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Maximizing PV peak shaving with solar load control: validation of a web-based economic evaluation tool

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Abstract

We present an evaluation of a new version of the web-based clean power estimator (CPE) capable of evaluating the effectiveness and value of solar load control (SLC) for commercial applications in the US. Three experimental building case studies are used as a validation benchmark. The selected buildings include a large office building near New York City, a department store in Long Island, and another department store in Hawaii. The results of the CPE calculations are compared against results obtained using actual building load and colocated hourly actual solar radiation data.

Keywords: Photovoltaics; Utilities; Load Control; Software; Peak-shaving; Capacity credit

1. Introduction

Commercial customer-sited PV represents a valuable sector for PV deployment because:

- These customer-side-of-the-meter applications are valued against retail energy rates
- Thanks to the natural PV-load correlation characterizing many commercial buildings (e.g. see Perez et al., 1997, 1999), these applications also capture value from billed load demand reduction;
- Commercial operators can take advantage of local and national financial benefits available to businesses, such as accelerated depreciation, tax credits, or localized incentives (see DSIRE (2003), for instance, for a list of incentives available in the USA).

It has been shown that the second value element—peak load reduction—could be enhanced substantially with minor levels of end-use solar load control (Perez et al., 2000). Although it may be considered as a truism that controlling a building's load can make up for any noncontrollable power source deficit, the fact that—in the case of PV—only a benign amount of load control can deliver full capacity equivalent is less evident.

The objective of this paper is to evaluate one of the tools capable of gauging the performance and economics of solar load control.

2. Methods

2.1. Solar load control

The good correlation observed between PV output and commercial building loads leads to demand reduction at retail demand rates (e.g. see Perez et al., 1997). However, this correlation is not perfect. Since demand charges are assessed based on the highest load during some time period, a cloud passing over the PV system during a peak load event, or a slight offset between building peak and solar peak could substantially reduce the demand reduction provided by the PV system.

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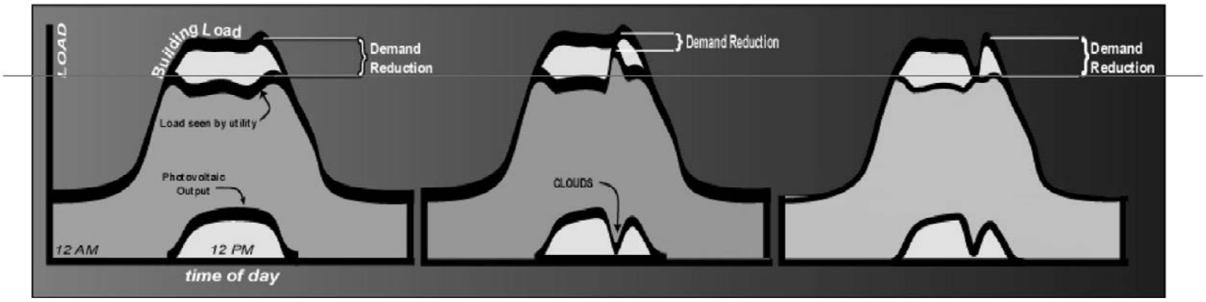

Fig. 1. Solar load control principle.

One remedy is to include a device called a solar load controller (SLC) with the PV system. The SLC enhances peak demand reduction by mitigating end-use load drivers in response to critical load/temperature situations. As shown in Fig. 1, a small amount of load control (right) can substantially increase demand reduction achieved with PV alone (center) if conditions are not ideal (as shown left).

Thermostat setting adjustment during the cooling season is an effective means of implementing solar load control. This solution is attractive, because, as shown in Fig. 4, there is a strong correlation between building load and temperature above a threshold corresponding to a building's cooling balance point. Furthermore, there is a strong time of day/day of week component to the relationship as well (Perez et al., 2001b). SLC prototype applications based on thermostat adjustment have already been carried out with satisfactory results (Perez et al., 2000). The present evaluation of the CPE focuses on this temperature-based type of load control.

2.2. Clean power estimator

The CPE (Hoff, 1999) is a web-based program designed to perform customized customer-sited PV economic evaluations based upon a comprehensive base utility retail rates and local/national incentives. Residential versions of the program have been developed for several countries (Bpsolar, 2002), while a commercial version of the program is available for the US (e.g. CEC, 2002).

The standard CPE inputs include PV system size, array geometry, cost, location, customer economic profile and system financing options. Corresponding utility rates and incentives are determined from the user-selected location. Location also determines the solar resource that is imbedded within the CPE based upon published TMY-type data.

The additional SLC-specific inputs are:

1. The maximum daily discomfort a building occupant is willing to allow (in degree–hours of temperature increase)
2. Seasonal building load profiles (defaults are available)
3. The building's cooling balance point (i.e. the outdoor temperature above which the building requires cooling) and
4. The building's load-temperature coefficient—i.e. the load-temperature trend illustrated in Fig. 4; this last input may be estimated from past bills by comparing highest summer demand and off-season demand (defaults are available as well).

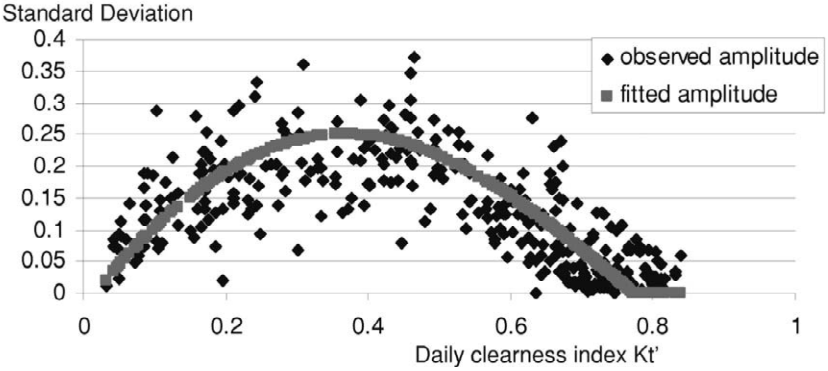

Fig. 2. Observed and modeled hourly clearness index standard deviation–amplitude—from the daily averaged valued as a function of the latter.

Based on this set of inputs the program automatically calculates demand reduction. The effectiveness and value of load control is assessed by running the program again without the SLC and comparing results.

The SLC calculations outlined below are based on site-specific 8760-h simulations (Marion and Urban, 1995). However, in order to minimize the web transfer of so many data points and to facilitate the generation of the hourly load data, the TMY data are first condensed to a set of 365 daily parameters. The data are then ‘‘reinflated’’ on the user’s computer. The condensed TMY-based information includes 365 daily values of (1) daily clearness index, (2) the ratio between daily clear-sky global irradiance and daily clear-sky irradiance on the 15th day of each month, (3) the daily minimum temperature and (4) the daily temperature range.

On the host computer, the program generates hourly ambient temperatures derived from the daily minimum temperature and range following ASHRAE guidelines (ASHRAE, 1997), as well as hourly clearness indices from the daily values using a semi-statistical methodology (Perez, 2001). In a nutshell, this methodology generates hourly indices by introducing a random Gaussian deviation from the daily average. The amplitude of this random deviation is a function of the daily clearness index value, empirically derived from measured data in varied climatic environment. This function is illustrated in Fig. 2.

Hourly PV outputs are obtained by modulating the standard (12-months×24-h) average PV output tables generated within the CPE with the hourly clearness index.

In parallel, hourly building loads are generated via a simple linear modulation of the reference building load profiles with hourly temperature above the building’s balance point—using the input load temperature coefficient specified above.

This condensed approach allows one to generate hourly output for arbitrary PV configurations ‘‘on the fly’’, along with time coincident building demand, using only a small number of transferred data, and hence allowing very fast web-based computations.

Once hourly building loads and PV outputs are computed, the program calculates the monthly demand reduction resulting from PV, as well as the additional reduction made possible by the SLC if that option is selected. The additional load reduction from the SLC is done iteratively, by adjusting the peak day threshold line downwards until the selected maximum daily SLC degree−hours amount is exhausted, following:

$$\Sigma_{\text{day}} \max(0,(\text{load} - PV\text{–threshold}))$$

$$= \text{selected\_degree–hours} * \text{temperature\_coefficient}$$

2.3. Experimental building data

We selected three buildings with differing characteristics where hourly load data were available and where site/time coincident solar resource data could be obtained either from colocated solar radiation measurements or from satellite remote sensing (Perez et al., 2001c).

The buildings include a large air-conditioned office building near New York City, a department store in Long Island, New York, and another department store in Hawaii. The peak load profile of these buildings is shown in Fig. 3. Note the typical ‘‘9−5’’ load shape of the NYC building, with a daytime excursion well in phase with the solar resource. The longer operating hours of the Long Island store are clearly noticeable. The Hawaii store is a 24-h operation, with a small daytime peak superimposed on a high baseload.

Load temperature responses are shown in Fig. 4. The New York office building clearly shows a winter mode with little temperature dependence on the left, and a

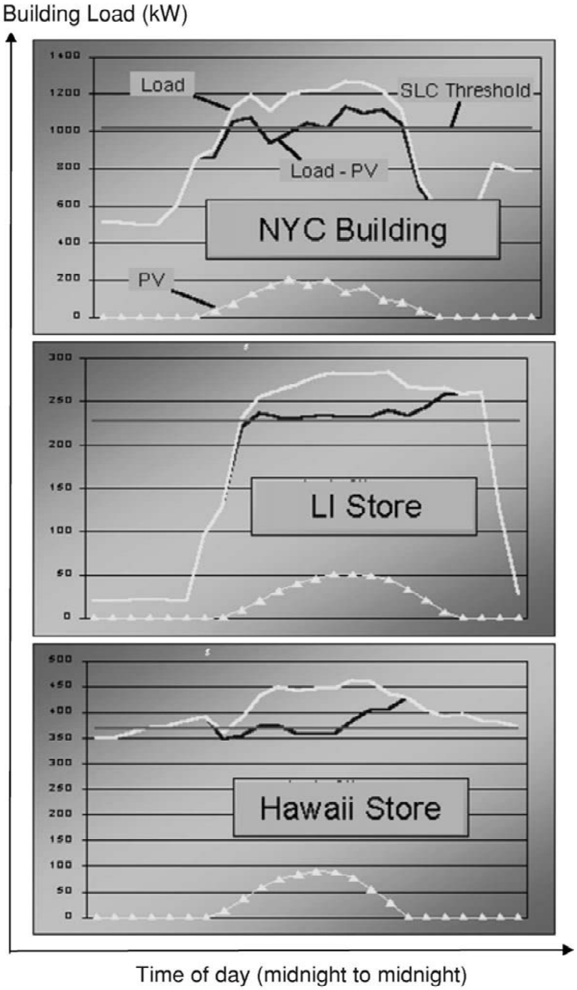

Fig. 3. Yearly peak day load profile, PV output (at 20% penetration) and load control threshold for the selected buildings.

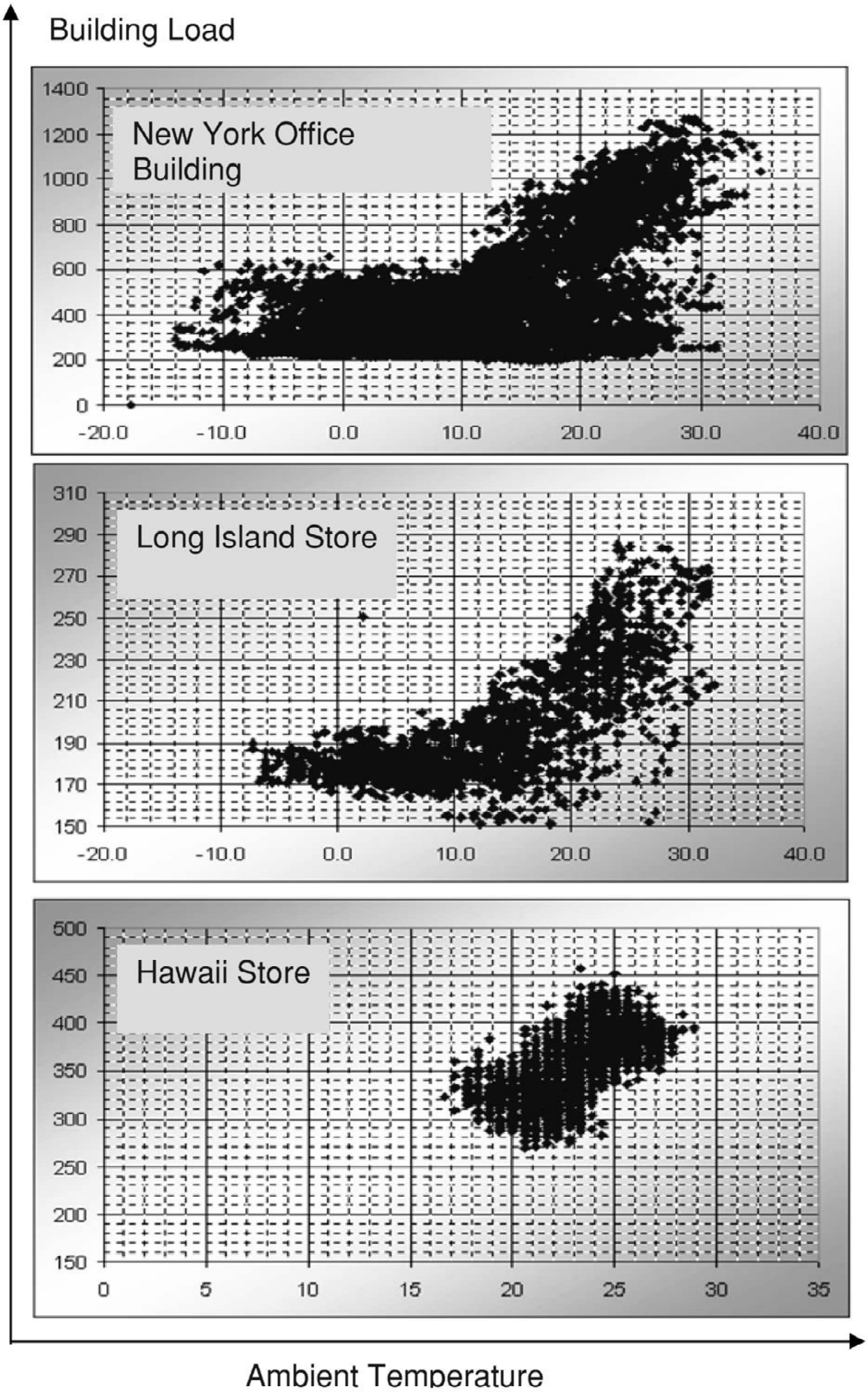

Fig. 4. Load vs. ambient temperature signature for the selected buildings.

summer cooling mode on the right with strong temperature dependence. Also note the dual weekend/week-day traces, with weekends showing little temperature-induced load increase. The Long Island store also exhibits the winter and summer modes, but no weekend trace. The Hawaii store only exhibits a cooling mode signature.

2.4. Evaluation metrics

For each building we compare results obtained with actual load and solar resource data to the results obtained using the CPE. The only building specific input consists of average load shapes and temperature–load coefficients. The comparative results include:

- Peak load reduction without solar load control at 5%, 10% and 20% PV penetration
- Peak load reduction with solar load control set at a maximum 1-day burden of 10 °C-hours.
- Present value of the solar load control assuming a 30-year system life and a 7% discount rate and a 2% rate of inflation, using large general service demand rate from the corresponding local electric utilities.

3. Validation results

Peak load reduction without load control (Table 1): On a yearly basis PV peak load reduction estimated from actual data is very close to CPE estimates for the two New York buildings. Agreement is reasonable as well for individual months—this is important because demand reduction is valued on a monthly billing cycle. PV-alone load reduction is substantial for both buildings, but tends to degrade more rapidly with penetration for the department store as a result of this building's longer evening shoulder. PV-alone peak load reduction is not as strong for the Hawaii building particularly as penetration increases, as would be expected from the low daily load excursion. The CPE tends to overestimate peak load reduction but within reasonable limits.

Peak load reduction with SLC (Table 2): The CPE correctly estimates yearly peak load reduction results for the New York office building, with a small tendency toward underestimation for monthly values. Overall the ten degree—hours maximum daily SLC allowance more than doubles the PV-alone peak load reduction. Results for the Long Island department store are very close, both on an annual and monthly basis. For Hawaii, the results are remarkably close on an annual basis, with a tendency to CPE underestimation on a monthly basis.

Solar load control value (Table 3): The best match is obtained for the Long Island store where the CPE accurately predicts the SLC value. For New York and Hawaii the CPE predictions are on the conservative side par-

Table 1
Peak load reduction without solar load control

	Installed	Pv-size	Peak load reduction without SLC (kW)												
	PV as % of peak load	kW-ptc					May	Jun	Jul	Aug	Sep				Year
NYC Building							Derived from actual data								
	20	253					122	98	106	133	131				133
	10	127					90	79	82	66	70				66
	5	63					52	48	53	33	37				33
							Estimated with clean power estimator								
	20	250					151	112	147	72	58				112
	10	125					95	69	101	69	35				69
	5	63					54	40	58	39	23				39
LI Store							Derived from actual data								
	20	57					25	23	23						23
	10	29					25	22	22						22
	5	14					12	11	13						11
							Estimated with clean power estimator								
	20	57					28	25	23						23
	10	29					17	17	23						23
	5	14					9	9	13						13
Hawaii Store			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
			Derived from actual data												
	20	92	39	32	14		26	31	17	35	29	13	7	15	15
	10	46	28	21	7		16	16	9	23	22	12	11	7	15
	5	23	14	15	3		10	8	5	12	16	10	8	7	15
			Estimated with clean power estimator												
	20	92	32	47	27		41	30	22	35	41	27	32	26	27
	10	46	28	38	19		34	24	20	30	27	24	27	25	24
	5	23	14	18	15		17	12	17	17	13	14	13	14	14

Table 2
Peak load reduction with solar load control

	Installed PV as % of peak load	Pv-size kW-ptc	Peak load reduction with 10 deg-hours max SLC (kW)												
NYC Building			Derived from actual data												
	20	250	252	223	237	250	271	223							
	10	125	169	171	162	178	203	178							
	5	63	125	137	120	136	161	136							
			Estimated with clean power estimator												
	20	250	250	195	221	166	140	195							
	10	125	165	128	149	142	111	142							
	5	63	115	90	110	114	92	114							
LI Store							May	Jun	Jul	Aug	Sep				Year
							Derived from actual data								
	20	57					49	46	45						46
	10	29					35	33	40						33
	5	14					25	26	37						26
							Estimated with clean power estimator								
	20	57					51	49	49						49
	10	29					38	35	37						35
	5	14					30	26	29						26
Hawaii Store			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
			Derived from actual data												
	20	92	87	78	83		68	70	72	77	80	57	71	60	69
	10	46	77	72	72		54	59	58	70	64	48	65	55	61
	5	23	67	64	63		46	51	50	58	49	39	52	49	50
			Estimated with clean power estimator												
	20	92	56	74	52		65	57	42	62	70	62	63	53	65
	10	46	48	57	44		56	47	38	48	58	51	59	45	58
	5	23	42	46	37		44	38	35	39	45	42	49	38	45

Table 3
Present value of solar load control

Installed PV as % of peak load	Pv-size kW-ptc	Average performance and NPV of SLC with 1-day action of 10-C hours					
		From actual data			From CPE		
		Monthly peak reduction (kW)			Monthly peak reduction (kW)		
		w/o SLC	with SLC	NPV	w/o SLC	with SLC	NPV
Long Island Dept. Store							
20	57	24	46	$27,376	25	50	$29,455
10	29	23	36	$16,084	19	37	$21,572
5	14	12	29	$20,547	10	28	$21,777
Hawaii Dept. Store							
20	92	23	73	$102,725	33	60	$56,613
10	46	16	63	$97,584	27	50	$48,368
5	23	10	53	$89,557	15	41	$54,924
New York Office Building							
20	250	120	247	$173,548	108	194	$116,637
10	125	76	177	$133,929	74	139	$88,018
5	63	43	136	$123,206	43	104	$82,888

ticularly in Hawaii, where the Clean Power Estimator overestimates PV-alone peak load reduction, while it underestimates the PV + SLC reduction, thereby ''squeezing'' the SLC's impact. Overall however, the CPE predictions remain representative of the solar load control value.

4. Discussion

Two important issues are highlighted by the present analysis: (1) The performance of solar load control as a PV peak shaving enhancer; (2) the performance of the clean power estimator as a web-based, widely accessible, simulation tool.

SLC performance: the present case studies confirm that solar load control can substantially enhance PV load reduction and that this enhancement is synergistic—i.e. the same 10-degree hours of maximum daily user discomforts ''buy'' more kW of peak load reduction as PV system size increases, with a corresponding impact on the SLC value, much like a diversified portfolio whose total combined value potential exceeds the sum of its individual components (Perez et al., 2001b). The SLC present value, ranging from a few $10 000s for the smallest building to over $100 000 for the largest building, is worth several times the anticipated value of solar load control units (Perez et al., 2000).

CPE performance: the CPE simulations come very close to the actual data-based simulations on an annual basis. On a monthly basis, they are on the optimistic side for PV-alone simulations, and a bit conservative for PV + SLC simulations, resulting in a conservative but nevertheless representative estimate of SLC value—worth several times its projected cost. The cause of this under/overestimation likely lies in the building load shape characterization. The CPE currently uses daily average load profiles modulated by ambient temperature. Actual building loads tend to be noisier than average profiles, penalizing PV-alone peak load matching, with a higher probability of an ''out-of-sync'' secondary peak. On the other hand, the nosier load profiles with narrow secondary peaks tend to favor the effectiveness of load control.

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References

ASHRAE, 1997. Handbook of Fundamentals, Section 28.6 Table 2.

Bpsolar, 2002. www.bpsolar.com

CEC, 2002. www.consumerenergycenter.com/renewable/

Hoff, T.E., 1999. Clean Power Estimator. ASES-1999 Conference, Portland, ME. The SLC version of the CPE may be accessed at: http://www.clean-power.com/nrelpv/login.asp

Marion W., Urban K., 1995. User's Manual for TMY2, NREL Report, NREL, Golden, CO.

Perez, R., Seals, R., Herig, C., 1997. Determination of the end-use effective capacity of photovoltaics. In: Proc. 14th European PV Conference, Barcelona, Spain.

Perez, R., Kmiecik, M., Herig, C., Wenger, H., 1999. Mapping the Value of Commercial PV Applications in the US Accounting for Externalities. In: Proc. ASES Annual Meeting, Portland ME.

Perez, R., 2001. Report on TMY data extrapolation methodology, Contract AXE-0-30070-01, Technical Status Report No. 3. NREL, Golden CO.

Perez, R., Schlemmer, J., Bailey, B., Elsholtz, K., 2000. The solar load controller—end-use maximization of PV's peak shaving capability. In: ASES-2000 Conference, Madison, WI.

Perez, R., Hoff, T., Ball, G., 2001b. Using Product Portfolios to Increase the Value of Customer-Sited PV. Proc. Solar Electric Power Association Meeting, UPEX'01, Sacramento, CA.

Perez, R., Kmiecik, M., Renné, D., Herig, C., 2001c. Remote monitoring of PV performance using geostationary satellites. Solar Energy 71 (4), 255–261.

DSIRE, 2003. The Database of State Incentives for Renewable Energy (DSIRE) www.dsireusa.org/