APPENDIX A

Photovoltaic (PV) Cost and Performance Characteristics for Residential and Commercial Applications

Final Report

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Executive Summary

Technical performance and cost characteristics were developed for residential and commercial photovoltaic (PV) systems for a time horizon extending to 2035. Characteristics were developed for six typical PV systems shown in **Table 1**. As indicated, crystalline and thin-film PV technologies were evaluated in three sizes – 5, 25, and 250 kW$_{DC}$. The 5 kW$_{DC}$ size is representative of residential applications, and the 25 and 250 kW$_{DC}$ sizes are representative of commercial installations.

Table 1. PV Prototypes

Application	Technology	Size (kW$_{DC}$)
Residential	Crystalline	5
	Thin-film	5
Commercial	Crystalline	25
		250
	Thin-film	25
		250

Based on a comprehensive literature search, discussions with PV stakeholders, and ICF in-house data, the following characteristics were developed:

- Module Efficiency[1]
- System Efficiency[2]
- Degradation
- Life
- Installed Capital Costs
- O&M Costs

Key results and observations from this study include:

Module Efficiency. Module efficiencies for crystalline technologies operating in the field are estimated to range from 14% in 2008 to 20% in 2035. For thin-film technologies, module efficiencies are anticipated to range from 10% to 14% over this same time span (2008 to 2035).

System Efficiency. System efficiencies (DC to AC power) for crystalline technologies are expected to increase from levels in the range of 78% to 82% in 2008, to levels in the range of 86% to 90% in 2035. For thin-film technologies, system efficiencies are forecast to increase from a range of 77% to 81% in 2008, to a range of 86% to 90% in 2035.

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[1] In this report, module efficiency refers to the conversion of sunlight to direct current (DC) power.
[2] System efficiency refers to the conversion of DC to AC power.

Degradation. Forecast degradation rates for crystalline technologies start at 0.60%/yr in 2008, and decline to 0.33%/yr in 2035. Forecast degradation rates for thin-film technologies are higher, ranging from 1.00%/yr in 2008 and falling to 0.73%/yr in 2035.

Lifetime. Crystalline PV modules and balance of plant components (except the inverter) are forecast to have an expected lifetime of 25 years in 2008. Thin-film modules and balance of plant components (except the inverter) are forecast to have a lifetime of 20 years in 2008. Both technologies are forecast to have a lifetime of 30 years by 2035. Inverters, which are assumed to be identical for both crystalline and thin-film technologies, are forecast to have lifetime of 10 years in 2008, rising to 15 years by 2035.

Residential Installed Capital Costs (expressed in 2008 dollars). For residential systems, crystalline technologies are forecast to have lower costs compared to thin-film technologies. Forecast costs for installed residential PV systems are approximately $7,100/kW$_{DC}$ (crystalline) and $7,300/kW$_{DC}$ (thin-film) in 2010. These costs fall to approximately $4,000/kW$_{DC}$ (crystalline) and $4,100/kW$_{DC}$ (thin-film) by 2035.

Commercial Installed Capital Costs (expressed in 2008 dollars). For commercial applications, thin-film technologies are forecast to have lower costs compared to crystalline systems (reverse situation compared to residential systems). In 2010, forecast costs for installed commercial PV systems are in the range of $5,500/kW$_{DC}$ (thin-film, 25 kW$_{DC}$) to $6,800 (crystalline, 25 kW$_{DC}$). By 2035, forecast costs are estimated to decline to an approximate range of $3,200/kW$_{DC}$ (thin-film, 25 kW$_{DC}$ and 250 kW$_{DC}$) to $3,800/kW$_{DC}$ (crystalline, 25 kW$_{DC}$)

O&M Costs. O&M consists of periodic system inspection and solar panel cleaning. For forecasting purposes, it is assumed that both commercial and residential PV system owners will properly maintain their systems. Residential homeowners will likely take a "do it yourself" approach, while commercial sites will use a maintenance contract. In the case of a DIY approach, a cost is still incurred in terms of time required to complete the maintenance. O&M is assumed to scale in direct proportion to panel size, which decreases as module efficiency increases, and with overall system capacity (decreases as capacity increases). Crystalline O&M costs are forecast to decline 30% between 2008 and 2035, reaching levels in the range of $11.20/ kW$_{DC}$ to $$16.80/kW$_{DC}$ by 2035. For thin-film, forecast costs decline 29%, reaching levels in the range of $16.00/kW$_{DC}$ to $24.80/kW$_{DC}$ by 2035.

The recommended characteristics described above correspond to a reference case, or business-as-usual, scenario. In addition to a reference case analysis, an advanced case was developed based on more aggressive assumptions concerning technology advancements and market penetration. The primary difference between the reference case and the advanced case is that installed capital costs decline more quickly over time in the advanced case as a result of accelerated R&D investments.

1.   Introduction

The Energy Information Administration (EIA) produces a wide range of analyses and reports, including forecasts for energy supply and demand, and the diffusion of technologies in the marketplace. To develop forecasts, EIA uses the National Energy Modeling System (NEMS), which is a robust model that describes energy markets in the United States. Each year, EIA produces the *Annual Energy Outlook* (AEO), which includes projections generated with NEMS. The AEO report covers a time horizon of 25 to 30 years, and includes market penetration estimates for a wide range of technologies, including residential and commercial photovoltaic (PV) systems.

To develop reliable projections using NEMS, it is important to have accurate technical performance and cost characteristics describing supply side and demand side technologies. Regarding demand side technologies, the residential and commercial PV characteristics that EIA has previously used to support NEMS are based on a solar roadmap baseline projection prepared in 2004.[3]

1.1   Objective

The objective of this project was to develop a recommended set of technical performance and cost characteristics for residential and commercial PV technologies for the time period extending from 2010 to 2035.

1.2   Approach

ICF conducted a comprehensive literature review and talked with solar experts at manufacturing organizations, national laboratories, and academic institutions. This information was analyzed and used to shape a forecast of PV characteristics through 2035. Recommended characteristics were developed for six PV system prototypes as shown in **Table 2**. The 5 kW_{DC} size is intended to be representative of residential applications, and the 25 and 250 kW_{DC} capacities are consistent with commercial installations (25 kW_{DC} at the low end, and 250 kW_{DC} at the high end).

Table 2.   PV Prototypes

Capacity (kW_{DC})[4]	Technology
5, 25, 250	Crystalline
5, 25, 250	Thin-film

As indicated in **Table 2**, the prototypes are based on crystalline and thin-film solar cell technology. Multi-junction technologies were also evaluated. However, multi-junction technologies are not expected to have significant market penetration in residential and

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[3] Our Solar Power Future, *The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond*, September 2004.
[4] Unless noted otherwise, all PV power ratings (kW_{DC}) in this report are based on direct current (DC) at standard test conditions (STC). Standard test conditions are 1,000 W/m^2 of solar irradiance, cell temperature of 25 ^{o}C, and air mass (AM) of 1.5.

commercial applications in the foreseeable future, and prototypes were therefore based only on crystalline and thin-film systems.

Using the prototypes shown in **Table 2**, a set of recommended PV characteristics was developed that is consistent with a reference case scenario. The reference case scenario is intended to reflect a business-as-usual outcome, assuming that the current pace of R&D investments and policy drivers will prevail over the forecast time horizon. In addition to the reference case scenario, a set of recommended PV characteristics was also developed for an advanced case. The advanced case is based on a scenario that includes higher levels of R&D investments that may accelerate the adoption of residential and commercial PV.

1.3   Report Organization

This report is organized as shown in **Table 3**. An overview of PV technologies is provided in Section 2, followed by a discussion of markets in Section 3. Historical cost trends from 1998 through 2008 are covered in Section 4. In Section 5, PV characteristics used in the AEO 2010 report are discussed. Results from discussions with PV experts and the literature search are presented in Section 6. In Section 7, recommended PV characteristics for a reference case are presented, and in Section 8 characteristics for an advanced case are described.

Table 3.   Report Organization

Section	Title
1	Introduction
2	Technologies
3	Markets
4	Historical Costs
5	Forecast of PV Characteristics – Reference Case
6	Forecast of PV Characteristics – Advanced Case

2. Technologies

For residential and commercial PV applications, the two main components are a PV array (also called solar array) and an inverter. A third component in many PV installations is bank of batteries for energy storage. The PV array produces direct current (DC) from sunlight, and the inverter converts the direct current to alternating (AC) current. The AC power is then used on site or exported to the grid. A simplified schematic for a residential PV installation is shown in **Figure 1** (no battery backup).
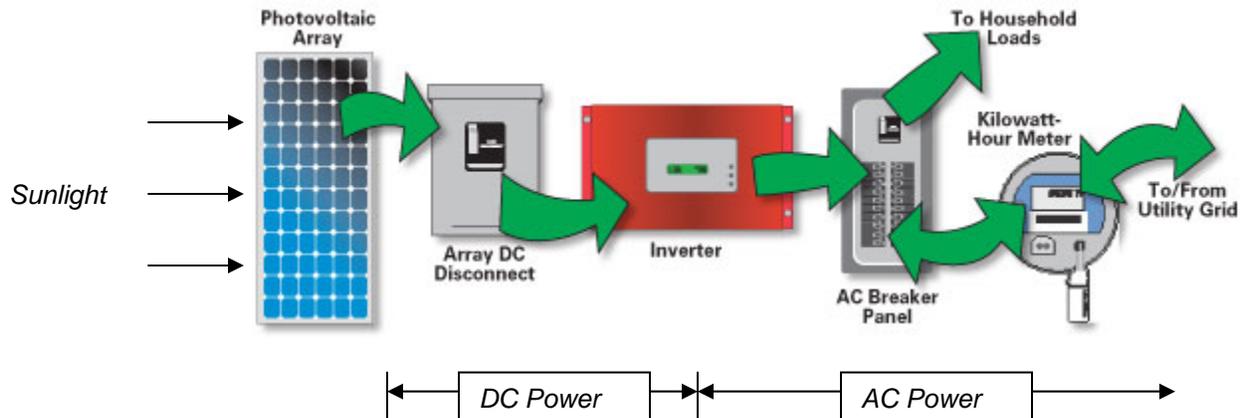
Source: Homepower magazine

Figure 1.   Illustration of Grid-connected PV System

Residential and commercial PV systems can be connected to the grid or configured as an off-grid system. Off-grid installations are typically only used in remote locations, and have little or no impact on the national energy forecast; as a result, this report is focused on grid-connected PV only.

In this section, key components of a PV system are discussed, including the current status and development trends. The discussion is organized into the following sections:

- PV Cells
- Modules & Arrays
- Tracking Systems
- Inverters
- System Efficiency

2.1   PV Cell Technology

The building block for a PV system is a PV cell (or solar cell). Multiple PV cells are interconnected and assembled in a support structure, or frame, to form a PV module (or solar panel). Multiple modules are then combined to form a PV array (see **Figure 2**).
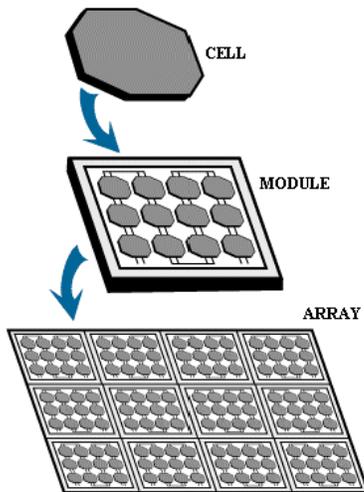
Source: NASA

Figure 2.   Relationship of PV Cells, Modules, and Arrays

Photovoltaic (PV) technologies are constructed using semiconductor materials that have the ability to convert sunlight into electricity. PV technologies are typically divided into three categories – crystalline silicon, thin-film, and multi-junction (see **Table 4**).

Table 4.   PV Technologies

Category	Semiconductor Material
Crystalline Silicon	---
Thin-film	Cadmium Telluride (CdTe)
	Gallium Arsenide (GaAS)
	Copper Indium Gallium Diselenide (CIGS)
	Amorphous Silicon (a-SI)
Multi-junction	---

Of the three categories, crystalline technologies are the oldest, and were commercialized by Bell Labs in the 1950s. Crystalline PV cells are manufactured by slicing silicon into thin wafers, with state-of-the-art technology near 170 microns (Shah 2009). There are two types of crystalline cells – monocrystalline and polycrystalline. Compared to polycrystalline cells, monocrystalline cells offer higher efficiencies, but are more expensive to manufacture. Polycrystalline cells have lower efficiencies, but are lest expensive to manufacture.

Thin-film PV cells are produced by depositing very thin layers of a semiconductor material on an inexpensive substrate, such as glass, plastic, or metal. **Table 4** shows four common types of semiconductor materials that are used in thin-film PV cells. Compared to crystalline technologies, thin-film cells are typically less expensive to manufacture, but tend to have lower efficiencies.

Multi-junction cells are fabricated using thin-film techniques, but have two or more different semiconductor materials. The semiconductor materials in a multi-junction cell capture solar energy from different ranges of the solar spectrum, thereby optimizing the conversion of solar energy to electricity. Compared to crystalline and thin-film technologies, multi-junction cells are significantly more expensive to manufacture. Due to the high cost, multi-junction cells do not currently compete in residential and commercial markets.

Crystalline Technology – Trends and Observations

Crystalline modules have dominated residential and commercial PV markets. Crystalline cell efficiencies in the field have improved from approximately 11% to over 14% over the past five years (Shah 2009, Barnett 2009). Efficiencies in the lab, which are higher than efficiencies in the field, have reached 26% under standard test conditions (STC) (Green 2009).

In recent years, the silicon wafer thickness has been reduced from approximately 300 to 170 microns, and manufacturers have generally increased warranty times from 20 to 25 years. Crystalline cell research is currently focused on reducing material costs, increasing efficiencies, improving the manufacturing processes, and improving reliability of modules (DOE 2008).

Thin-film Technology – Observations and Trends

Over the past five years, thin-film efficiencies have increased from the range of 5-8% to approximately 10% (Barnett 2009). The thin-film market is currently dominated by modules using cadmium telluride (CdTe) as a semiconductor (Maycock and Bradford 2007; Ullal and von Roedern 2007; Venkataraman 2009). In the lab, CdTe modules have reached efficiencies greater than 16% (Green 2009). Two emerging thin-film technologies are copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS). These two cell technologies have shown lab efficiencies of approximately 19% (Green 2009). Another thin-film technology is based on the deposition of amorphous silicon (a-Si) less than a micron thick (Maycock and Bradford 2007). One advantage of a-Si is that these cells can be manufactured in long continuous rolls rather than by batch production (Maycock and Bradford 2007).

Thin-film technologies continue to undergo advancements. CdTe manufacturers are working to standardize film growth equipment, achieve higher efficiencies, and prevent moisture ingress (Ullal 2007). CIGS manufacturers are developing standardized layer deposition equipment and working to achieve higher efficiencies and reduced layer thicknesses (Ullal 2007).

Cell Efficiency – Observations and Trends

As indicated in **Figure 3**, solar cell efficiencies have increased at a steady rate over the last several decades (DOE 2006). Efficiencies for advanced multi-junction technologies have approached 40% in laboratory settings at STC conditions. However, efficiencies

for practical cells, such as crystalline and thin film technologies, are well below these levels in the field.
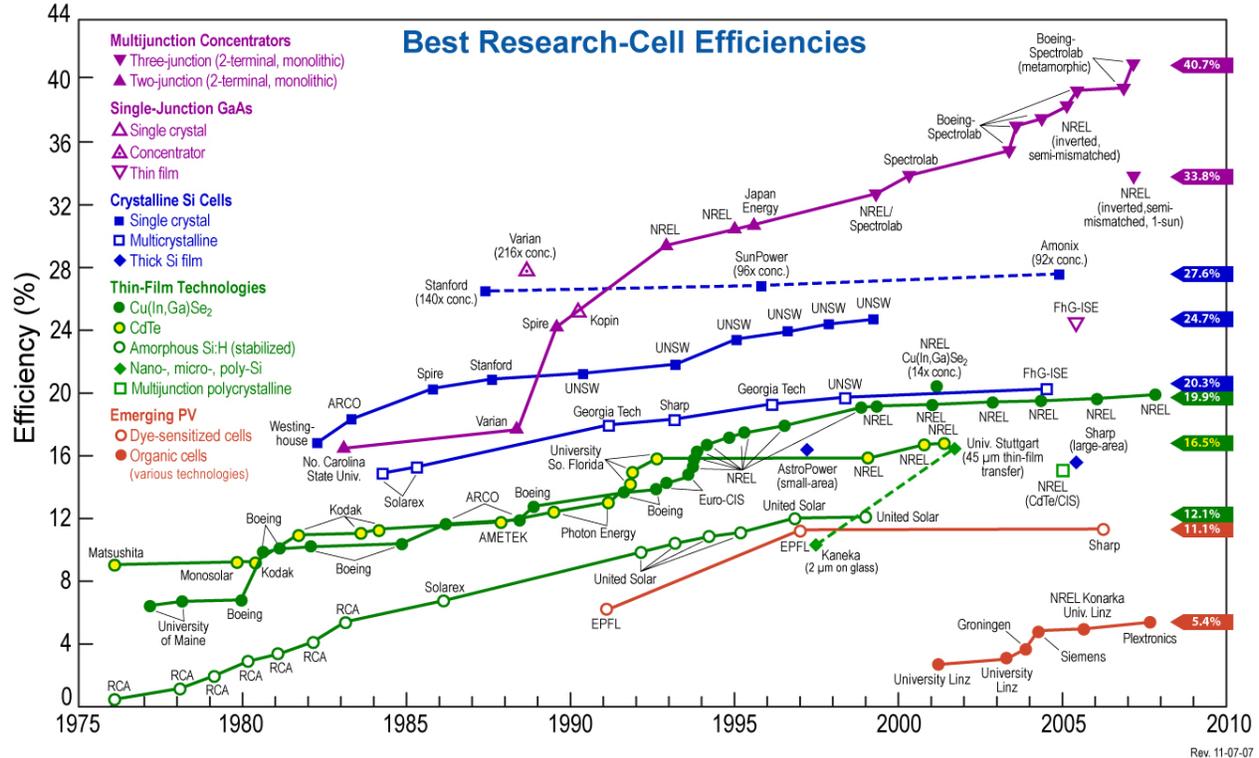
Source: NREL (2010)

Figure 3.   Historical Laboratory Cell Efficiencies – Best Research.

2.2   Modules & Arrays

Optimizing Performance

Several environmental factors contribute to system output losses, including sub-optimal orientation with respect to the sun, soiling, shading, and seasonal snow cover. The soiling factor is the percent of output lost by dirt or any other film that obscures the module surface, and ranges from slightly under 1% to 4% (Xantrex 2009). The amount of soiling depends on factors such as physical location (proximity to dusty roads, etc.), type of dust or film, and length of time since the last rainfall. Regular cleaning minimizes the impact of soiling (Xantrex 2009).

PV modules are connected in series, and a mismatch in electrical output between modules will decrease the electrical production of the PV array. Electrical mismatch can occur due to shading from buildings, trees, or other obstacles that interfere with direct sunlight striking the solar array. The magnitude of the mismatch depends on the array area affected, length of time, and time of day (Xantrex 2009). In colder climates, seasonal snow cover also shades systems and leads to mismatch. All of these factors need to be taken into account when estimating conversion losses of a PV system.

The electrical efficiency of a solar cell in the lab under Standard Test Conditions (STC) is almost always higher than the field efficiency, in part due to temperature differences. For STC measurements, the solar cell is held at 25 $^{\circ}$C. The efficiency of a solar cell decreases with increasing temperature, and the field temperature of a solar cell is almost always higher than 25 $^{\circ}$C. Roof mounted arrays can reach temperatures of 70-80°C (Wiles 2009). For rooftop conditions, the California Energy Commission recommends a de-rating factor of 89% from STC lab conditions to expected field power (Xantrex 2009).

Building Integrated PV (BIPV)

This report is primarily focused on PV panels that are rack mounted. However, an interesting development is the growth of building integrated PV (BIPV). BIPV technologies are currently more expensive than rack mounted systems, but BIPV breakthroughs could push down PV costs in residential and commercial applications (Chiras 2009).

2.3   Tracking Technology

Maximum PV output occurs when a solar panel is oriented perpendicular to incoming sunlight. The optimum orientation changes through the day as the sun moves across the sky, and on a seasonal basis as the height of the sun above the horizon changes. Tracking systems can be added to PV arrays to optimize electrical output.

In most residential applications, PV panels are placed on roof tops in fixed frames (also called "racks"), and tracking systems are not utilized. When the panels are located directly on the roof top, they are referred to as "flat racked" systems. Unless the roof is pitched at the local latitude angle, the system's power output can be increased by tilting the racking to be closer to the latitude angle to capture more sunlight (see **Table 5**). This type of tilting is referred to as "latitude racking."

Latitude racking is more expensive than flat-racking for both the residential and commercial sectors. Compared to flat-racked systems, significantly more hardware, assembly, and labor is involved in latitude racked systems. However, there is a financial trade off to consider. Even though flat-racking costs less, the modules are 20-30% less efficient than latitude racked systems (Focusing on Energy 2008).

In addition to static latitude racking, more sophisticated dynamic tracking systems can be used. Dynamic tracking systems can be either single-axis or dual-axis designs. A single axis design follows the daily east-west arc of the sun. With a dual axis system, hourly tracking (east-west) is achieved as well as seasonal tracking (north-south).

Table 5.   Impact of Azimuth and Tilt on Solar Energy [5]

Tilt Angle (degrees from the horizontal plane) \ Azimuth Angle (degrees east or west of due south)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
90	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
85	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6
80	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
75	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7
70	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
65	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7
60	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.7
55	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8
50	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8
45	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8
40	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9	0.8
35	1	1	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9
30	1	1	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.9
25	1	1	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9
20	1	1	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9
15	1	1	1	1	1	1	1	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9
10	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9
5	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	0.9	0.9
0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

2.4   Inverters

PV arrays produce direct current (DC) from sunlight; and this DC current is converted to alternating (AC) current with an inverter. Inverters are not 100% efficient, and energy is lost during this conversion process.

Today, the highest inverter conversion efficiency of DC to AC power is 96-97%, compared to approximately 94% in the 2004 time frame (Waiter 2009). In practice, typical inverter efficiencies in the field range from 92% to over 94% (Shah 2009). Residential inverters are smaller and slightly less efficient than larger scale commercial inverters, which leads to larger conversion losses in the residential sector (Shah 2009).

For a PV system that includes battery energy storage, there are additional energy losses that occur as batteries are charged and discharged. The battery efficiency, which is often referred to as the "roundtrip" efficiency, depends on several factors, including the type of battery (e.g., lead acid or nickel cadmium) and the state of charge

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[5] This table is derived from the NREL Surface Orientation Factor charts in: Christensen, Craig B. and Greg M. Barker. *Effects of Tilt and Azimuth Angle on Annual Incident Solar Radiation for United States Locations.* Washington, DC: Proceedings of Solar Forum 2001 – Solar Energy: The Power to Choose, April 21-25, 2001. The table is presented for a latitude of approximately 32°N.

(i.e., near full charge or at some lower charge level). Deep discharge lead acid batteries are frequently used for PV applications, and these batteries have a roundtrip efficiency level typically near 80% (i.e., 80% of the energy used to charge the battery is available for discharge).

A common configuration for residential and commercial PV systems is to use a single inverter (see **Figure 1**) located near the electrical service panel for the building. PV systems that use multiple inverters – referred to as microinverters – are entering the market. Microinverters convert DC to AC power in a unit attached directly to each PV module, instead of through a single stand-alone inverter that serves the entire PV array. Microinverters are an emerging technology, and there is limited data available to assess actual performance and costs. However, potential advantages of microinverters may include:

- Increased reliability. A separate inverter for each module means there is no single point of failure. If one microinverter fails, other modules continue to operate.

- Longer life. Enphase, a manufacturer of microinverters, reports that their microinverters are designed for a service life greater than 20 years.[6]

- Improved performance of each module. A separate microinverter on each module maximizes performance of that module.

- Lower installation costs. Simplified installation with no wiring required for a central inverter.

2.5   System Efficiency

Inverters are just one source of power loss when converting from DC to AC power. An example of other factors that contribute to power losses in PV systems is shown in **Table 6**. This table, which is taken from NREL data used in the PVWATTS tool, shows that there are 10 factors in addition to the inverter that may contribute to power losses. For the default values in the PVWATTS tool, the inverter derate factor is 0.92 and the overall derate factor is 0.77.

In this report, a detailed analysis and forecast of derate factors, or efficiency losses, by component, was not conducted. Rather, the analysis and forecast was divided into two categories:

- System efficiency (includes all factors that contribute to DC to AC power with the exception of age)

- Degradation (accounts for power losses that occur due to the age of the system)

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[6] Enphase web site,
http://www.enphaseenergy.net/downloads/Enphase_WhitePaper_Reliability_of_Enphase_Micro-inverters.pdf , accessed March 2010.

A cross map of PVWATTS derate factors and efficiency factors used in this report is show in **Table 7**.

Table 6. **Derate Factors Used in PVWATTS**

Component Derate Factors	PVWATTS Default	Range
PV module nameplate DC rating	0.95	0.80 - 1.05
Inverter and Transformer	0.92	0.88 - 0.98
Mismatch	0.98	0.97 – 0.995
Diodes and connections	1.00	0.99 – 0.997
DC wiring	0.98	0.97 - 0.99
AC wiring	0.99	0.98 – 0.993
Soiling	0.95	0.30 – 0.995
System availability	0.98	0.00 – 0.995
Shading	1.00	0.00 - 1.00
Sun-tracking	1.00	0.95 - 1.00
Age	1.00	0.70 - 1.00
Overall DC-to-AC derate factor	0.77	---

Source: NREL PVWATTS, http://rredc.nrel.gov/solar/calculators/PVWATTS/system.html

Table 7. **Relationship of PVWATTS Derate Factors to Efficiency Values**

Derate Component in PVWATTS	Efficiency Component in this Report
PV module nameplate DC rating	System Efficiency (changes by year, cell material, and capacity)
Inverter and Transformer	
Mismatch	
Diodes and connections	
DC wiring	
AC wiring	
Soiling	
System availability	
Shading	
Sun-tracking	
Age	Degradation Rate (changes by year and PV cell material)

3. Markets

3.1 U.S. Market Perspective

Federal, state, and utility incentives provide strong drivers that push the adoption of PV systems. At the Federal level, there is an investment tax credit (ITC), which provides an income tax credit for residential and commercial PV installations. The ITC was revised in 2009 as part of the American Recovery and Reinvestment Act (ARRA). ITC provisions in ARRA that specifically relate to PV include:

- 30% ITC extended through end of 2016 for both residential and commercial solar installations
- $2,000 cap eliminated for residential PV
- Utilities allowed to benefit from credit (utilities were previously excluded)
- Tax payers (both individuals and businesses) that are required to file Alternative Minimum Tax (AMT) are allowed to claim credit (previously excluded)

PV market size, maturity, and total installed costs vary widely from state to state. The growth of residential and commercial PV markets within a state has been driven almost entirely by state-based incentive programs (Venkataraman 2009). The overwhelming majority of residential and commercial PV installations have occurred in just two states – California and New Jersey (Wiser 2009). Both of these states have well developed incentive programs that have stimulated PV adoption.

In addition to capacity based incentives and performance based incentives, states have used a variety of other tools to encourage the installation of PV, including sales and property tax exemptions, net metering laws, feed-in tariffs, solar access laws, standardized and liberalized interconnection procedures, etc. The incentive mix changes continuously; refer to the Database of State Incentives for Renewables and Efficiency (DSIRE) for the most recent information (DSIRE 2009).

3.2 Installation and Financing

Historically, the installation of PV systems has been performed by companies that specialize in PV. However, the drop in demand for new construction and building retrofit work, coupled with growing demand for end-use PV, has motivated construction companies, roofing contractors, and electrical contractors to enter the PV installation business (Shah 2009). With their project management and business experience, these companies are streamlining the installation process and increasing competition within the industry.

In addition, new financing methods have begun to emerge that are encouraging the adoption of PV systems. The financial factors that influence a consumer's decision to purchase include upfront costs, financial incentives, utility bill savings, and maintenance costs. Due to the current weak economic conditions, residential homeowners and

commercial building owners/developers are reluctant to make expensive capital investments such as PV (Coughlin 2009). New financing methods, such as the commercial solar power purchase agreement (SPPA) and the residential solar lease, seek to overcome these financial barriers by significantly reducing or eliminating the upfront cost to commercial and residential customers (Coughlin 2009).

3.3   International Market Volatility

The U.S. PV industry is influenced by the volatility of the larger international solar market. Manufacturers focus their attention, and their sales, on the fastest growing and most profitable markets. For example, Spain's feed-in tariff motivated rapid growth and made Spain the largest PV market in the world in 2008. Unprecedented demand in Spain put a strain on global supply that kept equipment costs high in the U.S. and elsewhere in the world (Tarbell 2009). Growth in Spain has slowed recently, but growth in other markets has picked up. For example, Germany installed 3.8 GW of PV in 2009, and 1.45 GW in December alone.[7]

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[7] http://www.pv-tech.org/lib/printable/8828, accessed May 2010.

4. Historical Costs

Historical costs for PV systems are discussed in this section, which is organized as follows:

- Installed PV System Costs
- Component Costs

4.1 Installed PV System Costs

Technological developments across the PV supply chain, from commodities to efficiencies, have pushed total installed costs downward. An increase in silicon manufacturing has increased supply and lowered the price of silicon in crystalline PV modules (Hasan 2009). Improved manufacturing processes have increased the production output of facilities, while decreasing the costs of production (GT Solar 2009).

In recent years, streamlined manufacturing has led to decreased manufacturing costs. Machine manufacturers have begun to offer turn-key production lines which are complete manufacturing system packages. Turn-key solutions are sold for every stage of the supply chain, from wafer fabrication to module fabrication (GT Solar 2009). These automated turn-key production lines have helped increase productivity, quality, and yields, while lowering manufacturing costs. Automated systems have also made it easier for new firms to enter the manufacturing arena, thereby increasing competition and putting downward pressure on prices.

A recent report titled "Tracking the Sun II" by Lawrence Berkeley National Laboratory summarizes the installed cost of PV systems in the United State from 1998 through 2008. Costs in this report cover approximately 52,000 residential and non-residential systems, with a total capacity of 566 MW (71% of grid connected capacity in the United States at the end of 2008). PV installed capacity and coverage as reported in Tracking the Sun II are shown in **Table 8** and **Table 9**, respectively.

Table 8.   Installed PV in U.S. through 2008

Type of Installation	Capacity	
	(MW)	(%)
Grid Connected	798	88%
Off Grid	109	12%
Total	**906**	**100%**

Table 9.   Grid Connected PV Coverage in Tracking the Sun II

	Capacity		
	(MW)	(% of all grid connected)	(% of all PV)
Covered in TS II	566	71%	62%
Not Covered in TS II	231	29%	26%
Total Grid Connected	**798**	**100%**	**88%**

PV system data reported in *Tracking the Sun II* was collected from 16 states. A comparison of the PV installed capacity across the 16 states is shown in **Figure 4**, and a comparison of the number of PV installations by state is shown in **Figure 5**. As indicated, California has the highest representation in the sample, followed by New Jersey.
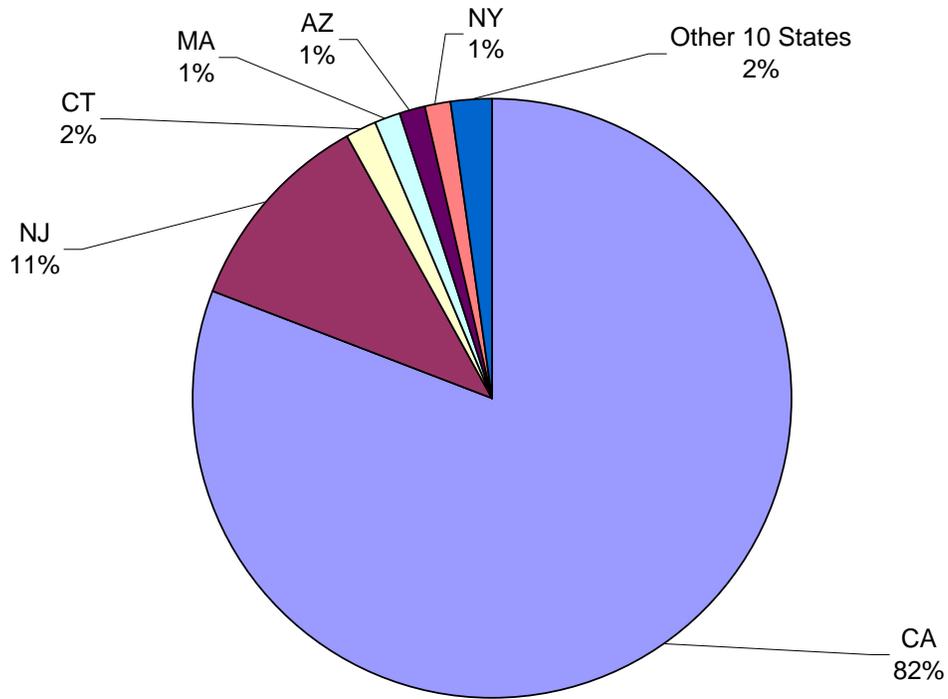
Figure 4.   Installed Capacity by State
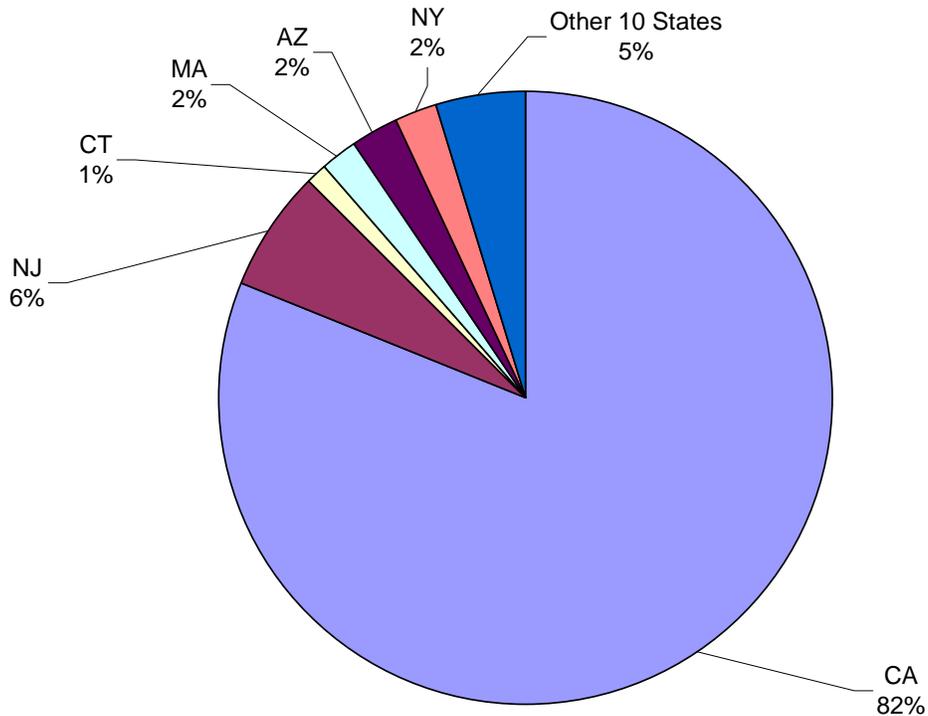
Figure 5. Number of Sites by State

Average annual costs for all PV systems in the LBNL sample are shown in **Table 10** and graphed in **Figure 6.** These data are based on all system types in the data sample (e.g., rack-mounted, building integrated, tracking, non-tracking, crystalline, thin-film, etc.). As indicated in the table, the simple average of PV installed costs has declined from $12,260/kW$_{DC}$ in 1998 to $8,243 in 2008 (a total decrease of 33%, or 3.9% per year).

Table 10. Grid Connected PV Coverage in Tracking the Sun II

Year	Number of Systems	Capacity (MW)	Installed Cost (2008$ / kW$_{DC}$)	
			Capacity Weighted	Simple Average
1998	39	0.2	10,849	12,260
1999	180	0.8	10,600	11,611
2000	217	0.9	9,485	10,900
2001	1,308	5.4	9,768	10,492
2002	2,489	15.0	9,754	10,455
2003	3,526	34.0	8,370	9,308
2004	5,527	44.0	8,287	8,566
2005	5,193	57.0	7,770	8,264
2006	8,677	90.0	7,838	8,385
2007	12,103	122.0	7,837	8,474
2008	13,097	197.0	7,480	8,243
	52,356	**566.3**		
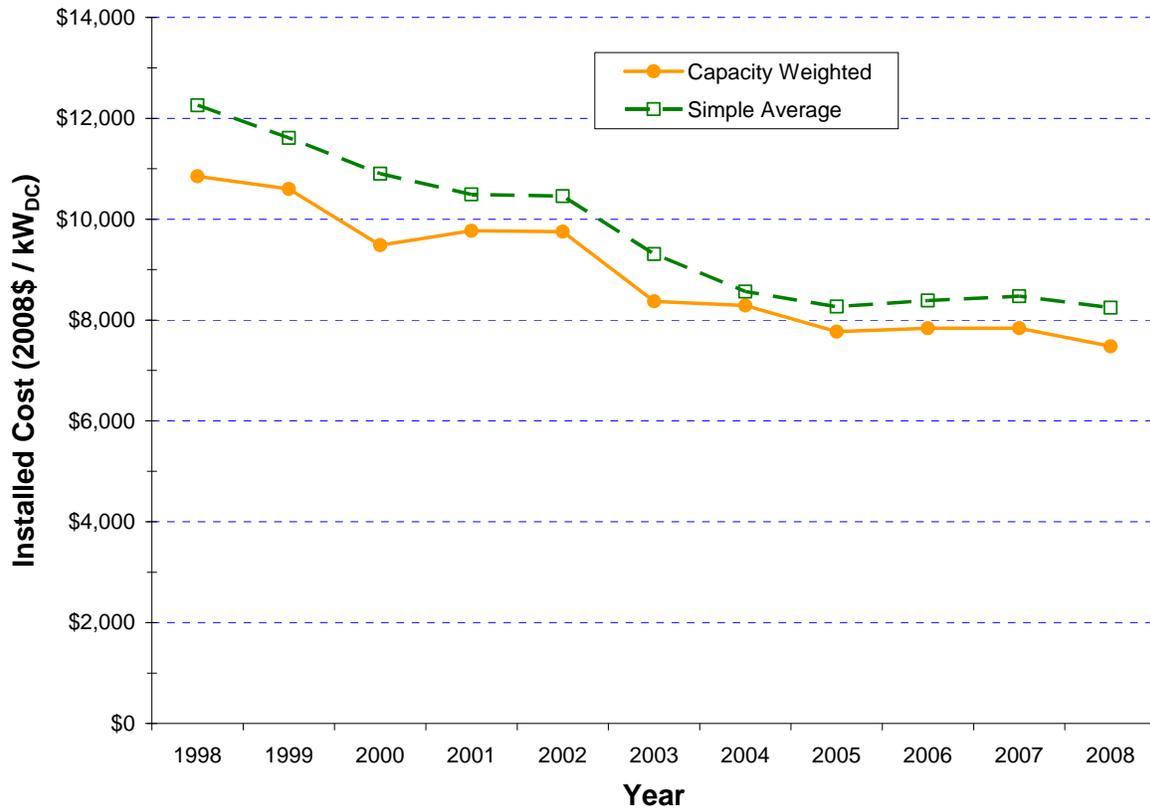
Figure 6.   PV Installed Cost Trends

Figure 7 shows a breakout of historical PV costs by size range. Systems less than 100 kW$_{DC}$ showed a steady decline from 1998 through about 2005, and then remained generally flat from 2005 through 2007, followed by a decline in installed costs for 2008. Compared to systems under 100 kW$_{DC}$, there are far fewer systems with capacities above 100 kW$_{DC}$, and the data are somewhat more scattered for these larger systems. However, based on **Figure 7**, it is clear that there are economies of scale, with larger systems consistently showing lower costs.
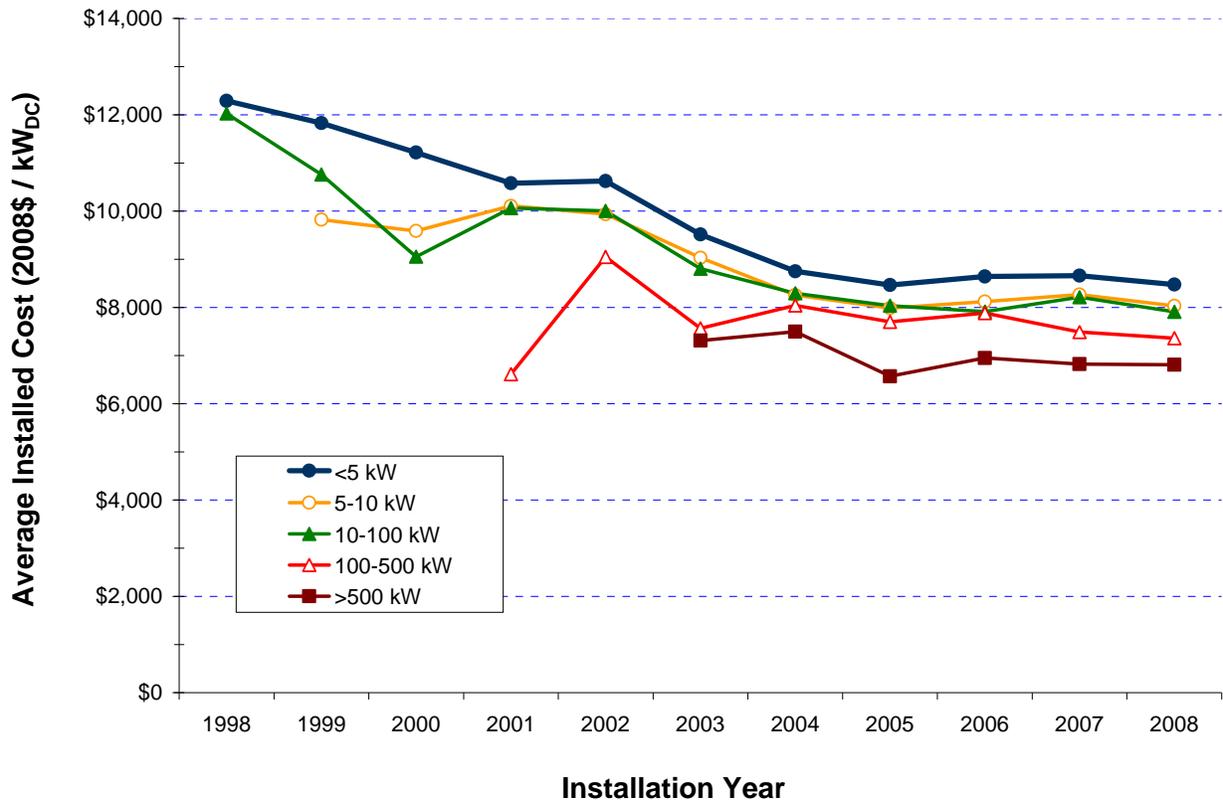
Figure 7.   PV Installed Cost Trends by System Size

Table 11 shows average costs for rack mounted PV technologies in 2008 with a breakdown for crystalline and thin-film technologies in three size categories. In 2008, similar to other years, the majority of PV installations have used rack mounted crystalline technology. In 2008, over 10,500 rack mounted crystalline systems were installed, representing 80% of the total PV installations tracked by LBNL in 2008 (13,097 total systems in 2008).

Table 11.   Rack Mounted Systems Installed in 2008

Size	Technology					
	Crystalline			Thin-film		
	Number of Systems	Capacity (MW)	Cost (2008$/kW$_{DC}$)	Number of Systems	Capacity (MW)	Cost (2008$/kW$_{DC}$)
< 10 kW$_{DC}$	9,179	43	8,200	22	0.1	8,500
10-100 kW$_{DC}$	1,098	24	7,900	16	0.7	6,400
>100 kW$_{DC}$	242	86	7,200	6	2.4	6,700
	10,519	**153**		**44**	**3.2**	

Compared to the population of crystalline systems, LBNL identified far fewer rack mounted thin-film installations. As indicated in **Table 11**, there are only 44 total thin film systems identified in all three size categories, with a combined capacity of 3.2 MW.

While the cost numbers for the thin-film systems seem reasonable (range from $6,400/kW$_{DC}$ to $8,500/kW$_{DC}$), these results should be viewed with caution given the small sample size. The cost numbers for thin-film technologies could change significantly as the sample size grows and becomes more statistically relevant.

Figure 8 compares the average costs for crystalline and thin-film technologies by the three size categories. For systems <10 kW$_{DC}$, crystalline technologies show slightly lower costs -- $8,200/kW$_{DC}$ for crystalline compared to $8,500 for thin-film. However, for systems >10 kW$_{DC}$, thin-film technologies have lower costs. In the 10-100 kW$_{DC}$ size range, the cost differential is $1,500/kW$_{DC}$ ($7,900/kW$_{DC}$ compared to $6,400/kW$_{DC}$), and in the >100 kW$_{DC}$ size range the differential is $500/kW$_{DC}$ ($7,200/kW$_{DC}$ compared to $6,700/kW$_{DC}$).
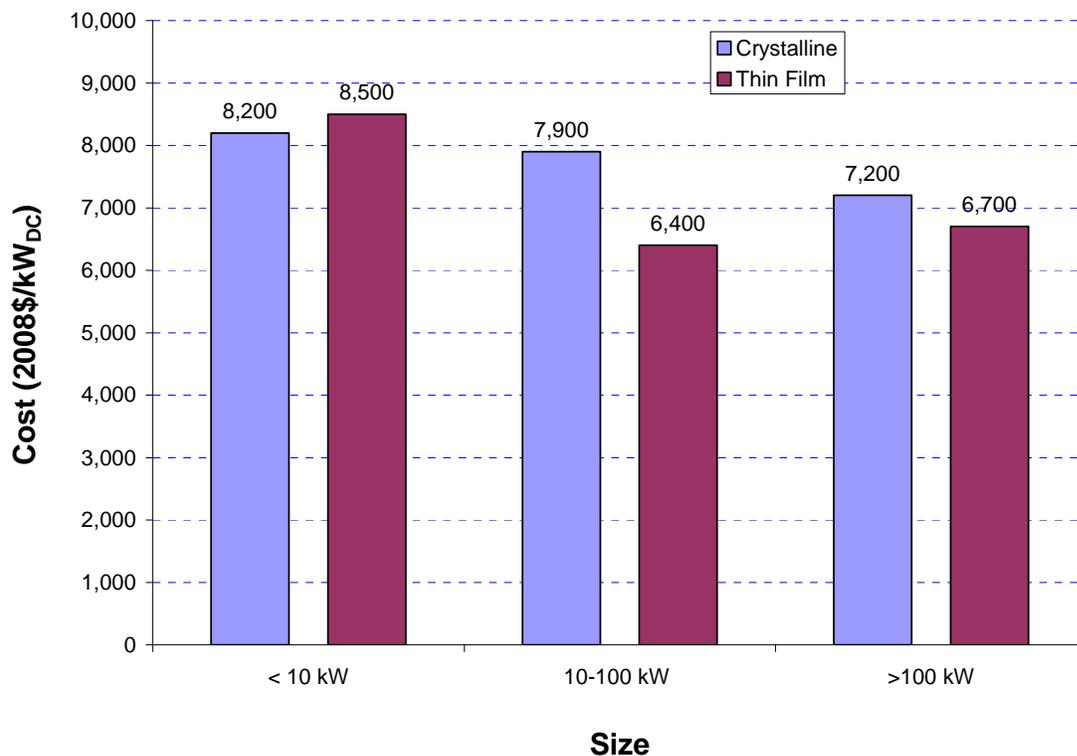

Figure 8.   PV Installed Costs for Crystalline and Thin-film Technologies

4.2   Component Costs

Component level cost data are scarce. However, in *Tracking the Sun II* component costs are reported for a single year (2008) as shown in **Figure 9**. The costs in this figure are average costs for crystalline and thin-film technologies combined. The costs

are separated into three different size ranges – 1) under 10 kW$_{DC}$, 2) 10-100 kW$_{DC}$, and 3) >100 kW$_{DC}$.
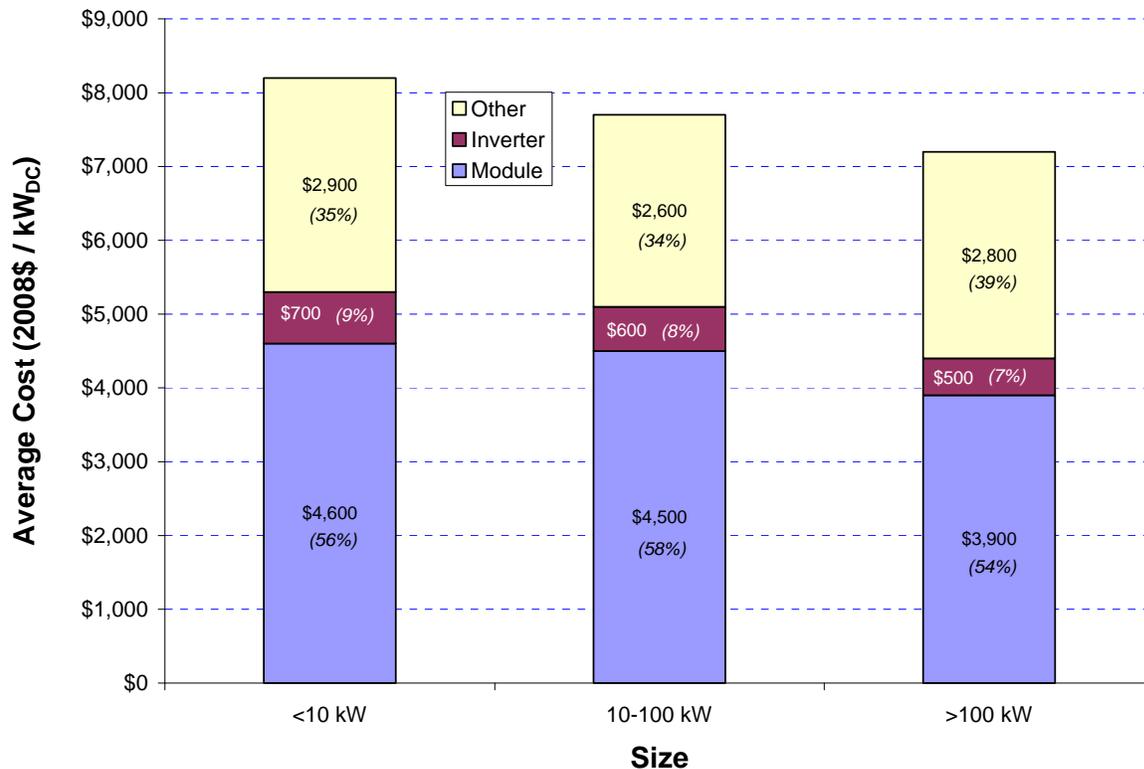
Figure 9.   Component Costs (systems installed in 2008)

As indicated in **Figure 9**, module costs account for the largest fraction of PV installed costs, ranging from 54% to 58% of the average total installed cost. Module costs are $600 to $700/kW$_{DC}$ lower for systems over 100 kW$_{DC}$ compared to the two small size bins, which suggests that there are may be bulk purchasing discounts that help reduce module costs for large systems.

Based on 2008 system data in the LBNL *Tracking the Sun II* report, inverters account for 7% to 9% of the total installed cost. As system sizes increase, inverter costs show declining costs (decline from $700/kW$_{DC}$ in smallest size bin to $500/kW$_{DC}$ in largest size bin). A report prepared by Navigant for NREL (NREL 2006) offers additional insights into inverter costs. In this report, which is based on data from 2006, inverters are estimated to account for 10-20% of the initial PV system installed cost (higher than the 7-9% reported by LBNL in 2008)

In **Figure 9**, the "other" category includes costs associated with design, engineering, installation labor, and regulatory compliance. These other expenses account for a third or more of total installed costs (range from 34% to 39% depending on PV size).

5.   Forecast of PV Characteristics – Reference Case

While there is ample research and analysis on the size and scope of the PV market, there are few detailed forecasts regarding PV costs and technical performance in the public domain. To develop a PV forecast, ICF collected information from several sources, including interviews with industry PV stakeholders, publicly available literature, and in-house ICF data. The data were grouped into three capacities (5, 25, and 250 kW_{DC}) and two technology types (crystalline and thin-film), resulting in six unique PV technology categories.

No rigid formula was used to develop a composite industry forecast of PV technical performance and cost characteristics.   Rather, all data were examined, and data that appeared to lie well outside norms were excluded. The remaining data were further examined and ICF forecasts were developed.

The characteristics described in this section correspond to a reference case scenario consistent with the assumptions used for the reference case described in the AEO 2010 report. The discussion of recommended reference case characteristics is organized as follows:

- Technical Performance
  - Module Efficiency
  - System Efficiency
  - Degradation
  - Lifetime
- Cost
  - Component Costs (including inverter)
  - Installed Capital
  - O&M

For reference, tables with selected results for the reference case are shown in **Appendix A** (crystalline technologies) and **Appendix B** (thin-film technologies). In these tables, and elsewhere in this report, costs are reported in 2008 dollars unless noted otherwise. Conversions between dollar years, if necessary, have been calculated using a gross domestic product (GDP) index shown in **Appendix C**.

5.1   Technical Performance

5.1.1 Module Efficiency

Module efficiencies are primarily dependent on the type of solar cell, and no significant efficiency differences are expected for different capacities. However, different efficiency curves are expected for crystalline and thin-film technologies.

To develop a forecast, ICF estimated values for module efficiency when installed in the year 2008, and then looked at potential upper limits. A range of module efficiencies were examined from manufacturers, industry experts, and research reports. Based on this review, ICF selected an average crystalline module efficiency in 2008 of 14%, and an average thin-film module efficiency of 10%. The analysis also suggested that a reasonable upper limit for crystalline modules is 20%, and a reasonable upper limit for thin-film is 14%.

Note that these module efficiencies are based on field performance, and not laboratory measurements. Laboratory measurements conducted at standard test conditions almost always exceed average field performance values.

Linear improvement rates were then developed to connect the starting values and end points. The improvement rates were adjusted by "eye" to achieve a smooth transition over time. The module efficiency forecast parameters are shown in **Table 12**, and the resulting values are shown in **Figure 10**.

Table 12.   Forecast Parameters, Module Efficiency

	PV Cell Technology	
	Crystalline	Thin-film
Starting Value (2008)	14% (0.140)	10% (0.100)
Annual Change	+0.005 thru 2018	+0.002 thru 2028
	+0.001 thru 2028	---
	no change after 2028	no change after 2028
Value in 2035	20%	14%
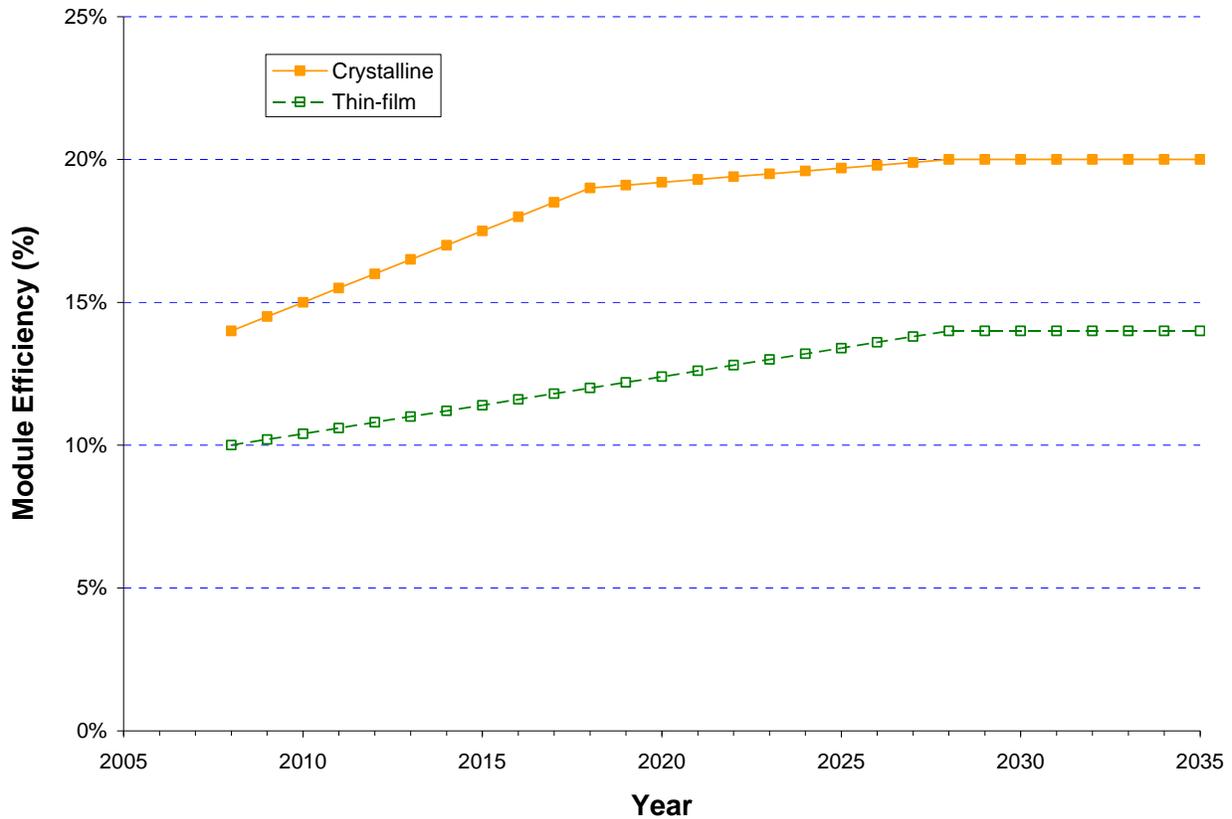
Figure 10.   Forecast, Module Efficiency, Reference Case

5.1.2 System Efficiency

The overall efficiency of a PV system is determined by several factors, including inverter losses, resistance of wires and connectors, soiling, and module mismatch.   While these factors affect all types of PV systems, there are also differences between PV system types. Residential inverters are smaller and therefore less efficient than commercial inverters, leading to generally lower system efficiencies in residential PV technologies (all other factors being equal).

Similar to module efficiencies, linear improvement rates were developed to connect starting values and end points. The improvement rates were adjusted to achieve a smooth transition over time. The system efficiency forecast parameters are shown in **Table 13**, and the resulting system efficiency curves are shown in **Figure 11**.

Table 13. **Forecast Parameters, System Efficiency**

	PV Cell Technology					
	Crystalline			Thin-film		
	5 kW	25 kW	250 kW	5 kW	25 kW	250 kW
Starting Value (2008)	78%	80%	82%	77%	79%	81%
Annual Change	+0.01 thru 2012			+0.01 thru 2012		
	+0.005 thru 2020			+0.005 thru 2022		
	no change after 2020			no change after 2022		
Value in 2035	86%	88%	90%	86%	88%	90%

As indicated, crystalline system efficiencies are expected to increase from levels in the range of 78% to 82% in 2008, to levels in the range of 86% to 90% in 2035. For thin-film technologies, the efficiencies increase from the range of 77% to 81% in 2008, to 86% to 90% by 2035 (same end point for thin film as crystalline).
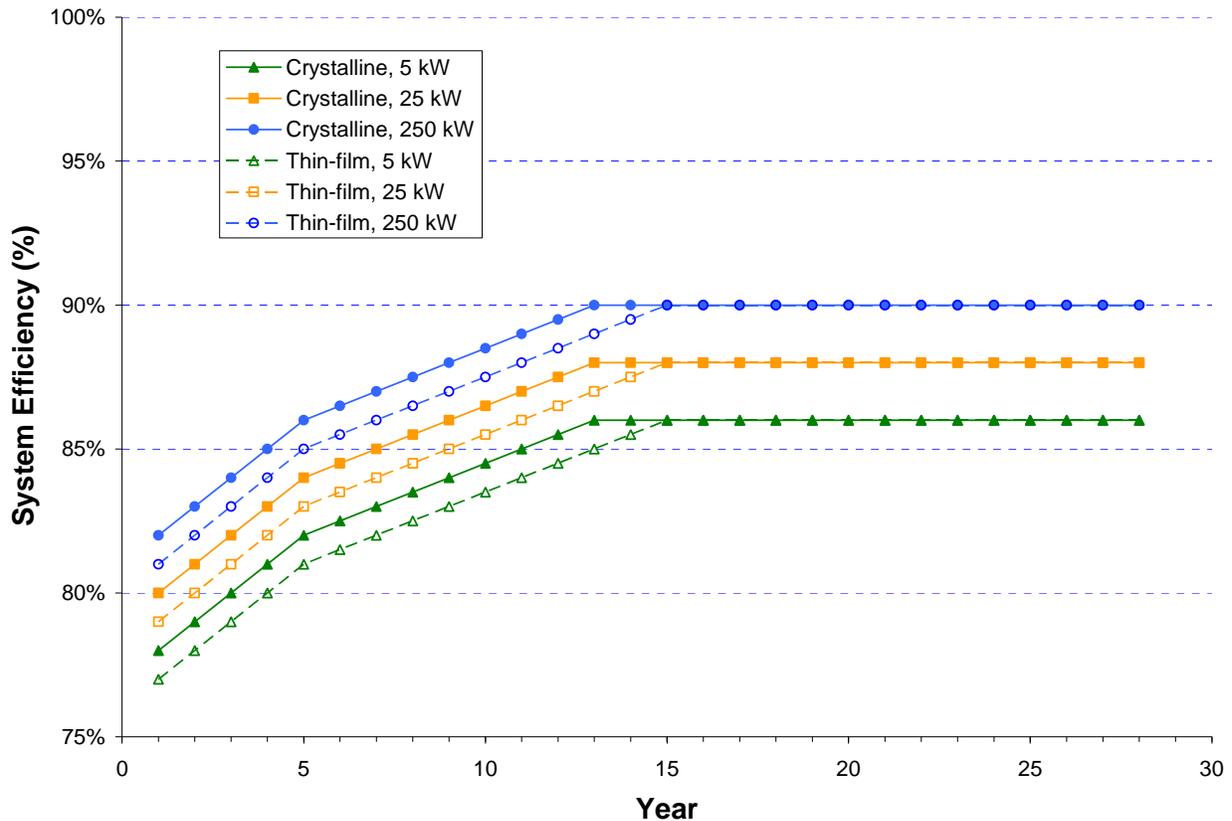
Figure 11. **Forecast, System Efficiency, Reference Case**

5.1.3 Degradation

PV modules typically lose capacity over time as a result of UV effects on construction materials and other aging factors. The rate at which modules lose capacity is debatable. However, based on sources consulted for this report ICF selected the starting values and annual change rates shown in **Table 14**. Based on these parameters, the resulting degradation curves are shown in **Figure 12**.

Table 14.   Forecast Parameters, Degradation (% per yr)

	PV Cell Technology	
	Crystalline	Thin-film
Starting Value (2008)	0.60% (0.0060)	1.00% (0.1000)
Annual Change	-0.0001 thru 2035	
Value in 2035	0.33%	0.73%
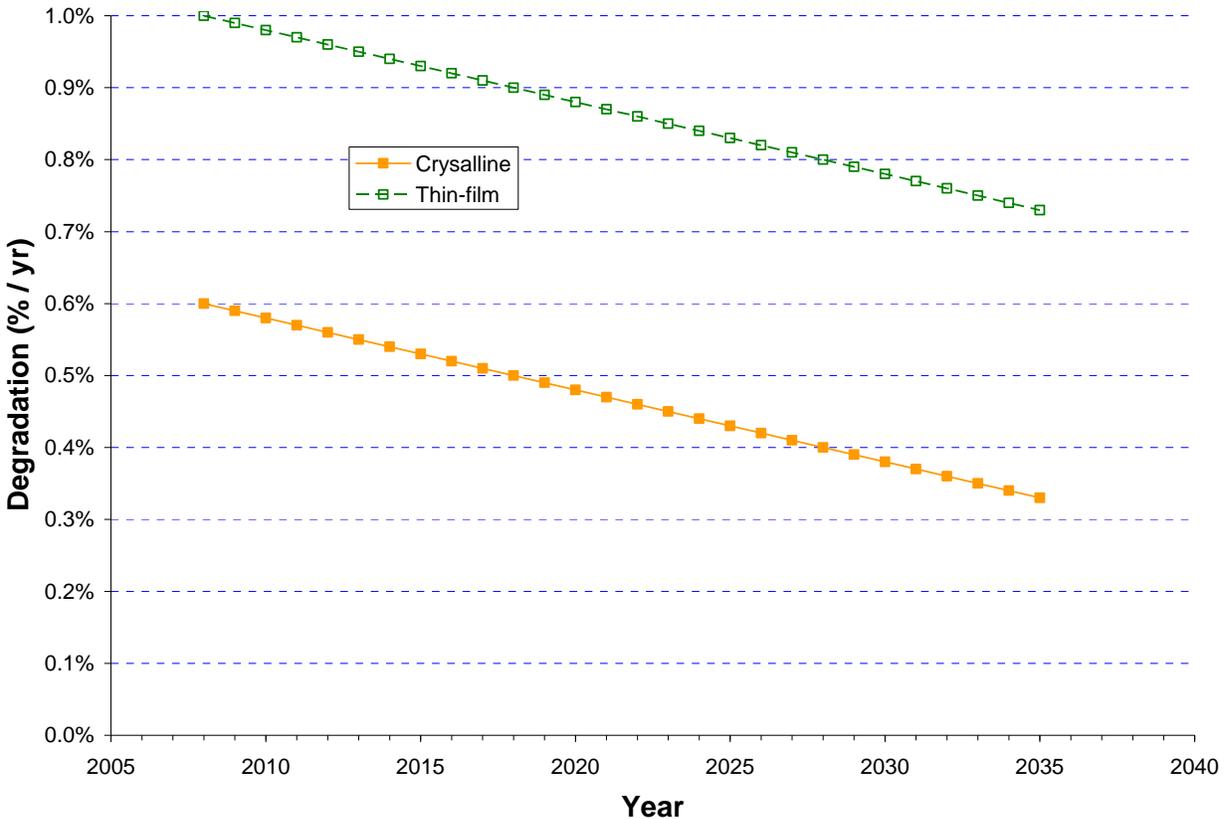
Figure 12.   Forecast, Degradation, Reference Case

In the ICF forecast, the degradation rate for crystalline technologies declines by about 45% between 2008 and 2035 (0.60% to 0.33%), and by about 27% for thin film technologies (1.00% to 0.73%).   Over the forecast horizon, thin-film degradation rates are held higher than crystalline technologies.

Thin-film technologies have a higher surface area than crystalline systems for equivalent rated capacity, and a higher surface area could contribute to higher degradation rates. However, in general, there are no fundamental reasons that thin-film systems should have higher degradation rates than crystalline systems. However, compared to crystalline technologies, there are fewer thin-film technologies currently being used in residential and commercial applications. The higher degradation rate for thin-film technologies is a conservative value based on a smaller data set with potentially unknown or not-well characterized degradation factors.

5.1.4 Lifetime

Thin-film technologies are relatively new, and there is little field experience data available to support lifetime projections. However, for forecasting purposes, ICF assumed that thin-film systems would follow similar lifetime trends as more mature crystalline technologies, but lag behind in terms of the time required to achieve these lifetime estimates. For crystalline technologies, ICF developed the forecasting parameters shown in **Table 15**. This table also shows the forecasting parameters developed for thin-film technologies and inverters.

Table 15.   Forecast Parameters, Module and Inverter Lifetime (yrs)

	PV Cell Technology		Inverter
	Crystalline	Thin-film	
Starting Value (2008)	25 yrs	20 yrs	10 yrs
Annual Change	+ 0.5 yrs thru 2018	+ 0.5 yrs thru 2018	+ 0.5 yrs thru 2018
	+ 0.5 yrs thru 2018	+ 0.5 yrs thru 2018	+ 0.5 yrs thru 2018
	no change after 2018	no change after 2028	no change after 2018
Value in 2035	30 yrs	30 yrs	15 yrs

Lifetime forecasts are shown in **Figure 13**. As indicated, the lifetime of thin-film modules is forecast to lag crystalline modules through 2028. From 2028 onward, the lifetime for both technologies is assumed to be 30 years. For forecasting purposes, ICF is estimating that average inverter lifetimes will start at 10 years in 2008, and increase to 15 years by 2018.
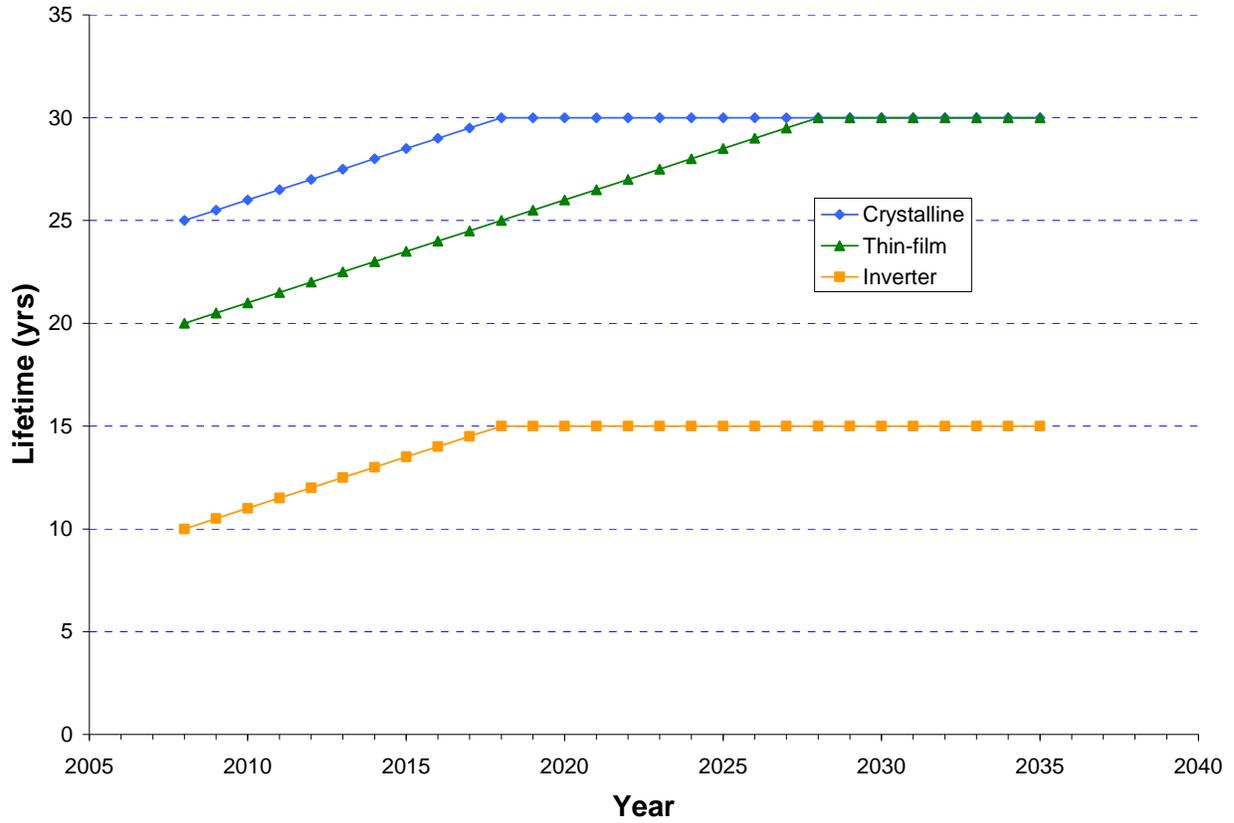
Figure 13.   Forecast, Module and Inverter Life, Reference Case

5.2 Cost

Long term cost projections for residential and commercial PV installations are scarce in the literature. However, industry stakeholders did provide opinions on long term cost trends. These opinions were combined with ICF in-house data to develop cost projections, which are provided in the following subsections:

- Component costs (including inverters)
- Installed capital costs
- O&M costs

5.2.1 Component Costs

For forecasting purposes, PV components were divided into three categories

- Module
- Inverter
- Other (installation labor, regulatory compliance, and overhead)

ICF set the starting point costs for inverters to be consistent with data reported in the LBNL *Tracking the Sun II* report (see **Figure 9**). These inverter starting point costs are shown in **Table 16**.

Table 16.   Starting Point Inverter Costs (2008$/kW$_{DC}$)

Cost by System Size ($/kW$_{DC}$) – same for crystalline and thin-film		
5 kW$_{DC}$	25 kW$_{DC}$	250 kW$_{DC}$
$700	$600	$500

Starting point costs for modules and other components (less the inverter) were combined and calculated by subtracting inverter costs from the total costs reported by LBNL for crystalline and thin-film technologies. These costs are shown in **Table 17**.

Table 17.   Starting Point Costs for Module Plus Other Components (2008$/kW$_{DC}$)

`	Cost by System Size ($/kW$_{DC}$)		
	5 kW$_{DC}$	25 kW$_{DC}$	250 kW$_{DC}$
Crystalline	$7,500	$7,300	$6,700
Thin-film	$7,800	$5,800	$6,200

Cost trends over time were then developed for modules and other components based on input from PV stakeholders and ICF in-house data. Module and other costs (less the inverter) were assumed to follow the same cost trend, which is shown in **Figure 14**.
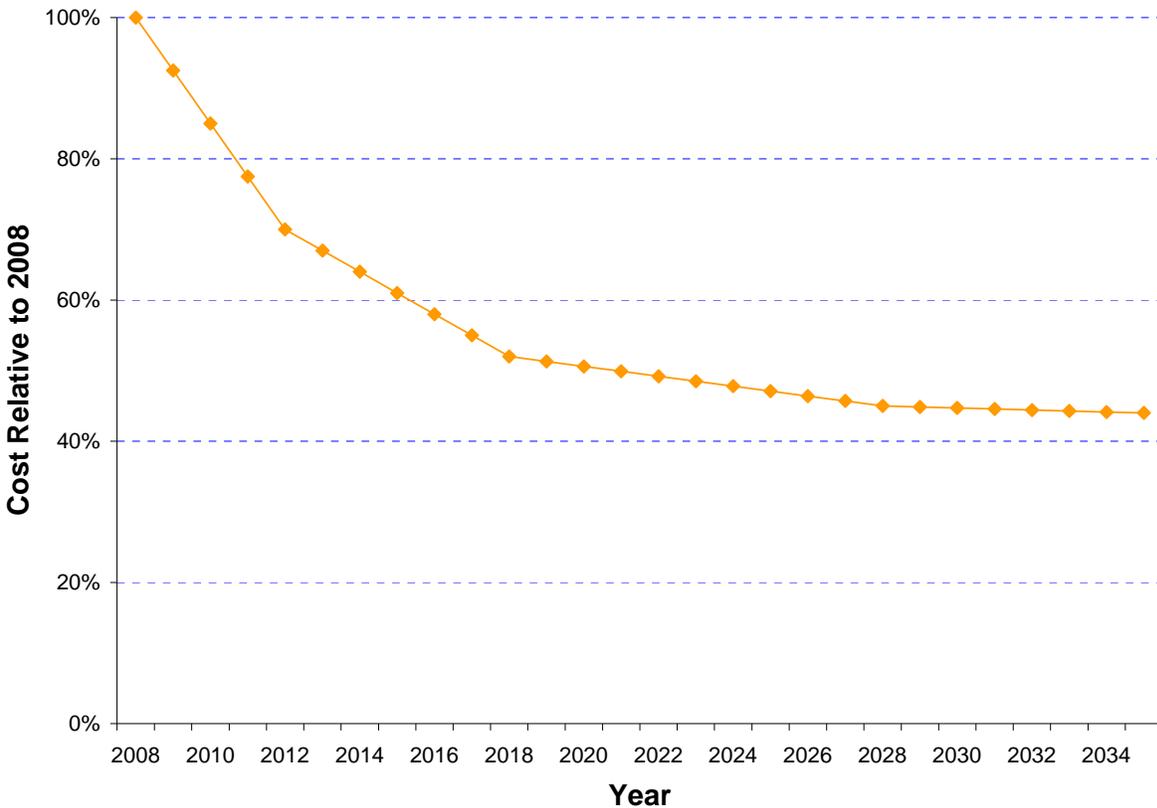
Figure 14.   Normalized Cost Trend for PV Modules and Other Components (does not apply to inverter)

Inverter costs presented somewhat of a dilemma. The technical performance of inverters is evolving (e.g., development of microinverters), but there is mixed information on whether inverter costs are declining or remaining steady. Some PV stakeholders suggested that inverter costs are remaining steady, although price declines have occurred in recent months.[8] ICF weighed the limited information available for inverter costs, and chose to forecast inverter costs as remaining unchanged in future years (same costs for crystalline and thin-film technologies). It is expected that inverter performance features will continue to advance, but for forecasting purposes ICF assumed that manufacturers will hold inverter prices relatively constant as inverter performance improves (i.e., inverter value will increase, but prices will remain steady).

An example of how the forecast costs for modules, inverters, and other components changes over time is shown in **Figure 15**. This figure corresponds to a 5 kW$_{DC}$ crystalline PV system. As indicated, costs start at \$8,200/kW$_{DC}$ (\$700 inverter plus \$7,500 for module and other components) in 2008, with inverters accounting for 9% of the installed cost. Inverters remain flat over the forecast horizon, while module and

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[8] Solarbuzz provides an index of monthly inverter and PV module costs (http://www.solarbuzz.com/Inverterprices.htm).

other components decline. By 2035, the total installed cost is forecast to decline to $4,000/kW_{DC} with inverters accounting for 18% of the total installed cost. Similar behavior is forecast for thin film technologies and larger sizes (25 kW_{DC} and 250 kW_{DC}).
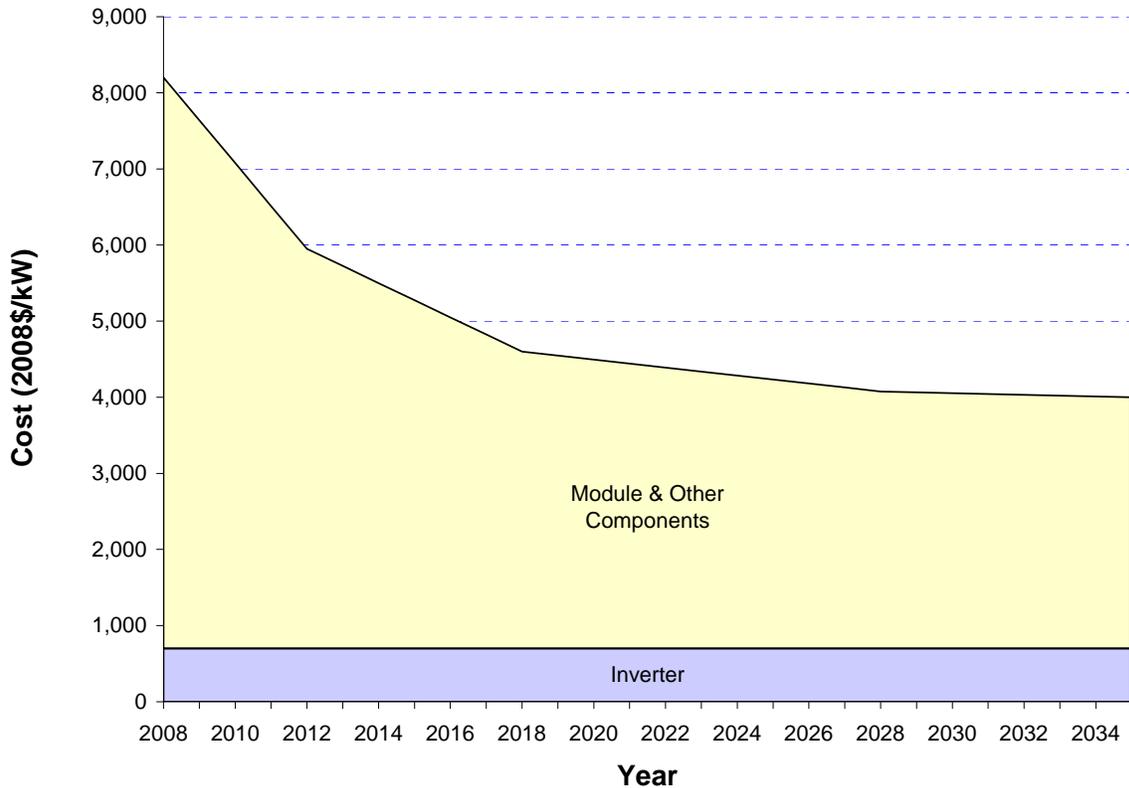
Figure 15.   Cost Projection for 5 kW_{DC} Crystalline System

5.2.2 Installed Capital Costs

Using the methodology described in the previous section, installed capital cost forecasts were developed for crystalline and thin-film technologies. Reference case cost projections for three sizes (5, 25, and 250 kW_{DC}) of crystalline technologies are shown in **Figure 16**, and cost projections for the same three sizes of thin-film technologies are shown in **Figure 17**. Unless noted otherwise, all costs are reported in 2008 dollars.

As indicated, installed capital costs for all three crystalline sizes start in the range of $7,000 to slightly greater than $8,000/kW_{DC} in 2008, and then decline to a range between $3,500 and $4,000/kW_{DC} in 2035. For thin film technologies, the 5 kW_{DC} size starts at approximately $8,500/kW_{DC} in 2008 and declines to slightly above $4,000/kW_{DC} in 2035. The larger 25 and 250 kW_{DC} sizes start near $6,500/kW_{DC} in 2008, and decline to slightly above $3,000/kW_{DC} in 2035.
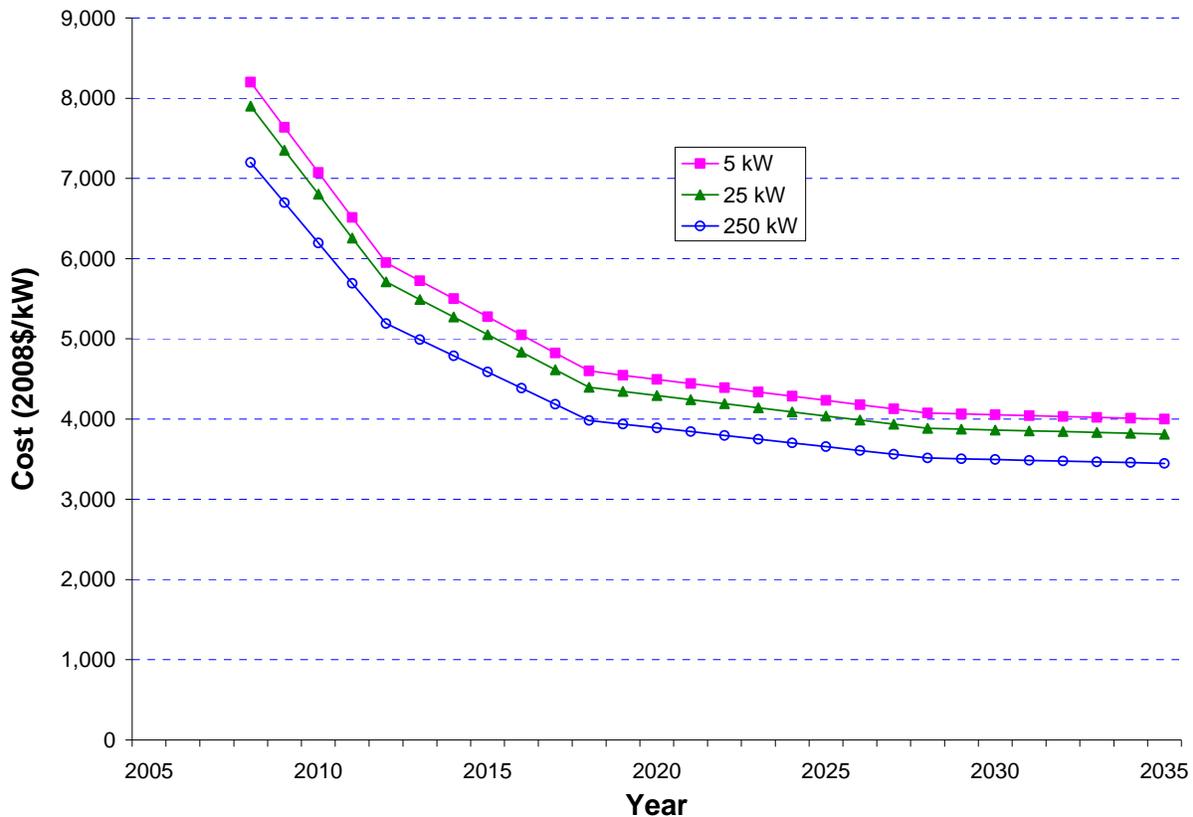
Figure 16.   Recommended Crystalline Installed Costs, Reference Case

One unexpected result shown in **Figure 17** is that costs for a 250 kW_{DC} thin-film system are forecast to be slightly higher than a 25 kW_{DC} system. Based on economy of scale considerations, one would expect costs for a 250 kW_{DC} system to be lower than a 25 kW_{DC} system. However, these forecasts are consistent with historical costs, which do show an up turn in costs for large thin film PV systems. Historical PV costs are discussed in Section 4.1, and this discussion includes an important note concerning thin-film costs. As mentioned in Section 4.1, historical thin-film costs should be viewed with caution because these costs are based on a small sample size. It would not be surprising if future thin-film costs follow economy of scale considerations (i.e., costs decline as capacities increase).
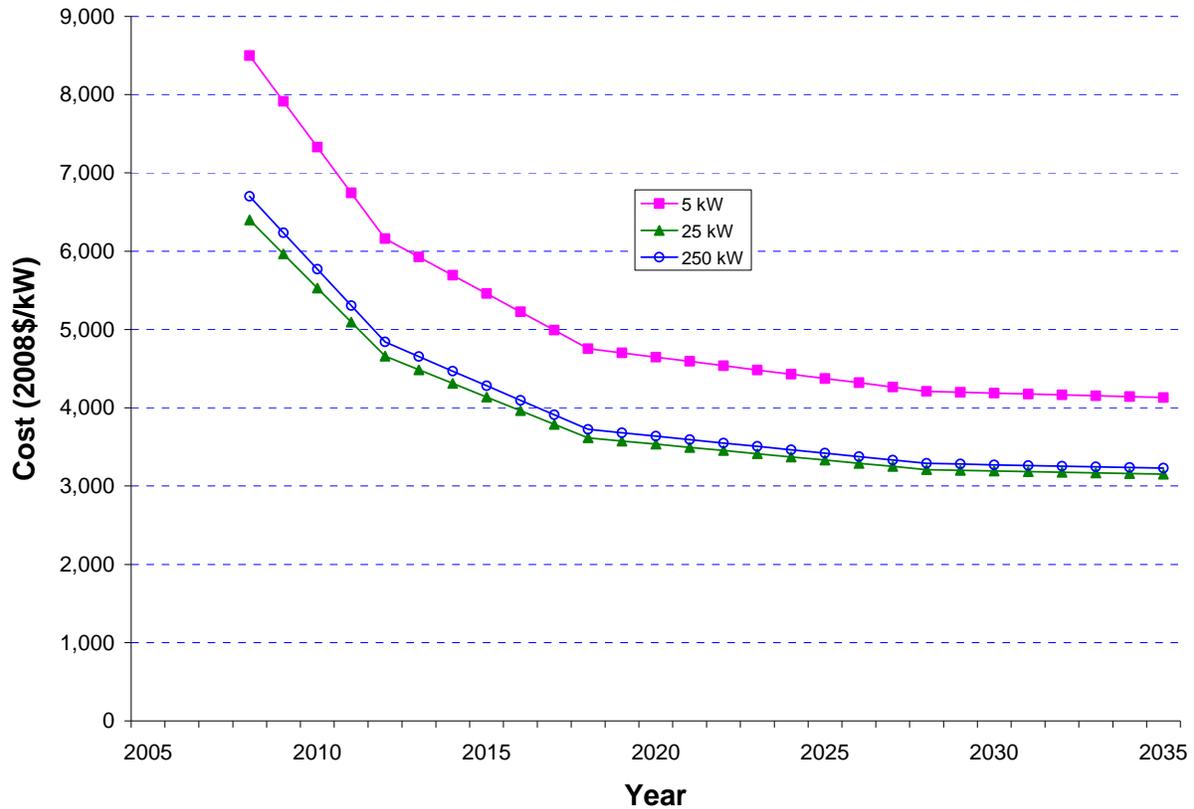
Figure 17.   Recommended Thin-film Installed Costs, Reference Case

Figure 18 offers a perspective of how the forecast PV costs correspond to residential applications. In this figure, 5 kW$_{DC}$ crystalline and 5 kW$_{DC}$ thin-film costs are shown, which are representative of the residential market. As indicated, costs start in the range of $8,000 to $8,500/kW$_{DC}$ in 2008, and then decline to approximately $4,000/kW$_{DC}$ by 2035. More specifically, costs are approximately $7,100 (crystalline) and $7,300 (thin-film) in 2010. These costs fall to approximately $4,000/kW$_{DC}$ (crystalline) and $4,100/kW$_{DC}$ (thin-film) by 2035.
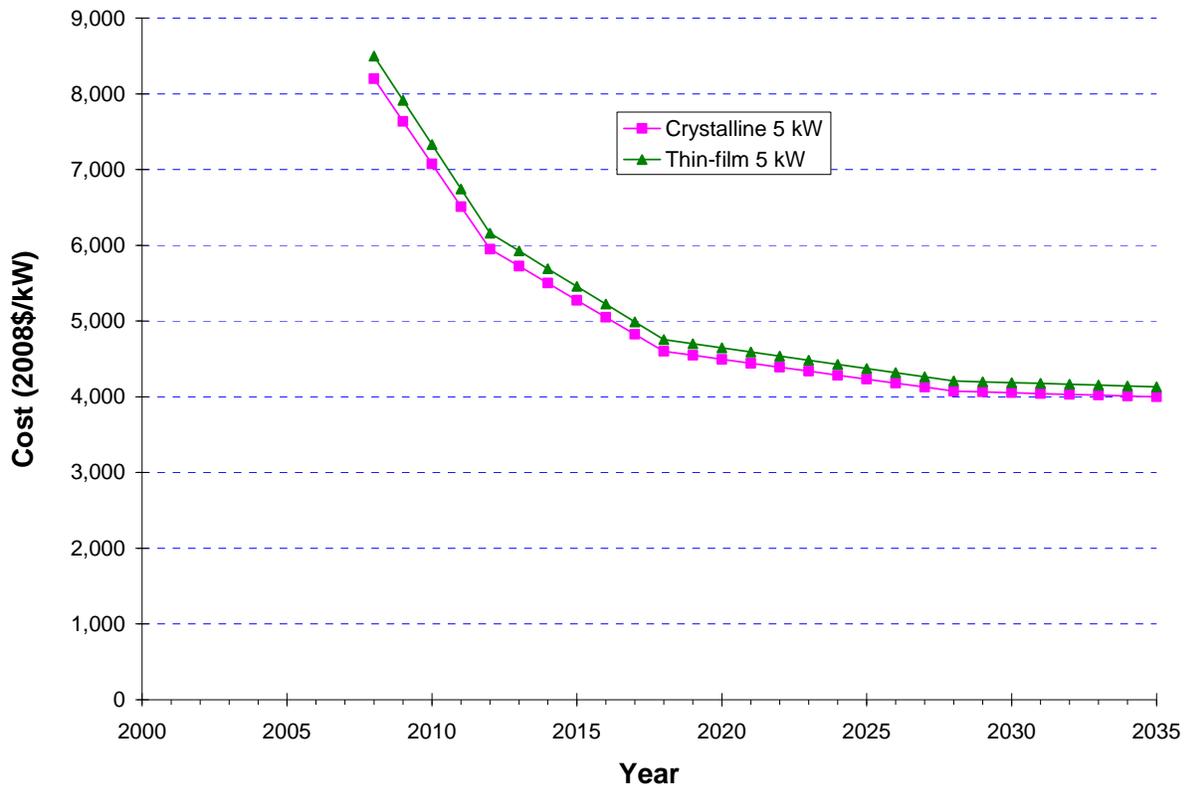
Figure 18.   Residential Installed Capital Costs, Reference Case

Figure 19 includes both historical residential PV installed costs along with recommended residential costs. Historical costs have fluctuated, but the trend over the next 5-10 years in recommended PV costs is generally consistent with historical cost trends over the past decade. As the market matures, PV costs begin to stabilize and decline at lower rates.
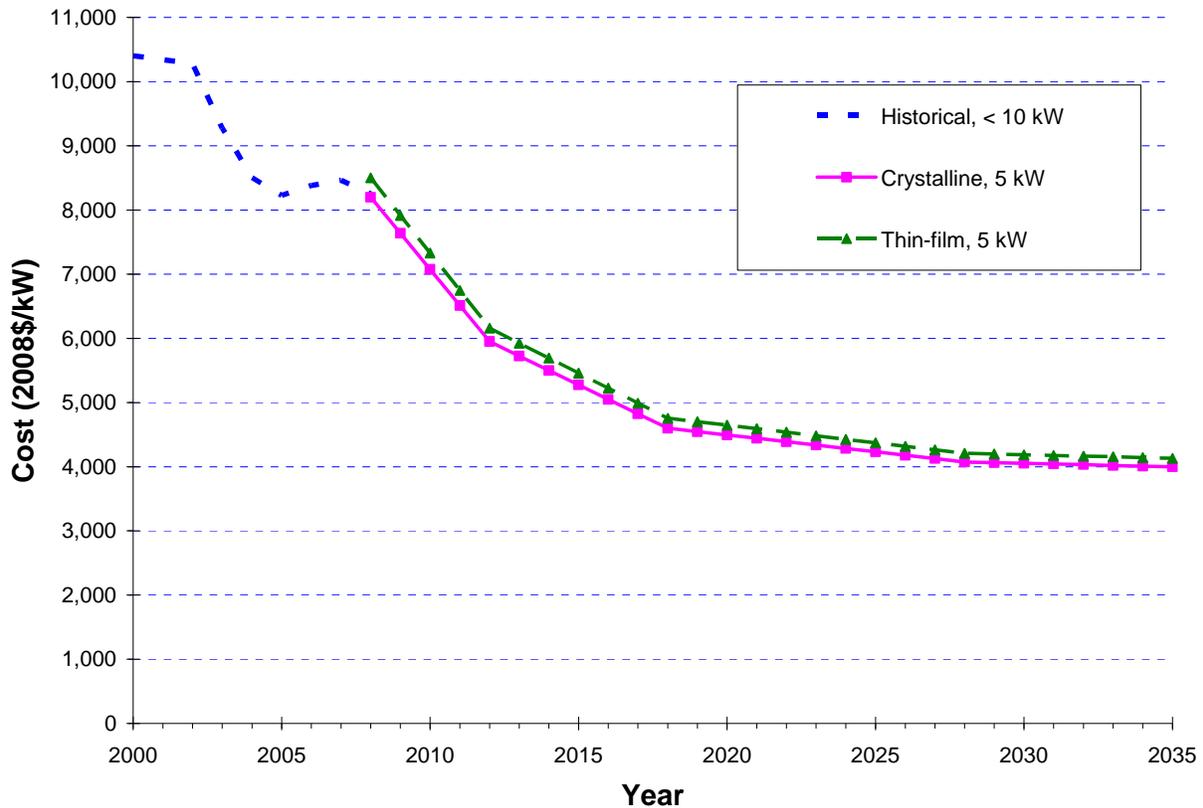
Figure 19.   Historical and Forecast Residential Capital Costs

Recommended commercial capital costs are shown in **Figure 20**. This figure includes recommended forecast values for four technologies (crystalline 25 kW_{DC}, crystalline 250 kW_{DC}, thin-film 25 kW_{DC}, and thin-film 250 kW_{DC}). As indicated, installed costs for commercial PV installations range from approximately \$6,500 to \$8,000/kW_{DC} in 2008, and then decline to a range between \$3,000 and \$4,000/kW_{DC} in 2035. More specifically, commercial costs in 2010 are approximately \$5,500/kW_{DC} (thin-film, 25kW_{DC}), \$5,800/kW_{DC} (thin-film, 250 kW_{DC}), \$6,200/kW_{DC} (crystalline, 250 kW_{DC}), and \$6,800 (crystalline, 25 kW_{DC}). In 2035, the costs are approximately \$3,200/kW_{DC} (thin-film, 25 kW_{DC} and 250 kW_{DC}), \$3,500/kW_{DC} (crystalline, 250 kW_{DC}), and \$3,800/kW_{DC} (crystalline, 25 kW_{DC})

For perspective, historical and forecast trends are shown in **Figure 21**. Similar to the residential results, historical cost trends have fluctuated, but the recommended cost trends over the next 5-10 years are generally consistent with historical trends. Similar to residential prices, the commercial prices begin to stabilize as the market matures.
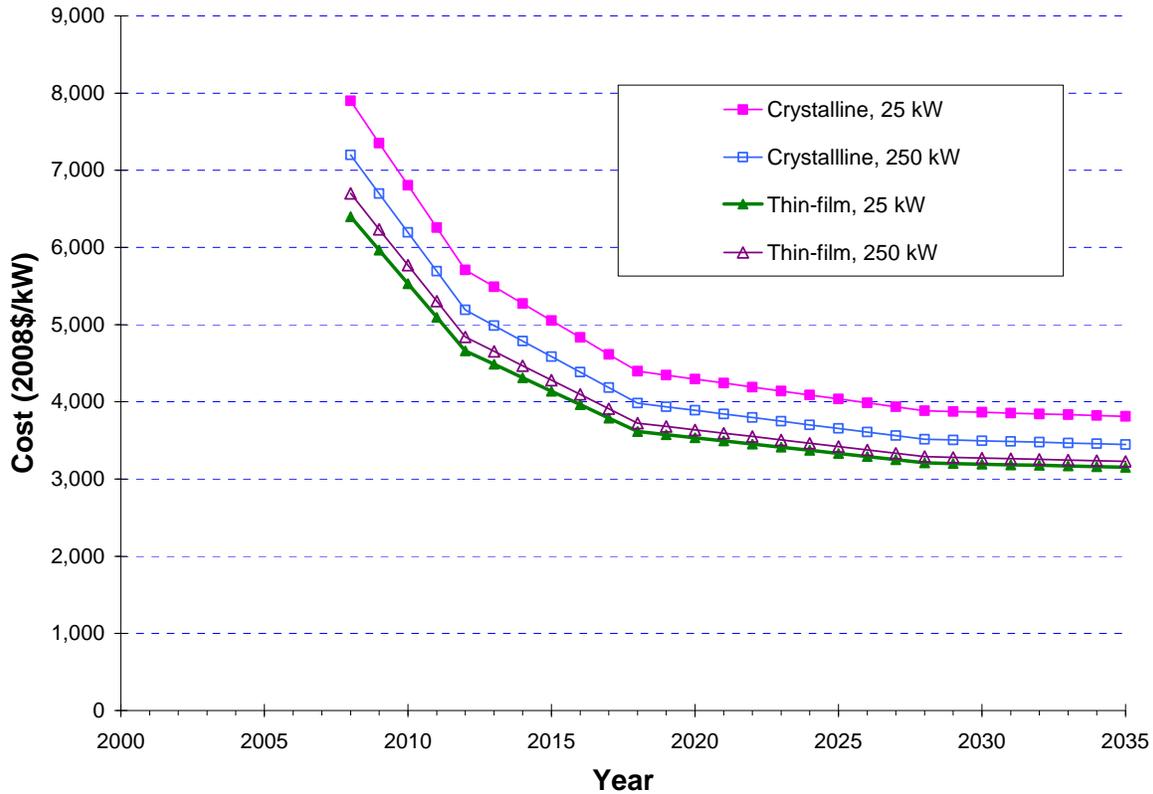
Figure 20.   Commercial Installed Capital Costs, Reference Case
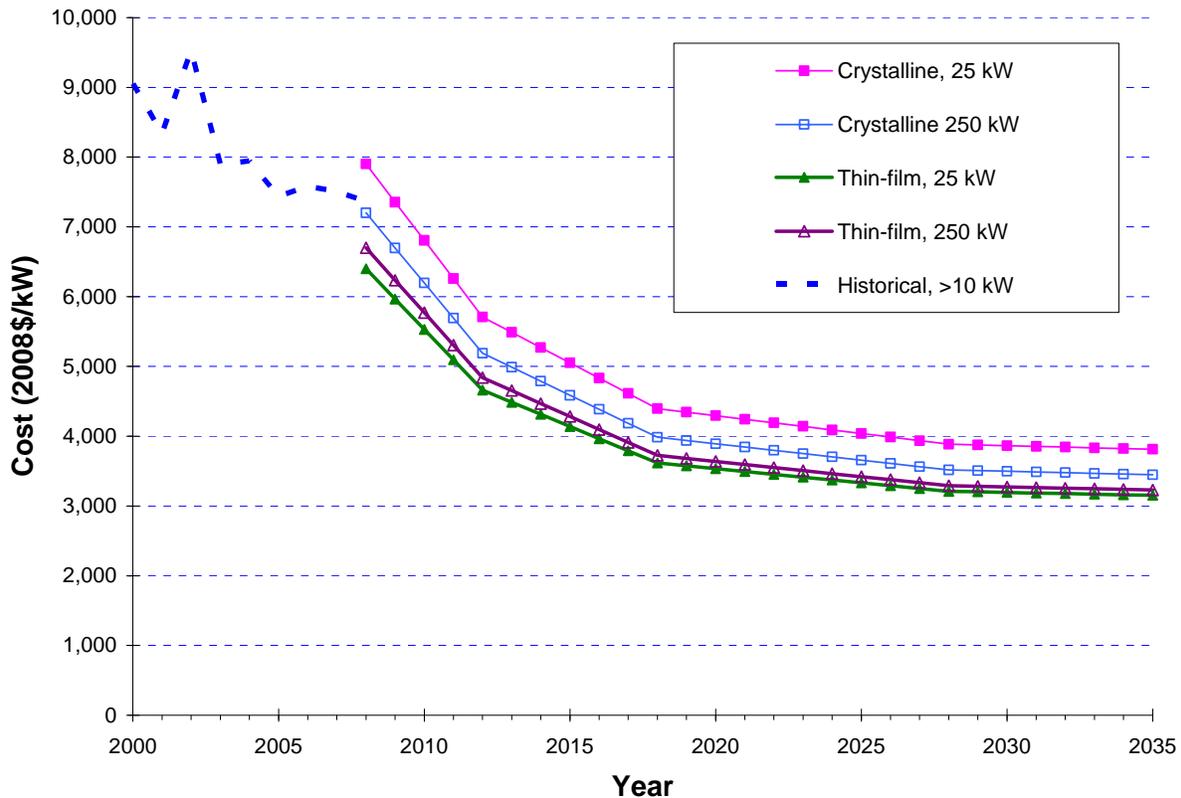
Figure 21.   Historical and Forecast Commercial Capital Costs

The forecast of installed capital costs presented in this report was developed based on opinions from PV stakeholders and other data sources concerning how costs may change over the next couple decades. The forecast was not developed in conjunction with a detailed demand forecast. While demand was not formerly considered, it is interesting to consider how the installed capital costs projected in this report might be correlated with a demand forecast.

Concerning the relationship of demand and PV costs, a recent EPRI report (EPRI 2009) presented data showing the global average sales price of PV modules as a function of cumulative sales between 1976 and 2008. During this time period, the market size grew by approximately a factor of 100,000 and prices fell by more than 90%. Based on the historical data, the EPRI report authors concluded that prices have been declining by about 20% in recent years for each doubling of market size (i.e., learning rate of 20%). The authors also concluded that the PV market has been growing by about 20% per year in recent years.

The ICF forecast of installed capital costs turns out to be more conservative compared to the results reported by EPRI. In rough terms, the ICF forecast shows a reduction of installed capital costs of approximately 50% between 2008 and 2035. This installed cost behavior is consistent with a learning rate of 12%, and an annual growth rate of

15%. The EPRI estimates suggest that learning rates and annual growth rates may both be closer to 20% over the next two to three decades.

5.2.3 O&M

For the purposes of this report, operation and maintenance (O&M) costs are assumed to include regular inspection and cleaning. Major maintenance requirements, such as replacing an inverter, are not included.

For PV systems, routine O&M consists primarily of washing the solar panels to ensure that electricity production is maximized. In both residential and commercial applications, it is possible that systems will not be properly maintained, including periodic washing of PV panels, in which case degradation rates will likely exceed the values reported previously in this report. However, for forecasting purposes, it is assumed that both residential and commercial PV installations will be properly maintained.

In the case of a commercial PV installation, it is reasonable to assume that a maintenance contract will be used to cover O&M. Maintenance contracts for basic service of commercial systems have been reported by SunEdison and others to be in the range of $15/kW to $25/kW (costs generally declining as system size increases).

For a residential PV installation, it is likely that a homeowner will take a "do it yourself" (DIY) approach for system inspection and cleaning. Even though a cash expense is not incurred for a DIY approach, the homeowner does incur an expense in terms of time required to complete PV system O&M. In some residential applications, it is possible that homeowners will choose to pay for routine PV inspection and cleaning, rather than undertaking these chores. In the forecast presented in this report, an O&M cost is assigned to residential PV installations to reflect the value of time for a DIY approach, or the cost of an O&M contract.

The O&M forecast was developed by starting with a $20/kW O&M cost for a 25 kW crystalline system. Costs were scaled by +/- 20% based on size (5 kW more expensive, 250 kW less expensive). It was further assumed that O&M will scale with surface area, since O&M is primarily associated with panel cleaning. O&M costs were therefore scaled using the module efficiencies discussed previously. A summary of the forecast parameters is shown in **Table 18**, and a graph of the O&M costs over time is shown in **Figure 22**.

Table 18. **Forecast Parameters, O&M Costs, (2008$ / kW$_{DC}$ / yr)**

	PV Cell Technology					
	Crystalline			Thin-film		
	5 kW$_{DC}$	25 kW$_{DC}$	250 kW$_{DC}$	5 kW$_{DC}$	25 kW$_{DC}$	250 kW$_{DC}$
Starting Value (2008)	$24.00 (20% more than 25 kW)	$20.00	$16.00 (20% less than 25 kW)	$33.60	$28.00	$22.40
Annual Change	Adjust based on module efficiency (see **Table 12** and **Figure 10**)					
Value in 2035	$16.80	$14.00	$11.20	$24.00	$20.00	$16.00

As indicated, the forecast is for crystalline O&M costs to decline 30% between 2008 and 2035, reaching levels in the range of $11.20/ kW$_{DC}$ to $$16.80/kW$_{DC}$ (costs decline as size increases). For thin-film, costs decline 29%, reaching levels in the range of $16.00/kW$_{DC}$ to $24.80/kW$_{DC}$ by 2035.
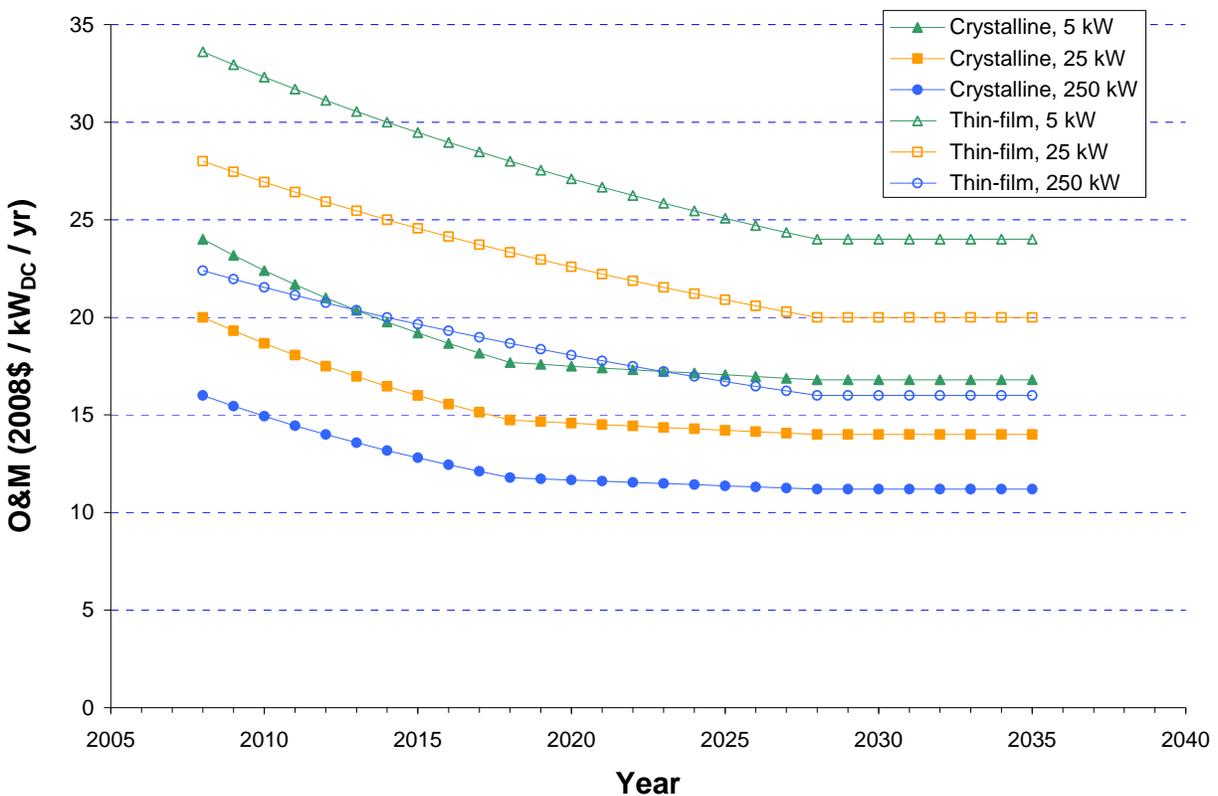
Figure 22. **Recommended O&M Costs, Reference Case**

6. Forecast of PV Characteristics – Advanced Case

In this section, PV characteristics for an advanced scenario are described. The rationale for the advanced case is that additional R&D investments will drive a high degree of technology innovation and accelerated cost improvements. In an advanced scenario, both technical characteristics and cost would be expected to improve compared with the reference case. However, as an initial step, the advanced case discussion in this section is focused on accelerated reductions in capital costs.

As a first step, a cost trend curve was developed for an advanced case. This cost trend is shown in **Figure 23**.
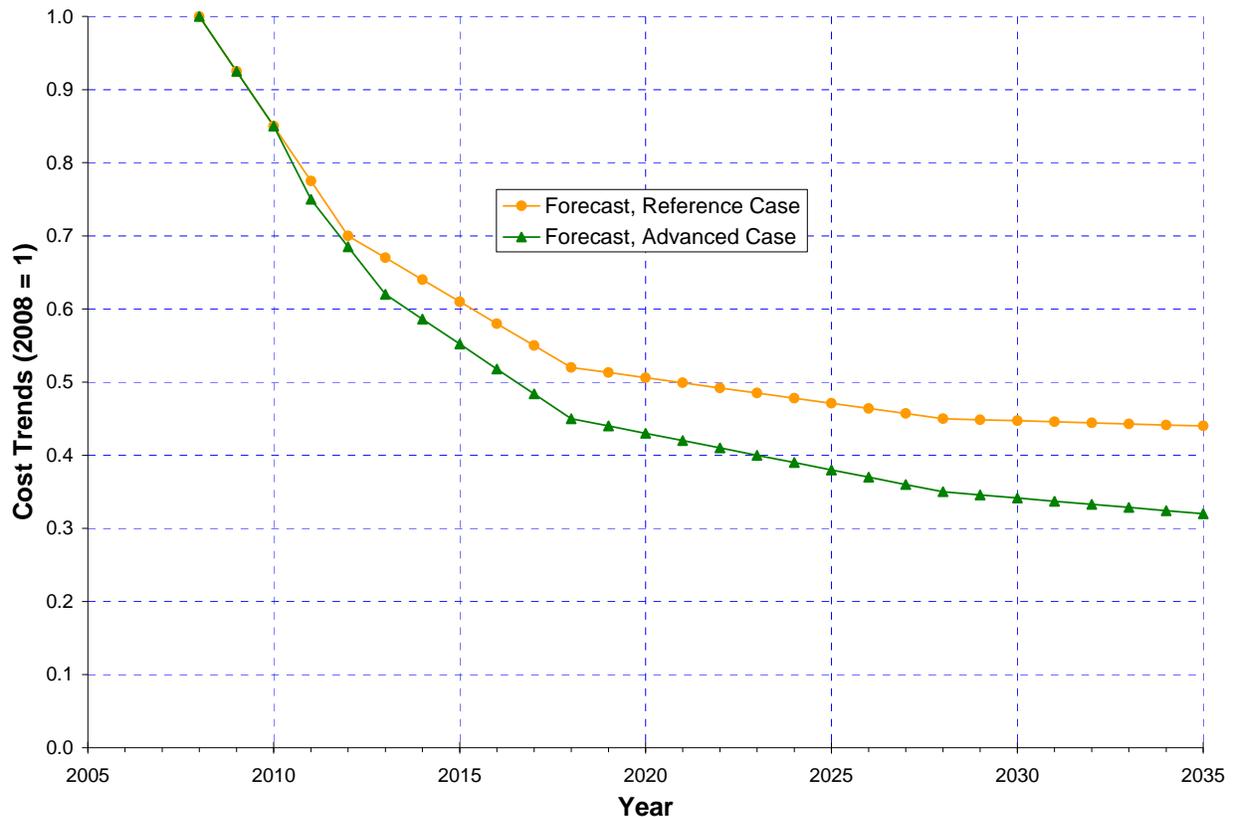
Figure 23. Cost Trends for Reference Case and Advanced Case

Using the advanced case cost trend, the expected costs for crystalline and thin film technologies were computed. The crystalline costs are shown in **Table 19**, and the thin-film costs are shown in **Table 20**. As discussed in greater detail in Section 5.2.2, thin-film costs appear to show a dis-economy of scale between 25 and 250 kW, which may be an artifact of a small sample size.

Table 19. Crystalline Costs, Reference and Advanced Cases

Year	Cost (2008$ / kW$_{DC}$)								
	5 kW$_{DC}$			25 kW$_{DC}$			250 kW$_{DC}$		
	Ref Case	Adv Case	Change	Ref Case	Adv Case	Change	Ref Case	Adv Case	Change
2010	$7,075	$7,075	0.0%	$6,805	$6,805	0.0%	$6,195	$6,195	0.0%
2015	$5,275	$4,773	9.5%	$5,053	$4,573	9.5%	$4,587	$4,151	9.5%
2020	$4,495	$3,820	15.0%	$4,294	$3,649	15.0%	$3,890	$3,306	15.0%
2025	$4,233	$3,415	19.3%	$4,038	$3,258	19.3%	$3,656	$2,949	19.3%
2030	$4,054	$3,095	23.6%	$3,864	$2,951	23.6%	$3,496	$2,669	23.6%
2035	$4,000	$2,909	27.3%	$3,812	$2,772	27.3%	$3,448	$2,508	27.3%

Table 20. Thin-film Costs, Reference and Advanced Cases

Year	Cost (2008$ / kW$_{DC}$)								
	5 kW$_{DC}$			25 kW$_{DC}$			250 kW$_{DC}$		
	Ref Case	Adv Case	Change	Ref Case	Adv Case	Change	Ref Case	Adv Case	Change
2010	$7,330	$7,330	0.0%	$5,530	$5,530	0.0%	$5,770	$5,770	0.0%
2015	$5,458	$4,939	9.5%	$4,138	$3,745	9.5%	$4,282	$3,875	9.5%
2020	$4,647	$3,949	15.0%	$3,535	$3,004	15.0%	$3,637	$3,091	15.0%
2025	$4,374	$3,529	19.3%	$3,332	$2,688	19.3%	$3,420	$2,759	19.3%
2030	$4,188	$3,198	23.6%	$3,193	$2,438	23.6%	$3,272	$2,499	23.6%
2035	$4,132	$3,005	27.3%	$3,152	$2,292	27.3%	$3,228	$2,348	27.3%

In the advanced scenario, installed capital costs begin diverging from the reference case in 2011, and fall approximately 27% below reference case values by 2035. In the advanced scenario, costs for all components, including the inverter, are reduced at the same rate relative to the reference case.

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Appendix A.   Recommended Characteristics, Crystalline PV, Reference Case

5 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	15.0%	80%	0.58%	26	11	$7,075	$700	$22.40
2015	17.5%	84%	0.53%	29	14	$5,275	$700	$19.20
2020	19.2%	86%	0.48%	30	15	$4,495	$700	$17.50
2025	19.7%	86%	0.43%	30	15	$4,233	$700	$17.06
2030	20.0%	86%	0.38%	30	15	$4,054	$700	$16.80
2035	20.0%	86%	0.33%	30	15	$4,000	$700	$16.80

25 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	15.0%	82%	0.58%	26	11	$6,805	$600	$18.67
2015	17.5%	86%	0.53%	29	14	$5,053	$600	$16.00
2020	19.2%	88%	0.48%	30	15	$4,294	$600	$14.58
2025	19.7%	88%	0.43%	30	15	$4,038	$600	$14.21
2030	20.0%	88%	0.38%	30	15	$3,864	$600	$14.00
2035	20.0%	88%	0.33%	30	15	$3,812	$600	$14.00

250 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	15.0%	84%	0.58%	26	11	$6,195	$500	$14.93
2015	17.5%	88%	0.53%	29	14	$4,587	$500	$12.80
2020	19.2%	90%	0.48%	30	15	$3,890	$500	$11.67
2025	19.7%	90%	0.43%	30	15	$3,656	$500	$11.37
2030	20.0%	90%	0.38%	30	15	$3,496	$500	$11.20
2035	20.0%	90%	0.33%	30	15	$3,448	$500	$11.20

Appendix B. Recommended Characteristics, Thin-film PV, Reference Case

5 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	10.4%	79%	0.98%	26	11	$7,330	$700	$32.31
2015	11.4%	83%	0.93%	29	14	$5,458	$700	$29.47
2020	12.4%	85%	0.88%	30	15	$4,647	$700	$27.10
2025	13.4%	86%	0.83%	30	15	$4,374	$700	$25.07
2030	14.0%	86%	0.78%	30	15	$4,188	$700	$24.00
2035	14.0%	86%	0.73%	30	15	$4,132	$700	$24.00

25 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	10.4%	81%	0.98%	26	11	$5,530	$600	$26.92
2015	11.4%	85%	0.93%	29	14	$4,138	$600	$24.56
2020	12.4%	87%	0.88%	30	15	$3,535	$600	$22.58
2025	13.4%	88%	0.83%	30	15	$3,332	$600	$20.90
2030	14.0%	88%	0.78%	30	15	$3,193	$600	$20.00
2035	14.0%	88%	0.73%	30	15	$3,152	$600	$20.00

250 kW$_{DC}$

Year	Module Efficiency (%)	System Efficiency	Degradation	System Life	Inverter Life	Installed Capital Costs (2008$/kW$_{DC}$)	Inverter Cost (2008$/kW$_{DC}$)	O&M Costs (2008$ / kW$_{DC}$ / yr)
2010	10.4%	83%	0.98%	26	11	$5,770	$500	$21.54
2015	11.4%	87%	0.93%	29	14	$4,282	$500	$19.65
2020	12.4%	89%	0.88%	30	15	$3,637	$500	$18.06
2025	13.4%	90%	0.83%	30	15	$3,420	$500	$16.72
2030	14.0%	90%	0.78%	30	15	$3,272	$500	$16.00
2035	14.0%	90%	0.73%	30	15	$3,228	$500	$16.00

Appendix C.   GDP Implicit Price Deflator Index
(Year 2005 = 1)

Year	GDP Index
1990	0.72201
1991	0.74760
1992	0.76533
1993	0.78224
1994	0.79872
1995	0.81536
1996	0.83088
1997	0.84555
1998	0.85511
1999	0.86768
2000	0.88647
2001	0.90650
2002	0.92118
2003	0.94100
2004	0.96770
2005	1.00000
2006	1.03257
2007	1.06214
2008	1.08483
2009	1.09777
2010	1.11100

Source: *1990 through 2009 data from U.S. Department of Commerce, Bureau of Economic Analysis. The 2010 value is from EIA's January 2010 Short-term Energy Outlook.*

The GDP Implicit Price Deflator index is used in this report to convert costs in constant dollars between different basis years. For example, to convert costs that are expressed in 2005 dollars to 2008 dollars, multiply the 2005 values by 1.08483 (1.08483 / 1.00000).