Short-Term Duty Cycle Test Report

PV Firming Duty Cycle

Battery Pack: EnerDel, Channel 4

March 2015

PREPARED FOR

National Renewable Energy Laboratory

PREPARED BY

Center for Sustainable Energy

Center for Sustainable Energy™

9325 Sky Park Court, Suite 100
San Diego, CA 92123
858.244.1177 *phone*
www.energycenter.org

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I. Overview

This test report summarizes the EnerDel Pack's performance under a PV firming application duty cycle. Twelve PV firming test cases were run on the battery pack. PV firming is an application duty cycle in which an energy storage device is used to "firm" the output generation from a solar PV array. This is most important on days when solar PV production is intermittent. The intention with PV firming is for the AC side of the electrical utility grid meter to see a continuous power output. PV firming increases the reliability and stability of using renewable energy, in this case solar PV, as a distributed grid resource.

The test cases explored here consider a novel approach to PV firming proposed by the National Renewable Energy Laboratory (NREL) in which the PV and energy storage assets are coupled via a multi-port inverter, as illustrated in Figure 1. This topology offers the benefits of improved overall system efficiency and reduced hardware costs, and also offers the ability to significantly time-shift system power output. However, it does present certain limitations to how the system can be used. Simulated operation of this system is demonstrated in Figure 2. The intent of the testing conducted herein is to demonstrate basic effectiveness and highlight operational limitations.

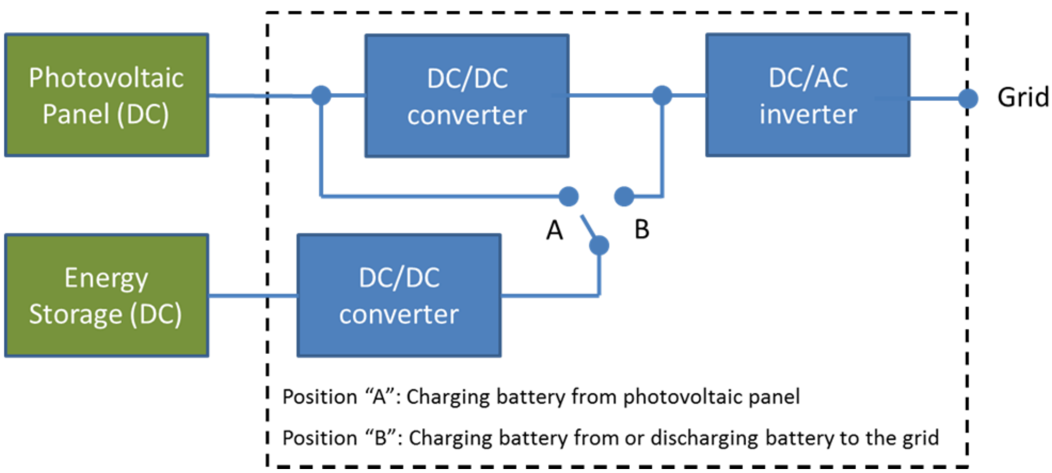

Figure 1: Conceptualized PV Firming Hardware Topology

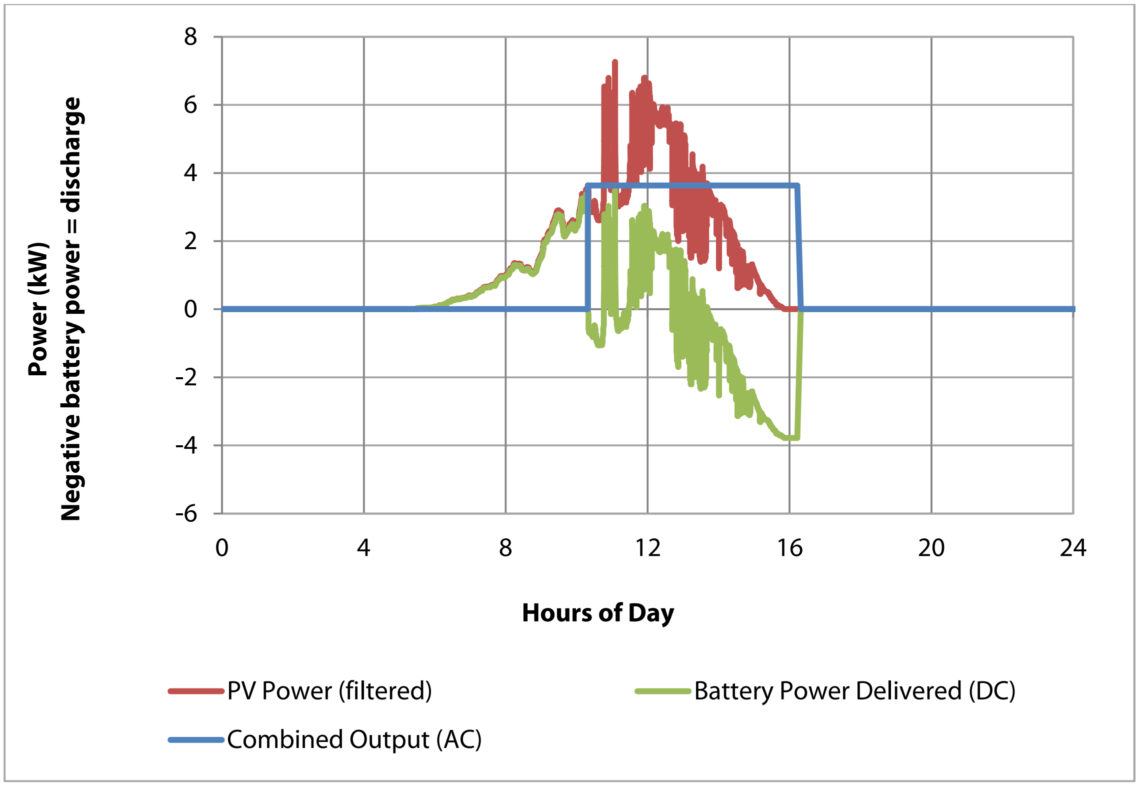

Figure 2: Example PV Firming Response with Proposed Hardware Topology

It should be noted that the envisioned hardware topology was not directly tested. Instead a virtual system comprised of individual battery and PV systems was controlled to represent operation in the proposed topology. The virtual system, however, suffered from numerous data acquisition frequency and latency issues that prohibited the precise timing of battery response and PV events (particularly on days with high solar intermittency). As such, this study was not able to address the high frequency performance capabilities of such a system. To support low-frequency analysis of system response, a 5-10 minute moving average was applied to the collected 1-minute interval Combined Output data that is presented herein.[1] Lastly, the PV output was filtered during data processing. When the PV generation data was less than 0 kW, the PV output was adjusted to 0 kW. This is important when studying the real-time test cases, because the real-time PV firming algorithm did not control for this and thus the battery responded to negative solar generation readings by the meter when cycling.

[1] Details on the moving average applied in each test case can be found in the specific test case subsection in Section II: Test Cases.

II. Test Cases

The twelve test cases cycled on the EnerDel Pack are summarized below in Table 1. In each case the real-time output of the 28.7-kW DC PV array served as the resource to firm. The PV Scale Factor is the factor by which the PV output generation is multiplied, resulting in the Effective PV Nameplate Power. The Firming Threshold represents the power level of the inverter stage. When the scaled PV output crosses this threshold, the system switches from a zero output battery charge mode to a firm output mode at the Firming Threshold. The Approximate Battery Starting SOC represents the state of charge (SOC) of the battery at the beginning of the day (i.e. midnight). Multiple SOC values were tested to illustrate the possibility of failure to fully firm the PV source when initial SOC is too low, as well as the possible need for curtailing solar when initial SOC is too high. Lastly, the Solar Characteristic describes the solar generation profile. Clear indicates there were no sudden dips in PV production while intermittent indicates there were many dips in PV production throughout the day.

Table 1: PV Firming Test Cases

<table>
<tr><th>Case Abbreviation</th><th>PV Scale Factor</th><th>Effective PV Nameplate Power (kW)</th><th>Firming Threshold (kW)</th><th>Approximate Battery Starting SOC</th><th>Solar Characteristic</th></tr>
<tr><td>1a-0.3/3.5/10/Clr</td><td rowspan="4">0.3</td><td rowspan="4">8.61</td><td rowspan="4">3.5</td><td rowspan="2">10%</td><td>Clear</td></tr>
<tr><td>1b-0.3/3.5/10/Int</td><td>Intermittent</td></tr>
<tr><td>1c-0.3/3.5/40/Clr</td><td rowspan="2">20-40%</td><td>Clear</td></tr>
<tr><td>1d-0.3/3.5/20/Int</td><td>Intermittent</td></tr>
<tr><td>2a-0.4/7.0/10/Clr</td><td rowspan="4">0.4</td><td rowspan="4">11.48</td><td rowspan="4">7.0</td><td rowspan="2">10%</td><td>Clear</td></tr>
<tr><td>2b-0.4/7.0/10/Int</td><td>Intermittent</td></tr>
<tr><td>2c-0.4/7.0/40/Clr</td><td rowspan="2">40%</td><td>Clear</td></tr>
<tr><td>2d-0.4/7.0/40/Int</td><td>Intermittent</td></tr>
<tr><td>3a-0.2/1.5/10/Clr</td><td>0.2</td><td>5.74</td><td>1.5</td><td>10%</td><td>Clear</td></tr>
</table>

3b- 0.2/1.5/10/Int					Intermittent
3c- 0.2/1.5/40/Clr				40%	Clear
3d- 0.2/1.5/40/Int					Intermittent

III. Test Log

The PV firming duty cycles were run in real-time as well as in a prescribed fashion. Real-time testing was conducted using Power Analytics' Paladin software and prescribed testing was conducted using AeroVironment's Battery Control Software (BCS). Table 2 below summarizes the PV firming testing days, the test case, the BMS-reported starting SOC of the battery at midnight, the testing platform utilized, and the solar PV production profile date.

Table 2: Test Log

Case Abbreviation	Battery Cycling Day	BMS-reported Starting SOC (%)	Testing Platform	Solar Data Day
1a-0.3/3.5/10/Clr	January 23, 2015	15.6	Paladin	Same as Battery Cycling Day
1b-0.3/3.5/10/Int	January 25, 2015	4.4	Paladin	Same as Battery Cycling Day
1b-0.3/3.5/10/Int	January 26, 2015	8.8	Paladin	Same as Battery Cycling Day
1c-0.3/3.5/40/Clr	January 27, 2015	44.8	Paladin	Same as Battery Cycling Day
1d-0.3/3.5/20/Int	January 20, 2015[2]	19.2	Paladin	Same as Battery Cycling Day
2a-0.4/7.0/10/Clr	February 5-6, 2015	11.6	BCS	October 2, 2014
2b-0.4/7.0/10/Int	February 13-14, 2015	8.4	BCS	October 20, 2014
2b-0.4/7.0/10/Int	February 18-19, 2015	9.2	BCS	January 25, 2015
2c-0.4/7.0/40/Clr	January 31-February 1, 2015	43.2	BCS	October 2, 2014
2d-0.4/7.0/40/Int	February 10-11, 2015	41.2	BCS	October 20, 2014
2d-0.4/7.0/40/Int	February 19-20, 2015	42.8	BCS	January 25, 2015
3a-0.2/1.5/10/Clr	February 8-9, 2015	10.8	BCS	October 2, 2014
3b-0.2/1.5/10/Int	February 14-15, 2015	8.8	BCS	October 20, 2014
3b-0.2/1.5/10/Int	February 26-27, 2015	10.8	BCS	January 25, 2015
3c-0.2/1.5/40/Clr	February 9-10, 2015	40.8	BCS	October 2, 2014
3d-0.2/1.5/40/Int	February 16-17, 2015	44.0	BCS	October 20, 2014
3d-0.2/1.5/40/Int	February 24-25, 2015	38.8	BCS	January 25, 2015

[2] This was a partial day of firming. On January 20, 2015, firming ended at 6:15 pm.

IV. Results

a. Test Case 1a-0.3/3.5/10/Clr – January 23, 2015[3]

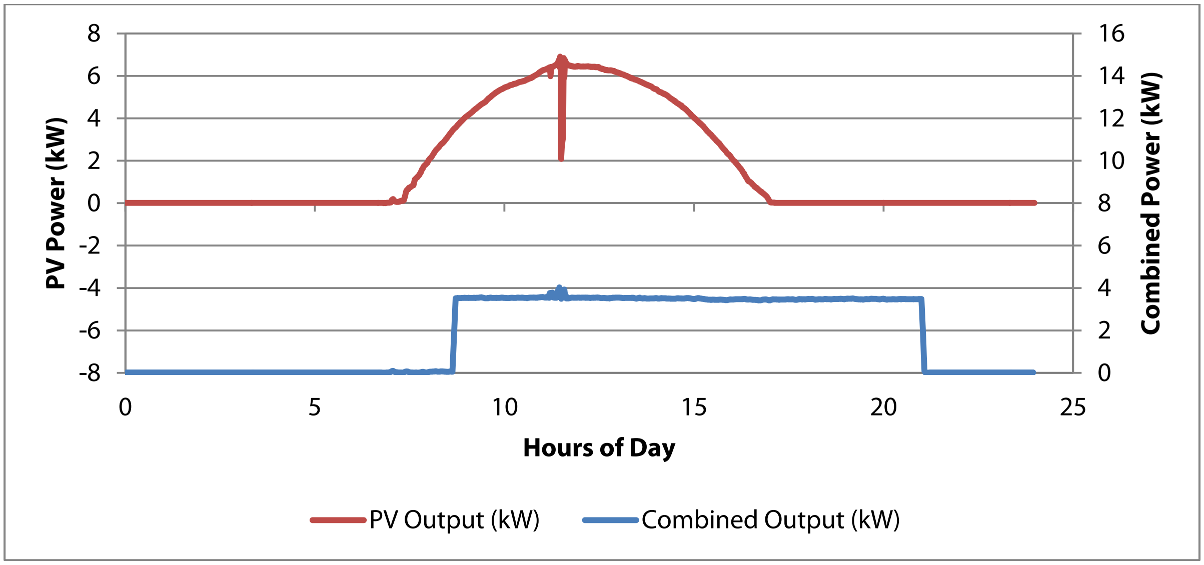

Figure 3: Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 1a – January 23, 2015

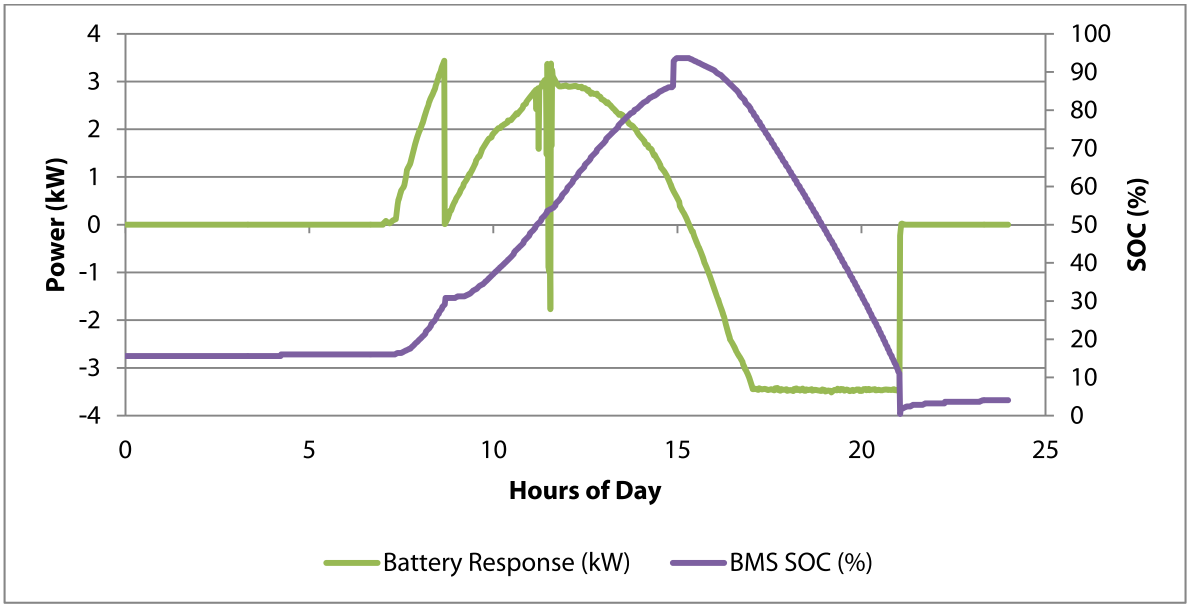

Figure 4: Battery Response for Test Case 1a - January 23, 2015

[3] A 5-minute moving average was applied to the Combined Output array.

Figure 3 represents a nearly ideal response of this system. Battery SOC begins at its lower limit, and the battery is charged while the system outputs zero power until the threshold is reached. Then the system begins outputting AC power at the threshold level and the battery continues to charge as PV power continues to rise. The battery reaches nearly 100% SOC while the PV power begins to decline, then switches to discharge mode and maintains a firm system level output until battery energy is depleted. Prior to applying the 5-minute moving average to the Combined Output array, it appeared as though the battery could not firm the middle-of-the-day dip in solar as seen in Figure 3, but with the application of the moving average which compensates for data acquisition frequency and latency issues of the virtualized system, we see the near ideal response. However, in an optimized system, system response must be faster than in our virtualized system to ensure that the output stays constant during such solar events.

b. Test Case 1b-0.3/3.5/10/Int – January 25, 2015[4]

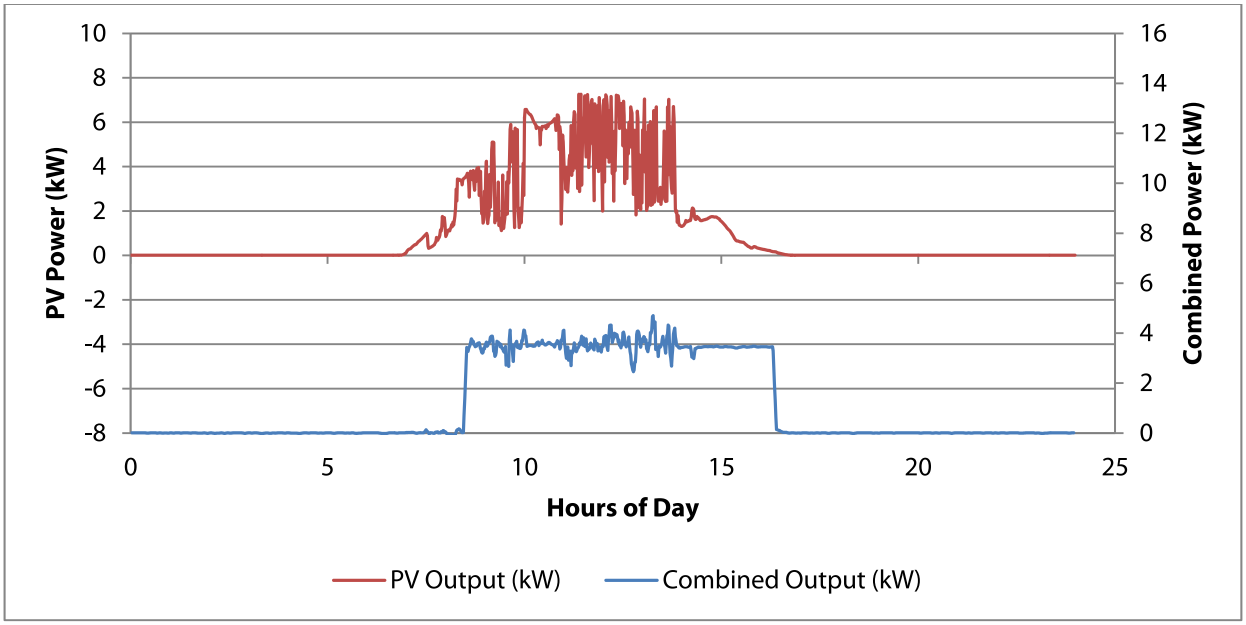

Figure 5: Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 1b – January 25, 2015

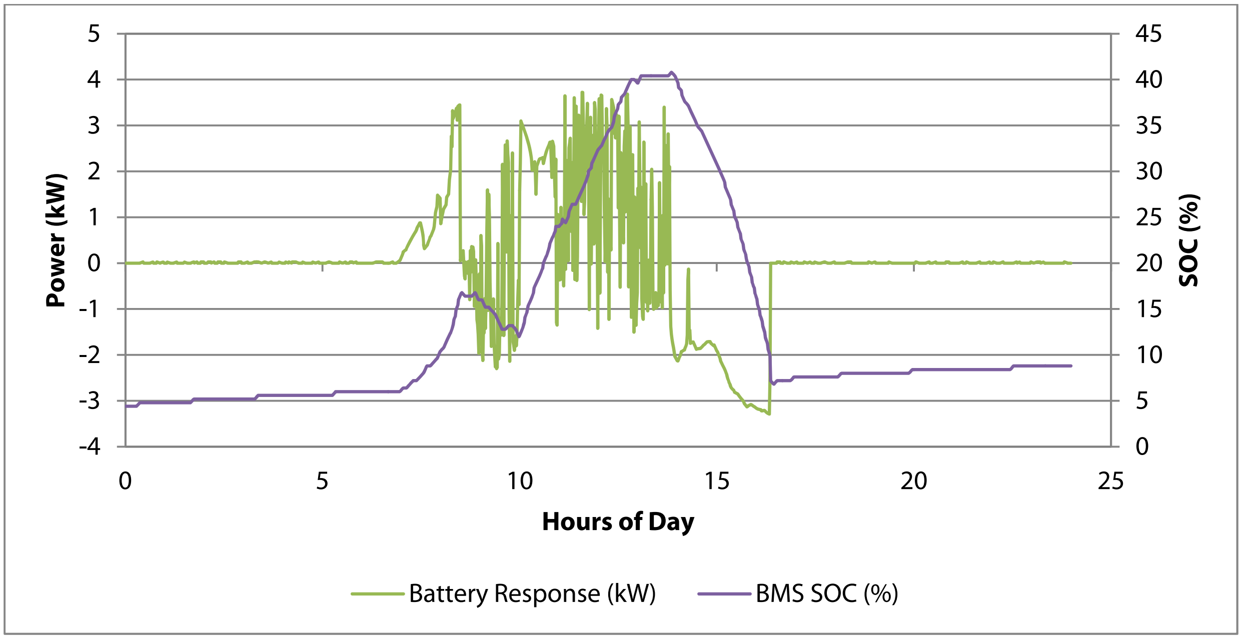

Figure 6: Battery Response for Test Case 1a - January 25, 2015

[4] A 5-minute moving average was applied to the Combined Output array.

This case illustrates the impact of an intermittent day on system output. As shown in Figure 4, the battery only reaches approximately 40% SOC at its max. This reduces the total duration firm power output from the system, as less energy is available for the battery's afternoon discharge. This case also shows considerable variability in the system level output; however, it is important to note that the failure of the system to perfectly firm the output is not due to limitations of the battery, but rather to the latency issues of the virtualized system noted previously. Properly designed physical hardware should be capable of eliminating this output variability.

c. Test Case 1b-0.3/3.5/10/Int – January 26, 2015[5]

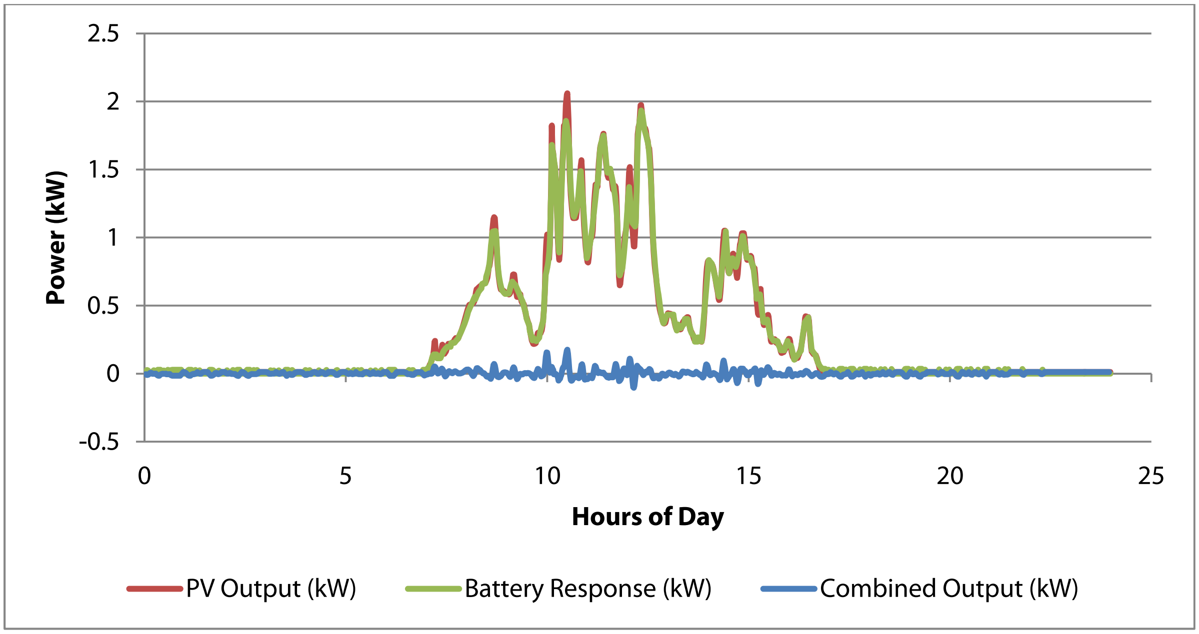

Figure 7: Scaled PV Generation, Battery Response, and Combined Output (Solar + Battery) for Test Case 1b – January 26, 2015

[5] A 5-minute moving average was applied to the Combined Output array.

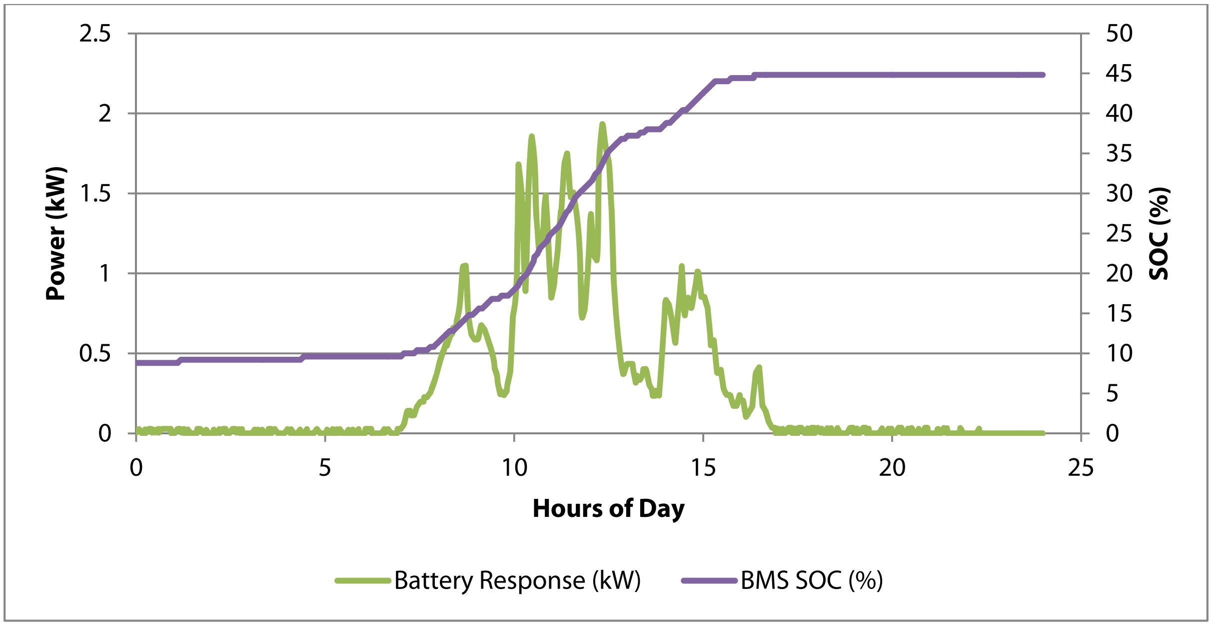

Figure 8: Battery Response for Test Case 1b - January 26, 2015

Figure 7 shows the battery response and the combined output of the solar array and the battery on a low solar intensity day when the PV output never cleared the Firming Threshold. As a result, the battery followed the solar PV for the entire day (i.e. the battery charged directly from the scaled PV output). The Firming Threshold for this test case was 3.5 kW and the max PV after scaling was 2.1 kW.

d. Test Case 1c-0.3/3.5/40/Clr – January 27, 2015[6]

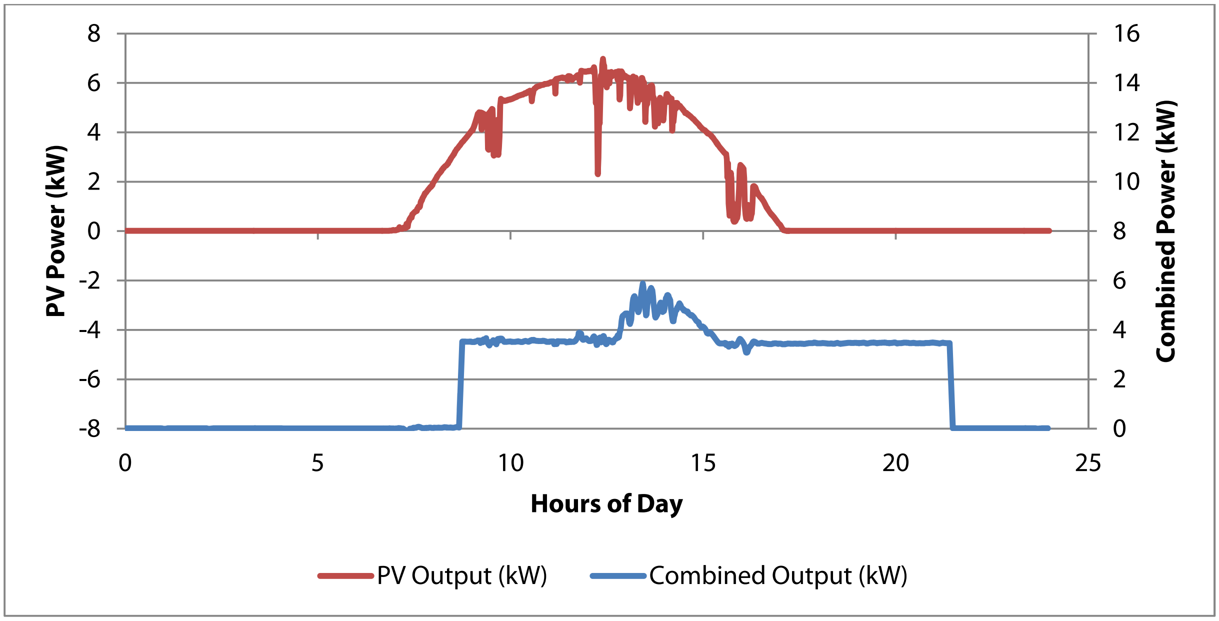

Figure 9: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 1c – January 27, 2015

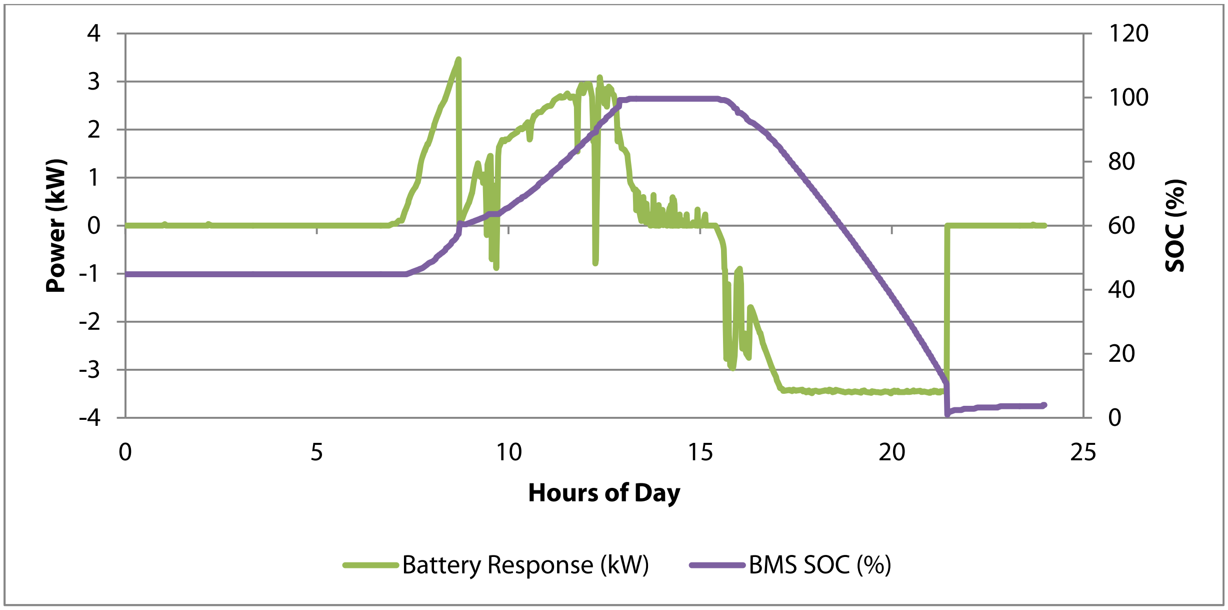

Figure 10: Battery Response for Test Case 1c - January 27, 2015

[6] A 5-minute moving average was applied to the Combined Output array.

In this case, the battery starts from a high SOC on a clear day. Around noon, the battery reaches its maximum SOC. As seen in Figure 7, the system level output increases beyond the Firming Threshold in response to this condition. If the proposed hardware topology had actually been tested, this would have exceeded the limits of the inverter stage and likely resulted in curtailment of solar energy. In practice, forecasts of daily PV production can be applied to avoid this situation by initiating the firm output of the system earlier in the day (before the Firming Threshold is reached).

e. Test Case 1d-0.3/3.5/20/Int – January 20, 2015[7]

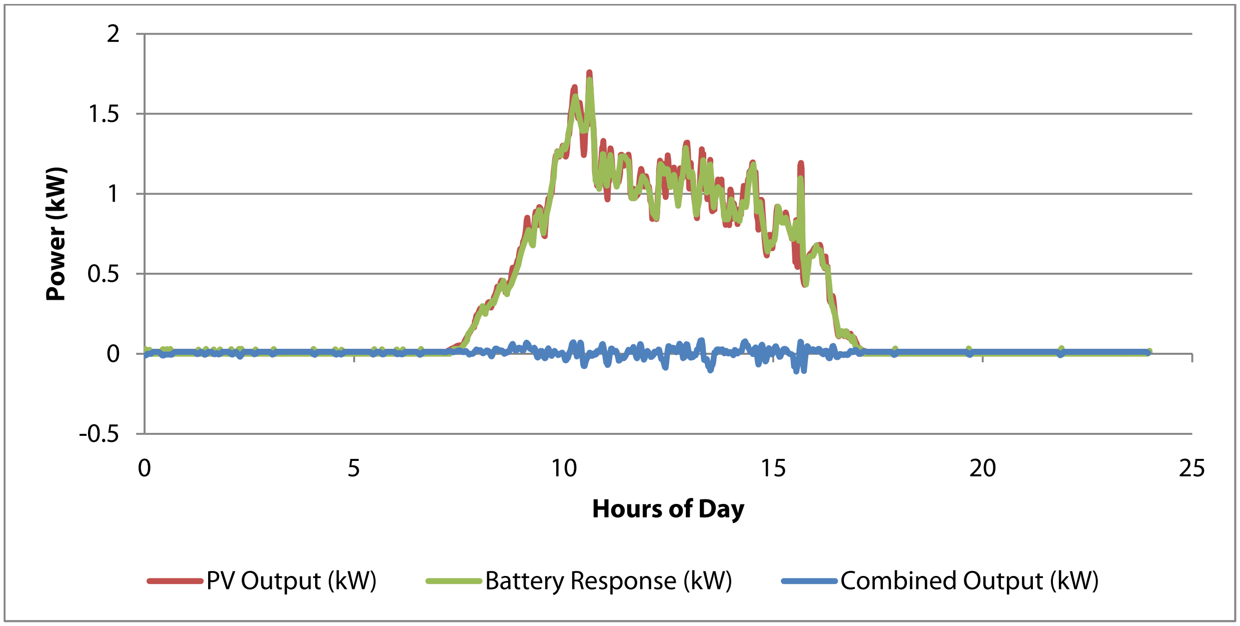

Figure 11: Scaled PV Generation, Battery Response, and Combined Output (Solar + Battery) for Test Case 1d – January 20, 2015

[7] A 5-minute moving average was applied to the Combined Output array.

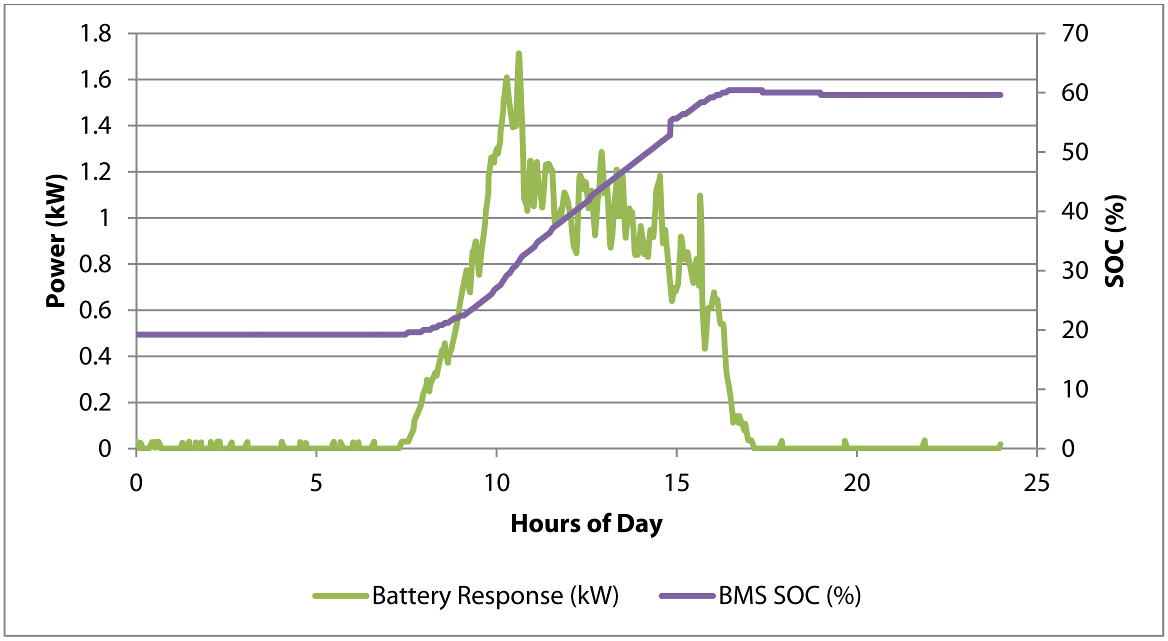

Figure 12: Battery Response for Test Case 1d - January 20, 2015

Figure 11 shows the battery response and the combined output of the solar array and the battery. From this figure it looks as though the battery did not cycle as intended under PV firming. Instead, the battery followed the solar PV for the entire day (i.e. the battery charged directly from the scaled PV output). If we take a closer look, though, we recognize that this occurred because the threshold to start PV firming was never reached. The Firming Threshold for this test case was 3.5 kW and the max PV after scaling was 1.8 kW. In cases where the Firming Threshold was too high for the PV production to reach, a more dynamic PV Firming algorithm which incorporates daily PV forecasts might be useful to automatically adjust the Firming Threshold if it had not been reached by a certain point in the day.

f. Test Case 2a-0.4/7.0/10/Clr – February 5-6, 2015[8]

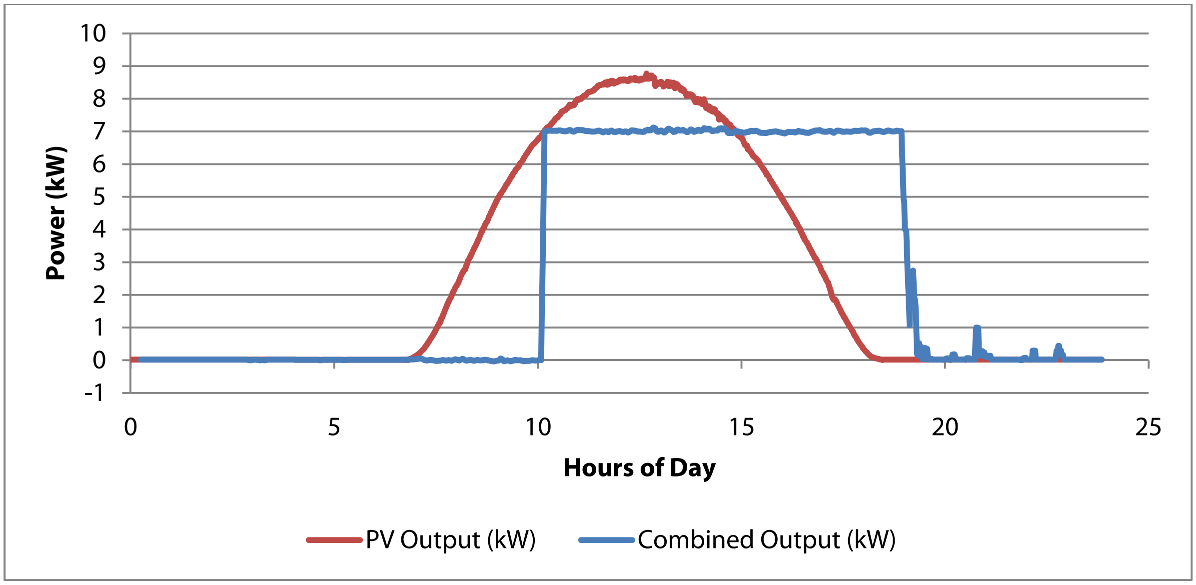

Figure 13: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2a – February 5-6, 2015

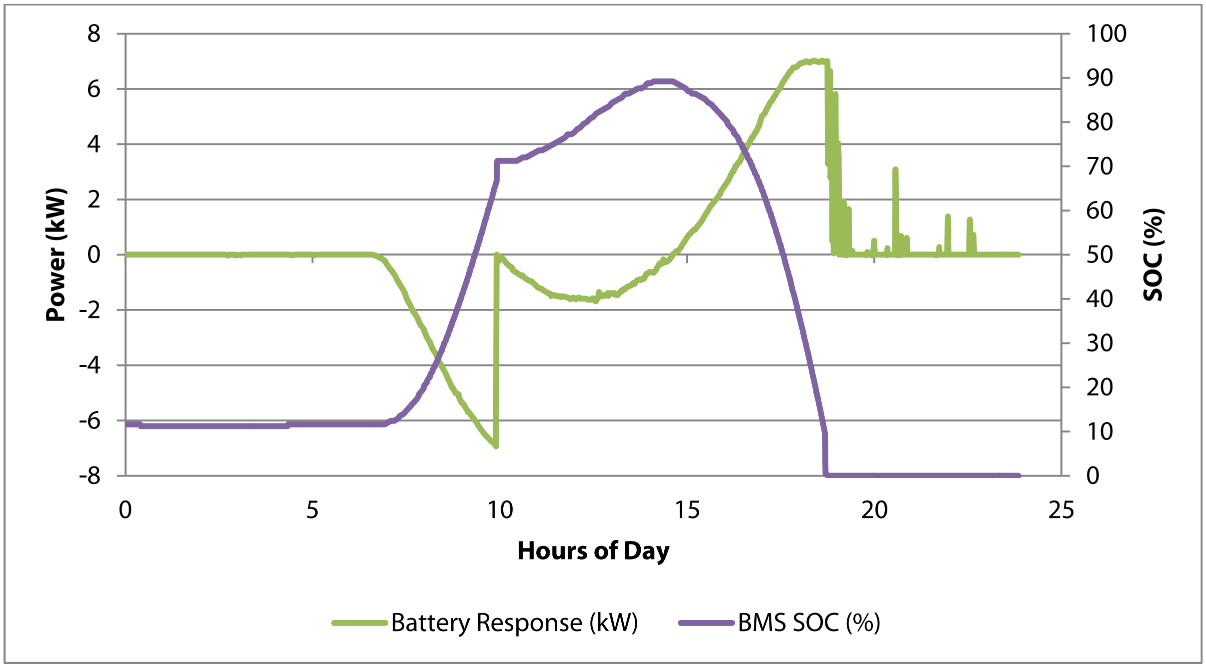

Figure 14: Battery Response for Test Case 2a – February 5-6, 2015

[8] A 5-minute moving average was applied to the Combined Output array.

This case again represents a nearly ideal response; however, relative to case 1a the ratio of total system output to peak PV production has been increased. This results in a short duration of firmed output at a higher level.

g. Test Case 2b-0.4/7.0/10/Int – February 13-14, 2015[9]

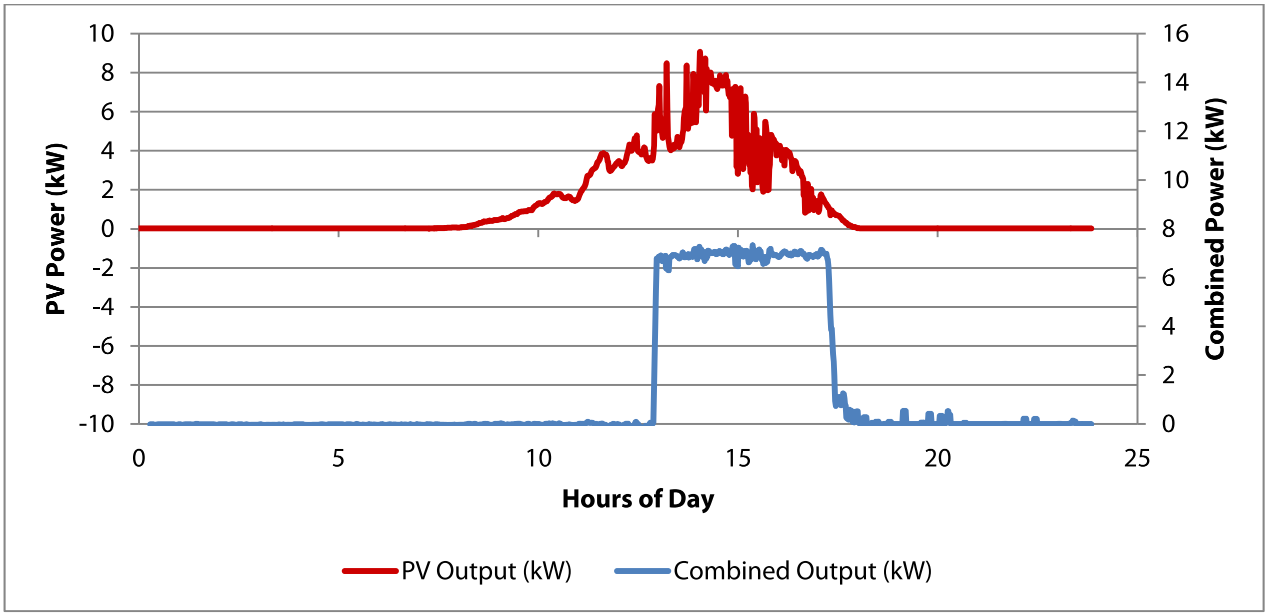

Figure 15: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2b – February 13-14, 2015

[9] A 5-minute moving average was applied to the Combined Output array.

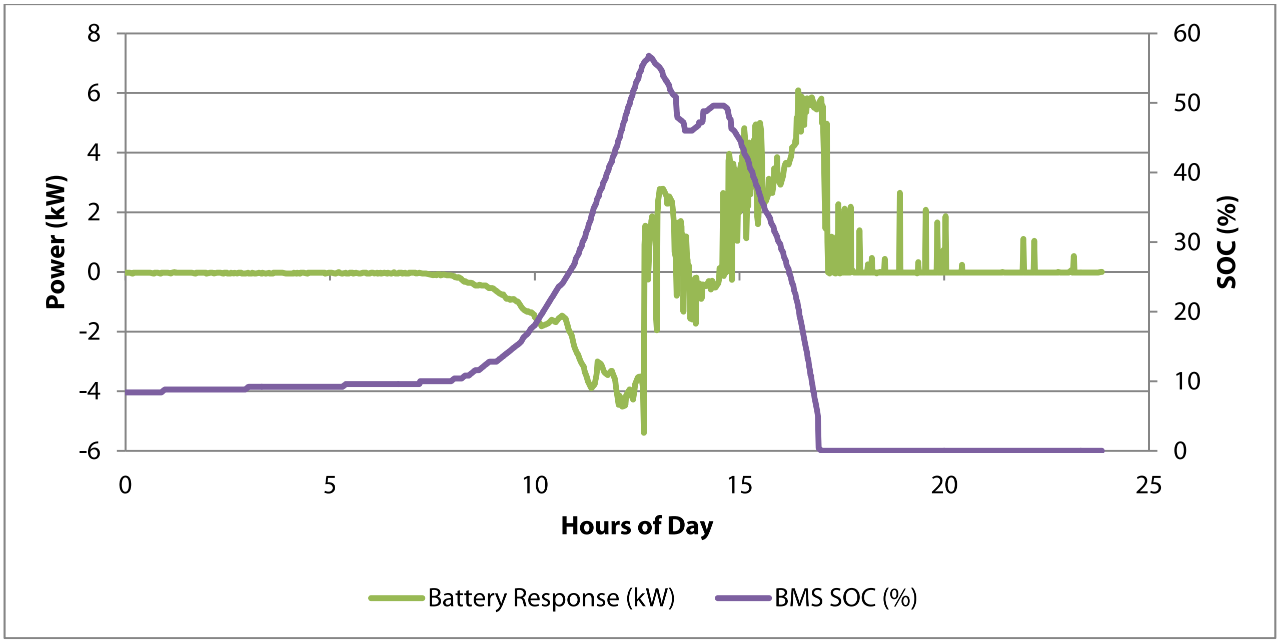

Figure 16: Battery Response for Test Case 2b – February 13-14, 2015

In this case the system illustrates a near ideal response on a day with high solar intermittency. Relative to a clear day (e.g. the previous case), the system yields a shorter duration of the firm output and the battery reaches a lower maximum SOC.

h. Test Case 2b-0.4/7.0/10/Int – February 18-19, 2015[10]

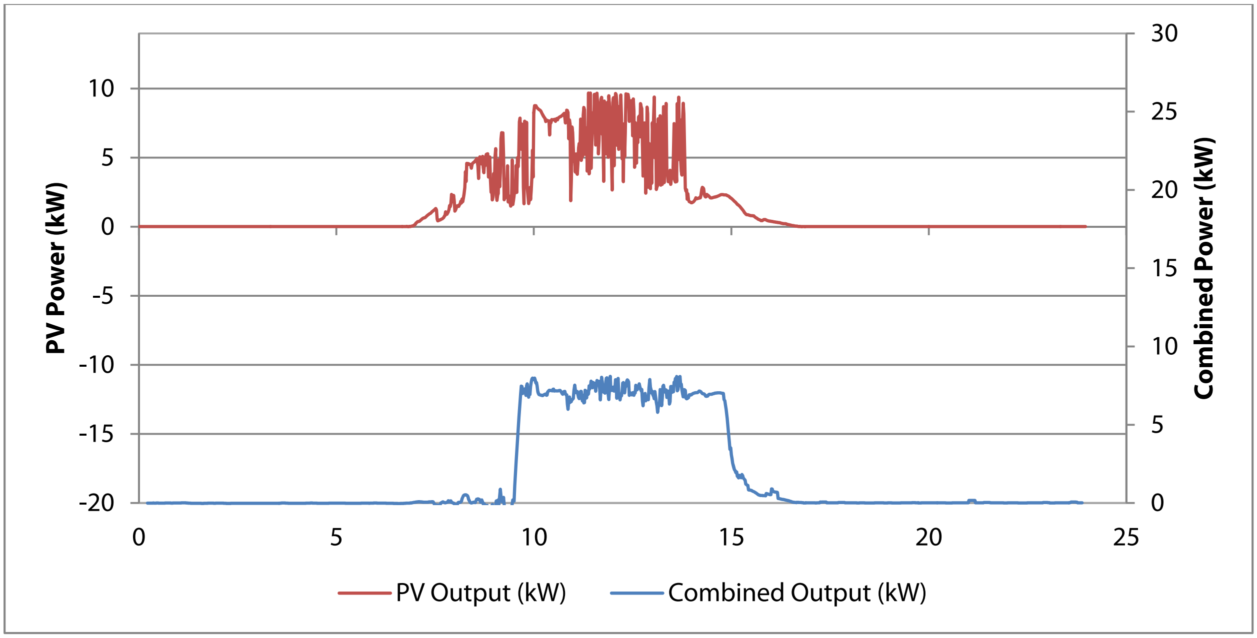

Figure 17: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2b – February 18-19, 2015

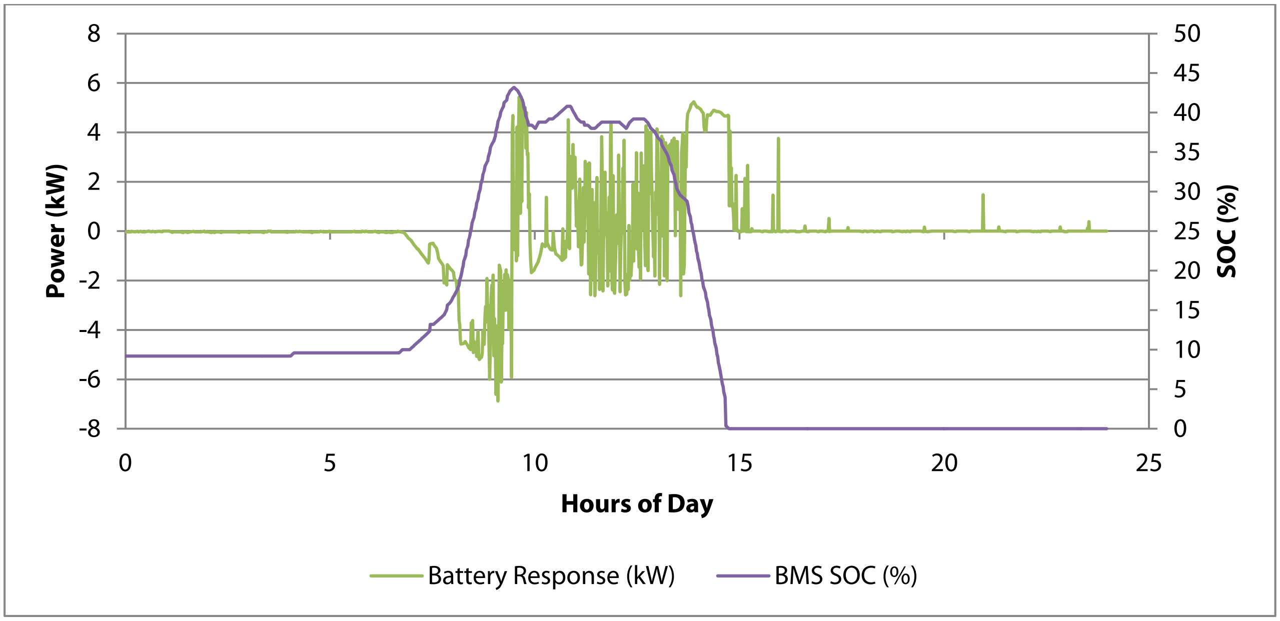

Figure 18: Battery Response for Test Case 2b – February 18-19, 2015

[10] A 10-minute moving average was applied to the Combined Output array.

i. Test Case 2c-0.4/7.0/40/Clr – January 31-February 1, 2015[11]

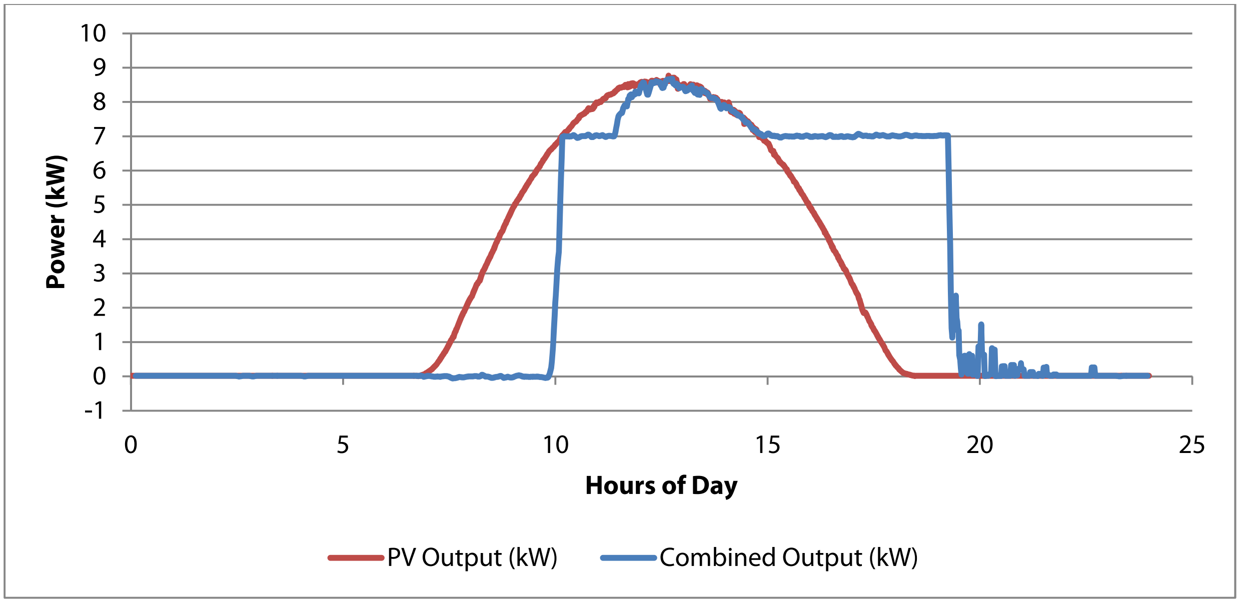

Figure 19: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2c – January 31-February 1, 2015

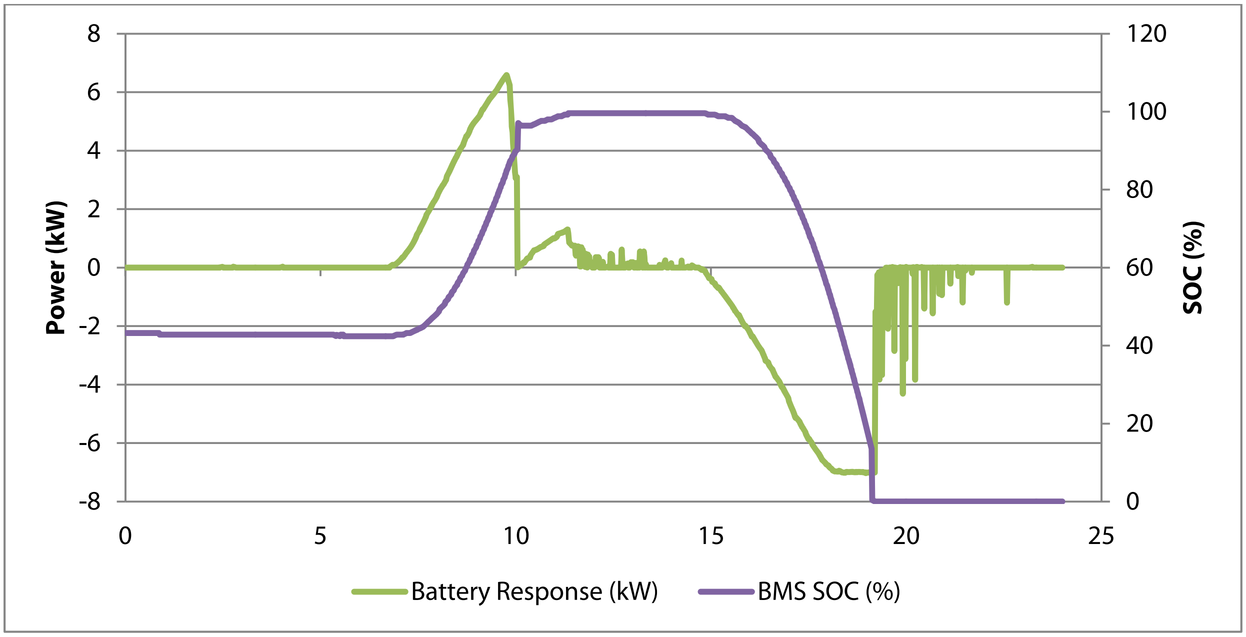

Figure 20: Battery Response for Test Case 2c - January 31-February 1, 2015

[11] A 5-minute moving average was applied to the Combined Output array.

Figure 19 shows that the battery was not able to firm the PV during the middle of the day. This is because the battery hit 100% SOC and it could no longer receive charge to firm the PV when the solar generation dropped below the Firming Threshold.

j. Test Case 2d-0.4/7.0/40/Int – February 10-11, 2015[12]

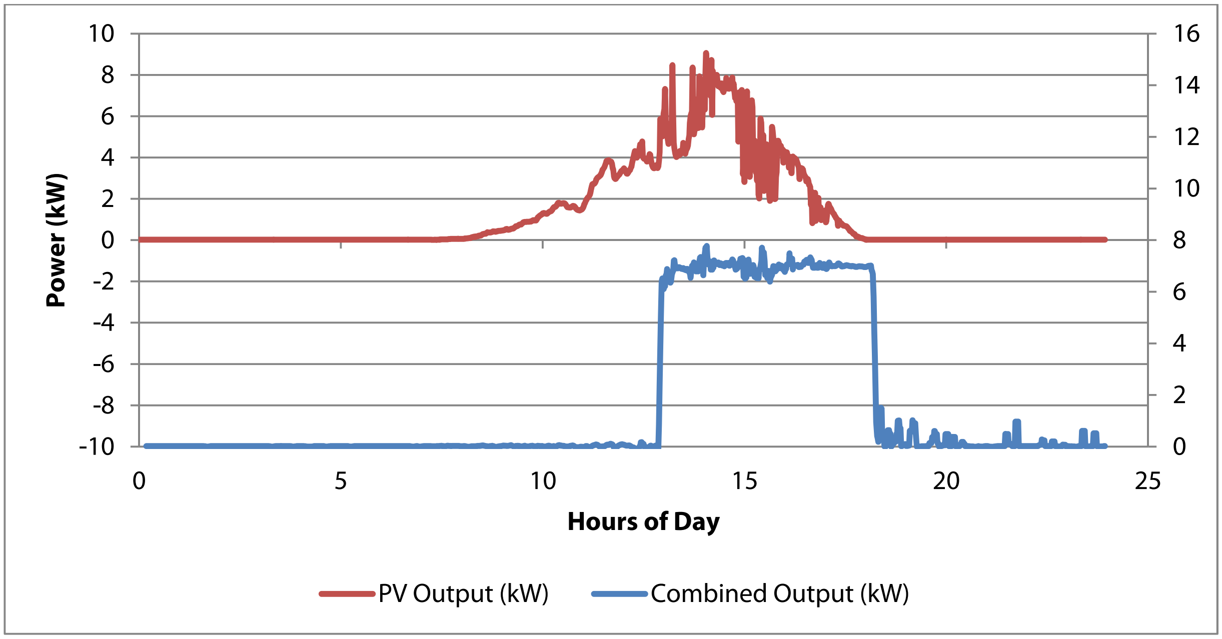

Figure 21: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2d – February 10-11, 2015

[12] A 5-minute moving average was applied to the Combined Output array.

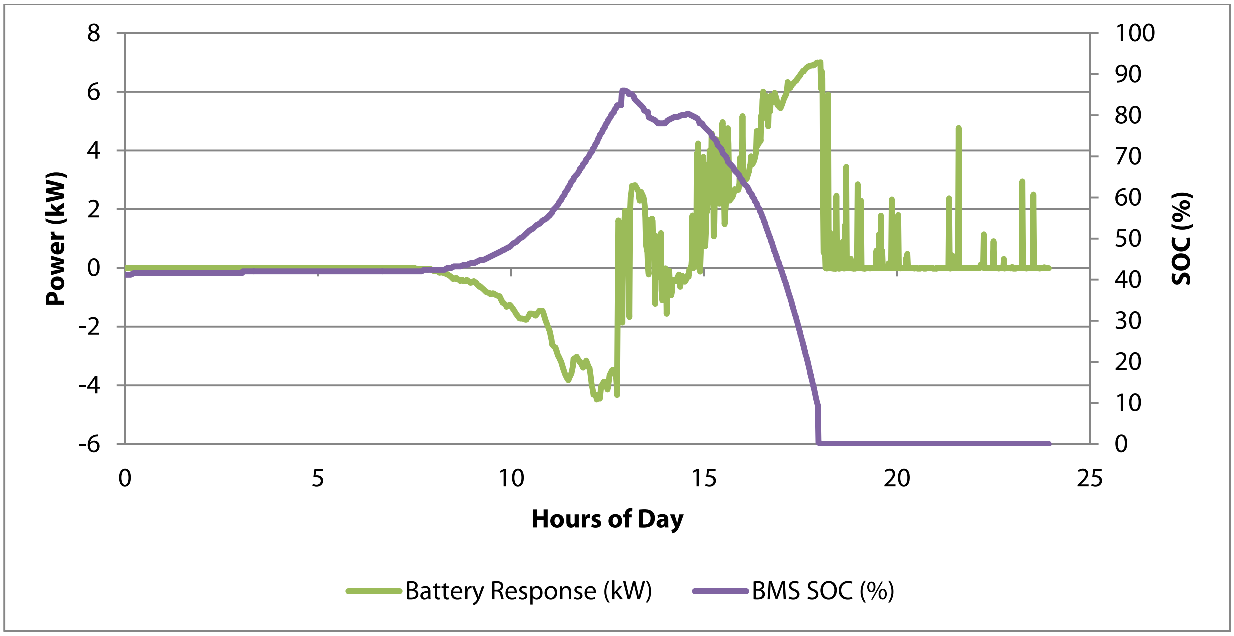

Figure 22: Battery Response for Test Case 2d – February 10-11, 2015

k. Test Case 2d-0.4/7.0/40/Int – February 19-20, 2015[13]

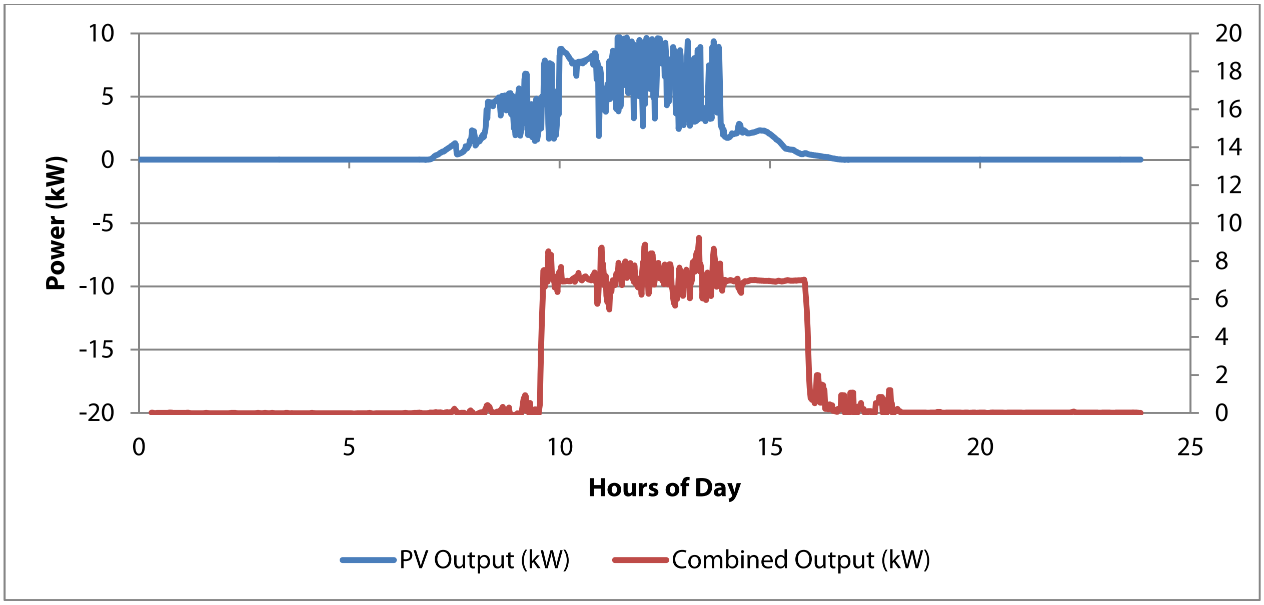

Figure 23: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 2d – February 19-20, 2015

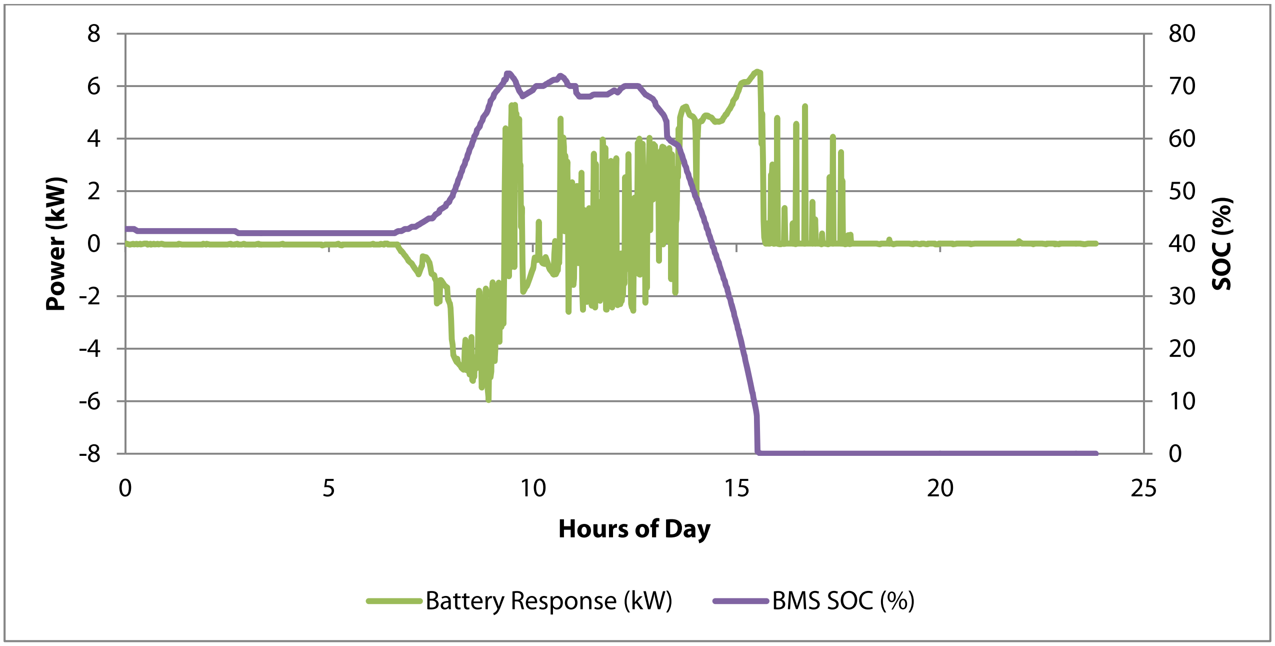

Figure 24: Battery Response for Test Case 2d – February 19-20, 2015

[13] A 5-minute moving average was applied to the Combined Output array.

I. Test Case 3a-0.2/1.5/10/Clr – February 8-9, 2015[14]

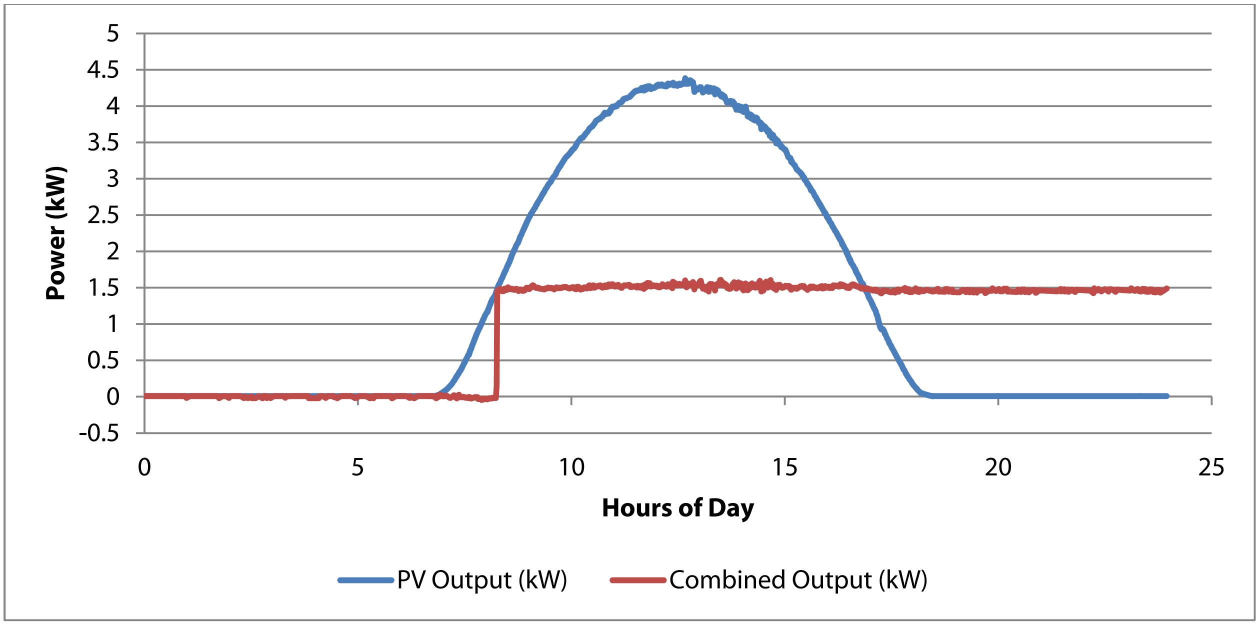

Figure 25: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3a – February 8-9, 2015

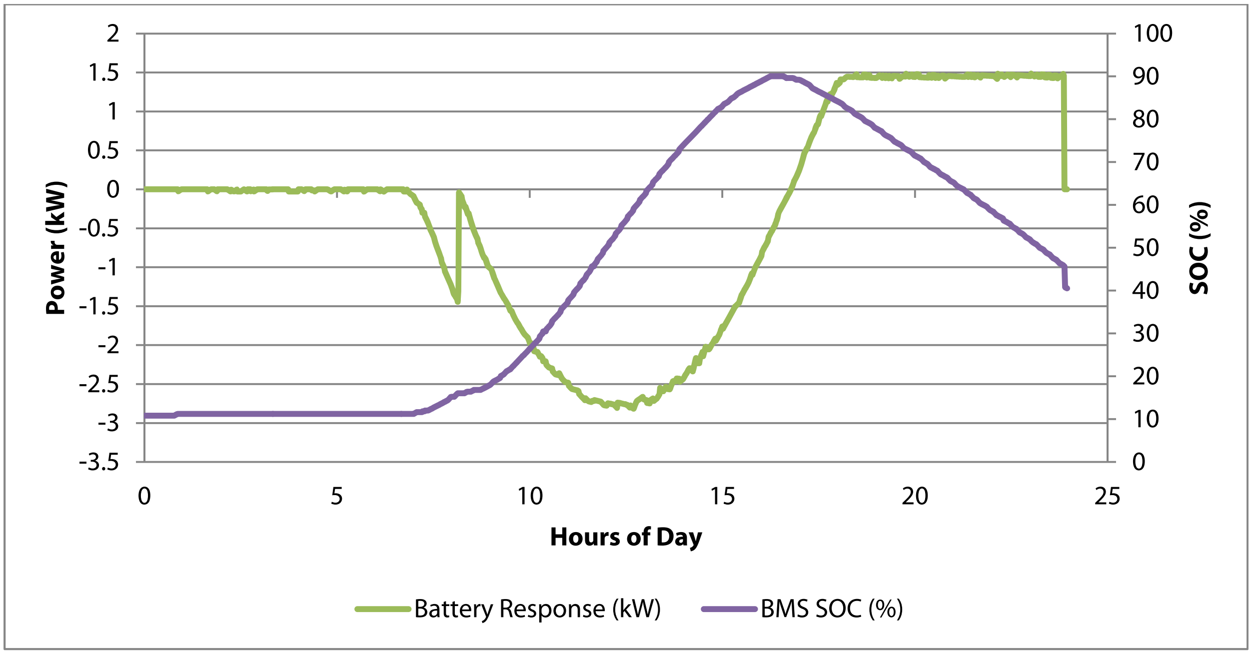

Figure 26: Battery Response for Test Case 3a – February 8-9, 2015

[14] No moving average was applied to the Combined Output array.

This near ideal response shows the ability of a system with a low ratio of combined output power to PV input power to dramatically shift the output of firmed PV power in time. At the end of the day, the battery had only reached a discharge level of approximately 40% SOC, implying that the firmed output could continue into the next day. Such a combination of parameters could be used to turn the system in to a constant-output generator; however, consideration for solar intermittency on cloudy days and the variability of clear day irradiance throughout the course of the year would need to be considered.

m. Test Case 3b-0.2/1.5/10/Int – February 14-15, 2015[15]

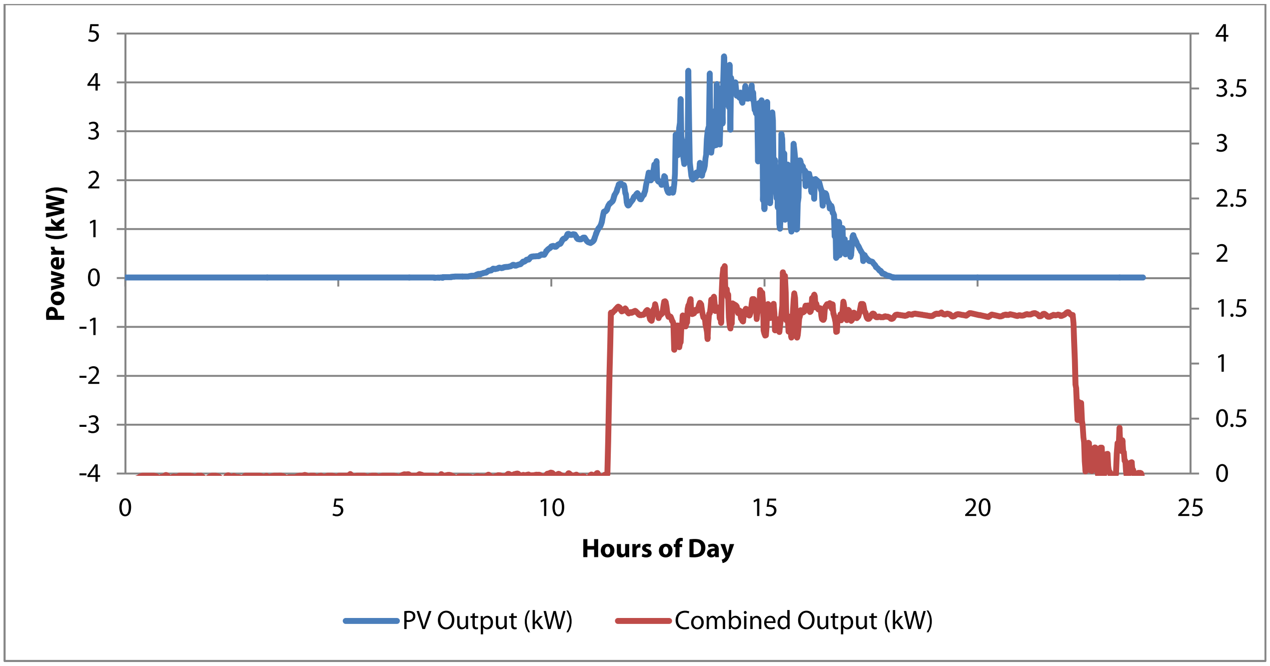

Figure 27: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3b – February 14-15, 2015

[15] A 5-minute moving average was applied to the Combined Output array.

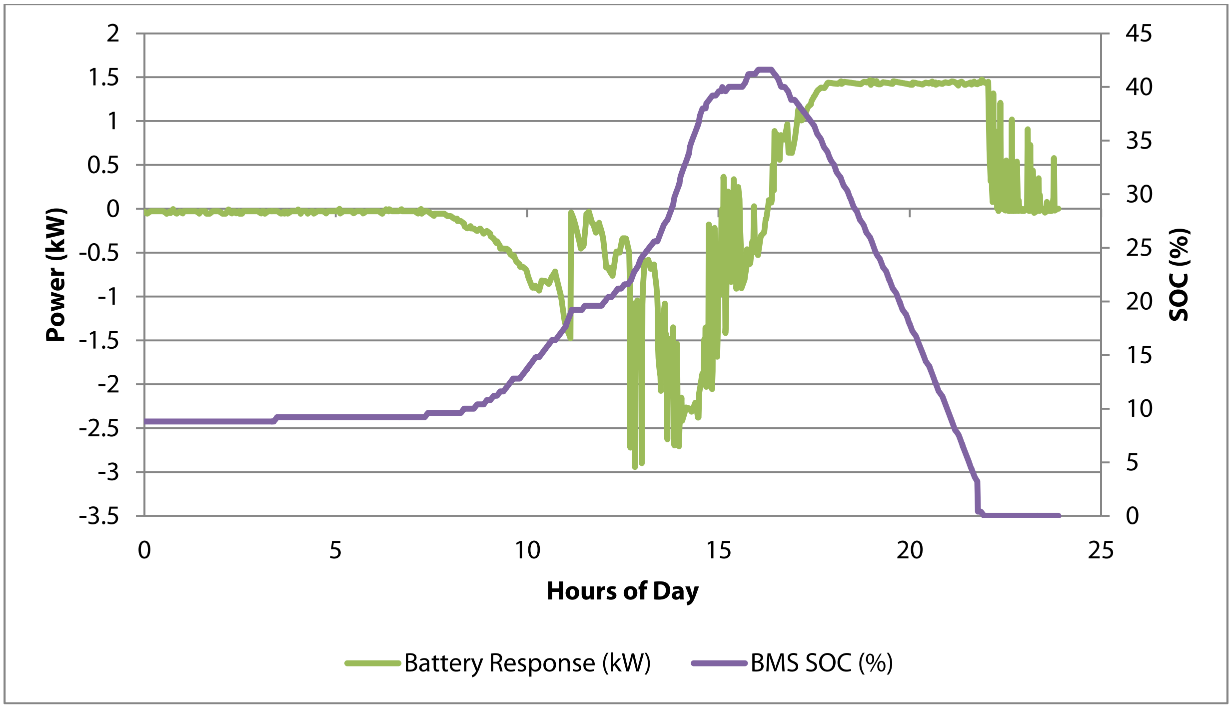

Figure 28: Battery Response for Test Case 3b – February 14-15, 2015

n. Test Case 3b-0.2/1.5/10/Int – February 26-27, 2015[16]

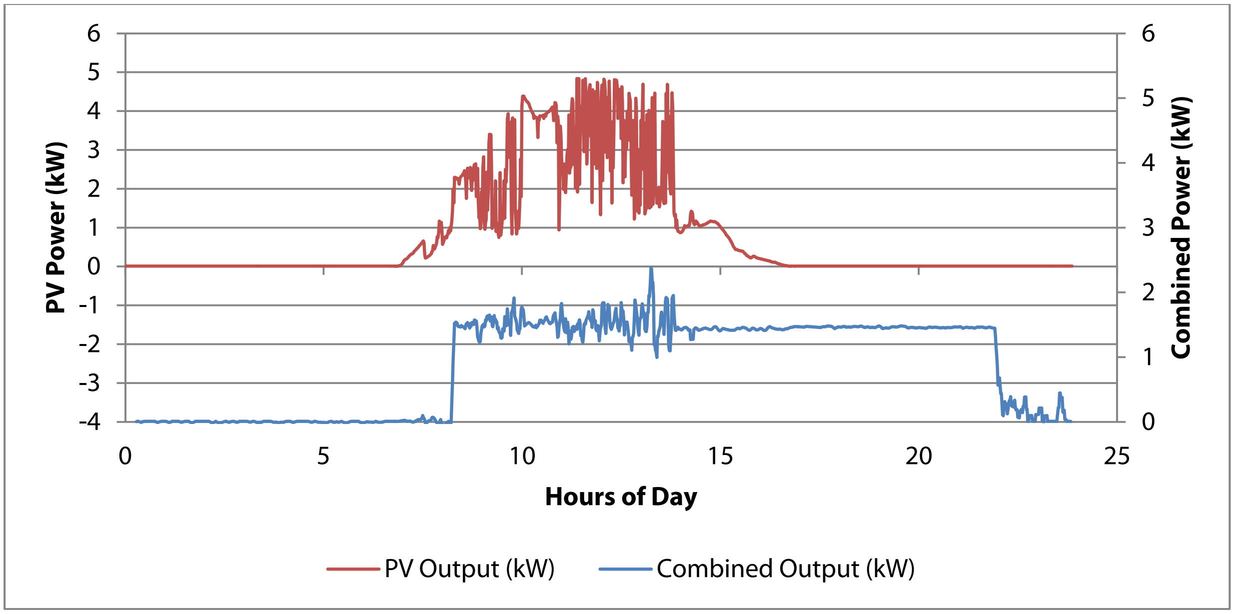

Figure 29: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3b – February 26-27, 2015

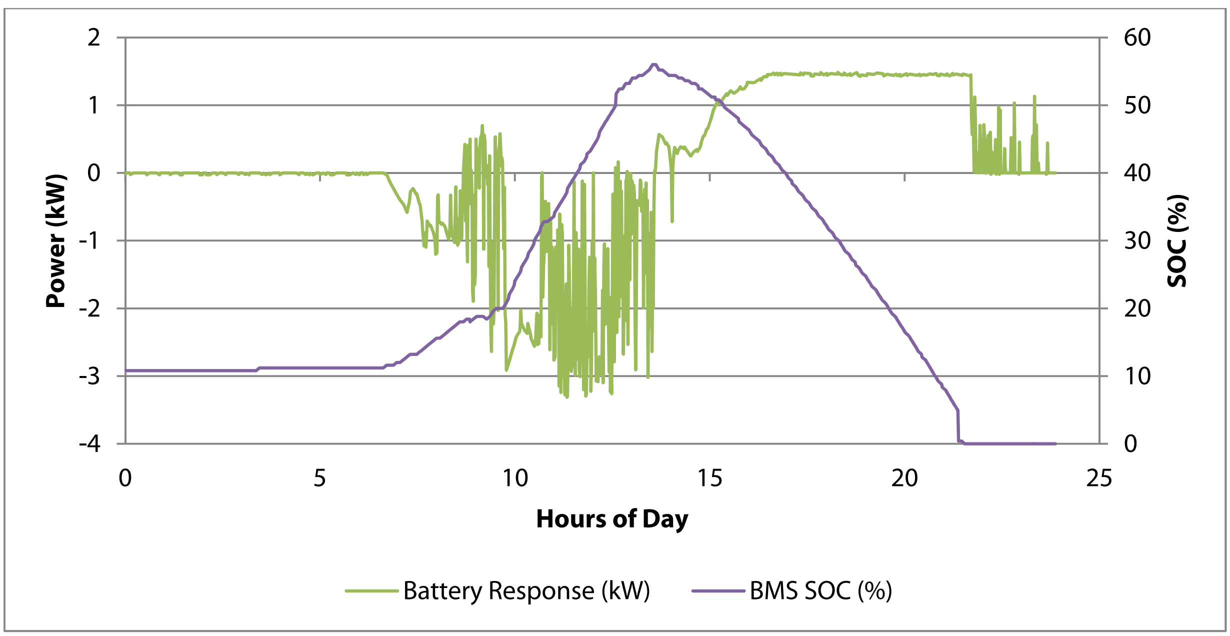

Figure 30: Battery Response for Test Case 3b – February 26-27, 2015

[16] A 5-minute moving average was applied to the Combined Output array.

o. Test Case 3c-0.2/1.5/40/Clr – February 9-10, 2015[17]

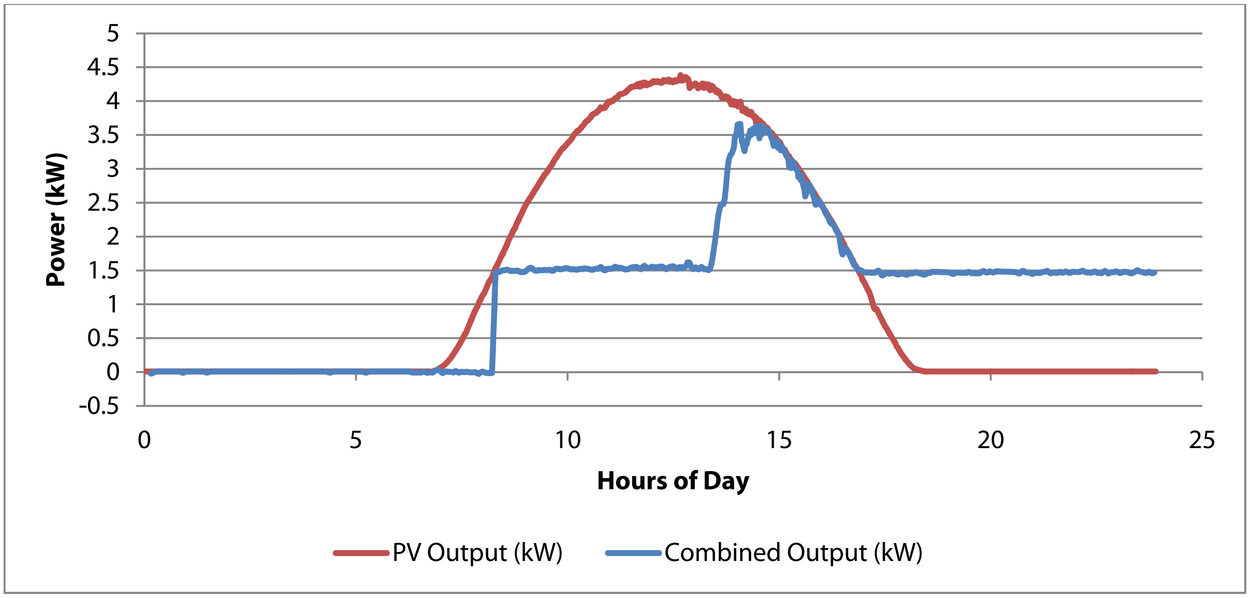

Figure 31: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3c – February 9-10, 2015

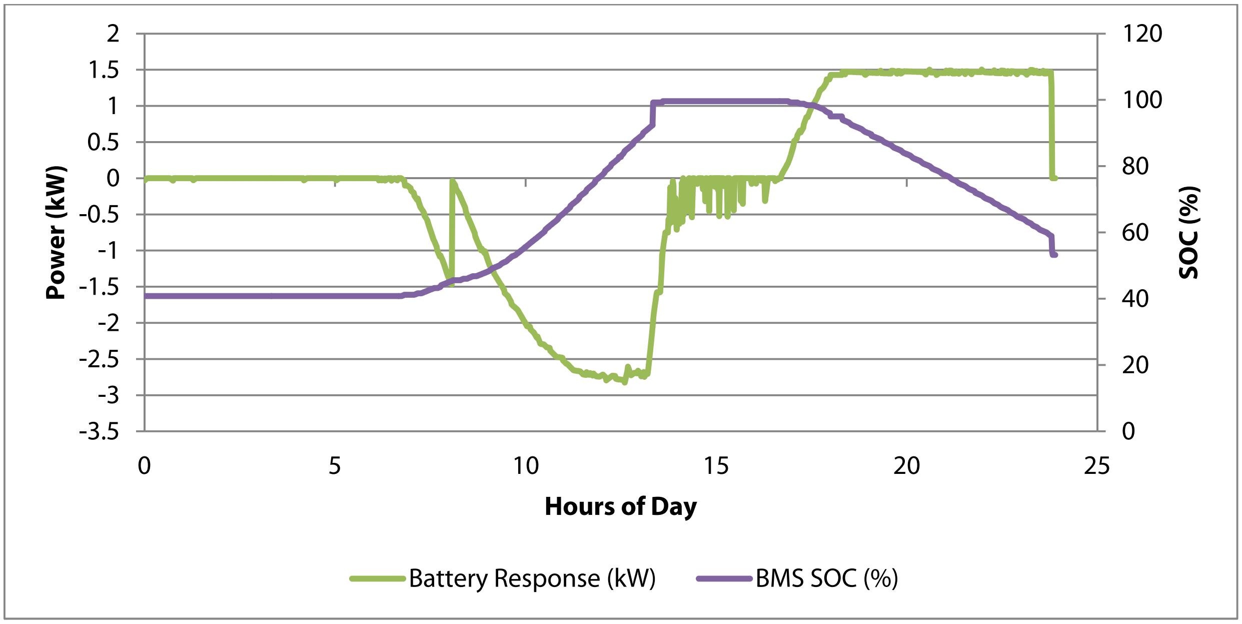

Figure 32: Battery Response for Test Case 3c – February 9-10, 2015

[17] A 5-minute moving average was applied to the Combined Output array.

p. Test Case 3d-0.2/1.5/40/Int – February 16-17, 2015[18]

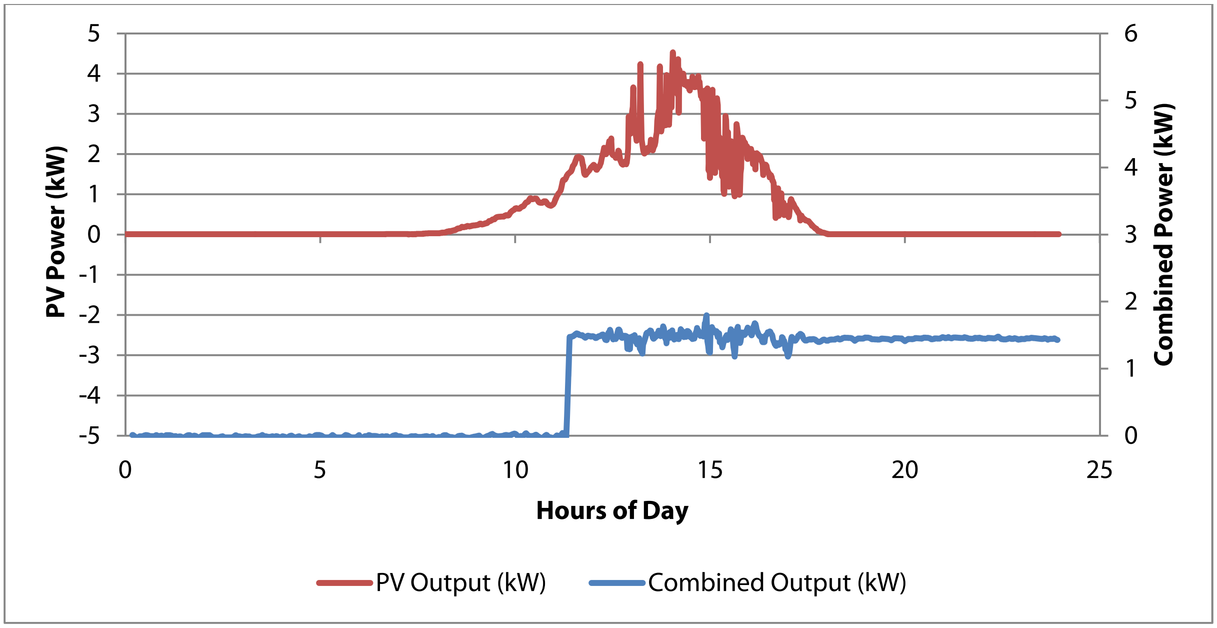

Figure 33: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3d – February 16-17, 2015

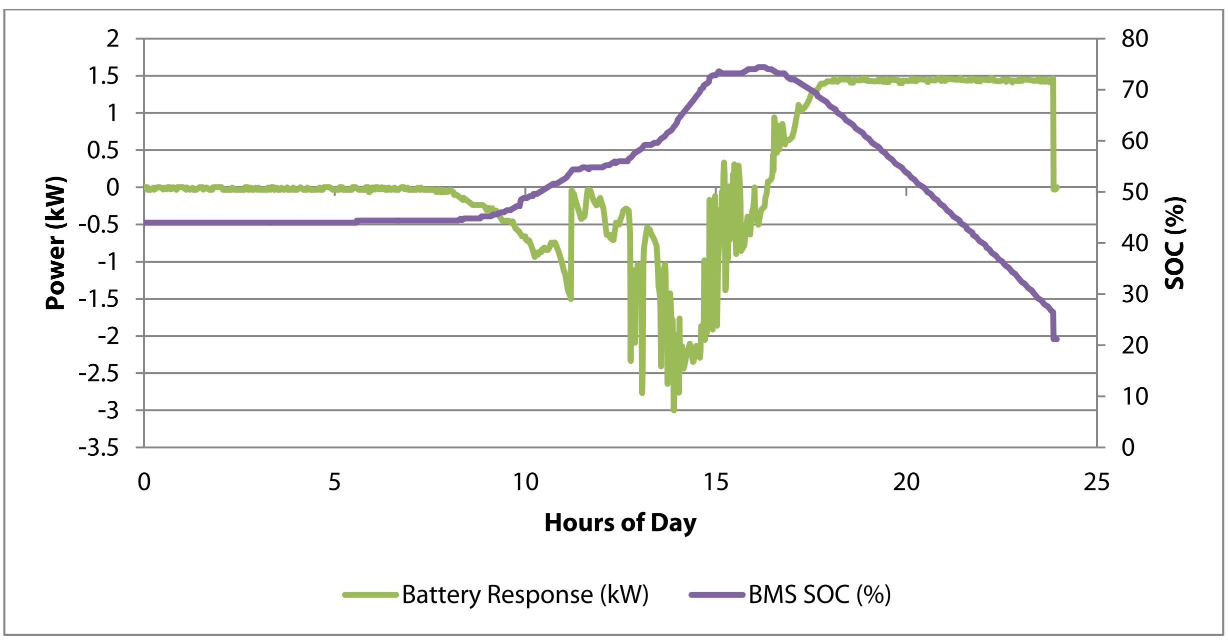

Figure 34: Battery Response for Test Case 3d – February 16-17, 2015

[18] A 5-minute moving average was applied to the Combined Output array.

q. Test Case 3d-0.2/1.5/40/Int – February 24-25, 2015[19]

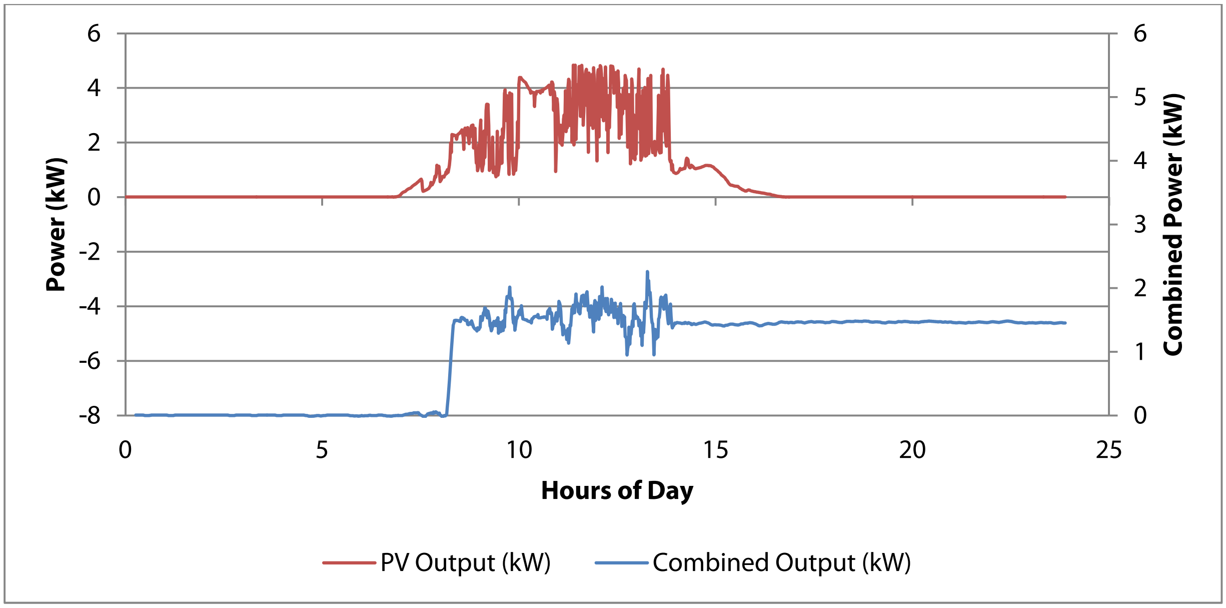

Figure 35: PV Scaled PV Generation and Combined Output (Solar + Battery) for Test Case 3d – February 24-25, 2015

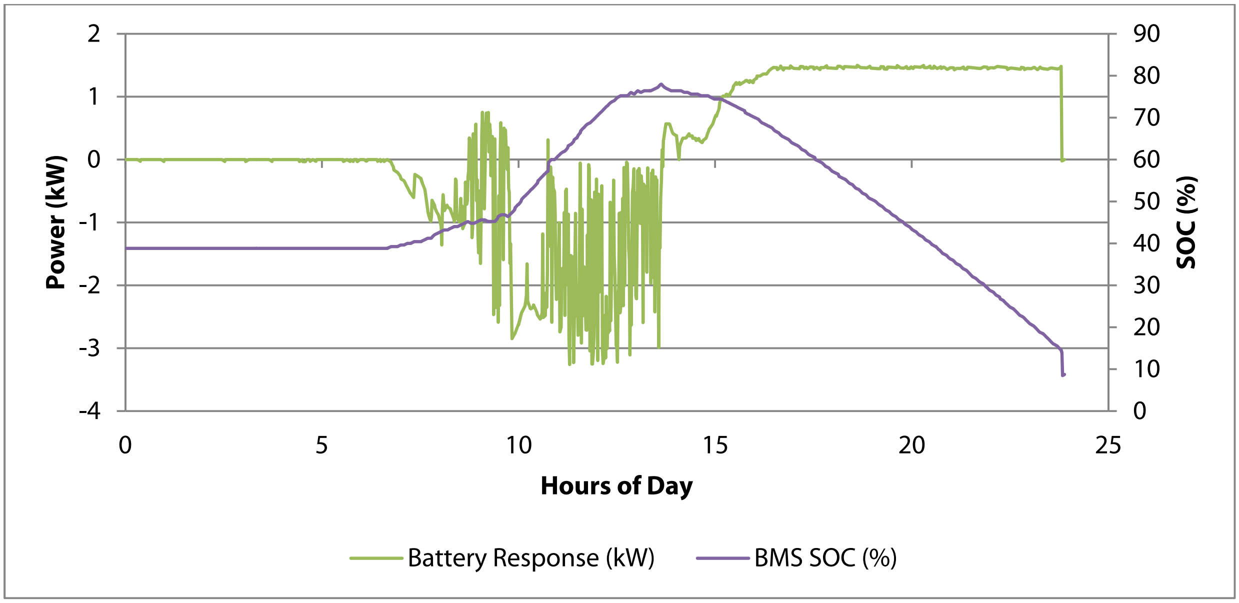

Figure 36: Battery Response for Test Case 3d – February 24-25, 2015

[19] A 10-minute moving average was applied to the Combined Output array.

V. Conclusion

This study has illustrated the coupled nature of PV and battery power levels, firming thresholds, initial SOC, and solar intermittency on a novel PV firming application for energy storage. The EnerDel pack employed for testing was shown capable of firming solar production on both clear and intermittent days. Low utilization of the battery on intermittent days, and the possibility of reaching 100% SOC and curtailing PV power on days where the initial battery SOC is high both point towards the need for improved control strategies that leverage daily forecasts of PV output. Accordingly, this area is recommended for future research.

Latency and related issues in our test system prevented the investigation of high frequency system response. Thus, in addition to investigating the benefits of incorporating PV forecasts into system control strategies, future testing should cycle a battery pack under more realistic hardware scenarios where the PV and battery control hardware are integrated to minimize latency and improve high-frequency system response.