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ASSESSING THE LOAD MATCHING CAPABILITY OF PHOTOVOLTAICS FOR US UTILITIES BASED UPON SATELLITE-DERIVED INSOLATION DATA

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ABSTRACT

The load matching capability of photovoltaic (PV) power generation is estimated for 20 utilities in the continental US. Load matching is determined experimentally by analyzing the interaction between the load requirements of each utility and the output of locally-sited PV plants. PV output is simulated using site/time specific hourly insolation data inferred from geostationary satellite-based remote cloud cover measurement.

As quantified with four independent benchmarks, PV load matching capability is found to be substantial for several utilities. A well defined relationship is observed between a utility's summer-to-winter peak load ratio (SWP ratio) and the load matching capability for that utility. Many of the highest load matching occurrences are found in locations not traditionally targeted for solar energy development, namely: the central US and the Mid-Atlantic seaboard.

INTRODUCTION

Our objective is to provide a preliminary estimate of the match existing between PV power generation and the load requirements of US utilities. For many of these utilities, yet unfamiliar with their PV development potential, this information is important because it may indicate whether the effective capacity, hence the value of PV is higher than that assigned to such non-controllable, non-dispatchable resource. While this investigation is currently limited to assessing utility-wide load-matching, it should be pointed out that a strong match at the utility-wide level will likely correspond to load matching occurrences at the transmission/distribution (T&D) level for that utility, hence to possible high value T&D/DSM PV development opportunities [e.g., 1,2]. An absence of utility-wide match, on the other hand, should not preclude localized development opportunities.

Actual, time-coincident utility load and PV output data covering a statistically significant period (at least one year) are necessary to characterize and quantify the relationship exiting between the two quantities. Hourly system load data are generally archived by utilities. However, actual PV output data are generally not available. Short of actual output data, it is possible to adequately simulate PV systems [3] if actual irradiance data are available. Unfortunately, with rare exceptions, that data are generally not available either. In this study, we circumvent the problem by using a proxy measurement of solar radiation with wide geographical coverage provided by geostationary satellites.

SATELLITE RESOURCE ACCURACY

A pilot study by the authors [4,5] demonstrated the validity of the satellite-based approach for northeastern US sites. An important part the present investigation was to confirm this finding for other climates/utilities. The results, which are summarized below, are detailed in related publications [6,7].

A critical element of this evaluation was to differentiate between the resource's "physical accuracy" (the agreement between satellite-derived and ground-measured irradiance) and its "end-use accuracy" (the agreement between satellite-derived and ground-based PV load matching capability)

In terms of physical accuracy, satellite-predicted global and direct rradiances were found to exhibit little bias when compared against ground truth data at nine climatically distinct locations in the US. Short term (RMS) errors were found to be more pronounced, notably for direct irradiance. However, it is fundamental to note that to better this level of RMS error, a ground-based measurement station would have to be located no further than about 50 km [5,6,7] from the considered site.

End-use accuracy was assessed by comparing satellite and ground based load matching capability for four of the participating utilities where corresponding ground truth data were available. The agreement between ground and satellite was found to be quite reasonable [6,7].

This assessment is likely to be conservative with respect to the ultimate capability of the satellite resource. Indeed, for budget/time reasons, we relied on GOES II satellite irradiance data preprocessed at NOAA [9] using a simple (yet effective) algorithm [8], with limited time and space resolution (hence had to rely on time and space inter/extrapolation and models to generate time/site specific hourly data [5]).

QUANTIFYING LOAD MATCHING FOR 20 UTILITIES

We use four complementary benchmarks to quantify the load matching capability of PV. Each may be determined from hourly PV output and utility load data. They include:

- The Effective Load Carrying Capability (ELCC): *This statistical measure of effective capacity was originally introduced by Garver [10] who defined it as the effective increase in a utility's installed capacity due to the added resource, at constant loss of load probability (LOLP). Here, in order to compare results between different utilities, we assume a generic LOLP for all utilities.*
- The Normalized Energy Worth (NEW): *This parameter was originally used by Hoff [11]. It is defined as the value of PV-generated energy using a normalized energy rate scale based on each utility's load duration curve*
- The Mean Output during Highest hourly Loads (MOHL): *This is defined as the mean PV output during the "n" highest observed hourly loads on the considered grid*
- The Minimum Buffer Energy Storage (MBES): *Unlike the three first measures which are statistical, MBES is a bottom line/worse case measure of load matching. It is defined as the minimum amount of ideal energy storage necessary, to guarantee that a PV+storage system will result in a firm peak load reduction equal to a fraction, F, of PV's installed capacity. As a measure of load matching, MBES is compared to the total energy storage, TES, that would be necessary to achieve the same load reduction in the absence of PV.*

Time Period of Load Matching Study

The load matching study spans the years 1987 and 1988. This selection is a compromise between affordability, data quality, and actuality. In terms of affordability, the GOES data were routinely pre-processed by NOAA-NESDIS and made available to this project [9]. In terms of quality, we were notified that, because of aging, the satellite's data quality had been deteriorating since the late 1980s [9]. In terms of actuality we were interested in the most recent data, since utility load do evolve over time. The climatological representativeness of 1987-88 in terms of solar resource will be formally investigated as part of the next phase of this program. However, the relevance of this matter to this study's conclusion should be minimal as pointed out below.

The 87-88 mean geographical distribution of global irradiance (see Fig. 1) has features which are slightly different from the original irradiance maps provided until now by the USDOE, with relatively more resource in the east and less in the west. The newly released 30-year NREL Solar Radiation Data Base [12] exhibits a comparable departure from the original maps.

Simulating PV Output

Hourly PV output is simulated using a modified version of PVFORM 3.3 [13]. This program was recently evaluated against field data [3] and was found to adequately model the output of mainstream flat-plate crystalline silicon PV systems. The input to PVFORM consists of hourly global and direct irradiance (inferred from the GOES satellite as mentioned above) plus hourly wind speed and temperature data from [15].

Two extreme array configurations were considered: fixed tilt at latitude and 2-axis tracking. We assumed PV systems rated in terms of summer AC output (nominal AC output at 1000 W/m2 and module temperature of 46 °C). We also assumed a 20% oversized PCU; hence PV output may exceed rated output for high insolation and/or cold weather conditions. Finally, for a given utility, the considered PV output is that of systems dispersed over its entire service area.

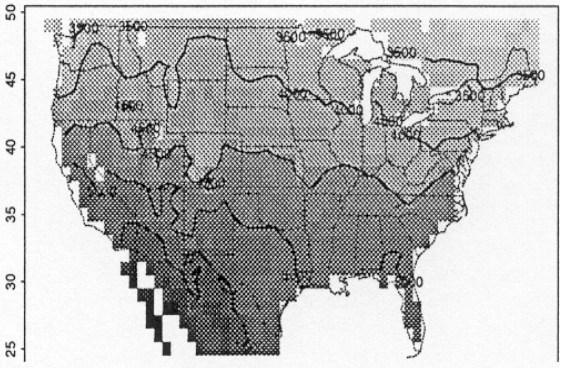

Fig. 1: Average satellite-derived 1987-88 daily global irradiance (Watt-hour/m^2/day) [9]

Selected Utilities

The participating utilities (or group of utilities) are listed below, along with their 1987-88 peak load as an approximate measure of their installed capacity.

1.	Atlantic Electric (AE)	1623 MW
2.	City of Austin Power & Light (APU)	1424 MW
3.	ConEdison (CONED)	8776 MW
4.	Delmarva Power (DELMARVA)	2204 MW
5.	Florida Power and Light(FPL)	12370 MW
6.	Gainsville Regional Utilities (GRU)	282 MW
7.	Idaho Power Corporation (IPC)	2161 MW
8.	Kansas City Power and Light (KCPL)	2656 MW
9.	Lincoln Electric System (LES)	502 MW
10.	Long Island Lighting Company (LILCO)	3819 MW
11.	NY. Power Authority (South) (NYPA)	1421 MW
12.	Niagara Mohawk Power Corp. (NMPC)	6177 MW
13.	Northern State Power (NSP)	6923 MW
14.	Omaha Public Power District (OPPD)	1600 MW
15.	Pacific Gas & Electric Company (PGE)	15771 MW
16.	Public Service Co. (Colorado) (CPSC)	3416 MW
17.	Salt River Project (SRP)	3060 MW
18.	Southern Electric System (SES)	26495 MW
19.	St. Joseph Light & Power Co. (SJPL)	323 MW
20.	Wisconsin Public Service Corp. (WPS)	1580 MW

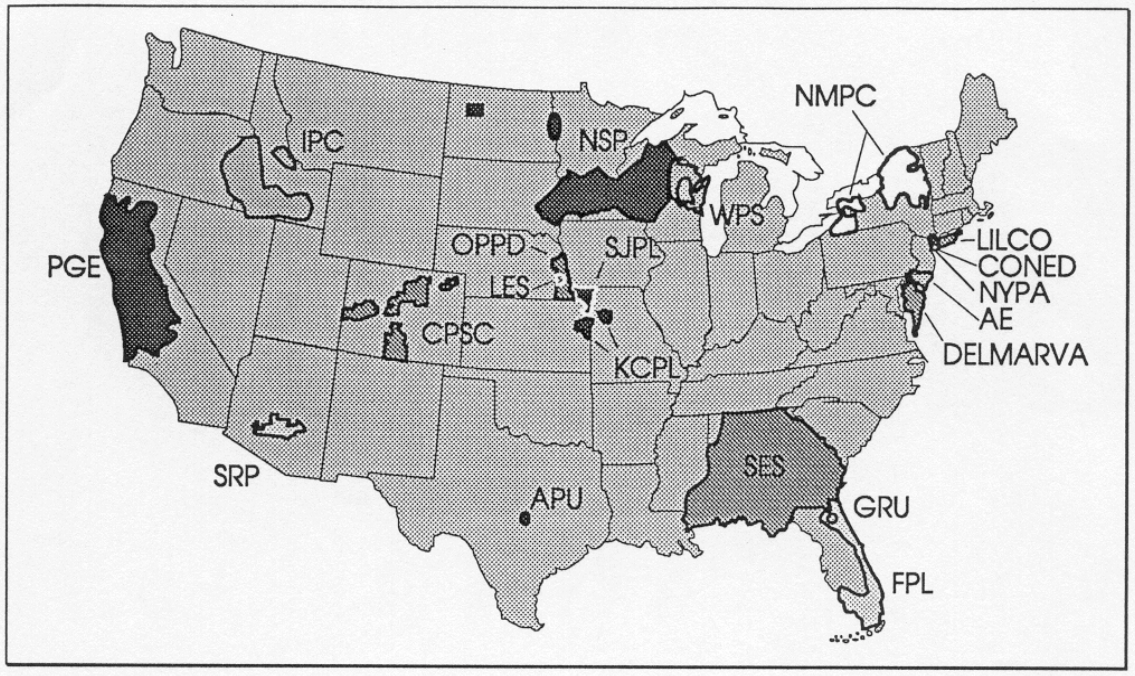

Fig. 2. Service areas of the considered utilities (note: the gray scale used to fill service areas correspond to the observed level of PV load matching)

The present utility sample is well balanced geographically (see Fig. 2). Service areas range in size from a few km^2 (GRU, APU, LES) to over 100,000 km^2 (e.g., PGE, NSP), whereas peak loads span two orders of magnitude.

All but one utility were summer peaking in 1987-88, both in terms of mean load (i.e., energy) and peak load; however, the hierarchy among utilities is markedly different for energy and capacity summer-to-winter ratios (see Fig. 3). For instance, FPL's summer-to-winter energy ratio is one of the highest, but its peak load ratio is only slightly summer-peaking (this can be qualitatively interpreted by the fact that despite a much broader energy demand from air conditioners in summer, a few winter cold snaps associated with electric heating may drive winter loads to high levels.) On the other hand, NSP, which is marginally summer-peaking in terms of energy, features a much higher capacity ratio (likely because of the impact of a few strong heartland summer heat waves on air conditioning).

Concerning the overall PV resource available to each utility, differences in summer resource throughout the US are not considerable. On the other hand, differences are much more pronounced in winter, and the hierarchy among locations is markedly different: two extreme examples are Florida Power and Light, with one of the highest winter resource, but one of the lowest in summer, and Idaho Power Corporation, with one of the highest summer resource, but a relatively low winter resource.

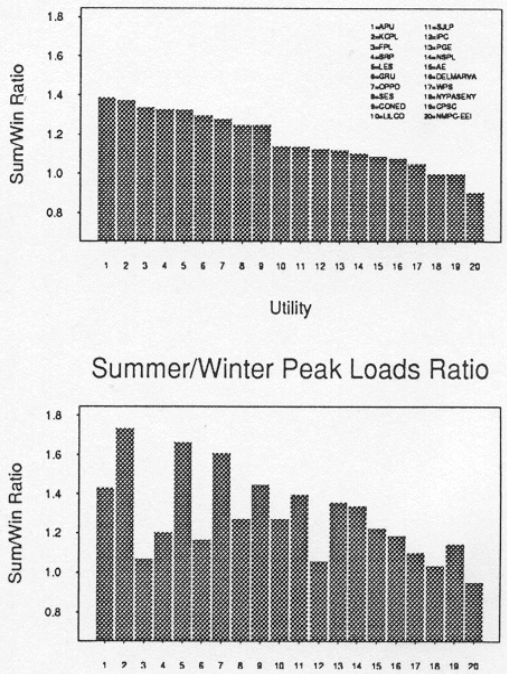

Fig. 3: Utility summer-to-winter mean load ratios (top) and peak load ratios (bottom).

LOAD MATCHING RESULTS

We present here a summary of a comprehensive set of results included in a related report [6], and focus our attention on two critical benchmark: ELCC and MBES.

We make extensive use of the utility summer to winter peak load ratio (SWP ratio), as a background against which to display these results because of the strong relationship observed between this ratio the load matching benchmarks.

ELCC

The relative ELCC of two-axis tracking systems is plotted against the SWP ratio for PV grid penetration levels of 2%, 10% and 20% (see Fig. 4). Each point represents one of the 20 selected utilities and is a mean for 1987 and 1988.

The ELCC reaches remarkably high values for several utilities, especially at low penetration levels. Note that the ELCC of fixed systems is about 10-20% less. As would be expected, ELCC decreases as utility penetration increases, particularly for utilities with low summer to winter peak load ratios.

The quasi-logarithmic growth of ELCC as a function of the SWP ratio is remarkable: all the utilities studied, from winter-peaking to highly summer peaking, fit the pattern, a priori regardless of their size or other specific characteristics. Further, some of the scatter around the main trend may be traceable to other load shape factors; for instance, points above the trend tend to correspond to utilities peaking earlier in the day in summer (e.g., DELMARVA) than points below the trend (e.g., SRP, AE).

MBES

The Minimum Buffer Energy Storage to guarantee that a ensemble of 2-axis tracking PV systems will result in a firm 10% peak load reduction is compared to the total energy storage (TES) that would be required to accomplish the same reduction without PV (see Fig. 5). The storage unit is system-hours (with system size = 10% of each utility's peak load). The use of the PV resource considerably reduces the needed energy storage requirements in all cases, including winter peaking NMPC (for this utility, as for most other utilities considered here, winter peaks are narrower than summer peaks, hence may be met with less storage, even if they are higher). The relative difference between MBES and TES is found to increase with the utility SWP ratio in a fashion similar to the ELCC [6].

Bottom Line

The results may be further summarized in order to provide a quick "bottom-line" overview of load matching capability (see Fig. 6). For this purpose, we arbitrarily defined a composite benchmark, CB, function of the four others. At a given grid penetration level v, CB is given by:

$$CB = 0.25\ [ELCC_v + NEW + MOHL_{n(v)} + (1\text{-}MBES_v/TES_v)],$$
with $n(v) = v \times 8760$ hr.

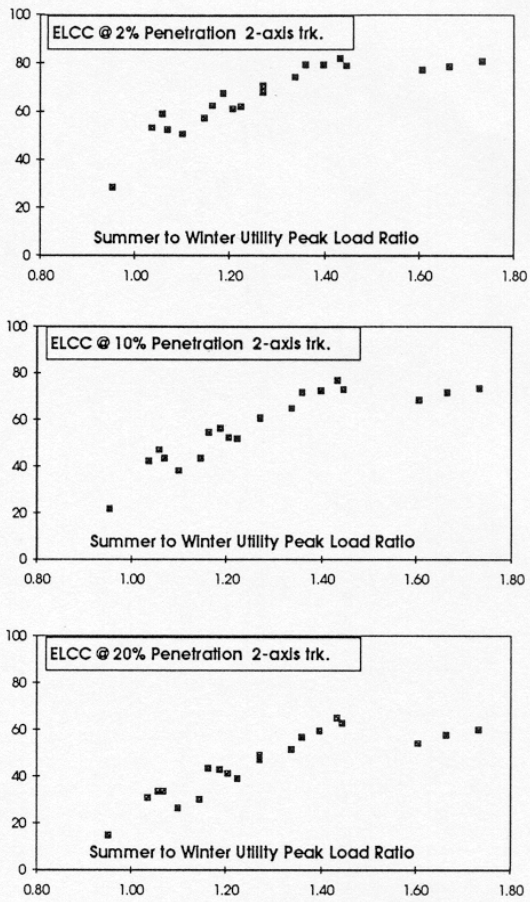

Fig. 4. ELCC at 2%, 10% and 20% PV penetration as a function of utility SWP ratio

Fixed vs. Tracking

The non-tracking option results in a 10-15% reduction of load matching capability as quantified by CB (see Fig. 6). Differences may be traced to the hour of the summer peak: for utilities such as CPSC or CONED whose loads peak early in the day [6], the performance of fixed systems approaches that of tracking systems. Conversely, for late peakers such as SRP, AE or LES, the difference is more pronounced.

Geographical Distribution

The gray scale used to fill the service area of each utility (see Fig. 2) relates to their load matching capability (see Fig. 6). Zones of highest load matching capability include the southwestern seaboard (a well documented fact [e.g., 2]), the heartland (from Texas to Minnesota), and to a lesser extent, the eastern seaboard; by contrast, two areas traditionally considered for solar development, Florida and the southwestern US do not fare as well on the load matching scale.

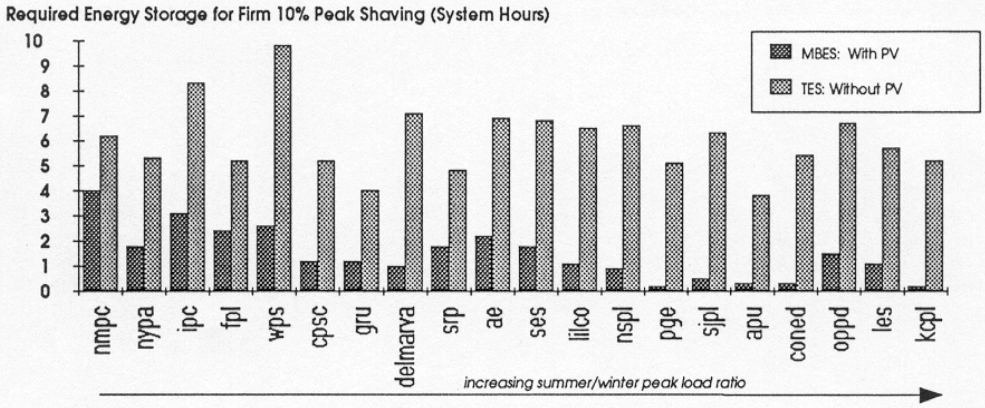

Fig. 5. Minimum buffer energy storage (with and without PV) to accomplish firm 10% peak load reduction

Solar Energy Resource vs. Load Matching

Comparing the solar resource map (see Fig. 1) and the load matching map (see Fig. 2), it is apparent that the distribution of the resource and PV load matching capability are not strongly related: provided that the summer solar resource is reasonable (as is the case for all regions studied), opportunities for load matching are not a function of the resource's overall magnitude, but of the load requirements in relation to the resource. This should not be interpreted as a statement that the solar resource is not relevant. The resource is critical, but less in terms of its overall magnitude than in terms of its feed-back relationship with load requirements.

Representativeness of the 1987-88 period

The climatological representativeness of the selected years will be formally investigated as part of a following phase to this study. However, based on the argument developed above, this question should not be critical. For now, comparing 1987 and 1988 results (less than 5% variation for most utilities), indicates the presence of a robust relationship between the solar availability and the load requirements.

CONCLUSIONS

The main objective of this study was to estimate the load matching capability of PVs for a selected group of utilities in the continental United States. To accomplish this objective it was necessary to access short time step insolation data are arbitrary location and time in the country. Geostationary satellites have the potential to provide the needed data. Hence a secondary objective was set to evaluate the accuracy of satellite-derived insolation data for the purposes of estimating PV-utility load matching. This evaluation pointed out that (1) satellite data are adequate to provide a preliminary estimate of load matching capability, (2) satellite data constitute the most accurate option beyond 35-50 miles of a ground-based measuring station and (3) currently operational satellite-to-irradiance procedures provide a conservative assessment of the ultimate potential of satellite-aided solar resource monitoring.

Concerning this study's primary objective, our main observation and conclusions are the following:

1. The load matching capability was found to be substantial for many of the considered utilities. Thus, a PV-based resource,

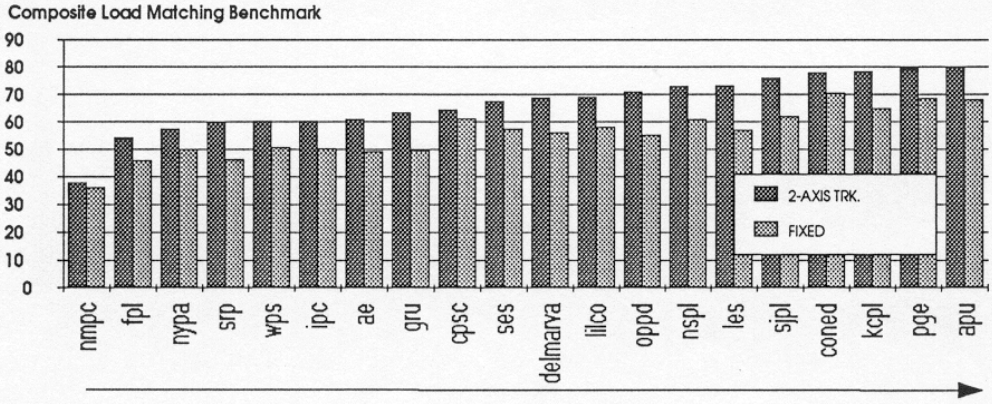

Fig. 6. Bottom line load matching capability

either on the demand or the supply side, could effectively contribute to meet theses utilities' capacity requirements.

2. A well defined relationship was observed between a utility's summer-to-winter peak load (SWP) ratio and the load matching capability of PV for that utility. This was observed independently of other characteristics that may have been deemed important a priori, such as the considered utility's size its generation or customer mix, and even its overall solar resource. We must caution that this observation is based on a limited 20-point data set. However should this trend be confirmed (and refined/qualified), its implications may be very important and useful for utility planners, particularly if it is found to persist at the sub-utility (T&D) level.
3. To the exception of California, most of the best PV load matching opportunities were found for locations not traditionally targeted for solar energy development, namely: the central US and the Mid-Atlantic seaboard. By contrast, the load matching potential of traditional solar energy regions (Florida, Arizona), was found to be more limited.

For many of the present utilities, these results constitute an initial screening of their utility-wide PV load matching potential. It is useful to repeat that a strong match will likely correspond to load matching occurrences at the T&D level. However, an absence of utility-wide match should not preclude localized development opportunities.

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