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Central-Station Photovoltaic Plant with Energy Storage for Utility Peak Load Leveling

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ABSTRACT

The impact of photovoltaic (PV) power generation with energy storage on the electric utility's load shape for load leveling purposes is explored. Results show that utilities employing battery storage for peak load shaving might benefit from use of photovoltaic power, the extent of its usefulness being dependent on the specific load shapes as well as the photovoltaic array orientations. Typical utility load shapes both in the eastern and in the western parts of the U.S. are examined for this purpose. While photovoltaic power generation seems to present a bigger impact on the load of the western utility, both utilities will experience considerable savings on the size of the battery system required to shave the peak loads and also in the off-peak base capacity required to charge the battery.

1.0 Introduction

A photovoltaic (PV) power plant converts sunlight directly into electricity and therefore is useful only during the hours of sunshine. A central station photovoltaic plant will be defined as one which produces electricity and supplies the entire generation to the power grid at either the sub-transmission or transmission level. Pacific Gas and Electric Company and Southern California Edison Company of California are operating the world's two largest multi-megawatt level PV plants [1, 2] which feed directly into the respective company's bulk transmission system. Direct application of very large-sized PV plants particularly with penetration of 5-10% of the total generating capacity of the utility, is still either questionable [3] or requires changes in the real-time operating strategy of the power system.

Central station PV plants may be made more attractive by considering energy storage options. With such an alternative, the energy storage element can absorb the excessive variations in the PV generations, thus allowing the grid to accept a smooth unvarying generation causing no undue constraints on the load following thermal generations. A viable option for energy storage could be storage batteries. With the availability of advanced batteries, it is possible to store large amounts of energy during the period that the PV plant is generating electricity. Additional storage energy may be taken form the grid itself during off-peak periods. The question of when to discharge the batteries may be solved by considering the peak demand period during which expensive combustion turbines are operating. Such an application of storage batteries is called "load leveling" and is certainly superior to discharging the batteries at any given time from a cost-saving point of view.

The objective of this paper is to provide an insight into how a PV plant can be used in conjunction with storage batteries for peak load leveling purposes. A comparative analysis of the benefits of PV-battery hybrid system over a battery alone will also be provided. In order to study the effects of such a hybrid system in different geographical regions, two different sites - one in the southeastern and the other in the southwestern U.S. have been looked at.

1.1 Rationale for a Combined Photovoltaic/Battery System

The PV plant may be generating power during the low-demand periods when the lower incremental cost machines are operating as base or intermediate capacity. This is not the most desirable form of operation as it cannot justify the high installation cost of the PV plant.

This leads to the general belief that a combined PV and energy storage system set up with an objective of reshaping the peak demand curve might prove to be an attractive option for the utility. Photovoltaics, in conjunction with a battery under the peak load management scheme, would have a unique application in utility peak load restructuring. Whereas, PV power combined with energy storage in stand-alone mode attempts to supply all of the load, the central station application of PV/energy storage combination attempts to shave the peak load where the most fuel savings can be earned by the combined system.

Utilities already planning on having PV power in the generation mix and further contemplating advanced battery energy storage for peak-shaving might be better off bringing the two technologies together for a more effective utilization. Advanced batteries at present are plagued by short cycle life. On the other hand, it is envisioned that photovoltaic technology can play an important role in extending the cycle life of a battery system when used together to perform load management. Details of the performance of such a system as well as the effect of the nature of PV array orientation on battery performance are discussed in the paper.

2.0 Photovoltaic Plant Design

Realistic PV systems are oriented at particular tilt angles so as to optimize the solar irradiance. There are a number of options that the designer might choose for the system. These options are generally dictated by cost-benefit ratios. Figure 1 shows the options that may be used to configure the PV array. Besides, among the systems options, the designer may choose one of two types: (a) flat plate and (b) concentrators. The choice of the right option in both the orientation and the system is a matter of simulating the relative performances throughout the year with long term data at any location. The performance characteristics are believed to vary considerably from location to location. While the southwestern U.S. is well suited for concentrator technology, the same is not true for the southeast or northeast. The reason is that, the southwest receives more direct normal irradiance annually. Array orientation strategies may strictly be based on array structure costs. While the two-axis tracking array orientation requires a computer controlled automatic tracker system, the simple fixed surface orientation does not incur the extra costs of tracking. On the other hand, energy collected by a 2-axis tracking system may prove to be twice as much as the fixed surface array during the year.

Two mathematical relationships which figure prominently in simulating the performance of an array oriented in one of the ways described in Fig. 1 are shown below:

1. Angle of incidence of solar radiation on a horizontal surface:

$$\cos \theta_h = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \omega = \sin \alpha = \cos \theta_z \qquad (1)$$

where:

θ_h = incidence angle on horizontal.
θ_z = zenith angle.
α = elevation angle of the sun.
δ = solar declination.
φ = latitude at the site.
ω = hour angle = $\cos^{-1}(-\tan \varphi \tan \delta)$

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Option	Description
1. Fixed surface	PV modules mounted horizontal to the surface.
2. Monthly tilt on fixed surface	Monthly tilt adjusted on modules facing south.
3. Monthly tilt on 2-axis fixed surface	Monthly tilt and azimuth adjustment on PV modules.
4. North-south axis tracking	Modules track the sun about a north-south axis with the entire plane tilted.
5. East-west axis tracking	Modules track the sun about an east-west axis.
6. Polar-axis tracking	Modules track the sun about a polar axis.
7. Monthly tilted with vertical axis tracking	Modules track east-west on a vertical axis with optimal monthly tilts applied on the modules.
8. Two-axis tracking	PV modules constantly updated maintaining it parallel with sun's rays.

Fig. 1. Array Orientation Options.

2. Angle of incidence of solar radiation on a tilted surface:

$$\cos \theta_t = \cos \alpha \sin \beta \cos (\gamma_s - \gamma) + \sin \alpha \cos \beta \qquad (2)$$

where:

θ_t = incidence angle (angle between direction of the sun and normal of the surface).

γ_s = solar azimuth angle.

$$= \sin^{-1}\left[\frac{\cos \delta \sin \omega}{\cos \alpha}\right] \qquad (3)$$

γ = surface azimuth angle.

β = slope of the planar array.

Three of the most important array orientations for central station PV systems, the simulation process and results of actual simulations are discussed next.

2.1 PV Performance Simulation Model

Simulation programs are essential for evaluation of the hourly performance of PV systems given the historically observed irradiance data, the ambient temperature data and in some cases, the wind speed data. The purpose of the simulation model is to calculate hourly plane-of-array irradiance at pre-specified tilt and azimuth orientations of PV arrays. Thermal models are then used to model cell temperatures at each interval of the simulation and various efficiencies are then calculated with the help of reference efficiencies. DC power output is calculated as a product of these efficiencies and the modular area of the PV array. DC/AC inversion efficiencies are either input as a curve or in the form of a regression polynomial. The major blocks of the performance simulation model are shown in Fig. 2.
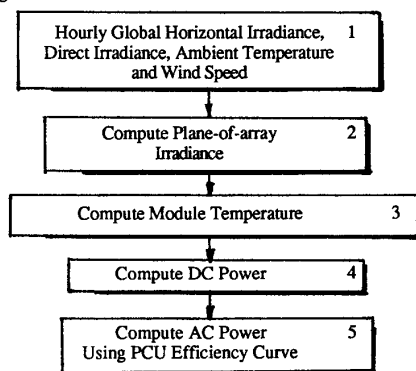
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┌─────────────────────────────────────────┐
│ Hourly Global Horizontal Irradiance,  1 │
│ Direct Irradiance, Ambient Temperature  │
│             and Wind Speed              │
└─────────────────────────────────────────┘
                    │
                    ▼
┌─────────────────────────────────────────┐
│      Compute Plane-of-array          2  │
│              Irradiance                 │
└─────────────────────────────────────────┘
                    │
                    ▼
┌─────────────────────────────────────────┐
│    Compute Module Temperature        3  │
└─────────────────────────────────────────┘
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┌─────────────────────────────────────────┐
│      Compute DC Power            4      │
└─────────────────────────────────────────┘
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                    ▼
┌─────────────────────────────────────────┐
│      Compute AC Power            5      │
│      Using PCU Efficiency Curve         │
└─────────────────────────────────────────┘
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Fig. 2. Functional Blocks in a PV Simulation Model.

Block 1 in the figure, is concerned with the availability of at least a full year's worth of irradiance and weather data at the site. The translation of horizontal irradiance on to tilted surfaces is accomplished in block 2. The irradiance on a tilted surface is also known as **plane-of-array** irradiance. Each component of the horizontal global irradiance get translated in a different way. While the direct normal irradiance on the plane-of-array depends only on the solar zenith angle, the same is not true for the diffuse irradiance component. There are a number of techniques proposed by different authors for this purpose. Some of the more widely used models are discussed in [4].

Block 3 is the cell temperature model. Such a model is required because the currents and voltages developed in a solar cell is a function of the cell temperature. Solar irradiance, ambient temperature and wind speed have a combined effect on the cell temperature. Some researchers do not consider wind speed in their modeling, and predict a linear relationship between cell temperature and the solar irradiance. A commonly used relationship is:

$$T_c = T_a + 0.3A \qquad (4)$$

where:

T_c = cell temperature.
T_a = ambient temperature.
A = plane-of-array irradiance.

Block 4 is the array electrical model. This model calculates currents, voltages and peak power using the output from block 3. The power conditioning model is incorporated in block 5. Here dc power is converted to ac for use in supplying directly to the grid or after a voltage boost.

2.2 South-facing Array

This is the most typical orientation for PV arrays in the northern hemisphere. The installation requires only a simple tilting structure. Use of the solar geometry and weather data at Raleigh, NC, latitude 35.75°, shows the fact that the optimal tilt angle varies for each month from 60° in January to 5° in June and back up to 60° in December. The surface azimuth angle in each case is held at 0°. Therefore in order to obtain the maximum available solar energy every month, it is required to change the tilt angles according to the figures obtained. On the other hand, it may be desirable to leave the array facing south at one specific tilt angle throughout the year. Then a new tilt angle may be found which optimizes the annual output. In this case for Raleigh, this angle is 30°. The curve in Fig. 3 shows, among other things the PV output from a south facing array on a typical day in the month of August at Raleigh. To show the effect of site diversity, similar results are also shown for a site at Hesperia, CA in Fig. 4. The month shown here is November. An annual tilt angle also of 30° is used at this site as well.

2.3 Optimal-Surface-Azimuth Oriented Array

Since maximizing PV output at noon time may not necessarily be of primal importance to a utility with a load shape peaking at another hour besides noon, it is only natural to try and maximize the PV output at or close to the hour of peak demand. It is found that this can be done by changing the surface azimuth angles as required to an angle suitable for maximizing the PV generations at any prescribed hour of peak load. This strategy is a special case of option 3 shown in Fig. 1. The orientation strategy is of course inherently linked with the fact that the overall energy generated during the day is less than that generated by a south-facing array. Also because of the diurnal nature of the solar radiation, optimal orientation is not possible for peak demands occurring after 1600 hours and in these situations it is better to leave the array facing a direction optimal for the 4 PM peak.

Results of maximizing the irradiance at the 16th hour of the day in August at Raleigh is shown in Fig. 3. Similar results of maximizing at the 13th hour of the day in November at the Hesperia site is shown in Fig. 4. Needless to say, the reason why these particular hours are chosen for maximization is the occurrence of the peak demands at those hours. For the Raleigh site, the optimal tilt angle and the optimal surface azimuth angle

are found to be 40° and 80° west of south respectively for the month shown in the figure. At the Hesperia site, these angles are determined to be 50° and 10° west of south respectively.

2.4 Two-axis Tracking Arrays

In this orientation strategy, the array is always facing the direction of the sun for maximum solar radiation at every hour. In other words, the incidence angle is constantly held at 0°. This strategy requires the use of expensive tracking mechanism in both the horizontal and vertical axes.

The output from a two-axis tracking array model at the Raleigh and Hesperia sites are shown in Figs. 3 and 4 along with the outputs from the other two strategies of array orientation. From the figures, it is obvious that two-axis tracking provides more energy during the day than either the south-facing or the optimal fixed surface azimuth arrays. However, the peak power generations are the same for all three. It will be seen in a later analysis that the peak generation at a desired hour is of greater importance than the total energy generated during the day in the case of utility integrated PV systems combined with a battery plant meant specifically for supply side load management. More specifically, to shave an equal percentage of the peak load, the battery size requirement actually increases with a two-axis tracking array option than either of the other two.
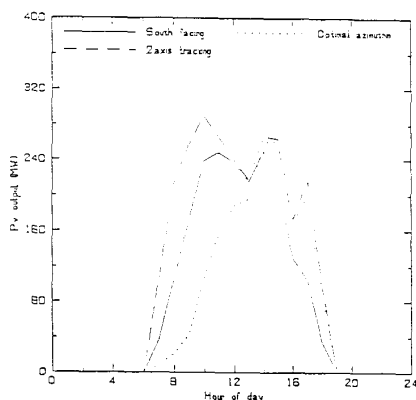

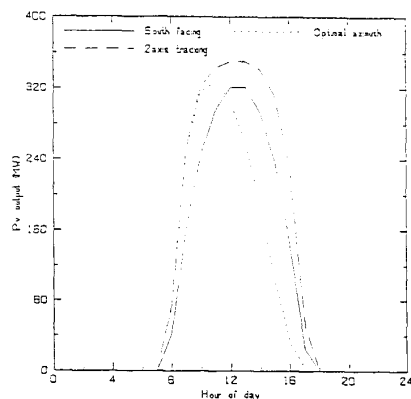*Fig. 3. PV Output Comparisons for Three Orientation Strategies in August at Raleigh, NC.*

Fig. 4. PV Output Comparison for Three Orientation Strategies in November at Hesperia, CA.

3.0 Energy Storage with Central Station PV Plant

Storing large amounts of energy during off-peak periods of the day for use during the peak periods can be easily done by storage batteries. This process is called **load leveling**. The rationale for this entire scheme revolves around the fact that energy during off-peak periods is cheaper and easily available whereas that during the peak periods of the day is very expensive and is derived from fossil fuel. Storage batteries are now looked at seriously by electric utilities for load leveling. The proposed 10 MW battery load leveling project for the Southern California Edison Co. at Chino, CA [5] is a case in point.

3.1 Battery Plant Design

Sizing a suitable battery adequate for shaving the peak demand hours in every month of the year is tantamount to determining the size of the battery required to supply the peak load of the month which contains the annual peak. However, this may not be true for low peak-shaving requirements. For example, if the month of August contained the annual peak and assuming that this month had a single daily peak occurring in the afternoons, then for a peak shaving requirement of up to 6% of the peak load, this particular month will always need the largest battery size. Any further reduction in the peak shaving requirement will shift the worse conditions to another month which most probably has double peaks in a day and therefore the size of the battery is determined according to that required in that month.

For load leveling purposes, advanced batteries are required. These batteries should have the following features: high efficiency, 70-75%; high cycle life, 3000-4000 cycles; discharge should be at constant power for 5-8 hours; low demand cost ($/MW) and low capacity cost ($/MWh).

Needless to say that the actual size of the battery will depend on the amount of peak-shaving desired. Some utilities have load profiles which will not allow peak shaving beyond a certain limit, the constraint being the depth of discharge limitations on the battery itself. A second factor is the fact that the costs of batteries are largely dependent on the MWh size of the plant rather than the MW size. Thus, utility planner would opt for a low MWh to MW ratio in sizing a battery plant. That means a small period of discharge. Also figuring prominently in the fixation of an optimal amount of peak shaving is the limitation on the total **base capacity** available for charging the battery. It so happens that the daily utility load experiences a low demand period during the early morning hours. Therefore, this period is suitable for charging the battery with the generating capacity which is available at this time. The operating costs of this generation, called here, as the base capacity, is minimal. On the other hand, there is also a limited amount of capacity to be spared, wherefore comes the limitation on the exact amount of peak shaving possible.

A fourth constraint on the lower limit of the peak shaving comes from the presence of photovoltaic power in the grid. The best possible use of PV generation, as pointed out earlier, is in its utilization during the peak shaving period. This decreases the capacity needed from battery discharge during these hours and is therefore conducive to the battery sizing. Reducing the peak load shaving amount certainly precludes the PV power from being optimally utilized and therefore works against the economics of the utility.

Once the peak shaving period/s have been fixed within the limitations as pointed out, some additional constraints must be kept in mind before arriving at a final size of the battery. These are:

- Battery discharge should be deep enough to supply an entire peak load duration.
- Base capacity (power taken from the reserve generation during the lowest daily demand periods on top of any available photovoltaic power) to charge the battery should be enough for charging at the specific charging rate of the battery.
- Back-up power, i.e. power outside of the combined capacity of the PV/battery system to shave the peak should be zero.
- Usage of PV power outside the peak demand region should be minimized. This is done in order to earn more fuel and capacity credit.

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4.0 Determination of PV and Storage Plant Sizes

The rating of the PV plant depends on the percentage of peak load to be shaved. Since the plant will run simultaneously with a battery plant, the size of the latter also affects the PV plant rating. If, on the other hand, the amount of peak load shaving has been predetermined, it becomes a matter of computer simulation runs to arrive at optimal plant sizes for both plants. An iterative computer optimization routine was employed for the determination of plant ratings. The load shape at a particular utility has significant influence on such ratings. Figures 5 and 6 show the load shapes for specific days at both locations. The load profiles for these regional utilities are produced from [6].
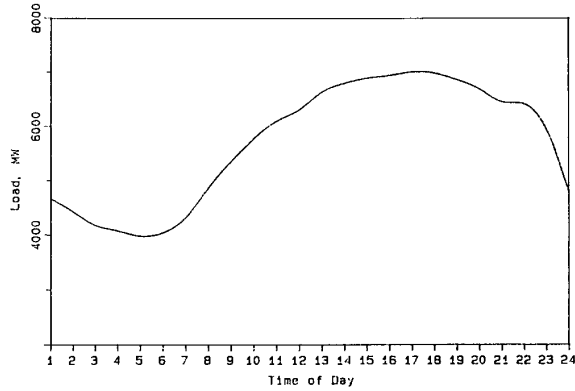
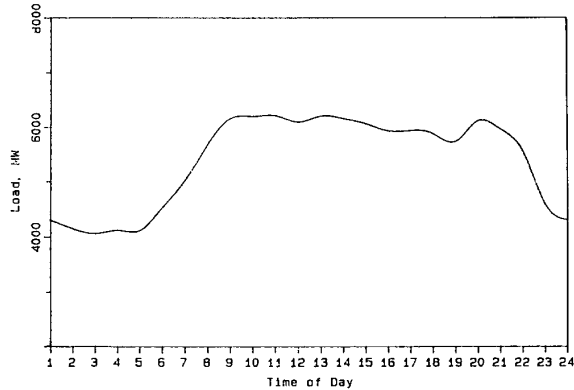*Fig. 5. A Daily Load Profile in August for the Southeastern Utility.*

Fig. 6. A Daily Load Proile in November for the Western Utility.

It was found that on an average, 5% peak load shaving is the optimal amount possible under the constraints discussed in Section 3.1. As a general rule, a PV plant rating of 5% of the annual peak demand was applied for the amount of load leveling. For the typical utility in the southeast and in the west, an annual peak of 7000 MW equates into a 350 MW rated PV plant. The size of the battery of course depends on the orientation strategy of the PV arrays. Figures 7 and 8 illustrate the change in capacity for percent peak load shaved in the southeastern and the western parts of the US respectively.
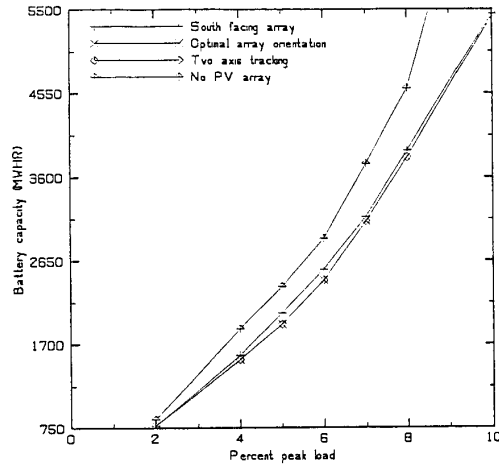
Fig. 7. Battery Capacity Requirement for Percent Peak Load Supplied. Site is Raleigh, NC.
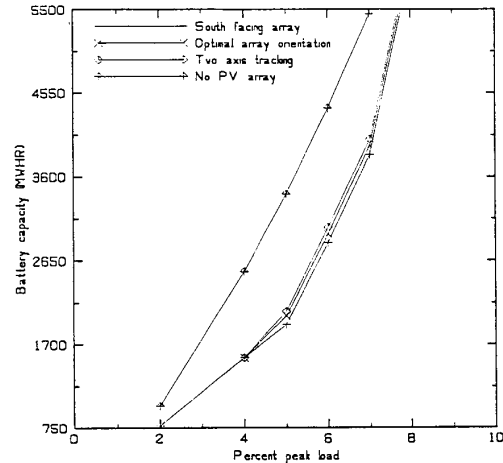
Fig. 8. Battery Capacity Requirement for Percent Peak Load Supplied. Site is Hesperia, CA.

The energy requirement of the battery depends on the period of discharge which is higher at Hesperia than at Raleigh.

5.0 PV/Battery Operating Strategy

The following steps describe how the combined operation of the PV and battery system is envisaged.

1. During the early morning hours, it is natural to find the battery State of Charge (SOC) down to a low level. This is from the preceding day's discharge during peak periods. Therefore, apply constant power to charge the battery to as high a level possible before the discharge cycle begins. The charging power is composed of base capacity and photovoltaic power generation, available only after sunrise, during the charge cycle.

2. Apply all the photovoltaic generations to the peak load during the load management period. If not sufficient, discharge the battery.

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3. The daily duty cycle of the battery consists of one of the following possibilities:

    a. Two charge cycles; two discharge cycles:

        -   charging is done in the early morning hours.
        -   charging again, done by photovoltaic power in the mid-afternoons when the morning peak has been shaved and the evening peak is ahead.
        -   discharge in the morning peak period.
        -   discharge in the evening peak period.

    b. Two charge cycles; one discharge cycle:

        -   same as in (a) except that only the morning peak is required to be shaved.

    c. One charge cycle; one discharge cycle:

        -   charging is done in the early morning hours.
        -   discharging during one long extended period.

4. During charge periods, if the battery SOC reaches 100%, then all photovoltaic power available is diverted to supply the load demand at that time even if the load is not within the peak load period. This is because the PV operating cost is zero and therefore any available power is an addition to the overall generation capacity with a higher dispatch priority over the other dispatchable generation.

6.0 Comparative Study Results

Typical utilities from the south-eastern and western regions are selected for analysis of the proposed load leveling strategy. The hourly load data for each of these utilities for an entire year is produced from [6]. The peak load occurs in the month of August for both utilities and is assumed to be 7000 MW in each case. Simulations concerning the PV power output are done by using the program PVFORM [7]. Battery (lead-acid) charging and discharging characteristics are taken from [8]. Specifications of the PV and battery plants used in the simulation are given in Appendix I.

For illustrating the seasonal effect on the load leveling strategy, four representative months are selected to represent the four seasons. These months are February, May, August and November which represent winter, spring, summer and fall respectively.

Results of the simulation are presented in Tables 1 and 2, with Table 1 being those for the southeastern utility and Table 2 being those for the western utility.

The following observations may be made from the these tables.

1. Photovoltaic power combined with battery storage makes a large difference in battery size compared to the case with no PV power assumed. The main differences are:

    -   South-facing array:

        Saving of 300 MWh in S-E utility.
        Saving of 1475 MWh in W utility.

    -   Optimal-surface-azimuth array:

        Saving of 425 MWh in S-E utility.
        Saving of 1375 MWh in W utility.

    -   Two-axis tracking array:

        Saving of 425 MWh in S-E utility.
        Saving of 1325 MWh in W utility.

2. PV/battery combination also has a large impact on base capacity required for charging the battery as opposed to the case with no PV power assumption. These are as follows:

    -   For S-E utility:

Table 1. Peak Shaving Characteristics in the Four Seasons for Typical Utility in the Southeast (assuming 7000 MW annual peak)

PV Array Orientation	Percent Peak Load Shaved*	Battery Capacity MW/MWh	Base Capacity for Charging MW
South-Facing	5% - WI 6% - SP 5% - SU 6% - FA	350/2050	150 - WI 50 - SP 50 - SU 0 - FA
Optimal Surface Azimuth	5% - WI 6% - SP 5% - SU 5% - FA	350/1925	125 - WI 50 - SP 75 - SU 0 - FA
Two-axis Tracking	5% - WI 6% - SP 5% - SU 5% - FA	350/1925	125 - WI 25 - SP 50 - SU 0 - FA
No PV Array	5% - WI 5% - SP 5% - SU 7% - FA	350/2350	175 - WI 200 - SP 325 - SU 250 - FA

*WI-Winter; SP-Spring; SU-Summer; FA-Fall

Table 2. Peak Shaving Characteristics in the Four Seasons for Typical Utility in the West (assuming 7000 MW annual peak)

PV Array Orientation	Percent Peak Load Shaved*	Battery Capacity MW/MWh	Base Capacity for Charging MW
South-Facing	5% - WI 7% - SP 6% - SU 5% - FA	350/1925	0 - WI 125 - SP 150 - SU 150 - FA
Optimal Surface Azimuth	6% - WI 7% - SP 6% - SU 5% - FA	350/2025	50 - WI 100 - SP 125 - SU 150 - FA
Two-axis Tracking	6% - WI 8% - SP 6% - SU 5% - FA	350/2075	25 - WI 150 - SP 0 - SU 150 - FA
No PV Array	7% - WI 5% - SP 5% - SU 5% - FA	350/3400	325 - WI 300 - SP 475 - SU 225 - FA

*WI-Winter; SP-Spring; SU-Summer; FA-Fall

25-50 MW saving in winter.
150-175 MW saving in spring.
275-300 MW saving in summer.
250 MW saving in fall.

For W utility:

275-325 MW saving in winter.
150-175 MW saving in spring.
325-475 MW saving in summer.
75 MW saving in fall.

The reductions in base capacity should be examined in the light of total PV installed capacity. Both utilities had 350 MW of rated PV power in these simulations, and looking at the above comparisons, the turnaround is quite attractive, particularly in spring and summer. The savings in summer for the typical western utility which comes

to 475 MW should be compared to the 350 MW of installed PV capacity. The savings in combined PV/battery case stems from the fact that less base generation capacity is required to charge a battery with smaller capacity size required compared to the stand-alone battery case.

3. Comparing the performance of the array orientation strategies against one another, it seems fairly obvious that while optimal-surface-azimuth oriented arrays are better than others in the southeast, the simple south-facing array provides a better perspective of load leveling in the west.

Table 3 shows further comparisons of the load leveling study after the array orientation strategy were fixed at the optimal-surface-azimuth orientation for the southeast and south-facing for the west. The indices to look for are the "peak effectiveness ratio" (column 4) and the "charging effectiveness ratio" (column 6). The former is defined here as the ratio of array energy supplied by the array to the grid during the peak period to the total energy supplied by the array to the grid, and the latter as the ratio of the energy supplied by the PV array to charge the battery to the total energy required for charging. Column 3 in the table also shows the total energy supplied by the PV array during the period of peak shaving. Column 2 presents the PV energy used to supply the overall load and column 5 shows the PV and base energy used to charge the battery. Column 4 is the ratio of column 3 over column 2 whereas column 6 is the ratio of the PV array energy used to charge the battery over column 5.

Table 3. Array Performance at the Two Sites.

PV Array Orient-ation	Total Array Energy to Load MWh	Total Array Energy During Peaks MWh	Peak Effec-tiveness Ratio	Total Energy to Charge Battery MWh	Charging Effective-ness Ratio
South-east Optimal azimuth orient.	38000-WI 78700-SP 7520-SU 50100-FA	16900-WI 70200-SP 62900-SU 39600-FA	0.44-WI 0.89-SP 0.84-SU 0.79-FA	29200-WI 22500-SP 21800-SU 13200-FA	0.75 0.36 0.22 0.20
West South-facing	32200-WI 46100-SP 41300-SU 27800-FA	11200-WI 37100-SP 25900-SU 10500-FA	0.35-WI 0.80-SP 0.63-SU 0.38-FA	16770-WI 20460-SP 24570-SU 14000-FA	0.53 0.61 0.69 1.00

Higher values in columns 4 and 6 indicate a more desirable feature. A higher "peak effectiveness ratio" means that the array power is used more effectively during the peak shaving period in terms of the amount of energy being supplied. A higher "charging effectiveness ratio" signifies the fact that lesser base capacity is used for charging the battery and that most of the charging power came from the existing PV array.

7.0 Conclusions

A specific application of central station photovoltaic plants that of load leveling, has been presented. Energy storage in the form of pumped hydro plants or battery plants are being considered by electric utilities for peak shaving. PV power combined with a battery plant presents an effective alternative for load leveling. There are a few advantages of using a combined PV/battery plant for peak shaving application as opposed to using only a battery plant. These are:

1. A large battery capacity saving results. Such capacity savings are considerably higher for the western U.S. utilities. These are: 39% for the two-axis tracking scheme; 43% for the south-facing scheme and 40% for the optimally fixed array. It should be mentioned here that in 2-axis tracking case, a higher percentage of the load is served by the PV system. Savings in the southeastern utilities are somewhat smaller. These are 18% for the two-axis tracking scheme; 13% for the south-facing array and 18% for the optimally fixed array. The difference in battery capacity saving originates from the fact that the average global irradiance (watts/sq-m) is higher in the western part of the U.S. which equates to a higher photovoltaic power.

2. There are large base capacity (power taken during off-peak periods for charging the battery) savings also. In the typical southeastern utility, these savings in base capacity over the "no PV in grid" case are as per season: winter - 28%; spring - 87%; summer - 92%; and fall - 100%.

Similarly, PV power has a bigger impact during summer in the typical western utility. The savings in the base capacity case are: winter-100%; spring - 50%; summer - 100%; and fall - 33%.

3. Since the battery depth of discharge is reduced in the PV/battery hybrid application, the life of the battery will be increased compared to battery-alone case.

4. PV power helps to maintain a higher state of charge in the battery. Therefore, the battery holds enough stored capacity after peak shaving which can be used as additional spinning reserve.

8.0 References

[1] T. Hoff, C. Jennings, "Match Between PG & E's Peak Demand and Insolation Availability," Proceedings of the 18th Photovoltaic Specialist Conference, pp. 235-239, 1985.
[2] D. J. Rosen, D. Thorpe, R. Spencer, "Design, Construction and Storage of the SMVDPV1 1 MWAC Photovoltaic Central Station Power Plant," IEEE Power Engineering Society Winter Power Meeting, 1985.
[3] S. T. Lee, Z. A. Yamayee, "Load-Following and Spinning Reserve Penalties for Intermittent Generation," IEEE Power Apparatus and Systems, Vol. 100, No. 3, pp. 1203-1211, 1981.
[4] B. Chowdhury, S. Rahman, "Comparative Assessment of Plane-of-Array Irradiance Models," Solar Energy, Vol. 39, No. 5, pp. 391-398, 1987.
[5] Electric Power Research Institute, "Design and Costs for a Generic 10-MW Utility Lead-Acid Battery Energy Storage Plant," EPRI AP-5845, June, 1985.
[6] Electric Power Research Institute, "The EPRI Regional Systems," EPRI P-1950-SR, July, 1981.
[7] D. F. Menicucci, J. P. Fernandez, "User's Manual for PVFORM: A Photovoltaic System Simulation Program for Stand-Alone and Grid-Interactive Applications," Final Report SAND 85-0376, Sandia National Labs, April, 1988.
[8] E. R. Hoover, "SOLCEL-II: An Improved Photovoltaic System Analysis Program," Report - SAND 79-1785, Sandia National Labs, February, 1980.
[9] GNB Inc., "Module Specifications," 1984.
[10] ARCO Solar Inc., "Module Specifications," 1985.

Appendix I

Specifications of the Battery and PV Plants

The Battery System (Source - GNB Inc., Ref. 9)

Type:	Lead-acid flooded electrolyte cell
Manufacturer:	GNB Incorporated
No. of cells per module:	6
Module voltage:	12 V
Module capacity:	40 KWh
Discharge rate:	C/4
Sample connection for peak shaving:	50,000 modules Eighty series modules in 645 parallel strings
Nominal voltage (dc side):	1000 V
Transmission voltage (ac side):	13.8 KV

The PV System (Source - ARCO Solar Inc., Ref. 10)

Type:	M75
Manufacturer:	ARCO Solar Inc.
No. of cells per module:	33 square cells
Cell efficiency:	11.7%
Module voltage (open circuit):	19.9 V
Module power:	47 Watts
Sample array (350 MW):	7,000,000 modules
Nominal voltage (dc side):	1000 V
Transmission voltage (ac side):	13.8 KV