Prepared for ASES Annual Meeting, Minneapolis, MN, July 1995

Geographical Distribution of Photovoltaic Effective Capacity in the United States

Richard Perez and Robert Seals
ASRC, The University at Albany, Albany, NY, USA

ABSTRACT

This paper presents a preliminary map of the effective capacity of grid-connected photovoltaic (PV) in the United States. The well defined relationship, recently observed by the authors, between the effective capacity of PV and utility load shapes, was used as a basis for the development of this map. Seasonal peak load data for most large and medium size US utilities for the year 1993 constitute the primary input to this exercise.

1. BACKGROUND

1.1 Defining PV's Effective Capacity

PV power plants have traditionally been given low or no capacity credit because their output cannot not be controlled or dispatched. However, many studies have shown [e.g., 1, 2] that, under favorable conditions, particularly when load requirements are driven by commercial air conditioning, PV power is available at peak time, and therefore, can *effectively* contribute to localized and/or utility-wide generating capacity. Under these conditions, the *effective capacity* of PV may be considerably higher than its capacity factor. This may have important economic implications, since much of the value of PV (including both its traditional capacity value and its local T&D value) is linked to its effective capacity.

1.2 Quantifying PV's effective capacity

Several parameters have been introduced to quantify effective capacity. These include both statistical parameters and deterministic parameters [e.g., see 2].

An example of statistical parameter is the *Effective Load Carrying Capability* or *ELCC*. This parameter was originally introduced by Garver [3] for non-interconnected utilities. It is defined as the increase in available capacity due to the added resource (in this case, PV) at constant loss of load probability (LOLP). A normalized version of the ELCC (see [2]) is used in this paper. This assumes a generic LOLP for any load studied, making the ELCC solely a function of the relationship between load requirements and PV output. ELCC is reported in % of installed PV capacity -- in this paper, installed PV capacity is assumed to be summer-peak time AC capacity.

An example of deterministic effective capacity parameter is the *Minimum Buffer Energy Storage (MBES)* needed, in addition to the PV resource, to guarantee 100% ELCC (see [2]). This parameter is a measure of the worse case mismatch between the load requirements and the resource. MBES is quantified in terms of installed PV capacity-hours.

In this paper, we focus our attention on the ELCC parameter as a measure of effective capacity. It should be said however, that, with few exceptions, all load matching parameters tend to agree closely [2].

The ELCC of peak-coincident, but intermittent, resources such as PV has been found to decrease as a function of the penetration of PV on the considered grid. For this study, we consider a moderate level of PV penetration of 2%. In addition, PV's effective capacity is, of course, a function of the considered type of PV array, and at this time, we consider exclusively 2-axis tracking configurations. Therefore, in the remainder of this paper, the terms "*effective capacity*", "*ELCC*", and "*2-axis tracking ELCC at 2% penetration*" will be used interchangeably.

2. OBSERVING A RELATIONSHIP BETWEEN LOAD SHAPE AND ELCC

It is an increasingly recognized observation that the effective capacity of PV is related to the indirect feed-back between solar irradiance and air conditioning-driven load requirements: high insolation conditions tend to enhance hot weather conditions which drive up day-time air conditioning demand.

However, because so many parameters influence loads (customer mix, load drivers, generation mix, building types, etc.), it would be extremely difficult to formulate the physical relationship between the effective capacity of PV and a given utility or substation load.

In practice, the only reliable approach to estimate the effective capacity of PV has been to proceed experimentally through the analysis of a representative sample of hourly (or shorter time step) utility load and time/site coincident PV output data.

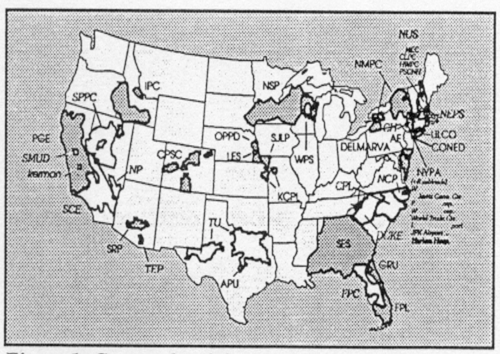

***Figure 1:** Geographical distribution of test utility, substation, and customer loads*

In an ongoing study by the authors [2,4,5], the effective capacity of PV was determined for a large sample of US utilities, substations, and large customers. The necessary time/site specific PV output data were derived from satellite remote sensing. The accuracy of the satellite-based approach has been reported in [6]. The load studied span several orders of magnitude, from a few 100 kW to several GW, and cover most US climatic and socio-economic regions (see Fig. 1).

Two key findings of this work are:

(1) Some of the highest effective capacities are found in regions which have not traditionally been associated with solar energy, in particular, the central US and the eastern sea board;

(2) A well defined relationship was observed between load shapes and effective capacity. This relationship is shown in Fig. 2. The load shape is characterized in terms of its "modified summer-to-winter peak load ratio" (a composite parameter based primarily on the load's summer-to-winter peak load ratio, but also accounting for time of peak, extent of evening shoulder, daily excursion, off-season load and load size).

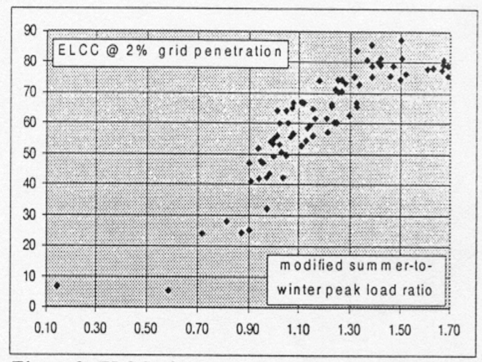

***Figure 2:** ELCC of PV vs. load shape parameter based on the analysis of 82 utility and substation load-years*

By contrast, ELCC was not found to be well correlated with the magnitude of the local solar resource as can be seen in Fig. 3.

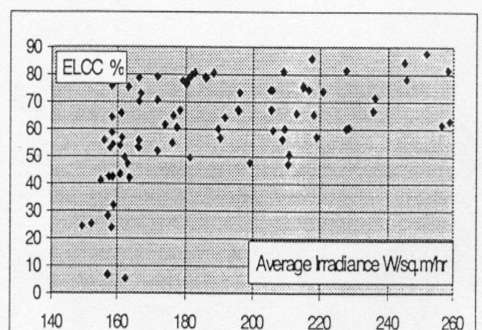

***Figure 3:** Effective capacity of PV vs. solar resource*

3. MAPPING PV's EFFECTIVE CAPACITY

3.1 Methods

The observation that some of the highest effective capacities are found in non-traditional solar regions (and vice-versa) was an incentive to take the issue a step further and to produce a map of PV capacity for the US.

The observation that load characteristics are well correlated with PV's effective capacity provided the tool to accomplish such a task, at least on a preliminary basis.

Input Data: Basic load shape data were obtained for the great majority of US utilities for the year 1993 [7]. The data consist of summer and winter peak loads for over 500 utilities with peak loads in excess of 75 MW. Direct application of the relationship observed between the summer-to-winter peak load ratio and PV capacity [2], provides an initial estimate of PV's effective capacity for each utility for the year 1993.

Gridding: Utility loads were gridded on a 2° latitude-by-2° longitude map. Each utility was distributed into one or more grid cells, depending on the size and shape of its service territory and the location its major points of use (i.e., large cities). Information on utility service territory was obtained from [8].

The resulting effective capacity of each grid cell was then estimated from a weighted average of utilities (or portion thereof) composing each cell.

A minor measure of smoothing was applied to the gridded map via deterministic interpolation: only about 10% of the cells with low assigned weight were subjected to such smoothing. Finally, for display purposes, the 2° resolution map was interpolated into a 1° resolution map.

3.2 Results

The product of the mapping exercise is shown in Fig. 4. The map features three main regions of high PV capacity:

- The largest region covers the central US from the northwestern great plains and the metropolitan areas of

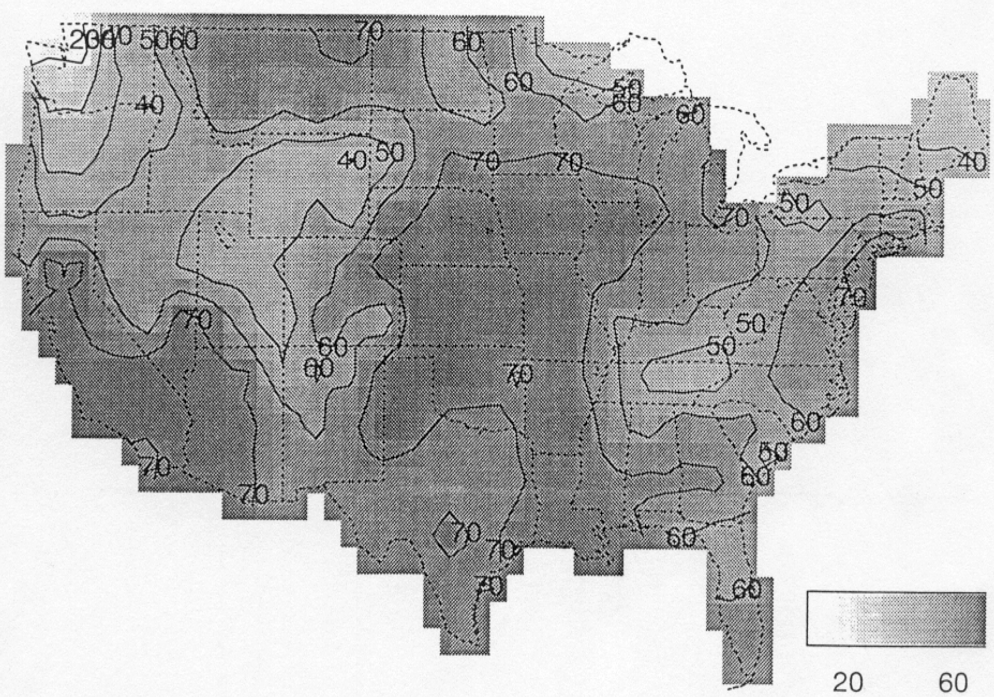

***Figure 4:** Distribution of PV ELCC in the United States*

Chicago and Detroit down to the lower Mississippi Valley and, to a lesser extent Texas. The core of this region features the highest capacities observed in the United States.

- The second region includes California, western Arizona, southern Nevada.
- The third region, the smallest geographically but very large in terms of installed utility capacity, spans the eastern metropolitan area extending from North Carolina to Boston.

The features of this map are fully consistent with the partial evidence gathered from the sample utilities shown in Fig. 1, and for which ELCC was formally derived. This is remarkable given the fact that the gridded map was derived solely from load shape data, without solar resource input.

These features confirm our preliminary findings, stating that regions of highest PV effective capacity do not always overlap with regions traditionally associated with solar energy development. For instance, if one compares Fig. 4 with the North American solar resource map shown in Fig. 5, there is for California and Western Arizona, for the Pacific Northwest, the extreme northeast and of the north end of the Great Lakes. However, this is not the case for much of the western US and the extreme southeastern US, two traditional solar regions. There is no overlap either for the northern heartland and the eastern seaboard which had not been considered to be regions of high solar potential

The map does reflect key climatic and socio-economic realities, the combination of which is highly relevant to the effective capacity of PV. The regions of high effective capacity tend to match areas associated with strong summer heat waves (particularly in the case of the central US region). These regions may also be associated with areas where utility demand is driven by commercial air conditioning (particularly in the case of the eastern and western metropolitan regions), and where the electrical heating load is not significant (i.e., absence of cold weather conditions and/or use of other energy sources such as oil or gas).

<u>Beyond this preliminary map</u>: The map in Fig. 4 is based only on 1993 data and could well reflect unusual [climatic or other] circumstances in some areas of the country, although it is doubtful that its overall structure should be questioned, given the consistency with of the present results the partial experimental evidence from 1987 and 1988. Nevertheless, it would be important (and relatively straightforward) to repeat the exercise over several years in order to: (1) eliminate the risk of unusual circumstances, (2) observe year-to-year variability, and (3) identify possible trends toward (or away from) increased PV's effective capacity.

Producing maps for other levels of PV penetration, fixed PV systems, and/or other load matching parameters should also be worthwhile efforts. To accomplish these tasks, however, other basic load shape parameters would be necessary beyond the summer and winter peak data used in the present analysis.

Finally, it must be stressed that the resolution of the present map is still very coarse and <u>does not reflect localized opportunities</u>. However, one should agree that a grid cell with high ELCC would translate into many local opportunities and vice-versa. Interested utilities could apply the present methodology to increase spatial resolution and identify high PV capacity areas within their service territory.

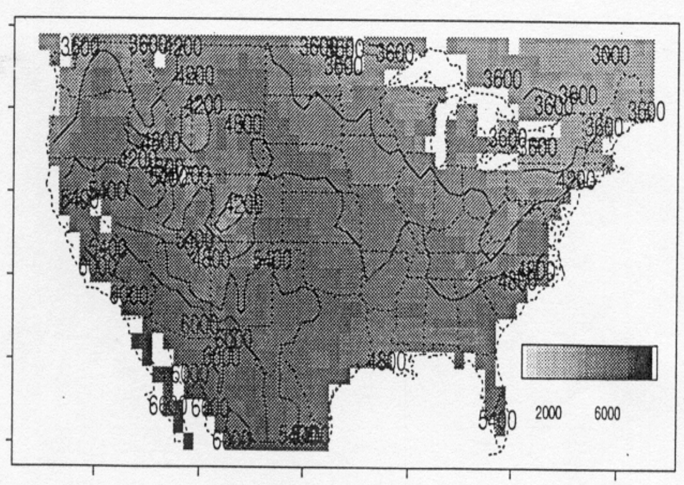

Figure 5: Distribution of solar resource in North America (direct irradiance [2])

4. CONCLUSIONS

A map of PV's effective capacity was produced as the result of a logical, multi-step investigative process involving:

- the development and evaluation of a procedure to access time-site specific PV production data from satellite remote sensing,
- the detailed analysis of over 30 test utilities,
- the identification of a well-defined relationship between load shape parameters and PV's effective capacity, and finally,
- the acquisition of load shape data for the great majority of US utilities.

The map confirms the fragmentary evidence assembled from the test utilities. That is, some of the highest effective capacities are found in regions which had not traditionally been associated with solar energy, in particular, the central US and the eastern seaboard.

The map should constitute a useful source of information for the economic and technical assessment of PV's opportunity in the US. An example of possible application is sketched in Fig. 6, merging the present capacity map, and the traditional solar resource (energy) map, with maps of capacity and energy value to identify the distribution of customer-sited grid-connected PV markets.

ACKNOWLEDGMENTS: This project was undertaken as a part of NREL contract XR-1-11168-1 with Roger Taylor, William Wallace, and Christy Herig as project managers. Thanks to David Renné and his team (NREL) and Dan Tarpley (NOAA) for their help throughout the load matching project. Thanks to Mike Bergman and the UPVG staff who played a key role in providing peak load data.

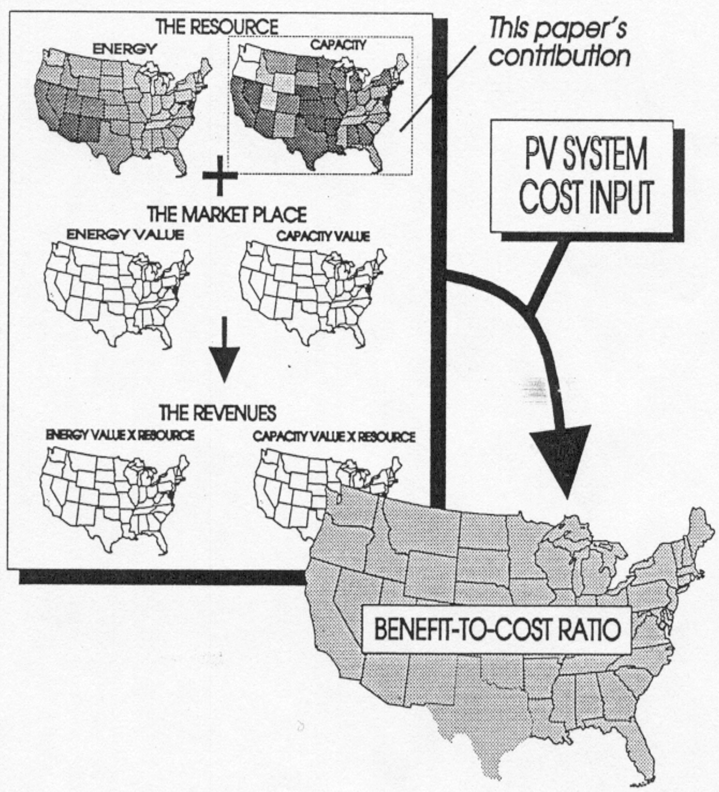

Figure 6: *An example of how the information produced in this paper could contribute to a nation-wide assessment of PV development opportunities.*

REFERENCE

1. T. Hoff, D. Shugar, A. Suchard, H. Wenger, K. Lau, G. Ball and J. Mead, (1992): T*he Photovoltaic Grid Support Project at Kerman Substation -- Project Plan.* PG&E Advanced Energy Systems Report 007.5-92.5 , Pacific Gas and Electric Company San Ramon, California

2. R. Perez, R. Seals and R. Stewart, (1993): Solar Resource -- Utility Load Matching Assessment, Interim Subcontract Report no. NREL/TP-411-6292, NREL, Golden, CO

3. L. Garver, (1966): *Effective Load Carrying Capability of Generating Units*. IEEE Transactions, Power Apparatus and Systems, Vol. Pas-85, no. 8

4. R. Perez, R., R. Seals and R. Stewart, (1993): Assessing the Load Matching Capability of Photovoltaics for US Utilities Based Upon Satellite-Derived Insolation Data, IEEE Transactions, pp. 1146-1149 (23d. PV Specialists, Louisville, KY).

5. R. Perez, R. Seals and R. Stewart, (1994): Matching Utility Peak Loads with Photovoltaics, Proc. RENEW-94, (NESEA), Stamford, CT, USA

6. R. Perez, R. Seals, R. Stewart, A. Zelenka and V. Estrada-Cajigal (1994): *Using Satellite-Derived Insolation Data for the Site/Time Specific Simulation of Solar Energy Systems* Solar Energy Vol. 53, 6

7. M. Bergman, (1994): Personal Communication, UPVG, Washington, DC, USA

8. Electrical Utilities of the United States (1990), Electrical World, McGraw-Hill, New York.