ABSTRACT
Grid-tied PV energy smoothing was implemented by using a valve regulated lead-acid (VRLA) battery as a temporary energy storage device to both charge and discharge as required to smooth the inverter energy output from the PV array. Inverter output was controlled by the average solar irradiance over the previous 1h time interval. On a clear day the solar irradiance power curve is offset by about 1h, while on a variable cloudy day the inverter output power curve will be smoothed based on the average solar irradiance. Test results demonstrate that this smoothing algorithm works very well. Battery state of charge was more difficult to manage because of the variable system inefficiencies. Testing continued for 30-days and established consistent operational performance for extended periods of time under a wide variety of resource conditions. Both battery technologies from Exide (Absolyte) and East Penn (Advanced Valve Regulated Lead-Acid) proved to cycle well at a partial state of charge over the time interval tested.

INTRODUCTION
The PV output from a grid connected array can change rapidly because of the movement of overhead clouds. In some cases, for example when a large PV system is connected to a relatively small grid or at the end of a weak feeder, rapid output power change can make it difficult to regulate voltage and frequency. The response time of steam turbines and other forms of generation can be too slow to mitigate the power fluctuations. It is possible to locally mitigate the effects of PV output variability using onsite energy storage. Effective PV energy smoothing requires an energy storage system that is integrated into the inverter and control system that will source and sink energy as the PV array power fluctuates according to the available solar resource. This mode of operation requires the energy storage system to operate at a partial state of charge (PSOC). The PV energy smoothing system described in this paper and shown in Figure 1 uses the battery at about 50% state of charge (SOC) and the energy in and out of the battery is determined by the average solar irradiance over a 1h time interval. On a clear day the solar power sold to the grid will be offset by about 1h. On a variable cloudy day the power curve will be smoothed based on the average solar irradiance and the battery capacity will be returned to the same state of charge at the end of the day as at the beginning of the day. Because battery energy is only used to smooth the PV array output, battery capacity can be relatively small. In this case model calculations indicate that battery capacity can be as low as 143 Ah at 48 volts for 3.5 kW of PV assuming a maximum DOD of 25%.

The intent of the energy smoothing algorithm is to reduce the rate and amount of fluctuations from the output PV power to meet utility requirements. Specifications for the 1.2 MW PV system at Lana’i in Hawaii require ramp rates of less than 6 to 60 kW/s depending on the time of day [1]. Modeling and Laboratory testing at Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) has shown that the ramp rates can easily exceed these values.

Figure 1: Grid-tied PV energy smoothing system.

The PSOC mode of battery operation is potentially very damaging to conventional valve regulated lead-acid (VRLA) batteries because of the formation of hard sulfation on the battery plates. In this test two battery types, the Absolyte from Exide and the carbon enhanced advanced VRLA from East Penn were used to evaluate their performance. The carbon enhanced VRLA technology has only recently been made available as a result of the Advanced Lead-Acid Battery Consortium (ALABC) development work directed at designing lead-acid batteries for use in hybrid electric vehicles [2,3]. The ALABC battery technology is now available through East Penn Manufacturing in a large industrial VRLA format [4]. The Absolyte battery technology has a long history in cycling solar and utility applications [5].
Laboratory testing at Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) has demonstrated that the new carbon enhanced advanced VRLA battery technology can tolerate the PSOC cycle operation more than ten times that of conventional float service VRLA batteries. Thus, the cost of energy storage for grid-tied PV systems can be significantly less because of the improved cycle-life.

The main challenge for the future will be to integrate all of the control functionality into the inverter to average irradiance, use the average irradiance to calculate inverter output, compensate for efficiency losses and manage the battery when the required recovery and discharge to 50% SOC is necessary.

**ENERGY SMOOTHING ALGORITHM**

The primary variable to determine how much energy to sell is the running average of the solar irradiance. This value is then multiplied by a scale factor and used to set the sell energy from the inverter. This delays and smoothes the output power and prevents fast power spikes to the grid. The longer the running average, the smoother the energy delivered, but it also requires more battery storage capacity. If the scale factors are set properly, the inverter will sell approximately the same amount of electricity back to the grid as without the smoothing control.

The second control variable is based on the battery capacity and the state of charge. Using irradiance alone does not guarantee the battery will remain in any particular state of charge, if the scale factor settings are too high or low. The battery operation is based on the state of charge; therefore the first operation required the batteries to be discharged to 50% state of charge. Once the capacity test, the batteries were received at a full state of charge; therefore the first operation required the batteries to be discharged to 50% state of charge. Once the batteries were discharged the power smoothing cycling begins. During this operation the batteries are subjected to PSOC-cycling that corresponds to the irradiance conditions for that day. The LabView based virtual energy management system will only sell enough PV power to the utility to keep the batteries at the desired PSOC. At night the inverters are a load on the batteries so for the next day of operation a small amount of extra charging of the batteries is required.

During the month long operation monitoring the state of charge is essential to the performance of the system and the health of the battery. A properly set power smoothing algorithm should maintain the 50% PSOC through the entire cycling period but an adjustment was made to maintain the desired level, which is an indication that system inefficiencies were not properly compensated for.

**TEST RESULTS**

A common assumption about battery based utility interconnected PV inverters is that the system will help alleviate the intermittency issue associated with cloud
cover, but this is not the case and the following data shows that prior to implementing the power smoothing the output power from these battery based systems is directly correlated to the irradiance level. The battery based utility interconnected PV inverter's output is dependant on irradiance and temperature conditions. The inverter output tracks the output of the photovoltaic array as can be seen in Figure 2. The high ramp rates that result can lead to stability concerns in weak grids or in high penetration regions.

Implementing the power smoothing algorithm can have a beneficial effect by energy shifting the output from the PV system and providing power during a more peak load time of the day. The following plot in Figure 3 shows the inverter output and the irradiance during a full day of operation. The results verify that the battery is operating close to a 50% SOC Wh capacity and selling PV power to the utility.

Both batteries underwent an initial and final capacity test at Sandia National Laboratories Power Sources Technology group using programmable battery testers designed for large industrial batteries. In Table 2 are the battery specifications and initial and final capacity measurements. The results show that both batteries increased in capacity slightly by about 5 to 13%. This is very encouraging and indicates that with proper battery management battery life should be good.

### Table 1: PV energy smoothing model results for a 3.5 kW PV array.

<table>
<thead>
<tr>
<th>Irradiance Smoothing Interval (h)</th>
<th>Minimum Battery Size (Wh)</th>
<th>Minimum Battery Size (Ah @ 48V)</th>
<th>Max Power Ramp Rate (W/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>6,840</td>
<td>143</td>
<td>0.875</td>
</tr>
<tr>
<td>0.50</td>
<td>3,488</td>
<td>73</td>
<td>1.75</td>
</tr>
<tr>
<td>0.25</td>
<td>1,756</td>
<td>37</td>
<td>3.5</td>
</tr>
<tr>
<td>0.00</td>
<td>NA</td>
<td>NA</td>
<td>1,575</td>
</tr>
</tbody>
</table>

### Table 2: Battery specifications and test results.

<table>
<thead>
<tr>
<th>Battery</th>
<th>Cell#</th>
<th>Specification Ah @ 8h rate (18A &amp; 45A)</th>
<th>Capacity Initial Ah @ 100A rate</th>
<th>Temp °C</th>
<th>Capacity Final Ah @ 100A rate</th>
<th>Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Type GP #90G09</td>
<td>1.0 to 12</td>
<td>344</td>
<td>317</td>
<td>31</td>
<td>326</td>
<td>31</td>
</tr>
<tr>
<td>East Penn ALABC Advanced #95-09</td>
<td>1.0 to 24</td>
<td>344</td>
<td>317</td>
<td>31</td>
<td>326</td>
<td>31</td>
</tr>
<tr>
<td>East Penn ALABC Advanced #95-09</td>
<td>1.0 to 24</td>
<td>380</td>
<td>351</td>
<td>33</td>
<td>330</td>
<td>33</td>
</tr>
</tbody>
</table>

During a cloudy day, the smoothing algorithm will reduce the rapid energy variations as shown in Figure 4. The energy sold to the utility in Figure 4 is dramatically smoothed during the dynamic irradiance conditions. Notice the rate of change is low and the utility interaction during this type of variation would be minimal as compared to the stability of a high penetration situation without smoothing.
The energy smoothing algorithm requires the battery to be at a PSOC so energy can flow in and out of the battery as needed during dynamic irradiance conditions. Operating the battery at a PSOC does present the system with the challenge of maintaining the battery at 50% SOC over repeated cycles. To accomplish this task it is necessary to keep accurate energy or Ah measurements and to include compensation factors in the control algorithm to accommodate small inefficiencies in the inverter and battery.

In Figure 5 and 6 are 30-day energy (Wh) and capacity (Ah) measurements. The results show that under constant energy (Wh) control, the Ah capacity was slowly drifting downward as a result of the higher inefficiencies that are inherent in controlling battery capacity using Wh vs. Ah control. The solution to this problem would be to control the battery SOC using Ah counting, thus the battery would stay much closer to the intended 50% Ah SOC. Also shown in Figure 5 and 6 is a full charge on one of the batteries near the end of March. This was caused by a system fault and the battery was promptly returned to 50% SOC.

Based on the daily maximum Ah DOD, which was measured at between 30 and 50 Ah, the minimum battery capacity should be between 120 and 200 Ah. This agrees reasonably well with the modeled capacity requirement of 143 Ah.

### SUMMARY

The work presented in this paper has demonstrated that all of the basic components of a grid-tied PV energy smoothing system are available and can be implemented to construct the system. The biggest obstacle to overcome will be the integration of the energy control algorithm into the inverter and the battery management functions required to operate the energy smoothing system.

Test and model results have shown that the irradiance averaging algorithm has worked well and requires only a relatively small battery to accomplish its function. In addition, the new cycling VRLA batteries from East Penn and Exide have proven to both cycle well with a slight capacity gain based on one month of operation. This is an indication that battery life may be good for many years. Based on the above initial results, PV grid-tied energy smoothing looks to be very achievable and at a reasonable cost.

### ACKNOWLEDGMENTS

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REFERENCES


