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Analysis of Interrelationships Between Photovoltaic Power and Battery Storage for Electric Utility Load Management

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ANALYSIS OF INTERRELATIONSHIPS BETWEEN PHOTOVOLTAIC POWER AND BATTERY STORAGE FOR ELECTRIC UTILITY LOAD MANAGEMENT

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ABSTRACT

The impact of photovoltaic power generation on the electric utility's load shape under supply-side peak load management conditions is explored. Results show that some utilities employing battery storage for peak load shaving might benefit from use of photovoltaic (PV) 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 night-time base capacity required to charge the battery. Results show that when the cost of 2-axis tracking PV systems drop to \$2/Wp, the southwestern utility will experience net cost savings when the PV-battery hybrid system is employed for load management. On the other hand, becaues of lesser availability of solar energy, the southeastern utility shows adverse economics for such a system.

1.0 INTRODUCTION

With the availability of advanced batteries, it is now possible to store large amounts of energy during off-peak periods of the day for use during the peak periods. 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. Considerable amount of research and development work has been performed at the battery test facility (BEST) in New Jersey [1]. 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 at Chino, California, is a case in point.

As the storage technology matures and becomes available for electric utility load leveling, there may be other ways to make it more viable. One such option may be to integrate batteries and photovoltaic (PV) energy system. The objective of this paper is to provide a comparative analysis of the cost and benefit of the battery alone versus the battery-PV hybrid system for load-leveling applications. 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 southwestern U.S. have been looked at.

1.1 Potential 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. In cases like this, Chinery [2] states that it is quite possible that the operating cash flow of some utilities can be adversely affected. This is because they sell power to many of their customers (especially residential) at the same rate regardless of whether the sale takes place during on-peak or off-peak periods. Cutting their load during off-peak periods forces them to sell less power when their profit margin is the greatest. This act reduces their revenues significantly without reducing their operating expenses.

These problems lead 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.

From the point of view of economics, Schueler, et al. [3] claim that utility owned energy storage perform better than dedicated storage for photovoltaic central station application. Therefore, 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 CONSIDERATIONS

The photovoltaic power from an array depends on the solar input to the cellular unit of the array. Naturally, the more intense the radiation (watts per sq. m) on the earth surface, the higher is the electrical output. Therefore, attempts are made to optimize the reception of the incoming radiation on the planar array by tilting the surfaces and facing the array at particular directions for maximum input. These directions are called surface azimuth angles. The particular tilt angles and surface azimuth angles are dictated by the earth-sun geometry.

Some relationships [4] which will be required in the analysis are stated below:

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

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

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 = $\cos^{-1}(-\tan\varphi\tan\delta)$

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

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

where:
θ_t = incidence angle (angle between direction of the sun and normal direction of the surface).
γ_s = solar azimuth angle.

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

γ = surface azimuth angle.
β = slope of the planar array.

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Equations 1-3 figure prominently in deciding on the optimal orientation of the PV array. Three of the most important array orientations for load management are discussed below.

2.1 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 was 30 °. The curve in Fig. 1 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. 2. The month shown here is November and using an annual tilt angle also of 30 °.

2.2 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 was only natural to try and maximize the PV output at or close to the hour of peak demand. It was 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 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 hrs and in these situations it is better to leave the array facing a direction optimal for the 4 PM peak. Inspite of these, as will be obvious later on in the paper, this orientation strategy, in most cases, is superior to all other strategies.

Results of maximizing the irradiance at 1600 hour of the day in August at Raleigh is shown in Fig. 1. Similar results of maximizing at 1300 hour of the day in November at the Hesperia site is shown in Fig. 2. Needless to say that the reason why these particular hours were chosen for maximization was the occurrence of the peak demands at those hours. For the Raleigh site, the optimal tilt angle and the optimal surface azimuth angle were found to be 40 ° and 80 ° west of south respectively for the month shown in the figure. At the Hesperia site, these angles were determined to be 50 ° and 10 ° west of south respectively.

2.3 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 Figures 1 and 2 along with the outputs from the other two strategies of array orientation. From the figures, it is obvious that two-axis tracking provides much 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.

2.4 PV Plant Rating

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. For instance, if it is desired to shave 5% of the annual peak demand with the combined PV/battery system, then a general rule of choosing a PV plant rating of 5% of the annual peak may be applied. This decision was arrived at after several simulation runs with different scenarios of the combined system. The combination which gave the *best* results was used in the study. (The term 'best' is used here with respect to the constraints defined in section 3.2.) For the typical utility in the south-east and in the west, an annual peak of 7000 MW equates into a 350 MW PV plant rating. Under this assumption, the battery plant size was found to be 350 MW/1925 MWh at Raleigh and 350 MW/2025 MWh at Hesperia. The energy requirement of the battery depends on the period of discharge which happens to be higher at Hesperia than at Raleigh. The battery plant sizing is discussed in details in the next section.

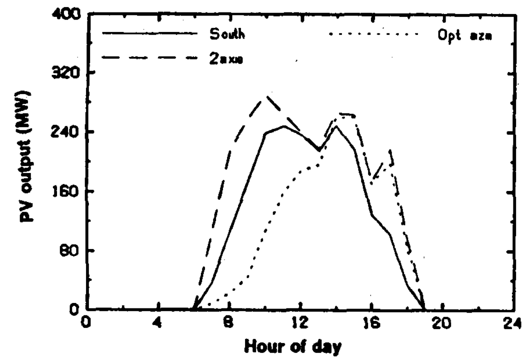

Fig. 1. PV output comparisons for fixed tilt, optimized and fully tracking arrays for August at Raleigh, N.C.

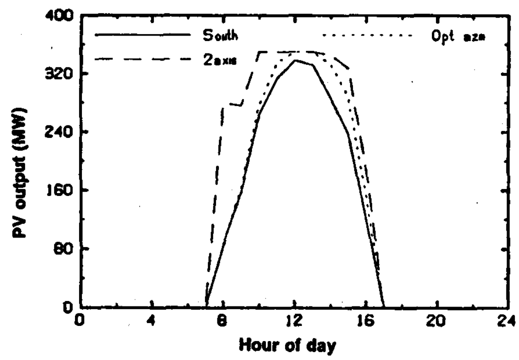

Fig. 2. PV output comparisons for fixed tilt, optimized and fully tracking arrays for November at Hesperia, CA.

3.0 BATTERY PLANT CONSIDERATION

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 upto 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.

3.1 Choosing the Battery Type

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). Although, all of these criteria are not met by any of the existing batteries, the following provide good choices:

1. Sodium-Sulfur,
2. Zinc-Bromine,
3. Hydrogen-Nickel, and
4. Lead-acid.

Out of the above four, only the lead-acid battery has been the front runner. A cycle life of 1000-1500 may easily be reached with the present technology. For the simulation results presented in this paper, an advanced lead-acid battery characteristics were used.

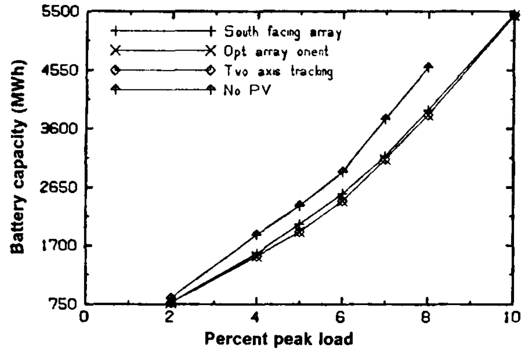

Fig. 3. Battery capacity requirement for percent peak load supplied. Site is Raleigh, NC.

3.2 Sizing the Battery

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 planners 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 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 third constraint on the lower limit of the peak shaving comes from the presence of photovoltaic power in the grid. The best possible use of photovoltaic 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 has 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:

1. Battery discharge should be deep enough to supply an entire peak load duration.

2. 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.

3. Back-up power i.e. power outside of the combined capacity of the PV/battery system to shave the peak should be zero.

4. Usage of PV power outside the peak demand region should be minimized. This is done in order to earn more fuel credit.

An iterative computer optimization method to satisfy the above constraints with the maximum possible peak shaving possible, was employed to yield the results enumerated below. In the two case studies performed on the typical utilities in the south-east and in the west, it was found that 5% peak load shaving was the optimal amount of load management possible under the constraints. The size of the battery of course depends on the orientation strategy of the PV arrays. Figures 3 and 4 illustrate the change in battery capacity for percent peak load shaved in the southeastern and the western parts of the U.S. respectively. Steeper slopes of these curves signify the fact that for each percent increase of peak shaving desired, the number of peak hours increases faster in the case of the western utility thereby requiring higher battery capacity. This also gives an indication that the peak periods in the western utility are more flat.

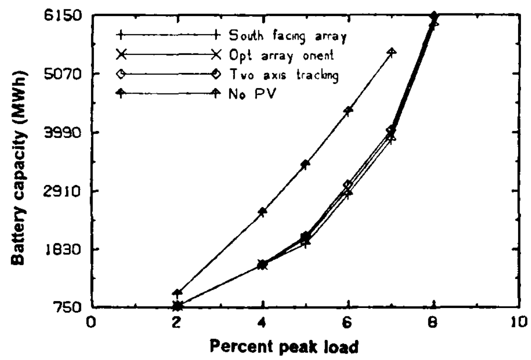

Fig. 4. Battery capacity requirement for percent peak load supplied. Site is Hesperia, CA.

3.3 PV/Battery Operating Strategy

Duty Cycle

It was found that a daily duty cycle rather than a weekly cycle would best suit the peak shaving purposes. This was agreed upon because of the excessive amount of battery capacity required for longer hours of storage in the weekly cycle application.

Cycle Life

One of the general concerns in battery operation for peak shaving is preserving the cycle life of the battery. The *depth of discharge* (DOD) of the batteries has a direct affect on the cycle life. Generally, an advanced lead-acid battery will last 3000 cycles if its cycling is limited to 50% DOD [5]. On the other hand an 80% DOD limits the cycle life to only 1500 cycles. Besides, temperature also has an affect on the life of the battery. Owing to the dependence of cycle life on the DOD, it is necessary to maintain the discharge level to a minimum possible. It will be proved later that PV power can help in preserving the cycle life of the battery through a combined operation of the two plants for peak shaving.

Combined Operation

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

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.

4.0 COMPARATIVE STUDY

Two model utilities from the south-eastern and the western regions of the U.S are selected for analysis of the load management strategy described in preceding sections. The Load profiles for these utilities are produced from [6]. The peak load occurs in the month of August for both utilities and are assumed to be 7000 MW in both cases. The assumption for the annual peak demand is actually immaterial. The most important factor influencing load management strategies is the shape of the daily load curve.

The PV array site representing the south-east was chosen to be Raleigh, NC and that representing the west was Hesperia, CA. Simulations concerning the PV power output itself are done by using the program PVFORM [7] developed at the Sandia National Laboratories. Battery (Lead-acid) charging and discharging characteristics were taken from Hoover [8].

4.1 Specifications of the PV/Battery System

The optimal load management strategies for both sites are determined by an optimization routine to be 5% peak shaving for the worst month (in terms of energy capacity requirement). Because of lower energy requirement in some other months particularly in the spring season, this translates into a higher (upto 8%) peak shaving capability by the same PV/battery system. Four representative months, viz., February, May, August and November representing the winter, spring, summer and fall respectively are chosen for presenting the results. The first part of this section deals with comparative performances of a PV/battery combined system as opposed to a battery system alone in peak load management schemes. The second part deals with the relative performances of the three competing array orientation strategies in the PV/battery combined system.

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

TABLE 1

Peak shaving characteristics in the four seasons for typical utility in the south-east (assuming 7000 MW annual peak)

CASE	PV array orientation.	Percent peak load shaved. [1]	Battery Capacity. MW/MWhr	Base Capacity for charging. MW
1	South-Facing	5% - WI 6% - SP 5% - SU 6% - FA	350/2050	150 - WI 50 - SP 50 - SU 0 - FA
2	Optimal surface azimuth	5% - WI 6% - SP 5% - SU 5% - FA	350/1925	125 - WI 50 - SP 75 - SU 0 - FA
3	Two-axis tracking	5% - WI 6% - SP 5% - SU 5% - FA	350/1925	125 - WI 25 - SP 50 - SU 0 - FA
4	No PV array	5% - WI 5% - SP 5% - SU 7% - FA	350/2350	175 - WI 200 - SP 325 - SU 250 - FA

[1] 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)

CASE	PV array orientation	Percent peak load shaved	Battery Capacity MW/MWhr	Base Capacity for charging MW
1	South-Facing	5% - WI 7% - SP 6% - SU 5% - FA	350/1925	0 - WI 125 - SP 150 - SU 150 - FA
2	Optimal surface azimuth	6% - WI 7% - SP 6% - SU 5% - FA	350/2025	50 - WI 100 - SP 125 - SU 150 - FA
3	Two-axis tracking	6% - WI 8% - SP 6% - SU 5% - FA	350/2075	25 - WI 150 - SP 0 - SU 150 - FA
4	No PV array	7% - WI 5% - SP 5% - SU 5% - FA	350/3400	325 - WI 300 - SP 475 - SU 225 - FA

4.2 With and Without PV: Comparative Advantages.

Table 1 shows the nature of the systems used in the peak load management scheme in the southeastern utility. Similar results for the western utility are shown in Table 2. The following observations may be made from Tables 1 and 2:

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

   - Case 1 vs. case 4: Saving of *300 MWh* in S-E utility
     Saving of *1475 MWh* in W utility
   - Case 2 vs. case 4: Saving of *425 MWh* in S-E utility
     Saving of *1375 MWh* in W utility
   - Case 3 vs. case 4: Saving of *425 MWh* in S-E utility
     Saving of *1325 MWh* in W utility

   Obviously, photovoltaics has a bigger impact on load management in the western utility in terms of battery size requirement.

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:
     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 for cases 1,2 and 3 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. The fact that PV power can cause low depth of discharge of the battery is evident from the comparison shown in Fig. 5. The "no PV" case shows that the DOD can reach over 70% on a typical day in the month of August at Raleigh while the PV/battery combined case exhibits a more preferable discharge characteristic, the DOD not reaching 50%. Similar characteristics are also seen in all the other months at both sites.

4. Another important issue of concern is the cycle life of the battery versus the PV array size. It was found that the number of charge-discharge cycles do not change significantly for small changes in the PV array size. Large changes in the latter is not possible in such applications without losing much of benefits earned in terms of percent of peak load shaved and amount of base generation capacity saved.

4.3 Relative Performance of Array Orientation Strategies

After comparing the attractiveness of PV/battery combination over the battery system alone, i.e. cases 1,2 and 3 versus case 4, it is useful to compare cases 1,2 and 3 against one another. In other words, to find out what array orientation strategy is the best for load management.

Once again from Table 1 (S-E utility):

- Case 2 vs. case 1: Saving in battery capacity of *125 MWh*.
  Saving in base capacity of *25 MW*
  in winter and *25 MW* in summer.
- Case 3 vs. case 2: Almost identical in all respects to case 2.

From Table 2 (W utility):

- Case 2 vs. case 1: Increase in battery capacity of *100 MWh*.
  Saving in base capacity of *25 MW*
  in spring and *25 MW* in summer.
- Case 3 vs. case 2: Increase in battery capacity of *50 MWh*.
  Saving in base capacity of *25 MW*
  in winter, *50 MW* in spring and
  125 MW in summer.

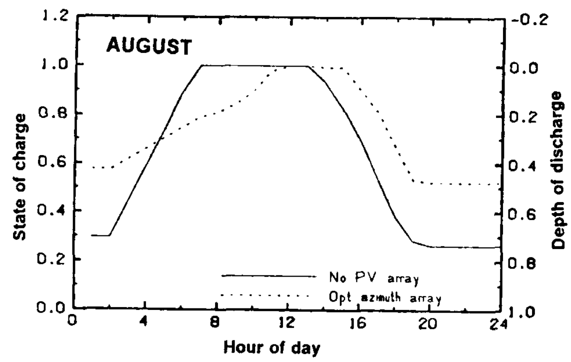

Fig. 5. Comparison of depth of charge and discharge of battery with and without PV power at Raleigh.

While optimal surface azimuth oriented arrays are better than others in the southeast, south-facing arrays provide a better perspective of load management strategy in the west. Of course the final choice of the orientation strategy would have to depend on the economics involved.

Tables 3 and 4 show the comparisons for the simulation runs involving the three strategies for PV array orientation. 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. The "charging effectiveness ratio" is defined 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 Tables 3 and 4 shows the total energy supplied by the PV array during the period of load management. 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.

Higher values in columns 4 and 6 indicate a more desirable feature. A higher "peak effectiveness ratio" means that the array power was used more effectively during the load management period in terms of the amount of energy being supplied. A higher "charging effectiveness ratio" signifies the fact that lesser base capacity was used for charging the battery and that most of the charging power came from the existing PV array. Evidently, from Tables 3 and 4, case 2 in which the array is optimally oriented for maximum power during peak shaving periods, is the best option in this perspective.

TABLE 3

Comparisons of the three PV array orientation strategies for the south-eastern utility.

PV array orient-ation	Total array energy to load. MWhr	Total array energy during peaks. MWhr	Peak effec-tiveness ratio	Total energy to charge battery. MWhr	Charging effec-tiveness ratio
Case 1. 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
Case 2. Optimal azimuth orient.	29800 - WI 47400 - SP 42700 - SU 29100 - FA	14000 - WI 37000 - SP 31900 - SU 10700 - FA	0.47 - WI 0.78 - SP 0.75 - SU 0.37 - FA	13270 - WI 20220 - SP 18700 - SU 8700 - FA	0.48 0.61 0.41 1.00
Case 3. 2-axis tracking	43400 - WI 61600 - SP 61700 - SU 41900 - FA	14600 - WI 45800 - SP 33700 - SU 11100 - FA	0.34 - WI 0.74 - SP 0.55 - SU 0.26 - FA	12970 - WI 17320 - SP 19530 - SU 9300 - FA	0.47 0.77 0.63 1.00

TABLE 4

Comparisons of the three PV array orientation strategies for the western utility.

PV array orient-ation	Total array energy to load. MWhr	Total array energy during peaks. MWhr	Peak effec-tiveness ratio	Total energy to charge battery. MWhr	Charging effec-tiveness ratio
Case 1. South-facing	35400 - WI 78600 - SP 75700 - SU 48200 - FA	10300 - WI 66900 - SP 6090 - SU 37900 - FA	0.29 - WI 0.85 - SP 0.80 - SU 0.79 - FA	25600 - WI 24500 - SP 23800 - SU 13000 - FA	1.00 0.28 0.20 0.18
Case 2. 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
Case 3. 2-axis tracking	50500 - WI 111000- SP 99100 - SU 59000 - FA	18200 - WI 91200 - SP 75700 - SU 44100 - FA	0.36 - WI 0.82 - SP 0.76 - SU 0.75 - FA	31000 - WI 31700 - SP 21900 - SU 12800 - FA	0.88 0.44 1.00 0.18

5.0 ECONOMIC CONSIDERATIONS

Economic models to evaluate both photovoltaic systems and battery plants in the utility perspectives have been introduced in the past [11,12]. However, these models are meant to evaluate such systems separately. To evaluate a hybrid system as proposed in this paper, some modifications need to be made in the analytical methodology available in the literature.

Before any economic analysis is done, it must be borne in mind that the objective is to weigh the merits of a PV hybrid system as opposed to battery alone for load leveling applications. Therefore, the scenarios for the analysis are set as the two distinct cases of i) battery alone and ii) battery-PV hybrid system. In other words, the economic analysis narrows down to a comparison of the cost of installing a PV system and the savings or credits earned by the hybrid system as proposed, versus the credits earned by the battery system alone.

For the purposes of this study, the installed cost of PV systems has been assumed to be $2.00/Wp for the tracking array case and $1.60/Wp for the fixed array case. This is within the range of cost estimates for middle 1990's. Summary of economic assumptions and other cost considerations are provided in Table 5. A life-cycle costing routine [13] run on these costs yields the energy costs of $0.042/KWh and $0.069/KWh respectively for the two array orientations at the southwestern site. The same for the southeastern sites are $0.155/KWh and $0.159/KWh respectively.

TABLE 5

Cost Considerations for the PV Array.

Description	2-Axis Tracking	Fixed
•Installed cost ($/Wp)	2.00	1.60
•Array size (MW)	350	350
•Annual energy produced (GWh)		
Western U.S.	1159.0	832.0
Southeastern U.S.	749.4	599.4
•O&M Cost (annual) (million $)	7.00	5.16
•Replacement cost per year (million $)	1.00	1.00
•Replacement cost every 5 years (million $)	10.00	10.00
•Life of PV array (years)	20	20
•Interest rate (%)	10.0	10.0
•Depreciation (years)	10	10

According to the battery performance requirements projected by Quinn [14], the cost/KWh requirement for a load leveling battery plant is $100. Recognizing the time-of-day production schedules for the utility, energy production costs are assumed to be $0.03, $0.05 and $0.10 per KWh for the base, intermediate and peaking time slots respectively. A cost comparison between the PV/Battery hybrid and battery-alone cases is presented in Tables 6 and 7. The numbers refer to the 2-axis tracking PV system. Item 1 in Table 6 shows the total annual cost of generating 1159 GWh from the PV array. Part of this energy is expended to charge the battery during off-peak demand periods and the rest of it goes directly to supply the load during peak and off-peak demand periods. Cost of battery charging comes from buying energy from the grid during the base periods and is shown as item 2. The cycle efficiency of the battery is imbedded in the charging energy. Item 3 shows the annual cost incurred in buying battery capacity. The cost of battery is taken as $100/KWh with a life of 8 years when used in battery-alone mode. The battery life is extended by 10% when used in the PV/battery hybrid mode. Items 5 and 6 show fuel credits from displacing conventional generation and are presented as negative numbers representing savings. The amount shown as the total amount reveals a saving of $16.02 million by the hybrid system. Table 7 shows the costs incurred by the battery-alone system. Annual cost of the battery capacity (item 2) is higher than in Case I because of a higher capacity required to shave the peak. No intermediate generation saving is possible in this case as no PV energy exists. A comparison of Tables 6 and 7 shows a net saving by the hybrid system of the amount of $51.10 million.

TABLE 6

Annual Cost/Benefit Characteristics of the Hybrid System in the Western Utility. (Case I)

Description	Million $
1. Cost of PV energy. 1159 GWh @ $.042/KWh	48.68
2. Cost of battery charging 136.7 GWh @ $0.03/KWh	4.10
3. Annual cost of battery	35.05
5. Saving of peaking generation 913 GWh @ $0.10/KWh	-91.30
6. Saving of intermediate generation 251.2 GWh @ $0.05/KWh	-12.55
Total:	-16.02

TABLE 7

Annual Cost/Benefit Characteristics of the Battery Plant Alone in the Western Utility. (Case II)

Description	Million $
1. Cost of battery charging 729 GWh @ $0.03/KWh	21.87
2. Annual cost of battery	61.91
3. Saving of peaking generation 486.6 GWh @ $0.10/KWh	-48.70
Total	35.08

Similar calculations were done for the fixed and the optimally fixed arrays. The fixed array used in the hybrid system yields an annual net saving of $23.77 million whereas, the optimally oriented array produces a net saving of $34.19 million.

Tables 8 and 9 show calculations for the southeastern site. The high cost of PV energy production figures prominently in Case II. The hybrid system shows a net expenditure of $66.50 million with a 2-axis tracking array. The same for fixed and optimally fixed arrays are $54.96 and $65.46 million respectively.

TABLE 8

Annual Cost/Benefit Characteristics of the Hybrid System in the South-eastern Utility. (Case I)

Description	Million $
1. Cost of PV energy. 749.4GWh @ $0.155/KWh	116.16
2. Cost of battery charging 76.43 GWh @ $0.03/KWh	2.29
3. Annual cost of battery	27.10
5. Saving of peaking generation 442.5 GWh @ $0.10/KWh	-44.25
6. Saving of intermediate generation 291.8 GWh @ $0.05/KWh	-14.59
Total:	**86.71**

TABLE 9

Annual Cost/Benefit Characteristics of the Battery Plant Alone in the South-eastern Utility. (Case II)

Description	Million $
1. Cost of battery charging 505.2 GWh @ $0.03/KWh	15.16
2. Annual cost of battery	35.66
3. Saving of peaking generation 306.06 GWh @ $0.10/KWh	-30.61
Total	**20.21**

6.0 CONCLUSIONS

An alternative method for peak load management has been presented. Energy storage in the form of pumped hydro plants or battery plants have hitherto been considered by electric utilities for peak shaving purposes. Photovoltaic power combined with a battery plant presents an effective alternative for peak load management. This type of application of photovoltaics may be one of the most viable forms for utility integrated PV plants.

There are a few advantages of using a combined PV/battery plant for peak load management as opposed to using only a battery plant. These are discussed below (reference to 5% peak shaving):-

1. There is a large battery capacity saving. 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 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.

The type of orientation strategy for the PV array makes a significant difference in the peak load management strategy. It is clearly evident from the results shown in this paper that two-axis tracking of arrays provide the best economics in such a unique application of photovoltaic power.

While the proposed load leveling scheme provides an optimistic cost/benefit ratio at the southwestern utility, the same cannot be projected for the southeastern utility. The latter region receives lesser amount of solar energy throughout the year and consequently, related costs go up. It is quite apparent from the results, that for this region, high PV energy production costs precludes the proposed scheme from being economically feasible at the projected cost of installed PV system in the next five to eight years. PV related costs would have to come down dramatically to make the hybrid system competitive in the southeastern U.S.

6.0 REFERENCES

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Discussion

O. D. Gildersleeve (Electric Power Research Institute, Palo Alto, CA): The incentives for combining photovoltaics (PV) with utility battery systems go beyond the advantages described in this paper. Also, a different operating strategy than the authors have evaluated may be motivated by utility system economics.

An additional advantage of pairing photovoltaics and batteries results from a particular load characteristic of most utilities. Namely, the nighttime customer load valley is usually shorter than the daytime load peak. As a result, a battery system (without PV) would need to be charged up in a shorter period of time than the period of discharge. Battery and charging losses give further reason for having an ac/dc converter that is sized about double that required for daytime battery discharge alone.

Since PV generation on the ground occurs in the daytime, the surplus daytime converter capacity of the battery system would be available for processing PV output. This concept provides almost free conversion capacity for the solar plant as well as additional spinning reserve at zero fuel cost for the utility.

Other forms of utility energy storage such as pumped hydro would not provide the same incentive for co-locating the PV and storage systems. However, the large sites that may be needed for significant amounts of PV may negate an attractive feature of batteries—that batteries may be able to be sited close to customer load centers.

In section 3.3, Chowdhury and Rahman describe how the combined PV and battery system may operate. Their strategy suggests that PV energy generated outside peak periods would be used to recharge the battery. This procedure has two disadvantages:

- battery losses would reduce by 30 to 50 percent the PV energy that otherwise could offset utility fuel requirements to satisfy customer load. For the many utilities that have to burn oil or gas during these daylight hours, high-cost fuel could be saved.
- PV charging of utility battery storage would offset battery charging by base load generation; the fuel saved would be of low cost.

The most attractive operating strategy for a PV/battery system would depend on the respective utility's generation mix and system loads. Production cost simulations using the EPRI regional systems, referenced in the paper, could be used to evaluate alternative operating procedures. Such analyses may also show that for fixed arrays, the best orientation may be offset somewhat toward local noon from the time of utility load peak. The resulting increase in solar energy production would reduce fuel requirements at other generating facilities. Overall utility system economics may be improved.

The high capital costs of PV and batteries, together with the recently demonstrated threat of low oil prices, continue to delay their commercial significance in bulk power markets. However, in combination, photovoltaics and batteries, when technically ready, may find an earlier market entry together than either technology alone. I encourage further analysis such as that provided by the authors to the extent that other research priorities allow.

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B. H. Chowdhury and **S. Rahman**: The authors would like to thank Mr. Oliver Gildersleeve for his interesting comments about our paper and the PV/battery concept in general. We appreciate the reference of two of his papers on this topic which we were not aware of at the time of writing our paper. These two papers seem to have been presented at some very specialized workshops organized and attended by a very select group of individuals, and we believe that the discusser would agree that these two papers are generally not accessible to the researchers in this field.

The advantages of a combined PV/battery system as described in our paper would obviously depend to a large extent on the specific utility's load shape. Due to the seasonal variation in the intensity and duration of sunshine there is also a seasonal factor in the value of PV/battery system to the electric utility. Regarding the operating strategy of the PV/battery system we suggested that the PV energy generated outside the peak period(s) would be used to recharge the battery only if the battery state of charge was found to be inadequate to meet the forthcoming peak. Otherwise, the PV plant should directly supply the load.

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