Performance Degradation of Photovoltaic and Combined Heat and Power Systems in a Statewide Incentive Program

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ABSTRACT

This paper summarizes an investigation of observed performance degradation of combined heat and power (CHP) and photovoltaic (PV) systems in the California Public Utilities Commission's Self Generation Incentive Program (SGIP). This analysis offered a unique opportunity to examine the hourly performance of a large number of systems (389 PV, 208 CHP) over an extended period (six years). We characterized the observed degradation and interviewed participants to understand the causes for changes in performance.

CHP system output decreased dramatically over time. These systems, on average, exhibited a five to eight percent year-over-year decrease in on-time compounded by a three percent year-over-year decrease in output during hours that the systems were running. The evaluation period coincided with a monotonic increase in fuel prices, but a regression analysis demonstrated comparable attribution of this effect to both system age and fuel prices. Interviews revealed that most systems had significant technical problems at some point, yet owners were satisfied when contractors bore the burden of investment risk, rather than owners.

On average, PV systems were available 97 percent of the time and output of the panels degraded at about the rates commonly cited from more controlled studies. We observed a year-over-year decrease in PV output of 0.8 percent, compounded by a small increase in system down-time.

Introduction

In 2001, The California Public Utilities Commission (CPUC) established the Self-Generation Incentive Program in response to peak demand problems in the state. This program is implemented by four Program Administrators (corresponding to the four major investor owned utilities in the state) under the auspices of the CPUC. Since its inception, the program has provided incentives for photovoltaics (PV); wind energy; and fossil and renewable-fueled internal combustion (IC) engines, fuel cells, microturbines, and small gas turbines. Since 2008, only wind energy, fuel cells, and storage technologies integrated with these generation technologies are eligible for incentives. As of December 31, 2009, over 1,300 SGIP projects had come on-line, exceeding 350 MW of installed capacity (Itron, Inc. 2010, EH-1). Many of these projects have been continuously metered for several years and provide a unique opportunity to examine the performance of distributed generation systems in the field through the course of the systems' lifetimes.

The SGIP Eighth-Year Impact Evaluation (Itron, Inc. 2009, 3-31 and 3-37) identified dramatic decreases in capacity factors for combined heat and power (CHP) systems driven by IC engines and microturbines, as well as a significant decrease in capacity factor for PV systems. The average capacity factor of CHP systems decreased by approximately 65 percent from the first to the sixth year; the average capacity factor of PV systems decreased approximately 20 percentage during this same period of aging. The report stated that "Understanding reasons for changes requires additional process evaluation information." (Itron, Inc. 2009, 1-11)

Following the Eight-Year Impact Evaluation, Navigant Consulting was selected to perform an analysis of this observed performance degradation on behalf of the four Program Administrators. We analyzed hourly metered data and interviewed participants to characterize the changes in performance and to identify root causes of these changes. We conducted separate analyses of CHP and PV systems, analyzing data from all 208 hourly-metered CHP sites (from 2002 through 2008) and 389 hourly-metered PV sites and interviewing 43 CHP participants and 35 PV participants. This paper highlights key-findings from these studies. The complete performance degradation analyses (Navigant 2010a and Navigant 2010b), the annual Impact Evaluations, and additional SGIP documentation can be found on the CPUC's SGIP website (CPUC 2011).

Combined Heat and Power

For the CHP Performance Investigation, we analyzed hourly metered system output for all 208 metered CHP systems and interviewed 43 participants of the metered sites. Table 1 summarizes the types of systems and the years of installation of the systems analyzed, and Table 2 summarizes this information for the interviewed sample.

Table 1. Summary of CHP Systems in Metered Data Analysis

Technology Type	Parameter	Install Year							
		2002	2003	2004	2005	2006	2007	2008	All Years
Fuel Cells	total installed capacity (kW)	200			2,000	3,950	500	250	6,900
	average system capacity (kW)	200			1,000	564	500	250	575
	count	1			2	7	1	1	12
Gas Turbines	total installed capacity (kW)			1,383	4,500	4,527			10,410
	average system capacity (kW)			1,383	4,500	4,527			3,470
	count			1	1	1			3
IC Engines	total installed capacity (kW)	9,735	33,422	18,619	9,039	5,270	2,120	1,059	79,814
	average system capacity (kW)	608	777	548	430	659	353	1,059	609
	count	16	43	34	21	8	6	1	131
Microturbines	total installed capacity (kW)	1,042	2,612	840	3,688	1,530	554		10,266
	average system capacity (kW)	104	137	120	231	255	139		166
	count	10	19	7	16	6	4		62
All Technologies	total installed capacity (kW)	10,977	36,034	20,842	19,227	15,277	3,174	1,309	107,390
	average system capacity (kW)	407	581	496	481	694	289	655	516
	count	27	62	42	40	22	11	2	208

blank cells indicate zero interviewed sites of this type

Table 2. Summary of CHP Systems of Interviewed Sample

Technology Type	Parameter	Install Year							
		2002	2003	2004	2005	2006	2007	2008	All Years
Fuel Cells	total installed capacity (kW)				1,000	3,000	500	250	4,750
	average system capacity (kW)				1,000	750	500	250	679
	count				1	4	1	1	7
Gas Turbines	total installed capacity (kW)			1,383	4,500				5,883
	average system capacity (kW)			1,383	4,500				2,942
	count			1	1				2
IC Engines	total installed capacity (kW)	1,200	5,540	2,265	1,705	750	340		11,800
	average system capacity (kW)	600	1,108	324	568	750	170		590
	count	2	5	7	3	1	2		20
Microturbines	total installed capacity (kW)	325	1,140	180	1,048		70		2,763
	average system capacity (kW)	108	228	60	524		70		197
	count	3	5	3	2		1		14
All Technologies	total installed capacity (kW)	1,525	6,680	3,828	8,253	3,750	910	250	25,196
	average system capacity (kW)	305	668	348	1,179	750	228	250	586
	count	5	10	11	7	5	4	1	43

blank cells indicate zero interviewed sites of this type

Analysis

Our data analysis focused primarily on system output (kWh) at each hour, in order to disaggregate the effects of part load operation and periods of no operation. Each hourly record was characterized as:

- **On hour** - An hour of system operation that recorded an electric net generation output greater than two percent of rated capacity. Allowing a two percent threshold minimizes false positives caused by data acquisition signal noise or drift.
- **Off hour** – An hour of system operation that recorded an electric net generation output less than two percent of rated capacity. This includes hours of zero output.
- **Missing hour** – An hour for which no data was present. We assumed that data gaps occurred because of problems with the data acquisition system rather than because of problems with the CHP system. The corollary of this assumption is that the operation of the CHP systems during the data gaps is the same as what is seen during the periods of recorded data. Hours of use, output levels, and zero use would all be similar.

We then looked at the chronological clusters of "off" hours for each site, characterizing clusters as:

- **Brief outages -** Off, less than one day, most likely part of a regular dispatch schedule or for brief routine maintenance.
- **Intermediate outages -** Off, one to three days, most likely part of a regular dispatch schedule (e.g., off for all or part of the weekend) or for routine maintenance.
- **Long outages -** Off, more than three days, either voluntary because of a shift in cost-effectiveness of self-generation or involuntary due to system failures.

We also used derived annual data for each site, which were developed for the prior impact evaluation (Itron, Inc. 2009). Derived annual values included capacity factor, average electrical efficiency, and average system (combined electrical and thermal) efficiency for each site and year. Finally, we determined year-over-year trends in annual statistics, grouping systems by type (IC engine, microturbine, fuel cell, gas turbine).

Few statistically significant differences in results were observed across PAs; only the aggregated statewide results are discussed in this paper.

Performance Trends

Figure 1 graphically summarizes the most significant performance trends observed in the output data. In this figure, annual data is grouped by system type and by system age. Grouping is by system age rather than year because new systems are added to the program in each year of the analysis. The count of site-years is provided, rather than the count of sites, because each site, at each year, provides one datapoint.

The top half of Figure 1 illustrates what systems did during *on* hours. The black solid bars in this graph indicate the total annual electrical output of systems, as a percentage of full capacity (i.e., the capacity factor). This is the product of the average output level during *on* hours (as a percentage of rated capacity) and the average *on* hours (as a percentage of all hours for which data was available). The gray dotted bar above the black bar represents the unused capacity during *on* hours, that is, the product of the difference between rated capacity and the average output level during *on* hours and the average *on* hours.

The bottom half of Figure 1 illustrates the durations of *off* periods. Red horizontal striped bars represent the portion of all hours for which there were *long* (greater than three days) outages. Green vertical striped bars represent the portion of all hours for which there were *intermediate* (one to three days) outages. Blue spotted bars represent the portion of all hours for which there were *short* (less than one day) outages.

Each composite bar has a length of 100 percent of annual output potential, illustrating how each type of system, at each age, "spends" its output potential.

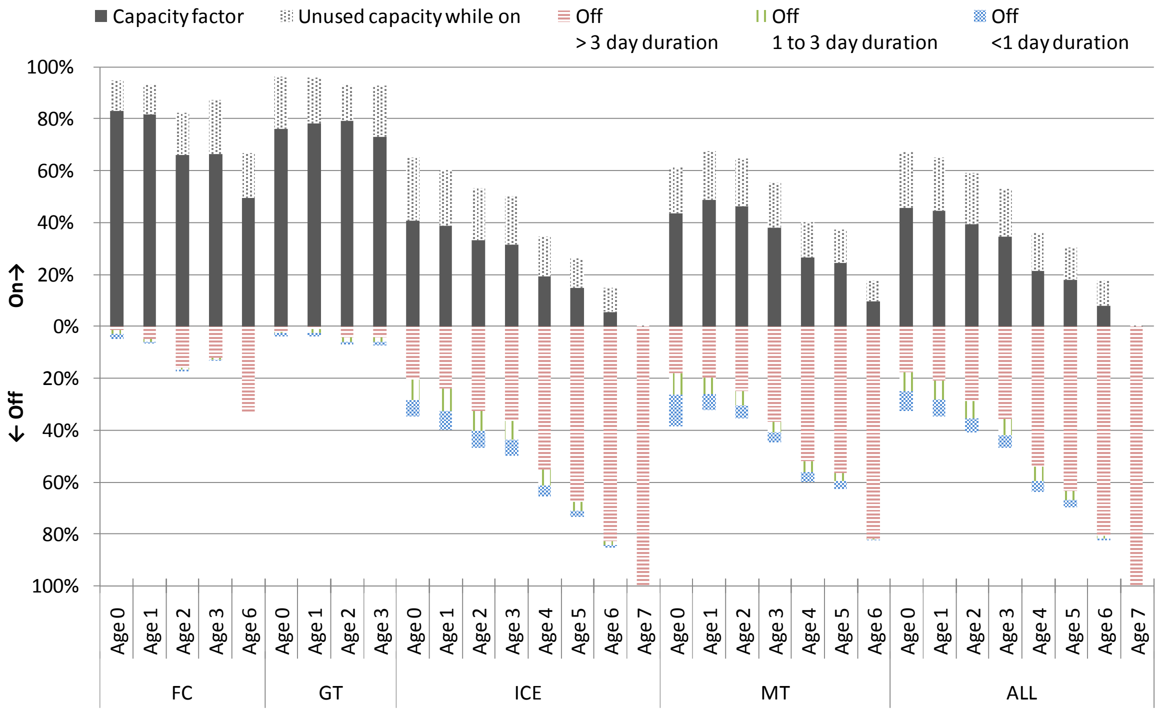

Figure 1. CHP Performance Trends

This graph shows the clear and dramatic capacity factor decrease of IC engines and microturbines, and a significant decrease in capacity factor for fuel cells. These decreases are driven primarily by an increase in long duration off periods, but also by a decrease in operating levels when systems are on.[1] In other words, CHP system were, on average, over time, run at lower output levels, and spent more time turned off for long durations (at least three days).

Table 3 summarizes annual percentage point changes in metrics. Each cell provides the estimated value, the 90 percent confidence range, and the number of data points that these statistics are based on. Cells in bold font indicate statistically significantly non-zero trends at the 90 percent confidence level. In other

Table 3. CHP Performance Trends

Technology Type	Parameter	Capacity Factor	Hours of Operation	Short Duration Off Time	Medium Duration Off Time	Long Duration Off Time	Load Level When On	Electric Efficiency	System Efficiency, PUC 216.6(b)
Fuel Cells	average annnual percentage point trend	**-6.7%**	**-4.7%**	**-0.5%**	-0.3%	**5.4%**	**-3.2%**	**-0.9%**	-0.8%
	90% confidence interval	**[-10.0%,-3.5%]**	**[-7.7%,-1.7%]**	**[-0.9%,-0.1%]**	[-0.6%,0.0%]	**[2.7%,8.1%]**	**[-5.5%,-1.0%]**	**[-1.4%,-0.4%]**	[-2.5%,0.9%]
	number of site-years	**33**	**33**	**33**	33	**34**	**33**	**33**	33
Gas Turbines	average annnual percentage point trend	-1.1%	-1.4%	0.0%	0.5%	1.0%	0.4%	-1.8%	**-10.1%**
	90% confidence interval	[-4.9%,2.8%]	[-3.5%,0.6%]	[-0.3%,0.2%]	[0.0%,0.9%]	[-0.9%,3.0%]	[-3.5%,4.3%]	[-5.7%,2.1%]	**[-15.7%,-4.6%]**
	number of site-years	10	10	10	10	10	10	10	**10**
IC Engines	average annnual percentage point trend	**-5.2%**	**-7.8%**	**-0.9%**	**-1.0%**	**9.8%**	**-2.3%**	-0.1%	**-1.1%**
	90% confidence interval	**[-6.3%,-4.1%]**	**[-9.4%,-6.2%]**	**[-1.3%,-0.6%]**	**[-1.4%,-0.6%]**	**[8.2%,11.4%]**	**[-3.4%,-1.3%]**	[-0.3%,0.1%]	**[-1.4%,-0.8%]**
	number of site-years	**496**	**496**	**496**	**496**	**496**	**423**	456	**456**
Microturbines	average annual percentage point trend	**-4.8%**	**-7.2%**	**-1.5%**	**-1.1%**	**9.8%**	-1.5%	0.0%	**-0.4%**
	90% confidence interval	**[-6.5%,-3.1%]**	**[-9.5%,-4.9%]**	**[-2.2%,-0.8%]**	**[-1.6%,-0.5%]**	**[7.5%,12.0%]**	[-3.1%,0.0%]	[-0.1%,0.2%]	**[-0.7%,-0.2%]**
	number of site-years	**238**	**238**	**238**	**238**	**238**	197	221	**221**

bold cells indicate statistically significant results at the 90 percent confidence level

[1] In Figure 1, this decrease in output during *on* hours is the ratio of the *unused capacity while on* bar to the *capacity factor* bar. While the *unused capacity while on* bars do not change much for year to year, the *capacity factor* bars do decrease in size each year.

words, with 90 percent confidence, we can say that these values are non-zero, that is, there is a trend. Cells that are not in bold font are not statistically significantly different than zero.

Trends for all systems combined are not presented because of their misleading nature: virtually all data for systems older than three years were for IC engines and microturbines, while data for systems up to three years old includes fuel cells and gas turbines. Combining the data from these technologies compounds technology-to-technology trends on top of year-over-year trends.

Table 3 indicates that:

- **Capacity factor** – Statistically significant decreases in annual capacity factors were observed for fuel cells, IC engines, and microturbines, ranging from 5 to 7 percentage points per year.
- **Hours of operation** - Statistically significant decreases in annual hours of operation (5 to 8 percentage points per year) were observed for fuel cells, IC engines, and microturbines.
- **Short, medium, and long duration off time** – The reduced hours of operation were primarily from increases in long duration (greater than three days) outages, offset by slight reductions in small and medium duration outages. Effectively, long duration outages "consume" short and medium duration outages over time. On average, long duration off time increased 5 to 10 percentage points annually.
- **Load level when on** – Statistically significant decreasing trends in system output during *on* hours were observed for fuel cells and IC engines, ranging from 2 to 3 percentage points per year. This compounds the reduction in capacity factor caused by decreases in hours of operation.
- **Electric efficiency** – Fuel cells showed a slight decreasing trend in electrical efficiency, which may, in part, explain the decreasing *load level when on* trend.
- **System efficiency** – This is the whole system performance metric, as defined by the PUC 216.6(b): the sum of the electric generation and half of heat recovery as a percentage of energy entering the system as fuel. System efficiencies showed decreasing trends that are greater in magnitude than the decreases in electrical efficiency, indicating that heat recovery is decreasing over time. This may be due to decreased performance of heat exchangers over time.

The previous analysis illustrated that there has been a steady decline in capacity factor of SGIP CHP systems over time, and that this decline is due primarily to an increase in long-duration (greater than three days) off events. However, gas prices increased steadily during the analysis years (from $5.32/MMBtu in 2002 to $11.09/MMBtu in 2008), making it unclear whether aging systems with increased maintenance needs, or gas prices were the cause of this decline. Therefore, we conducted a regression analysis to disaggregate the impacts of system age and the cost to produce electricity.

Table 4. Effects of age and self-generation cost on capacity factor

System Type	Statistic	Age	¢/kWh
Fuel Cell	average percentage point change in capacity factor	**-4.8%**	-4.4%
	90% confidence range	**[-7.9%,-1.7%]**	[-6.8%,-2.0%]
	number of site years	30	30
Microturbine	average percentage point change in capacity factor	**-2.3%**	**-2.5%**
	90% confidence range	**[-4.2%,-0.4%]**	**[-3.7%,-1.4%]**
	number of site years	226	226
IC Engine	average percentage point change in capacity factor	**-4.2%**	**-0.8%**
	90% confidence range	**[-5.3%,-3.0%]**	**[-1.2%,-0.5%]**
	number of site years	483	483
Gas Turbine	average percentage point change in capacity factor	**-0.3%**	**-0.3%**
	90% confidence range	[-7.1%,6.5%]	[-2.5%,1.9%]
	number of site years	7	7
All Types	average percentage point change in capacity factor	**-4.3%**	**-1.2%**
	90% confidence range	**[-5.3%,-3.3%]**	**[-1.6%,-0.9%]**
	number of site years	755	755

The results of this model are presented in Table 4. Here, the indirect influence of fuel cost on capacity factor is statistically significant for all technologies except gas turbines. On average, a one cent increase in the cost to generate electricity results in 1.2 percentage point decrease in capacity factor, and a one year increase in system age results in a 4.3 percentage point decrease in capacity factor.

Interviews

Participant interviews were conducted with representatives from a sample of 43 CHP sites from the data analysis. The primary objective of these interviews was to collect qualitative information on system performance and factors affecting system performance. We asked the interviewees to describe the ownership, maintenance, operations, and performance of their systems. We also asked then to identify times and durations of significant outage events.

The sample was designed to include at least two sites of each technology type for each PA, as well as a range of performance characteristics and installation years. The performance characteristics considered were the trend in monthly capacity factor (characterized as normal, erratic, generally increasing, or generally decreasing) and the character of outages at least one month long (none; at least one, followed by more on time; ending in a terminal outage). After sorting sites according to utility and technology type, sites were randomly selected and then reviewed to ensure a mix of performance experiences and system ages were represented.

The interview sample was designed to capture qualitative information about the full diversity of technologies and experiences, rather than to capture a representative sample of the population. Therefore, results from the survey may not be representative of the population of participants and are only presented here in qualitative terms.

Key results for the interviews include:

- **Ownership** – Approximately three quarters of respondents own and operate their systems. Of the remaining quarter, most are owned by a third party that sells electricity to the host site through a power purchase agreement arrangement (PPA), and one site is leased from a third party.
- **System operations** – The dominant operating schedule was load following, which approximately half of respondent systems use as a control strategy. About one quarter of respondent sites run their systems continuously, most for economic reasons and some (fuel cell hosts) for optimal equipment performance. The remaining quarter of respondents regularly adjust their operating schedule based on changes in gas and electricity prices.

  Some respondents conducted periodic studies of their system's economics to determine whether or not to take the system out of operation based on economic factors. None consider these factors more than a few times a year.
- **Maintenance responsibilities** - Most respondents explained that their systems are complex and require regular maintenance from highly specialized technicians in order to perform properly. Approximately three quarters of respondents either have, or have at some point had a service contract for their system. Service contracts vary in the breadth of components they cover. In some cases, a respondent's service contract would cover the engine, but the system owner was responsible for all other components. For most respondents with service contracts, however, the service provider is responsible for keeping the entire system running smoothly.
- **System specific experiences** –
  - ***Fuel cell*** – All seven fuel cell systems experienced problems with system performance. Approximately half of respondents with fuel cells expressed that the equipment problems resulted in lower than expected system performance. However, almost all respondents with fuel cells characterized their fuel cell systems as "generally reliable" despite the fact

that they had experienced problems with system performance. Furthermore, all respondents with fuel cells indicated that their system components are "high quality," and that their systems were designed appropriately to meet the needs of their facilities.

- ***Microturbines and IC engines***– In contrast to the experience of respondents with fuel cells, respondents with microturbines and IC engines had higher expectations for their systems' performance and were less likely to have a risk-mitigation strategy, such as a PPA, in place. The respondents were more disappointed by their experience with their systems than were respondents with fuel cells; approximately half of the respondents with microturbines and half of the respondents with IC engines reported that system performance fell short of their expectations. Approximately two thirds of respondents of both of these system type groups characterized their systems' components as "high quality" and designed to suit the needs of their facility.
- ***Gas turbines*** – We were only able to interview two gas turbine hosts. Neither expressed performance problems or lower than expected performance.

Conclusions and Recommendations

This purpose of this investigation was to identify and quantify reasons for the performance degradation in SGIP CHP systems noted in recent SGIP impact evaluations. The results presented here suggest that this degradation is due primarily to increased long-duration outages (greater than three days) and secondarily to reduce levels of output during on-time. As a percent of all hours, off time increases approximately five to seven percentage points per year. Adding to the reduction in capacity factor are two to three percentage point annual reductions in operating level when CHP systems are on (IC engines and fuel cells only).

Furthermore, both system age and the cost to produce electricity are independently correlated to capacity factor. On average, controlling for fuel costs, capacity factors decrease by 4.3 percentage points per year of system age. Each additional cent per kWh that it costs to generate electricity on-site reduces capacity factor by 1.2 percentage points per year; variables affecting costs include fuel costs, the site's use for waste heat, and system efficiency.

Additionally, a slight annual decrease in electrical efficiency was observed (0.4 percentage points per year), possibly due to the decreasing trend in operating levels. System efficiency is decreasing more rapidly (1.3 percentage points per year) than electrical efficiency, due to a decreased portion of recoverable heat being utilized. One cause for this effect may be the technical problems with heat exchangers noted by several of the hosts interviewed.

The interviews with CHP hosts underscored the complexity of CHP systems. CHP systems are technically complex, requiring expertise for both scheduled and unscheduled maintenance to keep a system running. This makes the host customers heavily dependent on the services of third-party maintenance providers. Unfortunately, many maintenance contractors are slow in responding to clients whose systems require maintenance and repair. Systems also require an internal champion to monitor and sustain the system, yet the expected lifetime of a CHP system is longer than the expected employment period at most sites. The necessity of internal and third-party attention is supported by the negative effect of age on capacity factor observed in the data, even when controlling for increasing fuel prices.

These interviews also highlighted the economic complexity of CHP systems: fuel costs, use for recoverable heat, unpredictable demand changes, maintenance costs, maintenance contract costs, and costs to litigate deficient maintenance service must all be considered on an ongoing basis. At any given time, system operators must consider all of these factors in their decisions to operate the system or not.

Many of the sites interviewed reported that system performance and economics did not live up to what was proposed to them. Half would not install a system again if they were making the decision now.

However, host experience with fuel cells is a notable exception. Although all seven of the host customers interviewed experienced technical problems with their systems, six of the seven were satisfied with the performance of their systems and five of the seven said that they would install a CHP system if faced with the decision today. Interviews revealed that fuel cell hosts often received risk mitigating contractual arrangements with manufacturers and developers, and that their systems received adequate maintenance to keep the system running. These types of arrangements and services typical of fuel cell systems may be a positive example for promoters of other CHP systems because they reduce the complexity of the system from the perspective of the site.

For programs hoping to incent both CHP installation *and* long-term operation, the authors recommend the following program design considerations:

- **Institute measures to mitigate the uncertainties of CHP system operation.** Doing so will support predictable and long-term results and participant satisfaction by keeping CHP operation simpler and economically favorable for participants. Long-term, favorable gas rates; reduced electric demand charges ($/kW) or exceptions for brief demand surges from temporary outages; system design assistance including cost/benefit analysis; mandatory high-quality maintenance contracts; and long-term product warrantees. The length of these contracts should be as long as the expected lifetime of systems assumed in the program design. The lack of risk mitigation is currently contributing to performance degradation. However, the additional costs of instituting these measures to may outweigh the benefits to program participants and ratepayers.
- **Undertake activities to bring existing but non-functioning systems back online**. Numerous SGIP-incented systems have been retired well before the end of their useful lives for maintenance or economic reasons. The SGIP has overcome a major hurdle in getting these systems installed to begin with; it may be worthwhile to provide additional support to these systems to get them back online and keep them operating for their full useful lives. Support might include subsidizing new, longer-term maintenance contracts; offering favorable, long-term gas contracts; and providing engineering resources to identify and correct operational issues. However, providing these services may be considered double-paying for capacity that the program and rate payers have already procured through previous SGIP incentives. The costs of these benefits relative to the additional program costs should be explored further.

Photovoltaics

We conducted a similar analysis of metered PV systems in the program to shed light on the character and causes of PV system capacity factor declines.

Table 5 summarizes the total installed capacity, average capacity per project, and number of projects in the dataset. Projects are characterized by the year in which they became operational, not necessarily the year that the project was approved by SGIP (could be earlier) and not necessarily the first year for which adequate data were available (could be later). The number of systems per year of installation is not cumulative: the count of systems for a particular year includes only those systems that became operational during that year, not the cumulative number of systems that became operational from the start of the program through that year.

Table 5. Summary of PV systems in data analysis and interviews

Parameter	Install Year							
	2002	2003	2004	2005	2006	2007	2008	All Years
All Metered Sites								
Total Capacity (kW)	3,270	11,994	11,653	15,210	15,045	12,503	2,359	72,032
Average Capacity (kW)	102	146	131	193	264	321	214	185
Count	32	82	89	79	57	39	11	389
Interviewed Sites								
Total Capacity (kW)	473	1,617	1,320	1,896	77			5,382
Average Capacity (kW)	59	231	94	379	77			154
Count	8	7	14	5	1			35

blank cells indicate zero systems for that year of installation

Analysis

We received PV output data for 389 SGIP projects with a total installed capacity of 72 MW. This data was matched to hourly weather data (solar insolation) at nearby weather stations. Weather data was used to determine daylight hours, and only daylight hours were considered for the analysis. Solar insolation data from weather stations were used to normalize annual output with respect to variation in annual insolation. Output data were disaggregated into hours of missing data, hours of zero/near-zero output, and all other hours (deemed "normal" hours). System performance during normal hours was used to estimate the aggregate impacts of system degradation, dirt accumulation, and shading changes on systems. The ratio of zero/near-zero output to normal output was used to estimate the aggregate impacts of system failures and catastrophic shading. This section describes the data collection and cleaning process.

Performance Trends

For each project, each daylight hour from the first hour of data until the last daylight hour of 2008 was classified as:

- missing (data gap);
- below a minimum output threshold level (0.5 percent of rated capacity);
- above a maximum output threshold level (150 percent of rated capacity); or
- normal (anything not characterized as missing, below minimum, or above maximum).

Table 6 summarizes the data character and year-over-year trends in these categories. No data points were observed to be above the maximum threshold (150 percent of rated capacity). Systems are categorized

Table 6. Summary of PV data character and data character annual trends

Parameter	Description	Statistic	Install Year							
			2002	2003	2004	2005	2006	2007	2008	All Years
percent normal mid-day hours	**normal mid-day hours, as a percentage of all available mid-day hours**	**estimate**	97.9%	97.8%	97.7%	96.7%	98.2%	97.3%	98.8%	97.6%
		90% confidence range	[97.0%,98.8%]	[97.2%,98.4%]	[97.1%,98.4%]	[95.7%,97.7%]	[97.2%,99.1%]	[96.3%,98.4%]	[97.8%,99.8%]	[97.2%,97.9%]
		number of site-years	143	342	331	263	121	64	11	1,275
		annual trend	-0.4%	**-0.3%**	**-1.3%**	0.2%	0.7%	-1.7%		**-0.4%**
		annual trend 90% confidence range	[-0.8%, 0.1%]	**[-0.7%,0.0%]**	**[-2.1%,-0.5%]**	[-0.7%,1.1%]	[-0.5%,1.8%]	[-3.9%,0.5%]		**[-0.6%,-0.1%]**
output during normal mid-day hours	**output during normal mid-day hours, as a percentage of this output in the year of installation**	**estimate**	96%	97%	100%	99%	100%	102%	100%	99%
		90% confidence range	[92.8%,99.4%]	[95.5%,99.3%]	[97.0%,102.2%]	[98.1%,100.0%]	[96.1%,103.9%]	[97.1%,106.3%]	[100.0%,100.0%]	[102.3%,99.3%]
		number of site-years	n = 32	n = 82	n = 88	n = 79	n = 57	n = 39	n = 11	n = 389
		annual trend	**-1.3%**	**-1.1%**	-0.2%	-0.6%	0.0%	3.4%		**-0.8%**
		annual trend 90% confidence range	**[-2.4%,-0.2%]**	**[-1.8%,-0.3%]**	[-1.5%,1.1%]	[-1.3%,0.0%]	[-3.9%,3.9%]	[-5.8%,12.6%]		**[-1.3%,-0.4%]**
percent low/no output mid-day hours	**zero/near-zero output mid-day hours, as a percentage of all available mid-day hours**	**estimate**	2.1%	2.2%	2.3%	3.3%	1.8%	2.7%	1.2%	2.4%
		90% confidence range	[1.2%,3.0%]	[1.6%,2.8%]	[1.6%,2.9%]	[2.3%,4.3%]	[0.9%,2.8%]	[1.6%,3.7%]	[0.2%,2.2%]	[2.1%,2.8%]
		number of site-years	143	342	331	263	121	64	11	1,275
		annual trend	0.4%	**0.3%**	**1.3%**	-0.2%	-0.7%	1.7%		**0.4%**
		annual trend 90% confidence range	[-0.1%,0.8%]	**[0.0%,0.7%]**	**[0.5%,2.1%]**	[-1.1%,0.7%]	[-1.8%,0.5%]	[-0.5%,3.9%]		**[0.1%,0.6%]**
percent missing data	**missing data, as a percentage of all daylight hours**	**estimate**	26%	33%	25%	9%	10%	1%	10%	22%
		90% confidence range	[22%,31%]	[30%,36%]	[22%,28%]	[7%,11%]	[6%,13%]	[1%,2%]	[3%,18%]	[21%,24%]
		number of site-years	n = 32	n = 32	n = 32	n = 32	n = 32	n = 32	n = 32	n = 32
		annual trend	**6.3%**	**7.8%**	**7.6%**	0.9%	0.7%	0.0%		**5.7%**
		annual trend 90% confidence range	**[3.5%,9.0%]**	**[5.9%,9.8%]**	**[5.4%,9.8%]**	[-0.9%,2.6%]	[-3.8%,5.2%]	[-1.2%,1.2%]		**[4.9%,6.5%]**

annual trends are not provided for systems installed in 2008 because there was only one year of data (2008) available, and at least two years of data would be needed to determine the annual trend

trends in bold font are statistically significant at the 90 percent confidence level by first year of operation. Results are weighted by system (i.e., each system has equal weight) rather than by installed capacity (i.e., greater weight for larger systems) to prevent larger systems from biasing character statements. Analyses of normal and below-threshold output were limited to mid-day hours (10 am to 2 pm) to avoid mis-categorizing morning or late afternoon hours with expected low output.

For each year, five rows of data are shown. The first row is the average value for all systems of that install year. The second row is the 90 percent confidence interval of this estimate for the full population of SGIP systems. The third row is the number of systems with the designated year of installation. The fourth row is the average annual percentage point increase in the parameter as the systems age. The fifth row is the 90 percent confidence interval of this trend estimate.

This table shows that:

- Normal output during times when systems are online and producing power declines by 0.8 percent (relative to the first year of output) per year, after controlling for annual variation in solar insolation. This decline in performance is on par with manufacturer claims (typically 20 percent degradation after 20 years) and observed performance from other studies.
- On average, systems are online and producing power 97 percent of daytime hours; and this on-time decreases at a rate of 0.4% of all daylight hours, per year.
- 22 percent of output data is missing, and the percentage of all hours for which data is available decreases by 5.7 percentage points per year.

Missing data and increases in missing data limit the ability to draw conclusions about subsets of the population and as systems age. We found significant differences in the amount of missing data across the four PAs, ranging from 5 percent to 43 percent. Additionally, the amount of missing data is significantly less in systems installed in 2004 or later than in systems installed in 2002 and 2003. These significant differences across time and PA suggest that the amount of missing data can be minimized through data acquisition implementation best practices.

In addition to hourly output data, the impact evaluation contractor provided the annual capacity factor for each system, as determined by them and detailed in the SGIP Eight-Year Impact Evaluation. Table 7 summarizes the average capacity factor by first year of operation and system age. The blue bars indicate the relative magnitudes of each value: the shortest bar represents a value of 0.131 and the longest bar represents a value of 0.193.

This table is revealing: The clear declining trend in capacity factor by age is seen in the bottom row of data, particularly for ages 4 through 6. However, the individual columns tell a very different story: that new system have higher capacity factors each year. For a particular first year of operation, the trend in capacity factor as those systems age is much less significant (and even increasing from one year to the next in some cases, most likely due to natural variation in solar insolation from year to year). Newer systems with high capacity factors inflate the average capacity for systems of low age, while the only systems in the dataset with higher ages are the older systems, which had lower capacity factors to begin with.

Table 7. Capacity factor as a function of installation year and system age.

First Year of	Age							
Operation	0	1	2	3	4	5	6	All Ages
2002	0.131	0.162	0.157	0.149	0.145	0.157	0.138	0.152
2003	0.145	0.161	0.157	0.153	0.164	0.154		0.156
2004	0.165	0.166	0.16	0.17	0.157			0.164
2005	0.166	0.171	0.175	0.174				0.172
2006	0.168	0.191	0.189					0.185
2007	0.179	0.184						0.182
2008	0.193							0.193
All Years	0.164	0.171	0.168	0.165	0.157	0.155	0.138	0.165

Interview Results

Participant interviews were conducted with a sample of 35 of the PV sites for which performance data was provided. The objectives of these interviews were to 1) correlate data gaps and strings of zero/near-zero output data to participant experience and 2) collect qualitative information on system performance and factors affecting system performance.

The interview sample was designed to span the four PAs and the range of observed data character and performance. Only sites with three or more years of data were considered; otherwise, there were no trends to observe.

Sites were ranked on four criteria:

- Zero/near-zero output data time a percentage of all normal and zero/near-zero hours.
- Standard deviation of annual performance.
- Correlation of annual performance to system age.
- The product of [1- correlation] and the standard deviation of output score: this identified sites with high standard deviation but little net movement, implying significant annual variation, but on average, no change.

Because of the non-random sample selection, these results are not necessarily representative of the population of SGIP PV systems. However, in keeping with the objective of this performance degradation examination, these interview results describe the host experience for those sites with the most significant deviation from "normal" output.

For the sites with the most significant performance variation, interviews revealed a range of host attention to system, widespread and frequent cleaning, and significant system failures:

- **Monitoring** - Most of interviewed participants are not closely monitoring their systems – approximately half of interviewed participants reported low levels of monitoring, and a quarter reported no monitoring. As noted above, system performance and inverter performance does change over time; if these systems are not monitored, performance issues resulting in poor to no performance may persist.
- **Cleaning** - Most systems are cleaned regularly – most interviewed participants either clean their panels regularly or contract others to clean their panels regularly.
- **Reliability** - PV systems are error prone – The notion of "plug and play" systems with high reliability because of the absence of moving parts is not accurate:
    - ***Inverters*** – Approximately half of interviewed participants experienced problems with their inverter performance. One third did not, and the rest were not sure.
    - ***Panels*** – Approximately one quarter of interviewed participants had their panels replaced (at no cost to them) due to panel performance issues.

Additional findings emerging from interviews with PV system contacts include the following:

- When warranties expire, improper attention to maintenance is a strong possibility. A few of the more sophisticated respondents are entering into maintenance contracts after their warranties expire, but this is a minority of respondents.
- Contracts are hard to enforce and equipment failures can easily go undetected (meaning warranty terms would never by enforced). Many respondents had inverters replaced under warranty, but a similar number had little formal monitoring and were uncertain about systems' performance. In these cases, it is possible that faulty equipment went undetected. One respondent explained that he had a performance guarantee and maintenance contract with his installer, but the installer had stopped honoring the terms of the agreement, and then was bought out by another company that also failed to follow through on the performance guarantee.

- Project owners typically rely on the original system installer to conduct repairs and maintenance.
- The relationship a site host has with an installer seems to have strong bearing on how well a system is monitored / maintained over time.
- A number of respondents were not familiar enough with the system components / configuration to be able to understand system performance issues.
- Some unique maintenance requirements can arise due to poor system configuration and design. One respondent noted that panels were located so close together on a roof with vegetation growth that weeding had become a maintenance hassle. There was not enough room between modules to weed effectively. Another respondent noted that the system was installed too close to the edge of the roof to provide necessary roof access for the fire department, and would need to be reinstalled.
- Only one respondent noted that there had been a roof leak as a result of their PV system installation.

Conclusions and Recommendations

The objective of this analysis was to characterize PV performance degradation and identify its causes. We found that performance degradation of individual systems is significantly less than that implied by the capacity factor versus age analysis provided in the eighth-year impact evaluation and that the performance degradation we did observe was reasonable. Two thirds of degradation is attributable to reductions in output during hours that the system is online and producing power. This is not a controllable cause of degradation.

The remaining one third of degradation is attributable to outages (periods of zero/near-zero data output). Performance gains could be achieved by reducing hours of zero/near-zero output by working with equipment manufacturers and installers to minimize equipment (panels and inverters) performance issues. However, as it is, systems are online and producing power 97% of the time. Even if attentive monitoring and maintenance were able to halve this outage time, this would only increase expected annual energy output of a system by 1.5 percent; this increased diligence may not prove to be cost-effective.

In the course of this analysis, the significant extent of missing data and the significant year-over-year increase in missing data stood out. The amount of missing data varied dramatically by PA and by year of installation, which suggests that high and increasing levels of missing data are not unavoidable. Further analysis is recommended to determine the data acquisition equipment and protocols applied to the most complete data sites, as a benchmark for future SGIP and California Solar Initiative data acquisition. The current data and data quality only allows for the most general statements of output and trends, particularly as systems age. High levels of data availability will be necessary to examine performance by subgroups, such as module type or installer.

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