Life-cycle Characteristics of Customer-sited Small-scale Residential Photovoltaic Systems

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ABSTRACT

In 1998, the Los Angeles Department of Water and Power (LADWP) implemented a spearhead research program for the purpose of determining the real world, in-situ, life-cycle performance of small scale photovoltaic (PV) systems. These systems were to be owned and operated by the municipal utility, installed on residential structures, and would introduce the use of photovoltaics into the LADWP's electric generation portfolio.

The early results obtained from the program provided the necessary background electrical performance and installation feasibility experience that was necessary to develop the utility's larger $150 million, 10-year, solar power customer incentive "buydown program," initially offered to its residential and commercial customers beginning in September 2000. The buydown program continues to be offered to LADWP customers through June 30, 2011.

In the 1998 program, the utility provided 2.5 kilowatt roof-mounted PV systems and installation labor, and requested program volunteers from its residential customer base. The volunteer sites provided roof space for the photovoltaic modules and wall mounting space for the balance of system and dedicated meter. The systems were connected directly to the local distribution circuit, and provided solar generated electricity directly to the municipal grid. From a number of respondents, 12 sites were qualified for installation of the systems.

In 2004, the utility formally began its phase out of the research program by either removing those systems from service or transitioning them to private customer ownership.

This article examines the experiences gained from this research program, discusses the role of these small residential systems within the distribution network of a large municipal utility, summarizes the life-cycle characteristics of these systems when placed in the urban municipal customer environment, and examines the role of "early adopters" in utility-sponsored renewable energy programs.

BACKGROUND

Prior to 1998, the Los Angeles Department of Water and Power (LADWP) did not have a solar photovoltaic program. With the adoption of California Assembly Bill 1890 into the Public Utilities Code, all California utilities were required to allocate a percentage of revenue towards public benefits. The public benefits allocation was included in the legislation to support continued research and development, renewable energy, and other public benefit programs in the context of a deregulated electric industry. Eventually, LADWP would implement a comprehensive solar power program. To do so, it was necessary to obtain detailed experience with solar power systems that would be available to utility consumers.

The program conceptualized a solar study that utilized system hosting on a basis where the utility would provide the labor and materials for the installation of a solar power generation system, and utility customers would provide space to install these systems. Basically, utility customers who were interested in renewable energy were asked to 'volunteer' their roofs so that the utility could obtain needed experience and data to develop a solar power program. The volunteer program was offered to all utility customers, and it was hoped that the utility's Green Power subscribers would opt in to the R&D effort. After a period of less than one year, the program had obtained a number of candidates and had successfully installed 14 systems.

INITIAL PHASE

The selection of installation sites was based on a set of potential performance criteria and drawn from the pool of candidate sites. The systems were standardized on a specific combination of photovoltaic modules, inverter, and installation hardware.

Basic Selection Criteria:

1 LADWP residential customer

2 new or recent roofing installation

3 availability and access to roof

4 adequate roof space to accommodate 32 PV modules

5 unobstructed solar access (shading)

6 favorable cardinal orientation (within 45 degrees of south)

The systems were installed by LADWP crews at 12 locations in various areas of Los Angeles (see Table 1).

Table 1. Installation Sites

Key	*Street Location*	*LA Area*	*Location*	*Orientation*
1. SP01	Vestal Ave.	Central	Echo Park	S
2. SP02	Russell Ave.	Central	LA	SE
3. SP03	Plummer St.	Valley	Northridge	S
4. SP04	Tuba St.	Valley	Northridge	S
5. SP05	Cozycroft Ave	Valley	Canoga Park	SW
6. SP06	Valecrest Dr.	Central	Sun Valley	S
7. SP07	Willowcrest Ave.	Central	Toluca Lake	S
8. SP08	Jersey St.	Valley	Granada Hills	S
9. SP09	Nancy St.	West	Westchester	S
10. SP10	Bagley Ave.	Central	LA	S
11. SP11	Westridge Terrace	Central	LA	S
12. SP12	Firth Ave.	West	LA West	S

Basic System Specification:

2.52 kilowatt peak DC output

36 Siemens Solar SP-70 photovoltaic modules

Two or three Xantrex inverters

Grid-tied at utility side of service connections

Dedicated individual electric meter

OPERATIONS PHASE

The solar power systems operated nearly maintenance free, with some notable exceptions. The systems that experienced operational anomalies were designated as disqualified data for purposes of the analysis (see Tables 2 and 3).

Table 2. Summarized 5-Year Performance, 2000-2004

		Qualified Data	*LA Area*		*Total kWh*	*2000*	*2001*	*2002*	*2003*	*2004*
1	SP01	Vestal Ave.	Central	S	15197	2991	3052	3196	3021	2938
2	SP02	Russell Ave.	Central	SE	10912	2472	2424	1170	2443	2404
4	SP04	Tuba St.	Valley	S	9735	1978	1939	2010	2033	1775
5	SP05	Cozycroft Ave	Valley	SW	7285	1558	1590	957	1464	1716
6	SP06	Valecrest Dr.	Central	S	15438	3137	3075	3102	3085	3039
7	SP07	Willow-crest Ave.	Central	S	10581	2082	2125	2000	2304	2070
8	SP08	Jersey St.	Valley	S	11154	2382	2336	1765	2326	2345
9	SP09	Nancy St.	West	S	13836	2723	2778	2726	2627	2982
10	SP10	Bagley Ave.	Central	S	13539	2751	2697	2783	2734	2574
11	SP11	Westridge Terrace	Central	S	16353	3218	3284	3334	3253	3264
		Disqualified Data								
3	SP03	Plummer St.	Valley	S	5023	1216	1241	1256	86	1225
12	SP12	Firth Ave.	West	S	10622	3446	3310	3378	488	0

Data Qualifications

The outlying data from systems SP3 and SP12 was removed from the analysis set. In addition, it was necessary to normalize the data set because two of the systems installed with a smaller set of modules than the standard specification. Because the power output generally varies linearly with the number of modules in the series circuit string, the 30 module systems were normalized to a 36-module system with the data reflecting the larger energy output that would have been obtained (see

Table 3. List of Anomalies

	Key	*Street Location*	*LA Area*	*Operational Anomalies*
1.	SP01	Vestal Ave.	Central	—-
2.	SP02	Russell Ave.	Central	—-
3.	SP03	Plummer St.	Valley	System vandalized when homeowner rented house
4.	SP04	Tuba St.	Valley	—-
5.	SP05	Cozycroft Ave	Valley	—-
6.	SP06	Valecrest Dr.	Central	—-
7.	SP07	Willowcrest Ave.	Central	—-
8.	SP08	Jersey St.	Valley	—-
9.	SP09	Nancy St.	West	—-
10.	SP10	Bagley Ave.	Central	—-
11.	SP11	Westridge Terrace	Central	—-
12.	SP12	Firth Ave.	West	Owner misinterpreted agreement and relocated system to new house outside LA City service, system returned.

Table 4 and Figure 1). The applied normalizing coefficient was a direct ratio of 1.2.

Los Angeles Climate Area Grouping

To distance individual system variance from typical system performance, the data was grouped by geographic area of Los Angeles.

The Los Angeles basin includes three distinct areas in which the systems were installed. The fourth area, in which no small PV systems in the R&D were installed is the area south of Los Angeles known as the Port of Los Angeles. This area is adjacent to Long Beach, and includes marine layer effects, which may reduce the insolation. We expected that the systems installed in the West area would exhibit similar marine layer effects.

Observed Performance by Climate Area

Contrary to our expectations, the actual results obtained and demonstrated in the analysis, implies that the marine layer effects previously

Table 4. Summarized 5-Year Performance, 2000-2004, Data Normalized

	Key	*Street Location*	*LA Area*		*Total kWh*	*2000*	*2001*	*2002*	*2003*	*2004*
1	SP01	Vestal Ave.	Central	S	15,197	2,991	3,052	3,196	3,021	2,938
2	SP02	Russell Ave.	Central	SE	10,912	2,472	2,424	1,170	2,443	2,404
4	SP04	Tuba St.	Valley	S	9,735	1,978	1,939	2,010	2,033	1,775
5	SP05	Cozycroft Ave	Valley	SW	7,285	1,558	1,590	957	1,464	1,716
6	SP06	Valecrest Dr.	Central	S	15,438	3,137	3,075	3,102	3,085	3,039
7	SP07	Willowcrest Ave.	Central	S	12,697	2,499	2,550	2,400	2,765	2,484
8	SP08	Jersey St.	Valley	S	11,154	2,382	2,336	1,765	2,326	2,345
9	SP09	Nancy St.	West	S	13,836	2,723	2,778	2,726	2,627	2,982
10	SP10	Bagley Ave.	Central	S	16,247	3,301	3,236	3,340	3,281	3,089
11	SP11	Westridge Terrace	Central	S	16,353	3,218	3,284	3,334	3,253	3,264

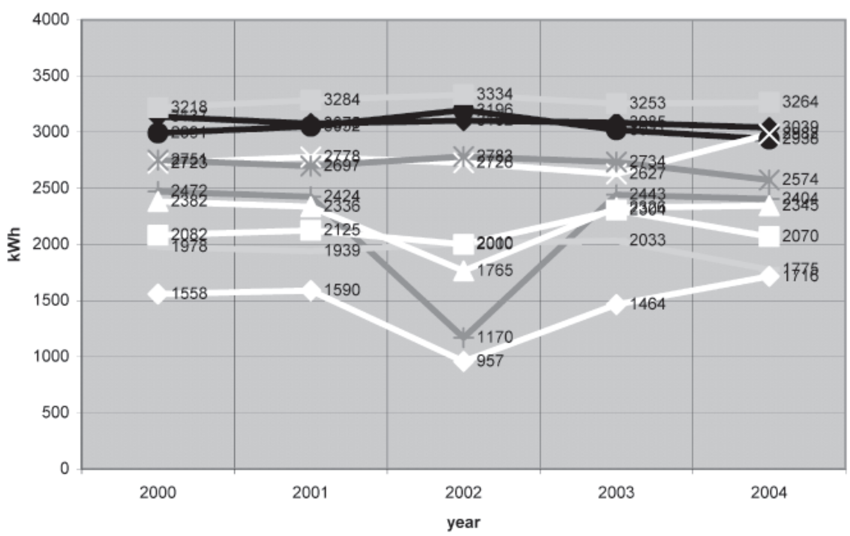

Figure 1. Annual Output (qualified data)

considered to be a detrimental factor in the performance of these small solar power systems, actually did not present itself in the data. As can be seen in Table 5, the actual performance of systems in the Valley area performed poorly compared to the Central and Western areas (also see Figure 2).

Table 5. Summarized 5-Year Performance, 2000-2004, by L.A. Climate Area

Per Installation	LA Area	n	Avg 5yr	2000	2001	2002	2003	2004	Avg 1yr
	Central	6	14,474	2,936	2,937	2,757	2,975	2,870	2,895
	Valley	3	9,391	1,973	1,955	1,577	1,941	1,945	1,878
	West	1	13,836	2,723	2,778	2,726	2,627	2,982	2,767

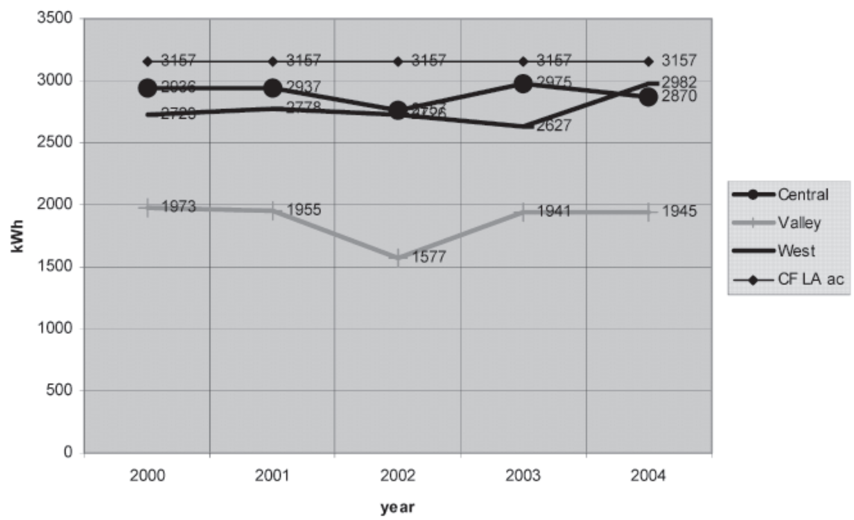

Figure 2. Average Annual Output by L.A. Area (normalized system size)

We hypothesize that the marine layer effect, may actually moderate heat buildup in the modules to a degree that offsets the insolation reduction. This is supported by the fact that the average mean temperature in the Valley is substantially higher than the Central and the West areas.

Mean temperatures in the Central and West areas during the best summer months range in the mid 80s(°F). The Valley during those same months experiences mean temperatures in the mid to upper 90s(°F). On several occasions during the summer, 3 to 5 day heat waves may push Valley temperatures to 100°F and above. These elevated temperatures may be negatively impacting the PV module efficiency.

Capacity Factors

Electric power utilities compare electric power generation facilities based on various components, including capacity factor (CF). Simply, CF indicates the ratio of equivalent actual energy generating output to possible generating output. The possible generating output is calculated assuming performance of the equipment at 100% manufacturer rating and at a 100% duty cycle. For example, an imaginary generating power plant running continuously, with 0% losses, would exhibit a CF = 1.0.

Typical power plants perform with CF significantly less than 1.0. A coal-fired power plant, with its need to maintain boilers and steam generators at optimal temperatures, would exhibit a CF in the 0.8 to 0.9 range. However, such high CF is reduced by scheduled repair and maintenance outages (SIRs) and system disturbances. A more typical CF would be 0.75 to 0.85.

Renewable energy systems vary widely in CF. A biomass power plant would perform similarly to other fossil-fuel-fired power plants, because the generation equipment is analogous. However, intermittent energy source renewable energy systems such as wind and solar, do not approach typical fossil-fueled boiler or turbine power plant CF levels. Wind is highly variable, and availability may not coincide with energy load schedule. The Los Angeles utility experiences peak energy demand in the summer months and during the midday to late afternoon period.

Solar energy is highly predictable, but is available only during a specific window of time during the day. Peak energy content in the insolation radiation occurs at midday and during the summer months. As a result, although solar energy is highly variable (from 0 at night to 100% during the day), it is highly predictable. The high predictability provides a critical feature to energy dispatchers at the electric utility, in that solar energy is predictably *dispatchable*.

We calculated expected CF from the DOE NREL* insolation data for the Los Angeles areas, deducting losses for actual photovoltaic module radiant sky energy capture, typical atmospheric and environmentally induced soiling, and non-optimal solar orientation. Further losses accounted for and deducted in our calculation were the DC to AC electrical conversion losses, which include wiring and inverter losses.

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*U.S. Department of Energy, National Renewable Energy Laboratory

As can be seen in the analysis tabulated in Tables 6 and 7 the Central area of Los Angeles most nearly approached the calculated and expected capacity factors: 0.146 achieved versus 0.159 expected by calculation (see also Figure 3).

Performance and total energy output varied from system to system, but remained typically in a 15% to 20% range from mean. This result confirmed our expectations that site selection would be a critical component, along with system orientation.

Note that the West area included only two systems, of which one was disqualified because the property owner physically relocated the system in 2003, causing the system to remain inoperative. However, the standard deviation calculation cannot be performed without consideration of that system. The data shown in the 2000 through 2002 columns for that system show a deviation of 511, 376, and 461 kilowatt-hours. These values compare favorably with the Central and Valley data, 364, 362, 852, and 412, 373, 551, respectively. Thus, we conclude that the one

Table 6. 5-Year Performance, 2000-2004, Kilowatt-hours at Various Capacity Factors

Per Installation		*n*	*2000*	*2001*	*2002*	*2003*	*2004*	*Avg 1yr*
100% Duty Cycle	CF 1.0	1.00	19,881	19,881	19,881	19,881	19,881	19,881
LA Average Insolation (5.5h)	CF LA in	0.23	4,556	4,556	4,556	4,556	4,556	4,556
LA Insolation Capture	CF LA pv	0.18	3,580	3,580	3,580	3,580	3,580	3,580
Delivery to AC grid	CF LA ac	0.16	3,157	3,157	3,157	3,157	3,157	3,157

Table 7. 5-Year Performance, 2000-2004, Capacity Factors CY LA Area

Per Installation		*2000*	*2001*	*2002*	*2003*	*2004*	*avg 1yr*
Expected CF	Calculated	0.159	0.159	0.159	0.159	0.159	0.159
Actual CF	Central	0.148	0.148	0.139	0.150	0.144	0.146
	Valley	0.099	0.098	0.079	0.098	0.098	0.094
	West	0.137	0.140	0.137	0.132	0.150	0.139

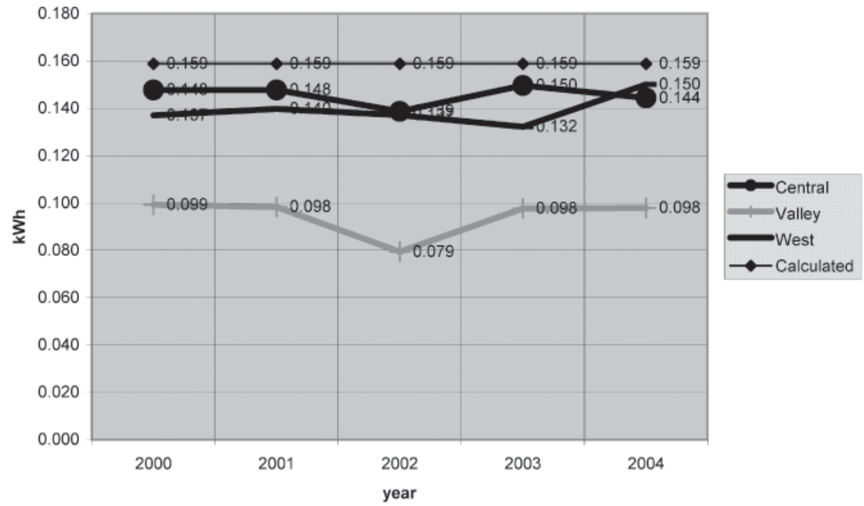

Figure 3. Annual Capacity Facotrs by L.A. Area (normalized system size)

system in the West area that completed the 2000-2004 test period can be relied upon to provide typical system response for that geographic area (see Tables 8 and 9 and Figure 4 and 5).

FINAL PHASE

The final phase of the R&D project consisted of decommissioning the systems. However, it was suggested by program participants that the systems be decommissioned in-place, and offered to the host property owners for purchase at remaining cost.

The offer to purchase was extended to the program participants, and 10 of the 11 sites opted to purchase the systems. One participant requested that the system be removed and roof space restored to prior condition.

Once purchased, the systems become customer-owned grid tied systems, and interconnection is governed by established electric safety and system operation rules. Many of these rules developed as a result of and concurrent with the operation of this research project.

Customers connecting to the LADWP grid are required to sign an interconnection agreement, which provides the benefit of net metering

Table 8. 5-Year Performance, 2000-2004, Kilowatt-Hours, Standard Deviation

Analysis	*LA Zone*	*2000*	*2001*	*2002*	*2003*	*2004*
Std Dev	Central	364	362	852	320	347
Std Dev	Valley	412	373	551	438	347
Single Data Point	West	0	0	0	0	0
Std Dev (nonqualif)	West(NQ)	511	376	461	1513	2109
Std Dev	All	565	566	891	581	549

Table 9. 5-Year Performance, 2000-2004, Variance Coefficient

LA Zone	*2000*	*2001*	*2002*	*2003*	*2004*
Central	0.124	0.123	0.309	0.108	0.121
Valley	0.209	0.191	0.349	0.226	0.179
West	0.000	0.000	0.000	0.000	0.000
West (non-qualified)	0.166	0.124	0.151	0.971	1.414
All	0.215	0.216	0.371	0.221	0.211

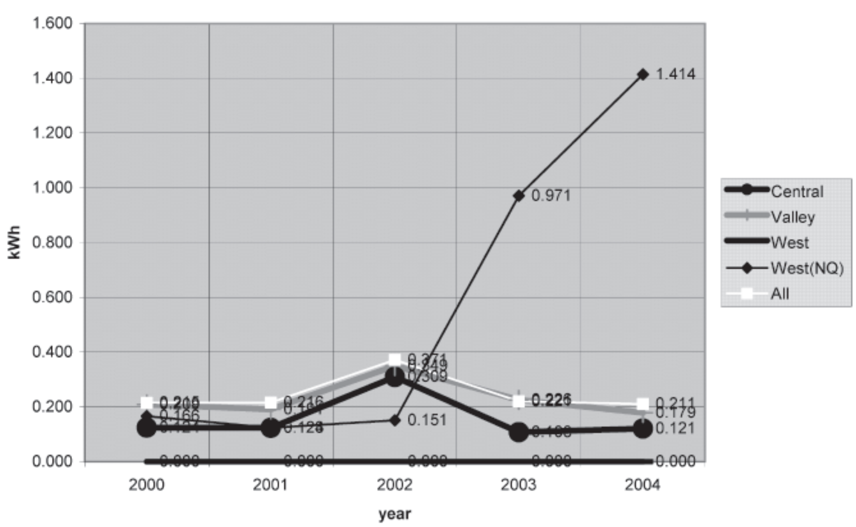

Figure 4. Variance by L.A. Climate Area (including non-qualified data)

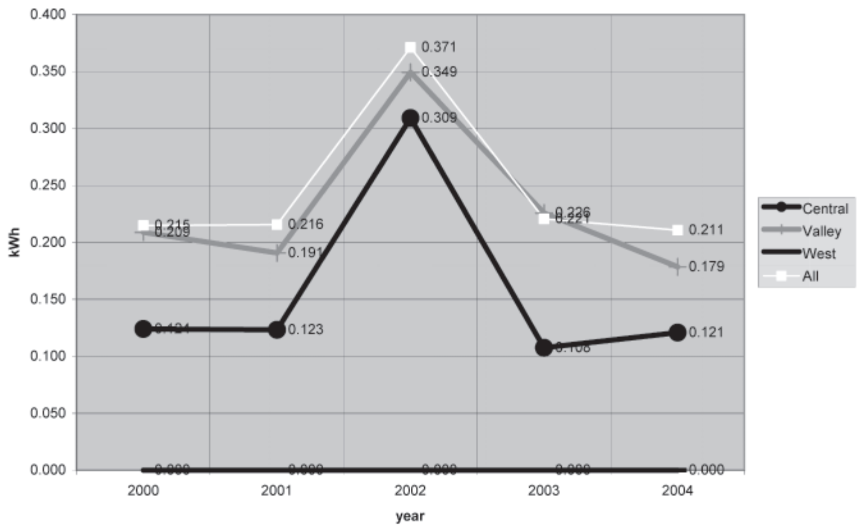

Figure 5. Variance by L.A. Climate Area (system sized normalized, qualified data)

rates (tariffs) for the customer, and provides a contractual agreement for the utility, by which system operation and safety rules can be monitored and enforced. Systems are labeled with required signage that indicates where system disconnect switch(es) are located on the property, and marked with standard cogeneration symbols used by LADWP.

The solar hosting program systems are expected to operate for the duration of the life of the original equipment, which includes warranted performance by the module manufacturer to 20 years from original installation. Inverters are expected to require servicing, upgrading, or replacement during the remaining warranty on the photovoltaic modules.

CONCLUSION

The solar hosting program yielded valuable data regarding the installation and performance of small residential solar power systems. The immediate direct results included:

- Establishment in September 2000 of a solar power system rebate program for LADWP customers.

- Experience and hands-on training for LADWP support personnel, including construction trades, design engineers, and electrical inspectors.
- Support for establishment of a $150 million dollar, 10-year solar power program, which continues today in its fifth year.
- Allocation of regular annual funding in LADWP budgets for solar power system rebates.
- Creation of a need for other groups within the LADWP and the City of Los Angeles to enact and support key legislation, including residential net metering, LADWP electric rate ordinances (tariffs), and work leading to commercial net metering.

The detailed analysis of the residential system performance resulted in several observations:

- Solar insolation in the Los Angeles area is relatively unaffected by the presence of the "June gloom" marine layer.
- Solar performance during the hottest months in Los Angeles, when temperatures hover into the 100°F range, results in a substantial decrease as evidenced by performance in the San Fernando Valley area.
- Residential solar power systems are reliable, with no module or inverter failures during the test period.

ABOUT THE AUTHOR

Thomas Honles, P.E., S.E. is a registered California civil engineer and structural engineer. Mr. Honles graduated in 1987 with a Bachelor of Science in civil engineering from California State University, Los Angeles. He obtained his Professional Engineer, Civil license in 1990, and the Structural Engineer license in 1995. He has been involved with photovoltaic systems since 2000 and has designed and managed the construction of several solar photovoltaic installations in Los Angeles, totaling over one megawatt peak power capacity. Mr. Honles has been employed with the Los Angeles Department of Water and Power (LADWP) since 1987. He has designed electric substations, dealt extensively with seismic strengthening issues, and participated in emergency utility operations, including after the 1994 Northridge Earthquake. Recently, from 2001 through 2003, Mr. Honles managed the LADWP $150 million, 10-year

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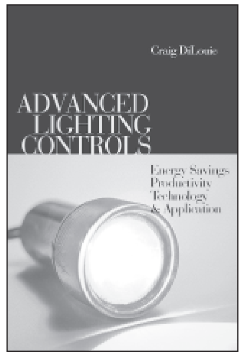

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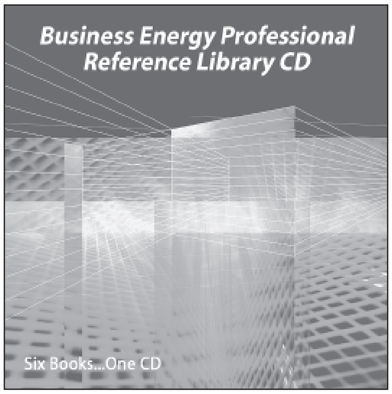

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solar power program, achieving an installed base capacity of over 8 MW of customer-sited solar electric generation. He is currently involved with the design and construction of several solar power systems on City of Los Angeles public buildings as project manager and structural design engineer. In addition to public presentations on photovoltaic technology and programs at LADWP, Mr. Honles has also spoken on issues of seismic safety, energy efficiency, and water conservation. Mr. Honles may be contacted at *thomas.honles@ladwp.com*.