Pergamon

Solar Energy, Vol. 53, No. 6, pp. 491–495, 1994

0038-092X/94 $6.00 + .00

0038-092X(94)00087-5

USING SATELLITE-DERIVED INSOLATION DATA FOR THE SITE/TIME SPECIFIC SIMULATION OF SOLAR ENERGY SYSTEMS

RICHARD PEREZ,* ROBERT SEALS,* RONALD STEWART,* ANTOINE ZELENKA,** and VICENTE ESTRADA-CAJIGAL***
*State University of New York, ASRC, Albany, NY 12205, U.S.A.; **Swiss Meteorological Institute, 8044 Zurich, Switzerland; ***Solartronics, Cuernavaca, Morelos, Mexico

Abstract—In this paper, the question of satellite-derived irradiance is addressed on two levels. First, the question of physical accuracy is addressed by comparing satellite-predicted hourly/daily global and direct irradiance with controlled ground measurements in climatically distinct environments. This accuracy is compared to the error made as a function of distance when extrapolating the needed data from the closest ground measurement site. Second, the question of end-use accuracy is addressed by comparing satellite-derived, photovoltaic-utility load-match benchmarks with actual benchmarks for three US electric utilities where ground measurements were available.

1. INTRODUCTION

When evaluating the usefulness of satellite remote-sensing to estimate solar irradiance at the earth's surface, it is important to define the type of data one needs. This study distinguishes between (a) climatological data and (b) real data. Climatological data are site-specific, but need not be time-specific: Typical meteorological year data sets are examples of such data. Real data are both site- and time-specific: the time, day and year of each data point must be known. Real-time data are an extreme example of real data.

Climatological data are often sufficient to design systems for a given site, but not to investigate the interaction between these systems and their intended utilization if an undetermined relationship between the two exists. This is the case for solar systems (e.g., photovoltaics, PVs) versus the needs of some electric utilities (e.g., see Hoff, (1987) or Perez *et al.,* (1989). If a positive relationship exists, PVs may be used in high-value, peak-load reduction applications (e.g., Wenger *et al.,* 1992). However, real insolation data are necessary to characterize and quantify this potential. Here, it is shown that satellites are a sensible option to obtain usable real data in the absence of very dense ground measurement networks.

A distinction is made between the physical accuracy of insolation estimates and their end-use accuracy for a specific task. (a) The physical accuracy is the actual difference between estimated and measured insolation and is benchmarked in terms of mean bias (long term) error (MBE), and root mean square (short term) error (RMSE). The latter is primarily relevant to real data. (b) End-use accuracy is task-dependent and is assessed in terms of the error performed on the end-product of the data analysis. In this article, the end product is the load matching capability of PV generation for a given utility.

2. PHYSICAL ACCURACY

2.1 *Satellite versus extrapolation from ground measurements*

When no insolation data exist for a given site, a common palliative has been to use data from another point, or set of points, where data are available. This approach may be warranted when climatological data are needed, as long as (micro) climatic/environmental differences are small. This is much less true for real data because the time element becomes crucial.

A study recently undertaken by Zelenka *et al.* (1992), under the auspices of the International Energy Agency (IEA), dealt specifically with the issue of global irradiance network interpolation/extrapolation. One of its most interesting findings is reported in Fig. 1, where a clearly defined relationship has been established between the extrapolation distance and the resulting RMSE. This increases with the square root of the distance and reaches 20% at 50 km, confirming limited earlier observations by Hay (1984). This trend appears to be universal since it is derived from over 70 measuring station-years in 6 climatically diverse networks in Switzerland, Germany, Sweden, and the northeastern, northwestern, and southwestern United States. A similar, although not as readily quantifiable trend, was found in the case of interpolation between stations, with a perceptible but small RMSE reduction when using sophisticated interpolation methods such as kriging (see Zelenka *et al.,* 1992).

By contrast, the study found that the RMSE of satellite-derived daily global irradiance was of the order

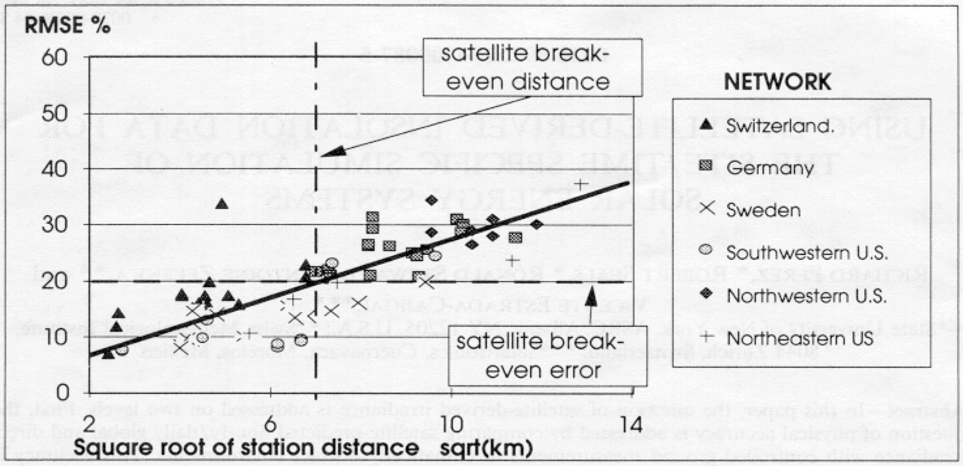

Fig. 1. Extrapolation root mean square error as a function of distance from measuring station (from Zelenka *et al.*, 1992), based on data from six networks in Europe and the US.

of 17–22% for a large number of test sites in Europe, with a perceptible but overall small dependence on the location, the satellite and on the sophistication of the algorithm (see Zelenka *et al.*, 1992). Note that the IEA study involved both the GOES and METEOSAT satellites and several distinct physically-based and empirical satellite-to-irradiance conversion algorithms. Hence, for real data, satellite-derived insolation becomes preferable to ground extrapolation if distance exceeds 40–50 km.

These results are limited to daily global irradiance. However, extrapolation errors are likely to be higher for hourly values since the cause of error, cloud cover inhomogeneities, would no longer be averaged. On the other hand, for satellite data, a limited study for the northeastern US by Perez *et al.* (1991), showed only a small RMSE increase from a daily to an hourly basis. In this case, the cause of error (determination of turbidity and cloud thickness) is fundamentally different from that of extrapolation and is less affected by the time scale. Note also that these results are conservative with respect to the ultimate accuracy of satellites, because of the large, ground footprint satellite data resolution and non-exact collocation of satellite and ground truth points used here.

2.2 *Physical validation of satellite-estimated hourly global direct and tilted irradiance for North American sites*

Satellite-estimated, hourly global irradiance is compared against ground-measurements at nine climatically distinct sites in the US. The accuracy of satellite-derived hourly direct irradiance and simulated PV output is also evaluated. The test sites are Cape Canaveral, Florida (subtropical, humid), Albany, New York (continental, humid), Mesa, Arizona, Carissa Plains, California (arid), Keystone, California (semi-arid, mountains), San Jose, California (semi-arid/oceanic), and Lamberton and Waseca, Minnesota (continental, dry).

For the satellite, five to six global irradiance estimates per day on a × 1 degree latitude–longitude grid are relied upon, based on the Justus–Tarpley algorithm (Justus *et al.*, 1986). Each point is an integrated value of 25 pixels and represents a ground footprint of about 2,500 km^2. (Note that data/resolution was used for practical reasons: chiefly availability and affordability for the considered task. It must be pointed out, however that the ultimate resolution of geostationary satellites today is of the order of a few km^2.) Hourly data are time-extrapolated from these five to six daily instantaneous readings as explained by Perez *et al.* (1991). Estimates at a specific location are interpolated from the grid (extrapolated for coastal sites, since the Justus–Tarpley method is not used over water). Satellite-direct irradiance is further modeled from global from Perez *et al.* (1992). Finally, PV output for a tilted collector is modeled using PVFORM (Menicucci *et al.*, 1988). (Note that ground-reference PV output is also modeled.)

It is important to remark that this assessment of satellite accuracy is very conservative and could be improved in the future because: (a) the simplest, yet effective, satellite algorithm is used (the only routinely exploited for North America), (b) time/space inter/extrapolation is relied upon, and (c) direct is modeled from global, amplifying any error in its global input.

The results are presented in Fig. 2, where satellite estimates of global irradiance are plotted against ground values. They are consistent with the IEA findings for global irradiance: negligible MBE (±5% range); and RMSE ranging from 16% in California to 26% in New York. For direct, the scatter is much stronger, whereas MBEs remain reasonable (±10%), and RMSEs are in the 30–50% range. However, the simulated, tilted PV output is little affected by the noise in the direct component. The MBE and RMSE of simulated PV are

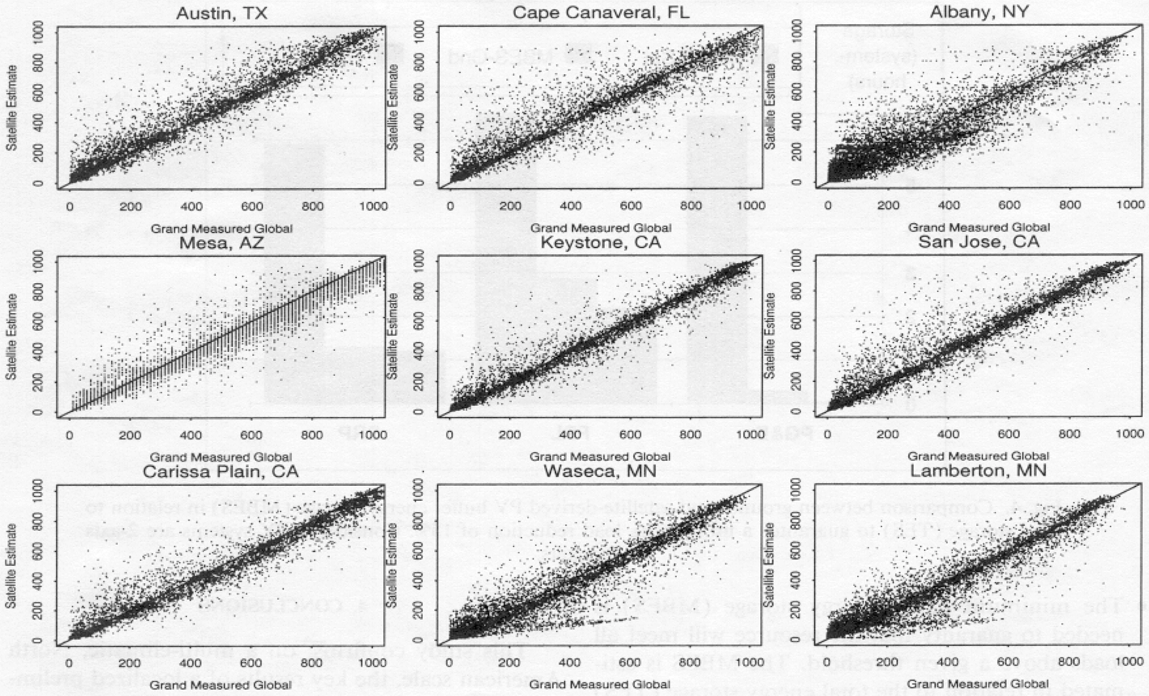

Fig. 2. Satellite-predicted (Y-axis) versus ground-measured hourly global irradiance (X-axis) for 9 North American sites.

comparable to that of global irradiance (this is because for south-facing collectors, any error on the direct tends to be compensated by an opposite error in the anisotropic diffuse component).

3. EFFECTIVE "END-USE" ACCURACY

There are several benchmarks that can be used to quantify the peak load matching capability of non-dispatchable generating sources (e.g., Hoff, 1987 or Perez *et al.*, 1989). These benchmarks may be derived from the analysis of time-coincident utility load data and power plant output data. Here, attention is focussed on two critical benchmarks. The first benchmark is statistical, whereas the second represents an absolute worst-case measure of the resource's ability to meet demand.

- The resource's effective load carrying capability (ELCC) is defined as the effective increase in the utility's available capacity due to the added resource. If the resource is able to meet all the utility's high loads, its ELCC will approach 100%.

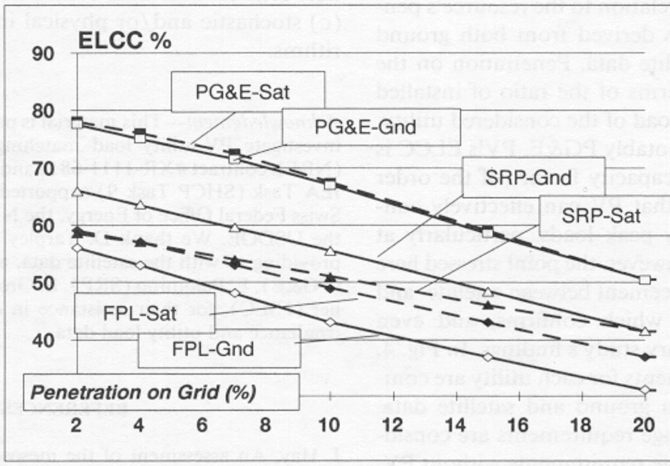

Fig. 3. Comparison between ground (-Gnd) and satellite-derived (-Sat) ELCC of PV power generation for three US electric utilities as a function of PV grid penetration.

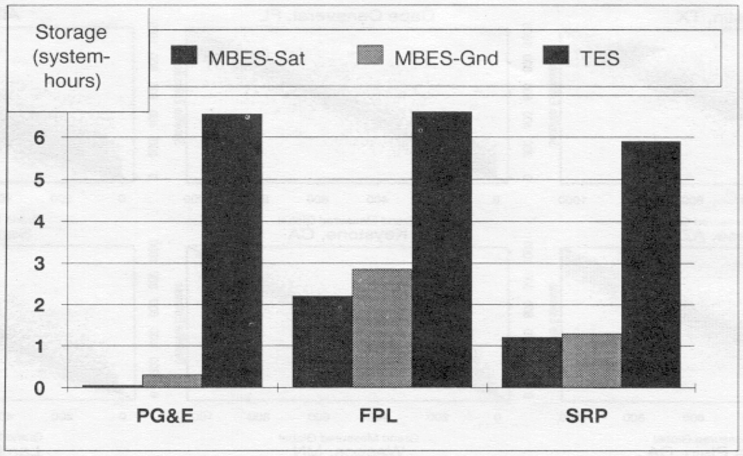

Fig. 4. Comparison between ground- and satellite-derived PV buffer energy storage (MBES) in relation to total storage (TES) to guarantee a utility peak load reduction of 15%. Considered PV systems are 2-axis trackers.

- The minimum buffer energy storage (MBES) is needed to guaranty that the resource will meet all loads above a given threshold. The MBES is estimated in relation to the total energy storage (TES) needed to meet the same goal in the absence of the resource. For an ideally peaking resource, MBES = 0. For a resource with no load matching potential, MBES = TES.

A preliminary study in New York by Perez *et al.* (1991) concluded that the error between satellite- and ground-derived benchmarks was not considerable and that satellite data could be used effectively for this type of investigation. Here, we extend this investigation to other climates and utilities, including Florida (Florida Power and Light—FPL), Arizona (Salt River Project—SRP) and California, (Pacific Gas and Electric—PG&E). In each case, results are based on 2 years (1987—1988) of ground insolation and satellite and utility hourly load data.

In Fig. 3, we have plotted the variations of PV's ELCC for each utility in relation to the resource's penetration on their grid, as derived from both ground insolation data and satellite data. Penetration on the grid is defined here in terms of the ratio of installed PV capacity to the peak load of the considered utility. Note that, in each case, notably PG&E, PV's ELCC is much higher than PV's capacity factor (of the order of 20–25%), indicating that PV can effectively contribute to meeting utility peak loads, particularly at low penetration levels. However, the point stressed here is the reasonably good agreement between satellite- and ground-derived ELCCs, which confirms, and even strengthens the preliminary study's findings. In Fig. 4, MBES and TES requirements for each utility are compared, as estimated from ground and satellite data. Note that PV buffer storage requirements are considerably smaller than storage requirements without PV, confirming the above benchmark even in the worst case situation. As above, the remarkable agreement between satellite and ground derived MBES is stressed.

4. CONCLUSIONS

This study confirms, on a multi-climatic, North American scale, the key results of a localized preliminary study by Perez *et al.*, (1991), making constructive use of the results of a comprehensive IEA task (Zelenka *et al.*, 1992). These results are: (a) the physical accuracy of satellite-derived, hourly, global irradiance or fixed-tilt, south-facing irradiance is of the order of 20–25% RMSE and negligible MBE, making the satellite more suitable to real data acquisition than extrapolation beyond 50 km of a ground station; (b) Satellite-derived insolation is an effective means of assessing the potential of PV generation in relation to the needs of electric utilities for places with little access to ground data.

Finally, it is stressed again that this study is conservative with respect to the ultimate capabilities of the satellite. Three avenues for future improvement are: (a) higher resolution on-board sensors, (b) a combination of satellites for spatial coverage and ground networks for real-time local satellite calibration, and (c) stochastic and/or physical improvement of algorithms.

Acknowledgment—This material is part of an NREL effort to investigate PV-utility load matching in the United States (NREL contract #XR-1111-681) and of a recently completed IEA Task (SHCP Task 9) supported, among others, by the Swiss Federal Office of Energy, the NY Power Authority and the USDOE. We thank D. Tarpley of NOAA-NESDIS for providing us with the satellite data, and T. Hoff, H. Wenger (PG&E), E. Palomino (SRP), L. Greene (FPL), and K. Collier (FSEC), for their assistance in obtaining ground truth irradiance and utility load data.

REFERENCES

J. Hay, An assessment of the mesoscale variability of solar radiation at the earth's surface, *Solar Energy* **32,** 425–434 (1984).

T. Hoff, Calculating photovoltaic value: A utility perspective. *Proc. 19th IEEE PV Specialists Conference* (1987).

C. Justus, M. Paris, and J. Tarpley, Satellite-Measured insolation data in the US and Mexico. *Remote Sensing Env.* **20,** 57–83 (1986).

D. Menicucci, and J. Fernandez, User's manual for PVFORM. Report #SAND85-0376-UC-276. Sandia Natl. Labs, Albuquerque, NM (1988).

R. Perez, W. Berkheiser, III, R. Stewart, M. Kapner, and G. Stillman, PV load matching potential for metropolitan utilities and large commercial users in the Northeastern US, *Proc. 9th European PV Conference,* Freiburg, Germany (1989).

R. Perez, P. Ineichen, G. Maxwell, R. Seals, and A. Zelenka, Dynamic global-to-direct irradiance conversion models. *ASHRAE Transactions-Research Series,* 354–369 (1992).

R. Perez, R. Seals, R. Stewart, M. Kapner, and G. Stillman, Meeting utility load requirements with photovoltaics. *Proc. ISES World Congress,* Denver, Colorado (1991).

H. Wenger, T. Hoff, and R. Perez, Photovoltaics as DSM option: Benefits of a utility–customer partnership. *World Energy Engineering Congress,* Atlanta, GA (1992).

A. Zelenka, G. Czeplak, V. D'Agostino, W. Josefsson, E. Maxwell, and R. Perez, Techniques for supplementing solar radiation network data, *Final Report of International Energy Agency Solar Heating and Cooling Program,* Task 9, subtask 9D. IEA, Paris, France (1992).