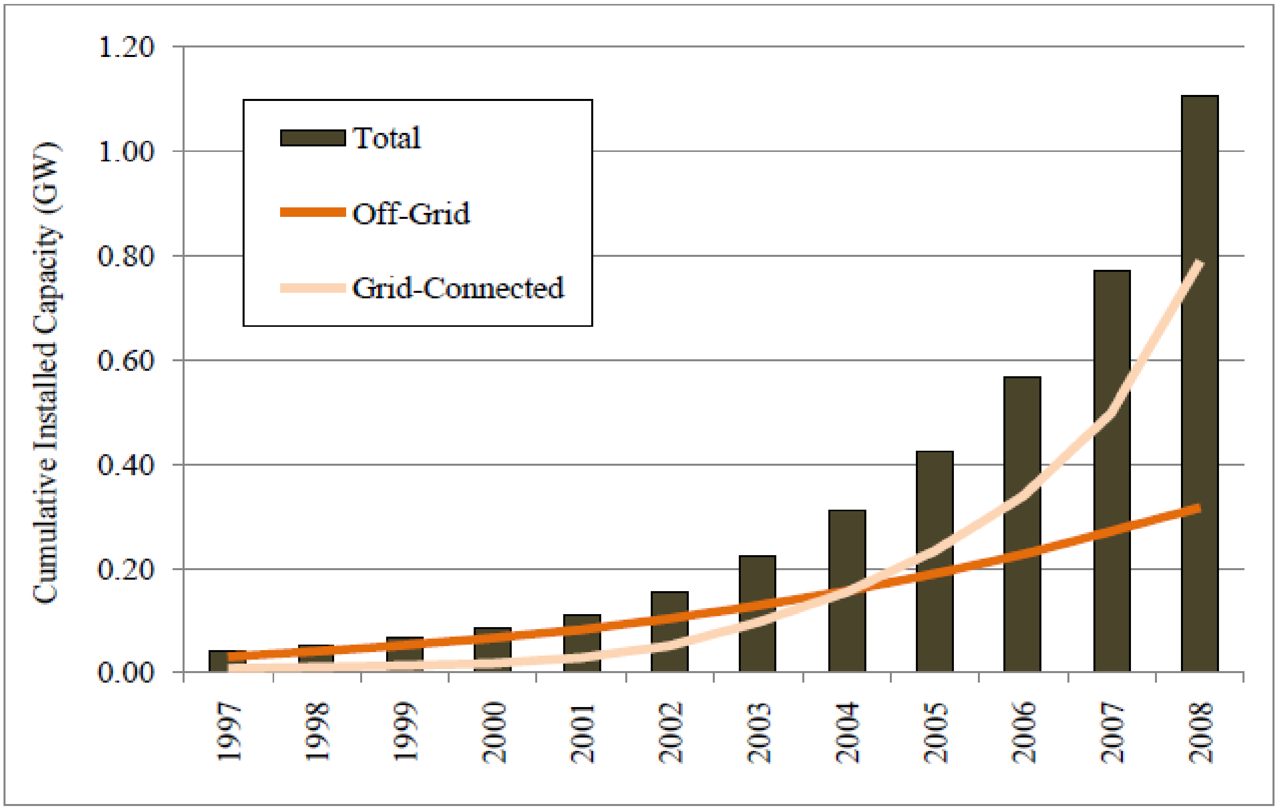
2.3 Trends in Installed PV Capacity

How much PV capacity has been installed in the United States for producing electricity? Figure 2-1 shows the total cumulative installed PV capacity from 1997 through 2008. Prior to the late 1990s, the amount of electricity produced in the nation from PV was negligible. By 2008, total cumulative installed capacity had reached approximately 1.1 GW.

The figure also shows that through the early 2000s, installations of PV were mainly off-grid. But by 2004, grid-connected installations of PV exceeded off-grid installations, and the gap has steadily widened since in favor of grid-connected installations.

In terms of numbers of systems installed, most of the grid-connected installations have been distributed systems for residential applications; and a smaller, but growing number have been centralized grid-connected systems added by the commercial and utility sectors. In terms of capacity added, the much larger systems added in the commercial and utility sectors have greatly exceeded the capacity added by grid-connected residential systems over the last decade.[4]

Figure 2-1. Cumulative Installed PV Capacity in the United States by Interconnection Status



Source: DOE 2008 Solar Technologies Market Report, Fig. 1.6 (2009).

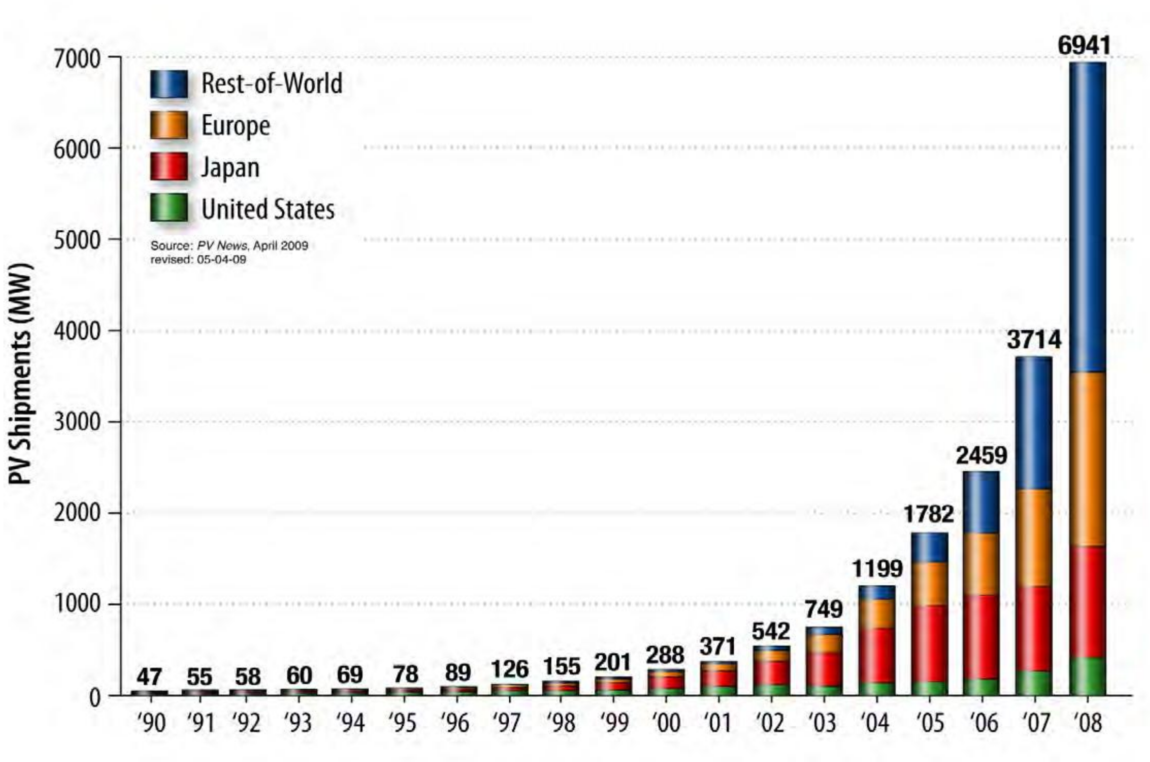
Sixty-seven percent of the cumulative, installed grid-connected PV capacity in the United States was in California, as of the end of 2008. New Jersey was in second place with 9%, Colorado had 4.5%, Nevada had 4%, and Arizona and New York, each had 3%.

Globally, the annual growth in installed PV capacity in the United States has lagged behind that of Germany and Spain, and also, for much of the past decade, Japan. By the end of 2008, the United States had just 8% of the world's cumulative installed PV capacity, while Germany, Spain, and Japan had 38%, 24%, and 15%, respectively.[5]

[4] DOE Solar Technologies Market Report (2008), Figs 1.8 and 1.9.
[5] Ibid., Figs 1.1 and 1.9.

Figure 2-2 shows that the U.S. share of the global PV industry (as indicated by annual PV shipments) has become steadily smaller even as annual U.S. PV shipments have increased. Recently, China has experienced rapid growth in its production of PV modules, and in 2006, China outstripped the United States in terms of global shipments of PV modules. Both China and Taiwan (part of "Rest-of-World" in Figure 2-2) have gained market share as the U.S. market share has declined.[6]

Figure 2-2. Growth of Global PV Industry, Shown in Annual PV Shipments, 1990-2008.



Source: Raffaelle (2010).

Of global annual PV cell/module shipments, those made of polycrystalline silicon comprised the largest share (49%) in 2008. Thin-film PV has become a major competitor of traditional PV cells of crystalline silicon, growing from 5% of the total PV global market share in 2003 to 14% by 2008.[7]

2.4 Overview of DOE's Solar Energy PV Subprogram

Notwithstanding the advances that have been made in PV, further advances in module efficiencies, inverter performance, and improvements in cost, reliability, and balance-of-system components are held critical to the wider commercial success of PV technologies.[8] In the past,

[6] DOE Solar Technologies Market Report (2008), p.21.
[7] Ibid., p. 24.
[8] NREL Photovoltaic Research, Projects (www.nrel.gov/pv/projects.html, effective as of July 2010).

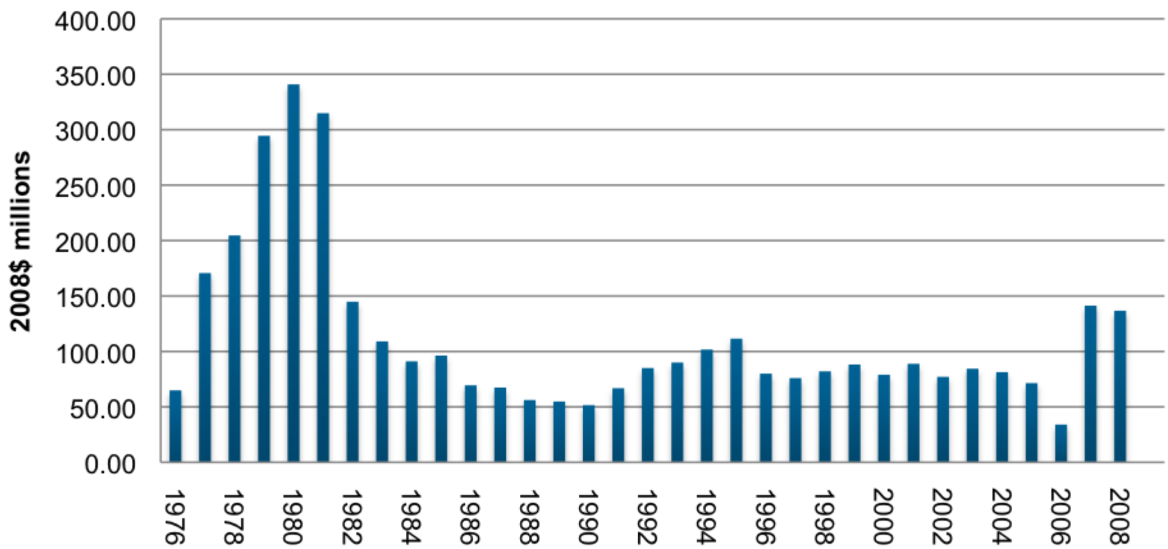
DOE has made large advances through its funding of PV research, and it seeks continued progress.

2.4.1 Subprogram Structure and Budget

Figure 2-3 shows DOE's investment in PV energy systems, year-by-year from 1976 through 2008, with all amounts adjusted to 2008 dollars to hold constant the purchasing power of the dollar. In constant 2008 dollars the total DOE investment in PV was approximately $3.7 billion during this period.

The annual data show a large spike in funding in the late 1970s as a government response to the oil embargo crisis was mounted. This was followed by a steep decline during the 1980s, a rise in the 1990s, and, more recently, a second much smaller spike from 2007 to 2008.

Figure 2-3. DOE Investment in PV Energy Systems, 1976–2008, in 2008 Inflation-Adjusted Dollars



Source: The graph is prepared from data provided by DOE and included in O'Connor, et al. (2010), Appendix F, Table F-3.

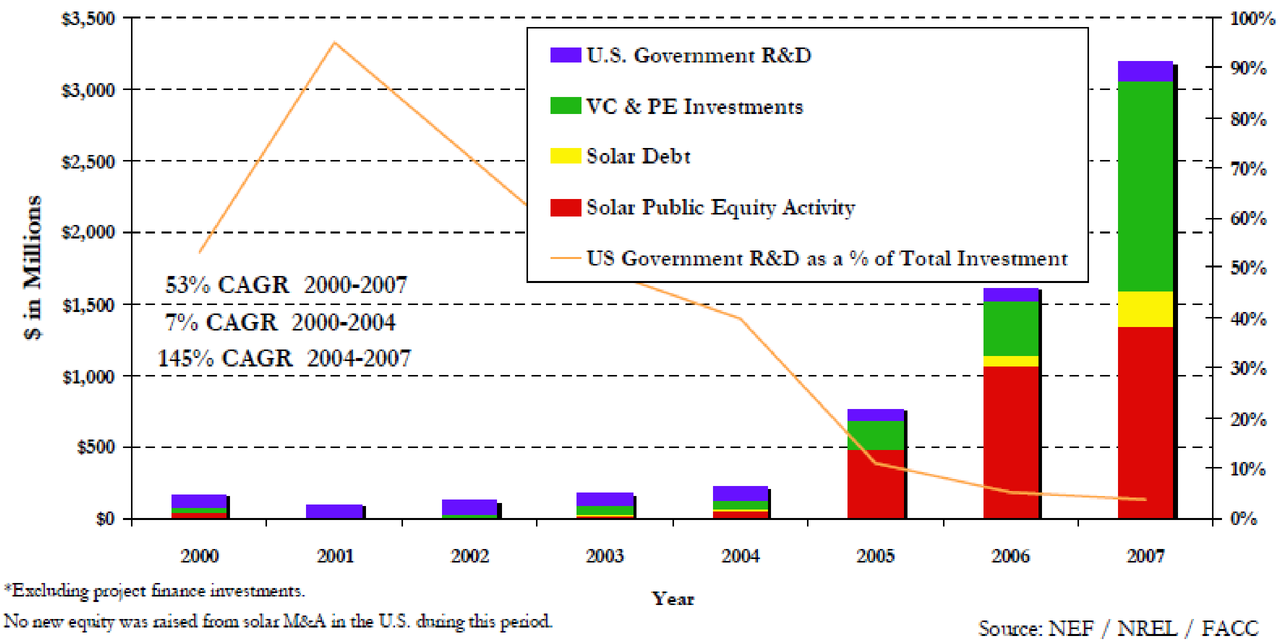
Since 1985, the DOE Solar Photovoltaic Subprogram has received more than half the annual funding from Congress to DOE for solar energy, and in recent years it has received most of the funding.[9] The funding has supported PV research in the DOE national laboratories, as well as in industry through public-private partnership programs, and in academia through research grants to universities. The majority of the PV Subprogram's activities have been conducted through two primary research centers: the National Renewable Energy Laboratory (NREL) in Golden, CO, which began operations in 1977 as the Solar Energy Research Institute (SERI), and in 1991

[9] In addition to photovoltaics, the DOE Solar Energy Program includes three additional subprograms: Concentrating Solar Power, Systems Integration, and Market Transformation. Solar Thermal initiatives are located in the Buildings Technologies Program (see www.eere.energy.gov/buildings).

became NREL; and Sandia National Laboratories (SNL), in Albuquerque, NM. Other DOE laboratories, such as Brookhaven National Laboratory (BNL), in Upton, Long Island, NY, also have provided program support over the period examined. The National Center for Photovoltaics (NCPV) was established in 1996, and located at NREL to coordinate the use of resources and research capabilities of the national labs and universities.[10]

Figure 2-4 shows a breakdown of the total U.S. investment in solar energy from 2000 to 2007. The bars indicate that the compound annual rate of growth (CAGR) in investment soared from 7% during the 2000-2003 period to 145% during the 2004-2007 period. The gold line shows that DOE funding of solar technologies—a significant portion of which went towards PV research—dropped as a percentage of the total investment in U.S. solar from 53% in 2000, to 4% in 2007, as public equity, venture capital, and private equity investment in solar energy increased.

Figure 2-4. Total U.S. Investment in Solar Energy, 2000-2007



Source: Jennings, Margolis, and Bartlett (December 2008), p. 8.
Note: CAGR abbreviates Compound Annual Growth Rate in total U.S. investment in solar energy.

2.4.2 R&D Initiatives

Figure 2-5 shows major DOE Solar PV Subprogram research initiatives from 1975 to the present. The length of each initiative and its starting and ending positions are shown by the span of the figure's bars. As indicated by the figures, initial attention was given to the Flat Plate Solar Array Project. Under this decade-long effort, most of the funding for PV research came from DOE but was managed by NASA's Jet Propulsion Laboratory (JPL) to transfer JPL's space-based PV expertise in flat-plate solar array (FPA) technology from space applications to the nascent

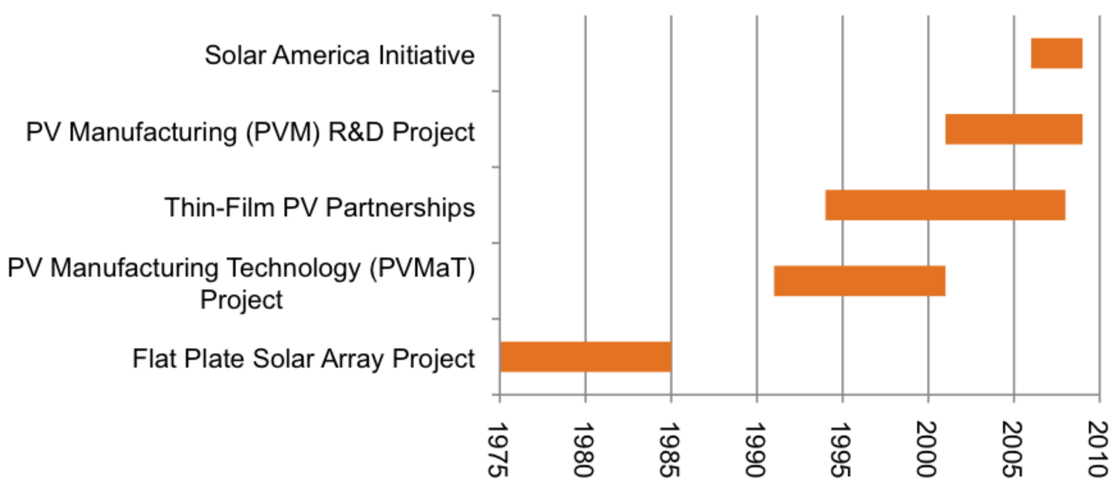
[10] DOE Solar Energy Technologies Program Annual Reports, esp. the report for FY 2006, and Raffaelle (2010).

terrestrial industry and DOE's newly established Solar Energy Research Institute (SERI). In addition to technology transfer efforts, DOE's Project focused on extending FPA technologies for terrestrial applications.[11]

In the early 1990s, NREL initiated a new, long-term project focused on improving PV manufacturing technology. The goal was to convert manufacture of PV equipment from hand work and high costs to automated processes that could be scaled-up efficiently, as was required to build the foundation for a domestic PV industry—which it was feared at the time might otherwise vanish from the United States. The Photovoltaic Manufacturing Technology (PVMaT) project was initiated as a cost-shared effort with industry.

In 2001, the manufacturing initiative was extended and became the PV Manufacturing R&D project, which was continued through 2008. This nearly two-decade long effort entailed a number of phases, with varying areas of focus. Topics included improvements to module manufacturing processes, assembly, product packaging, process controls, automation, in-line diagnostics, intelligent processing, scaling, component technology such as batteries and inverters, system integration, and demonstration of life-cycle cost reductions and of a "market-ready" product.

Figure 2-5. Major DOE Solar PV Subprogram Initiatives, 1975-2010



Source: Constructed by the study from program data.

In its early period, SERI conducted research on thin-films as an alternative to silicon wafers. Then, in the mid-1990s, this early line of research was expanded to become the Thin-Film PV Partnership project with industry, as shown in Figure 2-5. The goal was to advance a range of thin-film technologies, including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS). The project encouraged collaboration among industry, the national laboratories, and universities through teams that organized research activities. Between

[11] O'Connor, et al. (2010), p. ES-2.

1994 and 1999, approximately $20 million (in nominal dollars) in DOE annual funding went to the effort, decreasing between 2000 and 2006 to $12.5 million annually (in nominal dollars). From 2006 to 2009, new cost-shared solar energy R&D was initiated under the Solar America Initiative (SAI), a national program aimed at ensuring that solar energy technologies would play a growing role in U.S. energy supplies and the U.S. economy by making the technology cost-competitive in the near future. Activities under SAI were focused on making solar electricity cost competitive with conventional forms of electricity by 2015. Through the R&D activities of SAI, DOE-funded industry and university-industry teams to reduce cost and to scale up production across the PV value chain. SAI had four R&D activities: Future Generation PV focused on creating revolutionary future-generation PV technologies with full commercialization in the 2020–2030 time frame; PV Incubator focused on overcoming the barriers of systems and system components and demonstrating cost, reliability, or performance advantages to achieve commercialization by 2010; Technology Pathway Partnerships focused on the design of PV components and systems ready for mass production and capable of delivering electricity at target costs immediately; and University PV Product and Process Development targeted university research in materials science and process engineering to support industry-led teams developing PV systems for commercialization in the 2010–2015 time frame[12] Though SAI was concluded in 2009, activities developed during its tenure were reportedly incorporated into the current portfolio of the DOE Solar Energy Technologies Program.

An internal DOE assessment concluded that the partnership projects to improve manufacturing had helped move U.S. PV companies "ahead at a faster pace than their previous trajectory suggested during the past decade." The assessment also concluded that the Thin-Film PV Partnership project contributed to increases in the efficiencies of laboratory cells and large-area modules and helped a number of companies move new PV technologies into production.[13]

Current research activities include developing microsolar energy technology. According to DOE, this technology stands to revolutionize the way solar energy is collected and used.[14]

[12] DOE/EERE Solar Energy Technologies Program website describing the Program and its past initiatives, found at www.eere.energy.gov/solar/initiatives.html; Margolis, et al. (2006); and a description of SAI, dated March 2008, found at www.greenhoustontx.gov/solar/solaramericafactsheet.pdf, as of July 2010.
[13] Margolis, et al. (2006), pp. 2-7.
[14] DOE/EERE Solar Energy Technologies Program website describing the Program, found at www.eere.energy.gov/solar/initiatives.html, as of July 2010.

3. Evaluation Methodology

This chapter describes the framework and methods used by the study to identify and trace linkages from research outputs of DOE's Solar Energy PV Subprogram to downstream power generation and other applications. Because evaluation methods have limitations both in theory and practice, the chapter closes with a discussion of limitations.

3.1 Historical Tracing Framework: Overview

An applied civilian research program such as DOE's Solar Energy PV Subprogram produces explicit and tacit knowledge outputs, and these outputs generally require time to be taken up by others, further developed, and moved into downstream applications. Furthermore, a research program, such as the PV Subprogram, that is attempting to bring a new technology from its very early stages to readiness for commercial application often requires sustained effort over a number of years. The paths from the laboratory to commercial use tend to be not only lengthy but complex. When viewed retrospectively, a research program's contributions are often obscured by the many twists and turns taken by a technology's advancement from the laboratory to the shelf. Moreover, the adoption of the program's knowledge in other fields and applications is usually unanticipated and tends to remain unknown in an evaluative sense.

A historical tracing framework is appropriate for examining the creation and diffusion of the knowledge outputs of the more than 30 years of DOE-funded PV research. A historical tracing framework identifies Program outputs that are feasible to trace, matches those outputs with suitable tracing methods, and traces the outputs over time to determine who has used them and for what applications. Historical tracing allows one to trace forward from the research to wherever it leads. This approach is termed "forward tracing." Forward tracing allows the analysis to reveal both expected and unexpected areas of use. Historical tracing also allows one to trace from a known outcome of interest back to see if, and to what extent, the outcome is linked to a particular research effort. This approach is termed "backward tracing."

When these two approaches are applied to tracing the output of patents in this study, the terms used are "forward patent tracing" and "backward patent tracing," and the observed forward and backward links are patent citations. The forward patent analysis looks for all downstream citations; the backward patent analysis starts with downstream innovations of interest and investigates linkages back to the initial research. (See Section 3.3)

3.1.1 Formulating Study Questions

To inform the evaluation study, first a logic model of DOE's Solar Energy PV Subprogram, i.e., a layout of its mission and objectives, its activities, and its intended outputs and outcomes, based on Program documents, was developed.[15] With this background, a series of study evaluative

[15] For an introduction to logic models see Kellogg Foundation (2004, updated). Also, see McLaughlin and Jordan (2004).

questions were formulated to drive the analysis. Table 3-1 summarizes the set of questions and pairs each question with the specific method the study used to answer it.

Table 3-1. Study Questions and Evaluation Methods Used to Answer Them

Study Question	Method Used
Did the results of DOE's research in solar PV reach a downstream audience well-positioned to take the research results into commercial development for electricity production from solar energy?	Bibliometrics: Starting with 2 groups of potential users, (1) top U.S. solar PV producers & (2) leading innovative companies in solar energy worldwide, backward patent tracing determines if company patents are linked to earlier DOE-funded PV research
How does the influence of DOE's body of solar PV patents compare with that of the leading companies in the field?	Bibliometrics: Comparing organizations on the extent of citing by others of their bodies of patents
Which DOE-attributed PV patents have most strongly influenced subsequent solar energy innovations?	Bibliometrics: Backward patent tracing at the individual patent level
Which patents of leading companies have the most citation links back to DOE-attributed solar PV patents?	Bibliometrics: Backward patent tracing at the individual patent level
What are the highest-impact solar patents of leading companies that link back to DOE-attributed solar PV patents?	Bibliometrics: Backward patent tracing at the individual patent level
Within the solar energy industry, who, beyond the leading companies, have used the DOE solar PV research results?	Bibliometrics: Forward patent tracing at the organizational level, to assess the broader influence on solar energy of DOE's solar PV research
Were there indications of interest in the DOE solar PV research results outside of the solar energy industry?	Bibliometrics: Forward patent tracing at the organizational level, to assess the broader influence beyond solar energy of DOE's solar PV research
What have been the principal downstream innovations in all fields and by all organizations flowing from DOE's solar PV research?	Bibliometrics: Forward patent tracing at the individual patent level
To what extent has authoring/co-authoring of PV publications provided a path of knowledge dissemination?	Bibliometrics: Analysis of publication authoring/co-authoring
Who has cited DOE PV publications, and to what extent?	Bibliometrics: Analysis of publication citations
What has been the direct involvement of companies and universities with the DOE Solar PV Subprogram?	Database and document review to identify funded companies and universities
What are other modes of transferring the results of DOE-funded PV research to others?	Document review and interview

3.1.2 Choice of Evaluation Methods

Among the multiple evaluation methods[16] that are available and useful for conducting historical tracing of an R&D program are the bibliometric methods of patent and publication citation analyses. Bibliometric methods can be used to provide objectively derived, quantitative measures of linkages from publication and patent outputs to other publications and patents outside and downstream of the program's research. The analysis can indicate that knowledge has been created, who created it, the extent to which it has been disseminated, and to whom. Bibliometric methods are particularly applicable to federal civilian research efforts, such as the DOE Solar PV Subprogram, because patents and publications are important explicit forms of knowledge outputs by which further downstream developments are enabled and program goals accomplished.

The methodological focus of this study is the analysis of patents resulting from research funded by the DOE Solar PV Subprogram. These include patents directly assigned to DOE, the DOE laboratories, and the organization that operated the DOE laboratories. They also include patents resulting from DOE funding of PV research at companies, universities and other organizations, but generally assigned to the funded organizations rather than to DOE. A secondary focus is on using publication analysis, including authoring/co-authoring analysis and publication citation analysis, to assess samples of DOE-funded PV publications. The purpose is to determine the extent to which publishing has been a collaborative activity, who is citing the publications, and how much citing has occurred. In addition, the study identifies other knowledge outputs and other modes of dissemination.[17]

3.2 Why Emphasize Patent Analysis?

When looking for connections between knowledge creation in an applied research program and further innovations and 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. Indeed, patent citation analysis has been used extensively in the study of technological change.[18]

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 that 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, trade magazines, or other forms of relevant information.

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[16] For a directory of evaluation methods used for evaluating R&D programs and illustrations of their uses, see Ruegg and Jordan (2008).

[17] As indicated previously, the patent and publication citation analysis presented in this report was also supportive of a parallel benefit-cost impact study (O'Connor, et al., 2010).

[18] For patents as a window on the process of technological change and the “knowledge economy,” see Jaffe and Trajtenberg (2005).

Patent citation analysis centers upon the links between generations of patents, and between patents and scientific papers, that are made by these prior art references. The analysis is based on the idea that the prior art referenced by a patent has had some influence on the development of the later patent. The prior art is thus regarded as part of the foundation for the later invention. In the patent analysis presented in this report, the idea is that the downstream technologies represented by patents that cite earlier patents attributed to DOE's funding of solar PV research have built in some way on the knowledge base that research has generated.

An additional concept employed in the study is that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. A patent that forms the basis for many new innovations tends to be 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.[19]

Patent analysis has been employed in other studies of DOE/EERE, as it is here, to assess linkages from an R&D program to downstream technological developments. These include studies of energy storage for vehicles, wind energy, vehicle combustion research, and geothermal energy.[20]

3.3 Forward and Backward Patent Tracing

Two approaches to patent analysis are used in the study—forward patent tracing and backward patent tracing. These two approaches are applied at two levels—the organizational level and the individual patent level.

3.3.1 Forward Patent Tracing

The idea of forward patent tracing is to take a given body of research, and to trace the influence of this research upon 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. The influence of these patents on downstream innovation as revealed by two generations of citations is then evaluated. This tracing is not restricted to later solar PV patents. Rather it is recognized that the influence of a body of research may extend beyond its immediate targeted technology area. Hence, the purpose of the forward tracing element of this project is to determine the influence of DOE-funded solar PV patents on the development of downstream PV technologies, solar technologies more broadly, and other technologies beyond solar energy.

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[19] For background on the use of patent citation analysis to identify important technological information, including a summary of validation studies supporting the use of patent citation analysis, see Breitzman and Mogee (1999) and Chapter 3 of Thomas (1999).

[20] See Ruegg and Thomas (2008, 2009, 2010A, and 2010B) for other historical tracing studies of energy efficiency and renewable energy systems.

3.3.2 Backward Patent Tracing

The idea of backward patent tracing is to start with the intended (targeted) area of DOE's research program (downstream of the program), and determine if this targeted area did, in fact, build on the earlier DOE-attributed patents. In the context of this project, there is particular interest in whether DOE's research results were taken up by companies well positioned to take these results into PV commercial application. To address this question, two groups of firms and their relevant patents were selected for the backward patent tracing: (1) top U.S. PV producers, and (2) leading innovators in solar energy worldwide (as indicated by having the most patents in solar energy). An indication of the relative importance of DOE in establishing a knowledge base on which these leading companies developed further innovations in PV and other solar energy technologies is provided by organizational comparisons.

3.4 Extensions of the Patent 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 two ways:

(1) Extension to Multiple Generations of Citations Links

It extends the analysis by the addition of a second generation of citation links. This means that the study traces forward through two generations of citations, starting from DOE-attributed PV patents, and also backward through two generations starting from the patents of the two groups of leading companies.
The idea behind adding this second generation of citations is that federal agencies such as DOE often support elements of fundamental scientific research that may take time and multiple generations of research to be used in an applied technology such as that described in a patent. The impact of the research may not therefore be reflected in a study based on referencing a single generation of prior art. Adding a second generation of citations allows for a more detailed analysis of the impact of the DOE-funded research.

That said, adding additional generations beyond two may bring in too many patents with little connection to the starting set, and, hence, is avoided in this study. The problem is that, if one uses enough generations of links, 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 earlier patents and papers will be linked to the starting set. Based on previous experience, using two generations of citation links is appropriate for R&D tracing studies such as this; adding additional generations may bring in too many patents with little connection to the starting set.

(2) Extension Beyond the U.S. Patent System

The report extends the analysis by looking 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 PV research and subsequent technological developments in and outside the United States.

3.5 Constructing Data Sets Used in the Patent Analysis

The forward patent tracing starts from the set of solar PV patents attributed to DOE's R&D funding. If complete records are unavailable—as in this case—the analysis must begin by supplementing and validating the data set of DOE-attributable PV patents. The data-construction step and results are described below in Section 3.5.1, with supplementary material in Appendix A-1, and the resulting list of patents in Table B-1 of Appendix B.

The backward patent tracing starts from two sets of patents: (1) those of the top U.S. PV producers, and (2) those of the leading innovators in solar energy worldwide. Both of these groups are positioned to access newly generated knowledge in the field, and they comprise potential commercial developers of new technologies in PV and solar energy more broadly. These data sets had to be constructed by the study. The data-construction step and results are described in Section 3.5.2, with supplementary material in Appendix A-II.

3.5.1 Identifying the Set of DOE-Attributable Solar PV Patents

Challenges in Identifying 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 and acquisitions.

In contrast, a government agency such as DOE may fund research in a variety of organizations. 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 SNL may be assigned to Lockheed Martin.

A further complication is that DOE not only funds research in its own labs and research centers. It also funds research carried out by private companies, universities, and other organizations. If the research results in patented inventions, these patents are likely to be assigned to the company, university, or other organization carrying out the research, rather than to DOE. Sometimes these patents acknowledge a government interest in the patent, but not always.

Constructing a Database Containing DOE-Attributed Patents. To identify patents resulting from DOE-funded solar PV research, the study started with the following data sources to identify most of the population of DOE-funded patents:

OSTI Database — The first source used was a database developed by DOE's Office of Scientific & Technical Information (OSTI). 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 had 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.

Identifying Candidate DOE-Attributed Solar PV Patents from the Larger Population by Applying a Patent Filter. The study constructed and applied a patent filter to search within the broadly constructed DOE patent database for additional DOE-attributed patents related to solar PV. As a starting point for constructing the filter, the study identified a set of U.S. Patent Office Classifications (POCs) and International Patent Classifications (IPCs) related to solar energy, provided in Appendix A, Table A-1.

The initial search was restricted to patents in the POCs and IPCs listed in Table A-1. Restricting the search by patent classification reduces the likelihood of including irrelevant patents using the same terms, especially the same acronyms. For example, PV is not only used as an acronym for photovoltaic, it is also used for terms such as "pointer value" in computer programming, an acronym for "present value" in studies of economic return, and to indicate "position velocity" in physics. Along with the patent classifications in Table A-1, a set of keywords and phrases related to solar and PV technologies were identified by the study to focus the filter on solar PV. These keywords are shown in Appendix A, Table A-2, and the patent filter equation is provided in the appendix text following the table.

Identifying 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 broad database of DOE-attributed patents, the study also identified DOE-attributed solar PV patents based on a review of DOE annual reports and other program documents. These documents identified some of the companies that were funded by DOE to develop solar PV technologies, under programs such as the Photovoltaic Manufacturing Technology (PVMaT) program. The documents also identified the time periods during which these companies were funded and the technologies they were funded to develop. 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 by reviewing DOE documents were added to the list of patents obtained by 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 of DOE-attributed solar PV patents, requiring validation by DOE experts in the field prior to use.

Narrowing the Candidate PV Patent List by DOE Expert Review. The list of candidate solar PV patents to be attributed to DOE-funded research, as identified by the study, was sent to DOE for validation. DOE scientists and program managers—experts in the solar PV field—provided feedback 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 also ultimately omitted because of uncertainty regarding the degree of DOE funding that underlay them, and, hence, uncertainty about DOE attribution.

Arriving at a Final List of DOE-Attributed Solar PV Patents. Based on the process outlined above, the study arrived at a final list of 331 solar PV U.S. patents attributed to DOE-funded PV research. Next, 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 the U.S. patent system again for U.S. patents that were 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 U.S. patents plus their continuations, etc.), 75 EPO patents, and 113 WIPO patents. A list of these patents can be found in Appendix B, Table B-1.

3.5.2 Constructing Patent Families Based on "Priority Applications"

Equivalent patents on a single invention may result as 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 may also file for protection of this invention in other countries. In addition, continuations of a given patent may result as organizations add supplementary material to a patent within a given patent system. For example, a U.S. company may file for a series of patents in the United States based on the same underlying invention. There may be multiple patent documents for the same invention, as was found for the set of DOE-attributed solar PV patents and the patents of other organizations used in the study.

To avoid counting the same invention multiple times, the study constructed "patent families" for patents used in the study. A patent family contains all of the patents and patent continuations that result from the same original patent application (named the "priority document"). A family may include patents/applications from multiple countries, and also multiple patents/applications from the same country. The study constructed PV patent families attributed to DOE; solar energy patent families attributed to the top U.S. PV producers; solar energy patent families attributed to the leading worldwide innovators in solar energy; and patent families for all of the patents linked to these sets through citations.

To construct these patent families, the study matched the priority documents of U.S., EPO, and WIPO patents/applications, and grouped them into the appropriate families. Fuzzy matching algorithms were used 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.

The study grouped the DOE-attributed PV patents into 274 distinct patent families. These 274 families contained the 343 U.S. patents (including the 331 U.S. patents plus their continuations), 75 EPO patents, and 113 WIPO patents as described in Section 3.5.1.

3.5.3 Identifying Companies and their Patents for Backward Tracing

Two company groups were identified for use in the backward patent analysis: 1) the top U.S. producers of PV, and 2) the leading companies in solar energy patenting worldwide.

Identifying the Top U.S. Producers of PV. Only the top eight U.S. producers of PV had significant production output; the reported production output of producers below the top eight was negligible. The study identified the number of solar energy patent families owned by each of these eight companies. In total, these eight companies owned 609 solar energy patent families, containing a total of 321 U.S. patents, 204 EPO patents, and 172 WIPO patent applications. These companies and their number of solar energy patent families are listed in Table 3-2.

BP Solar and Energy Conversion Devices (ECD) head this list, with portfolios large enough for both of these companies to also be among the ten leading companies worldwide in terms of the number of their assigned solar energy patent families. (See Table 3-3). The other six U.S. producers of PV have much smaller solar energy portfolios, ranging in size from SunPower’s 79 patent families, down to Global Solar’s three patent families.

The study used the set of patent families of the top eight U.S. PV producers to better assess the influence of DOE’s earlier solar PV research specifically on later technology development by these companies. The purpose was to provide a group characteristic of companies the Solar PV Subprogram would have needed to reach to achieve downstream commercial impact in the intended application area.

Table 3-2. Top Eight U.S. Solar PV Producers

Company	Number of Solar Energy Patent Families
BP Solar	213
Energy Conversion Devices (ECD) (also United Solar)	166
SunPower	79
Solar World	55
Schott	46
Evergreen Solar	31
First Solar	16
Global Solar	3

Identifying the Leading Companies in Solar Energy Patenting Worldwide. The leading companies in solar energy patenting worldwide were used as the second element of the backward tracing analysis to assess the influence DOE's solar PV research has had more broadly on innovation by international leaders in solar energy.

To identify these companies, the study first defined the universe of solar energy patents using a modified version of the patent filter used previously and described in Appendix A-I. The modification was made to avoid introducing large numbers of irrelevant patents. The modified version of the patent filter is described in Appendix A-II. Using the modified 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 using the process described in Section 3.5.2.

The study then identified the 10 companies with the largest number of patent families, taking into account patents assigned to subsidiaries, and obtained through acquisitions. The companies in declining order of their number of solar energy patents are listed in Table 3-3. In total, these 10 companies were responsible for 1,812 solar energy patent families. The 1,812 patent families were constructed from a total of 1,105 U.S. patents, 642 EPO patents, and 273 WIPO patents.

The purpose of selecting the top 10 companies was to keep the number of companies to a manageable size for the analysis. The purpose of selecting the leading companies based on their solar patenting, rather than, for example, their sales volume, was to provide a basis for comparing the level of influence among organizations engaged in solar innovation.

Two companies, BP Solar and ECD, have a large number of solar energy patent families and are also leaders in U.S. PV production, and, therefore, are on both lists of companies used for the backward tracing analysis. It should also be noted that Canon, which owns a very large patent portfolio in solar energy, has recently been issued fewer patents than earlier. Furthermore, there is little mention of solar energy on Canon's website, and there have been reports of Canon exiting the solar energy business. Nevertheless it is included in the analysis because of its large solar energy portfolio at the time of the study.

Table 3-3. Ten Companies with the Largest Number of Solar Energy Patent Families

Company	Number of Solar Energy Patent Families
Canon	455
BP	213
Sanyo	202
Sharp	199
ECD	166
Siemens	137
General Electric	129
Boeing	128
ExxonMobil	95
Mitsubishi Electric	88

3.6 Publication Co-Authoring and Citation Analyses

As a major output of research organizations, publications are also of interest as a linkage mechanism. However, in bibliometric theory, citations of scientific papers by other papers in a field are generally considered to acknowledge scientific and intellectual debts, whereas, citations of patents by other patents are taken to acknowledge technological debts, and citations of publications by patents are considered to acknowledge the intellectual debt of a technology to the science base on which it draws.[21] Thus, analysis of publications offers a supplementary approach to patent analysis for identifying linkages from DOE's PV research to downstream innovations.

The importance of publications as a knowledge output is suggested by their volume over time. Co-authoring of the publications by DOE researchers with researchers from other organizations may indicate collaboration and linkages of DOE researchers to those involved in downstream technology development, commercialization, and applications. Citations of publications resulting from DOE's research may show paths of knowledge flow and suggest additional areas of influence.

The publication citation search is facilitated by the use of a publication citation database and search engine. For an extended period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information (ISI)) was the principal entity facilitating publication citation analysis. However, today there are a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, which provide comprehensive coverage beyond the major journals, including, for example, conference proceedings, book chapters, dissertations, and research reports.[22] For this study's publication-to-publication analysis, conference papers and technical research reports were the most prominent types of

[21] See Martin (2005), especially Chapter 4, "Differences between Scientific and Patent Citations," (Universal-Publishers, 2005).

[22] Meho (January 2007), p. 32.

publications in the samples drawn. Google Scholar was used because it included these kinds of publications in its search capability.[23, 24]

[23] Meho (January 2007), pp. 31-36.
[24] A comparison of alternative publication search tools rated Google Scholar among the best.

4. Patent Analysis

The patent analysis is presented in four sections. First, patenting trends in solar PV and solar energy more broadly are examined. Second, the results of the organizational analysis based on backward patent tracing highlight the effects of DOE-funded PV research on leading companies in PV and in solar energy more broadly. Third, the results of an organizational analysis based on forward patent tracing show the effects on other companies in and outside the solar energy industry. Fourth, the results of a patent-level analysis based on both backward and forward patent tracing identify particularly noteworthy patents attributed to DOE-funded PV research, as well as those of other organizations linked to the DOE set.

Findings include the following: Solar energy patenting in the United States has outstripped that in other countries in every five-year interval from 1974 to 2008. Much of the impact of DOE-attributed PV patents has been on subsequent technologies developed in the United States. At the organizational level, DOE's PV research has generated a knowledge base on which further innovations by leading commercial companies in solar energy in general and solar PV in particular have built. DOE's PV research has influenced innovations beyond PV applications, such as innovations in the broader semiconductor industry and nanotechnology. A number of noteworthy patents are identified among the set attributed to DOE-funded PV research, or among those linked to that set.

4.1 Trends in Patenting

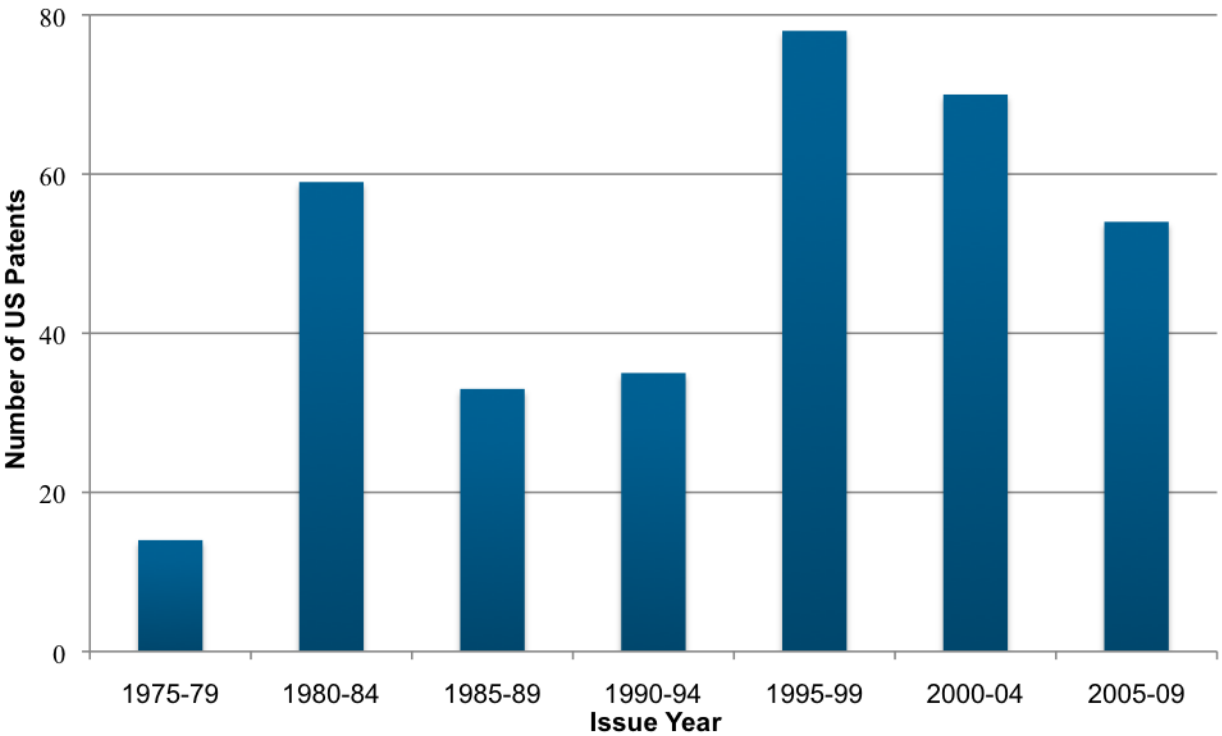
It is instructive, prior to the backward and forward tracing analyses, to consider trends in the output of solar PV patents attributed to DOE-funded research. For perspective, it is also useful to review DOE's trend in solar PV patenting compared with total patenting in solar energy.

4.1.1 Trends in DOE-Attributed Solar PV Patenting and All Solar Energy Patenting[25]

Figure 4-1 shows the trend in the number U.S.-granted solar PV patents attributed to DOE-funded research between1975 and 2009. Two spikes appear in the figure: the first in the early 1980s, followed by a decline, and a second between 1995 and 2004, followed by a decline.

[25] Distinguishing PV patents from other solar energy patents, as was done for the DOE-attributed set of patent families, was not feasible for other organizations because of the large numbers of solar energy patents and the inability to be able to distinguish all PV patents by patent title. While it is possible to state with a high degree of confidence that most of the solar energy patents owned by the top U.S. producers of solar PV are solar PV patents, and it is also likely that a high percentage of solar energy patents owned by the leading worldwide innovators in solar energy are also solar PV patents, in the absence of proof, these patents of the non-DOE organizations receive the more general designation of "solar energy patents."

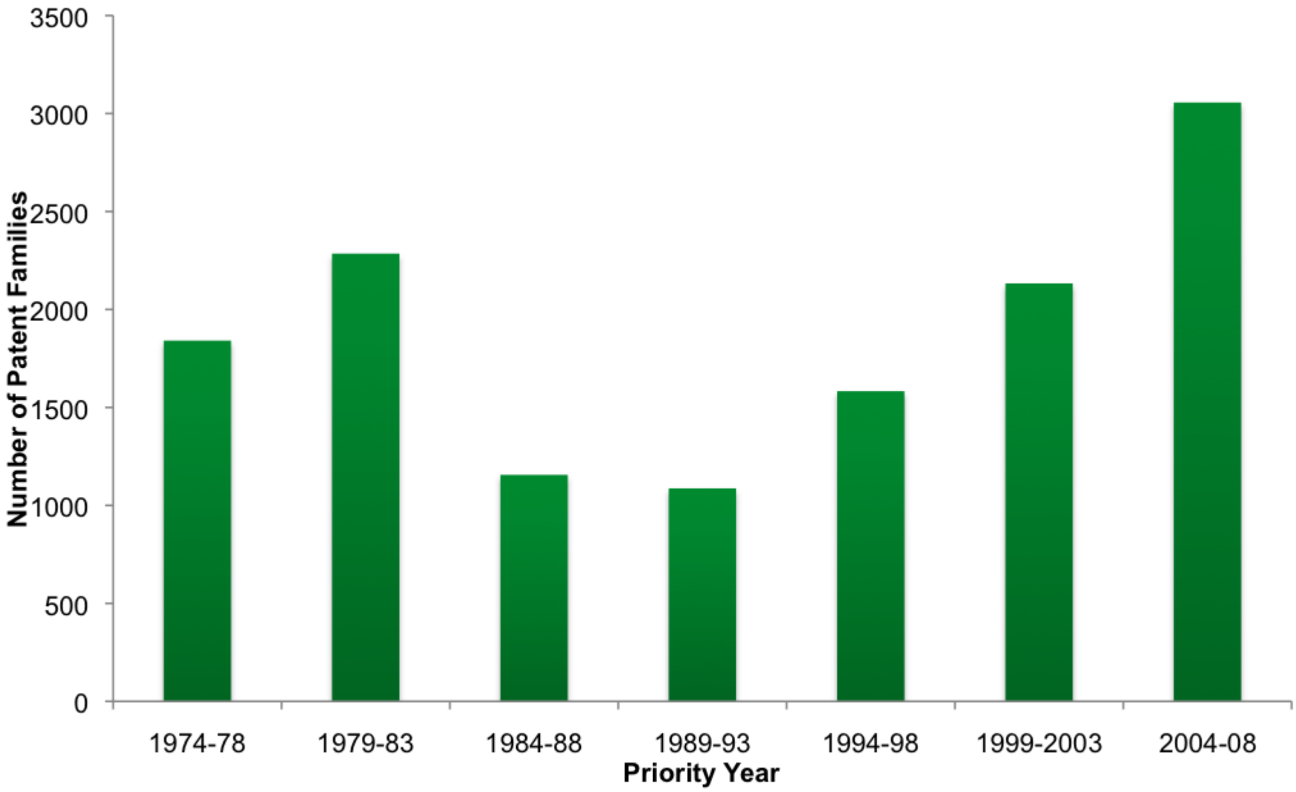
Figure 4-1. Number of DOE-Attributed U.S. Solar PV Patents by Issue Year, 1975-2009



Note: there is typically a lag of at least several years between research funding and related patent issue.

Figure 4-2 shows the total number of solar energy patent families of all organizations since 1974. Until the most recent time period, the trend of these data followed a similar pattern to the trend in DOE-attributed U.S. solar PV patents, shown in Figure 4-1, i.e., the same peak in patenting in the first half 1980s, followed by a period of reduced patenting between 1984 and 1993, and then followed by an increase in patenting between 1994 and 2003. Since 2004, the trends in DOE-attributed U.S. solar PV patenting and overall solar energy patenting by all organizations have diverged.

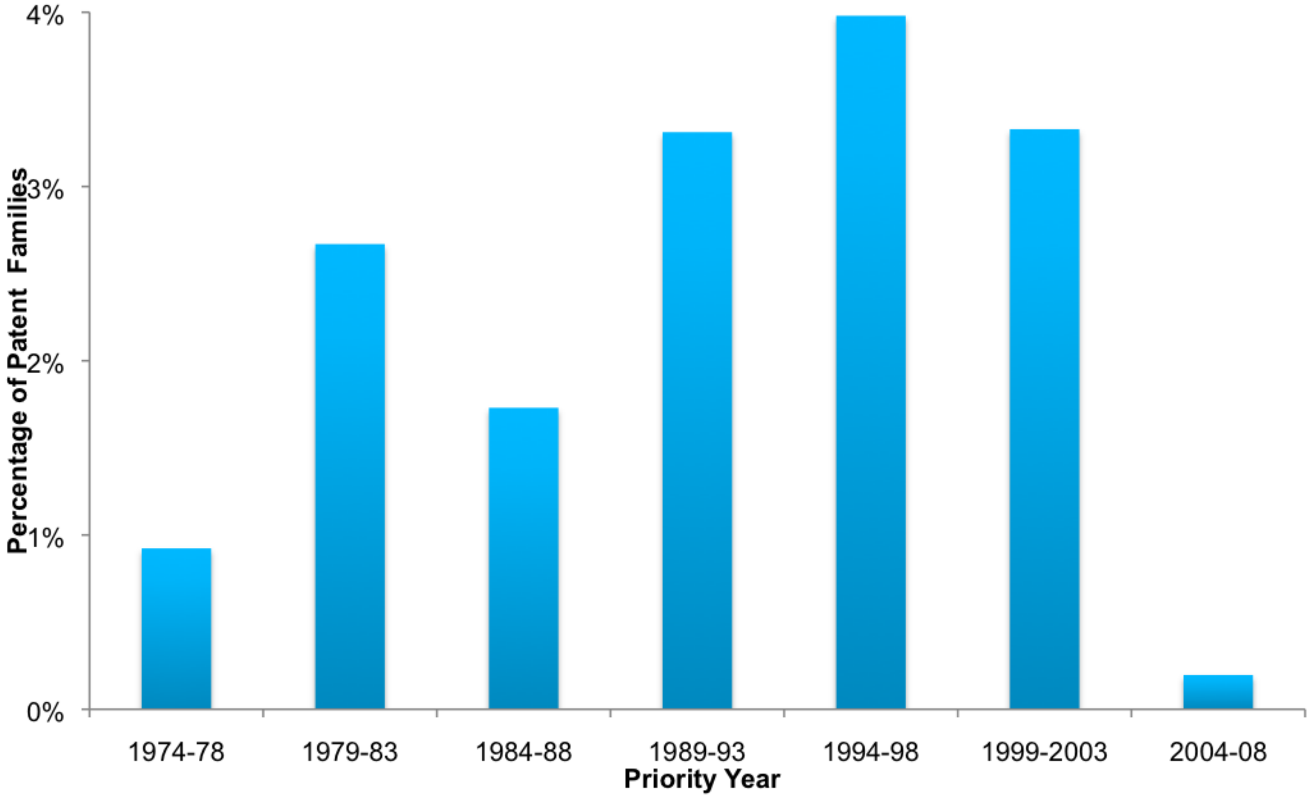
Figure 4-2. Total Number of Solar Energy Patent Families of All Organizations by Priority Issue Year, 1974-2008



The overall number of solar energy patent families filed by all organizations increased to its highest level between 2004 and 2008, while the number of DOE-attributed U.S. solar PV patents fell.

This recent divergence in the trends of DOE-attributed solar PV patenting and overall solar energy patenting is also reflected in Figure 4-3. This figure shows, for each five-year period since 1974, the percentage of all solar energy patent families composed of the DOE-attributed U.S. solar PV patents. This percentage varied from 1-3% between 1974 and 1988, increased to a range of 3-4% between 1989 and 2003, but fell to an average of only 0.2% between 2004 and 2008. This finding is consistent with Figure 2-4, which showed DOE funding of solar technologies as a percentage of total investment in U.S. solar energy. DOE funding of solar technologies fell sharply from 2000 to 2007, as public equity, venture capital and private equity investment increased.

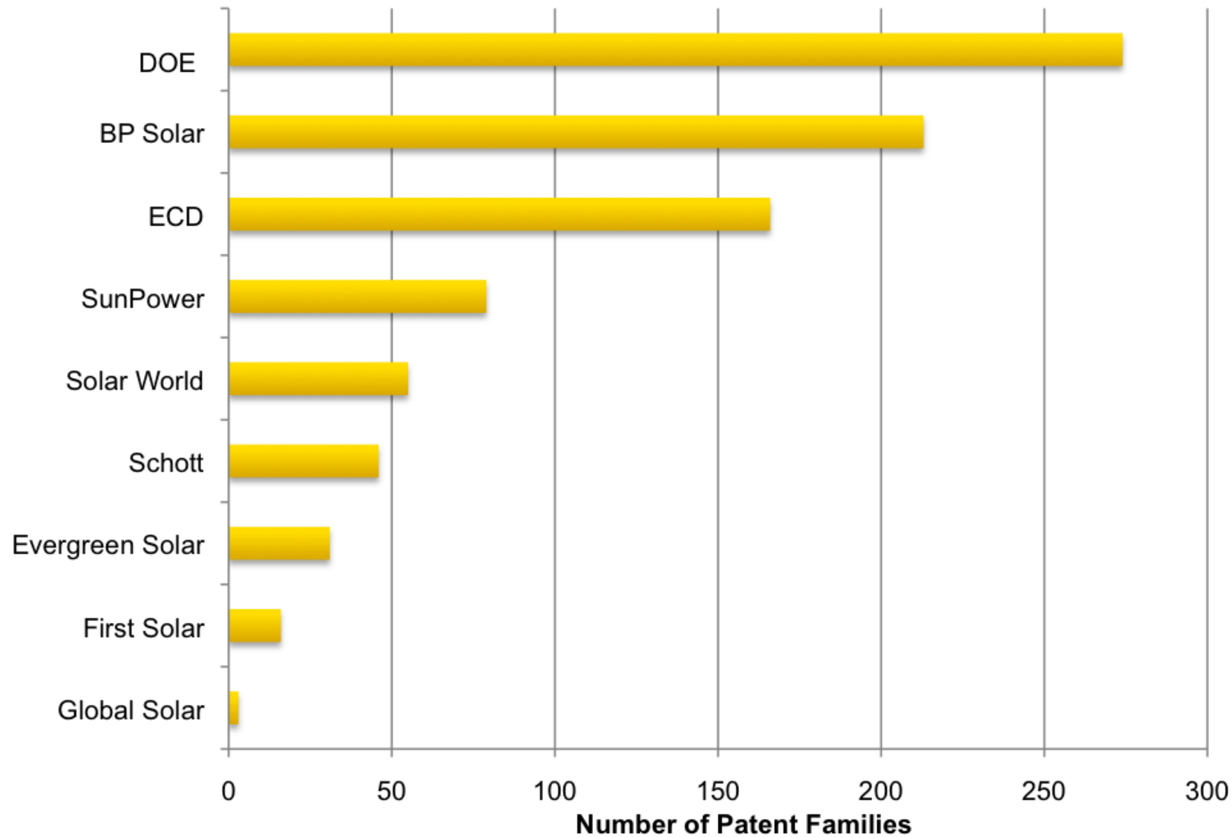
Figure 4-3. DOE-Attributed U.S. Solar PV Patents as a Percentage of Solar Energy Patent Families of All Organizations, 1974-2008



4.1.3 Comparison of DOE-Attributed Solar PV Patenting with Solar Energy Patenting of the Top U.S. Producers of PV

Figure 4-4 shows the number of solar energy patent families owned by the top eight U.S. producers of PV, plus the set of DOE-attributed solar PV patent families. After DOE (with 274-attributed PV patent families), BP Solar and ECD head the figure, with 213 and 166 solar energy patent families respectively. As noted earlier, the portfolios of BP Solar and ECD are large enough for both of these companies to also be among the leading companies worldwide in overall solar energy patenting. This is not true for the other six top U.S. producers of PV, who have much smaller solar energy patent portfolios.

Figure 4-4. Comparison of DOE-Attributed Solar PV Patenting with Solar Energy Patenting of the Top U.S. Producers of PV

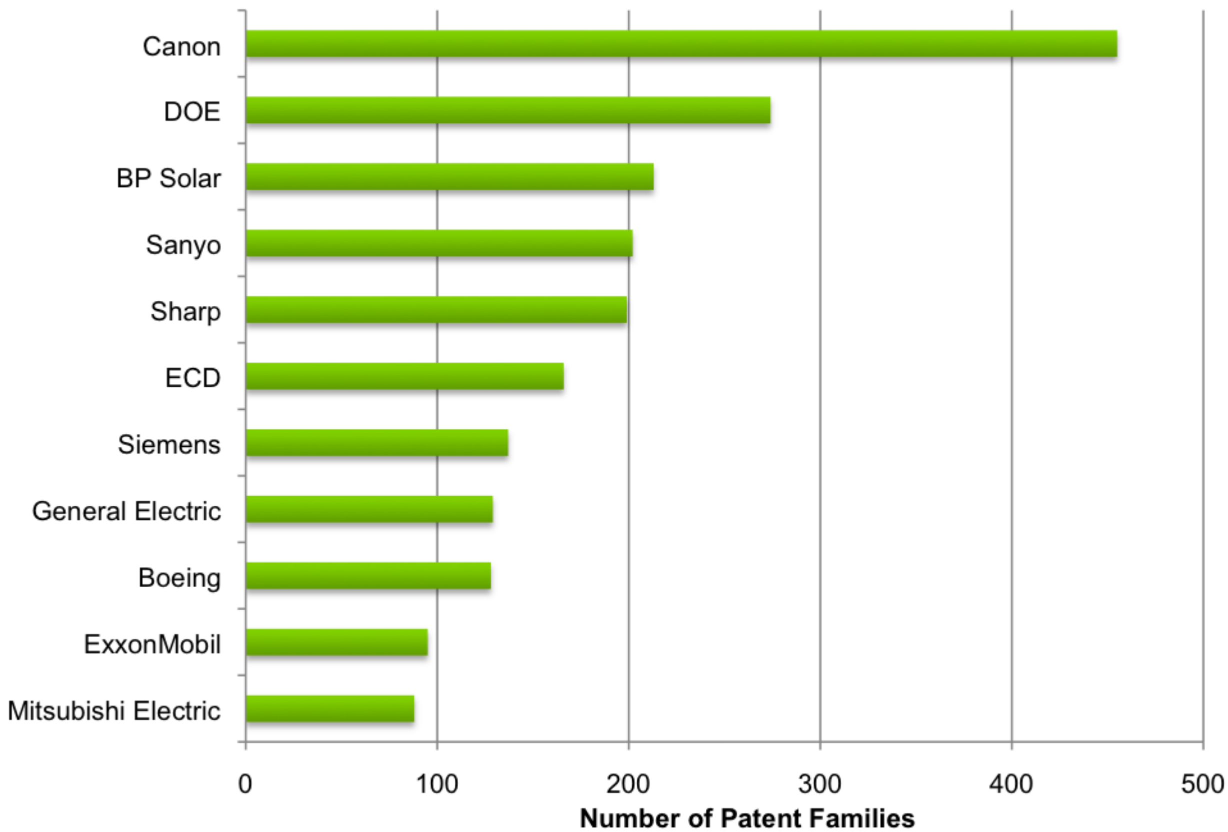


4.1.4 Comparison of DOE-Attributed Solar PV Patenting with Solar Energy Patenting of the Leading Companies Worldwide

Figure 4-5 shows the number of solar energy patent families owned by the 10 leading patenting companies in solar energy worldwide, plus the set of DOE-attributed solar PV patent families. This figure reveals that DOE is second to Canon in terms of portfolio size of solar energy patent families.

It is also apparent that Figure 4-5 is dominated by very large companies from a range of industries. They include electronics companies (Sanyo and Sharp), energy companies (BP Solar and ExxonMobil), and broader conglomerates (GE and Siemens). In contrast, ECD focuses on a small range of renewable energy technologies, notably solar PV power and energy storage.

Figure 4-5. Comparison of DOE-Attributed Solar PV Patenting with Solar Energy Patenting of the Leading Solar Energy Innovators Worldwide

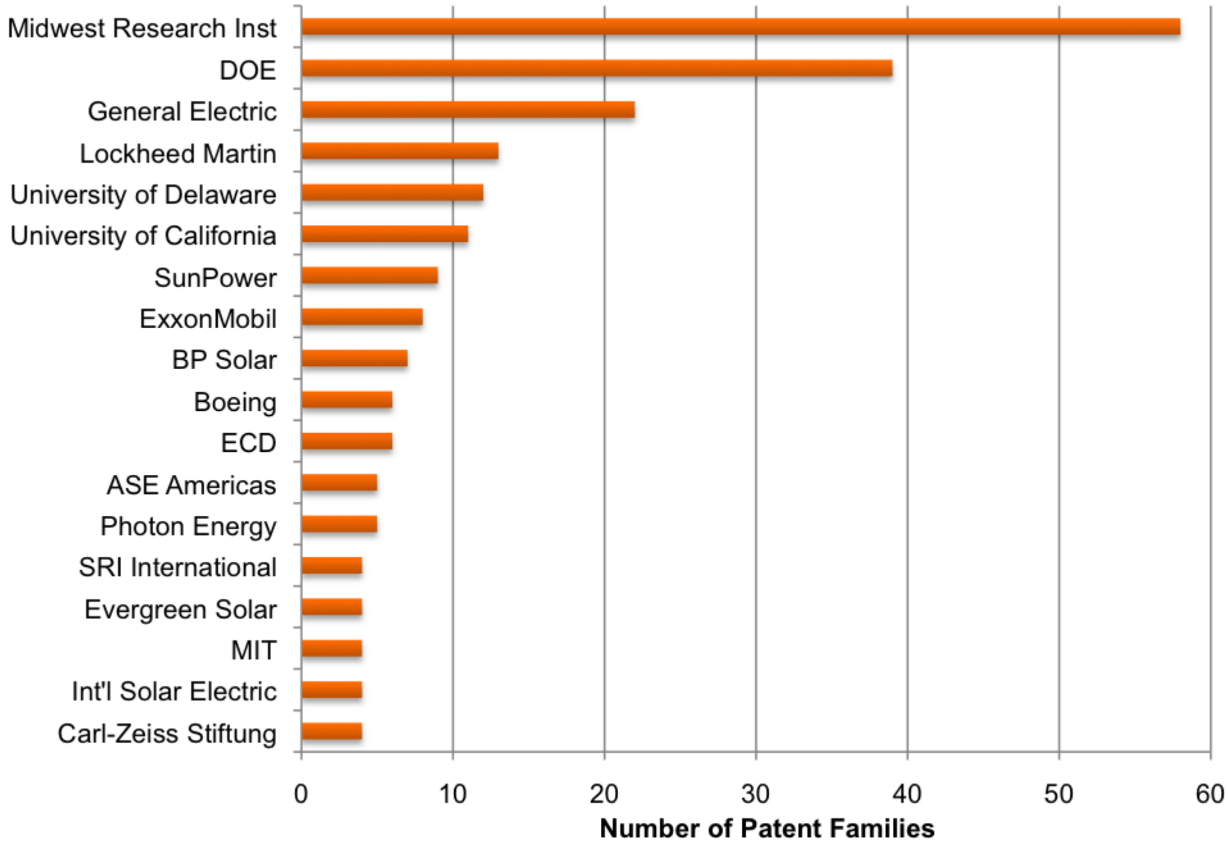


It should be noted that the number of patent families for DOE is derived somewhat differently from the patent family counts for the other organizations in Figures 4-4 and 4-5. For one thing, the DOE set is limited to solar PV, whereas the company sets are for solar energy more broadly. But more to the point, DOE's set of 274 patent families consists of patents based on research funded by DOE, not all of which are assigned to DOE.

The assignees responsible for the largest number of the PV patent families attributed to DOE are shown in Figure 4-6. Midwest Research Institute, the manager of NREL, is the leading assignee in Figure 4-6, with a total of 58 DOE-attributed patent families. DOE itself is the second most prolific assignee, and other DOE lab managers (Lockheed Martin and University of California) are also prominent. This suggests that a great deal of the solar PV research funded by DOE has been carried out in the DOE laboratories.

It should also be noted, however, that DOE has funded a portion of the solar energy research carried out by 5 of the 10 leading solar energy companies listed in Figure 4-5: General Electric (22 patent families based on DOE-funded research), ExxonMobil (8 patent families); BP (7 patent families); Boeing (6 patent families); and ECD (6 patent families). Hence, in Figure 4-5, there is some overlap between the patent family counts for DOE and each of these five companies. For example, General Electric has a total of 129 solar energy patent families in Figure 4-5. Twenty-two of these patent families were based on research funded by DOE, and these 22 families are counted in both the GE and DOE totals in Figure 4-5. At the same time, most of these companies' solar energy patents were not attributed to DOE. For instance, there is no overlap for 107 of the General Electric patent families.

Figure 4-6. Number of DOE-Attributed Solar PV Patent Families by Assignee



Because DOE has been a source of funding for solar energy research for many years, there is a large portfolio of DOE-attributed solar energy patents both at DOE labs and at leading solar energy companies. Nevertheless, as noted, there has been a sharp decrease in the number of DOE-attributed solar PV patent families filed in recent years. (This drop in PV patent filings is partially obscured in the patent issue data of Figure 4-1, which reflects the recent issue of patents filed earlier.)

4.1.5 Country Comparisons

A comparison among countries in terms of where priority patents of the solar energy patent families have been filed reveals that priority filing in the United States has far outstripped that in other countries in every five-year interval from 1974 to 2008. The early start of the United States relative to other countries is quite apparent. Japan and Germany follow the United States in number. Japan began to increase its filings of priority solar energy patents significantly beginning in the mid-1990s. Figure 4-7 shows the country comparisons.

Figure 4-8 shows that the United States has, by a wide margin, the largest number of patent families from all technology areas linked to earlier DOE-attributed solar PV patent families. Japan has the second-largest number of technology linkages back to the DOE PV set, followed by Germany, France and Australia. The order of countries in Figure 4-8 follows closely the order of countries in Figure 4-7 (which was by their number of solar energy patent families) except that Italy moves up in order and Spain, Sweden, and South Korea are added. The findings of Figure 4-8 indicate that the impact of the DOE-funded PV research has been largely on technologies developed in the United States, and that the technology portfolios of a number of other countries have also been impacted by the DOE-funded PV research.

Figure 4-7. Number of Solar Energy Patent Families by Priority Year and Priority Country, 1974-2008

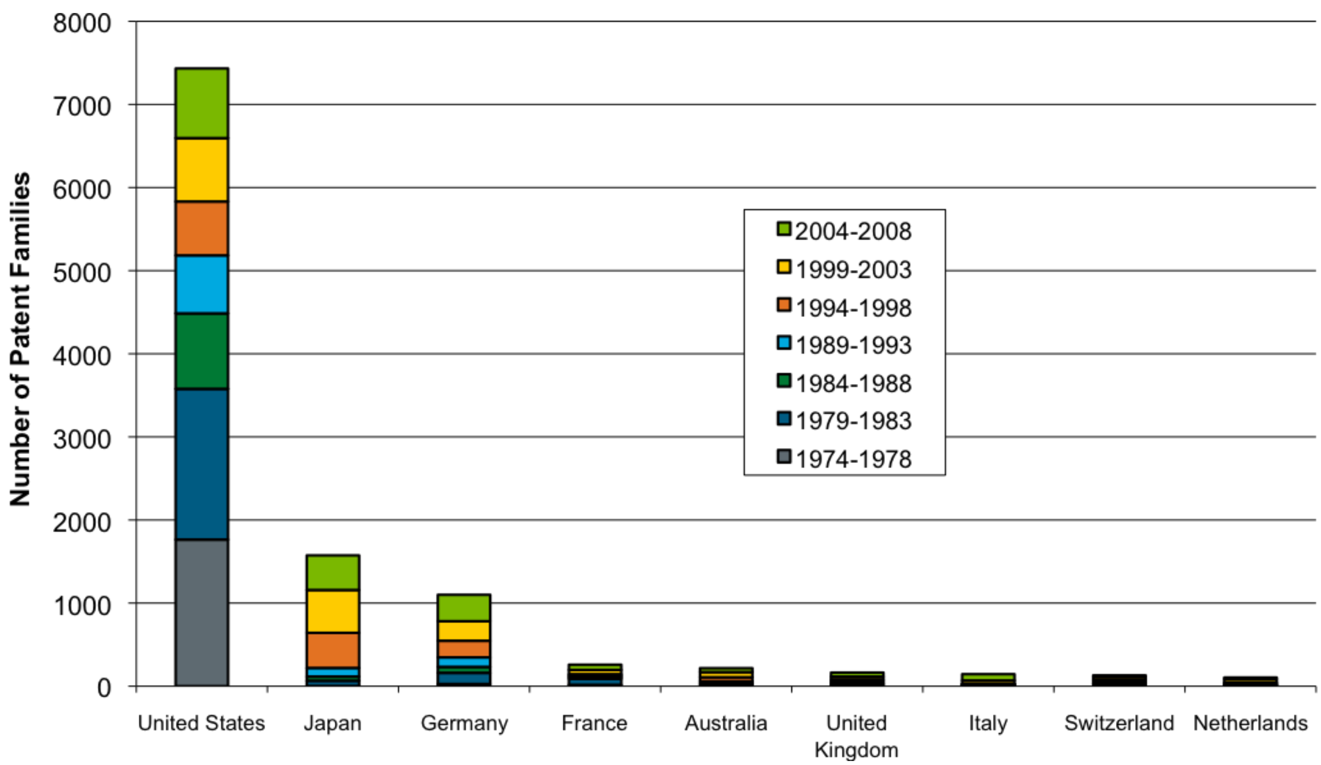
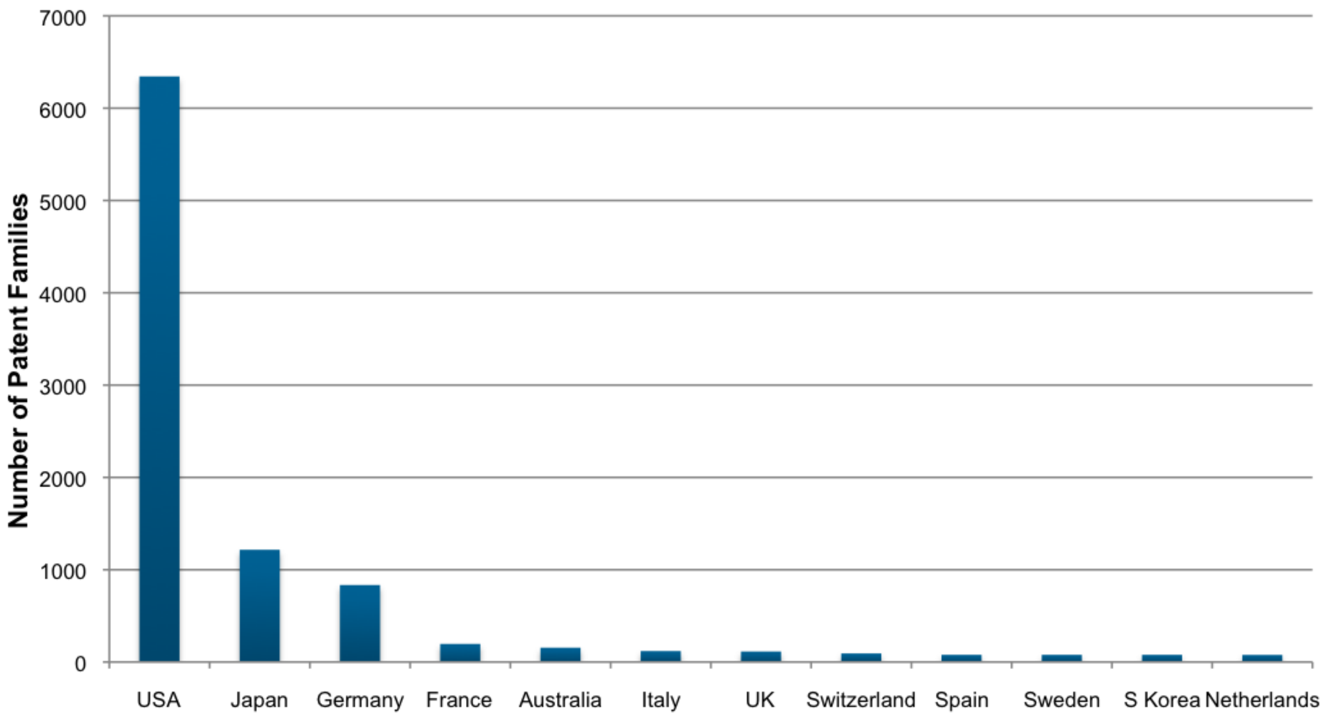


Figure 4-8. Countries with the Largest Number of All Patent Families Linked to Earlier DOE Solar PV Patent Families, Based on Priority Country



4.2 Results of Tracing Backward from Commercial Companies to DOE PV Research

This element of the study's backward patent tracing analysis is designed to help answer the following question:

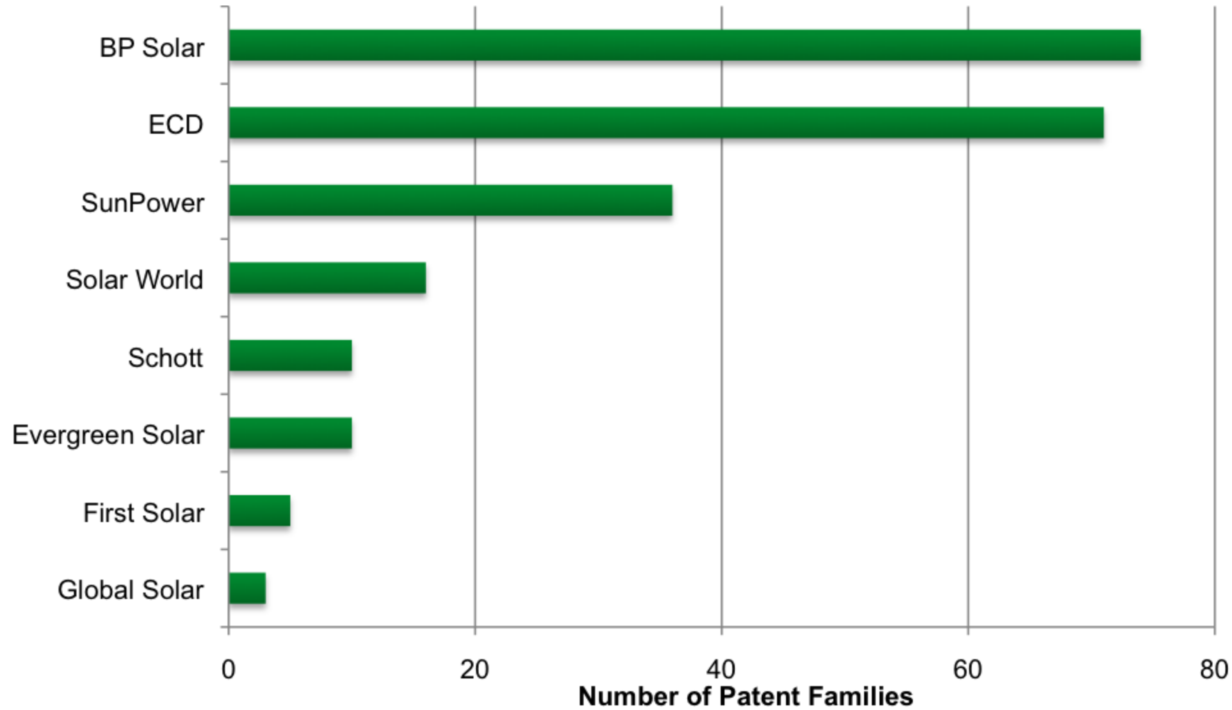
- Did the results of DOE funded research in solar PV technology reach a downstream audience well-positioned to take the research results into commercial development?

The analysis is applied first to the top U.S. producers of PV, and second to the leading companies in solar energy patenting worldwide. Overall, the findings of the backward tracing element of the analysis reveal that the technology capabilities of these companies trace strongly back to DOE-funded PV research.

4.2.1 Tracing Backward from Top U.S. Producers of PV to DOE

Figure 4-9 reveals the extent of the linkages of solar energy patent families of the top U.S. solar PV producers to earlier PV patents attributed to DOE. BP Solar and ECD lead by a wide margin, each with over 70 patent families linked to earlier DOE solar patents. They are followed by SunPower, which has 36 families linked to earlier DOE research.

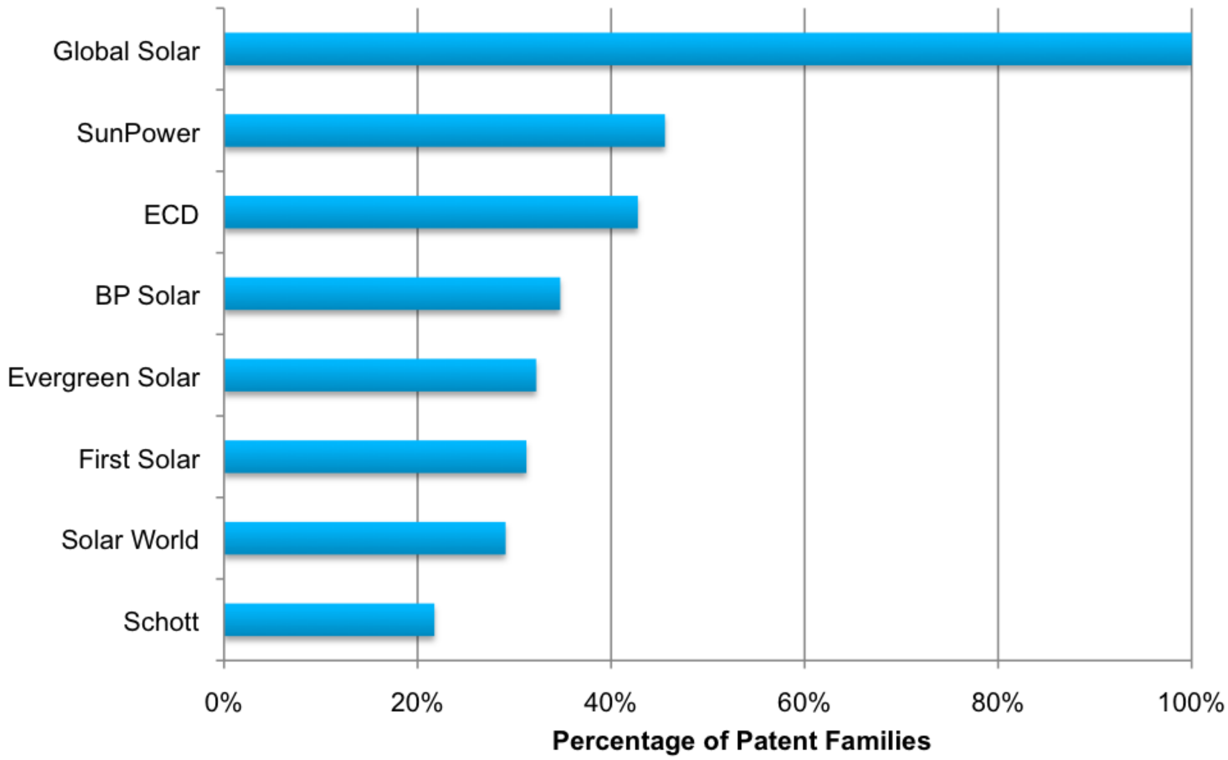
Figure 4-9. Number of Solar Energy Patent Families of Top U.S. PV Producers Linked to Earlier DOE-Attributed Solar PV Patents



However, Figure 4-9 has a natural bias towards companies with extensive solar energy patent portfolios, because it is based on absolute numbers of patent families linked to DOE. Figure 4-10 overcomes this bias by looking at the percentage of each of these companies' solar energy patent families that is linked to earlier DOE-attributed solar PV patents, rather than their absolute numbers of patents.

Global Solar is at the head of Figure 4-10, with 100% of its patent families linked to earlier patents in the DOE set. However, this is based on only three patent families. More interesting is the finding that each of the top eight U.S. producers of PV has more than 20% of its solar energy patent families linked to earlier solar PV patents in the DOE-attributed set. This finding suggests that DOE-funded PV research has had a relatively significant and broad impact upon the U.S. PV industry.

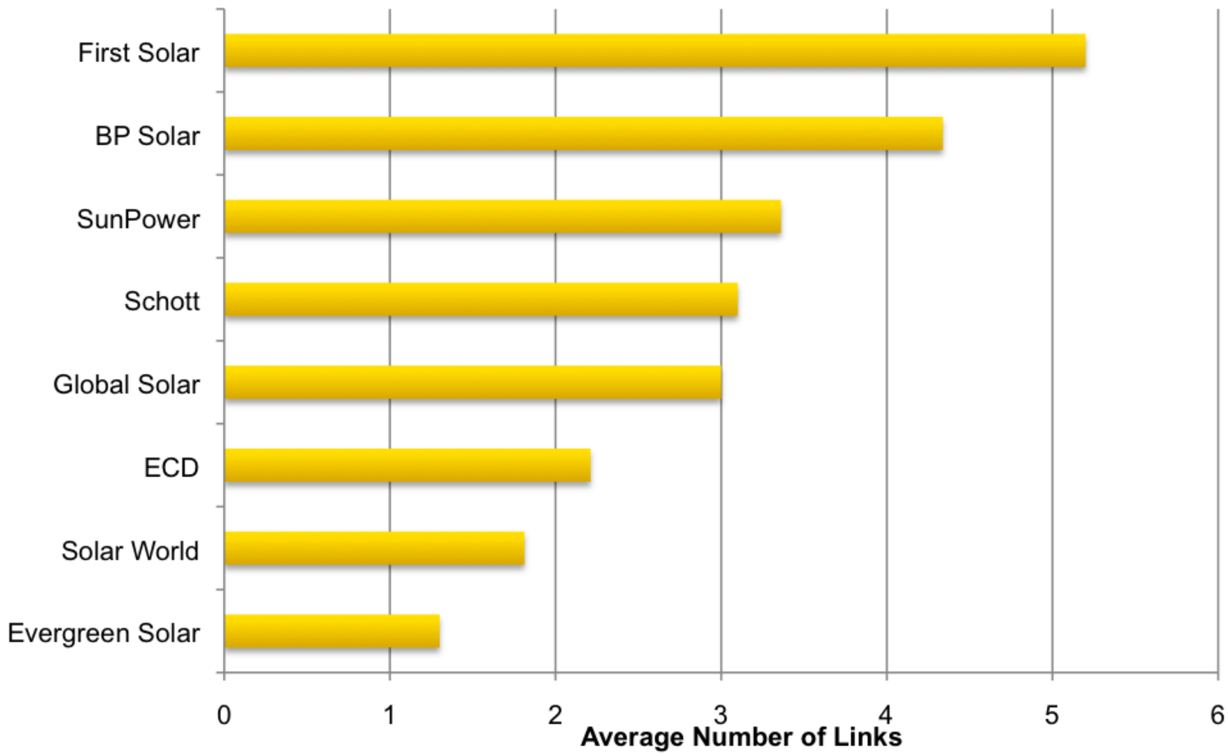
Figure 4-10. Percentage of Solar Energy Patent Families of Top U.S. PV Producers Linked to Earlier DOE-Attributed Solar PV Patents



Another way of examining the impact of DOE-funded solar energy research on the top U.S. PV producers is provided by Figure 4-11. This figure shows, for each of these PV producers, the average (mean) number of links to DOE per patent family with at least one link to DOE. Thus, rather than simply counting how many patents owned by each company are linked to DOE, this figure shows the extent of the influence denoted by these links. For example, a patent family linked to five previous DOE patents is regarded as being connected to DOE research more extensively than a patent family with only a single link to DOE.

First Solar is at the head of Figure 4-11. First Solar's patent families with links to previous DOE research are linked to an average of more than five previous DOE solar PV patent families each. This suggests that these First Solar patent families have extensive links to DOE research, not just passing links made by a single prior art reference. The same can be said for BP Solar (4.33 links per family), SunPower (3.36 links per family), Schott (3.1 links per family), and Global Solar (3.0 links per family). ECD is towards the lower end of the range, but still has on average more than two links per family to previous DOE-attributed solar PV patent families.

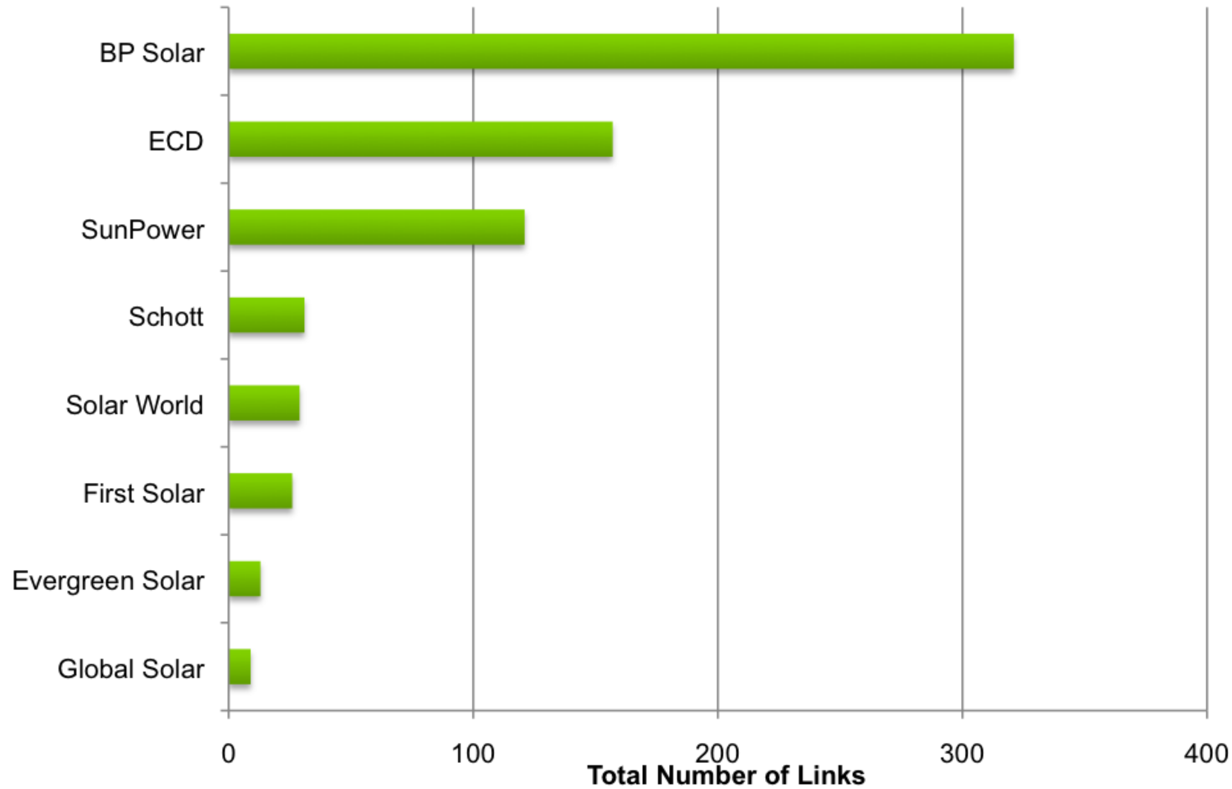
Figure 4-11. Average Number of Citation Links per Patent Family of Leading U.S. PV Producers Linked to Earlier DOE-Attributed Solar PV Patents



The results of Figures 4-9 and 4-11 are combined in Figure 4-12, to show the total number of links from each of the top U.S. PV producers to DOE's portfolio of solar PV patent families. Figure 4-12 is derived by multiplying the number of patent families linked to DOE (Figure 4-9) by the average number of links per linked family (Figure 4-11). Thus, Figure 4-12 provides an overall view of the extent of influence of the DOE-attributed solar PV patent set on the technology developed by each of the top U.S. PV producers, taking into account both the breadth of linkage (number of their families linked to DOE) and depth of linkage (average number of links per linked family).

BP Solar is at the head of Figure 4-12 by a wide margin, followed by ECD, and SunPower. BP Solar leads ECD by a wider margin than it did in Figure 4-9, because it not only has a large number of its patents linked to the DOE set, but it also has a higher average number of linkages for each patent linked to DOE. These finding suggests that the solar energy technologies of BP Solar, ECD, and SunPower are linked both broadly and deeply to DOE's solar PV research.

Figure 4-12. Total Number of Links from Solar Energy Patent Families of Top U.S. PV Producers to Earlier DOE-Attributed Solar PV Patent Families



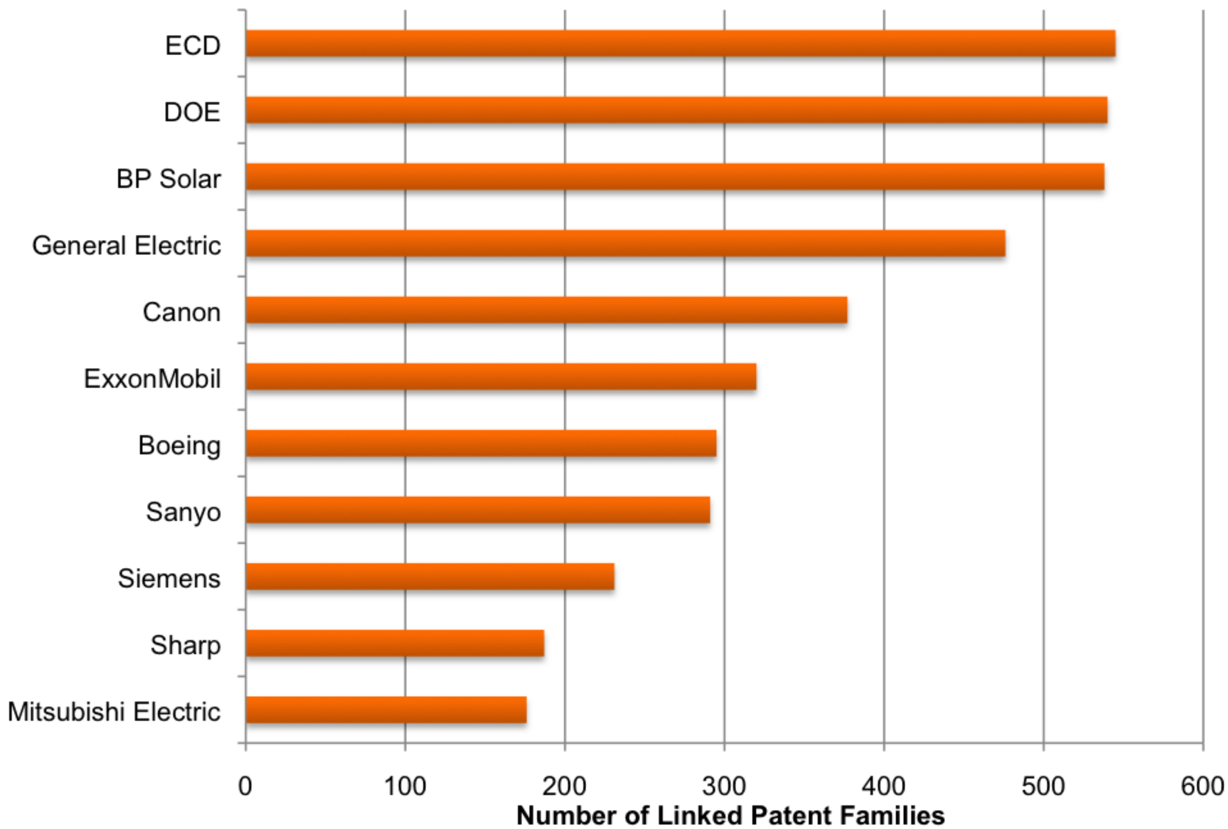
4.2.2 Tracing Backward from Leading Companies in Solar Energy Patenting Worldwide to DOE

This section extends the backward tracing to assess the degree to which DOE's PV research has influenced not only top U.S. PV producers, but leading innovators in solar energy patenting worldwide.

The influence of DOE-attributed solar PV patent families is compared to the influence of solar energy patent families of each of these leading innovators in Figure 4-13. Specifically, Figure 4-13 ranks DOE and the leading innovating companies by the extent to which their solar energy patent families (and DOE PV patent families) have been cited by later patent families of each of these leading companies.

DOE is one of three organizations at the head of Figure 4-13, all of which are linked to an almost identical number of later patent families owned by the leading innovative solar energy companies. ECD is at the head of this figure by a slight margin. ECD’s solar energy patents are linked to 545 subsequent solar energy patent families owned by the leading companies in this technology. ECD is followed by DOE (linked to 540 leading company patent families) and BP Solar (linked to 538 families). There is then a decrease in the number of linkages, with General Electric next, followed by Canon.

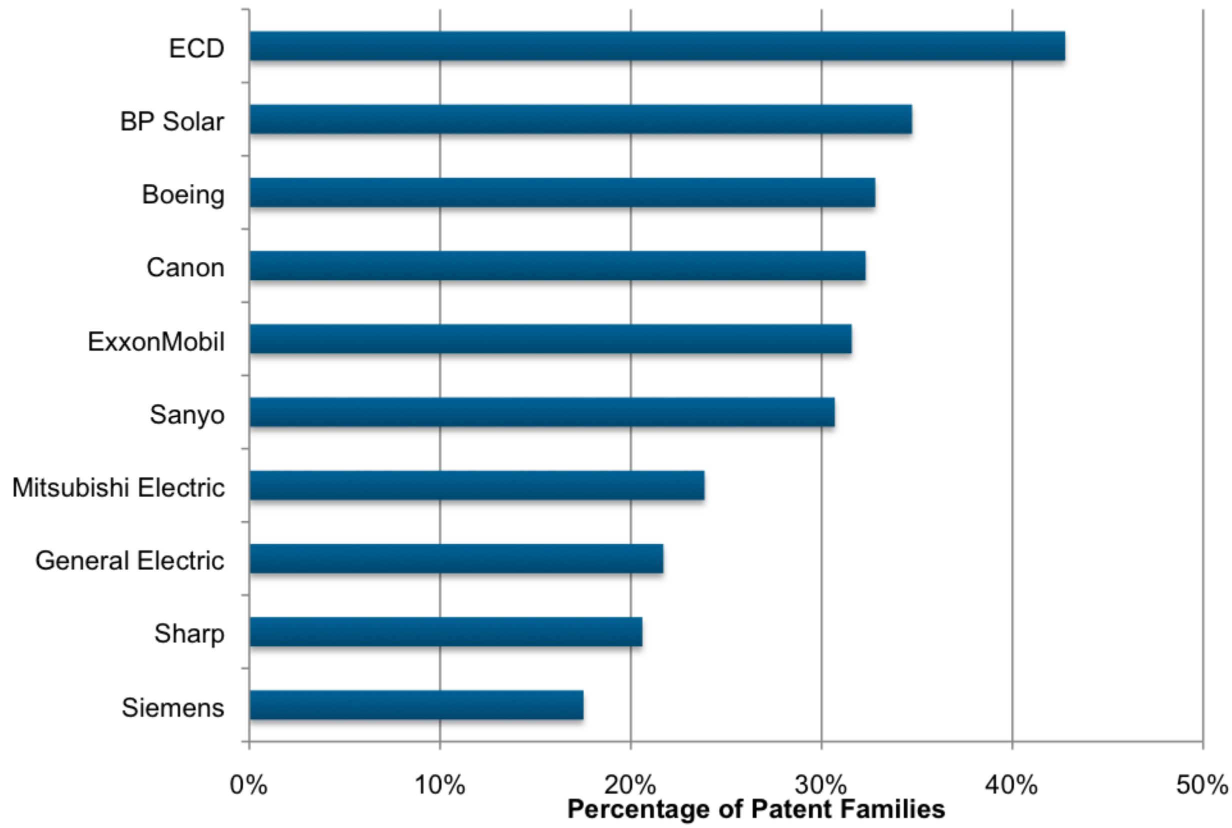
Figure 4-13. A Comparison of DOE and Leading Innovative Companies in Terms of the Number of Solar Energy Patent Families Subsequently Linked to Their Solar Energy Patent Families



As was noted in Section 3.5.3, a total of 1,812 solar energy patent families were identified as owned by these 10 leading companies. Hence, 30% of these families are linked to earlier ECD solar energy patents, 30% to earlier DOE-funded PV patents, and 30% are linked to earlier BP solar energy patents, where each percentage is rounded to the nearest whole number. This finding provides further evidence that DOE-funded PV research has formed an extensive part of the foundation for subsequent developments made by leading companies in solar energy innovation.

Figure 4-14 shows the percentage of each of these 10 companies' solar energy patent families that is linked to earlier DOE-attributed PV patents. This figure reveals that, with the exception of Siemens, all of these leading innovators in solar energy have at least 20% of their patent families linked to earlier DOE-funded PV patents families. The distribution also suggests that DOE-funded PV research has had a broad impact worldwide on solar energy innovation, rather than having its impact only on domestic PV companies

Figure 4-14. Percentage of Solar Energy Patent Families of Leading Innovators in Solar Energy Worldwide Linked to Earlier DOE-Attributed PV Patent Families



4.3 Results of Tracing Forward from DOE-Funded PV Research to All Organizations and Technology Areas

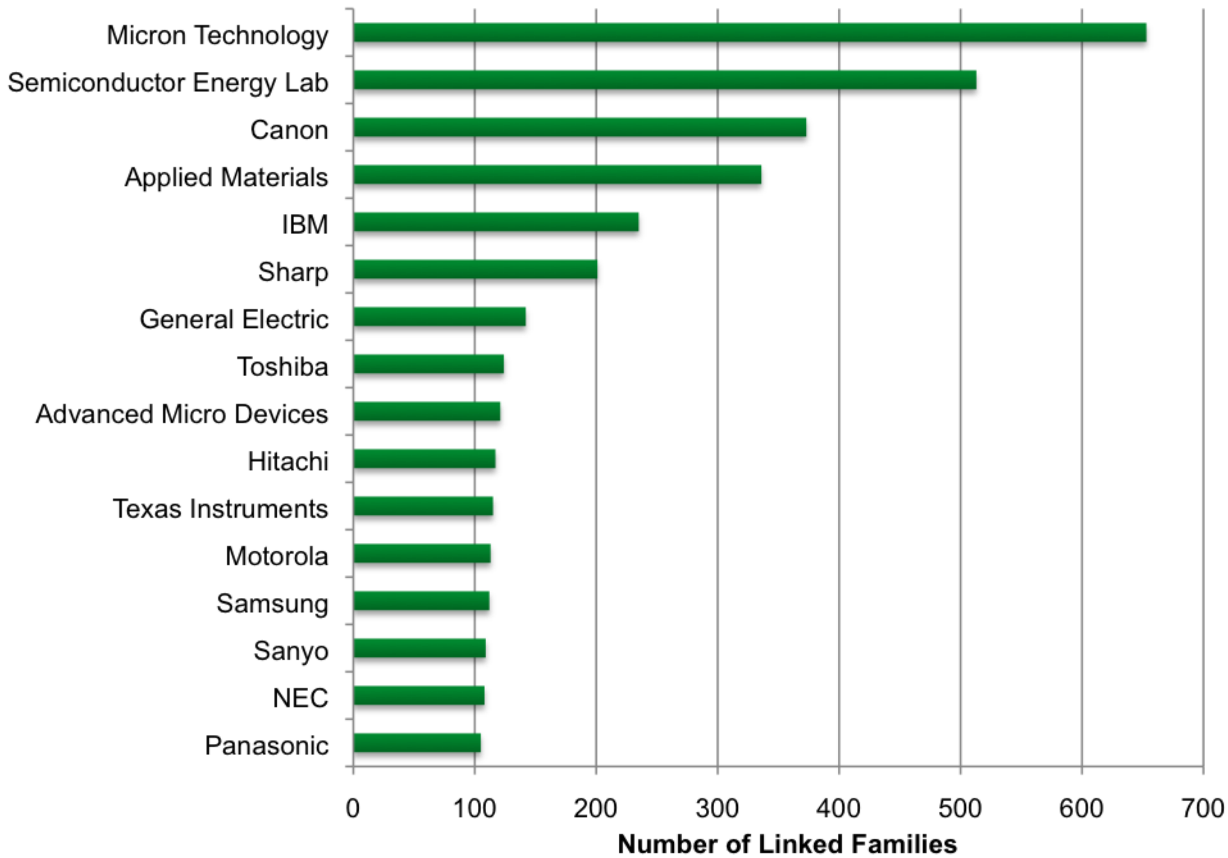
This element of the study continues the previous section's focus at the organization level, but the results here are from forward tracing. The focus is on assessing more broadly the influence of DOE-funded PV research on subsequent technological developments both within and outside the solar energy industry, by all organizations. It is designed to help answer the following question:

> Are there indications of influence of the DOE solar PV research results outside the area of solar energy?

4.3.1 Forward Linkages of DOE-Attributed PV Patent Families to All Organizations

To help answer this question, the organizations with the largest number of patent families linked to earlier DOE-attributed PV patents are shown in Figure 4-15. This figure includes patent families assigned to all organizations, not just the leading solar energy companies. It also includes all patent families from these organizations, rather than just their solar energy patent families. Dominating Figure 4-15 are organizations with strong links to the semiconductor industry, notably Micron Technology, Semiconductor Energy Lab, Applied Materials, and IBM. These results suggest that DOE-funded PV research has had a strong impact on subsequent developments in semiconductor technology beyond those related to PV devices.

Figure 4-15. Organizations from All Industry Areas with the Largest Number of Patent Families from All Technologies Linked to Earlier DOE-Attributed PV Patents



4.3.2 Forward Linkages of DOE to Major Technology Areas

To further identify areas of influence outside of solar energy the forward tracing analysis identified the primary IPCs, at the 4-digit level, of patent families linked to the DOE-attributed PV patent families.[26] The results for two-generations of citations are shown in Figure 4-16.[27]

The IPC concerned with semiconductor devices (H01L) dominates the figure. The patents in IPC H01L shown here are divided into two groups—those in "H01L 31," which is a specific subclass directed to light sensitive semiconductor devices including photovoltaic cells, and those in other subclasses beyond PV devices, designated "H01L other." The idea behind this division is to examine the influence of DOE solar PV research on subsequent patents concerned specifically with photovoltaic cells, i.e., those patents in H01L 31, and those concerned with semiconductor devices more generally, i.e., those patents in H01L other (although it is acknowledged that any division based on IPCs, such as this, is far from perfect).

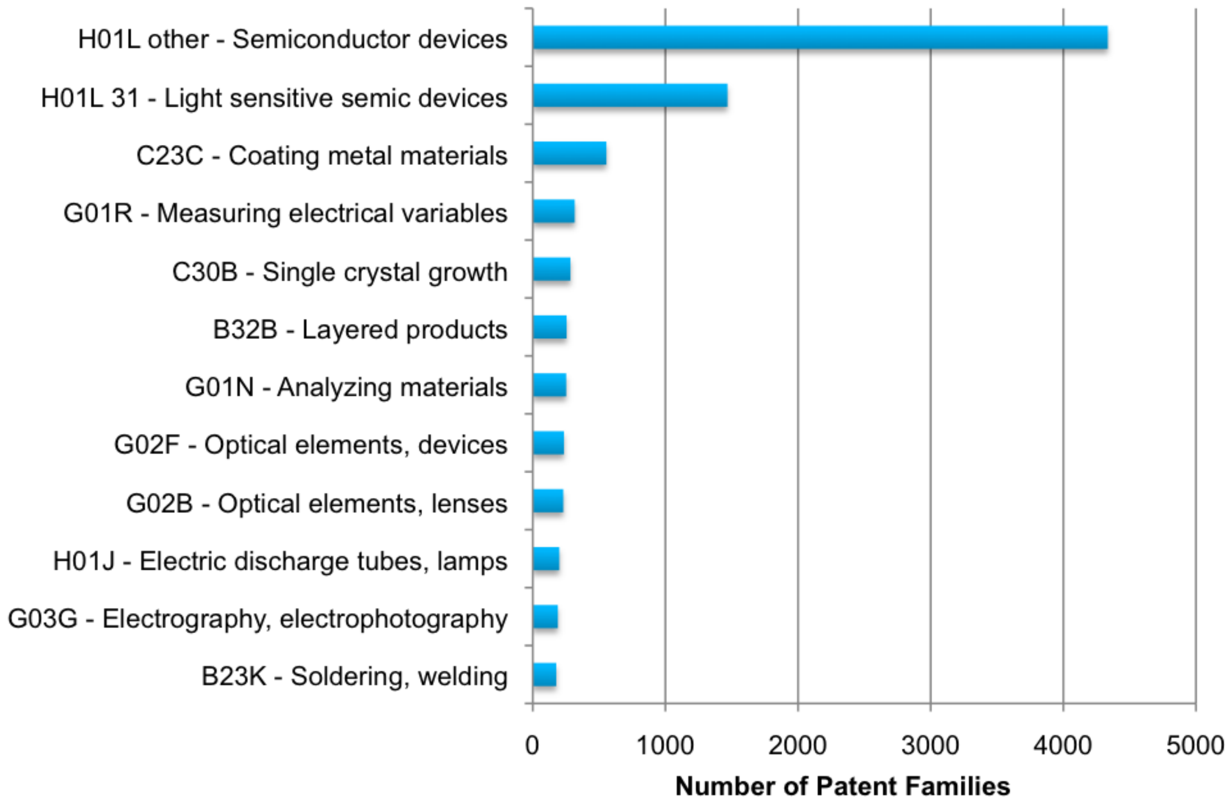
Figure 4-16 also contains IPCs related to coating methods (C23C); measuring and testing (G01R and G01N); and crystal growth (C30B), though the numbers of patents in these IPCs are small compared to the number in H01L. This suggests that the impact of DOE-funded PV research has been particularly strong on developments related to the design and manufacture of semiconductor devices, including photovoltaic cells, but there has been a weaker impact in a number of other technology fields.

For comparison, an analysis was also conducted using only a first-generation of citations rather than the two-generation analysis of Figure 4-16. Adding a second generation of patenting markedly increased the relative number of links to semiconductor patents beyond PV devices (i.e., H01L other) as compared with the number of links to PV devices. This suggests that, over time, the influence of DOE PV research has spread extensively to the broader semiconductor device industry.

[26] In some cases, different patent documents within a patent family may have different first IPCs, although it is unusual for the IPCs to differ at the 4-digit level used here. To avoid possible multiple IPCs for a given patent family, the study used the primary IPC for the anchor patent in each patent family.

[27] In this forward tracing analysis, the second generation of citations does not include self-citations made by organizations (i.e., cases where an organization cites one of its own earlier patents as prior art, which in turn cites DOE are excluded). Typically such self-citations are not removed in the study because they often reveal an organization building successive generations of technology. However, in this case, there are a small number of companies that cite their own patents so extensively that this would skew the analysis significantly, so second-generation self-citations are removed.

Figure 4-16. Number of Patent Families by IPC Linked to Earlier DOE Solar PV Patents through Two-Generations of Citations



4.4 Patent-Level Results of Backward and Forward Tracing

This section shows results of both the backward and forward tracing analyses at the individual patent level. It is designed to answer the following questions:

- Which solar energy patent families of the top U.S. PV producers and of the leading innovators in solar energy worldwide have the most citation links to earlier DOE-attributed PV patent families? (See Section 4.4.1.)
- Which high-impact solar energy patents of these same companies are linked to earlier DOE-attributed PV patent families? (See Section 4.4.2.)
- Which other high-impact patents of other organizations are linked to earlier DOE-attributed PV patent families? (See Section 4.4.3.)
- Which DOE-attributed PV patents are linked to the largest number of subsequent patent families of leading innovators in solar energy? (See Section 4.4.4.)
- Which are the most highly cited of the DOE-attributed PV patents across all industries and organizations? (See Section 4.4.5.)

4.4.1 Patent Families of Top U.S. PV Producers and of Leading Innovators in Solar Energy Linked Most Strongly to Earlier DOE-Attributed PV Patent Families

Table 4-1 shows which of the individual solar energy patent families (represented by anchor patents) owned by the top U.S. PV producers have the largest number of links to earlier DOE-attributed PV patent families. BP Solar patent families occupy three of the top four positions in Table 4-1. Two of these three BP Solar families, US #6,121,541 and US #6,368,892) describe multi-junction solar cells formed from amorphous silicon and copper indium diselenide. These two BP Solar families are linked to 32 and 14 earlier DOE-attributed PV families, respectively. The ‘541 patent cites 44 U.S. patents as prior art, among them earlier DOE-attributed Solarex (subsequently part of BP Solar) patents describing amorphous silicon solar cells, and also DOE-attributed RCA and Boeing patents describing thin film solar cells. As such, the ‘541 patent appears to have built on a variety of earlier DOE-funded technologies.

Table 4-1. Top U.S. PV Producers' Solar Energy Patent Families with the Most Citation Links to Earlier DOE-Attributed PV Patent Families

Anchor Patent[a]	Issue Year	# Links to DOE	Assignee	Title
6121541	2000	32	BP Solar	Monolithic multi-junction solar cells with amorphous silicon and CIS and their alloys
6111189	2000	22	BP Solar	Photovoltaic module framing system with integral electrical raceways
6617507	2003	16	First Solar	Photovoltaic array
6368892	2002	14	BP Solar	Monolithic multi-junction solar cells with amorphous silicon and CIS and their alloys
7297866	2007	12	SunPower	Ventilated photovoltaic module frame
6883290	2005	11	SunPower	Shingle system and method
7328534	2008	11	SunPower	Shingle system
6465724	2002	9	BP Solar	Photovoltaic module framing system with integral electrical raceways
5246506	1993	8	BP Solar	Multijunction photovoltaic device and fabrication method
5230746	1993	7	BP Solar	Photovoltaic device having enhanced rear reflecting contact
6729081	2004	7	ECD	Self-adhesive photovoltaic module
5296045	1994	7	ECD	Composite back reflector for photovoltaic device

Table 4-1 (continued). Top U.S. PV Producers' Solar Energy Patent Families with the Most Citation Links to Earlier DOE-Attributed PV Patent Families

Anchor Patent[a]	Issue Year	# Links to DOE	Assignee	Title
5256887	1993	6	BP Solar	Photovoltaic device including a boron doping profile in an I-type layer
4633033	1986	6	ECD	Photovoltaic device and method
7435897	2008	6	Schott	Apparatus and method for mounting photovoltaic power generating systems on buildings
5078803	1992	6	Solar World	Solar cells incorporating transparent electrodes comprising hazy zinc oxide

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

The other BP patent family at the top of Table 4-1 (indicated by anchor patent US #6,111,189) describes a photovoltaic module framing system for mounting on roof surfaces. This patent family is linked to 22 earlier DOE-attributed PV patent families. Also prominent in Table 4-1 are patent families owned by First Solar, describing photovoltaic arrays (anchor patent US #6,617,507); and patent families owned by SunPower describing photovoltaic roof shingles systems (anchor patents US #6,883,290 and #7,328,534), as well as photovoltaic module frames (anchor patent US #7,297,866). Additional patent families of BP Solar and patent families of ECD figure prominently in the remaining list. Schott and Solar World also are among the top U.S. PV producers having patent families strongly linked back to the DOE PV set.

This analysis is broadened by looking beyond the top U.S. producers of PV to the leading innovators in solar energy worldwide. Table 4-2 lists solar energy patent families (again indicated by anchor patents) owned by this group of companies that are linked particularly extensively to earlier DOE-attributed PV patents. As this table shows, there are six solar energy patent families owned by the leading innovators that are linked to 14 or more earlier DOE-funded PV patent families. All six of these patent families are assigned to either BP Solar or Sanyo. The BP Solar patents also appear in Table 4-1, because BP Solar is among both the top U.S. PV producers and the leading innovators of solar energy worldwide.

What Table 4-2 adds is the influence of DOE-funded PV research on solar energy patenting by Sanyo, Canon, Boeing, and General Electric. There are three Sanyo patent families near the head of Table 4-2. Two of these patent families (indicated by anchor patents US #6,818,819 and US #6,667,434) describe two-sided weatherproof photovoltaic modules. Meanwhile, the third patent family (anchor patent US #7,030,413) describes a thin film amorphous silicon photovoltaic device. All three of these Sanyo patents are linked to more than 20 earlier DOE-attributed PV patent families. Most of these links are indirect links resulting from the three Sanyo patents all citing the same DOE-attributed BP Solar (Solarex) patent as prior art. This BP patent (US #6,077,722, issued in 2000) in turn cites numerous earlier DOE-attributed patent families dating back to the 1970s and 1980s. This is an example of Sanyo's solar energy technology being linked to different generations of DOE-funded solar energy research.

Table 4-2. Leading Solar Energy Innovators' Patent Families with the Most Citation Links to Earlier DOE-Attributed PV patents

Anchor Patent[a]	Issue Year	# Links to DOE	Assignee	Title
6121541	2000	32	BP Solar	Monolithic multi-junction solar cells with amorphous silicon and CIS and their alloys
7030413	2006	27	Sanyo	Photovoltaic device with intrinsic amorphous film at junction, having varied optical band gap through thickness thereof
6818819	2004	26	Sanyo	Solar cell module
6667434	2003	24	Sanyo	Solar cell module
6111189	2000	22	BP Solar	Photovoltaic module framing system with integral electrical raceways
6368892	2002	14	BP Solar	Monolithic multi-junction solar cells with amorphous silicon and CIS and their alloys
5885725	1999	9	Canon	Photovoltaic device
6476314	2002	9	Boeing	Solar tile and associated method for fabricating the same
6465724	2002	9	BP Solar	Photovoltaic module framing system with integral electrical raceways
6906253	2005	9	Boeing	Method for fabricating a solar tile
6670541	2003	9	Canon	Solar battery, solar generating apparatus, and building
6914182	2005	8	Sanyo	Method of installing solar cell modules, and solar cell module
7122733	2006	8	Boeing	Multi-junction photovoltaic cell having buffer layers for the growth of single crystal boron compounds
7189917	2007	8	Canon	Stacked photovoltaic device
6420643	2002	8	General Electric	Silicon thin-film, integrated solar cell, module, and methods of manufacturing the same
5500055	1996	8	Canon	Photovoltaic device
5589403	1996	8	Canon	Method for producing photovoltaic device
5981867	1999	8	Canon	Photovoltaic module

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

4.4.2 High-Impact Solar Energy Patents of Top U.S. PV Producers and of Leading Innovators in Solar Energy Linked to DOE-Attributed PV patents

Tables 4-3 and 4-4 identify the most influential innovations by the top U.S. PV producers and leading innovators in solar energy that are linked to DOE-funded PV research.

Table 4-3 identifies the particularly influential (highly cited) patents of the top U.S. PV producers that are linked to the DOE-attributed PV set. All of the patents in this figure have Citation Index values[28] above two. This means that each of them has been cited more than twice as frequently as expected given their age and technology. As such, these patents represent high-impact technologies owned by the top U.S. PV producers that are linked to earlier DOE-funded PV research.

Table 4-3. Highly Cited Solar Energy Patents of Top U.S. PV Producers Linked to Earlier DOE-Attributed PV Patents

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
4419533	1983	47	4.52	ECD	Photovoltaic device having incident radiation directing means for total internal reflection
5164019	1992	51	4.08	SunPower	Monolithic series-connected solar cells having improved cell isolation and method of making same
6534703	2003	12	3.12	SunPower	Multi-position photovoltaic assembly
6111189	2000	19	2.93	BP	Photovoltaic module framing system with integral electrical raceways
6353042	2002	12	2.92	Evergreen Solar	UV-light stabilization additive package for solar cell module and laminated glass applications
6570084	2003	11	2.86	SunPower	Pressure equalizing photovoltaic assembly and method
4514583	1985	31	2.82	ECD	Substrate for photovoltaic devices
4419530	1983	28	2.69	ECD	Solar cell and method for producing same
5746839	1998	30	2.64	SunPower	Lightweight, self-ballasting photovoltaic roofing assembly

[28] The Citation Index 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 as indicated by its Patent Office Classification (POC). For example, the number of citations received by a particular 2002 patent in POC 60/278 is divided by the mean number of citations received by all patents in that POC issued in 2002 to derive its Citation Index. The expected Citation Index for a patent is one. An index of 10 means that the patent has been cited 10 times more frequently than would be expected given its age and technology. An index of 0.7 means that a patent has been cited 30% less often than expected.

Table 4-3 (continued). Highly Cited Solar Energy Patents of Top U.S. PV Producers Linked to Earlier DOE-Attributed PV Patents

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
6148570	2000	17	2.59	SunPower	Photovoltaic building assembly with continuous insulation layer
4517403	1985	28	2.54	BP	Series connected solar cells and method of formation
6465724	2002	14	2.51	BP	Photovoltaic module framing system with integral electrical raceways
4915745	1990	29	2.38	BP	Thin film solar cell and method of making
5164020	1992	29	2.32	BP	Solar panel
4532372	1985	25	2.27	ECD	Barrier layer for photovoltaic devices
6288325	2001	15	2.19	BP	Producing thin film photovoltaic modules with high integrity interconnects and dual layer contacts
6501013	2002	12	2.15	SunPower	Photovoltaic assembly array with covered bases

[a] Note that this column does not reference anchor patents as do some of the tables, rather just "patents." The reason is that this table contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The Citation Indexes are calculated at the individual patent level, not at the patent family level.

The patents in this table describe a range of technologies. They include ECD patents describing the fabrication of thin film solar energy cells (see US #4,419,533); SunPower patents for series connected solar cells (US #5,164,019) and photovoltaic assemblies (US #6,534,703); BP Solar patents detailing photovoltaic framing systems (US #6,111,189 and #6,465,724) and thin film solar cells (US #4,915,745); and an Evergreen Solar patent (US #6,353,042) describing a UV stabilizer for a solar cell. The two BP Solar patents describing photovoltaic framing systems appear in both tables, showing that they are both high-impact patents and among those most closely linked to DOE-funded PV research.

Table 4-4 extends the finding of Table 4-3, by listing highly cited solar energy patents owned by leading innovators in solar energy worldwide that are linked to earlier DOE-funded PV research. All of the patents in this table also have Citation Index values above two, meaning that each of them has been cited more than twice as frequently as expected given their age and technology.

The presence of a series of Canon patents in Table 4-4 suggests that, while Canon’s patents in general are not particularly strongly linked to earlier DOE research, a number of its high-impact patents are linked back to DOE. For example, the patent at the head of this figure (US #6,682,990) is a Canon patent describing a solar cell fabrication method that helps to reduce damage to the substrate. This Canon patent, which cites an earlier DOE-attributed Midwest Research Institute/NREL patent (US #5,544,616) as prior art, has in turn been cited by 22 subsequent patents, almost five times as many citations as expected given its age and technology.

Two other companies with multiple highly cited solar energy patents linked to earlier DOE-attributed PV patents are Sharp and ECD. Sharp's patents in Table 4-4 describe thin film solar cells. For example, Sharp's patent US #6,242,686 outlines a pin junction photovoltaic device. This patent has been cited by 33 subsequent patents, attracting more than four times as many citations as expected. It cites an earlier DOE-attributed BP (Solarex) patent (US #4,718,947) as prior art, suggesting this earlier DOE-funded research helped form part of the foundation for Sharp's high-impact pin junction photovoltaic device technology.

ECD has four highly cited patents in Table 4-4 that are linked to earlier DOE-attributed PV patents. Three of these ECD patents are older patents describing the fabrication of thin film solar cells (see, for example, US #4,419,533 issued in 1983). The fourth ECD patent (US #6,729,081) is much more recent, having been issued in 2004. This patent describes a self-adhesive photovoltaic module. It has already started to attract more citations than expected, and appears to be closely related to ECD's UNI-SOLAR rooftop solar module products. This '081 patent is linked to seven different earlier DOE-attributed PV patents, suggesting that DOE-funded research has helped form an important part of the foundation for this rooftop PV module technology.

Table 4-4. Highly Cited Solar Energy Patents of Leading Innovators in Solar Energy Worldwide Linked to Earlier DOE-Attributed PV Patents

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
6682990	2004	22	4.97	Canon	Separation method of semiconductor layer and production method of solar cell
6242686	2001	33	4.66	Sharp	Photovoltaic device and process for producing the same
4419533	1983	47	4.52	ECD	Photovoltaic device having incident radiation directing means for total internal reflection
5221365	1993	49	3.91	Sanyo	Photovoltaic cell and method of manufacturing polycrystalline semiconductive film
6316832	2001	49	3.52	Canon	Moldless semiconductor device and photovoltaic device module making use of the same
6190937	2001	37	3.35	Canon	Method of producing semiconductor member and method of producing solar cell
4536608	1985	33	3.00	Exxon Mobil	Solar cell with two dimensional hexagonal reflecting diffraction grating
6150605	2000	21	2.99	Sharp	Photovoltaic cell and manufacturing method thereof
6452092	2002	21	2.97	Sharp	Photovoltaic cell and solar cell utilizing the same

Table 4-4 (continued). Highly Cited Solar Energy Patents of Leading Innovators in Solar Energy Worldwide Linked to Earlier DOE-Attributed PV Patents

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
6111189	2000	19	2.93	BP Solar	Photovoltaic module framing system with integral electrical raceways
6383576	2002	13	2.91	Canon	Method of producing a microcrystal semiconductor thin film
6091020	2000	19	2.90	Boeing	Photovoltaic cells having a concentrating coverglass with broadened tracking angle
6175075	2001	20	2.85	Canon	Solar cell module excelling in reliability
6729081	2004	6	2.83	ECD	Self-adhesive photovoltaic module
5441577	1995	36	2.82	Mitsubishi Electric	Thin film solar cell and production method therefore
4514583	1985	31	2.82	ECD	Substrate for photovoltaic devices
5091018	1992	35	2.80	Boeing	Tandem photovoltaic solar cell with III-V diffused junction booster cell
4419530	1983	28	2.69	ECD	Solar cell and method for producing same

[a] Note that this column does not reference anchor patents as do some of the tables, rather just "patents." The reason is that this table contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The Citation Indexes are calculated at the individual patent level, not at the patent family level.

4.4.3 Other High-Impact Patents Linked to Earlier DOE-Attributed PV Patent Families

Tables 4-5 and 4-6 show how DOE-funded PV research has helped form part of the foundation for subsequent high-impact technologies developed by other organizations both in and outside of solar and PV technology. These high-impact patents are revealed by the forward patent tracing analysis, and exclude those already examined in the backward tracing analysis, featuring the top eight U.S. PV producers and 10 leading innovators in solar energy.

Table 4-5 lists the "other" highly cited solar energy patents that are linked to earlier DOE-funded PV research. There is no dominant assignee in this figure. Rather, the patents are assigned to a wide range of organizations, including large corporations (Raytheon and NEC), smaller specialist solar energy companies (Nanosys and SunPower), and universities (Princeton, Columbia, and Ecole Polytechnique Federale de Lausanne). This suggests that DOE research has had a broad impact on technology developments in the solar energy industry.

Table 4-5 also reveals that DOE's impact can be seen on wider developments in thin film technology (see, for example, US #6,706,963 assigned to Konarka; and US #6,340,788 assigned to Raytheon). Its influence can also be detected on patents describing methods for connecting thin film photovoltaic devices (see, for example, US #5,164,019 assigned to SunPower, and US #6,069,313 assigned to Ecole Polytechnique Federale de Lausanne).

It is also interesting to note that DOE patents are linked to highly cited recent patents describing photovoltaic devices based on nanoscale compositions. These patents include US #6,878,871 assigned to Nanosys, and US #6,946,597 assigned to Nanosolar. This suggests that DOE research is closely linked to recent developments related to the new generation of nanostructure-based photovoltaic devices.

Table 4-6 shows highly cited patents outside of solar and PV technologies that are linked to earlier DOE-attributed PV patents. It thus shows the influence of DOE-funded PV research on high-impact technologies beyond solar energy, confirming its influence on subsequent developments in semiconductor technology. Most of the patents in this figure describe semiconductor manufacturing techniques, notably deposition of thin films (see, for example, US #6,342,277 assigned to ASM International; US #6,176,992 assigned to Nutool; and US #5,000,113 assigned to Applied Materials). There are also patents in Table 4-6 describing other technologies, such as organic LEDs (US #5,707,745 assigned to University of Princeton) and image sensors (US #6,407,381 assigned to Amkor). However, the main focus of patents in this figure is on semiconductor device fabrication. As such, this reinforces the earlier finding that the impact of DOE solar and PV research beyond solar technology has been primarily on developments in the semiconductor industry.

Table 4-5. Highly Cited Solar Energy Patents of Others[a] Linked to DOE-Attributed PV Patents

Patent[b]	Issue Year	# Cites Received	Citation Index	Assignee	Title
6878871	2005	27	11.97	Nanosys Inc.	Nanostructure and nanocomposite based compositions and photovoltaic devices
6946597	2005	17	7.54	Nanosolar Inc.	Photovoltaic devices fabricated by growth from porous template
6580027	2003	29	6.33	Princeton University	Solar cells using fullerenes
6060327	2000	82	6.05	Keensense Inc.	Molecular wire injection sensors
6239355	2001	43	5.91	Columbia University	Solid-state photoelectric device

Table 4-5 (continued). Highly Cited Solar Energy Patents of Others[a] Linked to DOE-Attributed PV Patents

Patent[b]	Issue Year	# Cites Received	Citation Index	Assignee	Title
6340788	2002	36	5.80	Raytheon Co.	Multijunction photovoltaic cells and panels using a silicon or silicon-germanium active substrate cell for space and terrestrial applications
6852920	2005	12	5.32	Nanosolar Inc.	Nano-architected/assembled solar electricity cell
6706963	2004	15	5.13	Konarka Technologies	Photovoltaic cell interconnection
4860509	1989	46	4.29	Unassigned	Photovoltaic cells in combination with single ply roofing membranes
5482570	1996	54	4.26	Swatch Group AG	Photovoltaic cell
5164019	1992	51	4.08	SunPower Corp.	Monolithic series connected solar cells having improved cell isolation and method of making same
5596981	1997	27	3.99	Unassigned	Solar device and method for assembly
6441298	2002	23	3.70	NEC Corp.	Surface-plasmon enhanced photovoltaic device
6013871	2000	23	3.64	Unassigned	Method of preparing a photovoltaic device
6245988	2001	28	3.56	Ecole Polytechnique Federale de Lausanne	Metal complex photosensitizer and photovoltaic cell
4677248	1987	32	3.37	Unassigned	Apparatus for mounting solar cells
6069313	2000	21	3.26	Ecole Polytechnique Federale de Lausanne	Battery of photovoltaic cells and process for manufacturing same

[a] Note that "other" excludes patents of the top eight U.S. PV producers and of the 10 leading innovators in solar energy worldwide that were treated in the backward tracing analysis.

[b] Note that this column does not reference anchor patents as do some of the tables, rather just "patents." The reason is that this table contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The Citation Indexes are calculated at the individual patent level, not at the patent family level.

Table 4-6. Highly Cited Non-Solar Energy Patents Linked to DOE-Attributed PV Patents

Patent[a]	Issue Year	# Cites Received	Citation Index	Assignee	Title
6342277	2002	163	27.34	ASM International N.V.	Sequential chemical vapor deposition
6176992	2001	244	24.64	Nutool Inc.	Method and apparatus for electro-chemical mechanical deposition
5916365	1999	294	23.59	ASM International N.V.	Sequential chemical vapor deposition
5000113	1991	420	21.38	Applied Materials Inc.	Thermal CVD/PECVD reactor and use for thermal chemical vapor deposition of silicon dioxide and in-situ multi-step planarized process
5204314	1993	189	20.83	ATMI Inc.	Method for delivering an involatile reagent in vapor form to a CVD reactor
5703436	1997	244	19.06	Princeton University	Transparent contacts for organic devices
5707745	1998	217	18.50	Princeton University	Multicolor organic light emitting devices
6388324	2002	148	14.99	Arizona State University	Self-repairing interconnections for electrical circuits
6153010	2000	158	14.67	Nichia Corporation	Method of growing nitride semiconductors, nitride semiconductor substrate and nitride semiconductor device
5147826	1992	382	14.50	Pennsylvania State University	Low temperature crystallization and pattering of amorphous silicon films
6143155	2000	141	14.07	Novellus Systems Inc.	Method for simultaneous non-contact electrochemical plating and planarizing of semiconductor wafers using a bipolar electrode assembly
6551929	2003	93	13.95	Applied Materials Inc.	Bifurcated deposition process for depositing refractory metal layers employing atomic layer deposition and chemical vapor deposition techniques

Table 4-6 (continued). Highly Cited Non-Solar Energy Patents Linked to DOE-Attributed PV Patents

Patent[a]	Issue Year	# Cites Received	Citation Index	Assignee	Title
6633831	2003	78	13.37	KLA-Tencor Corp.	Methods and systems for determining a critical dimension and a thin film characteristic of a specimen
5225561	1993	87	12.81	ATMI Inc.	Source reagent compounds for MOCVD of refractory films containing group IIA elements
6297170	2001	153	12.55	Philips Electronics N.V.	Sacrificial multilayer anti-reflective coating for mos gate formation
6407381	2002	76	12.22	Amkor Technology Inc.	Wafer scale image sensor package
5275851	1994	343	11.97	Pennsylvania State University	Low temperature crystallization and patterning of amorphous silicon films on electrically insulating substrates
5362526	1994	154	11.73	Applied Materials Inc.	Plasma enhanced CVD process using TEOS for depositing silicon oxide
6475869	2002	99	11.71	Advanced Micro Devices Inc.	Method of forming a double gate transistor having an epitaxial silicon/germanium channel region

[b]Note that this column does not reference anchor patents as do some of the tables, rather just "patents." The reason is that this table contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The Citation Indexes are calculated at the individual patent level, not at the patent family level.

4.4.4 DOE-Attributed PV and Other Patent Families Linked to the Largest Number of Leading Innovators' Subsequent Solar Energy Patent Families

This section shifts focus from company-owned patents to DOE-attributed patents. Table 4-7 shows the patent families in the DOE-attributed PV set that are linked to the most solar energy patent families of the leading innovators in this technology worldwide. Most of the anchor patents in this table are relatively old. This is not surprising, since older patents have had a longer time period to become connected to subsequent generations of technology. Thus, the patent families in Table 4-7 represent older foundation technologies that have extensive links to subsequent developments made by leading companies in the solar energy industry.

Patents of three assignees funded by DOE PV research dominate Table 4-7: General Electric, the University of Delaware, and Boeing. General Electric is responsible for the four patent families at the head of the table—the four patent families based on DOE-funded PV research that are linked to the largest number of subsequent solar energy patent families owned by leading innovators. The patent family at the top of the figure (indicated by anchor patent US #4,272,641) describes a solar cell constructed from multiple layers of amorphous silicon. It is one of a number of General Electric patent families in Table 4-7 describing elements of amorphous silicon solar cells. Other General Electric patent families describe processing techniques for producing the cells (anchor patent US #4,292,092); Schottky barriers for the cells (anchor patent US #4,167,015); and the connection of such cells to produce solar batteries (anchor patent US #4,316,049).

Table 4-7. DOE-Attributed PV Patent Families Linked to the Most Solar Energy Patent Families of Leading Innovators in Solar Energy Worldwide

DOE Anchor Patent[a]	Issue Year	# Linked Innovator Patent Families	Assignee	Title
4272641	1981	76	General Electric	Tandem junction amorphous silicon solar cells
4292092	1981	74	General Electric	Laser processing technique for fabricating series connected and tandem junction series connected solar cells into a solar battery
4166919	1979	67	General Electric	Amorphous silicon solar cell allowing infrared transmission
4167015	1979	67	General Electric	Cermet layer for amorphous silicon solar cells
4328390	1982	66	University of Delaware	Thin film photovoltaic cell
4816082	1989	62	ECD	Thin film solar cell including a spatially modulated intrinsic layer
4377723	1983	53	University of Delaware	High efficiency thin film multiple gap photovoltaic device
4335266	1982	48	Boeing	Methods for forming thin film heterojunction solar cells from I-III-VI/2 \ chalcopyrite compounds, and solar cells produced thereby
4523051	1985	38	Boeing	Thin films of mixed metal compounds
4316049	1982	38	General Electric	High voltage series connected tandem junction solar battery

Table 4-7 (continued). DOE-Attributed PV Patent Families Linked to the Most Solar Energy Patent Families of Leading Innovators in Solar Energy Worldwide

DOE Anchor Patent[a]	Issue Year	# Linked Innovator Patent Families	Assignee	Title
5078804	1992	35	Boeing	I-III-VI.Sub.2 based solar cell utilizing the structure CuInGaSe.Sub.2 CdZnS/ZNO
4387265	1983	34	University of Delaware	Tandem junction amorphous semiconductor photovoltaic cell
4162505	1979	33	General Electric	Inverted amorphous silicon solar cell utilizing cermet layers
4217148	1980	30	General Electric	Compensated amorphous silicon solar cell
4253882	1981	26	University of Delaware	Multiple gap photovoltaic device
4163677	1979	24	General Electric	Schottky barrier amorphous silicon solar cell with thin doped region adjacent metal Schottky barrier
4166918	1979	24	General Electric	Method of removing the effects of electrical shorts and shunts created during the fabrication process of a solar cell
4400244	1983	22	Monosolar Inc.	Photovoltaic power generating means and methods

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

The University of Delaware has a series of patent families based on DOE-funded PV research in Table 4-7 that are concerned with thin film solar cells. The University of Delaware patent family with the most links to subsequent leading innovator patent families (anchor patent US #4,328,390) describes a method for increasing the light absorption of thin film solar cells, while reducing the roughness of the electrical junction. The method makes the cell less susceptible to adverse environmental conditions.

Boeing also has a number of patent families based on DOE-funded PV research in Table 4-7 that are linked extensively to leading innovators' patents. These Boeing families (see for example anchor patents US #4,335,266 and US #5,078,804) describe large area, thin film solar cells formed from chalcopyrite compounds such as copper indium diselenide (CIS).

Table 4-8 lists the DOE-attributed non-PV patents that are linked to the largest number of subsequent solar energy patent families owned by leading innovators in solar energy worldwide. These patents are listed in recognition that solar energy patent families owned by leading innovators have built not only on earlier DOE-attributed PV patents but also on earlier "other" DOE patents describing related technologies.

The patents in this table can be broadly divided into two groups. The first group contains patents describing various aspects of thin films designed for both photovoltaic and other semiconductor applications. These patents describe defect reduction in thin films (US #4,181,538); plasma deposition of thin films (US #4,450,787); and electrical contacts for semiconductor devices (US #4,219,448). The second group contains patents related to solar collectors and concentrators (see, for example, US #4,491,681; US #4,327,707; and US #4,029,519). These DOE-attributed patents are related to solar energy, but were regarded as being outside this analysis' focus on DOE's investment in the PV aspects of solar energy technology.

Table 4-8. DOE-Attributed Non-PV Patent Families Linked to the Most Solar Energy Patent Families of Leading Innovators in Solar Energy Worldwide

DOE Patent[a]	Issue Year	# Linked Innovator Patent Families	Assignee	Title
4181538	1980	29	U.S. Dept. of Energy	Method for making defect free zone by laser annealing of doped silicon
4491681	1985	12	U.S. Dept. of Energy	Liquid cooled, linear focus solar cell receiver
4219448	1980	12	Unassigned	Screenable contact structure and method for semiconductor devices
4450787	1984	11	General Electric	Glow discharge plasma deposition of thin films
5417052	1995	10	Midwest Research Inst	Hybrid solar central receiver for combined cycle power plant
4327707	1982	9	U.S. Dept. of Energy	Solar collector
4029519	1977	7	U.S. Dept. of Energy	Solar collector having a solid transmission medium
4010733	1977	7	U.S. Dept. of Energy	Structurally integrated steel solar collector
3781612	1973	7	U.S. Dept. of Energy	Method of improving high purity germanium radiation detectors
4002499	1977	6	U.S. Dept. of Energy	Radiant energy collector
4217393	1980	6	General Electric	Method of inducing differential etch rates in glow discharge produced amorphous silicon

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

4.4.5 Most Highly Cited DOE-Attributed PV Patents

The forward patent tracing analysis identified highly cited DOE-attributed PV patents based on all fields, as determined by Citation Indexes, and as shown in Table 4-9. All of the patents in this table have Citation Index values above three, showing that each has been cited at least three times more frequently than expected and, in many cases, much more than that.

The patents listed in Table 4-9 are a mix of older patents that have attracted large numbers of citations from subsequent generations of patents, and more recent patents that are already attracting more citations than expected given their recent issue dates. An advantage of using Citation Indexes is that these two groups of patents can be compared directly, because each is benchmarked against its own peer group of patents of a similar age and technology.

Table 4-9. Highly Cited DOE-Attributed PV Patents Indicated by Citation Index

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
6996147	2006	19	27.04	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated therefrom
4775425	1988	137	11.13	ECD	Method of fabricating n-type and p-type microcrystalline semiconductor alloy material including band gap widening elements
4891330	1990	173	6.48	ECD	Nondestructive method for detecting defects in photodetector and solar cell devices
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 Inst 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

Table 4-9 (continued). Highly Cited DOE-Attributed PV Patents Indicated by Citation Index

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
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.	Multi-position photovoltaic 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

[a] Note that this column does not reference anchor patents as do some of the tables, rather just "patents." The reason is that this table contains citation counts and indexes for the specific patents listed, and not for patent families as a whole. The Citation Indexes are calculated at the individual patent level, not at the patent family level.

Among the older highly cited DOE-attributed PV patents in Table 4-9 are two patents issued in 1988 and 1990 to ECD. These patents (US #4,775,425 and US #4,891,330) describe thin film photovoltaic devices incorporating band gap widening elements. Wider gaps increase the transparency of the layers of the photovoltaic device, allowing more light to enter and 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. Both patents attracted many more citations than expected, which suggests that these DOE-attributed PV patents have had a strong impact on subsequent developments in PV technology.

Other older highly cited DOE-attributed PV patents in Table 4-9 include the General Electric amorphous silicon cell patents (US #4,272,641 and US #4,292,092) discussed earlier in the backward tracing element of the analysis. The previously referenced Boeing patents describing chalcopyrite compounds for thin film cells (US #4,335,266 and US #4,392,451) are also among the older highly cited DOE-attributed PV patents. In addition, there are patents that describe detecting defects in solar cells (US #4,287,473 assigned to DOE); large grain amorphous films (US #4,379,020 assigned to MIT); and multiple gap photovoltaic devices (US #4,253,882 assigned to the University of Delaware).

Table 4-9 also includes a number of more recent DOE-attributed PV patents that have already been cited by more subsequent patents than expected. These highly cited DOE-attributed PV patents include two patents assigned to North Carolina State University (US #6,420,648 and US #6,603,070) describing light harvesting rods for regenerative solar cells. They also include a Powerlight (now SunPower) patent (US #6,534,703) describing a photovoltaic module assembly and a mounting apparatus for this module, allowing for easier shipping and installation.

The patent at the head of Table 4-9 (US #6,996,147) is a University of California (DOE Berkeley National Laboratory) patent describing nanowires that can be used in a variety of energy conversion applications. This patent has broader potential applications than photovoltaic devices, but makes direct reference to such devices in its specification. Since being issued in 2006, this patent has already been cited by 19 subsequent patents. The mean number of citations for patents from the same year and technology classification is less than one, so this Berkeley patent appears to have had a particularly strong immediate impact on subsequent technological developments, notably related to nanotechnology.

The analysis based on a single generation[29] of citations and the Citation Index values given in Table 4-9 is now extended by adding a second generation of citations. The results, given in Tables 4-10 and 4-11, show the DOE-attributed PV patents linked to the largest number of all subsequent patent families through two generations of citations. In lieu of using the Citation Index (because two generations of citations are now being considered), these DOE patents are divided into the two tables to accommodate for age.

An interesting feature of Tables 4-10 and 4-11 is the division of the number of linked patent families into two groups by technology area. The first group contains solar energy patent families, while the second group contains all other patent families. Separating the linked patent families into these two groups makes it possible to determine which DOE patents have had their impact mainly within solar technology, and which have had their impact largely beyond solar energy.

Of the older DOE-attributed PV patent families in Table 4-10, examples of DOE-attributed PV patents with a strong impact on successive generations of solar technology include GE's amorphous silicon device patents (US #4,292,092) and Boeing's chalcopyrite device patents (US #4,335,266) highlighted earlier in the backward tracing element of the analysis. A significant percentage of the subsequent patent families linked to these GE and Boeing assigned patents are concerned with solar energy technology. As such, the technologies described in these patents may be regarded as having a strong impact on developments in solar and PV technology. The same can be said for University of Delaware patents (e.g. US #4,377,723) describing multi-layer photovoltaic devices.

An example of a DOE-attributed PV patent family that has had a strong impact, much of which has been beyond solar technology, is provided by the patent family at the head of Table 4-10: a Massachusetts Institute of Technology (MIT) family (anchor patent US #4,379,020) describing large grain amorphous films. This patent family was highlighted earlier as an older highly cited DOE-attributed PV patent family. Table 4-10 reveals that, of 637 subsequent patent families

[29] The Citation Index is computed based on a single generation of citations.

linked to this MIT family, only 19 are defined within solar energy technology. As such, a great deal of the influence of this patent family can be found outside solar energy technology, especially in more general semiconductor applications. A number of other DOE-attributed PV patent families in Table 4-10 concerned with thin films and film deposition also have their main influence outside solar energy technology. Among these are anchor patents US #4,588,451; US #4,237,151, and US #4,775,425.

Table 4-10. Pre-1990 DOE-Attributed PV Patent Families Linked to the Most Subsequent Patent Families

DOE Anchor Patent[a]	Issue Year	Total Linked Families	# Linked Solar Families	# Linked Other Families	Assignee	Title
4379020	1983	637	19	618	Massachusetts Institute of Technology	Polycrystalline semiconductor processing
4588451	1986	535	2	533	Advanced Energy Fund	Metal organic chemical vapor deposition of III-V compounds on silicon
4442185	1984	514	15	499	U.S. Dept. of Energy	Photoelectrochemical cells for conversion of solar energy to electricity and methods of their manufacture
4292092	1981	502	153	349	General Electric	Laser processing technique for fabricating series connected and tandem junction series connected solar cells into a solar battery
4775425	1988	474	23	451	ECD	P and n-type microcrystalline semiconductor alloy material including band gap widening elements, devices utilizing same
4322253	1982	455	26	429	General Electric	Method of making selective crystalline silicon regions containing entrapped hydrogen by laser treatment
4162505	1979	400	57	343	General Electric	Inverted amorphous silicon solar cell utilizing cermet layers

Table 4-10 (continued). Pre-1990 DOE-Attributed PV Patent Families Linked to the Most Subsequent Patent Families

DOE Anchor Patent[a]	Issue Year	Total Linked Families	# Linked Solar Families	# Linked Other Families	Assignee	Title
4335266	1982	373	137	236	Boeing	Methods for forming thin film heterojunction solar cells from I-III-VI/2 \ chalcopyrite compounds, and solar cells produced thereby
4287473	1981	336	3	333	U.S. Dept. of Energy	Nondestructive method for detecting defects in photodetector and solar cell devices
4237151	1980	330	7	323	U.S. Dept. of Energy	Thermal decomposition of silane to form hydrogenated amorphous Si film
4377723	1983	329	101	228	University of Delaware	High efficiency thin film Multiple gap photovoltaic device
4688068	1987	327	21	306	U.S. Dept. of Energy	Quantum well multijunction photovoltaic cell
4253882	1981	318	47	271	University of Delaware	Multiple gap photovoltaic device
4147563	1979	301	23	278	U.S. Dept. of Energy	Method for forming p-n junctions and solar cells by laser beam processing
4783421	1988	283	42	241	BP	Method for manufacturing electrical contacts for a thin film semiconductor device
4166919	1979	273	122	151	General Electric	Amorphous silicon solar cell allowing infrared transmission
4237150	1980	268	10	258	U.S. Dept. of Energy	Method of producing hydrogenated amorphous silicon film
4272641	1981	265	143	122	General Electric	Tandem junction amorphous silicon solar cells

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

Table 4-11 follows a similar pattern to Table 4-10, but is based on links to more recent DOE-attributed PV patents. Specifically, this table shows DOE patent families with anchor patents issued since 1990 that are linked to the largest number of subsequent patent families. Again, this figure divides the patent families linked to the DOE-attributed PV patent families into two technology groups, depending on whether or not they are defined within solar energy technology.

Recent DOE-attributed PV patent families in Table 4-11 that are linked to significant numbers of subsequent solar energy families include a series of patents describing copper indium gallium diselenide (CIGS) photovoltaic devices. These CIGS devices patent families are assigned to a number of different organizations, including Midwest Research Institute/NREL (anchor patent US #5,356,839); Boeing (US #5,078,804 and US #5,141,564); and International Solar Electric Technology (US #5,028,274). This suggests that DOE has funded technology related to CIGS devices in a number of different organizations, and this technology has had a significant impact on subsequent developments in solar energy.
Table 4-11 also contains a number of more recent DOE-attributed PV patent families that are linked to large numbers of subsequent patents outside solar and PV technology. Indeed, a very high percentage of the patents linked to the six DOE-attributed PV patents at the head of Table 4-9 are defined as outside solar energy technology. Four of these six PV patent families are assigned to Midwest Research Institute/NREL, including the family at the head of this table (anchor patent US #5,304,509). This patent family describes a method for hydrogenation of silicon substrates to reduce defects. It is linked to 436 subsequent patent families, all but three of which are defined as outside solar energy technology. These are mainly concerned with semiconductor fabrication techniques. Other NREL patents at the head of Table 4-11 are concerned with the growth of thin films, and are also linked to large numbers of subsequent semiconductor patents.

One other patent family in Table 4-11 that is worth noting is the Berkeley nanowire family discussed earlier (represented by anchor patent US #6,996,147). It is by far the most recent patent family in Table 4-11. This family is already linked to 117 subsequent patent families, even though its anchor patent was only issued in 2006. As such, it appears to be a high-impact patent family within the very active and rapidly developing nanotechnology industry.

Table 4-11. Post-1989 DOE-Attributed PV Patent Families Linked to the Most Subsequent Patent Families

DOE Anchor Patent[a]	Issue Year	Total Linked Families	# Linked Solar Families	# Linked Other Families	Assignee	Title
5304509	1994	436	3	433	Midwest Research Institute	Back side hydrogenation technique for defect passivation in silicon solar cells
4963949	1990	361	17	344	U.S. Dept. of Energy	Substrate structures for INP-based devices

Table 4-11 (continued). Post-1989 DOE-Attributed PV Patent Families Linked to the Most Subsequent Patent Families

DOE Anchor Patent[a]	Issue Year	Total Linked Families	# Linked Solar Families	# Linked Other Families	Assignee	Title
5711803	1998	318	5	313	Midwest Research Institute	Preparation of a semiconductor thin film
5456205	1995	294	0	294	Midwest Research Institute	System for monitoring the growth of crystalline films on stationary substrates
5406367	1995	222	0	222	Midwest Research Institute	Defect mapping system
5456763	1995	187	4	183	University of California	Solar cells utilizing pulsed energy crystallized microcrystalline polycrystalline silicon
5646050	1997	185	27	158	Amoco/ Enron Solar	Increasing stabilized performance of amorphous silicon based devices produced by highly hydrogen diluted lower temperature plasma deposition
5078804	1992	169	88	81	Boeing	I-III-VI.Sub.2 based solar cell utilizing the structure CuInGaSe.Sub.2 CdZnS/ZNO
5897331	1999	153	2	151	Midwest Research Institute	High efficiency low cost thin film silicon solar cell design and method for making
5141564	1992	150	55	95	Boeing	Mixed ternary heterojunction solar cell
5356839	1994	145	50	95	Midwest Research Institute	Enhanced quality thin film Cu(In,Ga)Se.sub.2 for semiconductor device applications by vapor phase recrystallization
4971633	1990	144	3	141	U.S. Dept. of Energy	Photovoltaic cell assembly

Table 4-11 (continued). Post-1989 DOE-Attributed PV Patent Families Linked to the Most Subsequent Patent Families

DOE Anchor Patent[a]	Issue Year	Total Linked Families	# Linked Solar Families	# Linked Other Families	Assignee	Title
5028274	1991	136	48	88	Int'l Solar Electric Technology	Group I-III-VI.sub.2 semiconductor films for solar cell application
6996147	2006	117	5	112	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated therefrom
5055416	1991	116	1	115	3M	Electrolytic etch for preventing electrical shorts in solar cells on polymer surfaces
5730808	1998	116	48	68	Amoco/ Enron Solar	Producing solar cells by surface preparation for accelerated nucleation of microcrystalline silicon on heterogeneous substrates
5426061	1995	109	6	103	Midwest Research Institute	Impurity gettering in semiconductors
5627081	1997	108	0	108	Midwest Research Institute	Method for processing silicon solar cells
5246506	1993	106	63	43	BP	Multijunction photovoltaic device and fabrication method

[a]The "anchor patent," generally the first granted U.S. patent in a family, is used to designate each patent family.

4.5 Summary of Patent Analysis

The study identified 274 solar PV patent families attributed to DOE-funding of PV research and used them as the starting point in the forward patent tracing analysis. The DOE Laboratories were prominent among assignees responsible for the largest number of the DOE-attributed PV patent families.

The study identified a total population of 13,156 solar energy patent families, of which 608 were found to be assigned to the top eight U.S. producers of solar PV, and 1,812 were found to be assigned to the 10 leading innovators in solar energy worldwide. These two groups of company patents were used as the starting points in the backward patent tracing analysis to determine the extent to which innovations of leading commercial companies in the field had built on DOE-funded PV research.

Until recently, the trend in DOE-attributed U.S. solar PV patents followed a similar pattern to that of the total population of solar patents, with patenting peaking in the first half of the 1980s, followed by a period of reduced patenting between 1984 and 1993, followed by an increase in patenting between 1994 and 2003. But in the period from 2004 to 2008, the trends diverge, with the DOE-attributed U.S. solar PV patenting declining and the larger population of solar energy patenting increasing. DOE-attributed U.S. solar PV patents as a percentage of total solar energy patents ranged from 1-3% between 1974 and 1988, from 3% - 4% between 1989 and 2003, but fell to an average of only 0.2% between 2004 and 2008.

A country comparison revealed that solar energy patenting in the United States has far outstripped that in other countries, followed by patenting in Japan and Germany. The country comparison showed that the United States has by a wide margin the largest number of patent families from all technology areas linked to earlier DOE-attributed solar PV patent families, followed again by Japan and Germany.

A comparison of the solar energy patent families owned by the top eight U.S. PV producers with the set of DOE-attributed solar PV patent families showed DOE in a leading role, followed by BP Solar and ECD. Backward patent tracing showed that each of the top eight U.S. producers of solar PV had 20% or more of its solar energy patent families linked to earlier solar PV patents in the DOE-attributed set, suggesting that DOE-funded solar PV research has had a relatively significant and broad impact upon the U.S. PV industry. Moreover, the backward patent tracing showed that, with the exception of Siemens, at least 20% of the solar energy patent families of the 10 leading innovators in solar energy worldwide were linked to earlier DOE-attributed PV patents. The results of backward tracing from solar energy patent portfolios of top PV producers and leading solar energy companies worldwide suggest that DOE-funded PV research has been influential on innovation by these companies.

The results of forward patent tracing showed that DOE-funded PV research has influenced semiconductor technology beyond PV devices. Numerous links were found between the DOE-attributed PV patent families and those of leading companies in the semiconductor industry, such as Micron, Semiconductor Energy Lab, Applied Materials and IBM.

An analysis based on patent classification categories showed that the impact of DOE-funded PV research has been particularly strong on developments related to the design and manufacture of semiconductor devices, including PV cells, but also showed impact in a number of other technology fields, such as coating methods, measuring and testing, and crystal growth.

Analyses at the individual patent level based on both backward and forward tracing identified particularly noteworthy patents using multiple perspectives. These noteworthy patents are listed below.

- The solar energy patent families of leading companies in PV and solar energy with the most citation links to earlier DOE-attributed PV patent families include the following: BP Solar patents describing multi-junction solar cells formed from amorphous silicon and copper indium diselenide, and a PV module framing system for mounting on roof surfaces; First Solar patents describing PV arrays; SunPower patents describing photovoltaic roof shingle systems, as well as photovoltaic module frames; Sanyo patents describing two-sided weatherproof photovoltaic modules, and a thin film amorphous silicon photovoltaic device; a Canon patent describing a stacked PV device; a General Electric patent describing silicon thin-film, integrated solar cell, module, and methods of manufacturing; and a Boeing patent describing a solar tile and an associated fabrication method.

- High-impact solar energy patents of leading companies in PV and solar energy that are linked to earlier DOE-attributed PV patent families include the following: ECD patents describing thin-film fabrication; SunPower patents for series connected solar cells and PV assemblies; BP patents detailing PV framing systems and thin-film cells; an Evergreen Solar patent describing a UV stabilizer for a solar cell; BP Solar patents describing PV framing systems; several Canon patents including one describing a solar cell fabrication method that helps to reduce damage to the substrate; three Sharp patents including one describing a pin junction PV device; four ECD patents variously describing fabrication of thin film cells and a self-adhesive PV module; an ExxonMobil patent describing a solar cell with two-dimensional hexagonal reflecting diffraction grating; as well as patents by Sanyo on a method of manufacturing polycrystalline semi-conductive film, several other BP solar patents, several Boeing patents, and one owned by Mitsubishi.

- Other high-impact patents (those not assigned to the top eight U.S. PV producers or the 10 leading innovators in solar energy worldwide) that are linked to earlier DOE-attributed PV patent families include solar energy patents assigned to large corporations such as Raytheon and NEC, smaller specialist solar energy companies such as Nanosys, and universities such as Princeton and Columbia. They also include highly cited patents outside solar energy—mainly concerning semiconductor device fabrication—such as ASM International's patent describing sequential chemical vapor deposition; Princeton University's patent describing organic LEDs; AmKor Technology's patent describing a wafer scale image sensor package; and a number of others. (See Table 4-6.)

- DOE-attributed PV patent families linked to the largest number of leading innovators' solar energy patent families include General Electric-assigned patents describing a solar cell constructed from multiple layers of amorphous silicon and those describing processing techniques for producing the cells, Schottky barriers for cells, and the connection of cells to produce solar batteries; University of Delaware-assigned patents that pertain to thin film solar cells, including one describing a method for increasing the light absorption of thin film cells while reducing the roughness of the electrical junction; and Boeing-assigned patents that describe large area, copper indium diselenide (CIS) thin film solar cells.

- The most highly cited of the DOE-attributed PV patent families (based on a Citation Index and taking into account all organizations and fields) include the following: patents assigned to ECD describing thin film PV devices that increase light absorption; several patents assigned to General Electric, including one describing multiple layers of amorphous silicon; patents assigned to Boeing describing chalcopyrite compounds for thin film cells; DOE-assigned patents describing the detection of defects in solar cells; an MIT-assigned patent describing large grain amorphous films; a University of Delaware-assigned patent describing multiple gap PV devices; patents assigned to NC State University describing light harvesting rods for regenerative solar cells; a patent assigned to SunPower describing a PV assembly and mounting apparatus for the module; and a recent patent, which is the most highly cited given its age and technology area, assigned to the University of California (DOE Berkeley National Laboratory) describing nanowires, useful not only for PV but for a variety of energy conversion applications.

- The analysis of highly cited DOE-attributed patent families was extended by looking across two generations of citations, separating DOE PV patent families by age, and separating citations of these patent families by whether they related mainly to solar technology or to other technologies. Examples of older DOE-attributed PV patent families with strong influence on successive generations of solar technology include GE's amorphous silicon device patents, Boeing's chalcopyrite device patents, and University of Delaware patents describing multi-layer photovoltaic devices. Examples of newer DOE-attributed PV patent families with strong impacts on successive generations of solar technology include a series of CIGS patent families assigned to a number of different organizations (NREL/Midwest Research Institute, Boeing, and International Solar Electric Technology). An example of an older DOE-attributed PV patent family whose influence has been largely in broader semiconductor applications is the MIT family describing large grain amorphous films. Other examples include patent families concerned with thin films and film deposition. An example of a more recent DOE-attributed PV patent family whose impact has been largely outside of solar technology is the University of California/LBNL's nanowire patent family. Another example is the Midwest Research patent family describing a method for hydrogenation of silicon substrates to reduce defects, which is strongly cited by patents concerned with semiconductor fabrication techniques.

5. Publication Analysis

The second phase of this bibliometric study is an analysis of solar PV publications sponsored by DOE. This focus on publications includes a publication profile, a co-author analysis, and a citation analysis.

An overall conclusion of the publication analysis is that DOE PV publications, like its patents, are a major output of the DOE PV Subprogram, and a means to disseminate DOE-funded PV research. As predicted by theory, publication-to publication citations appear less indicative of interest in commercial applications than do patent-to-patent citations.

5.1 DOE Solar PV Publication Profile

A search of the DOE Office of Scientific and Technical Information (OSTI) database for all solar PV publications sponsored by DOE yielded more than 1,000 publications, from 1976-2009.[30] A year-by-year distribution of the output of DOE solar PV publications by the leading publishers (i.e., NREL/SERI, SNL, LBNL, and LLNL) is shown in Figure 5-1. There are two peaks in DOE outputs of solar PV publications. The first occurs in the early 1990s; the second occurs after 2004, a period during which DOE-attributed solar PV patent issues dropped. Few publications from the period prior to 1990 were found using the keyword search criteria, and few were found from 2002-2004.

The distribution of DOE PV publications from 1976-2009 by sponsoring organization, appears in Figure 5-2. In addition to the DOE national laboratories shown in Figure 5-1, i.e., NREL/SERI, SNL, LBNL, and LLNL, Figure 5-2 includes Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), Brookhaven National Laboratory (BNL), and Idaho National Laboratory (INL). The comparatively large role played by NREL (formerly SERI) in DOE solar PV publishing is evident.

As shown in Figure 5-3, Technical Reports comprise the largest share (75%) of DOE PV publications, followed by Conference Reports (21%.) Special Reports and Theses and Dissertations comprise the remaining 4%. For NREL/SERI the composition by type of publication is similar to that for the total, with Technical Reports comprising 68%, Conference Reports comprising 25%, and Other comprising the remaining 7%.

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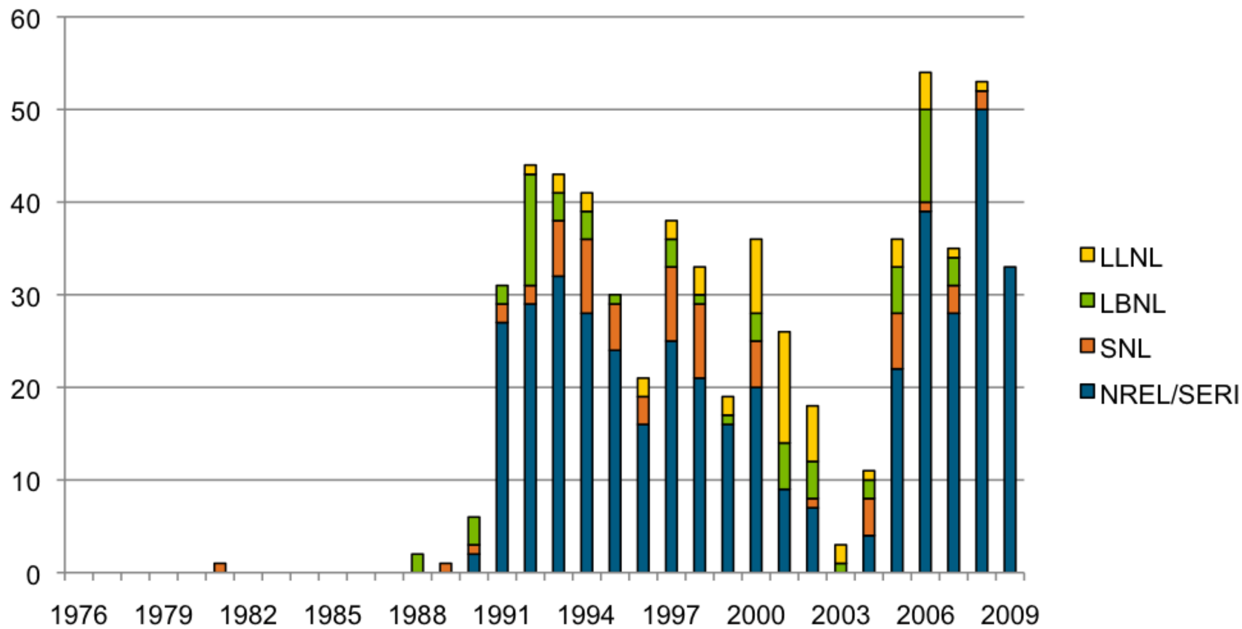
[30] A search was made for all fields containing "solar PV" or "solar photovoltaic" or "thin film" or PVmaT. The result is likely an under-count for these four laboratories, because not all of their DOE laboratory publications appear to be entered into the OSTI database; and some of their solar PV publications 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. The result definitely represents an under-count for DOE overall, because it only includes publications found for the four laboratories.

Figure 5-1. DOE Solar PV Publications for Selected Laboratories, 1976-2009



Note: Data for 2009 are incomplete.
Source: OSTI database.

Figure 5-2. DOE PV Publications by Sponsoring Organization, 1976-2009

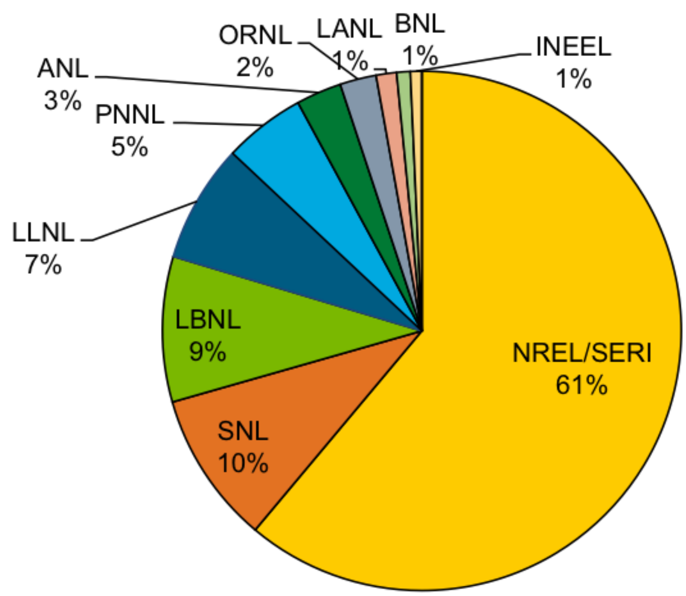
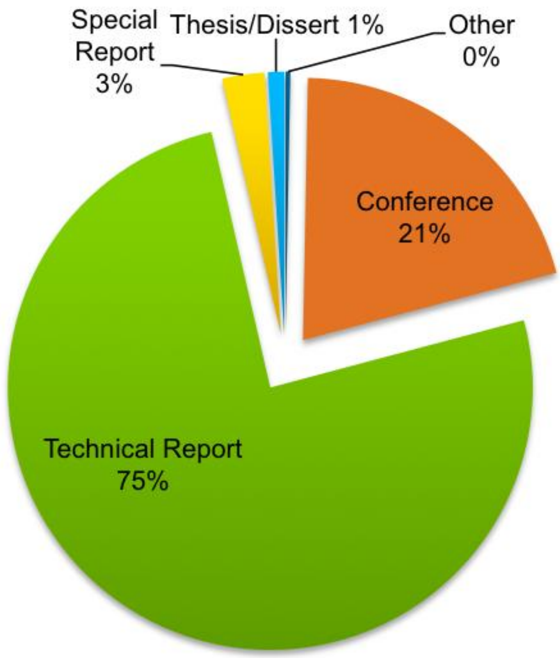


Figure 5-3. DOE PV Publications by Type



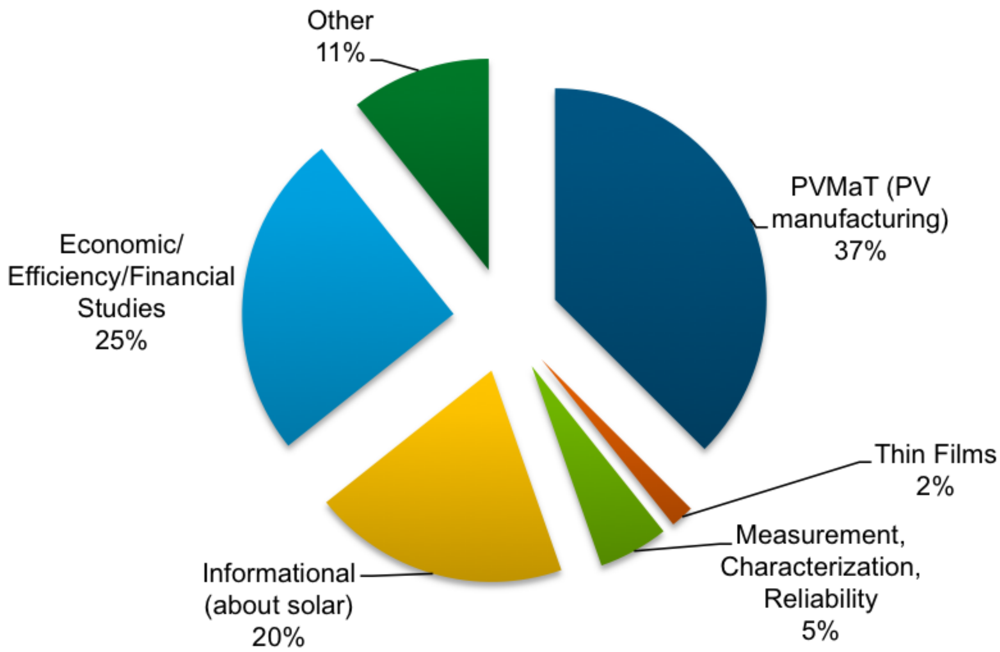
5.2 Publication Samples for Analyses

The publication analyses are based on two random samples drawn from the body of NREL/SERI publications, the largest group by a sponsoring organization. Random samples were drawn from the identified populations of NREL/SERI technical reports and conference reports. By distinguishing samples by type of publication the analysis is able to assess differences that may affect the path of knowledge dissemination. All the subsequent findings on characteristics, authoring/co-authoring, and citation analysis are based on the random samples of NREL technical reports and conference reports.

5.3 Topics of the Reports Analyzed

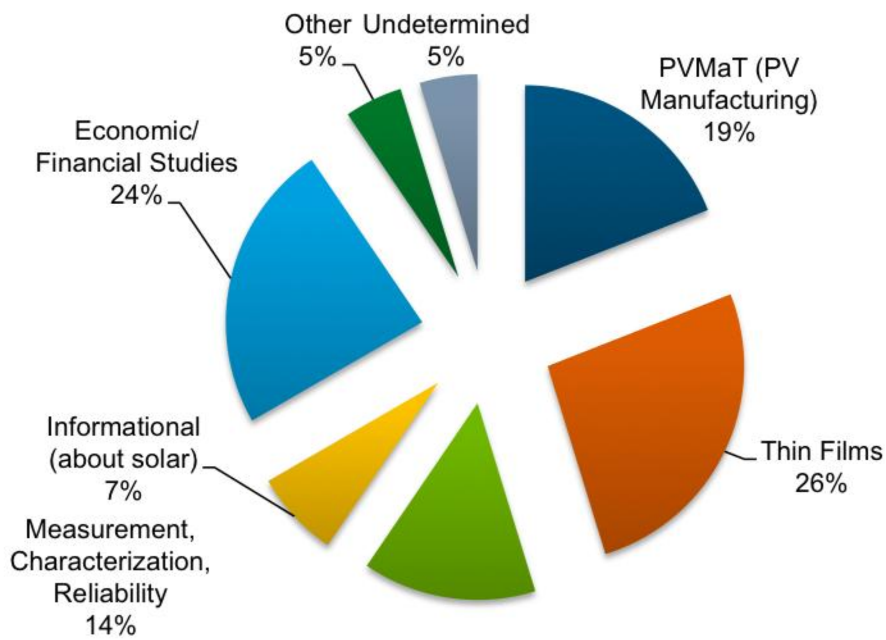
The distribution of topics for NREL PV technical reports is shown in Figure 5-4. PVMaT (PV manufacturing) makes up 37% of the sample. Economic/Efficiency/Financial Studies comprise another 25%. Informational reports comprise 20%. Thin films comprise only 2% of the total.

Figure 5-4. Distribution of NREL Technical Publications by Topic Category



The distribution by topics for NREL conference reports is shown in Figure 5-5. At 26% of the sample, Thin Films is a much more prominent topic category in the conference reports than in the technical reports.

Figure 5-5. Distribution of NREL Conference Reports by Topic Category



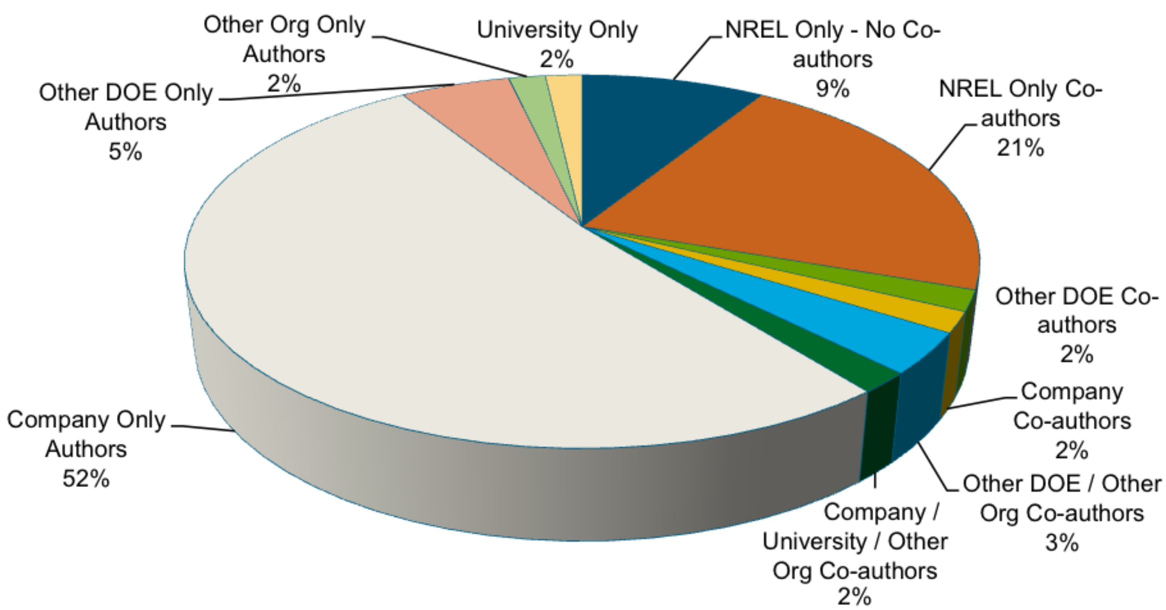
5.4 Authoring/Co-Authoring Analysis

The findings that follow do not suggest that co-authoring with outside researchers has been an important path of knowledge dissemination for NREL researchers in solar PV technology. The largest share of NREL technical reports were authored by company researchers alone or by NREL researchers alone. By far the largest share of NREL conference reports were authored/co-authored by NREL researchers alone. Co-authoring among NREL researchers and by NREL researchers by other DOE researchers suggests collaborative PV research within NREL and DOE.

5.4.1 Authoring/Co-Authoring of Technical Reports

Figure 5-6 reveals that company authoring was prominent for the technical reports, with 52% of the sample authored by company researchers. This would be expected, as many of the companies funded through DOE partnership programs prepared technical reports on their research. Figure 5-6 also reveals that NREL authors without co-authors (9%), NREL only co-authors (21%), and NREL and DOE co-authors (2%) accounted for 32% of the publications. Universities authoring alone, on the other hand, accounted for only 2% of the technical reports.

Figure 5-6. Distribution of Authorship of NREL Technical Reports



As shown in Table 5-1, company affiliations of authors of these technical reports 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.

Table 5-1. List of Organizational Affiliations of Non-DOE Authors/Co-Authors of NREL-Identified Technical Reports

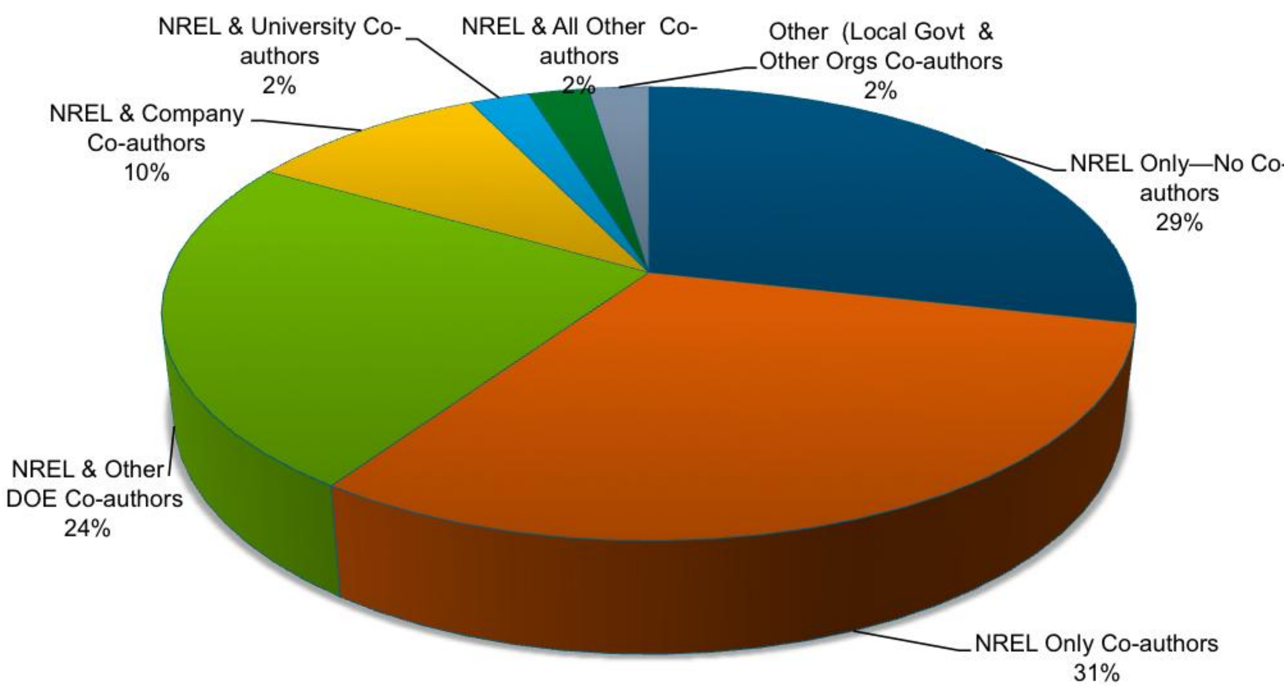
Companies	Universities	Other Orgs
Solarex Corporation	Georgia Institute of Technology	Research Triangle Institute
Utility Power Group, Inc.	University of Cape Town, South Africa	
Ascension Technology, Inc.		
Trace Engineering Company, Inc.		
Mobil Solar Energy Corporation		
Solar Design Associates, Inc.		
Springborn Laboratories, Inc.		
Energy Conversion Devices, Inc. (ECD)		
Navigant Consulting Inc.		
GE Global Research		
Siemens Solar Industries		
Spire Corporation		
ASE Americas, Inc.		
Advanced Energy Systems, Inc.		
Dow Corning Corporation		
BP Solar		
Navigant Consulting, Inc.		
TERI, New Delhi, India		
M. Pedden, Consultant		
Solarex Corp.		
Photovoltaics International, LLC (PVI)		
Kiss & Company Architects		
Solar Kinetics, Inc.		
AstroPower, Inc.		
Summit Blue Applied Materials		

5.4.2 Authoring/Co-Authoring of Conference Reports

Figure 5-7 shows extensive authoring (29%) and co-authoring (31%) by NREL researchers only—with a total of 60% of these reports authored solely by NREL researchers. Another 24%

were co-authored by NREL researchers with other DOE researchers. Thus, a total of 84% (29%+31%+24%) of the NREL conference reports were authored solely by DOE researchers. The largest single instance of co-authoring with researchers outside of DOE is by NREL with company-affiliated co-authors (10%). Company affiliations include EIKOS, Inc., Bechtel Bettis, Inc., GE Energy, EnerNex Corporation, Energy Systems Consulting Services, and Skyline Solar.

Figure 5-7. Distribution of Authorship of NREL Conference Reports



5.5 Citation Analysis

5.5.1 Citations of Technical Reports

The citation analysis showed that 9% of the NREL technical reports had been cited more than five times at the time of the study. Meanwhile, 30% had been cited between one and five times, and 61% had not yet been cited.

The organizational affiliations of those citing the NREL technical reports most frequently, as revealed by Figure 5-8, were government organizations (55%). This category was followed by universities (21%); other organizations, such as foreign and domestic national laboratories and institutes (18%); and companies (6%).

Figure 5-8. Organizational Affiliation of Those Citing NREL Technical Reports

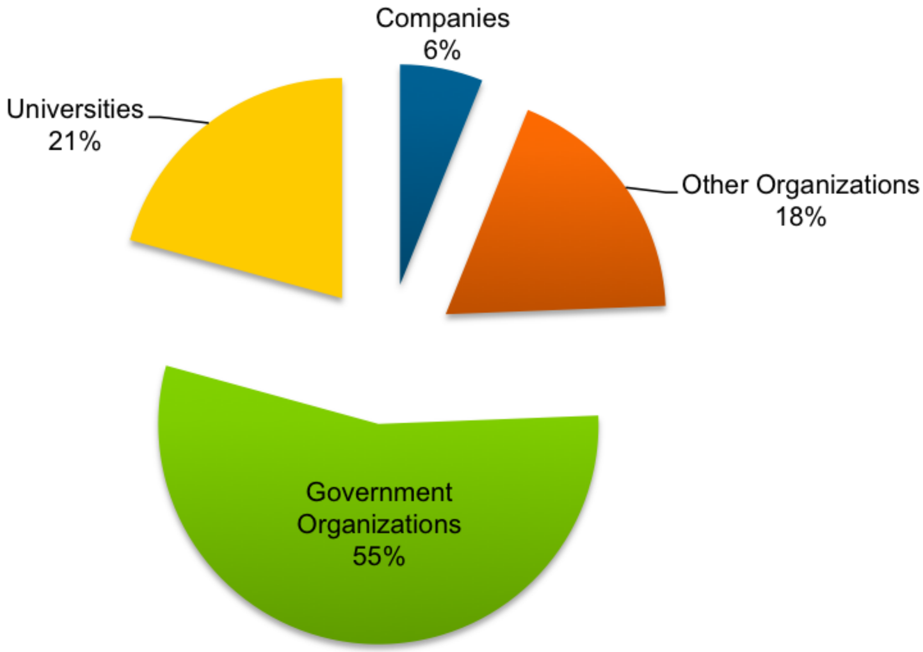


Table 5-2 lists the organizational affiliations of those citing NREL technical reports. Among those citing, the presence of researchers from a number of foreign national laboratories, such as the Energy Research Centre of the Netherlands, the Fraunhofer Institut für Solare Energiesysteme of Germany, and the Swedish National Testing and Research Institute, indicates an interest in the NREL solar PV 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, 1995, by Kiss and Company Architects, published in 1995. Another example is *Recent Progress in the Photovoltaic Manufacturing Technology Project* (PVMaT), NREL/TP-411-7416, (undated, but likely 1994), co-authored by researchers at NREL and SNL.

Table 5-2. Organizational Affiliations of Those Citing NREL Technical Publications

DOE Affiliated	Company Affiliated	University Affiliated	Other Organization Affiliated
NREL Affiliated	Spire Corporation	Reading University, UK	National Institute of Meteorology and Hydrology, Bulgaria
Sandia National Lab	Tricorona	University of California, Berkeley	Swedish National Testing and Research Institute
Lawrence Berkeley National Lab	CSG Holding and PV Curtain Wall Engineering Co., Ltd.	Central Queensland University	Engineer Research and Development Center
	Summit Blue	University of Nottingham, UK	The Energy Centre, KNUST, Ghana
		University of Puerto Rico	Stockholm Environment Institute - US
		University of Florida	International Institute for Applied Systems Analysis, Austria
		National Technical University of Athens, Greece	National Research Council of the U.S. National Academies
		Air Force Inst Of Tech	Kansas Corporation Commission
		Universidade do Minho	Fraunhofer-Institut für Solare Energiesysteme, Germany
		Colorado School of Mines	British Columbia Institute of Technology (BCIT)
			UCCEE-RISØ
			World Resources Institute

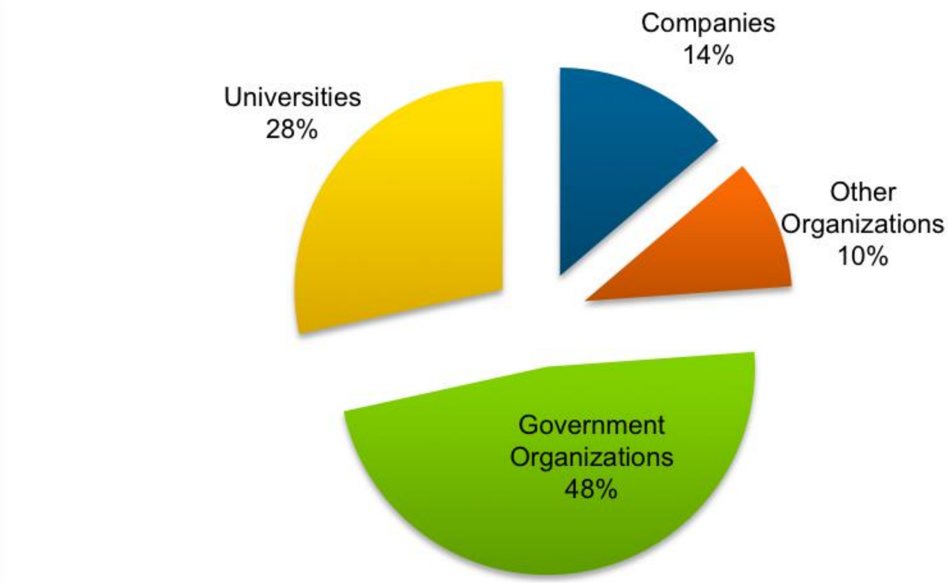
5.5.2 Citations of Conference Reports

The citation analysis of the sample of conference reports revealed that 24% of them had been cited more than 5 times. Another 19% had been cited between one and five times.

As revealed by Figure 5-9, organizational affiliations of those citing the NREL conference papers are more heavily represented by companies and universities, and less by government and other organizations than those citing the NREL technical reports. Yet, government organizations is the affiliation of those most often citing the conference reports.

Companies citing the NREL conference reports include Tucson Electric Power Company, IBM, GM, Spectrolab, Emcore Photovoltaics, Exxon, Solar Consulting Services, and Solexant, among others. The presence of companies such as IBM and Spectrolab re-enforces the finding of the patent analysis that interest in DOE's solar PV research results was strong in the semiconductor industry, as well as in the solar PV area.

Figure 5-9. Organizational Affiliation of Those Citing NREL Conference Reports



Companies cited NREL conference reports more frequently than they cited NREL technical reports. This finding may be surprising, given that it might be expected that companies would be more likely to cite other company-authored reports (prominent among the technical reports) than government reports (prominent among the conference reports).

Universities whose researchers cited the NREL conference reports include the University of Colorado; the Air Force Institute of Technology; the University of California; the University of London; the Universidad Nacional Autónoma de México; Technische Universität Darmstadt, Germany; and the Indian Institute of Technology Delhi, among others.

Foreign national laboratories and institutions whose researchers cited the conference reports include the EUITT-Instituto de Energia Solar-UPM, Spain; Solar Energy Research Institute of Singapore (SERIS); the Institute of Microstructure Physics and the Franhofer Institute, both in Germany; the European Space Agency/ European Space Research and Technology Centre (ESA/ESTEC), the Netherlands; the National Institute of Advanced Industrial Science and Technology (AIST), Japan; as well as organizations in Austria, Italy, and China.

An example of a heavily cited NREL PV conference report is *Lattice-Mismatched Approaches for High-Performance III-V Photovoltaic Energy Converters*, NREL/CP-520-37440, 2005, co-authored by NREL researchers with researchers from Bechtel Bettis, Inc. Other examples of heavily cited NREL conference reports from the sample are *PVMaT Advances in the Photovoltaic Industry and the Focus of Future PV Manufacturing R&D*, NREL/CP)-520-31436, 2002, co-authored by NREL and SNL researchers; and an earlier *Progress Update on the U.S. Photovoltaic Manufacturing Technology Project*, NREL/CP-520-22962, 1997, co-authored by NREL researchers in collaboration with the Solar Energy Industries Association.

6. Other Effects

A member of NREL's staff described DOE's PV patents and publication outputs as the "tip of the iceberg" in terms of indicating the totality of knowledge-transfer activities of the Solar PV Subprogram. Additional modes of knowledge transfer from DOE's solar PV research to others include formal and informal direct interactions of staff with companies and other organizations, including partnerships with companies; one-on-one discussions and talks with groups; provision of analytical services and measurement characterizations; collaborative research activities; and licensing. In addition, the human capital of trained students and researchers in solar PV is a major output of the DOE Solar PV Subprogram.

6.1 Direct Partnerships and Other Interactions with Companies

As indicated in Chapter 2, the DOE Solar PV Subprogram launched at least five research initiatives between 1975 and 2009, all of which entailed the formation of direct contractual relationships between DOE and companies for the purpose of pursuing the advancement of solar PV technology. The engagement of DOE with companies is particularly important because companies will ultimately translate the DOE-funded PV research results into commercial products and processes. While many of these relationships resulted in patents and publication outputs, many also yielded prototype devices, systems, processes, test data, demonstrations, or, at a minimum, advancements in knowhow not necessarily captured by the patent and publication analyses.

More than 160 different companies are identified as having participated in DOE PV partnerships between 1975 and 2009. These companies are listed in Table 6-1 (at the end of this chapter). Not all of the companies are still active by the name listed; some have been acquired by other companies, shown in parentheses where identified. This list of DOE's company partners in solar PV is a virtual “who's who” of companies in the industry.

An example of a company recently founded and funded as a startup under DOE's Solar America Initiative (SAI) is PrimeStar Solar. In June, 2007, the company was awarded a $3 million SAI agreement for commercial scale-up of the high efficiency thin film cadmium telluride PV technology that was developed at NREL. The agreement is milestone-based with stage-gate reviews and off ramps for non-performing awardees. PrimeStar Solar has reportedly met all milestones and passed through all stage-gate reviews successfully as of the date of this study. PrimeStar Solar, is located close to NREL and also has a Cooperative Research and Development Agreement (CRADA) with NREL.[31]

An example of how an earlier-founded company in PV benefited from its partnerships with DOE is provided by First Solar, an Arizona-based leader in the development and manufacture of solar

[31] PrimeStar Solar acknowledges its SAI award and commercialization of thin film cadmium telluride PV technology developed at NREL at its website, www.primestarsolar.com, under "About Us/Our Company", found online on August 3, 2010.

modules. Founded in 1999, First Solar, in collaboration with NREL's National Center for Photovoltaics, won an R&D 100 Award for the development of a high-rate vapor transport deposition (HRVTD) process in 2003. According to the company, this process is at the heart of First Solar's high volume manufacturing line to lower the cost of producing thin-film PV modules. By 2009, the company had achieved revenue of $2.1 billion. At the time of the R&D 100 Award, the manager of NREL's Thin Film Partnership, Ken Zweibel, was quoted as saying, "I believe this will help us turn the corner in thin film PV," and a manager of First Solar, Rick Power, was quoted as saying, "NREL's long standing support has been instrumental in achieving this breakthrough."[32]

6.2 Licensing of DOE Intellectual Property in PV

Companies are able to license available patented PV technology assigned to DOE, its laboratories, and managing organizations of the DOE laboratories. This provides another avenue through which the results of DOE-funded PV research move downstream.

The DOE/EERE Technology Commercialization Portal, also known as the Energy Innovation Portal,[33] provides online marketing summaries of selected DOE solar PV technologies currently available for licensing, describing the technologies, their applications, advantages, and stage of development. As of late July 2010, 21 of the several hundred solar PV technologies reportedly available for licensing were listed at the Commercialization Portal. Examples of DOE technologies available for licensing include *Controlled Structure of Organic-Nanomaterial Solar Cells; Fermentative Method for Making Nonoxide Fluorescent Nanoparticles*; and *Hot Electron Photovoltaics Using Low Cost Materials and Simple Cell Design*.

According to NREL staff, a few more than 100 of the PV patents have been licensed, or options for licensing have been arranged.[34] Although licensing agreements are treated as confidential by the NREL Technology Transfer Office, some of the companies, such as the example provided by PrimeStar Solar above, are publicly open about their adoption of PV technologies developed by the DOE laboratories for the purpose of further development and commercialization.

6.3 Training of Students and Researchers

The DOE Solar PV Subprogram has also funded at least 65 universities between 1975 and 2009, including those listed in Table 6-2. These universities, which are spread throughout the United States, have afforded the training of students and researchers, as well as the support of PV

[32] First Solar News Release (September 11, 2003).
[33] The Energy Innovation Portal is found at http://techportal.eere.energy.gov. The technologies for solar photovoltaic can be browsed, as well as other energy efficiency and renewable energy technologies developed by DOE laboratories and participating research institutions, and available for licensing. Launch of the site was announced by EERE in June 2010, referred to in the announcement as the Technology Commercialization Portal.
[34] Telephone interview and e-mail communication with David Christensen, contact person for working with NREL's PV Research Program and Partnerships, August 1-3, 2010. (www.nrel.gov/pv/working_with.html and www.nrel.gov/pv/partnerships.html).

technology advancement. The DOE Solar PV Subprogram has also sponsored mentoring of students by DOE researchers through internships for undergraduate and graduate students. These activities have generated tacit knowledge outputs whose impact is difficult to measure, but are widely recognized as important to continued scientific advancement.

Table 6-1. List of Companies Partnering with DOE in PV Partnership Initiatives

Advanced Energy Systems (AES)	Advanced Photovoltaic Systems	Aerochem Research Laboratories	Aerospace Corp.
AIA Research Corp.	Alpha Solarco, Inc.	AMETEK	Aminox
Amonix	Applied Solar Energy Corp.	Arco Solar Inc. (acquired by SolarWorld)	Ascension Technology (acquired by SCHOTT Solar, Inc.)
ASE Americas, Inc. (acquired by SCHOTT Solar, Inc.)	AstroPower (acquired by GE Energy USA LLC)	Astrosystems, Inc.	AVA Solar
Bechtel National, Inc.	Bernd Ross Associates	Blue Square Energy	Boeing Aerospace Corporation
BP Solar (BP Solar International, LLC)	Burt Hill Kosar Rittelmann Associates	C.T. Sah Associates	CaliSolar, Inc.
Calyxo USA, Inc.	Chronar Corporation	Coors Porcelain Co.	Crystal Systems (Crystal Systems, Inc.)
DayStar Technologies, Inc.	Dow Chemical	Dow Corning Corporation	Eagle-Picher Industries, Inc.
Energy Conversion Devices, Inc. (ECD) (Uni-Solar)	Enfocus Engineering	EIC Corporation	Electrik, Inc.
EMCORE Photovoltaics	Endurex Corp.	Energy Materials Corp.	Energy Photovoltaics, Inc. (EPV)
Entech, Inc.	Evergreen Solar (Evergreen Solar, Inc.)	Exxon Research & Engineering Company	First Solar
Florida Solar Energy Center	GE Energy USA LLC	Glasstech Solar, Inc.	Global Photovoltaic Specialists, Inc.
Global Solar Energy, Inc.	Gnostic Concepts, Inc.	Golden Photon (Kyocera Solar)	Gould Incorporated
GreenRay	Grumman Aerospace Corporation	. Hemlock Semiconductor Corp.	Honeywell International, Inc.

Hughes Aircraft Company	IBM Corp.	IIT Research Institute	Illinois Toolworks, Inc.
Institute of Gas Technology	International Solar Electric Technology Inc.	Iowa Thin Film Technologies, Inc. (PowerFilm Solar)	ITN Energy Systems, Inc.
J.C. Schumacher Co.	Kayex Corp.	Kinetic Coatings, Inc.	Konarka
Kopin Corporation	Kulicke & Soffa Industries	Lockheed Missiles and Space Company	Martin Marietta
Materials Research Group, Inc.	Mayaterials	Minnesota Mining and Manufacturing Company	MicroLink Devices, Inc.
Mitre Corp.	Mobil Solar Energy Corp. (SCHOTT Solar, Inc.)	Monosolar Inc.	Monsanto Research Corp.
Motorola, Inc.	MV Systems, Inc.	MZ International, Inc.	NanoSolar, Inc.
Nat'l Research for Geosciences Labs, Inc.	Northrop Corp.	Omnion Power Engineering Corporation	P.R. Hoffman (Norlin Industries)
Photon Energy, Inc.	Photovoltaics (PV) International, LLC (Eco-Energy, Inc.)	Photowatt International, Inc.	Plasma Physics
PlexTronics	Poly Solar	PowerLight Corporation (SunPower Corp.)	PrimeStar Solar (majority interest held by GE Energy)
Radiation Monitoring Devices	RCA Corporation	Research Institute of Colorado	Research Triangle Institute (RTI) International
Rockwell International Corporation	Scanning Electron Analysis Laboratory	SCHOTT Solar, Inc.	Science Applications, Inc.
Shell Solar Industries (acquired by SolarWorld)	Shingleton Design	Siemens Solar Industries, LP (acquired by SolarWorld)	Silicon Technology Corp.
Siltec Corp. Solyndra, Inc.	Solar Design Associates, Inc. (SDA)	Solaria	SolFocus, Inc.

Soliant Energy, Inc	SolPower	Sinton Consulting	SiXtron Advanced Materials, Inc.
Solar Cells, Inc. (acquired by First Solar, LLC)	Solar Electric Specialties, Inc.	Solar Energy Application Corporation	Solar Engineering Applicaton Corporation
Solar Kinetics, Inc.	Solar Power Corp.	Solar Technology International	Solarelectronics, Inc.
Solarex (acquired by BP Solar International, LLC)	SolarWorld USA (SolarWorld acquired Arco Solar, Shell Solar, and Siemens Solar)	Solasta, Inc.	Solavolt International
Solec International	Solexant	Solenergy Corp.	Soliant Energy
Sollos, Inc.	Soltaix	Specialized Technology Resources, Inc.	Spectrolab, Inc.
Sperry Univac	Spire Corporation	Springborn Labs, Inc. (Specialized Technology Resources, Inc.)	SRI International
Specialized Technology Resources, Inc. (STR))	SumX Corporation	SunPower Corp.	Superwave Technology, Inc.
Telic Corporation	Texas Instruments, Inc.	Texas Research & Engineering Institute	Theodore Barry & Associates
Trace Engineering Company, Inc. (Xantrex Technology, Inc.)	Tracor MB Associates	Tylan Corp.	UHT Corporation
Underwriters Labs, Inc.	Union Carbide Corporation	Uni-Solar (subsidiary of Energy Conversion Devices (ECD))	UPG (Kyocera Solar)
Utility Power Group, Inc.	Vactronics Laboratory Equipment	Varian Associates	Voxtel, Inc.
Wakonda Technologies, Inc.	Weizmann Institute of Science	Westinghouse Electric Corporation	World Industry Minerals
Wyle Laboratories	Xantrex Technology, Inc.	Xerox Corporation	Xunlight Corporation
Yeda R& D			

Table 6-2. List of University Recipients of DOE PV Funding

Arizona State University	Princeton University	University of Massachusetts
Brooklyn College of CUNY	Purdue University	University of Missouri
Brown University	Rochester Institute of Technology	University of North Carolina
California Institute of Technology	Southern Methodist University	University of Oregon
Carnegie Mellon University	Stanford University	University of Pennsylvania
Case Western Reserve University	State University of New York-Buffalo	University of South Carolina
Clarkson College	State University of New York—Albany	University of South Florida
Clemson University	Syracuse University	University of Southern California
Colorado School of Mines	Technion-Israel Institute of Technology	University of Texas at Arlington
Colorado State University	Tulane University	University of Texas at Austin
Cornell University	University of Arizona	University of Toledo
Duke University	University of Arkansas	University of Toronto
Georgia Institute of Technology	University of California at Davis	University of Utah
Harvard University	University of California at Los Angeles	University of Washington
Iowa State University	University of California at Santa Barbara	Virginia Institute of Technology
Lamar University	University of California at Santa Cruz	Washington State University
Louisiana State University	University of Central Florida	Washington University
Massachusetts Institute of Technology	University of Colorado	Wayne State University
North Carolina A & T University Foundation	University of Delaware	Wilkes College
North Carolina State University	University of Florida	
Oregon State University	University of Illinois	
Pennsylvania State University	University of Kentucky	
Polytechnic Institute of New York–Albany	University of Michigan	

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Ruegg, R. & Thomas, P. (2010 A). *Linkages from DOE's Vehicle Technologies R&D in Advanced Combustion to More Efficient, Cleaner-Burning Engines.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable.

Ruegg, R. & Thomas, P. (2010 B). *Linkages from EERE's Geothermal Program R&D to Commercial Power Generation.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable.

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Appendix A

Constructing Data Sets Needed for the Patent Analysis: Supporting Data

A-I Constructing a Filter for Searching the DOE Patent Database for Solar Energy PV Patents

The approach to identifying DOE-attributed solar PV patents is described in Section 3. Table A-1 shows the patent classifications used to develop a patent filter to identify DOE-funded solar energy patents from the larger database of DOE patents.

Table A-1. POCs and IPCs Used for Solar Energy PV Patent Filter

Patent Classifications	
US Patent Classifications (POCs)	
126/569-713	Solar heat collectors
136/243-265	Photoelectric batteries
60/641.1, 8-15	Power plants utilizing natural (solar) heat
257	Active solid state devices (transistors, diodes)
International Patent Classifications (IPCs)	
E04D 13/18	Solar roof coverings
F03G 6	Producing mechanical power from solar energy
F24J 2	Solar heat collectors
F24J 3	Heat production not from solar energy
H01L 25	Assemblies of multiple semiconductor devices
H01L 31	Semiconductors sensitive to light
H01L 31/042-058	Arrays of photoelectric cells e.g. solar cells

Along with the patent classifications in Table A-1, a set of keywords and phrases related to solar and PV technology was identified. These keywords are shown in Table A-2. In the keywords and phrases listed in this table, * is a wildcard denoting unlimited characters, while ? is a wildcard denoting zero or one character, including a space. Hence, the search term multi?crystal* covers the terms multi-crystal, multi crystalline, etc.

Table A-2. Keywords Used in the Solar Energy Patent Filter

Group 1	Group 2	Group 3
solar*	cell*	amorphous?si*
sun?light*	device*	CIGS/CIS
photo?voltaic*	energy*	Cu?In?Ga?Se
PV	generat*	CdTe
	power*	Cadmium?telluride*
	panel*	Copper?indium*
	collector*	GAAS
	battery	Gallium?arsenide*
	batteries	Single?crystal*
	module*	Multi?crystal*
	array*	Poly?crystal*
	element*	Czochralski
		Wafer?si*
		Multiple?exciton?generat*
		MEG

? wildcard denoting zero or one character, including a space
* wildcard denoting multiple characters

There are three groups of keywords in Table A-2. The first two groups are designed to be used in combination to cover a variety of different terminologies used to describe solar energy devices—i.e. patents are required to use one term from Group 1 and one term from Group 2 in their title or abstract. For example, this includes combinations such as solar + cell, PV + device, photovoltaic + module, etc. Patents that used such a keyword combination, and were in one of the patent classifications in Table A-1, were considered as candidate DOE-attributed solar energy patents.

The third group of keywords in Table A- 2 contains a list of terms related to specific materials and structures used to fabricate PV devices. For example, PV devices have been made from materials such as amorphous silicon and copper indium gallium diselenide. Different structures have also been employed, such as single and multi crystal thin films. The keywords in Group 3 are designed to cover these different materials and structures. Given that these keywords are so specific, there is no further restriction in terms of patent classifications. That is, patents referring to one of the terms in Group 3 were considered as candidate DOE-attributed solar energy patents, irrespective of their patent classification.

In simple terms, the patent filter was defined as ((POC&IPC + Group 1 Keyword + Group 2 Keyword) or Group 3 Keyword). To determine their relevance to solar and PV technology, all of the patents identified by this filter were read, and patents deemed to be irrelevant were removed. The remaining patents were included in those candidates sent to DOE for approval.

A-II Constructing a Patent Filter to Identify Worldwide Leading Companies in Solar Energy Patenting

To identify the group of leaders in solar energy patenting worldwide, the study started by defining the universe of solar energy patents using a modified version of the patent filter employed to identify DOE-attributed candidate solar patents. Specifically, the filter was POC&IPC (see Table A-1) + Group 1 Keyword + Group 2 Keyword (see Table A-2). This filter is somewhat narrower than that used to identify DOE-attributed patents, in that it does not include the Group 3 keywords.

The narrower filter was used due to practical considerations. In defining the DOE solar energy patent set, candidate patents were all read individually, first by study analysts, and then by DOE experts, in order to determine their relevance. This process was possible because the number of patents involved was relatively small. The same process of reading individual patents is not practical when the patent set is drawn from the entire universe of patents, not just those patents 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. This was not a problem with the patent classifications and keywords combinations in Groups 1 and 2, since these are aimed specifically at solar energy technology. However, the keywords in Group 3 describe materials and structures with much wider potential application than just solar energy. For example, there are over 3,000 U.S. patents that use the term ‘amorphous silicon’ in their title or abstract, and these patents describe a wide variety of applications beyond PV devices, such as thin film transistors for displays. It is not practical to read all of these patents to determine their relevance to PV technology (as a comparison, there are fewer than 60 DOE patents that use the term amorphous silicon).

Using the narrower filter, patents will not be included in the solar energy set simply on the basis that they refer to amorphous silicon, because this will bring in many irrelevant patents. However, the narrower patent filter will still pick up patents describing amorphous silicon provided they refer to a PV application, due to the keywords in Group 1 and Group 2. Also, it is worth noting that, while the backward tracing is restricted to patents defined within solar energy, the forward tracing has no such restriction. Hence, patents linked to DOE solar energy patents will be included in the analysis, even if they lie outside the solar energy patent set defined by this narrower filter.

A-III Constructing Patent Families based on the "Priority Application"

As explained in the methodology overview of Chapter 2, equivalent patents on a single invention may result as organizations often file for protection of their inventions across multiple patent systems. Within a patent system, organizations may file for continuations of a given patent as they add supplementary material. As a result, there may be multiple patent documents for the same invention. To avoid counting the same invention multiple times, this study constructed "patent families" for each of the two sets of identified patents. A patent family contains all of the patents and patent continuations that result from the same original patent application (named the "priority document"). A family may include patents/applications from multiple countries, and also multiple patents/applications from the same country.

In total, the patent searches yielded 343 U.S. patents, 75 EPO patents, and 113 WIPO patents in the list of patents attributed to DOE-funded research. A list of these patents can be found in Appendix B, Table B-1. The study then constructed solar PV patent families attributed to DOE from the set of 343 patents. As a result of this process, the DOE-attributed U.S., EPO and WIPO solar PV patents/applications were grouped into 274 patent families based on matching priority documents.

The patent searches for solar energy patents belonging to the top eight U.S. producers of solar PV yielded a total of 321 U.S. patents, 204 EPO patents, and 172 patent applications filed with the WIPO. These were grouped into 608 solar energy patent families for the eight companies.

The patent searches for solar energy patents belonging to the 10 leading companies in solar energy patenting worldwide yielded a total of 1,105 U.S. patents, 642 EPO patents, and 273 WIPO patents. These were grouped into 1,812 solar energy patent families for the 10 companies.

The study defined the universe of solar energy patents (using the modified version of the patent filter) as containing 6,793 U.S. patents, 4,093 EPO patents, and 3,971 WIPO patents. These patents were grouped into 13,156 patent families for the universe of solar energy patents.

Appendix B

DOE-Attributed Solar PV Patents

Note: Patent list is shown prior to forming patent families

Table B-1. List of DOE-Attributed Solar PV Patents in Chronological Order of Issue

Issue Date	Patent Number	Assignee	Title
1977	4052976	U.S. Dept. of Energy	Non tracking solar concentrator with a high concentration ratio
1978	4089705	National Aeronautical And Space Administration	Hexagon solar power panel
1978	4105470	U.S. Dept. of Energy	Dye-sensitized schottky barrier solar cells
1978	4118249	U.S. Dept. of Energy	Modular assembly of a photovoltaic solar energy receiver
1979	4177093	Exxon Mobil Corp.	Method of fabricating conducting oxide-silicon solar cells utilizing electron beam sublimation and deposition of the oxide
1979	4166919	General Electric Company	Amorphous silicon solar cell allowing infrared transmission
1979	4167015	General Electric Company	Cermet layer for amorphous silicon solar cells
1979	4162505	General Electric Company	Inverted amorphous silicon solar cell utilizing cermet layers
1979	4166918	General Electric Company	Method of removing the effects of electrical shorts and shunts created during the fabrication process of a solar cell
1979	4163677	General Electric Company	Schottky barrier amorphous silicon solar cell with thin doped region adjacent metal schottky barrier
1979	4139858	General Electric Company	Solar cell with a gallium nitride electrode
1979	4178395	Photon Power Inc.	Methods for improving solar cell open circuit voltage
1979	4147563	U.S. Dept. of Energy	Method for forming p-n junctions and solar cells by laser beam processing
1979	4152175	U.S. Dept. of Energy	Silicon solar cell assembly
1980	4193821	Exxon Mobil Corp.	Fabrication of heterojunction solar cells by improved tin oxide deposition on insulating layer

Issue Date	Patent Number	Assignee	Title
1980	EP0007192	Exxon Mobil Corp.	Process for manufacturing a semi-conductive heterojunction device
1980	EP0008236	Exxon Mobil Corp.	Tin oxide semiconductor heterojunction devices
1980	4200473	General Electric Company	Amorphous silicon schottky barrier solar cells incorporating a thin insulating layer and a thin doped layer
1980	EP0010828	General Electric Company	Amorphous silicon solar cell allowing infrared transmission
1980	4217148	General Electric Company	Compensated amorphous silicon solar cell
1980	4205265	General Electric Company	Laser beam apparatus and method for analyzing solar cells
1980	4215185	General Electric Company	Liquid junction schottky barrier solar cell
1980	EP0009401	University of Delaware	Photovoltaic cells employing a zinc phosphide absorber-generator
1980	4239553	University of Delaware	Thin film photovoltaic cells having increased durability and operating life and method for making same
1980	4190950	U.S. Dept. of Energy	Dye-sensitized solar cells
1980	4237150	U.S. Dept. of Energy	Method of producing hydrogenated amorphous silicon film
1980	4237151	U.S. Dept. of Energy	Thermal decomposition of silane to form hydrogenated amorphous si film
1981	4292092	General Electric Company	Laser processing technique for fabricating series connected and tandem junction series connected solar cells into a solar battery
1981	4272641	General Electric Company	Tandem junction amorphous silicon solar cells
1981	4249957	Unassigned	Copper doped polycrystalline silicon solar cell
1981	4251287	University of Delaware	Amorphous semiconductor solar cell
1981	4253882	University of Delaware	Multiple gap photovoltaic device
1981	4267398	University of Delaware	Thin film photovoltaic cells
1981	4243885	U.S. Dept. of Energy	Cadmium telluride photovoltaic radiation detector

Issue Date	Patent Number	Assignee	Title
1981	4287473	U.S. Dept. of Energy	Nondestructive method for detecting defects in photodetector and solar cell devices
1981	4246050	Varian Medical Systems Inc.	Lattice constant grading in the Al.sub.y.Ca.sub.1-y.As.sub.1-x Sv.sub.x alloy system
1982	EP0067860	Boeing Co. (The)	Methods and apparatus for forming thin-film heterojunction solar cells from I-III-VI.sub.2 chalcopyrite compounds, and solar cells produced thereby
1982	WO1982002459	Boeing Co. (The)	Methods and apparatus for forming thin-film heterojunction solar cells from I-III-VI.sub.2 chalcopyrite compounds,and solar cells produced thereby
1982	4335266	Boeing Co. (The)	Methods for forming thin film heterojunction solar cells from I-III-VI.sub.2 chalcopyrite compounds, and solar cells produced thereby
1982	EP0060363	Exxon Mobil Corp.	A P-I-N amorphous silicon semi-conductor device and method of manufacture
1982	4360702	Exxon Mobil Corp.	Copper oxide/n-silicon heterojunction photovoltaic device
1982	4366335	Exxon Mobil Corp.	Indium oxide/n-silicon heterojunction solar cells
1982	4339470	General Electric Company	Fabricating amorphous silicon solar cells by varying the temperature of the substrate during deposition of the amorphous silicon layer
1982	4316049	General Electric Company	High voltage series connected tandem junction solar battery
1982	4322253	General Electric Company	Method of making selective crystalline silicon regions containing entrapped hydrogen by laser treatment
1982	4320251	Solamat Inc.	Ohmic contacts for solar cells by arc plasma spraying
1982	4311870	Unassigned	Efficiency of silicon solar cells containing chromium

Issue Date	Patent Number	Assignee	Title
1982	4328390	University of Delaware	Thin film photovoltaic cell
1982	4342879	University of Delaware	Thin film photovoltaic device
1982	4364508	U.S. Dept. of Energy	Method of fabricating a solar cell array
1982	4350836	U.S. Dept. of Energy	Solar array construction
1982	4356341	Varian Medical Systems Inc.	Cascade solar cell having conductive interconnects
1983	4416916	BASF SE	Thin film solar energy collector
1983	4392451	Boeing Co. (The)	Apparatus for forming thin film heterojunction solar cells employing materials selected from the class of I-III-VI.sub.2 chalcopyrite compounds
1983	4407710	Exxon Mobil Corp.	Hybrid method of making an amorphous silicon P-I-N semiconductor device
1983	EP0077601	Exxon Mobil Corp.	Photovoltaic semiconductor device
1983	4417092	Exxon Mobil Corp.	Sputtered pin amorphous silicon semi conductor device and method therefor
1983	4378460	General Electric Company	Metal electrode for amorphous silicon solar cells
1983	4371738	General Electric Company	Method of restoring degraded solar cells
1983	4392011	General Electric Company	Solar cell structure incorporating a novel single crystal silicon material
1983	4379020	Massachusetts Institute of Technology	Polycrystalline semiconductor processing
1983	4400244	Monosolar Inc.	Photovoltaic power generating means and methods
1983	4388483	Monosolar Inc.	Thin film heterojunction photovoltaic cells and methods of making the same
1983	4409424	Unassigned	Compensated amorphous silicon solar cell
1983	4377723	University of Delaware	High efficiency thin film multiple gap photovoltaic device
1983	4387265	University of Delaware	Tandem junction amorphous semiconductor photovoltaic cell
1984	4437455	BASF SE	Stabilization of solar films against hi temperature deactivation

Issue Date	Patent Number	Assignee	Title
1984	4436765	Exxon Mobil Corp.	Method for forming indium oxide/n-silicon heterojunction solar cells
1984	4485265	Harvard University	Photovoltaic cell
1984	EP0125301	Harvard University	Photovoltaic cell
1984	WO1984002229	Harvard University	Photovoltaic cell
1984	4444992	Massachusetts Institute of Technology	Photovoltaic thermal collectors
1984	4425194	Monosolar Inc.	Photovoltaic power generating means and methods
1984	EP0118579	Monosolar Inc.	Thin film heterojunction photovoltaic cells and methods of making the same
1984	WO1984002514	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1984	WO1984002515	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1984	WO1984002516	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1984	4442082	SRI International	Process for obtaining silicon from fluosilicic acid
1984	4477688	University of Delaware	Photovoltaic cells employing zinc phosphide
1984	4443653	University of Delaware	Thin film photovoltaic device with multilayer substrate
1984	4431858	University of Florida	Method of making quasi grain boundary free polycrystalline solar cell structure and solar cell structure obtained thereby
1984	4471036	U.S. Dept. of Energy	Electrochemical photovoltaic cells and electrodes
1984	4442185	U.S. Dept. of Energy	Photoelectrochemical cells for conversion of solar energy to electricity and methods of their manufacture
1984	4427840	U.S. Dept. of Energy	Plastic schottky barrier solar cells

Issue Date	Patent Number	Assignee	Title
1984	4488943	U.S. Dept. of Energy	Polymer blends for use in photoelectrochemical cells for conversion of solar energy to electricity and methods for manufacturing such blends
1984	4475682	U.S. Dept. of Energy	Process for reducing series resistance of solar cell metal contact systems with a soldering flux etchant
1984	4482780	U.S. Dept. of Energy	Solar cells with low cost substrates and process of making same
1985	WO1985005221	Advanced Energy Fund LP	Silicon-gaas epitaxial compositions and process of making same
1985	USRE031968	Boeing Co. (The)	Methods for forming thin film heterojunction solar cells from I-III-VI.sub.2 chalcopyrite compounds, and solar cells produced thereby
1985	4523051	Boeing Co. (The)	Thin films of mixed metal compounds
1985	EP0139487	Exxon Mobil Corp.	A method for sputtering a pin or nip amorphous silicon semi-conductor device having partially crystallised P and N-layers
1985	EP0139488	Exxon Mobil Corp.	A method for sputtering a pin or nip amorphous silicon semiconductor device with the P and N-layers sputtered from boron and phosphorus heavily doped targets
1985	4528082	Exxon Mobil Corp.	Method for sputtering a pin amorphous silicon semi conductor device having partially crystallized P- and N-layers
1985	4508609	Exxon Mobil Corp.	Method for sputtering a pin microcrystalline/amorphous silicon semiconductor device with the p and n layers sputtered from boron and phosphorous heavily doped targets

Issue Date	Patent Number	Assignee	Title
1985	4556788	General Electric Company	Amorphous silicon cell array powered solar tracking apparatus
1985	4502225	General Electric Company	Mechanical scriber for semiconductor devices
1985	4525375	General Electric Company	Method of controlling the deposition of hydrogenated amorphous silicon and apparatus therefore
1985	4529576	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1985	EP0129555	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1985	EP0130996	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1985	EP0151569	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1985	4528503	U.S. Dept. of Energy	Method and apparatus for I-V data acquisition from solar cells
1985	4559924	U.S. Dept. of Energy	Thin film absorber for a solar collector
1986	4588451	Advanced Energy Fund LP	Metal organic chemical vapor deposition of III-V compounds on silicon
1986	EP0179138	Advanced Energy Fund LP	Silicon-gaas epitaxial compositions and process of making same
1986	4597948	SRI International	Apparatus for obtaining silicon from fluosilicic acid
1986	4584181	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1986	4594229	Unassigned	Apparatus for melt growth of crystalline semiconductor sheets
1986	4585581	U.S. Dept. of Energy	Polymer blends for use in photoelectrochemical cells for conversion of solar energy to electricity

Issue Date	Patent Number	Assignee	Title
1986	4564720	U.S. Dept. of Energy	Pure silver ohmic contacts to N-type and P-type gallium arsenide materials
1986	4575576	U.S. Dept. of Energy	Three junction solar cell
1987	4684761	Boeing Co. (The)	Method for making graded I-III-VI.sub.2 semiconductors and solar cell obtained thereby
1987	4650541	U.S. Dept. of Energy	Apparatus and method for the horizontal, crucible free growth of silicon sheet crystals
1987	4667059	U.S. Dept. of Energy	Current and lattice matched tandem solar cell
1987	4691075	U.S. Dept. of Energy	Energy conversion system
1987	4652332	U.S. Dept. of Energy	Method of synthesizing and growing Copper-Indium-Diselenide (Cu/nSe2) crystals
1987	4688068	U.S. Dept. of Energy	Quantum well multijunction photovoltaic cell
1988	4783421	BP P.L.C.	Method for manufacturing electrical contacts for a thin Film semiconductor device
1988	4718947	BP P.L.C.	Superlattice doped layers for amorphous silicon photovoltaic cells
1988	4762808	Dow Corning Corp.	Method of forming semiconducting amorphous silicon films from the thermal decomposition of fluorohydridodisilanes
1988	EP0296702	Dow Corning Corp.	Method of forming semiconducting amorphous silicon films from the thermal decompositon of fluorohydridodisilanes
1988	4775425	ECD	N-type and P-type microcrystalline semiconductor alloy material including band gap widening elements, devices utilizing same
1988	4779980	Midwest Research Institute	Atmospheric optical calibration system
1988	WO1988006718	Midwest Research Institute	Atmospheric optical calibration system

Issue Date	Patent Number	Assignee	Title
1988	4781565	SRI International	Apparatus for obtaining silicon from fluosilicic acid
1988	4748014	SRI International	Process and apparatus for obtaining silicon from fluosilicic acid
1989	4854974	BP P.L.C.	Electrical contacts for a thin film semiconductor device
1989	EP0301686	ECD	Methods of fabricating N-type and-P-type microcrystalline semiconductor alloy materials
1989	4816082	ECD	Thin film solar cell including a spatially modulated intrinsic layer
1989	EP0304145	ECD	Thin film solar cell including a spatially modulated intrinsic layer
1989	4845043	Unassigned	Method for fabricating photovoltaic device having improved short wavelength photoresponse
1990	4891330	ECD	Method of fabricating N-type and P-type microcrystalline semiconductor alloy material including band gap widening elements
1990	WO1990015445	International Solar Electric Technology Inc.	Improved group I-III-VI.sub.2 semiconductor films for solar cell application
1990	4950615	International Solar Electric Technology Inc.	Method and making group IIB metal Telluride films and solar cells
1990	EP0372930	Minnesota Mining And Manufacturing Company	Electrolytic etch for preventing electrical shorts in solar cells on polymer surfaces
1990	EP0372929	Minnesota Mining And Manufacturing Company	Light transmitting electrically conductive stacked film
1990	4940495	Minnesota Mining And Manufacturing Company	Photovoltaic device having light transmitting electrically conductive stacked films
1990	WO1990011247	Unassigned	Zinc oxyfluoride transparent conductor
1990	4909863	University of Delaware	Process for levelling film surfaces and products thereof
1990	4971633	U.S. Dept. of Energy	Photovoltaic cell assembly

Issue Date	Patent Number	Assignee	Title
1990	4963949	U.S. Dept. of Energy	Substrate structures for inp based devices
1991	4990286	Harvard University	Zinc oxyfluoride transparent conductor
1991	5028274	International Solar Electric Technology Inc.	Group I-III-IV.sub.2 semiconductor films for solar cell application
1991	5055416	Minnesota Mining And Manufacturing Company	Electrolytic etch for preventing electrical shorts in solar cells on polymer surfaces
1991	5022930	Photon Energy Inc.	Thin film photovoltaic panel and method
1991	5047112	U.S. Dept. of Energy	Method for preparing homogeneous single crystal ternary III-V alloys
1991	5019177	U.S. Dept. of Energy	Monolithic tandem solar cell
1992	5112410	Boeing Co. (The)	Cadmium zinc sulfide by solution growth
1992	5078804	Boeing Co. (The)	I-III-VI.sub.2 based solar cell utilizing the structure Cu(InGa)Se.sub.2 CdZnS/ZnO
1992	5141564	Boeing Co. (The)	Mixed ternary heterojunction solar cell
1992	EP0463079	Harvard University	Zinc oxyfluoride transparent conductor
1992	5110531	SRI International	Process and apparatus for casting multiple silicon wafer articles
1992	5153780	U.S. Dept. of Energy	Method and apparatus for uniformly concentrating solar flux for photovoltaic applications
1992	5167724	U.S. Dept. of Energy	Planar photovoltaic solar concentrator module
1993	5268327	Advanced Energy Fund LP	Epitaxial compositions
1993	5246506	BP P.L.C.	Multijunction photovoltaic device and fabrication method
1993	EP0523919	BP P.L.C.	Multijunction photovoltaic device and fabrication method
1993	5256887	BP P.L.C.	Photovoltaic device including a boron doping profile in an i-type layer
1993	EP0549707	ECD	Photovoltaic device with decreased gridline shading and method for its manufacture

Issue Date	Patent Number	Assignee	Title
1993	5228926	ECD	Photovoltaic device with increased light absorption and method for its manufacture
1993	WO1993008605	ECD	Photovoltaic device with increased light absorption and method for its manufacture
1993	5232519	ECD	Wireless monolithic photovoltaic module
1993	WO1993015526	ECD	Wireless monolithic photovoltaic module
1993	WO1993023591	Midwest Research Institute	Crystallization from high-temperature solutions of Si in copper
1993	WO1993014523	Photon Energy Inc.	Photovoltaic cell with thin CdS layer
1993	WO1993023881	Solar Cells Inc.	Process and apparatus for making photovoltaic devices and resultant product
1993	5223453	U.S. Dept. of Energy	Controlled metal Semiconductor sintering/alloying by one Directional reverse illumination
1993	5223043	U.S. Dept. of Energy	Current Matched high Efficiency, multijunction monolithic solar cells
1994	EP0608282	ECD	Photovoltaic device with increased light absorption and method for its manufacture
1994	5306646	Lockheed Martin Corp.	Method for producing textured substrates for thin Film photovoltaic cells
1994	5304509	Midwest Research Institute	Back Side hydrogenation technique for defect passivation in silicon solar cells
1994	5314571	Midwest Research Institute	Crystallization from high temperature solutions of Si in copper
1994	5358574	Midwest Research Institute	Dry texturing of solar cells
1994	5356839	Midwest Research Institute	Enhanced quality thin film Cu(In,Ga)Se.sub.2 for semiconductor device applications by vapor Phase recrystallization

Issue Date	Patent Number	Assignee	Title
1994	WO1994024696	Midwest Research Institute	Enhanced quality thin film Cu(In,Ga)Se.sub.2 for semiconductor device applications by vapor-phase recrystallization
1994	5342453	Midwest Research Institute	Heterojunction solar cell
1994	WO1994011905	Midwest Research Institute	Heterojunction solar cell
1994	5316593	Midwest Research Institute	Heterojunction solar cell with passivated emitter surface
1994	WO1994011906	Midwest Research Institute	Heterojunction solar cell with passivated emitter surface
1994	WO1994005036	Midwest Research Institute	Improved back-side hydrogenation technique for defect passivation in silicon solar cells
1994	WO1994027136	Midwest Research Institute	Improved defect mapping system
1994	5376185	Midwest Research Institute	Single Junction solar cells with the optimum band gap for terrestrial concentrator applications
1994	EP0623246	Photon Energy Inc.	Photovoltaic cell with thin cds layer
1994	5279678	Photon Energy Inc.	Photovoltaic cell with thin CS layer
1994	WO1994027327	Photon Energy Inc.	Series interconnected photovoltaic cells and method for making same
1994	5322572	U.S. Dept. of Energy	Monolithic tandem solar cell
1995	WO1995026571	Amoco/Enron Solar	Stabilized amorphous silicon and devices containing same
1995	5403404	BP P.L.C.	Multijunction photovoltaic device and method of manufacture
1995	5468652	Lockheed Martin Corp.	Method of making a back contacted solar cell
1995	5406367	Midwest Research Institute	Defect mapping system
1995	WO1995015010	Midwest Research Institute	Dry texturing of solar cells
1995	5429985	Midwest Research Institute	Fabrication of optically reflecting ohmic contacts for semiconductor devices
1995	WO1995019641	Midwest Research Institute	Fabrication of optically reflecting ohmic contacts for semiconductor devices
1995	EP0656149	Midwest Research Institute	Improved back-side hydrogenation technique for defect passivation in silicon solar cells

Issue Date	Patent Number	Assignee	Title
1995	5426061	Midwest Research Institute	Impurity gettering in semiconductors
1995	5441897	Midwest Research Institute	Method of fabricating high Efficiency Cu(In,Ga)(SeS).sub.2 thin films for solar cells
1995	5436204	Midwest Research Institute	Recrystallization method to selenization of thin film Cu(In,Ga)Se.sub.2 for semiconductor device applications
1995	5401331	Midwest Research Institute	Substrate for thin silicon solar cells
1995	WO1995007549	Midwest Research Institute	Substrate for thin silicon solar cells
1995	5456205	Midwest Research Institute	System for monitoring the growth of crystalline films on stationary substrates
1995	5460660	Photon Energy Inc.	Apparatus for encapsulating a photovoltaic module
1995	WO1995003631	Photon Energy Inc.	Apparatus for encapsulating a photovoltaic module
1995	WO1995003630	Photon Energy Inc.	Photovoltaic cell and manufacturing process
1995	5385614	Photon Energy Inc.	Series interconnected photovoltaic cells and method for making same
1995	EP0640247	Solar Cells Inc.	Process and apparatus for making photovoltaic devices and resultant product
1995	5470397	Solar Cells Inc.	Process for making photovoltaic devices and resultant product
1995	5468304	Texas Instruments Inc.	Output Increasing, protective cover for a solar cell
1995	5396332	Unassigned	Apparatus and method for measuring the thickness of a semiconductor wafer
1995	5477088	Unassigned	Multi Phase back contacts for CIS solar cells
1995	5425860	University of California	Pulsed energy synthesis and doping of silicon carbide
1995	5466302	University of California	Solar cell array interconnects
1995	5456763	University of California	Solar cells utilizing pulsed Energy crystallized microcrystalline/polycrystalline silicon
1995	5397737	U.S. Dept. of Energy	Deposition of device quality low H content, amorphous silicon films

Issue Date	Patent Number	Assignee	Title
1996	5558712	ASE Americas Inc.	Contoured inner after Heater shield for reducing stress in growing crystalline bodies
1996	5551977	ASE Americas Inc.	Susceptor for EFG crystal growth apparatus
1996	5510271	Georgia Institute of Technology	Processes for producing low cost, high efficiency silicon solar cells
1996	WO1996008043	Georgia Institute of Technology	Processes for producing low cost, high efficiency silicon solar cells
1996	5503898	Lockheed Martin Corp.	Method for producing textured substrates for thin Film photovoltaic cells
1996	WO1996009900	Midwest Research Institute	Application of optical processing for growth of silicon dioxide
1996	5544616	Midwest Research Institute	Crystallization from high temperature solutions of Si in Cu/Al solvent
1996	EP0694209	Midwest Research Institute	Enhanced quality thin film Cu(In,Ga)Se.sub.2 for semiconductor device applications by vapor-phase recrystallization
1996	EP0700512	Midwest Research Institute	Improved defect mapping system
1996	WO1996025768	Midwest Research Institute	Method of fabricating high-efficiency Cu(In,Ga)(SeS).sub.2 thin films for solar cells
1996	5487792	Midwest Research Institute	Molecular assemblies as protective barriers and adhesion promotion interlayer
1996	5541118	Midwest Research Institute	Process for producing cadmium sulfide on a cadmium telluride surface
1996	5484736	Midwest Research Institute	Process for producing large grain cadmium telluride
1996	EP0724775	Midwest Research Institute	Recrystallization method to selenization of thin-film Cu(In,Ga)Se.sub.2 for semiconductor device applications
1996	WO1996006454	Midwest Research Institute	Recrystallization method to selenization of thin-film Cu(In,Ga)Se.sub.2 for semiconductor device applications

Issue Date	Patent Number	Assignee	Title
1996	5581346	Midwest Research Institute	System for characterizing semiconductor materials and photovoltaic device
1996	WO1996010171	Midwest Research Institute	System for characterizing semiconductor materials and photovoltaic devices
1996	5588995	Midwest Research Institute	System for monitoring the growth of crystalline films on stationary substrates
1996	5501744	Photon Energy Inc.	Photovoltaic cell having a P-type polycrystalline layer with large crystals
1996	5578502	Photon Energy Inc.	Photovoltaic cell manufacturing process
1996	5536333	Solar Cells Inc.	Process for making photovoltaic devices and resultant product
1996	5538564	University of California	Three dimensional amorphous silicon/microcrystalline silicon solar cells
1997	5646050	Amoco/Enron Solar	Increasing stabilized performance of amorphous silicon based devices produced by highly hydrogen diluted lower temperature plasma deposition
1997	WO1997022152	Davis, Joseph & Negley	Preparation of Cu.sub.xIn.sub.yGa.sub.zSe.sub.n (X=0-2, Y=0-2, Z=0-2, N=0-3) precursor films by electrodeposition for fabricating high efficiency solar cells
1997	WO1997050130	Evergreen Solar, Inc.	Solar cell modules with improved backskin and methods for forming same
1997	5639520	Midwest Research Institute	Application of optical processing for growth of silicon dioxide
1997	WO1997022637	Midwest Research Institute	Encapsulating material for photovoltaic devices
1997	5627081	Midwest Research Institute	Method for processing silicon solar cells
1997	WO1997023004	Midwest Research Institute	Production of films and powders for semiconductor device applications

Issue Date	Patent Number	Assignee	Title
1997	5674325	Photon Energy Inc.	Thin film photovoltaic device and process of manufacture
1997	WO1997038185	Powerlight Corp.	Lightweight, self-ballasting photovoltaic roofing assembly
1997	5605171	University of Chicago	Porous silicon with embedded tritium as a stand-alone prime power source for optoelectronic applications
1997	5674555	University of Delaware	Process for preparing group Ib-iiia-via semiconducting films
1997	5626687	U.S. Dept. of Energy	Thermophotovoltaic in-situ mirror cell
1998	5730808	Amoco/Enron Solar	Producing solar cells by surface preparation for accelerated nucleation of microcrystalline silicon on heterogeneous substrates
1998	5804054	Davis, Joseph & Negley	Preparation of copper indium gallium diselenide films for solar cells
1998	WO1998048079	Davis, Joseph & Negley	Preparation of copper-indium-gallium-diselenide precursor films by electrodeposition for fabricating high efficiency solar cells
1998	5730852	Davis, Joseph & Negley	Preparation of Cu.sub.xIn.sub.yGa.sub.zSe.sub.n (X=0-2, Y=0-2, Z=0-2, N=0-3) precursor films by electrodeposition for fabricating high efficiency solar cells
1998	5741370	Evergreen Solar, Inc.	Solar cell modules with improved backskin and methods for forming same
1998	5766964	Georgia Institute of Technology	Processes for producing low cost, high efficiency silicon solar cells
1998	EP0881695	International Solar Electric Technology Inc.	A method of making group IB-IIIA-VIA compound semiconductor films and method of fabricating a photovoltaic device
1998	5792280	Lockheed Martin Corp.	Method for fabricating silicon cells
1998	5747967	Midwest Research Institute	Apparatus and method for maximizing power delivered by a photovoltaic array

Issue Date	Patent Number	Assignee	Title
1998	5776819	Midwest Research Institute	Deposition of device quality, low hydrogen content, amorphous silicon films by hot filament technique using "safe" silicon source gas
1998	WO1998053500	Midwest Research Institute	Interdigitated photovoltaic power conversion device
1998	WO1998047702	Midwest Research Institute	Photovoltaic device and its method of preparation
1998	5711803	Midwest Research Institute	Preparation of a semiconductor thin film
1998	5731031	Midwest Research Institute	Production of films and powders for semiconductor device applications
1998	5785769	Midwest Research Institute	Substrate for thin silicon solar cells
1998	5757474	Midwest Research Institute	System for characterizing semiconductor materials and photovoltaic devices through calibration
1998	5712187	Midwest Research Institute	Variable temperature semiconductor film deposition
1998	WO1998000856	Midwest Research Institute	Variable temperature semiconductor film deposition
1998	5746839	Powerlight Corp.	Lightweight, self-ballasting photovoltaic roofing assembly
1998	5763320	Unassigned	Boron doping a semiconductor particle
1998	5714404	University of California	Fabrication of polycrystalline thin films by pulsed laser processing
1998	5765680	University of Chicago	Porous silicon with embedded tritium as a stand-alone prime power source for optoelectronic applications
1998	5720827	University of Florida	Design for the fabrication of high efficiency solar cells
1998	WO1998004006	University of Florida	High efficiency solar cells and their fabrication
1999	5942049	Amoco/Enron Solar	Increasing stabilized performance of amorphous silicon based devices produced by highly hydrogen diluted lower temperature plasma deposition

Issue Date	Patent Number	Assignee	Title
1999	5994641	ASE Americas Inc.	Solar module having reflector between cells
1999	WO1999056317	ASE Americas, Inc.	Solar module having reflector between cells
1999	5871630	Davis, Joseph & Negley	Preparation of copper-indium-gallium-diselenide precursor films by electrodeposition for fabricating high efficiency solar cells
1999	EP0956600	Davis, Joseph & Negley	Preparation of Cu.sub.xIn.sub.yGa.sub.zSe.sub.n (X=0-2, Y=0-2, Z=0-2, N=0-3) precursor films by electrodeposition for fabricating high efficiency solar cells
1999	5977476	ECD	High efficiency photovoltaic device
1999	WO1999004971	Evergreen Solar, Inc.	Encapsulant material for solar cell module and laminated glass applications
1999	WO1999017379	Evergreen Solar, Inc.	Methods for improving polymeric materials for use in solar cell applications
1999	EP0958616	Evergreen Solar, Inc.	Solar cell modules with improved backskin and methods for forming same
1999	5986203	Evergreen Solar, Inc.	Solar cell roof tile and method of forming same
1999	WO1999023706	Evergreen Solar, Inc.	Solar cell roof tile and method of forming same
1999	WO1999005206	Evergreen Solar, Inc.	UV light stabilization additive package for solar cell module and laminated glass applications
1999	5972784	Georgia Institute of Technology	Arrangement, dopant source, and method for making solar cells
1999	5985691	International Solar Electric Technology Inc.	Method of making compound semiconductor films and making related electronic devices
1999	5944913	Lockheed Martin Corp.	High-efficiency solar cell and method for fabrication
1999	WO1999027587	Lockheed Martin Corp.	High-efficiency solar cell and method for fabrication
1999	5951786	Lockheed Martin Corp.	Laminated photovoltaic modules using back-contact solar cells

Issue Date	Patent Number	Assignee	Title
1999	5972732	Lockheed Martin Corp.	Method of monolithic module assembly
1999	5871591	Lockheed Martin Corp.	Silicon solar cells made by a self-aligned, selective-emitter, plasma-etchback process
1999	EP0957523	Matrix Solar Technologies Inc.	Boron doping a semiconductor particle
1999	5929652	Midwest Research Institute	Apparatus for measuring minority carrier lifetimes in semiconductor materials
1999	WO1999012045	Midwest Research Institute	Apparatus for measuring minority carrier lifetimes in semiconductor materials
1999	5948176	Midwest Research Institute	Cadmium-free junction fabrication process for cuinse.sub.2 thin film solar cells
1999	WO1999017377	Midwest Research Institute	Cadmium-free junction fabrication process for CuInSe.sub.2 thin film solar cells
1999	WO1999027588	Midwest Research Institute	Composition and method for encapsulating photovoltaic devices
1999	5897331	Midwest Research Institute	High efficiency low cost thin film silicon solar cell design and method for making
1999	5897715	Midwest Research Institute	Interdigitated photovoltaic power conversion device
1999	5922142	Midwest Research Institute	Photovoltaic devices comprising cadmium stannate transparent conducting films and method for making
1999	5976614	Midwest Research Institute	Preparation of Cu.sub.xIn.sub.yGa.sub.zSe.sub.n precursor films and powders by electroless deposition
1999	WO1999037832	Midwest Research Institute	Solution synthesis of mixed-metal chalcogenide nanoparticles and spray deposition of precursor films
1999	5909632	Midwest Research Institute	Use of separate ZnTe interface layers to form OHMIC contacts to p-CdTe films
1999	5868869	Photon Energy Inc.	Thin film photovoltaic device and process of manufacture

Issue Date	Patent Number	Assignee	Title
1999	EP0892877	Powerlight Corp.	Lightweight, self-ballasting photovoltaic roofing assembly
1999	WO1999017889	Unassigned	Method for forming solar cell materials from particulates
1999	5926727	Unassigned	Phosphorous doping a semiconductor particle
1999	WO1999059734	University of California	Generation of low work function, stable compound thin films by laser ablation
2000	6139811	ASE Americas Inc.	EFG crystal growth apparatus
2000	WO2000057980	ASE Americas, Inc.	EFG crystal growth apparatus
2000	6072116	Auburn University	Thermophotovoltaic conversion using selective infrared line emitters and large band gap photovoltaic devices
2000	6077722	BP P.L.C.	Producing thin film photovoltaic modules with high integrity interconnects and dual layer contacts
2000	EP0977911	Davis, Joseph & Negley	Preparation of copper-indium-gallium-diselenide precursor films by electrodeposition for fabricating high efficiency solar cells
2000	WO2000011726	ECD	Method for depositing layers of high quality semiconductor material
2000	6114046	Evergreen Solar, Inc.	Encapsulant material for solar cell module and laminated glass applications
2000	EP0998389	Evergreen Solar, Inc.	Encapsulant material for solar cell module and laminated glass applications
2000	EP1025594	Evergreen Solar, Inc.	Methods for improving polymeric materials for use in solar cell applications
2000	EP1029367	Evergreen Solar, Inc.	Solar cell roof tile and method of forming same
2000	EP0998524	Evergreen Solar, Inc.	UV light stabilization additive package for solar cell module and laminated glass applications

Issue Date	Patent Number	Assignee	Title
2000	EP0978882	International Solar Electric Technology Inc.	An oxide-based method of making compound semiconductor films and making related electronic devices
2000	6127202	International Solar Electric Technology Inc.	Oxide-based method of making compound semiconductor films and making related electronic devices
2000	EP1038322	Lockheed Martin Corp.	High-efficiency solar cell and method for fabrication
2000	6091021	Lockheed Martin Corp.	Silicon cells made by self-aligned selective-emitter plasma-etchback process
2000	EP0977258	Macronix International Co. Ltd.	Process and integrated circuit for a multilevel memory cell
2000	EP1010012	Midwest Research Institute	Apparatus for measuring minority carrier lifetimes in semiconductor materials
2000	6093757	Midwest Research Institute	Composition and method for encapsulating photovoltaic devices
2000	6124186	Midwest Research Institute	Deposition of device quality, low hydrogen content, hydrogenated amorphous silicon at high deposition rates with increased stability using the hot wire filament technique
2000	WO2000060368	Midwest Research Institute	Improved apparatus and method for measuring minority carrier lifetimes in semiconductor materials
2000	WO2000067001	Midwest Research Institute	Optical system for determining physical characteristics of a solar cell
2000	WO2000043573	Midwest Research Institute	Passivating etchants for metallic particles
2000	WO2000014812	Midwest Research Institute	Photovaltaic devices comprising zinc stannate buffer layer and method for making
2000	6137048	Midwest Research Institute	Process for fabricating polycrystalline semiconductor thin-film solar cells, and cells produced thereby

Issue Date	Patent Number	Assignee	Title
2000	WO2000077837	Midwest Research Institute	Process for polycrystalline silicon film growth and apparatus for same
2000	6126740	Midwest Research Institute	Solution synthesis of mixed-metal chalcogenide nanoparticles and spray deposition of precursor films
2000	6134784	Photovoltaics International LLC	Method of making solar collectors by in-situ encapsulation of solar cells
2000	WO2000038216	University of California	High voltage photovoltaic power converter
2000	6162707	University of California	Low work function, stable thin films
2001	EP1080498	ASE Americas, Inc.	Solar module having reflector between cells
2001	6288325	BP P.L.C.	Producing thin film photovoltaic modules with high integrity interconnects and dual layer contacts
2001	WO2001078154	Davis, Joseph & Negley	Preparation of cigs-based solar cells using a buffered electrodeposition bath
2001	6274461	ECD	Method for depositing layers of high quality semiconductor material
2001	EP1110248	ECD	Method for depositing layers of high quality semiconductor material
2001	6187448	Evergreen Solar, Inc.	Encapsulant material for solar cell module and laminated glass applications
2001	6320116	Evergreen Solar, Inc.	Methods for improving polymeric materials for use in solar cell applications
2001	6252287	Lockheed Martin Corp.	InGaAsn/GaAs heterojunction for multi-junction solar cells
2001	6329296	Lockheed Martin Corp.	Metal catalyst technique for texturing silicon solar cells
2001	WO2001037324	Midwest Research Institute	A novel processing approach towards the formation of thin-film Cu(InGa)Se.sub.2

Issue Date	Patent Number	Assignee	Title
2001	WO2001067503	Midwest Research Institute	A1 processing for impurity gettering in silicon
2001	6275060	Midwest Research Institute	Apparatus and method for measuring minority carrier lifetimes in semiconductor materials
2001	6239354	Midwest Research Institute	Electrical isolation of component cells in monolithically interconnected modules
2001	6201261	Midwest Research Institute	High efficiency, low cost, thin film silicon solar cell design and method for making
2001	6281035	Midwest Research Institute	Ion-beam treatment to prepare surfaces of p-CdTe films
2001	6300557	Midwest Research Institute	Low-bandgap double-heterostructure InAsP/GainAs photovoltaic converters
2001	6281426	Midwest Research Institute	Multi-junction, monolithic solar cell using low-band-gap materials lattice matched to GaAs or Ge
2001	6275295	Midwest Research Institute	Optical system for determining physical characteristics of a solar cell
2001	EP1066416	Midwest Research Institute	Passivating etchants for metallic particles
2001	6169246	Midwest Research Institute	Photovoltaic devices comprising zinc stannate buffer layer and method for making
2001	6281098	Midwest Research Institute	Process for Polycrystalline film silicon growth
2001	6251183	Midwest Research Institute	Rapid low-temperature epitaxial growth using a hot-element assisted chemical vapor deposition process
2001	EP1066418	Midwest Research Institute	Solution synthesis of mixed-metal chalcogenide nanoparticles and spray deposition of precursor films
2001	6221495	Midwest Research Institute	Thin transparent conducting films of cadmium stannate
2001	WO2001001498	Powerlight Corp.	PV-thermal solar power assembly
2001	6295818	Powerlight Corp.	PV-thermal solar power assembly

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2001	EP1160880	Unassigned	Apparatus and processes for the mass production of photovoltaic modules
2001	6268014	Unassigned	Method for forming solar cell materials from particulars
2001	6235615	University of California	Generation of low work function, stable compound thin films by laser ablation
2001	6265653	University of California	High voltage photovoltaic power converter
2001	6251701	U.S. Dept. of Energy	All-vapor processing of p-type tellurium-containing II-VI semiconductor and ohmic contacts thereof
2002	EP1171211	ASE Americas, Inc.	EFG crystal growth apparatus
2002	WO2002081044	ASE Americas, Inc.	EFG crystal growth apparatus and method
2002	WO2002084725	California Institute of Technology	A method of using a germanium layer transfer to si for photovoltaic applications and heterostructure made thereby
2002	6359211	Chemmotif Inc.	Spectral sensitization of nanocrystalline solar cells
2002	6353042	Evergreen Solar, Inc.	UV-light stabilization additive package for solar cell module and laminated glass applications
2002	WO2002046242	First Solar, LLC	Volatile organometallic complexes of lowered reactivity suitable for use in chemical vapor deposition of metal oxide films
2002	WO2002013279	Lockheed Martin Corp.	Metal catalyst technique for texturing silicon solar cells
2002	6468885	Midwest Research Institute	Deposition of device quality, low hydrogen content, hydrogenated amorphous silicon at high deposition rates
2002	WO2002017359	Midwest Research Institute	High carrier concentration p-type transparent conducting oxide films
2002	WO2002065553	Midwest Research Institute	Isoelectronic co-doping
2002	WO2002099860	Midwest Research Institute	Method of preparing nitrogen containing semiconductor material

Issue Date	Patent Number	Assignee	Title
2002	6436305	Midwest Research Institute	Passivating etchants for metallic particles
2002	6458254	Midwest Research Institute	Plasma and reactive ion etching to prepare ohmic contacts
2002	EP1194950	Midwest Research Institute	Process for polycrystalline silicon film growth and apparatus for same
2002	6468886	Midwest Research Institute	Purification and deposition of silicon by an iodide disproportionation reaction
2002	6420648	North Carolina State University	Light harvesting arrays
2002	WO2002009196	North Carolina State University	Light harvesting arrays
2002	6407330	North Carolina State University/Johns Hopkins	Solar cells incorporating light harvesting arrays
2002	WO2002009197	North Carolina State University/Johns Hopkins	Solar cells incorporating light harvesting arrays
2002	6495750	Powerlight Corp.	Stabilized PV system
2002	6423565	Unassigned	Apparatus and processes for the mass production of photovotaic modules
2002	WO2002080280	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated therefrom
2002	6402881	University of California	Process for electrically interconnecting electrodes
2002	6340403	University of California	Solar cell module lamination process
2003	6562132	ASE Americas Inc.	EFG crystal growth apparatus and method
2003	WO2003087493	Carl-Zeiss Stiftung	Apparatus and method for mounting photovoltaic power generating systems on buildings
2003	WO2003107439	Carl-Zeiss Stiftung	Photovoltaic module with light reflecting backskin
2003	WO2003095718	Carl-Zeiss Stiftung	Process for coating silicon shot with dopant for addition of dopant in crystal growth
2003	6660930	Carl-Zeiss Stiftung	Solar cell modules with improved backskin
2003	WO2003107438	Carl-Zeiss Stiftung	Solar cell modules with improved backskin

Issue Date	Patent Number	Assignee	Title
2003	WO2003038508	Colorado State University/Univ of Ferrara	Metal complex-based electron-transfer mediators in dye-sensitized solar cells
2003	WO2003036687	ECD	Non-contacting capacitive diagnostic device
2003	WO2003044832	Energy Photovoltaics	Method of junction formation for cigs photovoltaic devices
2003	6586271	Evergreen Solar, Inc.	Methods for improving polymeric materials for use in solar cell applications
2003	6559411	First Solar, LLC	Method and apparatus for laser scribing glass sheet substrate coatings
2003	WO2003013778	First Solar, LLC	Method and apparatus for laser scribing glass sheet substrate coatings
2003	EP1356132	First Solar, LLC	Volatile organometallic complexes of lowered reactivity suitable for use in chemical vapor deposition of metal oxide films
2003	6627765	First Solar, LLC	Volatile organometallic complexes suitable for use in chemical vapor depositions on metal oxide films
2003	WO2003036688	Lockheed Martin Corp.	Alternating current photovoltaic building block
2003	EP1316115	Lockheed Martin Corp.	Metal catalyst technique for texturing silicon solar cells
2003	6583350	Lockheed Martin Corp.	Thermophotovoltaic energy conversion using photonic bandgap selective emitters
2003	EP1358680	Midwest Research Institute	Isoelectronic co-doping
2003	WO2003017384	Midwest Research Institute	Method and apparatus for fabricating a thin-film solar cell utilizing a hot wire chemical vapor deposition technique
2003	WO2003017333	Midwest Research Institute	Method for producing high carrier concentration p-type transparent conducting oxides
2003	WO2003073517	Midwest Research Institute	Monolithic photovoltaic energy conversion device
2003	WO2003052836	Midwest Research Institute	Multi-junction solar cell device

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2003	6518086	Midwest Research Institute	Processing approach towards the formation of thin-film Cu(In,Ga)Se2
2003	EP1288163	Midwest Research Institute	Purified silicon production system
2003	WO2003044840	Midwest Research Institute	Reactive codoping of gaalinp compound semiconductors
2003	WO2003038161	Midwest Research Institute	Shallow melt apparatus for semicontinuous czochralski crystal growth
2003	WO2003034498	Midwest Research Institute	Stacked switchable element and diode combination
2003	WO2003007386	Midwest Research Institute	Thin-film solar cell fabricated on a flexible metallic substrate
2003	WO2003073518	Midwest Research Institute	Voltage-matched, monolithic, multi-band-gap devices
2003	6603070	North Carolina State University	Convergent synthesis of multiporphyrin light-harvesting rods
2003	EP1319255	North Carolina State University	Light harvesting arrays
2003	6596935	North Carolina State University	Solar cells incorporating light harvesting arrays
2003	EP1303884	North Carolina State University/Johns Hopkins	Solar cells incorporating light harvesting arrays
2003	6534703	Powerlight Corp.	Multi-position photovoltaic assembly
2003	6570084	Powerlight Corp.	Pressure equalizing photovoltaic assembly and method
2003	WO2003007388	Powerlight Corp.	Pressure-equalizing photovoltaic assembly and method
2003	WO2003071047	Powerlight Corp.	Shingle assembly
2003	WO2003071054	Powerlight Corp.	Shingle system
2003	WO2003072891	Powerlight Corp.	Shingle system and method
2003	WO2003017381	Powerlight Corp.	Stabilized pv system
2003	6537845	Unassigned	Chemical surface deposition of ultra-thin semiconductors
2003	WO2003021648	University of Delaware	Chemical surface deposition of ultra-thin semiconductors
2004	6784361	BP P.L.C.	Amorphous silicon photovoltaic devices
2004	WO2004070850	BP P.L.C.	Improved photovoltaic cell and production thereof

Issue Date	Patent Number	Assignee	Title
2004	EP1386349	California Institute of Technology	A method of using a germanium layer transfer to si for photovoltaic applications and heterostructure made thereby
2004	EP1372805	Carl-Zeiss Stiftung	EFG crystal growth apparatus and method
2004	6740158	Carl-Zeiss Stiftung	Process for coating silicon shot with dopant for addition of dopant in crystal growth
2004	6815246	Carl-Zeiss Stiftung	Surface modification of silicon nitride for thick film silver metallization of solar cell
2004	WO2004075252	Carl-Zeiss Stiftung	Surface modification of silicon nitride for thick film silver metallization of solar cell
2004	EP1423229	First Solar, LLC	Method and apparatus for laser scribing glass sheet substrate coatings
2004	EP1442473	Lockheed Martin Corp.	Alternating current photovoltaic building block
2004	6750391	Lockheed Martin Corp.	Alternating current photovoltaic building block
2004	EP1423881	Lockheed Martin Corp.	Photonically engineered incandescent emitter
2004	WO2004007634	Massachusetts Institute of Technology	Emissive, high charge transport polymers
2004	EP1410432	Midwest Research Institute	Al processing for impurity gettering in silicon
2004	6815736	Midwest Research Institute	Isoelectronic co-doping
2004	6713400	Midwest Research Institute	Method for improving the stability of amorphous silicon
2004	6787385	Midwest Research Institute	Method of preparing nitrogen containing semiconductor material
2004	WO2004039731	Midwest Research Institute	Nanostructures produced by phase-separation during growth of (III-V).sub.1-x(IV.sub.2).sub.x Alloys
2004	6712908	Midwest Research Institute	Purified silicon production system
2004	WO2004109768	North Carolina State University	Methods and intermediates for the synthesis of dipyrrin-substituted porphyrinic macrocycles
2004	6809251	Powerlight Corp.	Inclined photovoltaic assembly

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2004	EP1412988	Powerlight Corp.	Pressure-equalizing photovoltaic assembly and method
2004	6809253	Powerlight Corp.	Pressure-equalizing PV assembly and method
2004	6675580	Powerlight Corp.	PV/thermal solar power assembly
2004	EP1476617	Powerlight Corp.	Shingle system
2004	EP1476614	Powerlight Corp.	Shingle system and method
2004	6821559	Unassigned	Method of forming particulate materials for thin-film solar cells
2004	EP1374309	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated therefrom
2004	EP1428250	University of Delaware	Chemical surface deposition of ultra-thin semiconductors
2005	EP1597775	BP P.L.C.	Improved photovoltaic cell and method of production thereof
2005	WO2005060723	California Institute of Technology	Wafer bonded epitaxial templates for silicon heterostructures
2005	WO2005079198	California Institute of Technology	Wafer bonded virtual substrate and method for forming the same
2005	EP1602132	Carl-Zeiss Stiftung	Surface modification of silicon nitride for thick film silver metallization of solar cell
2005	6917209	ECD	Non- contacting capacitive diagnostic device
2005	6919530	First Solar, LLC	Method and apparatus for laser scribing glass sheet substrate coatings
2005	WO2005062440	General Electric Company	Photovoltaic power converter configured for compensating load harmonics
2005	WO2005018007	Lockheed Martin Corp./Advent Solar	Back-contacted solar cells with integral conductive vias and method of making
2005	6858462	Lockheed Martin Corp./Gratings Inc.	Enhanced light absorption of solar cells and photodetectors by diffraction
2005	6908782	Midwest Research Institute	High carrier concentration p-type transparent conducting oxide films
2005	6852371	Midwest Research Institute	Metal processing for impurity gettering in silicon

Issue Date	Patent Number	Assignee	Title
2005	WO2005036601	Midwest Research Institute	Wafer characteristics via reflectomeytry and wafer processing apparatus and method
2005	WO2005034247	Midwest Research Institute	ZnO/Cu(InGa)Se.sub.2 solar cells prepared by vapor phase Zn doping
2005	EP1573145	Powerlight Corp.	Shingle assembly
2005	6883290	Powerlight Corp.	Shingle system and method
2005	6911593	University of Arkansas	Transparent self-cleaning dust shield
2005	WO2005017957	University of California	Nanowire array and nanowire solar cells and methods for forming the same
2005	6852614	University of Maine	Method of manufacturing semiconductor having group II-group VI compounds doped with nitrogen
2006	7141834	California Institute of Technology	Method of using a germanium layer transfer to Si for photovoltaic applications and heterostructure made thereby
2006	7135069	Carl-Zeiss Stiftung	Coating silicon pellets with dopant for addition of dopant in crystal growth
2006	7019138	Colorado State University/Univ of Ferrara	Metal complex-based electron-transfer mediators in dye-sensitized solar cells
2006	7019208	Energy Photovoltaics	Method of junction formation for CIGS photovoltaic devices
2006	EP1642344	Lockheed Martin Corp./Advent Solar	Back-contacted solar cells with integral conductive vias and method of making
2006	7041910	Massachusetts Institute of Technology	Emissive, high charge transport polymers
2006	WO2006078319	Massachusetts Institute of Technology	Light trapping in thin film solar cells using textured photonic crystal
2006	7122736	Midwest Research Institute	Method and apparatus for fabricating a thin-film solar cell utilizing a hot wire chemical vapor deposition technique
2006	6984263	Midwest Research Institute	Shallow melt apparatus for semicontinuous Czochralski crystal growth

Issue Date	Patent Number	Assignee	Title
2006	7067850	Midwest Research Institute	Stacked switchable element and diode combination
2006	7053294	Midwest Research Institute	Thin-film solar cell fabricated on a flexible metallic substrate
2006	7095050	Midwest Research Institute	Voltage-matched, monolithic, multi-band-gap devices
2006	RE038988	Unassigned	Lightweight, self-ballasting photovoltaic roofing assembly
2006	6996147	University of California	Methods of fabricating nanostructures and nanowires and devices fabricated therefrom
2006	7141863	University of Toledo	Method of making diode structures
2006	7098058	University of Toledo	Photovoltaic healing of non-uniformities in semiconductor devices
2007	7238622	California Institute of Technology	Wafer bonded virtual substrate and method for forming the same
2007	7297868	Davis, Joseph & Negley	Preparation of CIGS-based solar cells using a buffered electrodeposition bath
2007	EP1870943	International Solar Electric Technology Inc.	An oxide-based method of making compound semiconductor films and making related electronic devices
2007	7170001	Lockheed Martin Corp./Advent Solar	Fabrication of back-contacted silicon solar cells using thermomigration to create conductive vias
2007	7300890	Midwest Research Institute	Method and apparatus for forming conformal SiN.sub.x films
2007	7309832	Midwest Research Institute	Multi-junction solar cell device
2007	7229498	Midwest Research Institute	Nanostructures produced by phase-separation during growth of III-V.sub.1-x(IV.sub.2).sub.x alloys
2007	7179665	Midwest Research Institute	Optical method for determining the doping depth profile in silicon
2007	7238912	Midwest Research Institute	Wafer characteristics via reflectometry and wafer processing apparatus and method
2007	7179677	Midwest Research Institute	ZnO/Cu(InGa)Se.sub.2 solar cells prepared by vapor phase Zn doping
2007	7178295	Powerlight Corp.	Shingle assembly
2007	7297865	SunPower Corp.	Compact micro-concentrator for photovoltaic cells

Issue Date	Patent Number	Assignee	Title
2007	7220321	Unassigned	Apparatus and processes for the mass production of photovoltaic modules
2007	7238878	Unassigned	Photovoltaic module with light reflecting backskin
2007	7202143	University of Arkansas	Low temperature production of large-grain polycrystalline semiconductors
2007	7265037	University of California	Nanowire array and nanowire solar cells and methods for forming the same
2007	7217882	University of California/Cornell University	Broad spectrum solar cell
2007	7202411	U.S. Dept. of Energy	Photovoltaic and thermophotovoltaic devices with quantum barriers
2008	7459188	Alliance For Sustainable Energy, LLC	Method and apparatus for making diamond-like carbon films
2008	7402448	BP P.L.C.	Photovoltaic cell and production thereof
2008	7341927	California Institute of Technology	Wafer bonded epitaxial templates for silicon heterostructures
2008	7435897	Carl-Zeiss Stiftung	Apparatus and method for mounting photovoltaic power generating systems on buildings
2008	EP1903614	First Solar, LLC	Method of manufacturing a photovoltaic device
2008	7368659	General Electric Company	Electrodes mitigating effects of defects in organic electronic devices
2008	7465872	General Electric Company	Photovoltaic power converter system with a controller configured to actively compensate load harmonics
2008	7329554	Midwest Research Institute	Reactive codoping of GaAllnP compound semiconductors
2008	7332599	North Carolina State University	Methods and intermediates for the synthesis of dipyrrin-substituted porphyrinic macrocycles
2008	7314773	Princeton University	Low resistance thin film organic solar cell electrodes
2008	EP1920480	Princeton University	Low resistance thin film organic solar cell electrodes

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2008	WO2008005027	Princeton University	Low resistance thin film organic solar cell electrodes
2008	7328534	SunPower Corp.	Shingle system
2008	7368658	U.S. Dept. of Energy	High efficiency diamond solar cells
2009	7517784	Alliance For Sustainable Energy, LLC	Method for producing high carrier concentration p-Type transparent conducting oxides
2009	7574842	Carl-Zeiss Stiftung	Apparatus for mounting photovoltaic power generating systems on buildings
2009	7482532	Massachusetts Institute of Technology	Light trapping in thin film solar cells using textured photonic crystal
2009	7545051	University of California	Nanowire array and nanowire solar cells and methods for forming the same

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