NREL/TP.620.29649
June 2001

Factors Associated with Photovoltaic System Costs

John Mortensen, National Renewable Energy Laboratory

National Renewable Energy Laboratory
A national laboratory of the U.S. Department of Energy

The Topical Issues Brief series is sponsored by
DOE's Office of Energy Efficiency and Renewable Energy
Office of Power Technologies

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

 Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

NREL/TP.620.29649
June 2001

Factors Associated with Photovoltaic System Costs

John Mortensen, National Renewable Energy Laboratory

National Renewable Energy Laboratory
A national laboratory of the U.S. Department of Energy

The Topical Issues Brief series is sponsored by
DOE's Office of Energy Efficiency and Renewable Energy
Office of Power Technologies

Contents

Tables

Figures

Acknowledgments

I thank the U.S. Department of Energy's Office of Power Technologies, in the Office of Energy Efficiency and Renewable Energy, for funding this analysis. Lynne Gillette and Tina Kaarsberg of the Office of Power Technologies, Tom Surek, Christy Herig, Terri Walters, and Larry Goldstein of the National Renewable Energy Laboratory provided numerous helpful comments on the draft report. I also thank Nancy Wells for her editorial review. Any remaining shortcomings are, of course, my own.

Abstract

A variety of factors affect the cost of photovoltaic (PV) systems, including whether the system is connected to the grid, its size, year of installation, and whether any policies are in place that reduce its cost. This report analyzes the relationship among such factors using information entered into a voluntary registry of PV systems.

A regression analysis of 278 systems installed from June 1997 to September 2000 showed statistically significant relationships between photovoltaic system cost and (a) grid connection, (b) installation year, (c) areas where the local utility had entered into volume purchasing agreements with PV suppliers (i.e., in this report, the Sacramento Municipal Utility District [SMUD]).

- Grid connection had the largest effect on system cost. Grid-connected systems cost about $4,800/kW less than non-grid-connected systems.
- Location in SMUD had the next largest effect. Systems in SMUD cost $3,900/kW less than systems outside SMUD.
- Year of installation had a moderate effect. With each additional year that passed, system costs were reduced by almost $600/kW.
- Size had the least influence and was not statistically significant. System costs decreased by $40/kW with each additional kW increase in system size.
- The 47% of the variance that was explained by these factors might be improved by including additional information on whether a tracking system was used, the cell type being used, whether the system is integrated into the building, and other factors.

Factors Associated with Photovoltaic System Costs

Introduction

A variety of factors affect the cost of photovoltaic (PV) systems, including the characteristics of the PV system, the year in which it was installed, and whether any policies were in place to reduce its cost. This report analyzes whether such factors were related to the cost of 278 PV systems installed from 1997 to 2000. Specific factors that were analyzed included whether the system was connected to the grid; system size; year of installation; and whether volume purchasing agreements, aimed at reducing system costs through economies of scale, were in place in the area in which the system was located.

Data were obtained from a voluntary registry of solar installations in the United States. The following information was entered into the registry by solar energy system providers, who in turn received recognition for their systems: PV system cost (in current dollars), size (in kW), grid connection (yes/no), building type (residential, commercial, schools, churches or places of worship, institutional, and other institutional), geographic location of the system, and installation date.

As of October 2000, the registry contained records on 817 PV systems installed from June 1997 through September 2000. Of these, 278 contained complete information on system cost, size, location, date of installation, grid connection, and building type.[1]

Some transformations of the registry data were necessary to foster the analysis. Installed cost was converted to real dollars and then divided by system size in kilowatts to account for inflation and cost variations due to system size. All cost figures cited in this report are in 1997 dollars per kW (1997$/kW), rounded to the nearest $100/kW. The cost for some systems was adjusted to exclude the effect of buy-down programs. Installation dates were converted to years and cover the period from 1997 to 2000. The location of the system was used to identify whether the system was located within the Sacramento Municipal Utility District (SMUD), where volume purchasing agreements are in place.

The following relationship hypotheses were explored:

(1) System costs would be lower for grid-connected systems than for non-grid-connected systems (because energy storage systems were not required)

(2) Systems costs would be lower where volume purchasing agreements were in place (due to economies of scale)

(3) System costs would decline over time (due to technological and manufacturing advances)

(4) System costs would decrease with increases in system sizes (due to the relatively smaller size of the inverter).

Regression analysis on the 278 systems showed that system cost was significantly associated with grid connection, installation year, and the presence of volume purchasing agreements in the manner hypothesized. System cost was not significantly associated with size. The magnitude of the associations is discussed on the following pages.

[1] Of the 817 PV systems in the registry, 783 had data on system size, 420 had data on grid connection, 316 had data on cost, and all had data on installation year and location. Some systems had missing data for multiple fields, reducing the total sample size to 278.

Cost vs. Grid Connection

Of the 278 PV systems analyzed, 220 (79%) were grid-connected. It was expected that grid-connected systems would cost less than non-grid-connected systems because they do not require energy-storage systems. The registry data supported this hypothesis, with the average grid-connected system costing about half that of non-grid-connected systems (Table 1). The average grid-connected system cost $7,400/kW, with a 95% confidence interval of $7,000-$7,900/kW. The average non-grid-connected system cost $14,000/kW, with a 95% confidence interval of $12,500-$15,400. System cost and grid connection were also moderately correlated (-0.57).

The $6,600/kW difference between grid-connected and non-grid-connected systems might be influenced by factors such as differences in system size, location, and year of installation. The regression analysis described later in this report showed that when these factors were controlled for, grid-connected systems cost about $4,800/kW less than non-grid-connected systems, with a 95% confidence interval of about $3,700-$5,900/kW. The data in Table 1 indicate why the cost difference declines to $4,800/kW under the regression analysis. On average, grid-connected systems were larger (4.85 kW) than non-grid-connected systems (2.08 kW), and a higher portion of them were located in the SMUD service territory (41% and 0%, respectively). Both of these factors are believed to lower the cost of grid-connected systems (see discussion). Thus, when these factors were accounted for in the regression analysis, the cost difference attributed to grid connection declined. Installation year, which was also included in the regression analysis, accounted for little or no portion of the decline because the average installation year was the same for grid and non-grid-connected systems (1998.7).

Table 1. PV System Characteristics by Grid Connection

Connection	Cost (1997$/kW)		Size (kW)		Year		In SMUD (%)
	Avg.	95% Conf. Interval	Avg.	95% Conf. Interval	Avg.	95% Conf. Interval	
Grid-Connected (n = 220)	$7,400	$7,000 to $7,900	4.85	3.92–5.78	1998.7	1998.6 to 1998.8	41%
Non-Grid-Connected (n = 58)	$14,000	$12,500 to $15,400	2.08	1.31–2.85	1998.7	1998.5 to 1998.9	0%
All Systems (n = 278)	$8,800	$8,300 to $9,400	4.27	3.51–5.04	1998.7	1998.6 to 1998.8	32%

Cost vs. Grid Connection vs. Location Inside or Outside SMUD

It was expected that PV system costs would be lower in SMUD because of the policy mechanisms in place there. In 1992, SMUD initiated its Sustained Orderly Development and Commercialization (SODC) effort. The SODC process includes an annual request for proposals for the supply of grid-connected PV systems. The annual solicitations are designed to be, and are presented to industry as, part of a larger multi-year process of volume purchases. SMUD's commitment to sustained purchasing has resulted in long-term contracts with PV manufacturers that have helped reduce the cost of the grid-connected systems to SMUD and its customers.[2] SODC also includes a "buy-down" program that reduces the cost of PV systems to customers by an additional 40-50%.[3] The cost of SMUD systems in the voluntary registry was adjusted to exclude the effect of the buy-down program.

The registry data confirmed a relationship between cost and location inside or outside SMUD. The average cost for grid-connected systems was $5,100/kW inside SMUD and $9,100 outside SMUD (Figure 1). The average cost for non-grid-connected systems was $14,000/kW outside SMUD. There were no non-grid-connected systems in SMUD. Cost and location inside or outside SMUD were moderately correlated (-0.60) for grid-connected systems.

The $4,000/kW difference in system costs for location inside or outside SMUD might also be influenced by the size of the system and when it was installed. Grid-connected systems inside SMUD were larger than those outside SMUD (5.44 kW and 4.44 kW, respectively). The average installation year was the same inside and outside SMUD (1998.7). The regression analysis described later in this report showed that when these factors were controlled for, systems installed inside SMUD cost about $3,900/kW less than systems installed outside SMUD, with a 95% confidence interval of about $3,000-$4,900/kW.

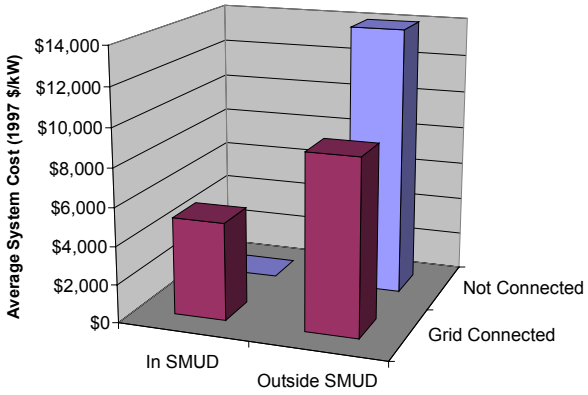

Figure 1. Average PV system costs by grid connection and location inside or outside SMUD

[2] Osborn, D.E. *Commercialization and Business Development of Grid-Connected PV at SMUD*. SMUD publication.

[3] Osborn, D.E. *Sustained Orderly Development and Commercialization of Grid-Connected Photovoltaics: SMUD as a Case Example.* Summer 2000 (version 8/25/2000).

Cost vs. Grid Connection vs. Year

It was expected that PV system costs would decline over time as technological and manufacturing advances occur. Although the time period covered by the registry data was relatively short, some cost declines were evident. Costs for grid-connected systems decreased from $9,800/kW in 1998 to $5,700/kW in 2000 (Table 2). However, costs increased from 1997 to 1998. The lower costs in 1997 might be due to the larger systems installed that year (average 5.79 kW) and the high percentage of systems (81%) installed in the SMUD service territory. Similarly, the higher costs in 1998 might be due to smaller systems being installed (average 3.12 kW) and the lower percentage of systems (4%) installed in SMUD. As a result, the correlation between system cost and year was relatively weak for grid-connected systems (-0.16), although it was statistically significant. For non-grid-connected systems, the trend was less clear. Costs oscillated back and forth, with a high of $15,300/kW in 1998 and a low of $13,400/kW in 1999. There was no correlation between system cost and year for non-grid-connected systems.

Although the simple correlations between system cost and installation year were weak for grid-connected systems and non-existent for non-grid-connected systems, the regression analysis described later showed that installation year was significantly associated with system cost when controlling for other factors such as size, location, and grid connection. The regression analysis showed that system costs declined by about $600/kW each year, with a 95% confidence interval of about $100-$1,100/kW. This was consistent with the $500-$570/kW annual declines in the cost of SMUD PV Pioneer II systems from 1998 to 2000. The cost of the Pioneer II systems, excluding the buy-down, declined from $5,070/kW in 1998 to $4,500/kW in 1999 to $4,000/kW in 2000.[4]

Table 2. PV System Characteristics by Year

	Grid-Connected				Non-Grid-Connected			
Year	N	Avg. Cost (1997$/kW)	Avg. Size (kW)	In SMUD (%)	N	Avg. Cost (1997$/kW)	Avg. Size (kW)	In SMUD (%)
1997	27	$6,100	5.79	81%	4	$14,200	0.97	0%
1998	46	$9,800	3.12	4%	15	$15,300	4.71	0%
1999	108	$7,400	5.54	41%	32	$13,400	1.28	0%
2000	39	$5,700	4.35	56%	7	$13,900	0.74	0%
All Systems	220	$7,400	4.85	41%	58	$14,000	2.08	0%

[4] Osborn, D.E. *Sustained Orderly Development and Commercialization of Grid-Connected Photovoltaics: SMUD as a Case Example.* Summer 2000 (version 8/25/2000).

Cost vs. Grid Connection vs. Size

Another potential explanation for differences in system cost is the size of the PV system. It was expected that costs would be lower for larger systems because the cost of the inverter was less relative to the size of the entire system. The registry data indicated only a weak relationship between cost and size. For grid-connected systems, cost and size were negatively, but weakly, correlated (-0.15). Grid-connected systems less than 10 kW had slightly higher average costs than grid-connected systems of more than 10 kW (Table 3). However, an upward cost trend within each of these categories partially mitigated this overall trend.

The higher costs for grid-connected systems of 5-10 kW and >30 kW might be due to the low percentage of these systems installed in SMUD (4% and 0%, respectively, Table 4). Similarly, the lower costs for systems of 10-20 kW might be due to the high percentage of systems installed in SMUD (75%). For non-grid-connected systems, system cost and size were not found to be significantly correlated.

The weak correlation between system cost and size for grid-connected systems and the lack of correlation for non-grid-connected systems was reflected in the regression analysis described later in this report. It showed that system cost was not significantly associated with system size when controlling for other factors such as year, location, and grid connection. The regression analysis showed that system costs declined by about $40/kW with each additional 1 kW increase in size. The weak relationship between cost and size might be due to smaller economies of scale for PV than for other distributed generation technologies.

Table 3. PV System Characteristics by Size

	Grid-Connected				Non-Grid-Connected			
Size (kW)	N	Avg. Cost (1997$/kW)	Avg. Year	In SMUD (%)	N	Avg. Cost (1997$/kW)	Avg. Year	In SMUD (%)
0.1–5.0	173	$7,500	1998.7	43%	52	$14,000	1998.8	0%
5.1–10.0	23	$8,700	1998.7	4%	5	$14,000	1998.0	0%
10.1–20.0	12	$5,800	1998.5	75%	1	$13,200	1998.0	0%
20.1–30.0	9	$6,200	1999.0	67%	0	--	--	--
>30.0	3	$6,600	1999.0	0%	0	--	--	--
All Systems	220	$7,400	1998.7	41%	58	$14,000	1998.7	0%

Cost vs. Grid Connection vs. Building Type

The voluntary registry also had information on the type of building in which the PV systems were installed: residential, commercial, schools, churches or places of worship, institutional, and other institutional. Average system costs by building type and grid connection are shown in Figure 2. Schools had the highest costs among grid-connected systems, and churches or places of worship had the lowest costs. The much lower costs for churches or places of worship might be due to the tax benefits that religious organizations receive, the large system size, and the high percentage of systems located in SMUD (Table 4).

The data were analyzed for consistency with earlier results (i.e., that cost differences across building types could be explained by differences in size, installation year, and location inside or outside SMUD). In general, the analysis showed that costs for grid-connected systems decreased as system sizes and the percentage of systems in SMUD increased. The exception was residential grid-connected systems, which had unusually low costs given their small size. The effect of size on the cost of residential grid-connected systems might have been mitigated by the portion of these systems located in SMUD (50%).

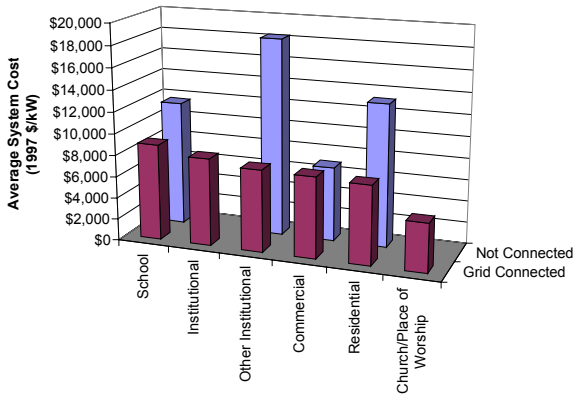

Figure 2. Average PV system costs by building type and grid connection

Table 4. PV System Characteristics by Building Type

Building Type	Grid-Connected					Non-Grid-Connected				
	N	Avg. Cost ($/kW)	Avg. Size (kW)	Avg. Install. Year	In SMUD (%)	N	Avg. Cost ($/kW)	Avg. Size (kW)	Avg. Install. Year	In SMUD (%)
School	25	$8,900	5.13	1999.0	0%	2	$11,600	1.00	2000.0	0%
Institutional	5	$8,100	10.00	1998.2	0%	0	--	--	--	--
Other Institutional	15	$7,600	10.41	1998.9	33%	11	$18,300	5.96	1998.3	0%
Commercial	20	$7,500	13.68	1998.9	20%	1	$6,900	2.60	1998.0	0%
Residential	148	$7,300	2.20	1998.7	50%	44	$13,200	1.15	1998.8	0%
Church or Place of Worship	7	$4,500	19.13	1998.6	100%	0	--	--	--	--
All Systems	220	$7,400	4.85	1998.7	41%	58	$14,000	2.08	1998.7	0%

Regression Analysis

A regression analysis was performed in which grid-connection, location inside or outside SMUD, year, and size were regressed on system cost. The analysis showed all variables except size to be significant at the 0.01 level. The regression equation explained 47% of the variance. No problems with multicollinearity were encountered. The regression parameters are shown in Table 5.

The regression equation indicated that grid-connected systems cost about $4,800/kW less than non-grid-connected systems, that systems in SMUD cost $3,900/kW less than systems outside SMUD, that system costs were reduced by almost $600/kW each additional year, and that system costs decreased by about $40/kW with each additional kW increase in system size.

Beta coefficients indicated the relative importance of the independent variables in the regression model. For example, the beta coefficients in Table 5 indicated that an increase of one standard deviation in year would lead to a decrease of 0.109 standard deviation in system cost. At the same time, an increase of one standard deviation in size would only lead to a decrease of 0.059 standard deviation in system cost. The beta coefficients in Table 5 showed that grid connection had the largest effect on system cost followed by location inside or outside SMUD, year of installation, and size.

Table 5. Regression Parameters

Variable	B	Beta	t	Significance	95% CI Lower Bound	95% CI Upper Bound
(Constant)	1,190,415	--	2.519	0.012	260,055	2,120,776
Grid-connected	-4,800	-0.416	-8.794	0.000	-5,875	-3,725
In SMUD	-3,947	-0.394	-8.389	0.000	-4,873	-3,021
Year	-589	-0.109	-2.489	0.013	-1,054	-123
Size	-43	-0.059	-1.321	0.188	-106	21

Summary Observations

The regression analyses in this report showed that PV system costs were significantly associated with whether the system was connected to the grid, year of installation, and whether the system was located in an area with volume purchasing agreements (i.e., in SMUD).

- Grid connection had the largest impact on system cost. Grid-connected systems cost about $4,800/kW less than non-grid-connected systems.

- Location in SMUD also had a significant impact. Systems inside SMUD were $3,900/kW less than systems outside SMUD.

- Year of installation had a moderate effect. System costs were reduced by almost $600/kW with each passing year.

- Size had a small effect. System costs decreased by about $40/kW with each additional kW increase in system size.

- The cost of grid-connected systems was lowest for churches and places of worship and highest for schools.

Numerous other PV system characteristics not contained in the voluntary registry might explain additional variation in system costs. Examples include whether a tracking system is used (e.g., single- or dual-axis), the type of photovoltaic cell used (e.g., crystalline silicon, amorphous silicon, cadmium telluride, or copper indium diselenide), and whether the system is integrated in the building (e.g., PV shingles).

Topical Issues Briefs Previously Published by the National Renewable Energy Laboratory*

Willingness to Pay for Electricity from Renewable Resources: A Review of Utility Market Research
July 1999
NREL/TP-550-26148

Grid-Connected Renewable-Electric Policies in the European Union
May 1999
NREL/TP-620-26247

Green-Power Marketing in Retail Competition: An Early Assessment
March 1999
NREL/TP-620-25939

The New Hampshire Retail Competition Pilot Program and the Role of Green Marketing
November 1997
NREL/TP-260-23446

Green Marketing in the Massachusetts Electric Company Retail Competition Pilot Program
October 1997
NREL/TP-460-23507

Power Marketing and Renewable Energy
September 1997
NREL/SP-460-21651

Net Metering Programs
September 1996
NREL/SP-460-21427

Small Turbines in Distributed Utility Application: Natural Gas Pressure Supply Requirements
May 1996
NREL/SP-461-21073

** See details inside front cover for information on ordering these reports.*