TEST REPORT
Reliability of a 500 kWh ZBB Battery Energy Storage System
California Energy Commission
PG&E Substation

Confidential

November 9, 2007

Acronyms

CEC	California Energy Commission
DUA	Distributed Utility Associates
DUIT	Distributed Utility Integration Test
EPRI	Electric Power Research Institute
FCL	Fault Current Limiter
PG&E	Pacific Gas and Electric Company
PIER	Public Interest Energy Research
T&D	Transmission and Distribution
ZBB	ZBB Energy Corporation

Table of Contents

Overview

Under the sponsorship of the California Energy Commission (CEC) Public Interest Energy Research (PIER) Program, a 500-kWh battery system was tested under controlled conditions at the Distributed Utility Integration Test (DUIT) site in San Ramon, California. The ZBB/DUIT Test Plan was intended to ensure that the battery energy storage system meets the functional requirements of the substation application and that it would perform reliably prior to installation at the PG&E substation site.

The critical component of the test plan was to demonstrate the reliability of the system in a load following mode over an extended time duration. It was necessary for the battery to demonstrate the ability to automatically charge during off-peak hours, provide load following discharges when necessary and self-strip without failures or intervention during the test period. This report discusses the results of the reliability testing, conclusions and future work needed to complete the demonstration program.

Reliability testing

The test was designed to validate reliability of the system in a load following mode for a Transmission and Distribution (T&D) deferral application in an accelerated test representing a 3 year period. If the duty cycle for this application were about 10 operating days per year, a 40-day test period would represent approximately 3 years of field experience.

Reliability Testing Procedure

PG&E substation load profiles were used to create 40 days of diurnal cycling. Simulated profiles were generated based on four different load profiles and a load threshold of 10 MW. The load profiles used for the reliability testing are shown in Figure 2.

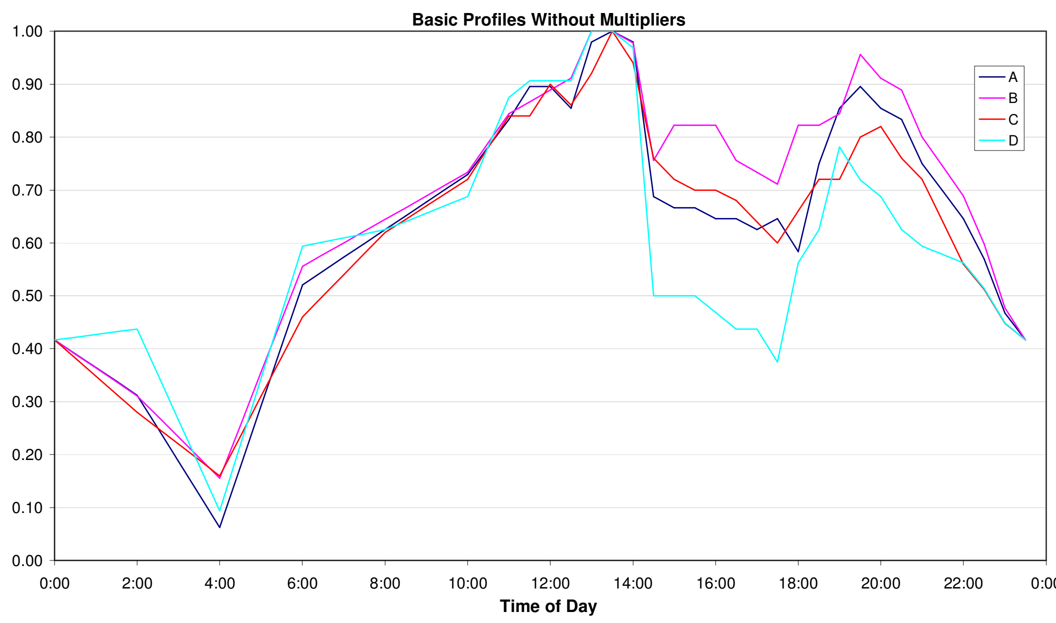


Figure 2. Load profiles generated from PG&E substation data.

The profiles were scaled to achieve various power and energy outputs from the battery system. During the load following period of the day, the battery would only discharge, up to 250 kW maximum, if a signal corresponding to a load greater than 10 MW was generated.

The signal generator was set up to read the load data from the file, then send a 0 to 5 volt signal to the battery based on the simulated load. The daily load data files were set up to range from 0MW to 10.32MW, and the battery was to supply power above 10 MW.

A series of cycles were developed (40 days) by randomly inputting one of the four load profiles and a peak load for each day. The loads were designed so that some days the load would be less than the 10MW threshold (no discharge) and some days the load is greater than the output capacity of the battery (which is 250 kW). The series of cycles are shown in Table 1.

Table 1. Summary of reliability testing parameters

Test day	Date Performed	Load Profile	Substation Peak (MW)	Battery Peak Output (kWh)		Test day	Date Performed	Load Profile	Substation Peak (MW)	Battery Peak Output (kWh)
1	9/11	A	10.13	128		21	9/30	D	7.92	0
2	9/11	B	9.84	0		22	10/01	A	10.08	80
3	9/12	C	10.20	200		23	10/02	B	10.08	80
4	9/13	A	9.84	0		24	10/02	C	9.84	0
5	9/14	B	10.32	320		25	10/03	A	10.08	80
6	9/15	D	7.68	0		26	10/03	B	10.08	80
7	9/16	D	7.92	0		27	10/03	D	8.4	0
8	9/17	C	10.08	80		28	10/03	D	7.44	0
9	9/18	A	10.08	80		29	10/03	C	10.08	80
10	9/19	B	9.84	0		30	10/03	A	10.08	80
11	9/20	C	10.20	200		31	10/03	B	9.84	0
12	9/21	A	10.08	80		32	10/04	C	10.20	200
13	9/22	D	8.4	0		33	10/05	A	10.08	80
14	9/23	D	7.44	0		34	10/06	D	8.40	0
15	9/24	B	9.96	0		35	10/07	D	7.44	0
16	9/25	C	10.32	320		36	10/08	B	10.08	80
17	9/26	A	9.84	0		37	10/09	C	10.32	320
18	9/27	B	10.08	80		38	10/10	A	9.84	0
19	9/28	C	10.32	320		39	10/10	B	9.84	0
20	9/29	D	7.68	0		40	10/10	C	10.32	320

Each weekday the battery is charged from 7:15am to 11:45 am. The battery is not charged on weekends since no discharges were scheduled for those days. Following charge the battery goes into a rest mode, waiting for a load signal from the PG&E simulation. If the simulated load goes above 10 MW, the battery dispatches energy. If the load signal never goes above 10 MW, the battery does not discharge. The load following period continues until 5:15 pm, at which time the battery is discharged to remove any remaining energy from the system prior to the next day's cycle.

Load Following Calibration

To calibrate the load following output from the battery, the system was charged and the PG&E software was used to generate signals in 0.25V increments that were sent to the battery. The signal generator sends a 0 to 5 volt signal to the battery, which then dispatches the appropriate amount of power to the load. The measured output of the battery system is compared to the simulated load values in Figure 3.

The limits of the output signal were set up so that 9.97MW produces a 0 volt signal and 10.25MW produces a 5 volt signal. The test plan intended for the signal to ask for discharges up to 320 kW and the battery should deliver only its maximum output of 250 kW. However, the way the test was actually set up, the signal only asked for a maximum discharge of 250 kW. The battery would have given the same output but the issue is that the signal generator set the maximum discharge value rather than the battery seeing a higher signal and providing 250 kW discharge. The signal should have been set up so that 5 volts = 10.32 MW, not 10.25MW. This was a miscommunication in setting up the parameters of the test and not a shortcoming of the battery system. Separate manual testing of the battery demonstrated that it will not deliver higher than 250 kW in the load following mode even if asked for higher outputs.

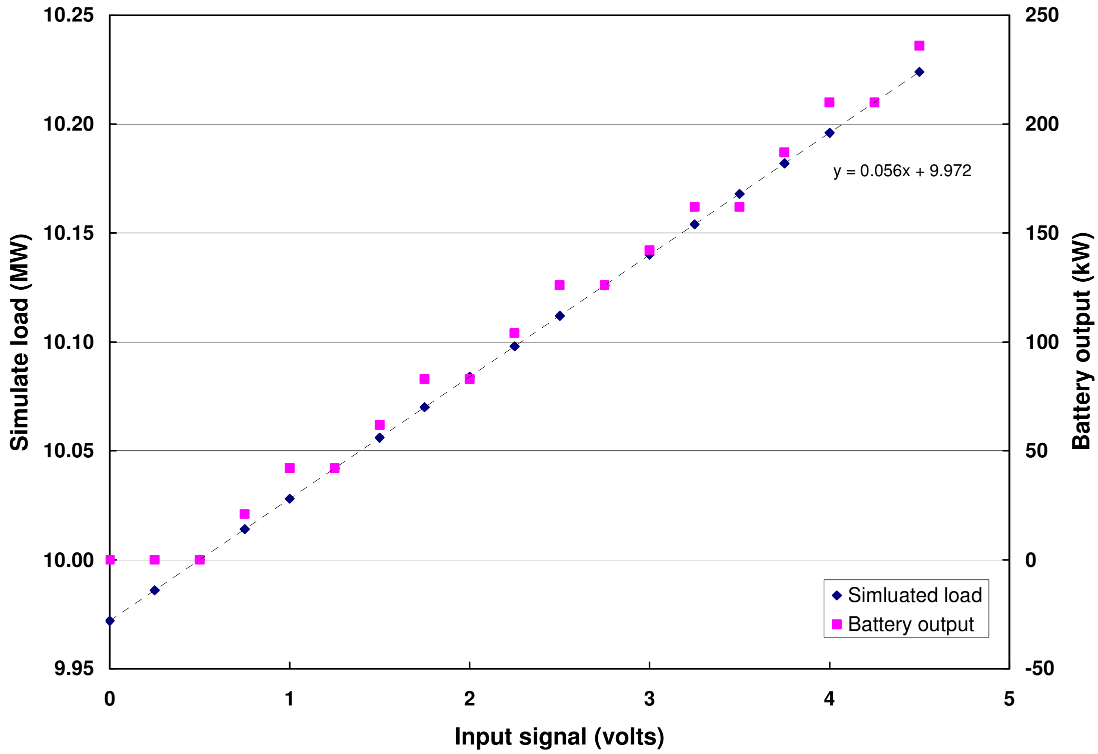


Figure 3. Load following calibration curve

Test Results

The battery system ran unattended in the automatic mode for 29 consecutive days and 40 load following discharge cycles. It dispatched the required energy every time that it received a signal from the PG&E simulation program software.

Figures 4 and 5 show battery power profiles during 200 kW and 250 kW load following discharge cycles respectively. Figures 6 and 7 expand the load following discharge portions of these cycles. Over the first three weeks of the reliability testing, the battery ran unattended and has performed properly with the battery discharge matching the load very closely.

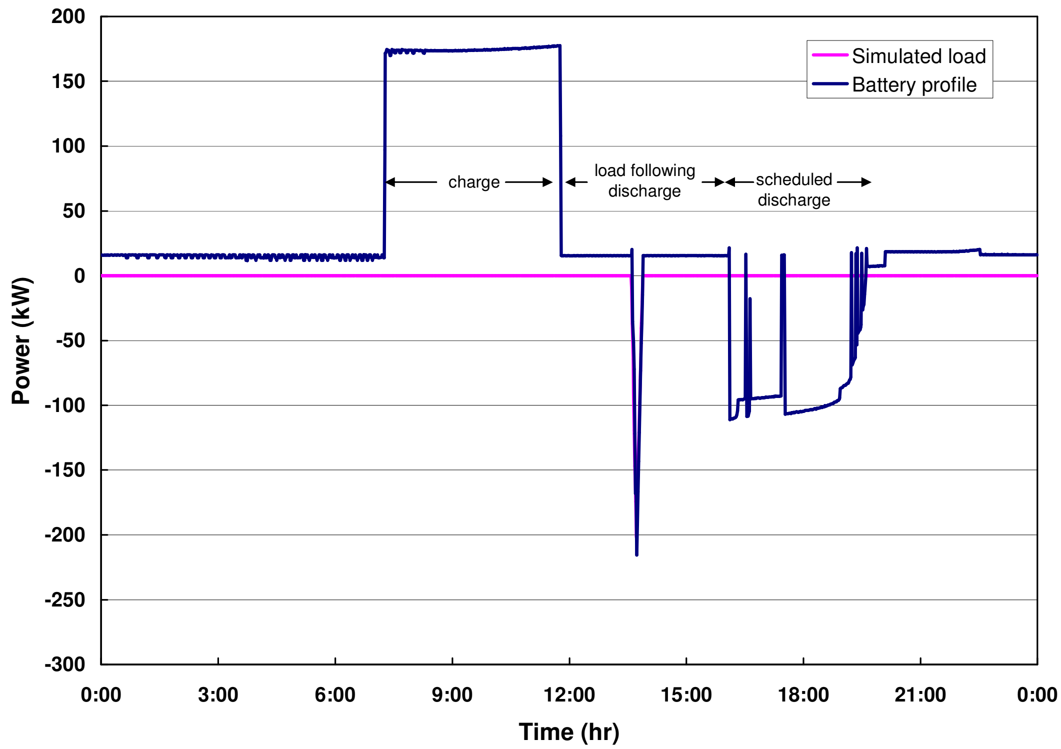


Figure 4. Power profile for 200 kW load following discharge cycle.

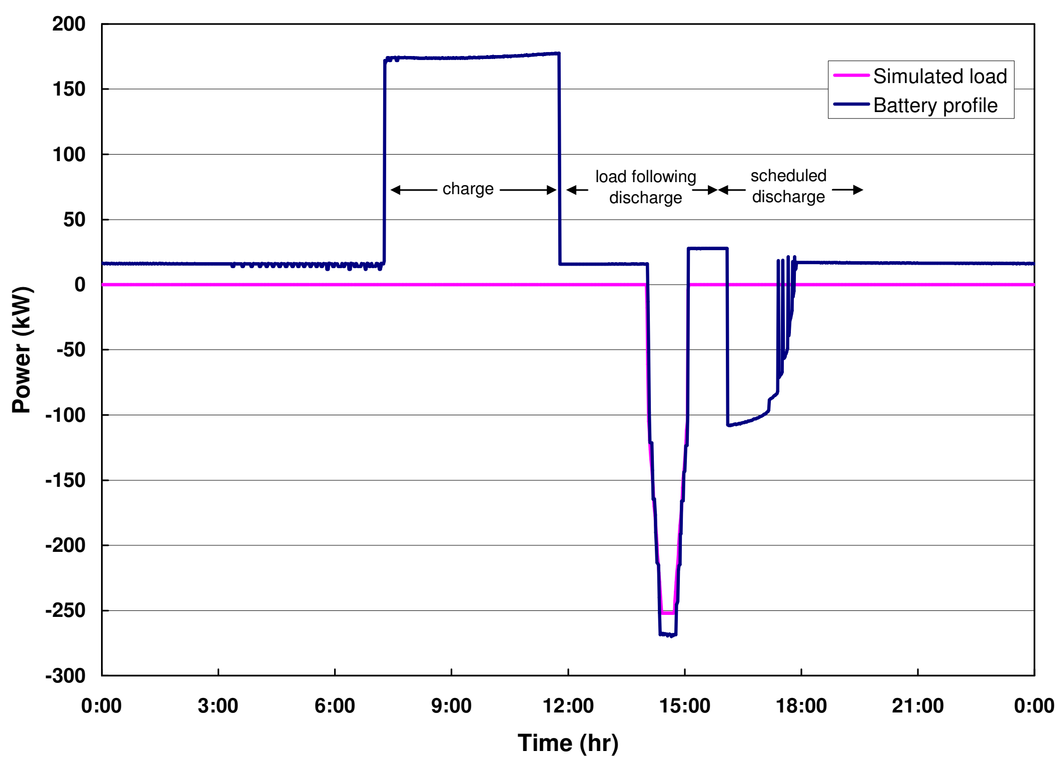


Figure 5. Power profile for 250 kW load following discharge cycle.

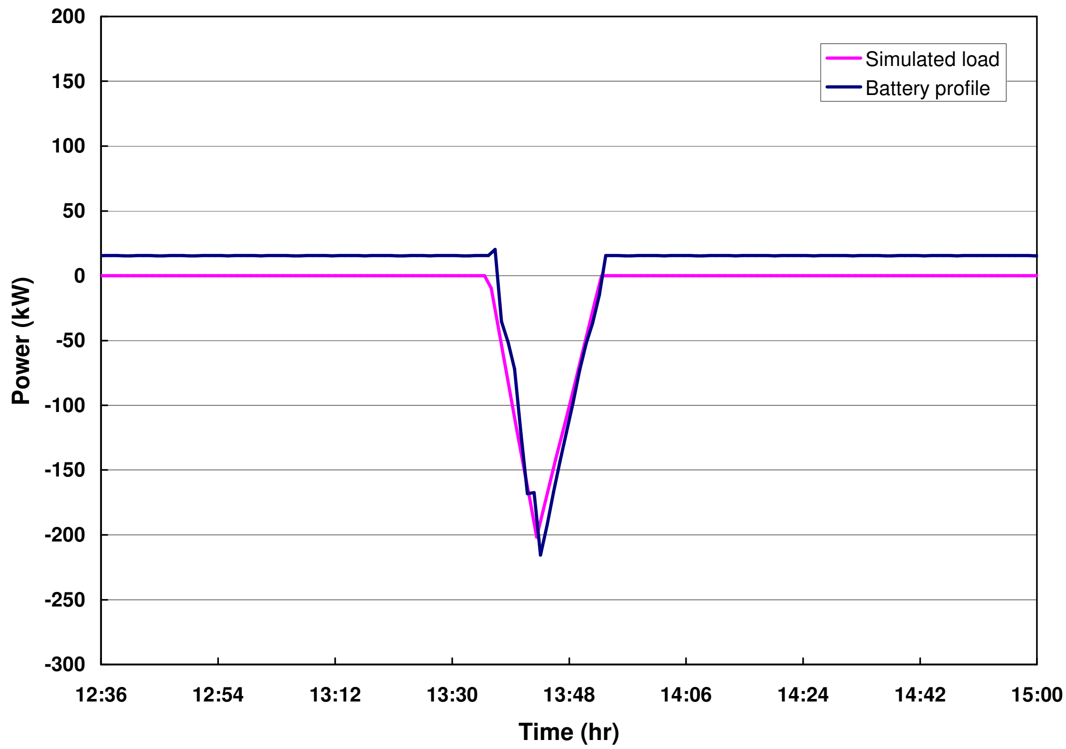


Figure 6. Expanded profile for 200 kW load following discharge cycle.

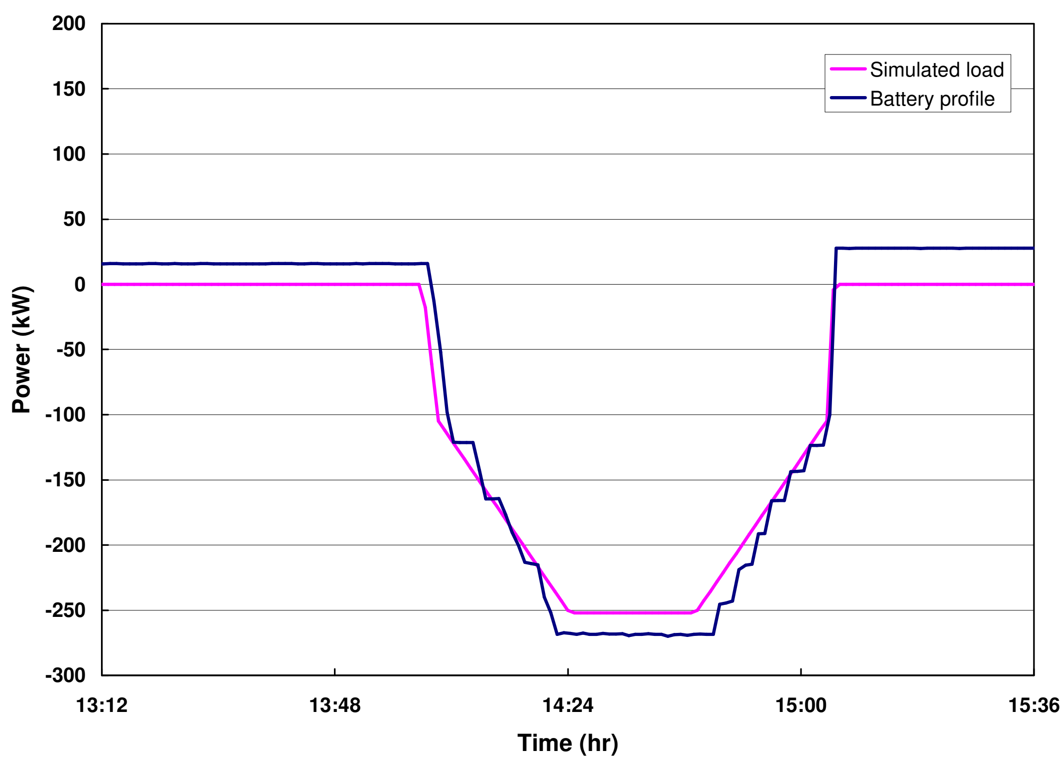


Figure 7. Expanded profile for 250 kW load following discharge cycle.

Technical Issues

A number of technical issues were addressed during the reliability testing of the 500-kWh battery system, consisting of both operational and timing issues. The issues and resulting responses to the issues are described in the following sections.

Drifting of the simulation timer

One issue that was addressed during the first few weeks of the reliability testing was that the timer on the PG&E simulation program tended to drift over time. After about 1 week, the time on the simulator had fallen behind the real time by more than 1 hour. After this point, the timer was reset, and it was reset periodically to keep the load profile simulator close to real time. This did not have any affect on the battery operation other than shifting the time of day when the load following discharge peak occurred.

Access to the DUIT facility

PG&E had scheduled testing of a fault current limiter (FCL) in the High Current Yard at DUIT starting on 10/15/07. Due to the size of the FCL and the associated equipment that was needed to be placed in the yard for this testing, the ZBB battery needed to be removed from the High Current Yard by Friday 10/12/07. Since this testing required the use of the 21000-480 volt transformer, the 21 kV power to the DUIT transformer facilities would not be available for three weeks beginning on Friday 10/12.

In order to complete all of the load following discharges in less than 40 days, it was decided to advance the simulator through the scheduled zero discharge days and to perform multiple discharges on a single battery charge. This illustrated that the battery is capable of multiple load following in a single day period, while allowing the completion of all scheduled load following events.

Multiple discharges in a single day

On 10/03/07 the battery performed multiple load following discharges from multiple days (total of 4) as shown in Figure 8. This was done to complete all the discharges for the 40 days in a fewer number of days.

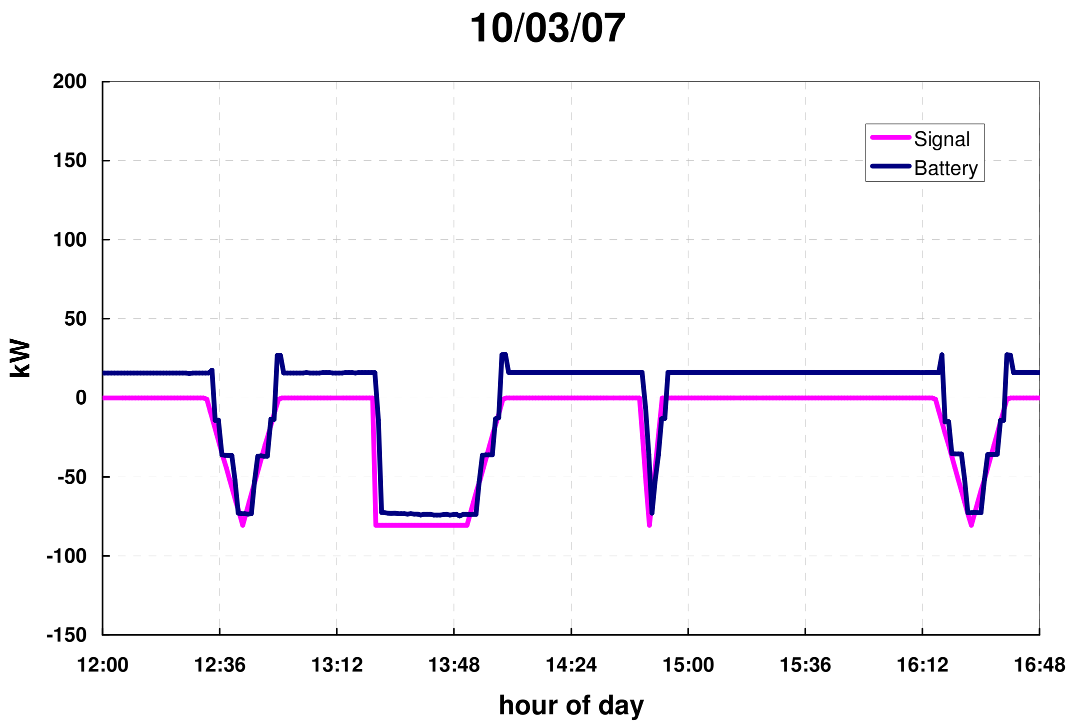


Figure 8. Multiple load following discharge during a single day

For this cycle, after completing each load following discharge the timer on the simulation software was moved to a later date with an expected discharge. The software was reset and the battery was allowed to follow the next simulated load. This allowed the battery to complete four discharge profiles in a single day.

Discharge Interruption on 09/25

The load following discharge on 9/25 was temporarily interrupted due to one of the modules being automatically taken out of the string. This 1-minute interruption is shown in Figure 9. This was caused by the incomplete discharge of one battery module from the previous day, due to an indication that one of the motor drives was operating improperly. The module was automatically bypassed and the remaining modules completed the remainder of the load following discharge. This unexpected event shows that the battery system is capable of detecting potential problems on individual modules, which can then be automatically bypassed and disconnected with only a short interruption in energy supply.

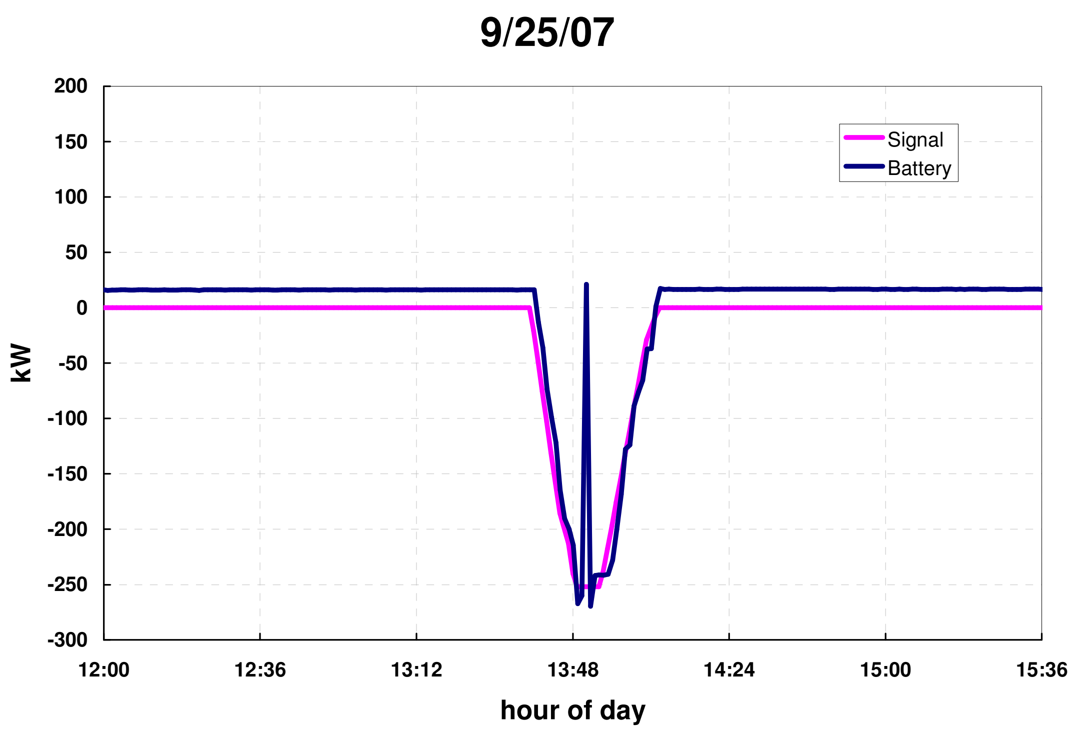


Figure 9. Interruption during load following discharge.

Contactor Issue on 10/09 and 10/10

During the cycle on 10/10, the battery was following the generated signal until the load reached about 230 kW when a contactor malfunctioned. ZBB had personnel on-site (along with representatives from DUA and EPRI-PEAC) who attempted to reset the condition. After several unsuccessful resets, it was established that the contactors on module #2 was not operating properly and they were replaced. The system operated properly after replacing the contactors, and successfully completed the load following profile. The initial contactor malfunction, manual resets and load following discharge can be seen in Figure 10.

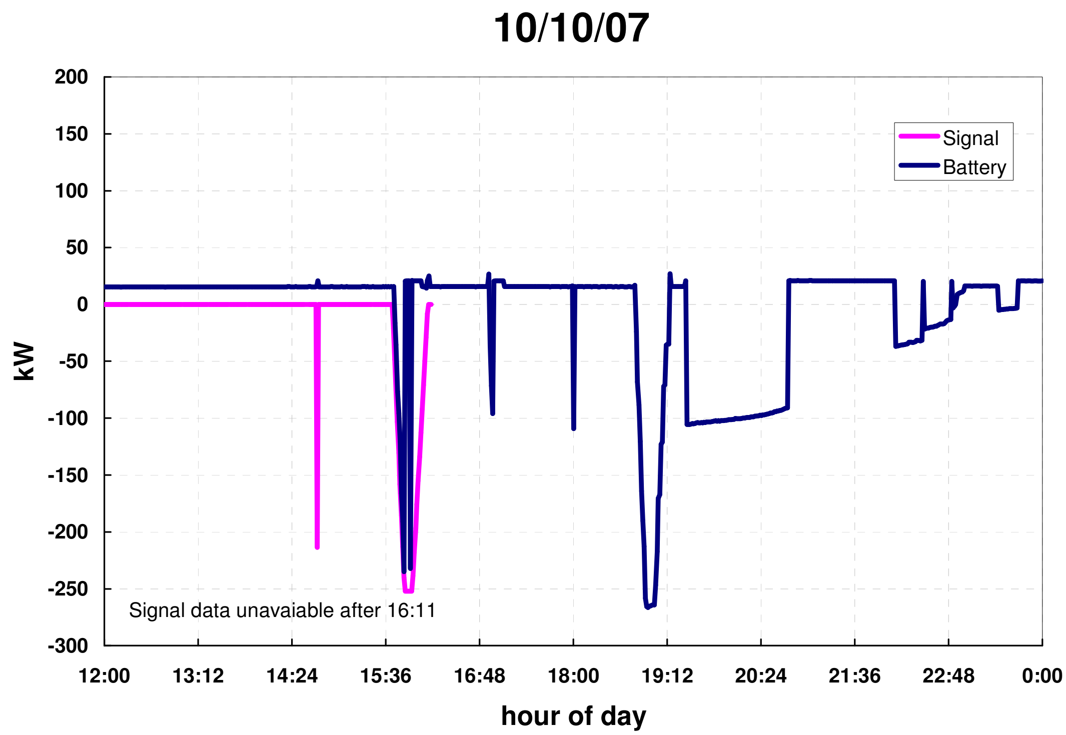


Figure 10. Load following discharge following contactor replacement.

After reviewing the data, we determined that a similar condition had also occurred on the previous day (10/09) as shown in Figure 11.

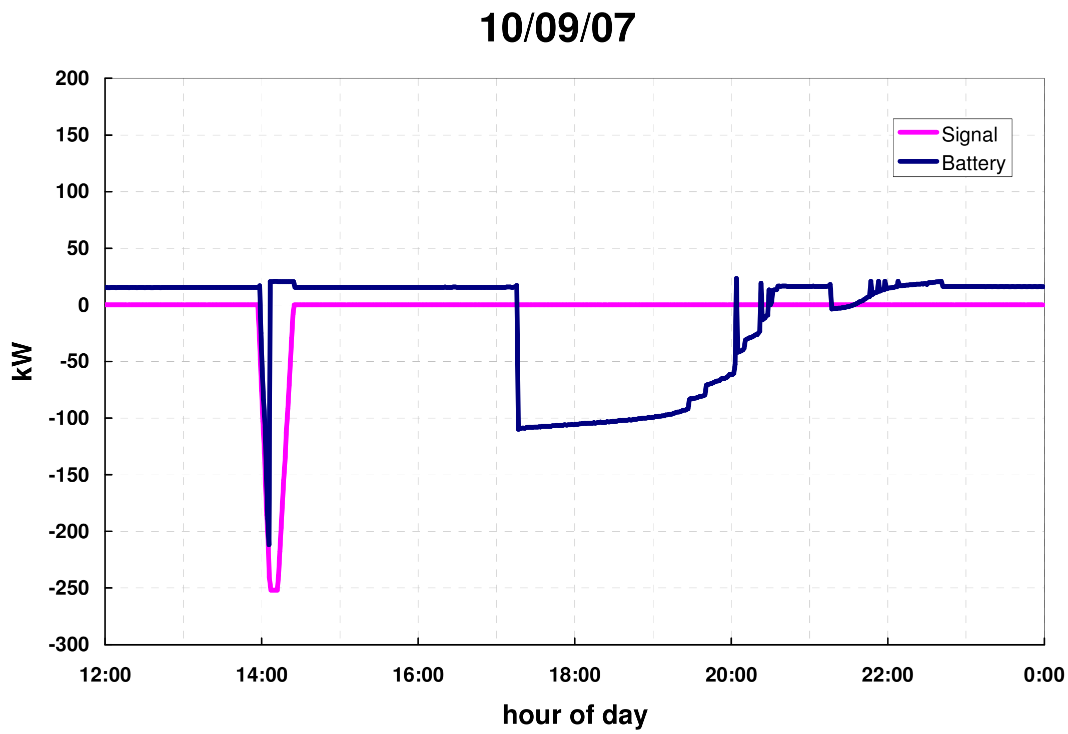


Figure 11. Load following interruption due to contactor malfunction.

Following completion of the reliability test period, the contactors from this module were inspected and ZBB found that they were installed improperly (a stainless steel lock washer was installed in the current carrying path). This caused the contactor to overheat and ultimately fail during the test. The installation procedure for installing the contactors has been updated and training has been implemented to prevent this type of failure from occurring in the future.

Missing data

Some of the data was missing from both the signal and battery (shark meter) files. The signal data was discontinued at 8:55 on 9/21 and was continued again at 9:01 on 9/24. All signal data between these times was missing. The battery data (shark meter) was missing on 9/25 before 8:24.

The signal data was also missing after 16:11 on 10/10. The battery still operated in the load following mode, indicating that the signal was still being generated, just not logged into the data file.

Calibration issues

The battery control software was set up to discharge in 20 kW increments rather than using a continuous range. Because of this, the battery discharged more than the required kW during some of the profiles (i.e., the battery discharged 260 kW for a 250 kW discharge signal). Also, the battery was found to deliver less than the desired output on a number of cycles, primarily during the 80 kW discharges as shown in Figure 12.

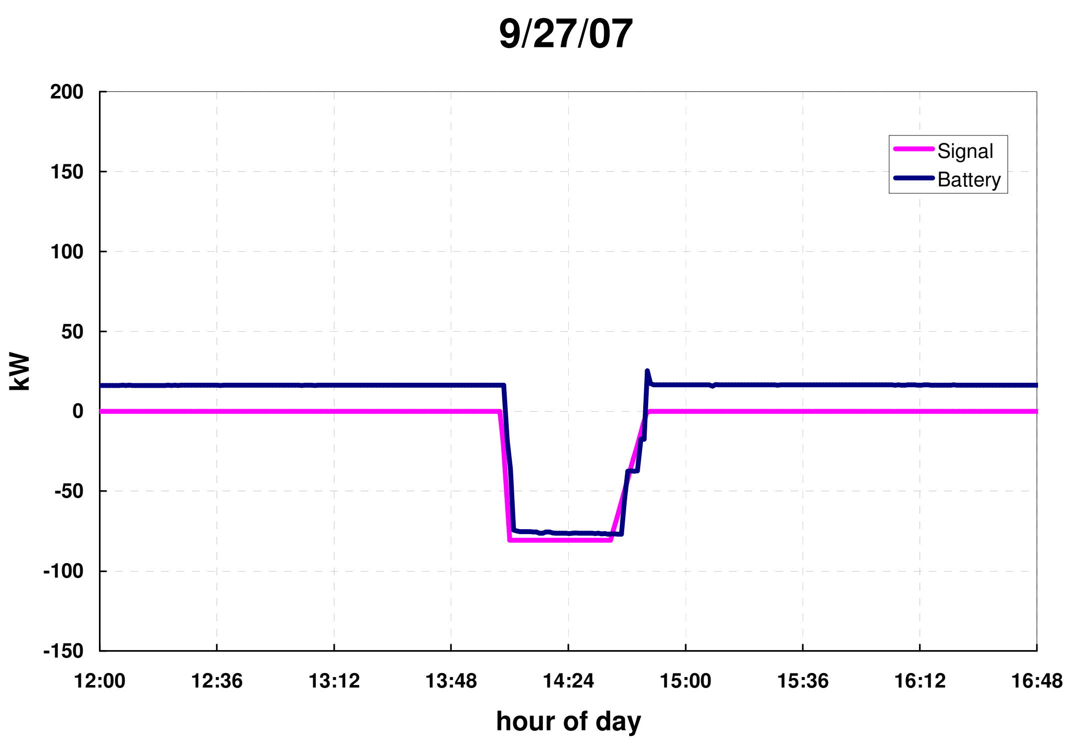


Figure 12. Variation between discharge signal and battery output.

The most likely reason for the discrepancy is the calibration of the battery output to the generated signal. The battery discharge should be recalibrated based on the actual battery output during the load following discharge tests.

Multiple signals with one discharge

This condition occurred on two days (10/4 and 10/10) when the timer from the simulation software was advanced to a day with an expected load following discharge. When the timer is changed, the software starts back at the beginning and scrolls through all of the load profiles at an accelerated rate. Some of the profiles are long enough that even at the accelerated rate, the simulator still sends a signal. To counteract this, the battery was put in the manual mode until the date and time are updated on the simulator. In this mode, the battery will not react to the signal.

This is what happened on the two days in question; the simulator produced a short 1 minute signal while the timer was being reset, but the battery didn't react to this signal because it had been taken out of the automatic mode. The signal data shows the occurrence of a peak but the battery didn't react to the peak as shown in Figure 13.

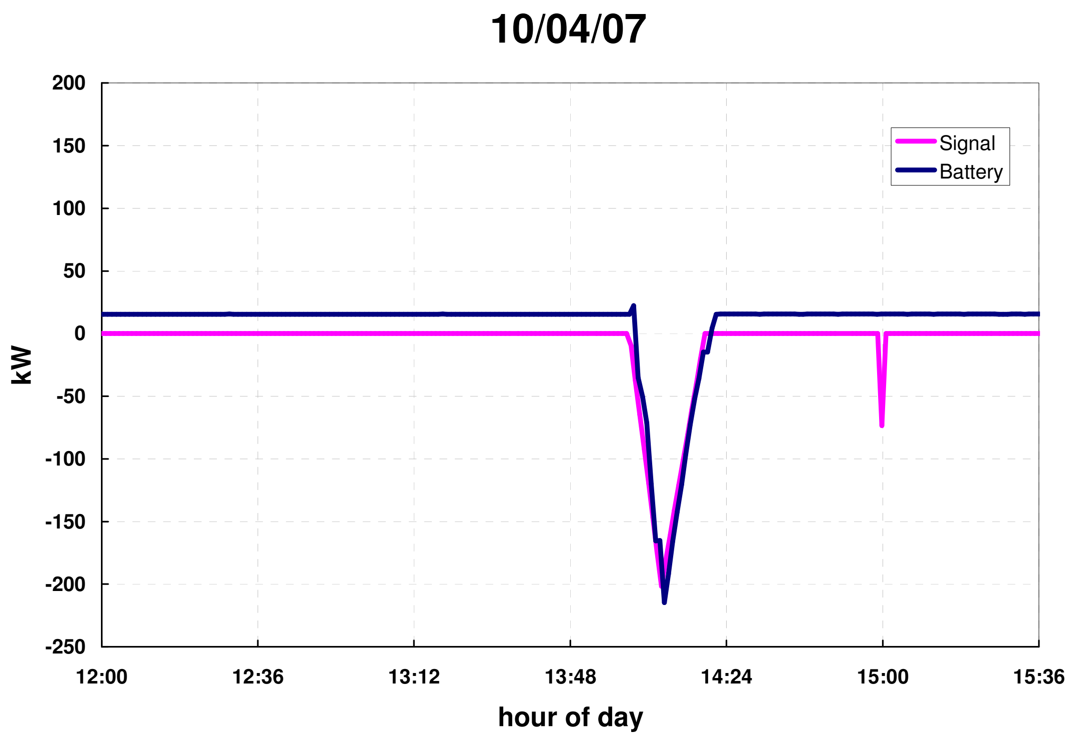


Figure 13. Signal generated while advancing the simulator clock.

Conclusions

ZBB Energy Corporation successfully completed 40 load following discharge cycles and 29 days of reliability testing for a 500-kWh battery energy storage system. The battery demonstrated the ability to automatically charge during off-peak hours, provide load following discharges when necessary and self-strip without failures or intervention during the test period. It dispatched energy to the simulated load every time that it received a signal from the PG&E simulation program software.

The duration of the test was reduced to provide access for alternate testing of PG&E equipment at the High Current Yard at the DUIT facility. Although the total number of test days was reduced, all of the load following discharges were completed by advancing the simulator through the scheduled zero discharge days and by performing multiple discharges on a single battery charge.

Future Work

Following the successful completion of the reliability testing of the 500-kWh battery system, the next phase of the program requires testing multiple battery units at a designated utility site (substation).

Appendix – Reliability Testing Results

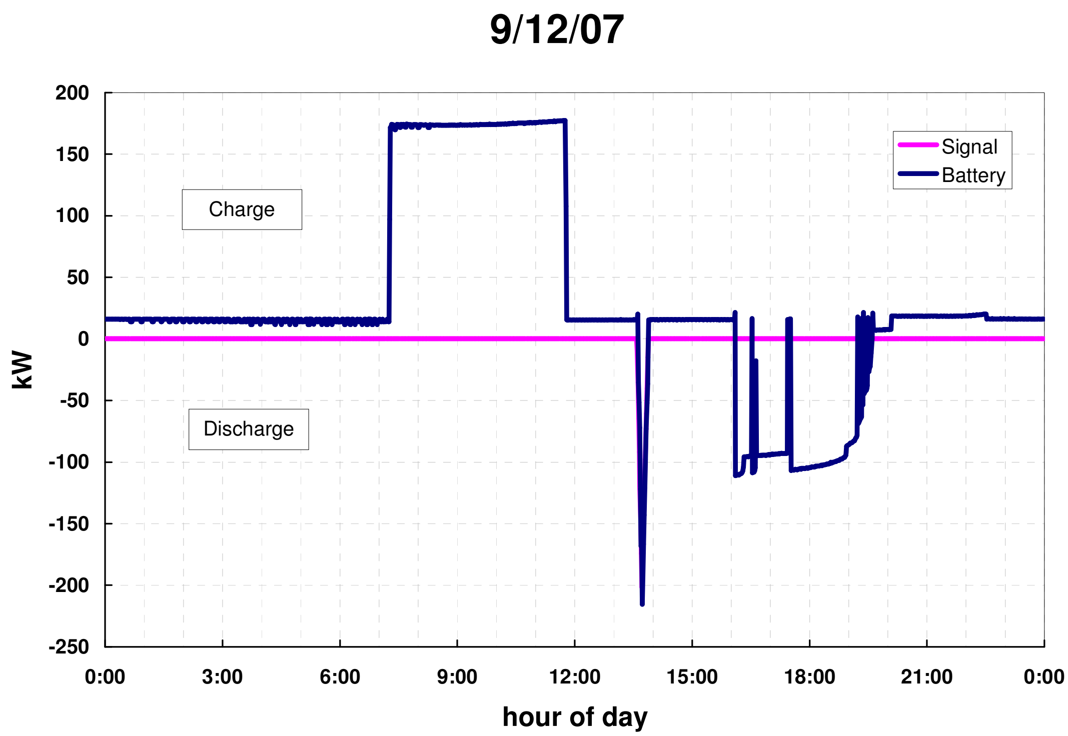


Figure A-1. Diurnal Results 9/12/07

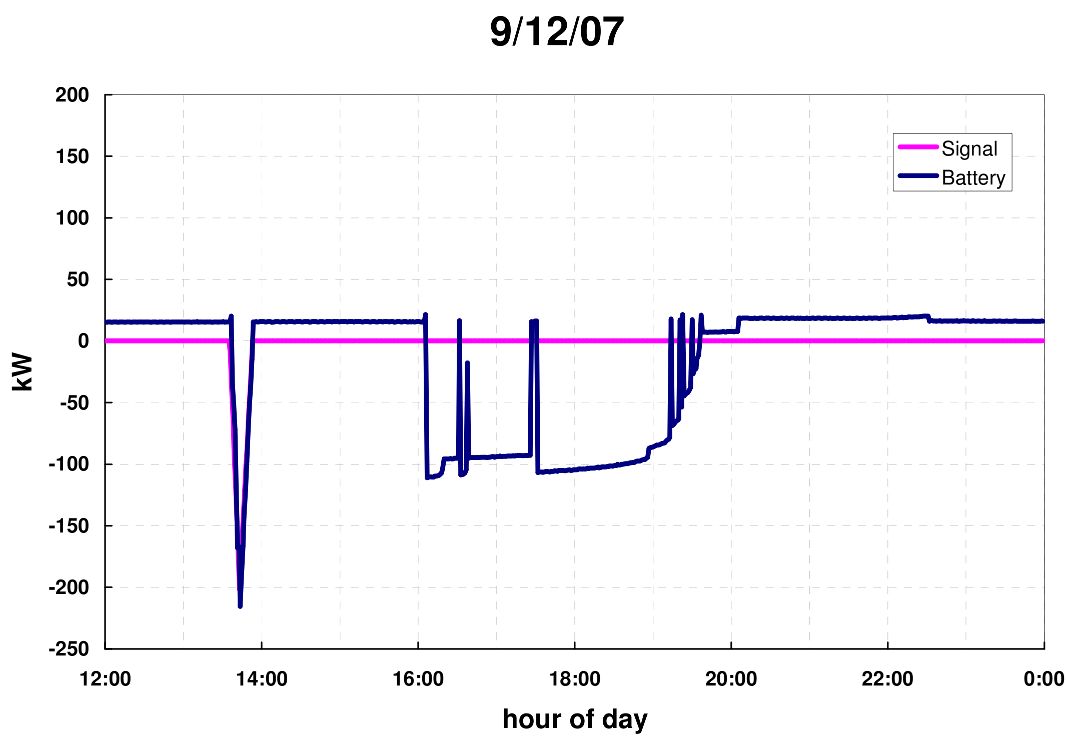


Figure A-2. Afternoon Results 9/12/07

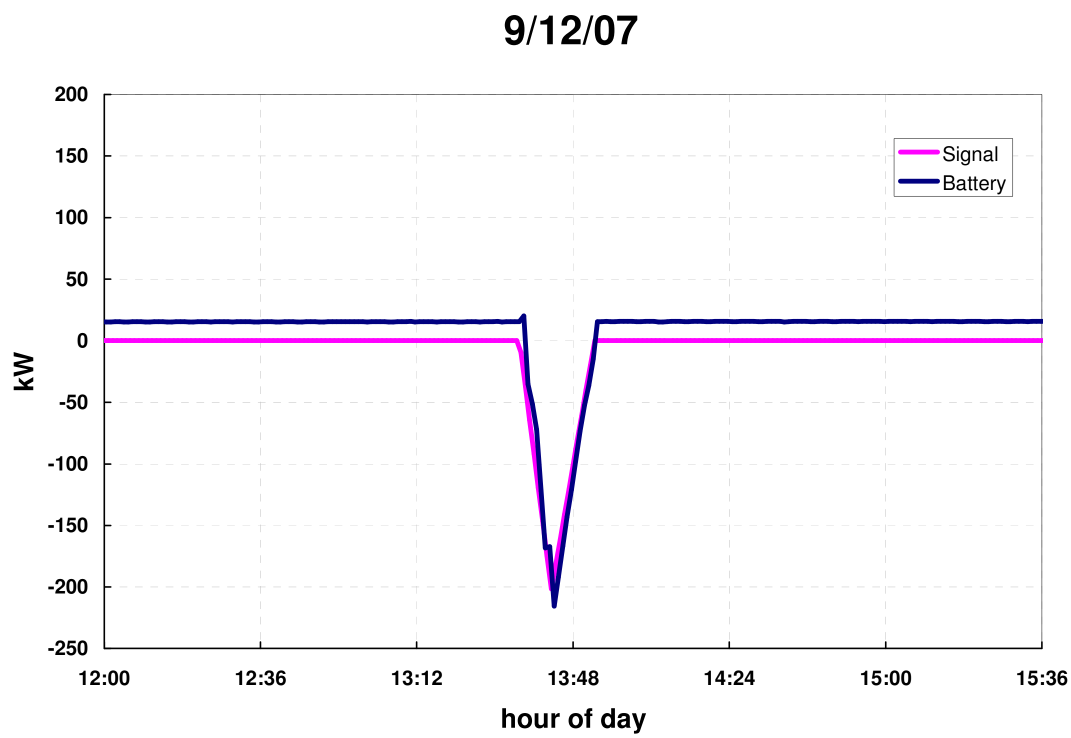
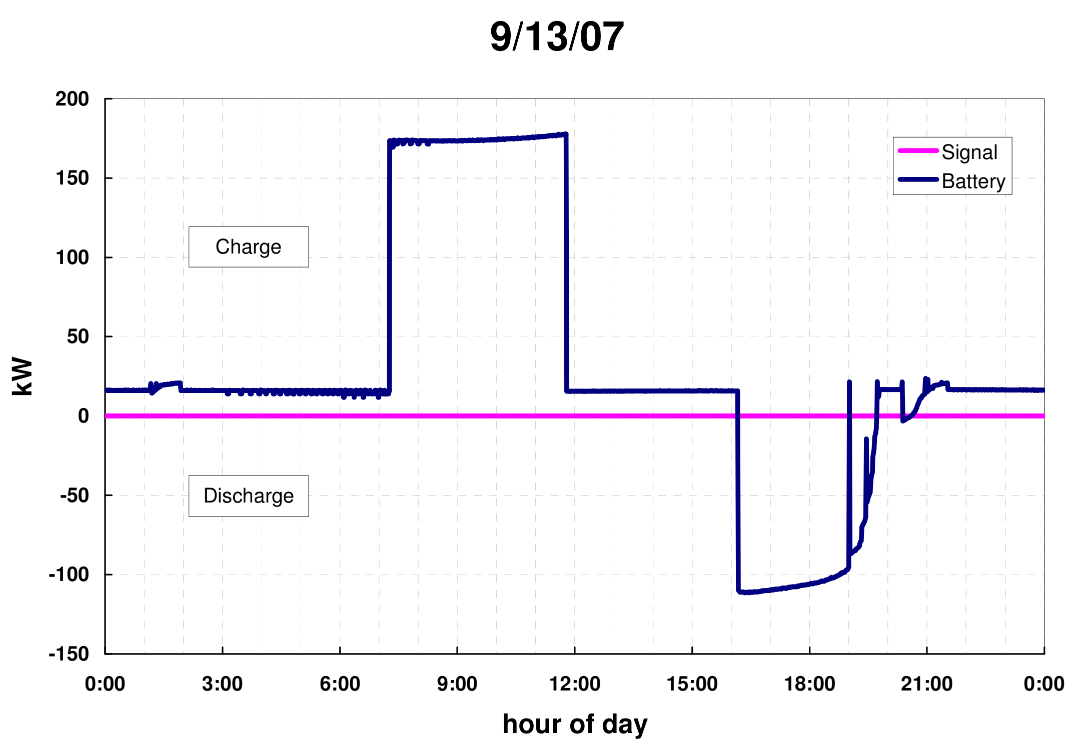


Figure A-3. Load Following Discharge 9/12/07



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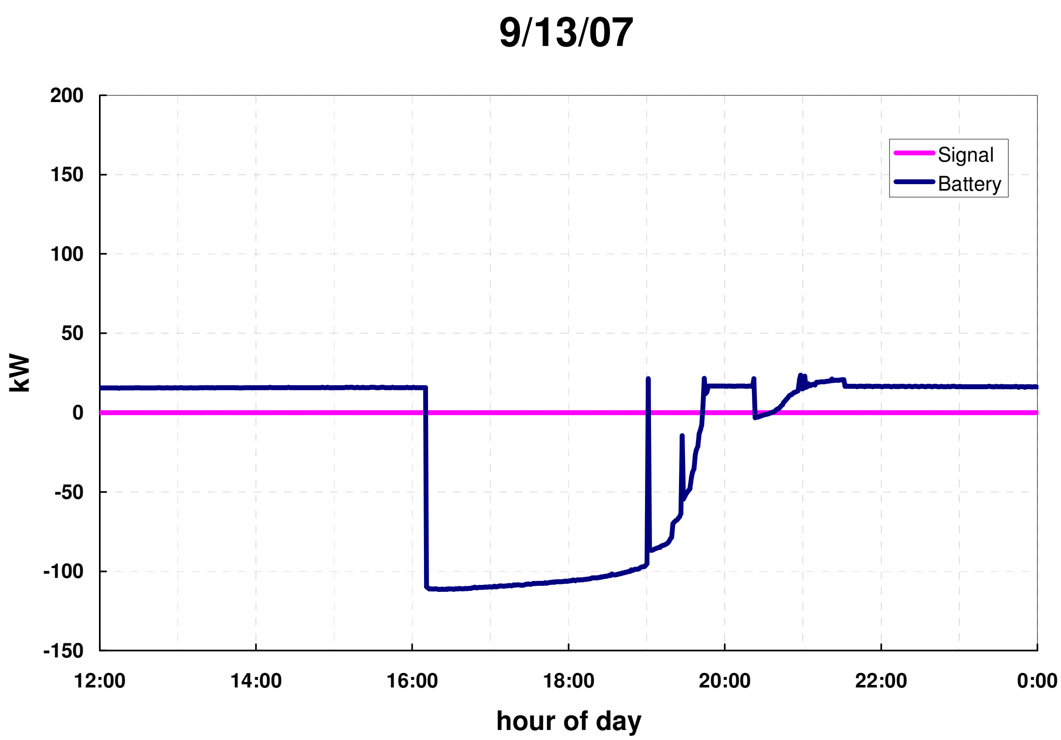

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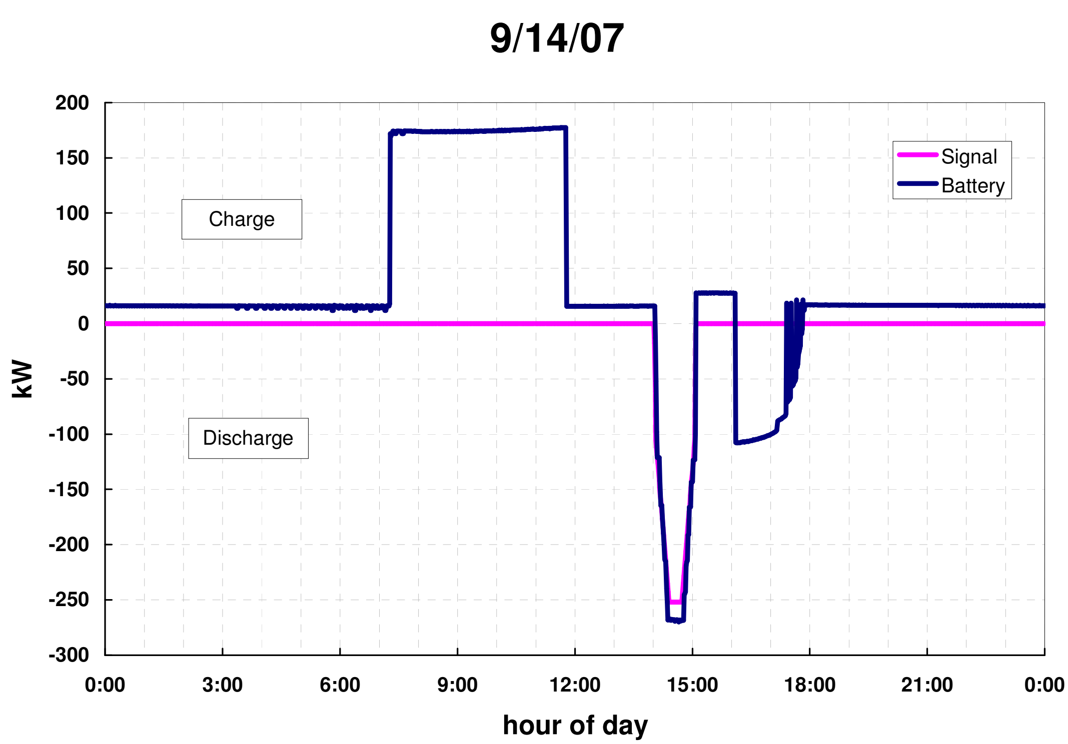

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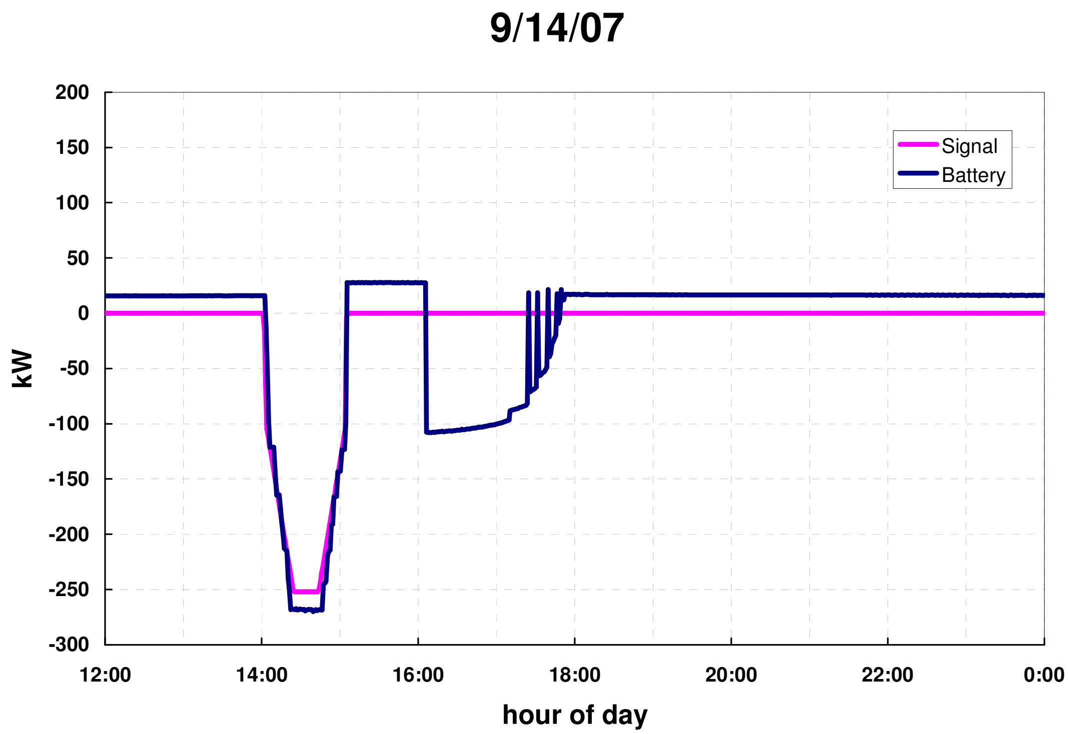

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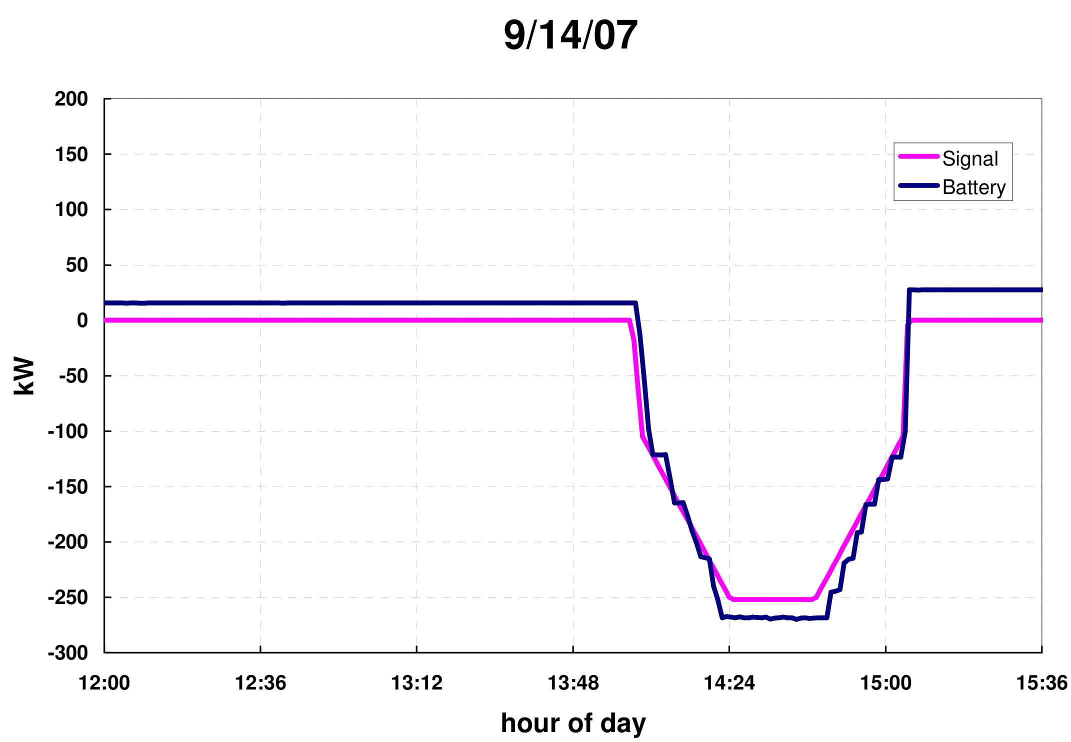

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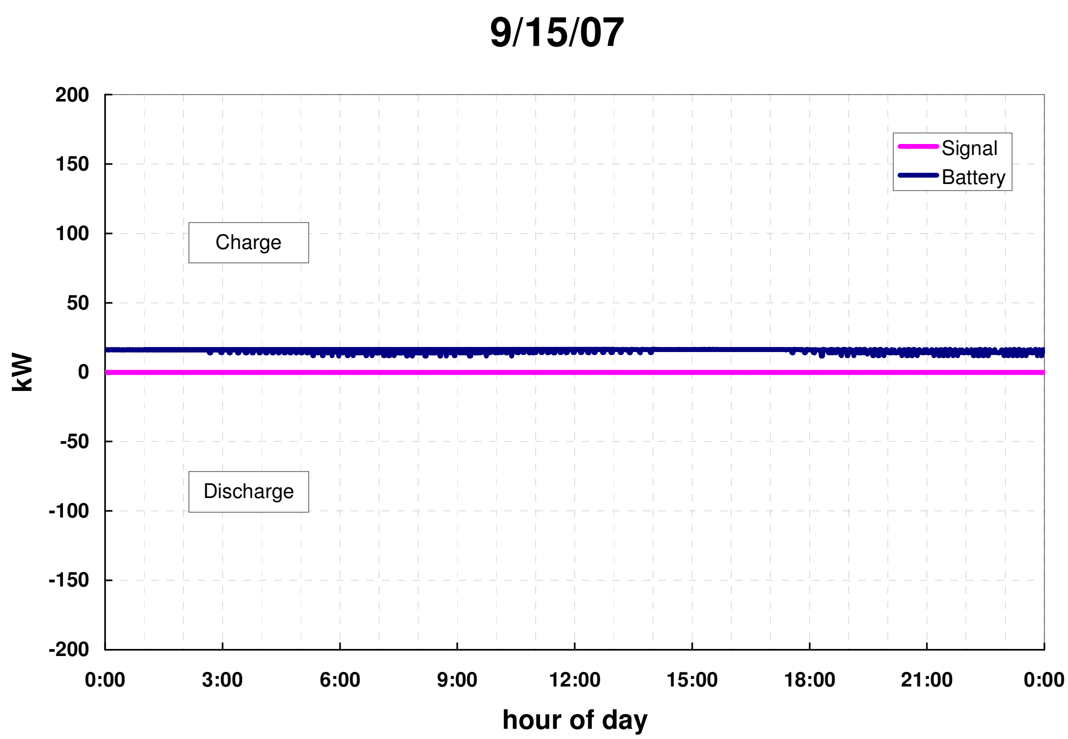


Figure A-9. Diurnal Results 9/15/07

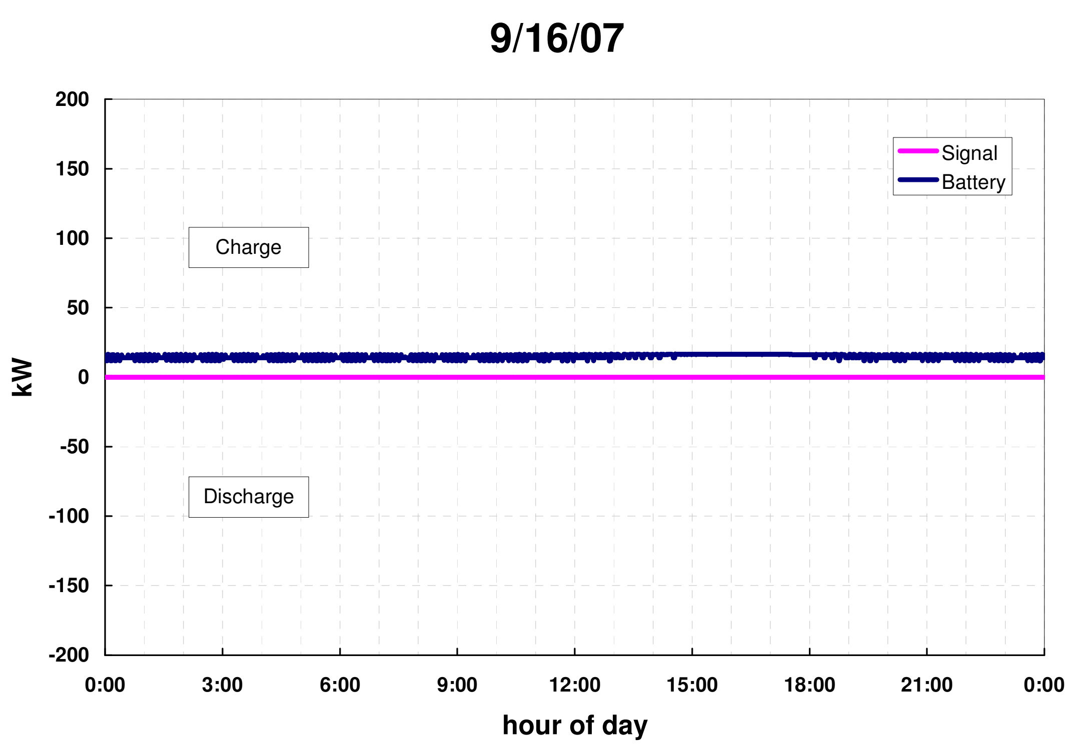


Figure A-10. Diurnal Results 9/16/07

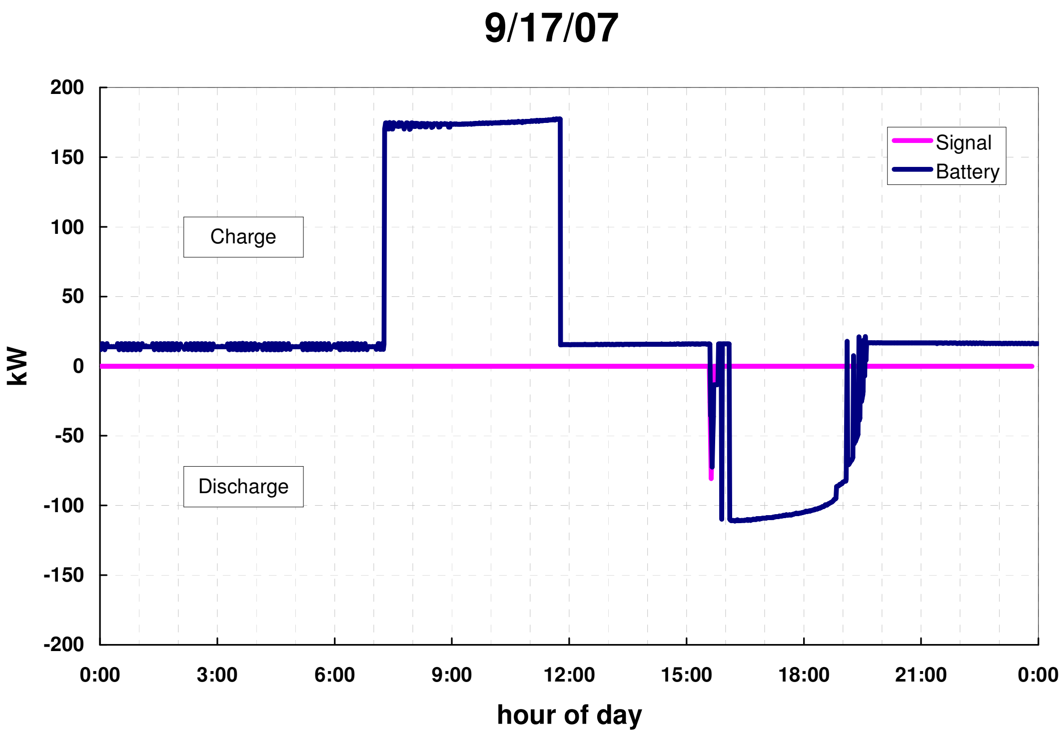
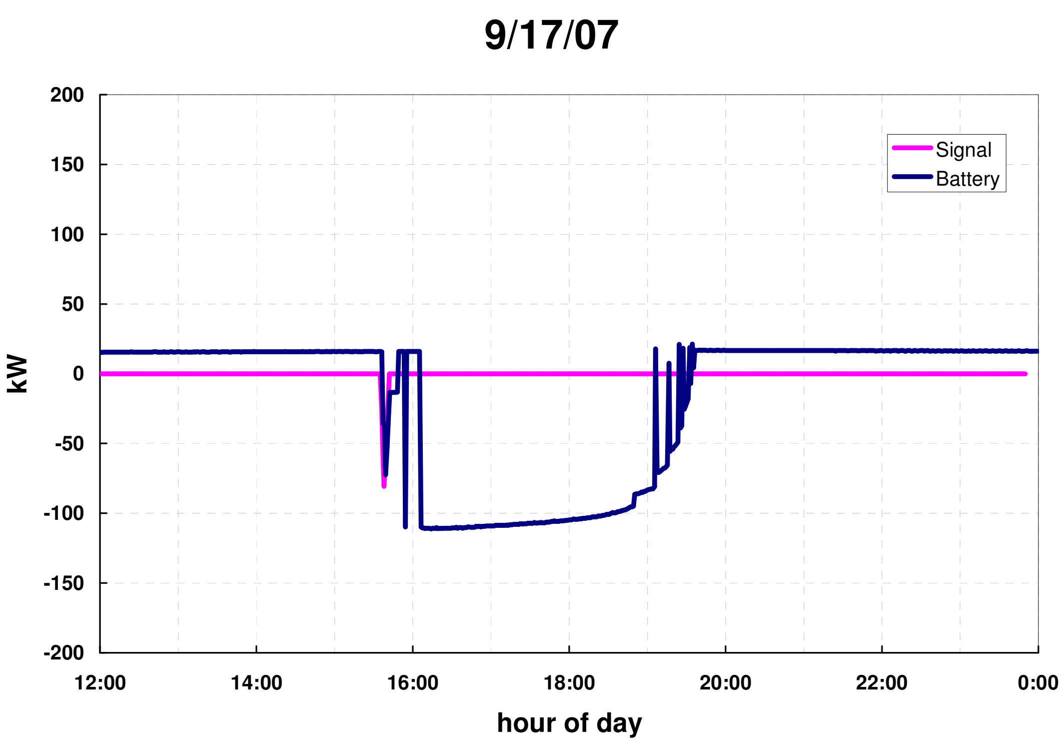


Figure A-11. Diurnal Results 9/17/07



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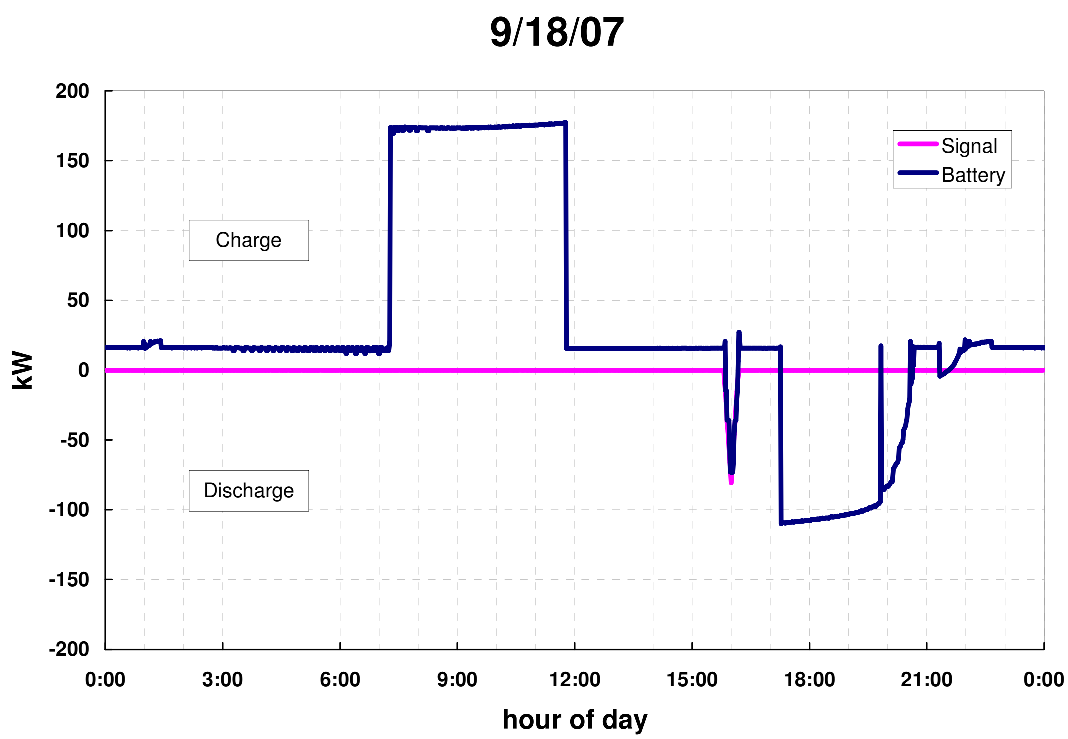

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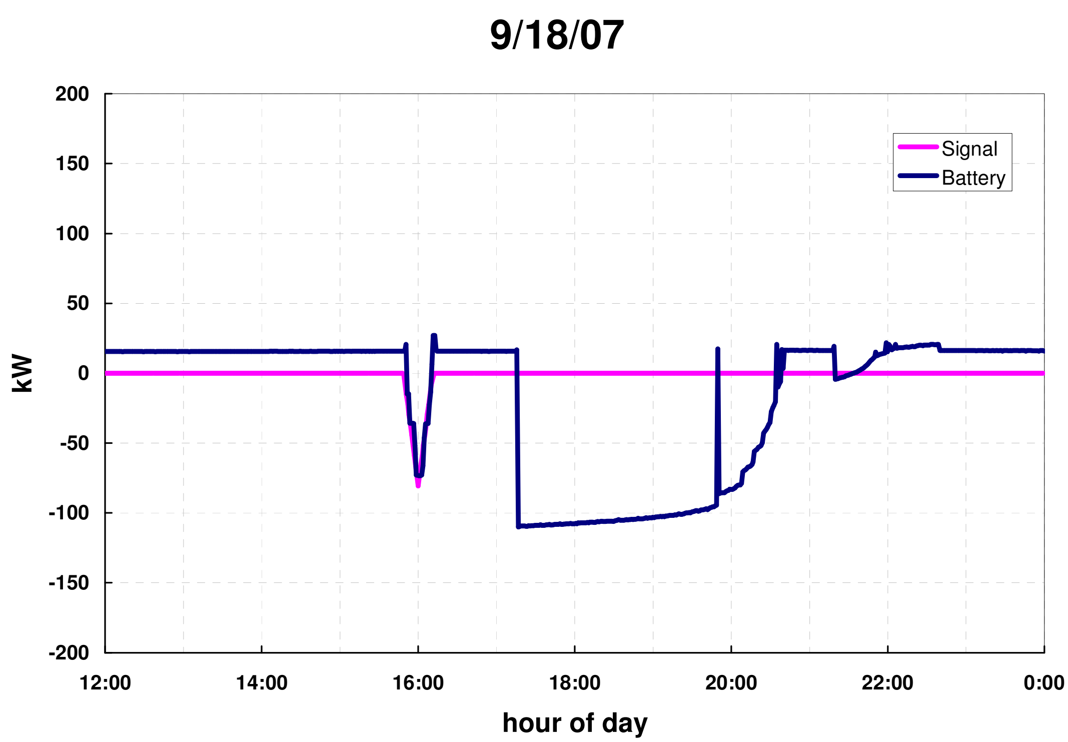


Figure A-14. Afternoon Results 9/18/07

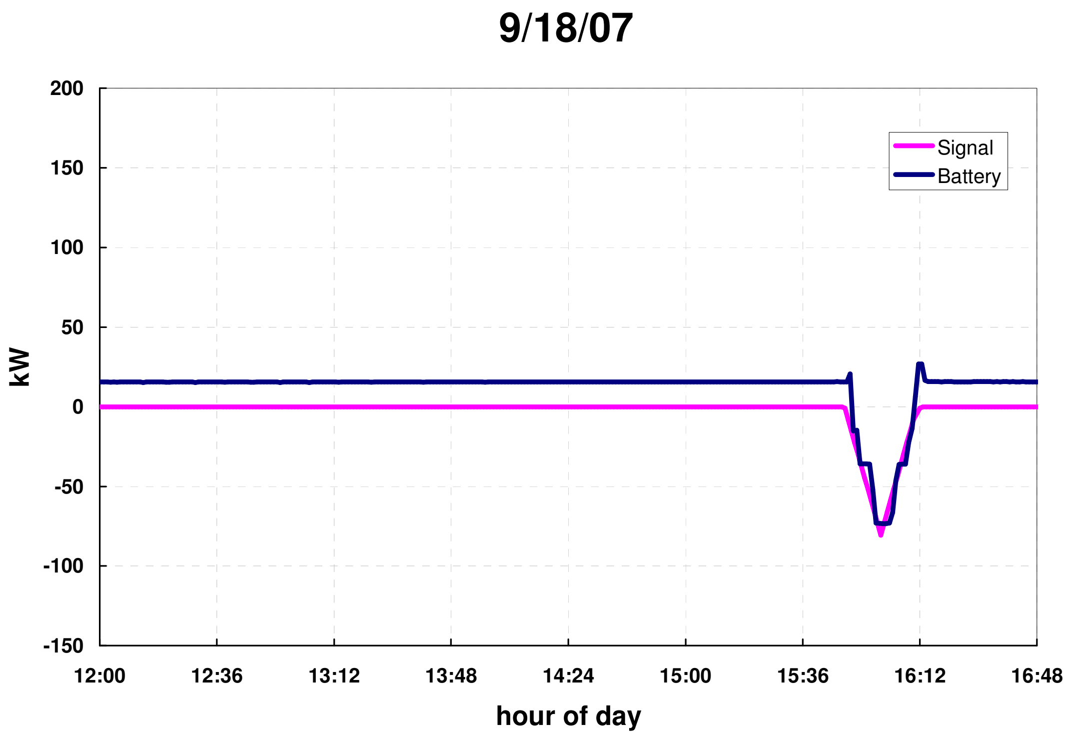
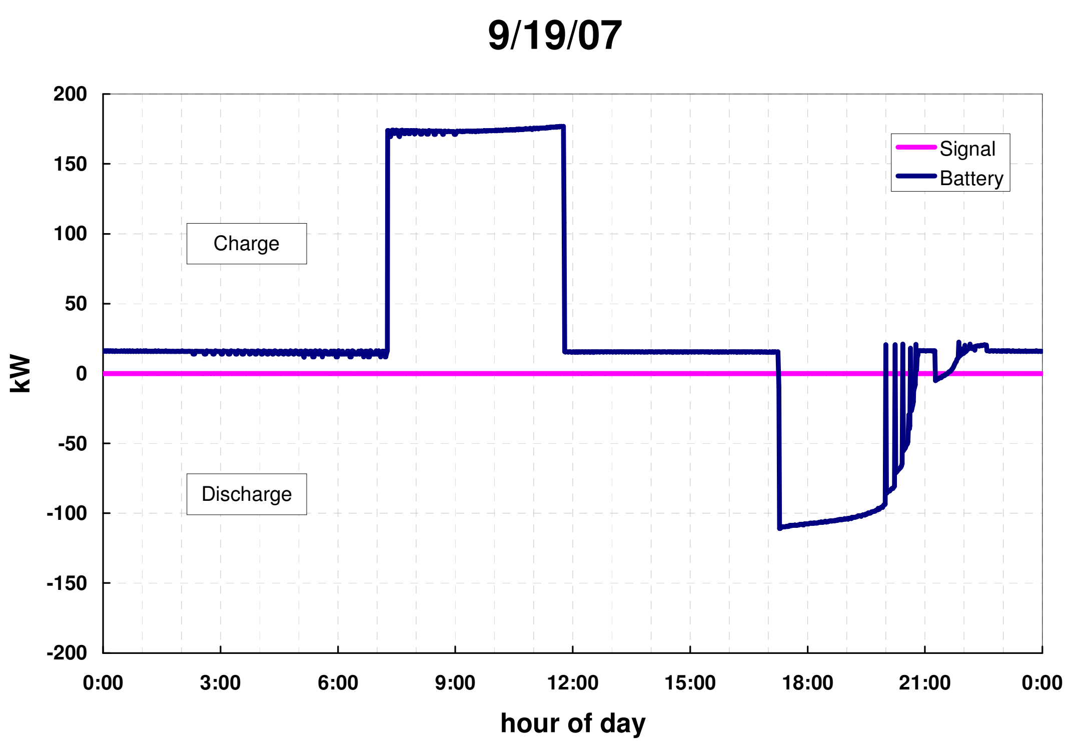


Figure A-15. Load Following Discharge 9/18/07



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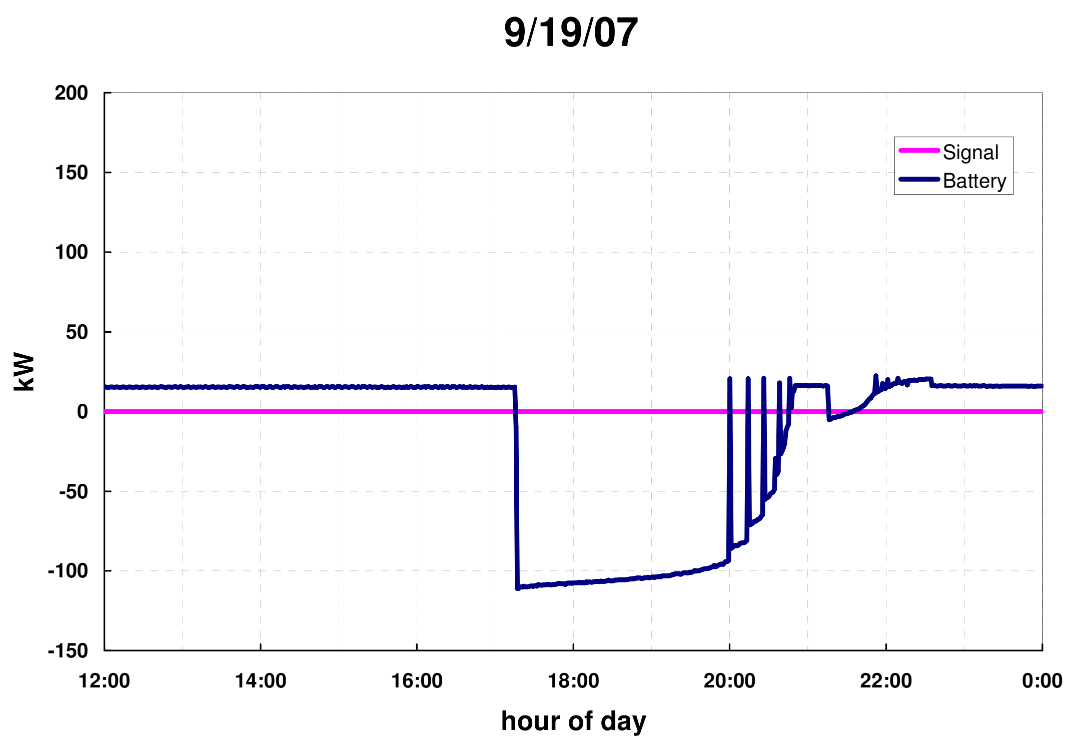

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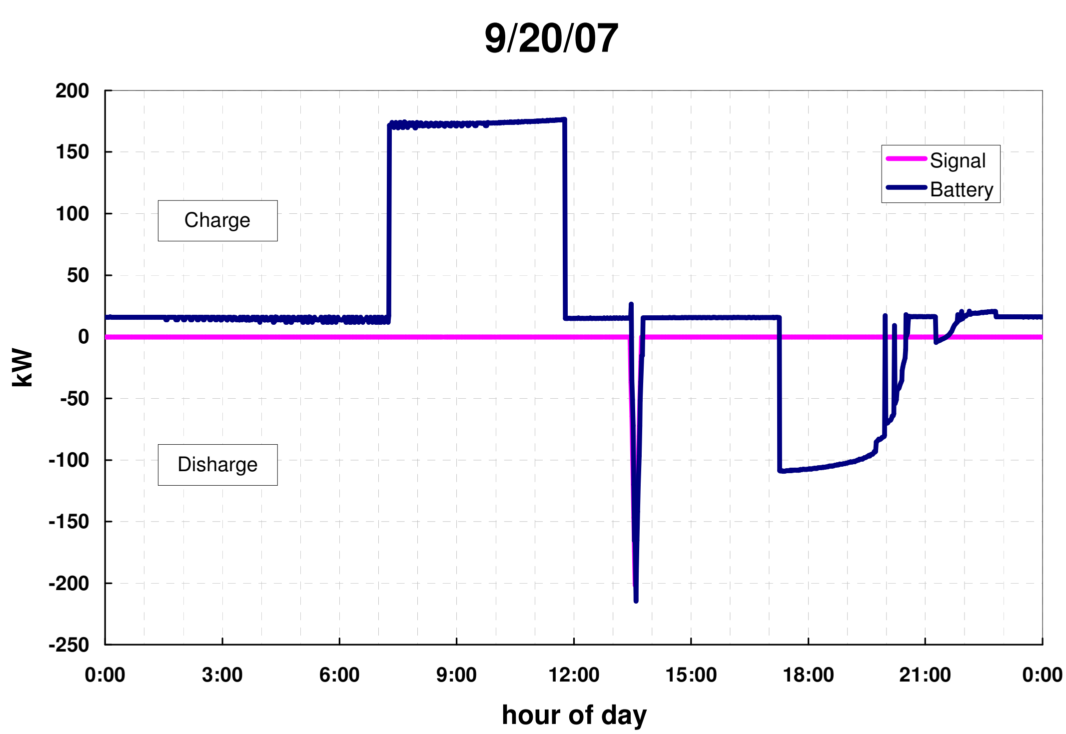

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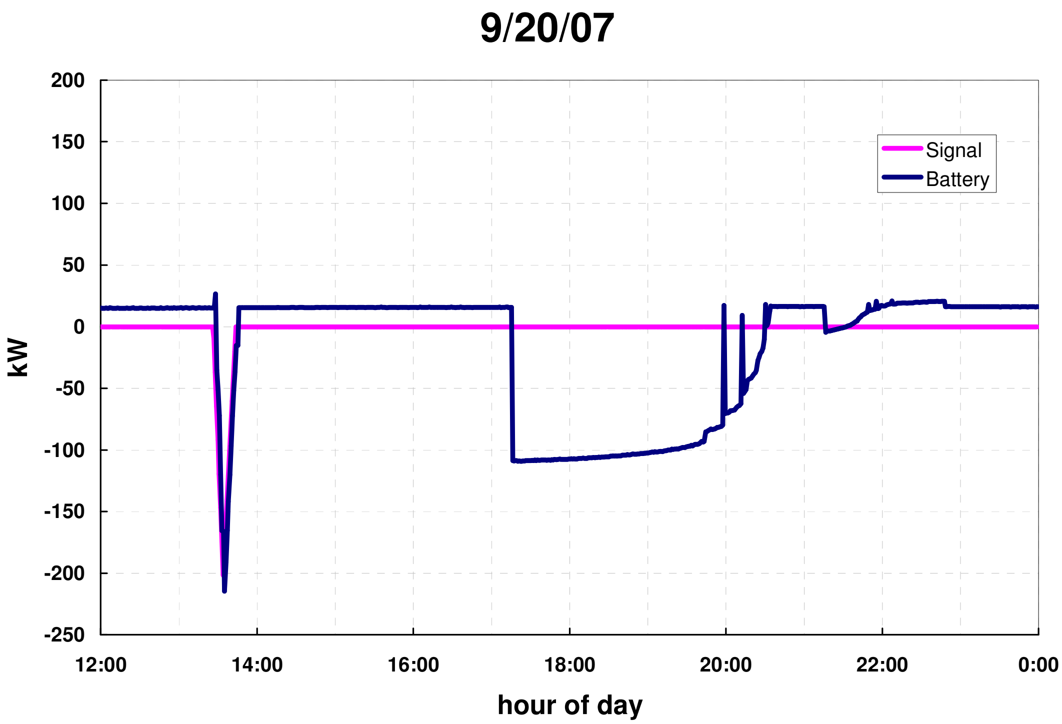

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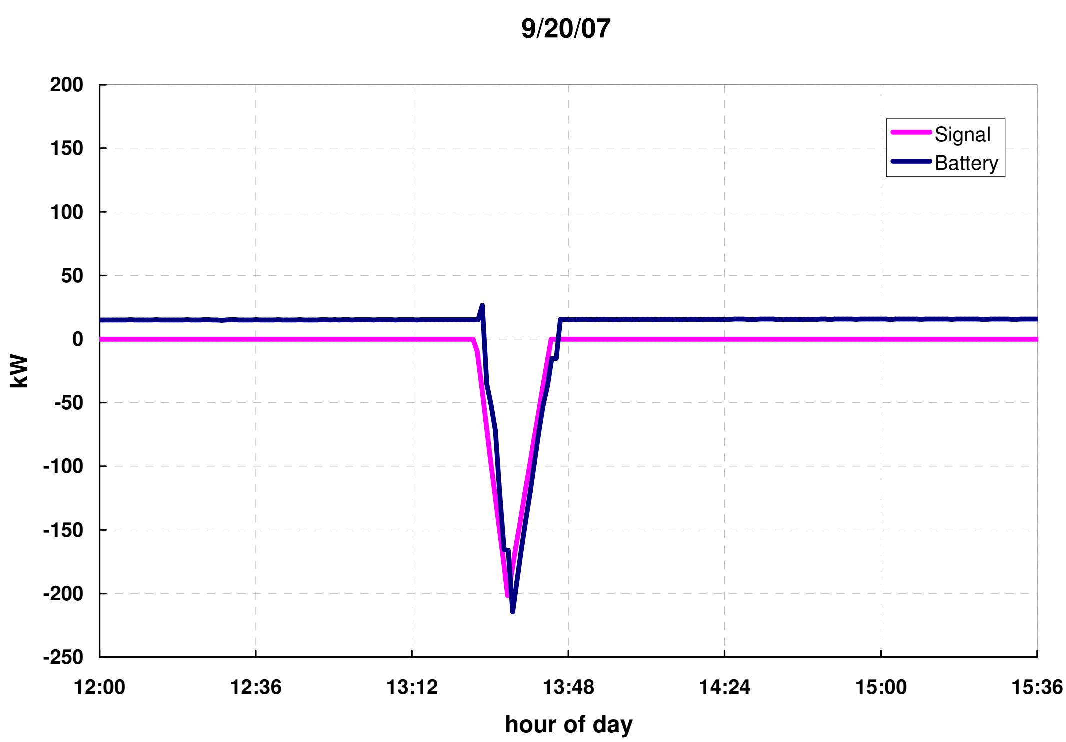

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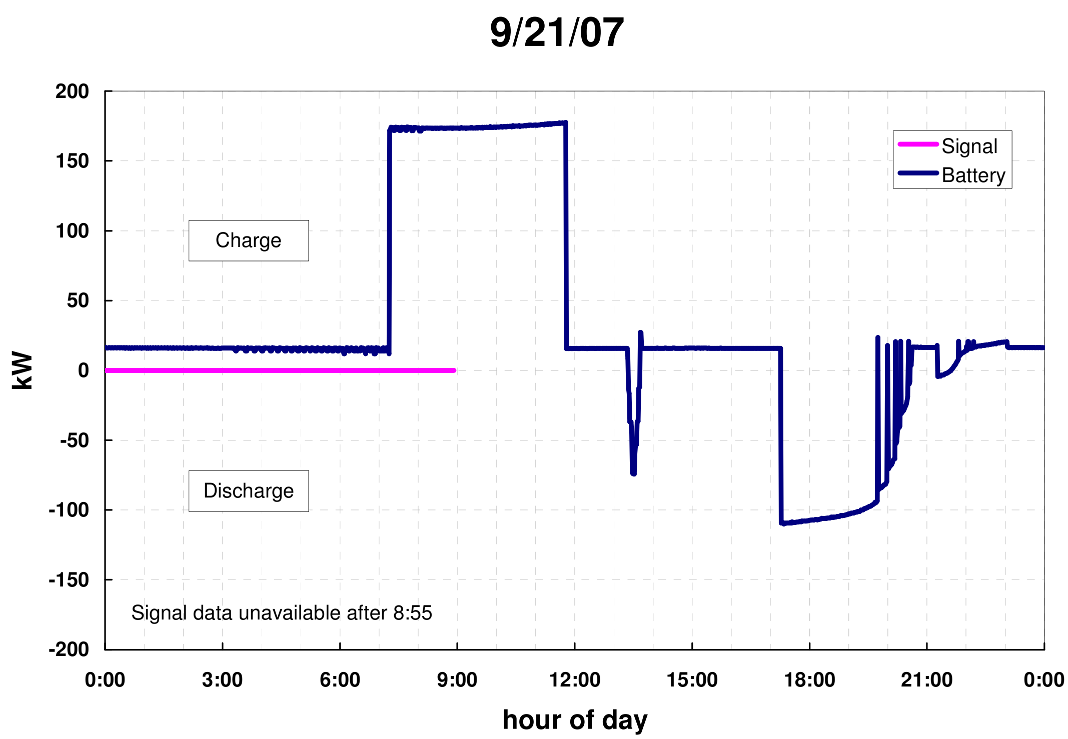

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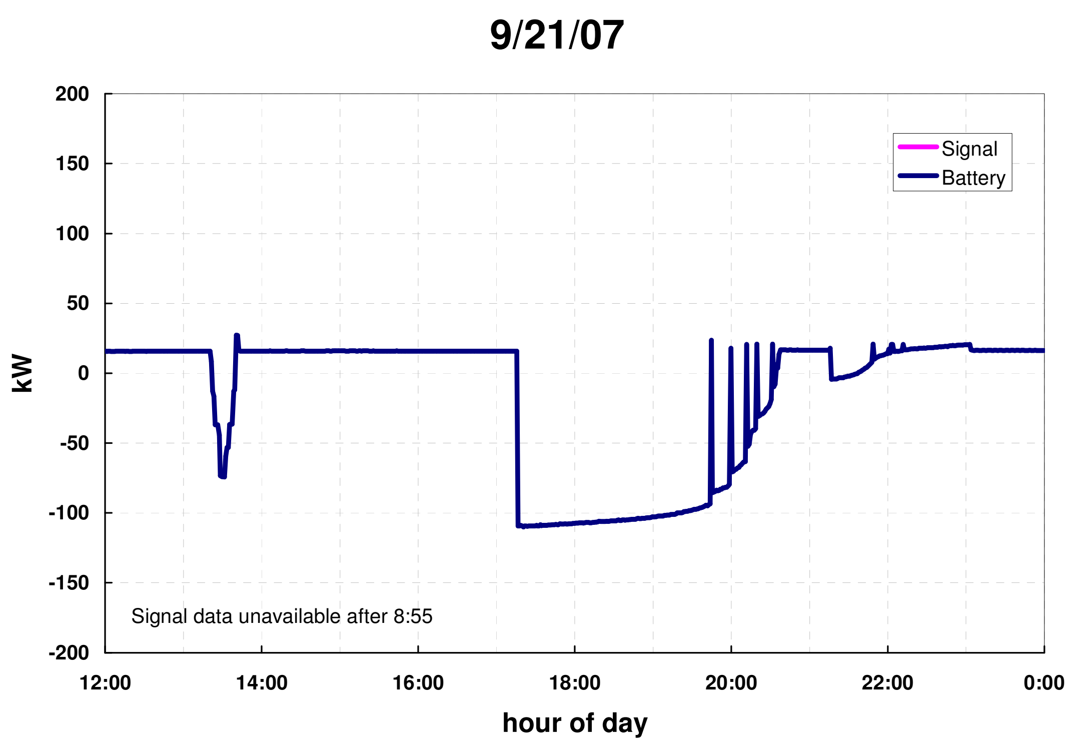

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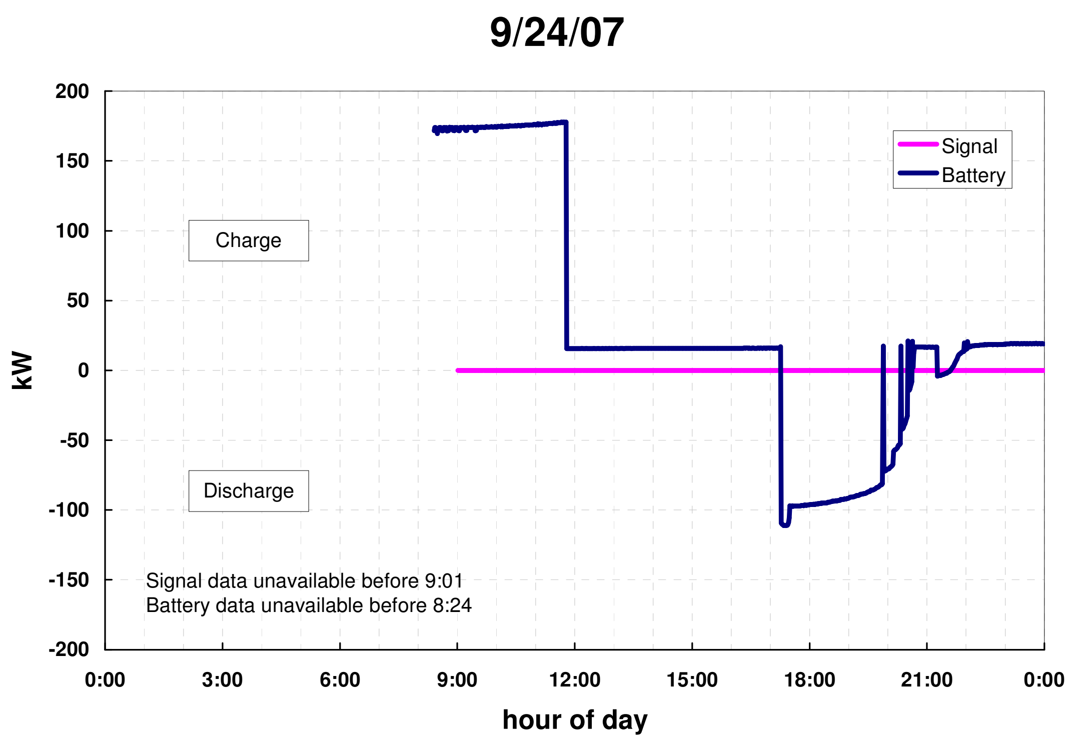

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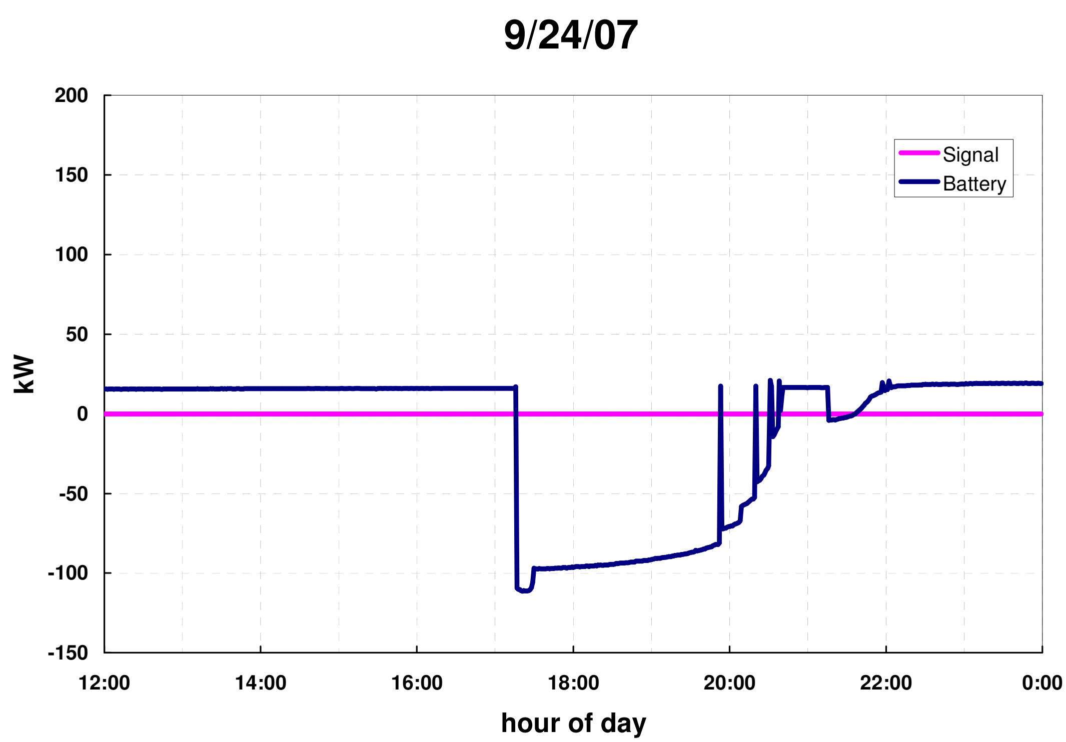

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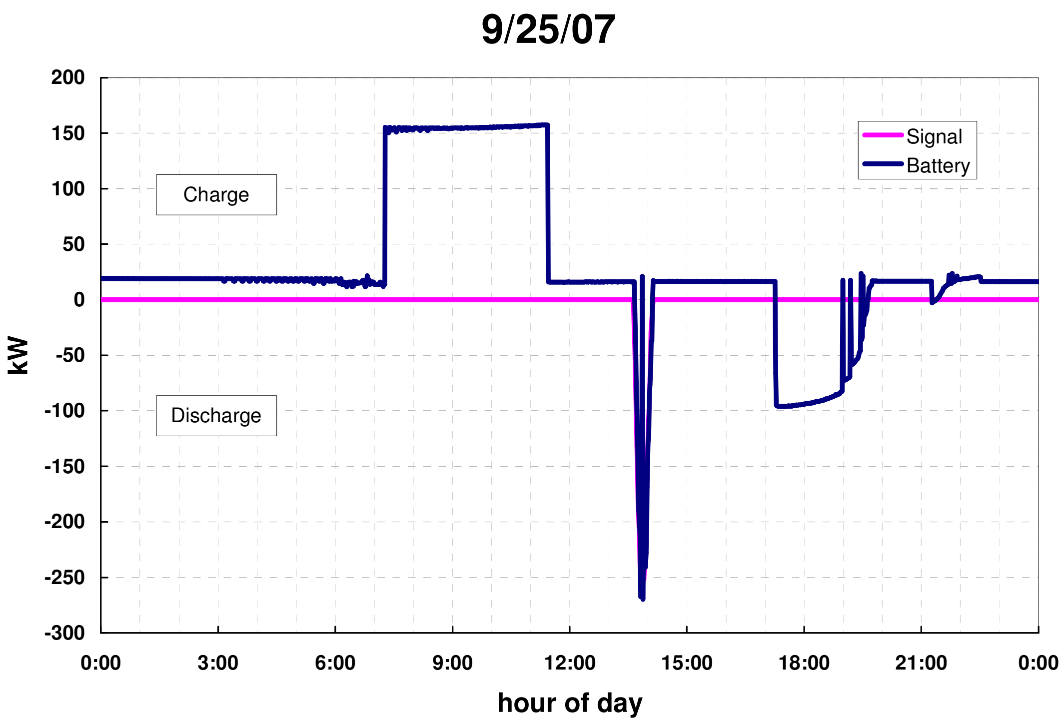

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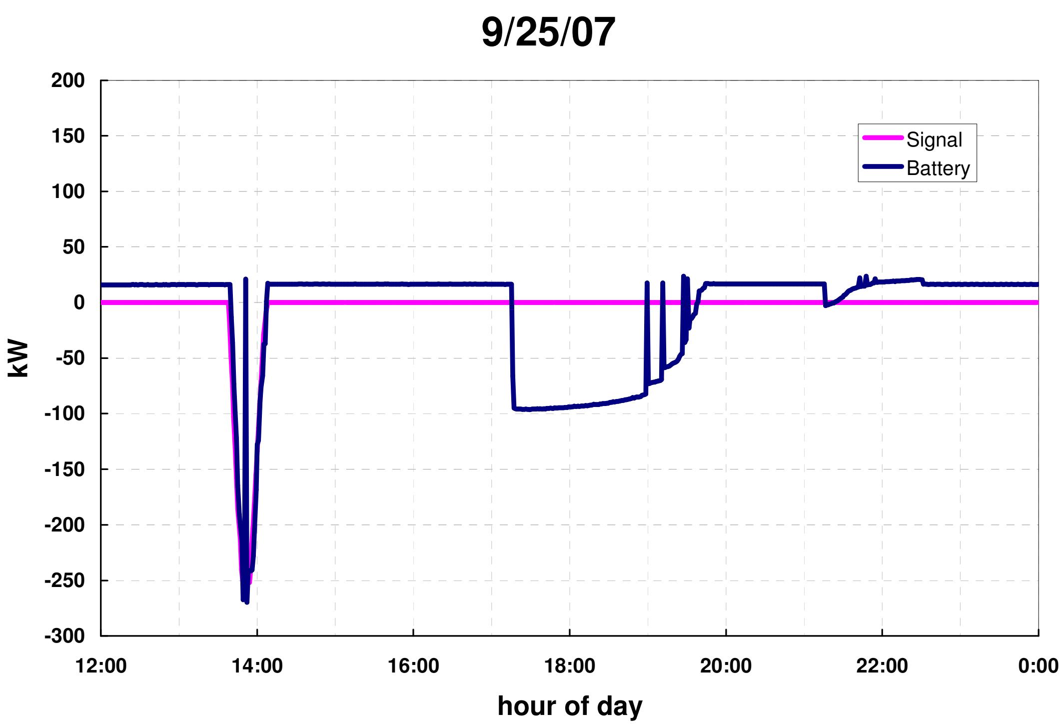

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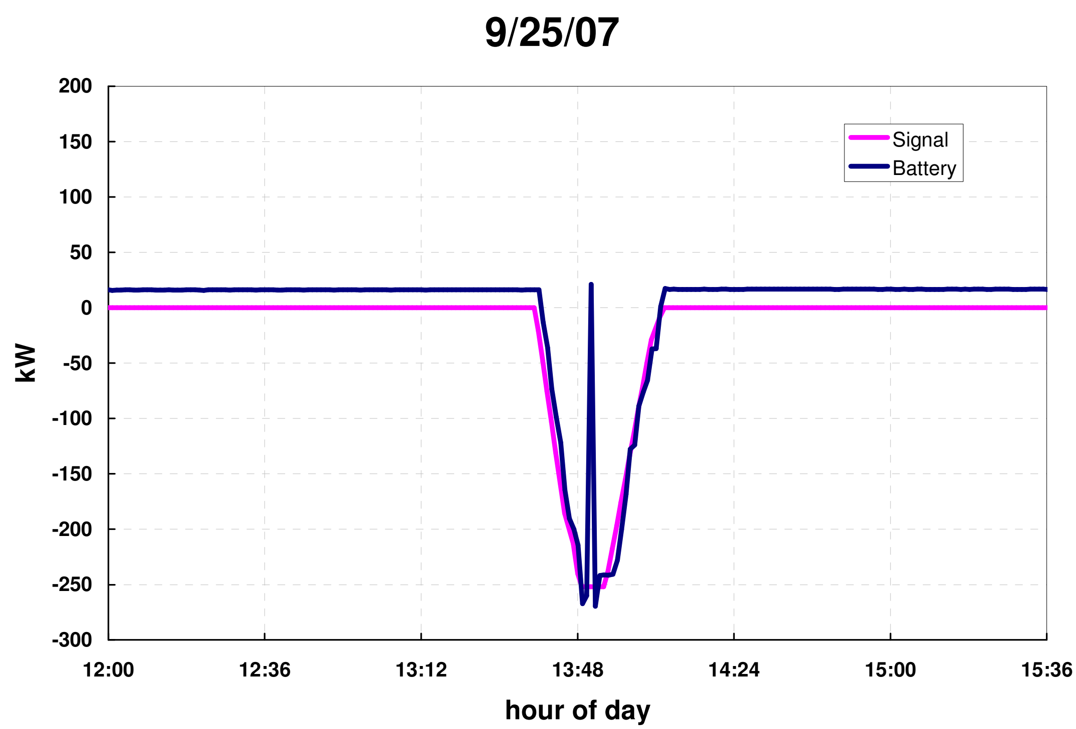

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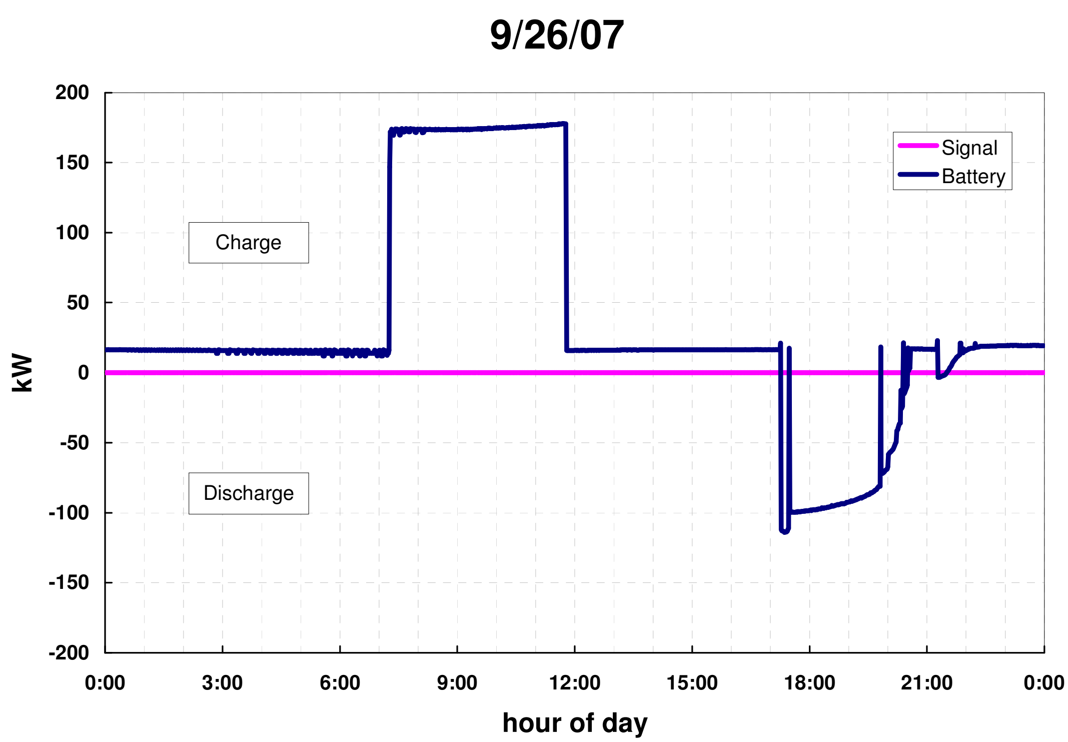

Figure A-28. Diurnal Results 9/26/07

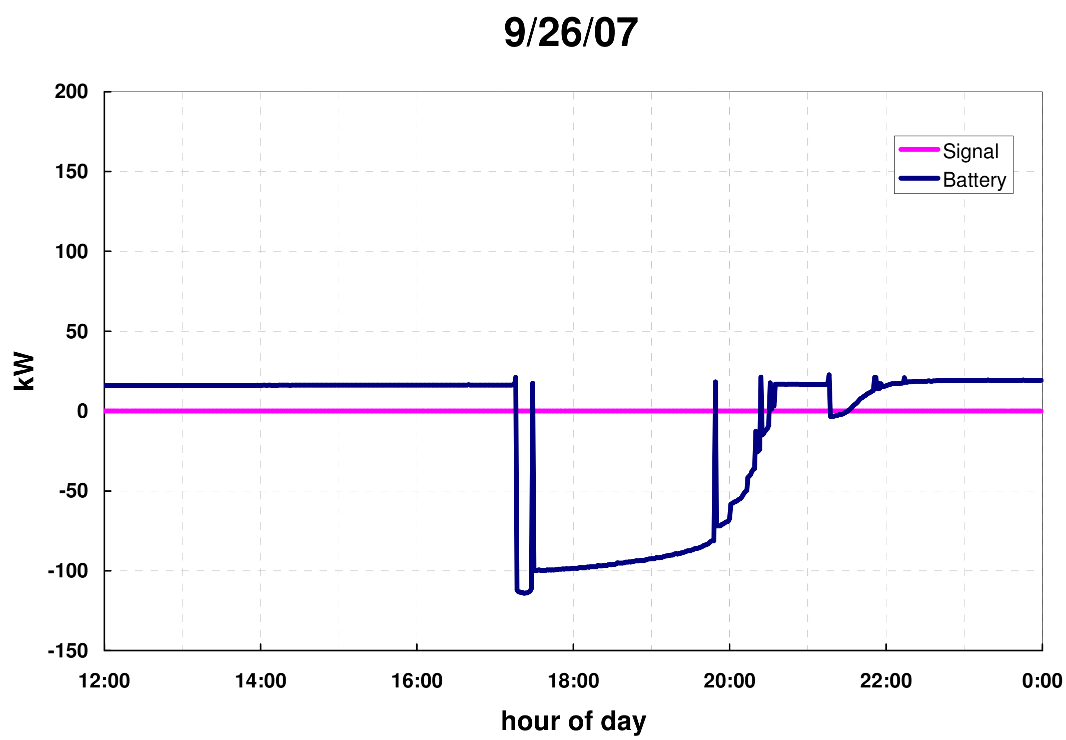

Figure A-29. Afternoon Results 9/26/07

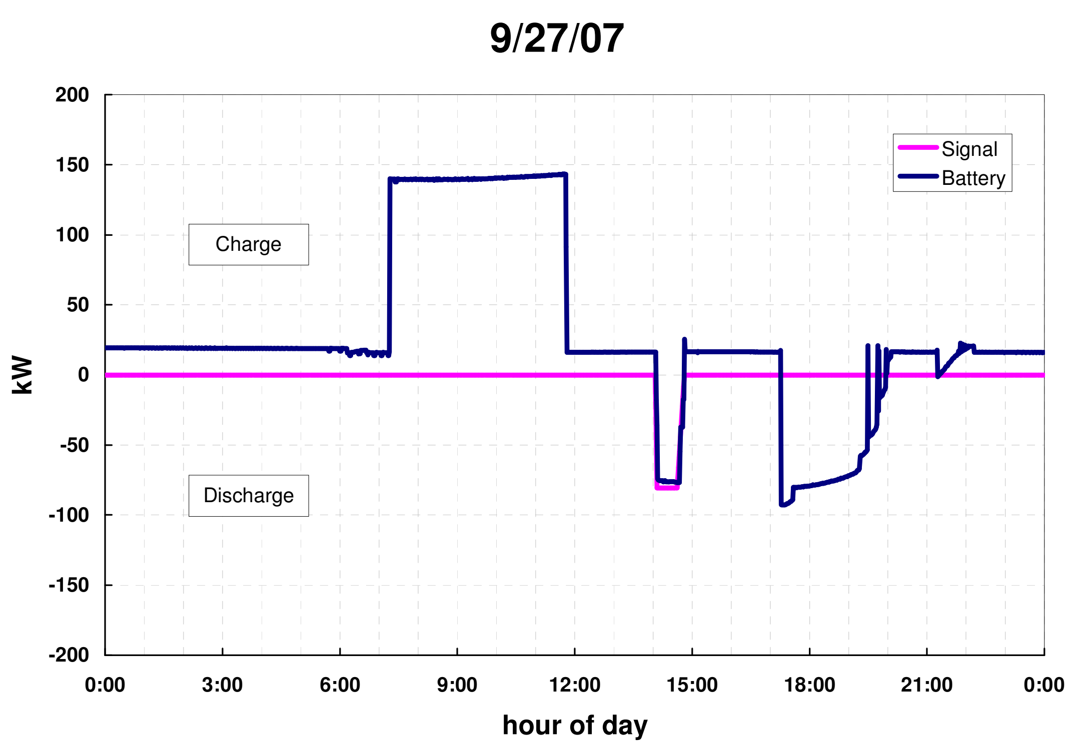

Figure A-30. Diurnal Results 9/27/07

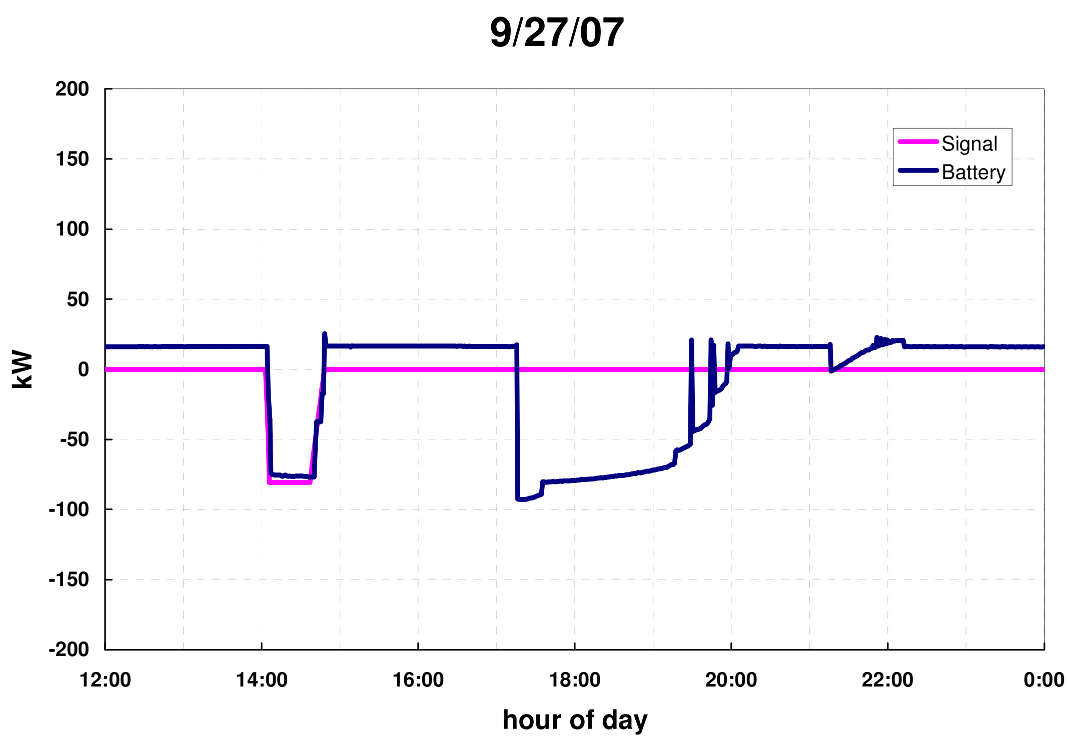

Figure A-31. Afternoon Results 9/27/07

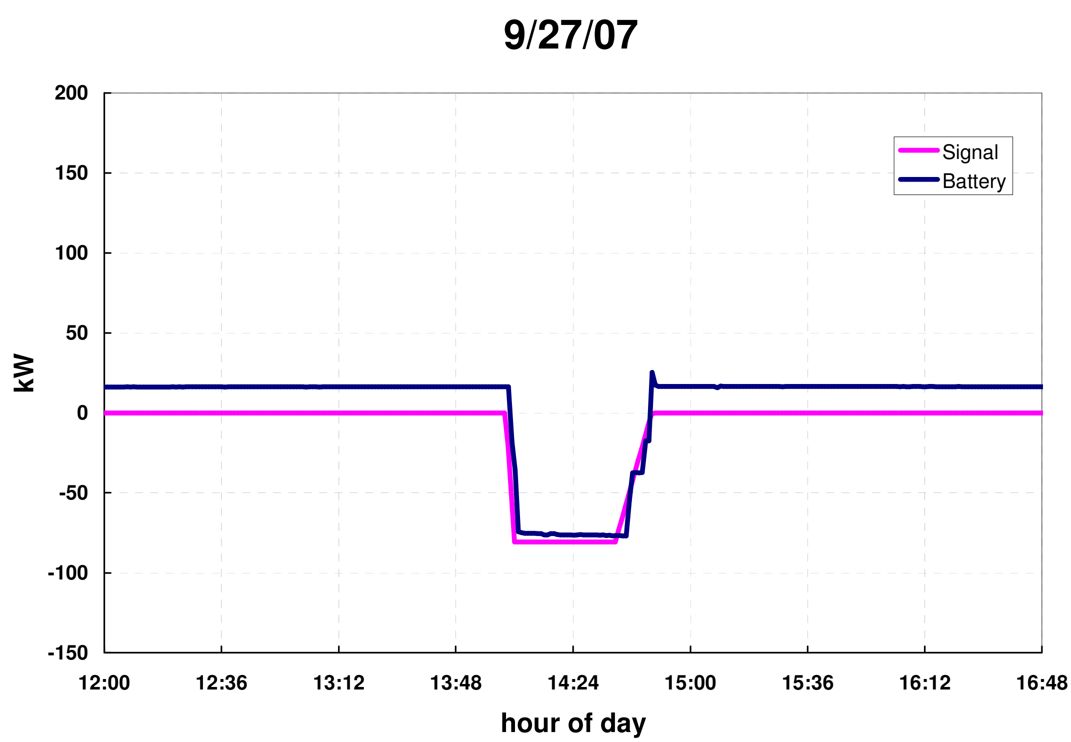

Figure A-32. Load Following Discharge 9/27/07

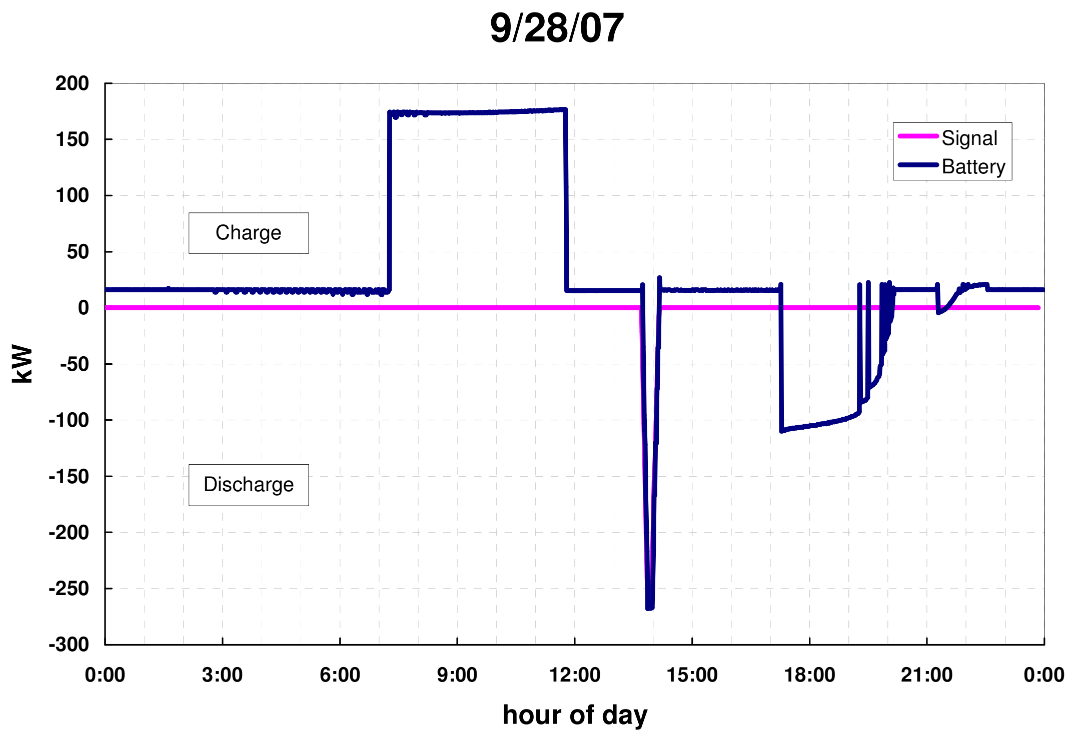

Figure A-33. Diurnal Results 9/28/07

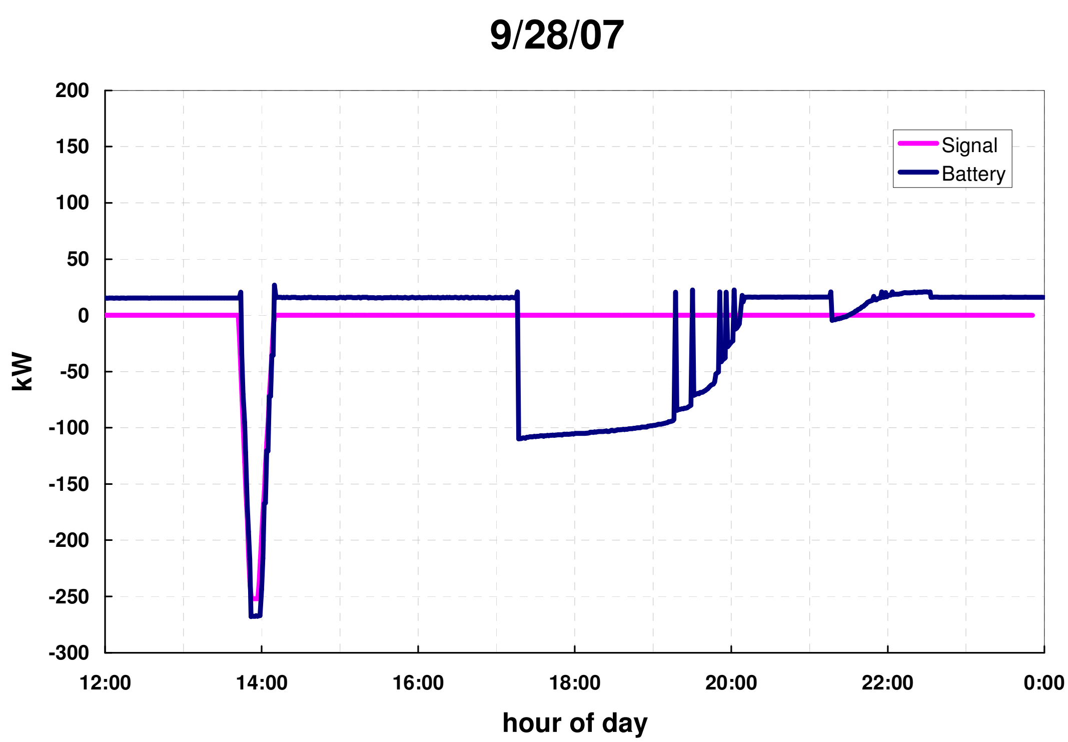

Figure A-34. Afternoon Results 9/28/07

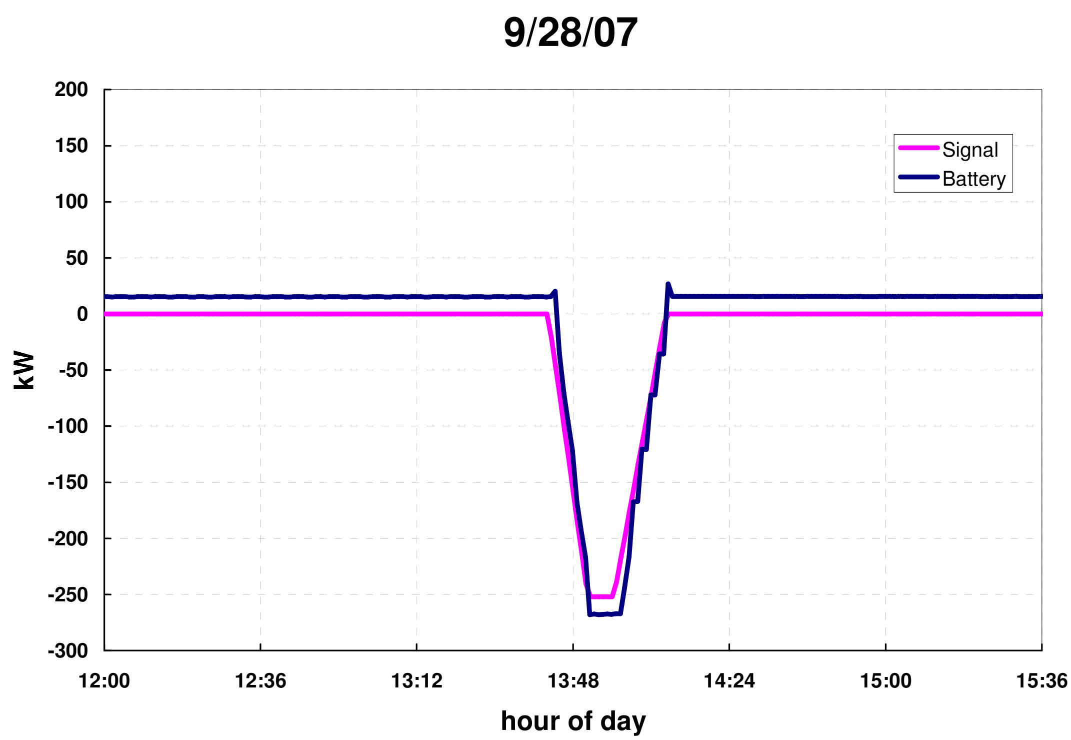

Figure A-35. Load Following Discharge 9/28/07

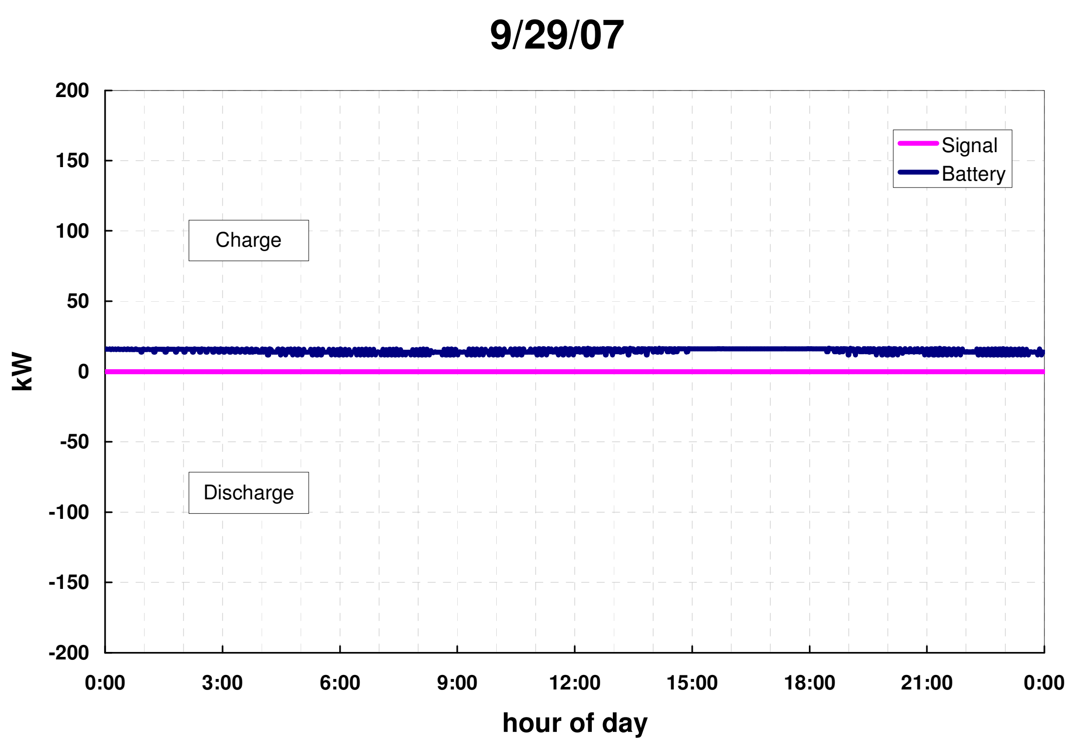

Figure A-36. Diurnal Results 9/29/07

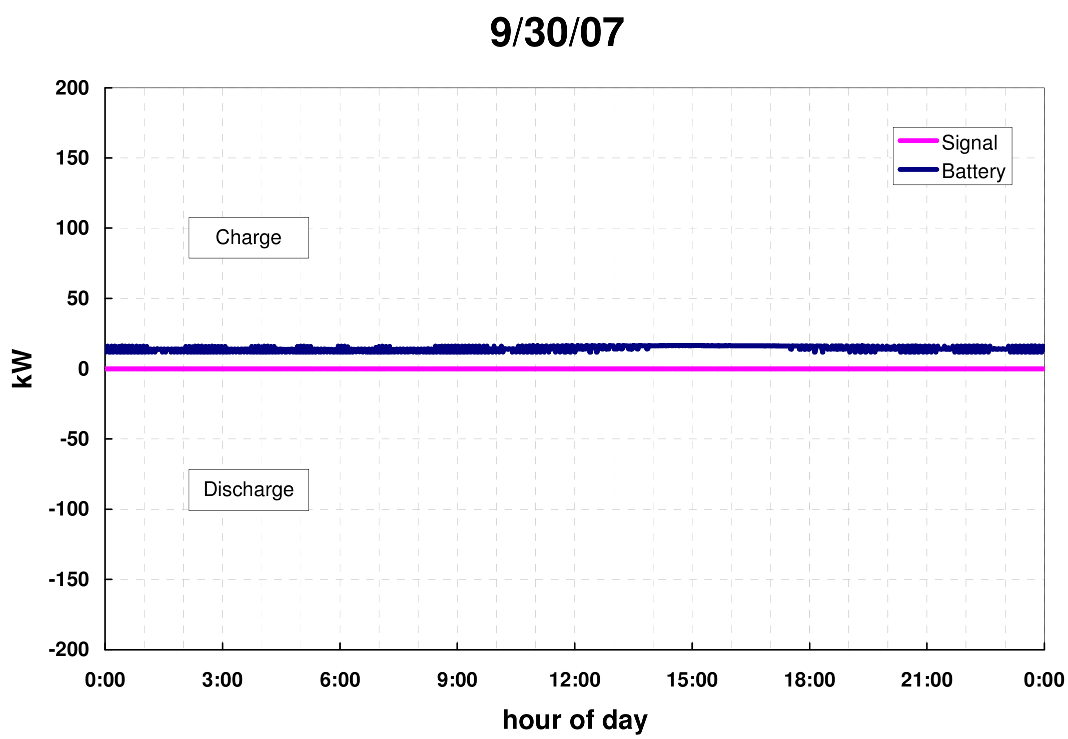

Figure A-37. Diurnal Results 9/30/07

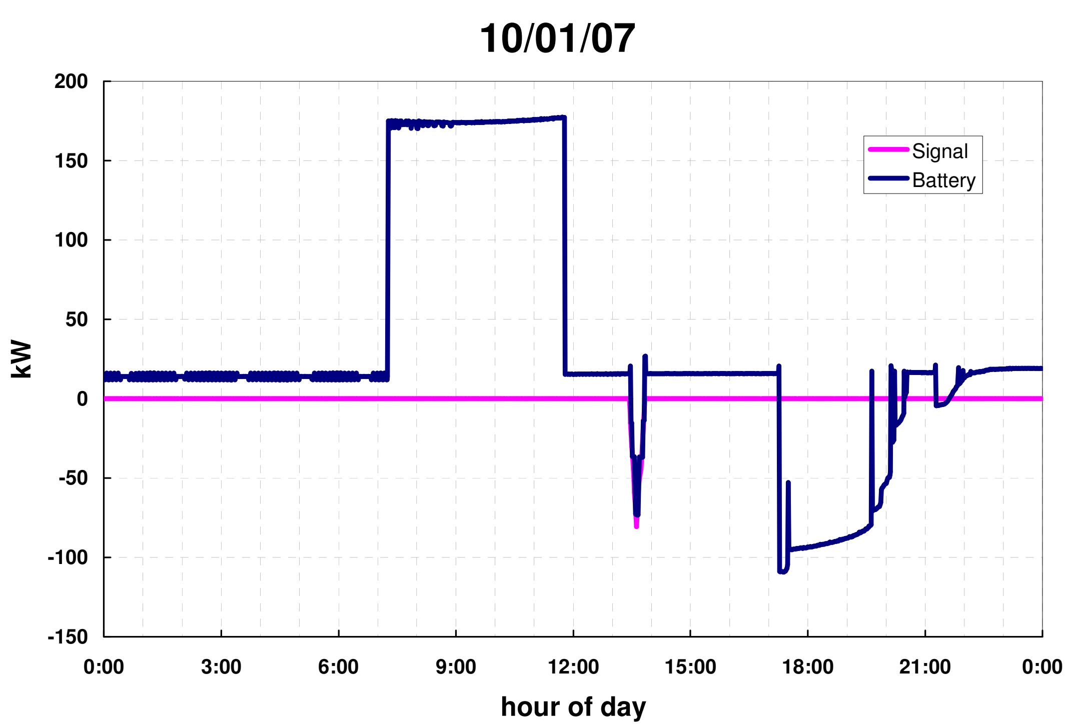

Figure A-38. Diurnal Results 10/01/07

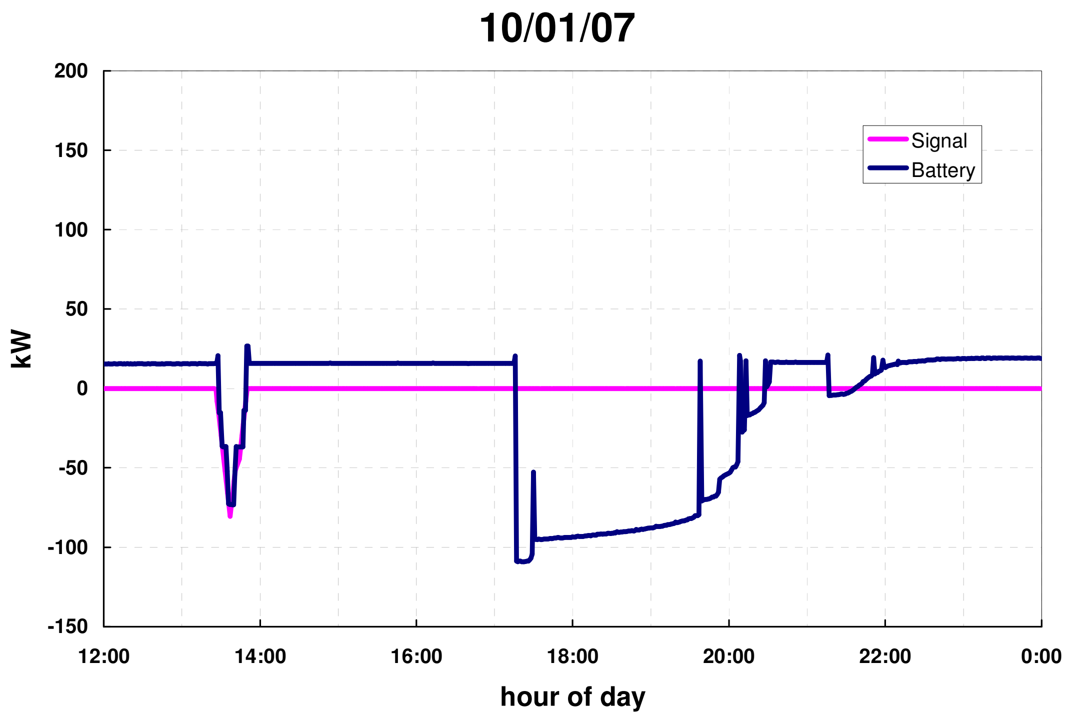

Figure A-39. Afternoon Results 10/01/07

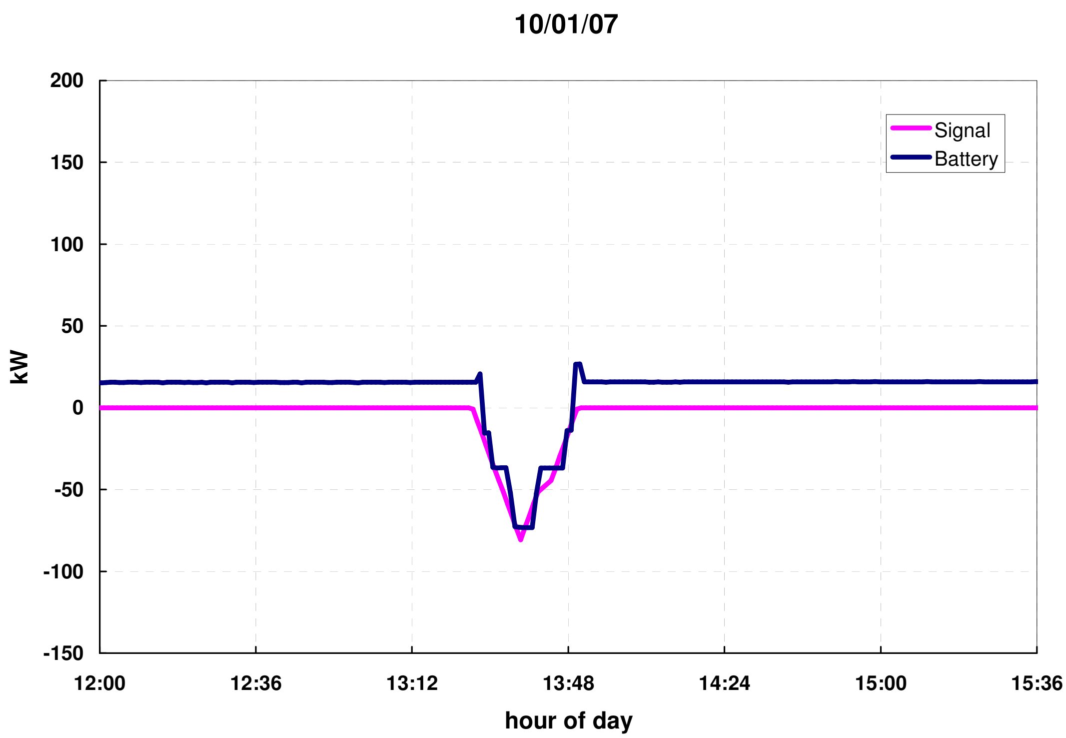

Figure A-40. Load Following Discharge 10/01/07

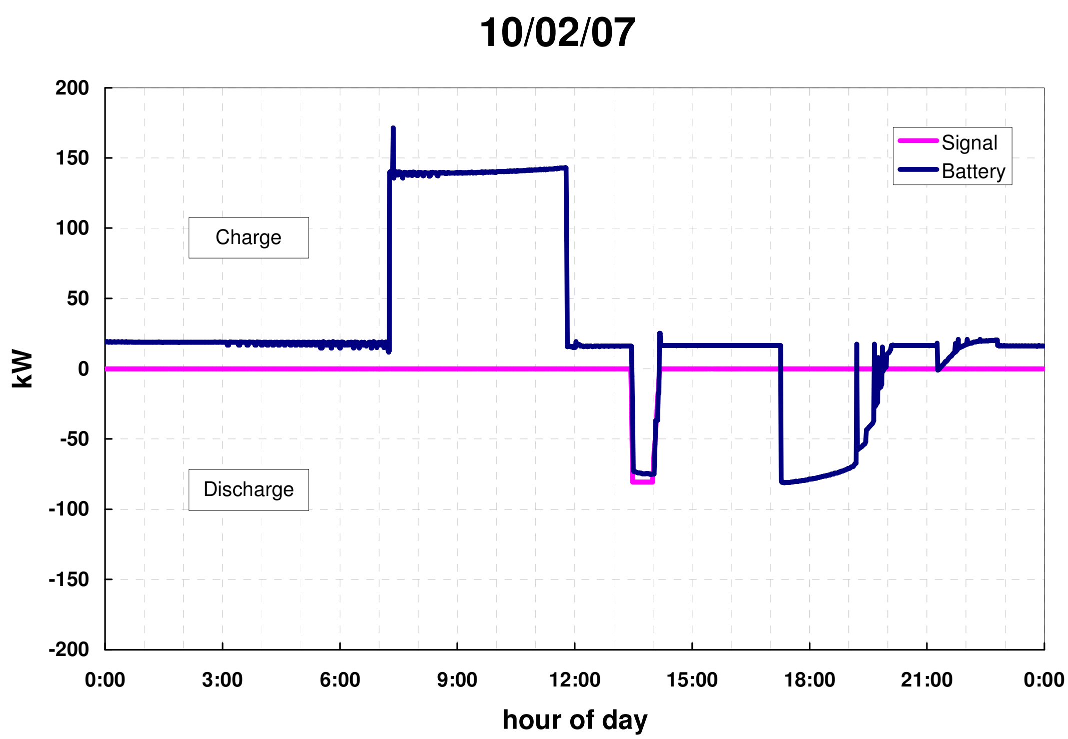

Figure A-41. Diurnal Results 10/02/07

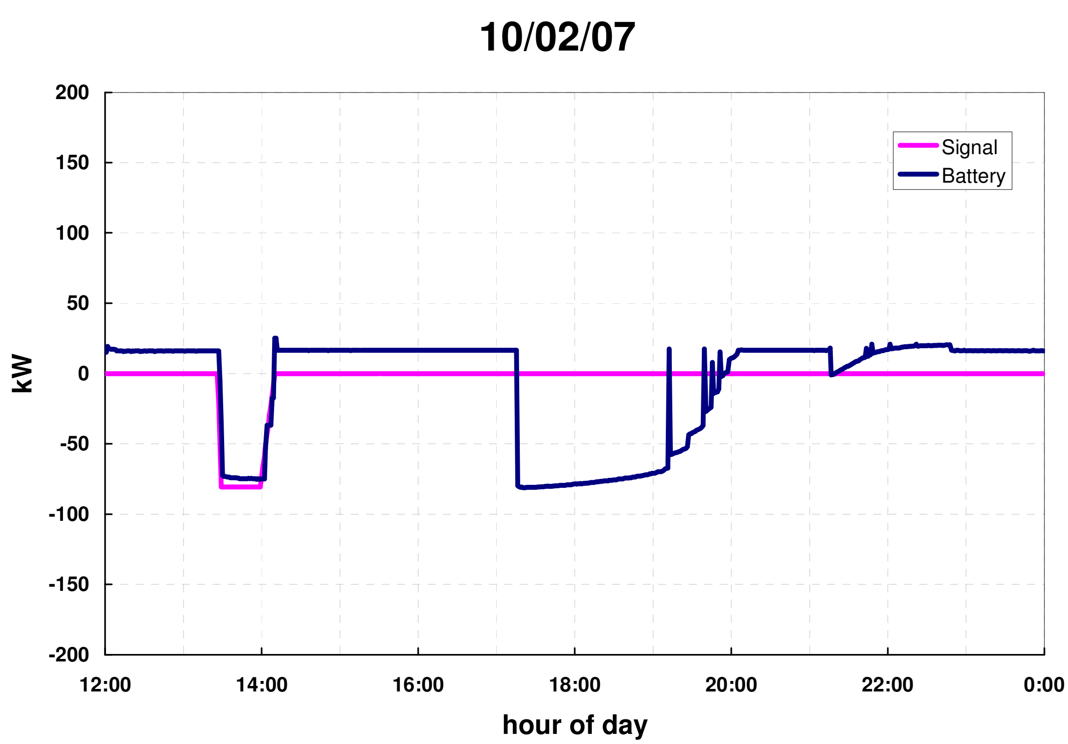

Figure A-42. Afternoon Results 10/02/07

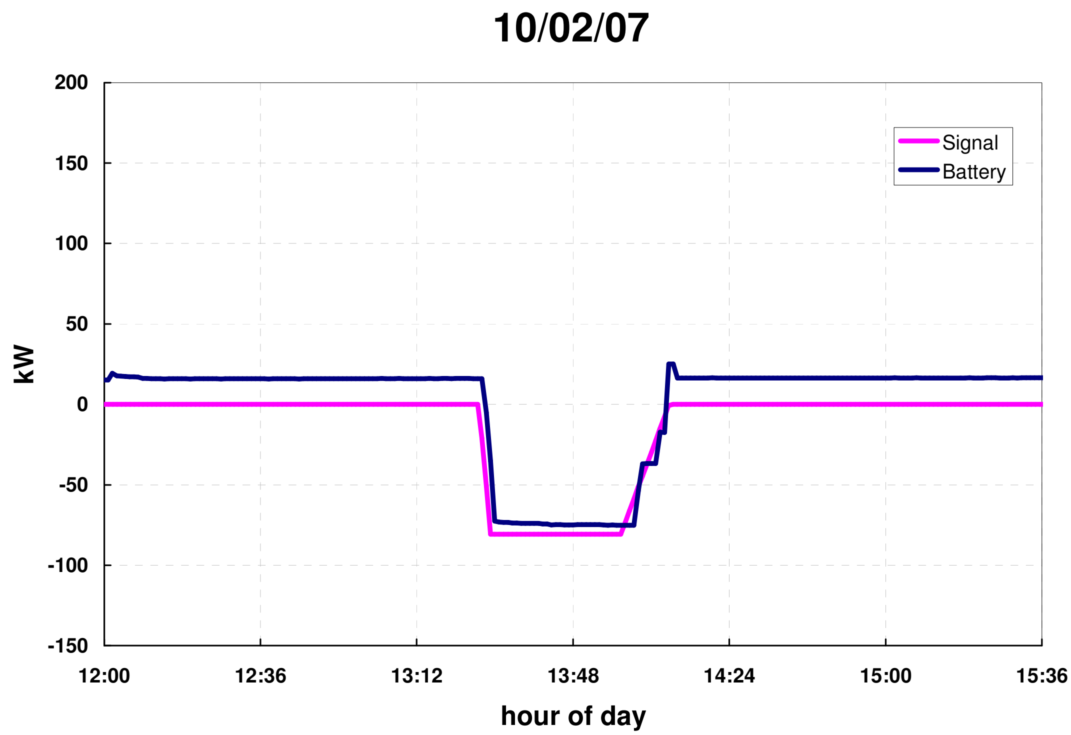

Figure A-43. Load Following Discharge 10/02/07

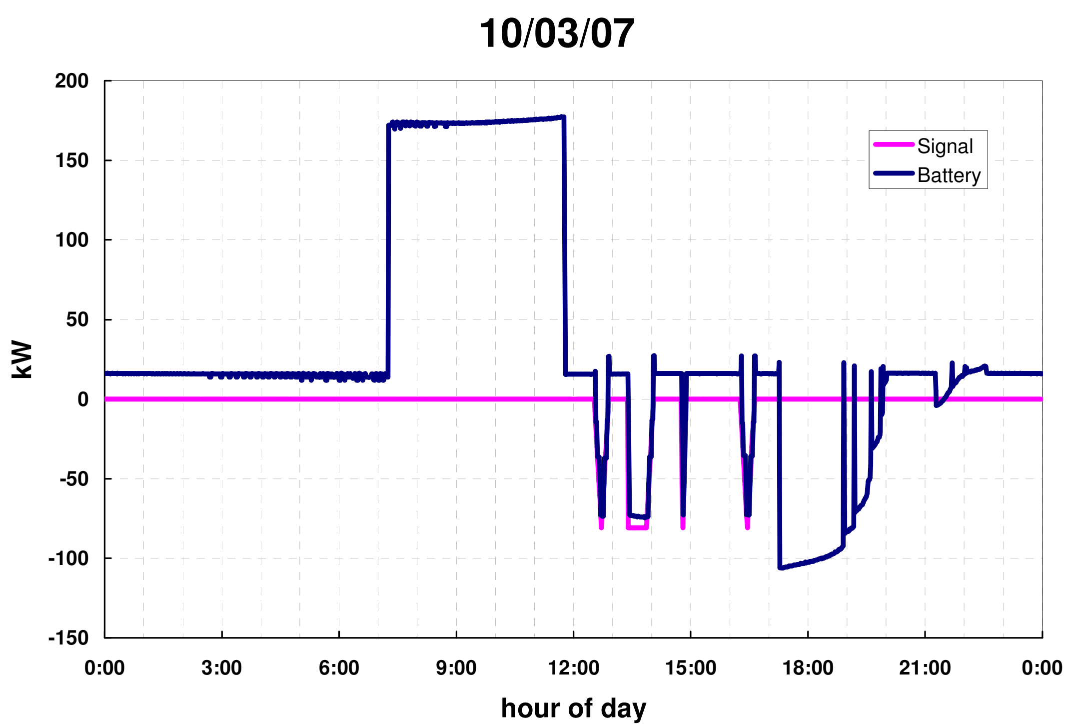

Figure A-44. Diurnal Results 10/03/07

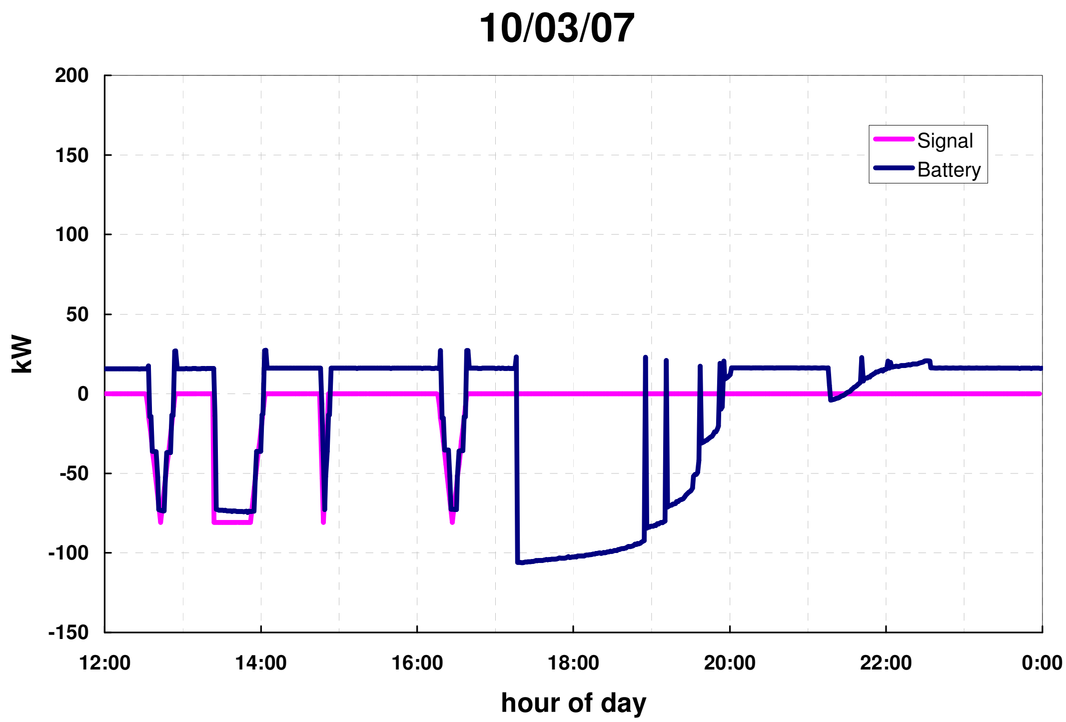

Figure A-45. Afternoon Results 10/03/07

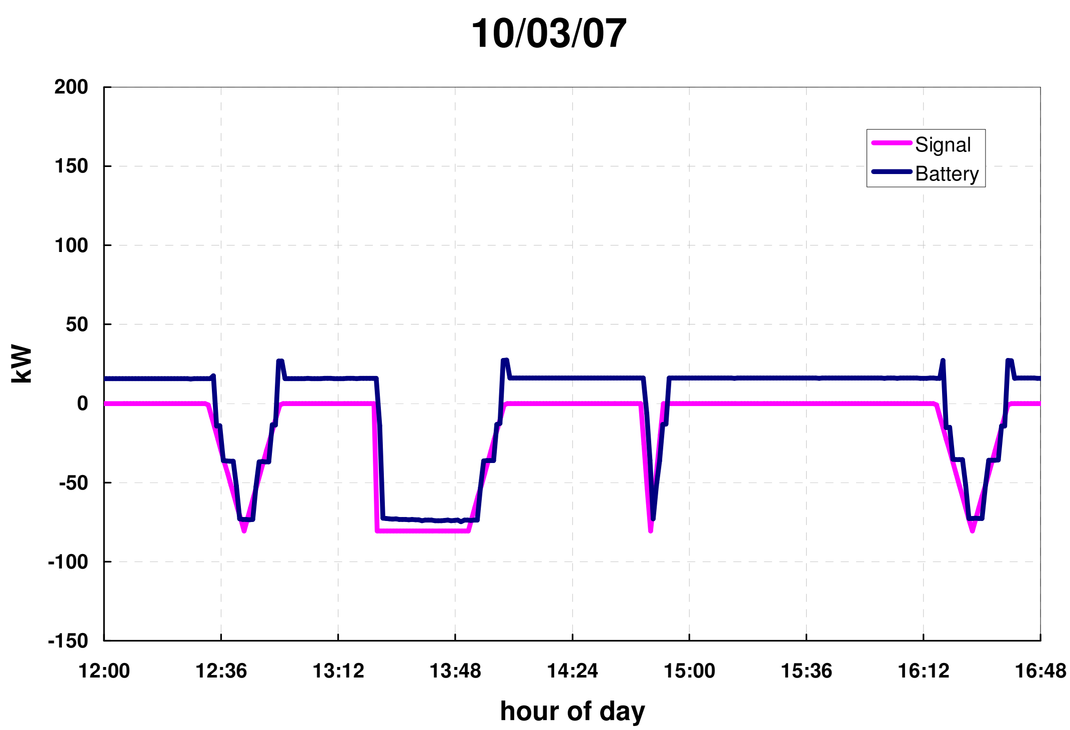

Figure A-46. Multiple Load Following Discharges 10/03/07

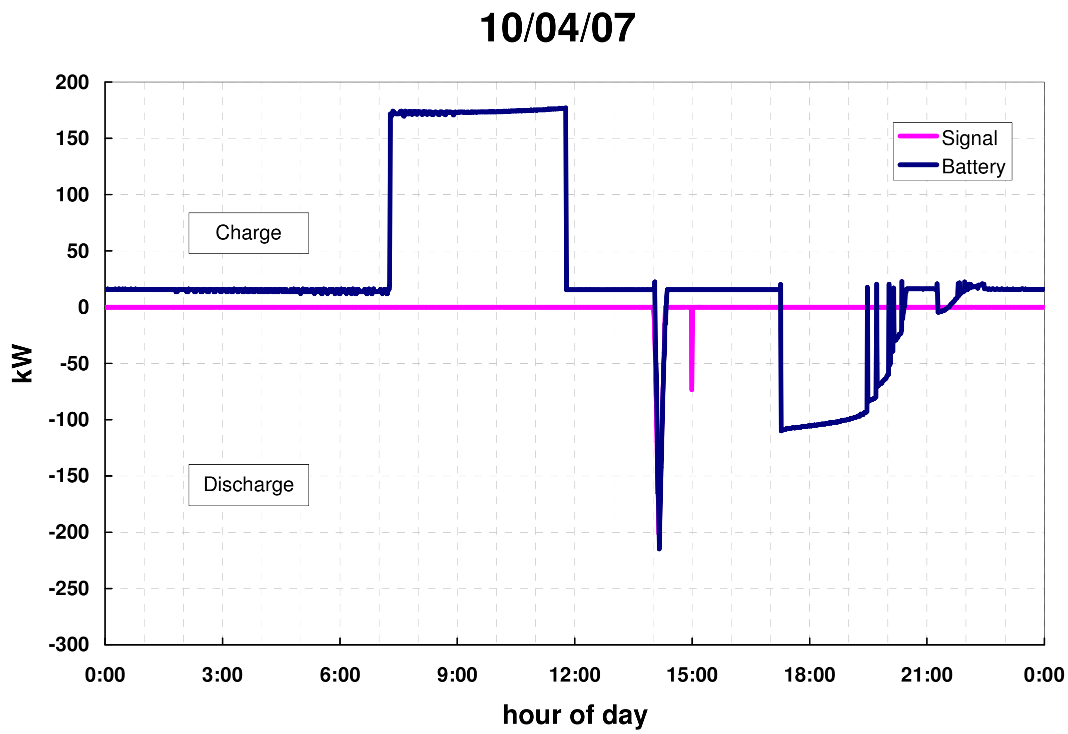

Figure A-47. Diurnal Results 10/04/07

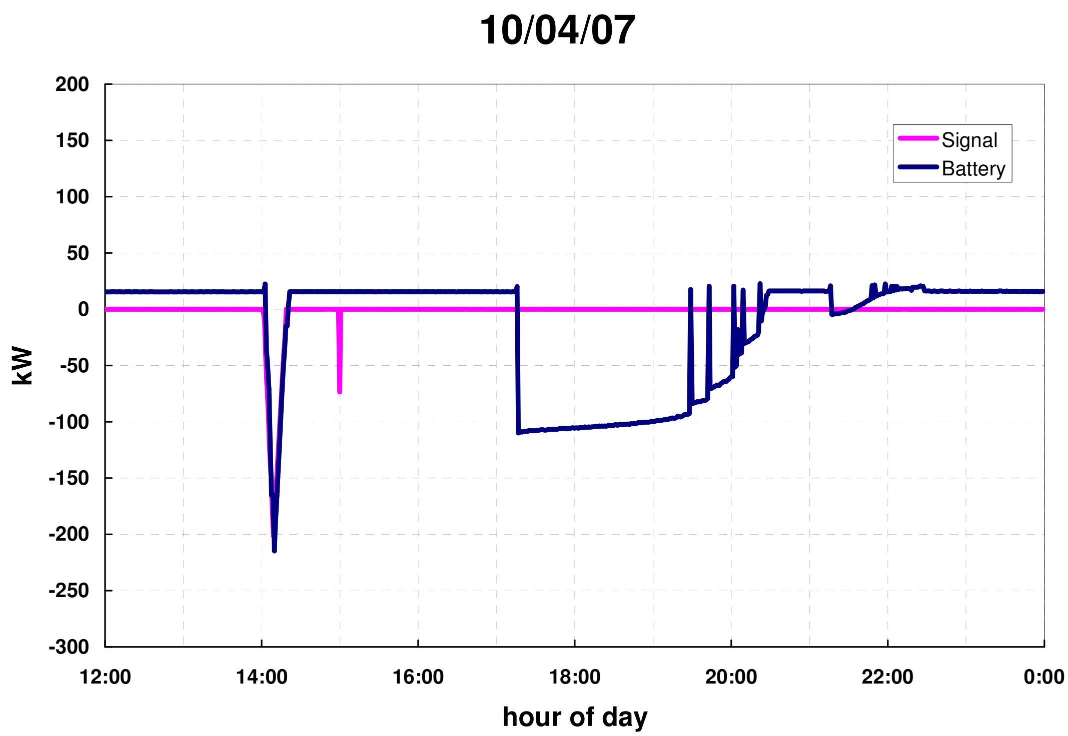

Figure A-48. Afternoon Results 10/04/07

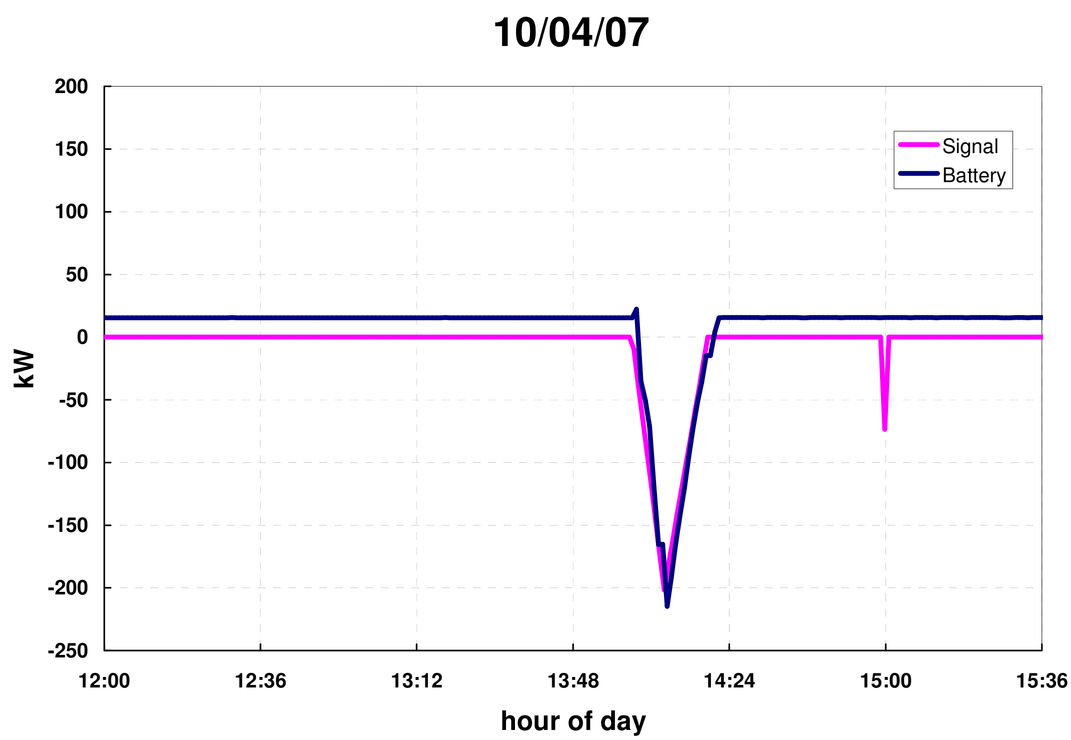

Figure A-49. Load Following Discharge 10/04/07

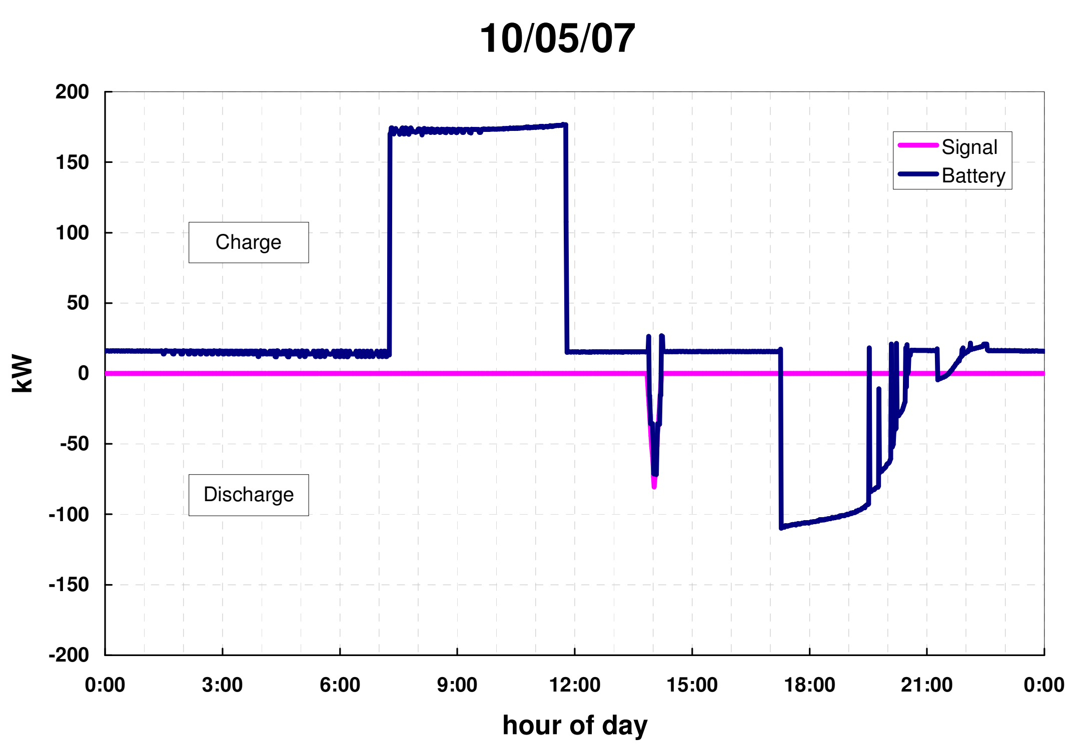

Figure A-50. Diurnal Results 10/05/07

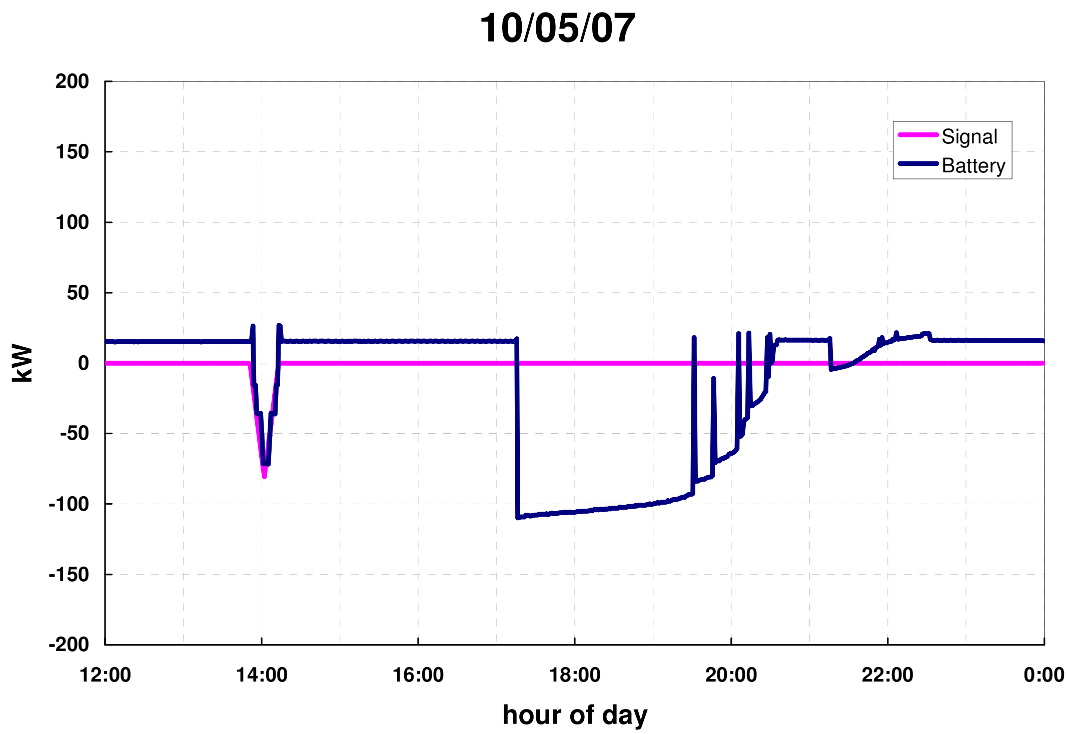

Figure A-51. Afternoon Results 10/05/07

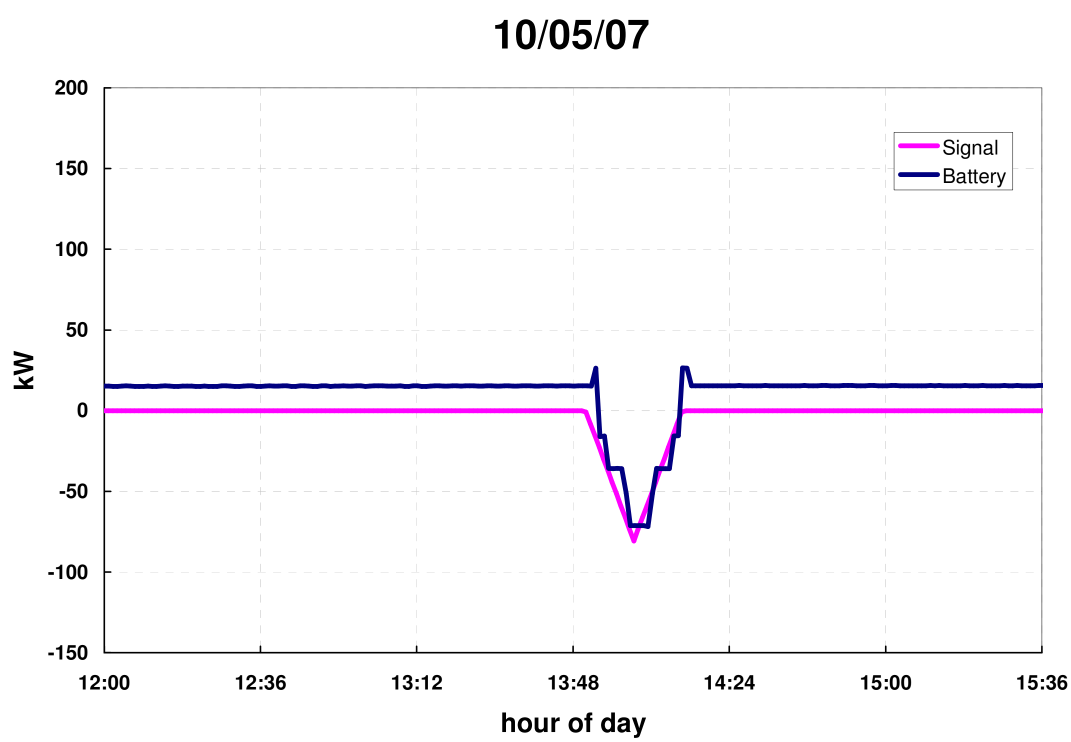

Figure A-52. Load Following Discharge 10/05/07

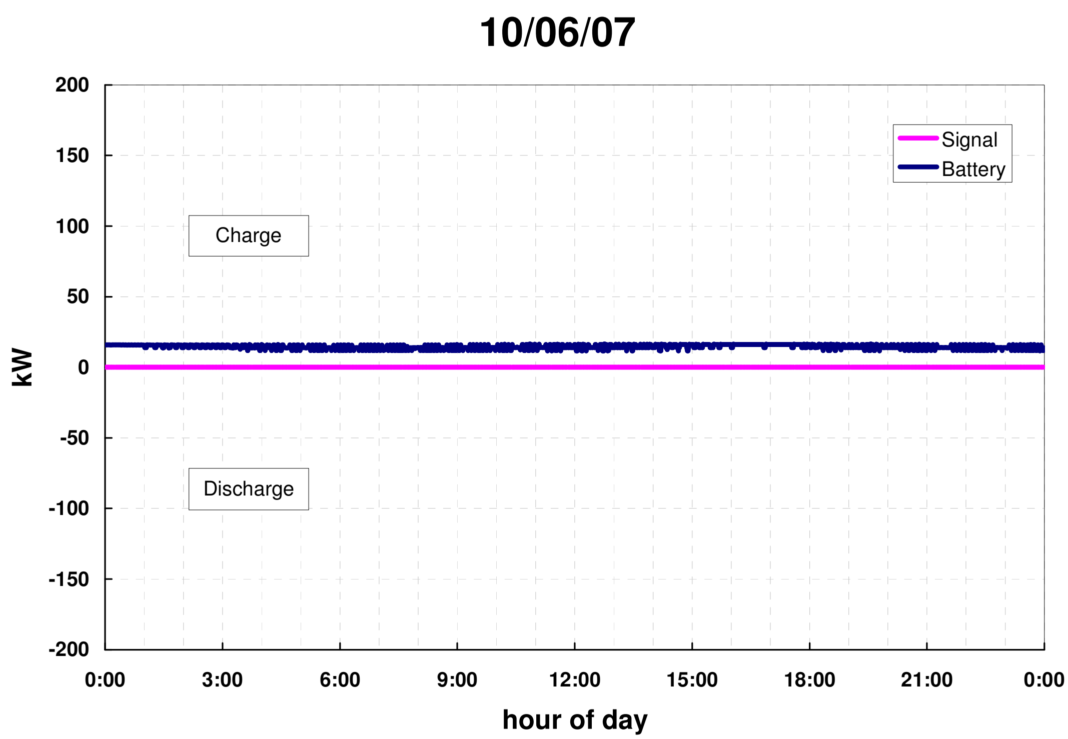

Figure A-53. Diurnal Results 10/06/07

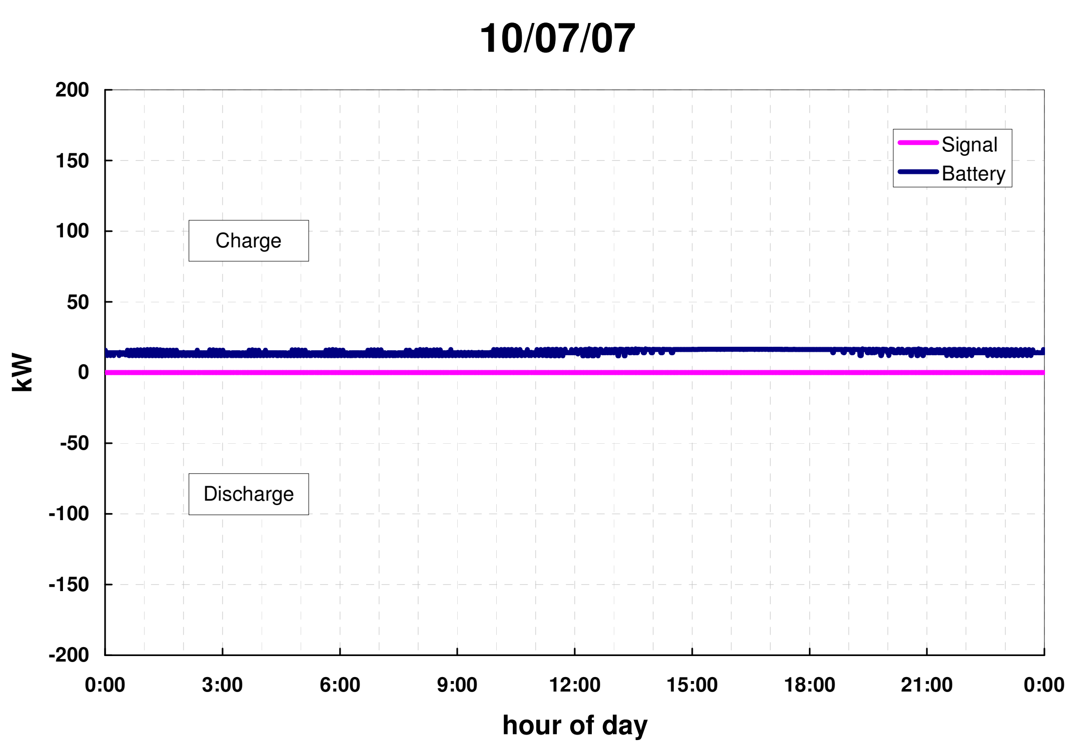

Figure A-54. Diurnal Results 10/07/07

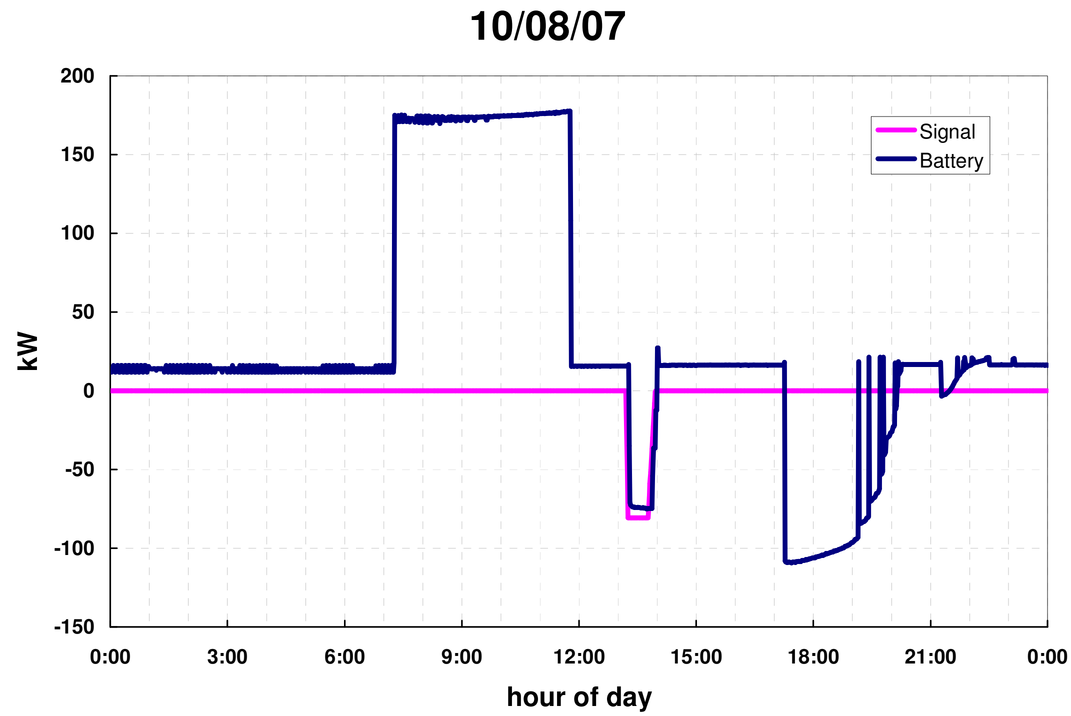

Figure A-55. Diurnal Results 10/08/07

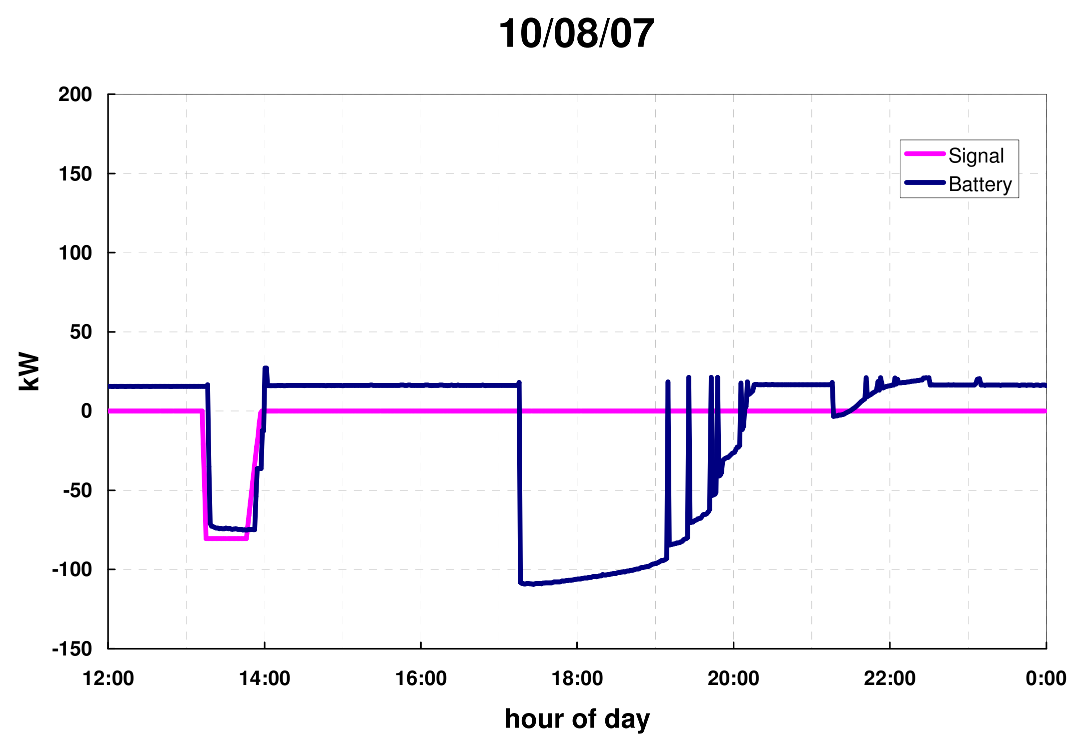

Figure A-56. Afternoon Results 10/08/07

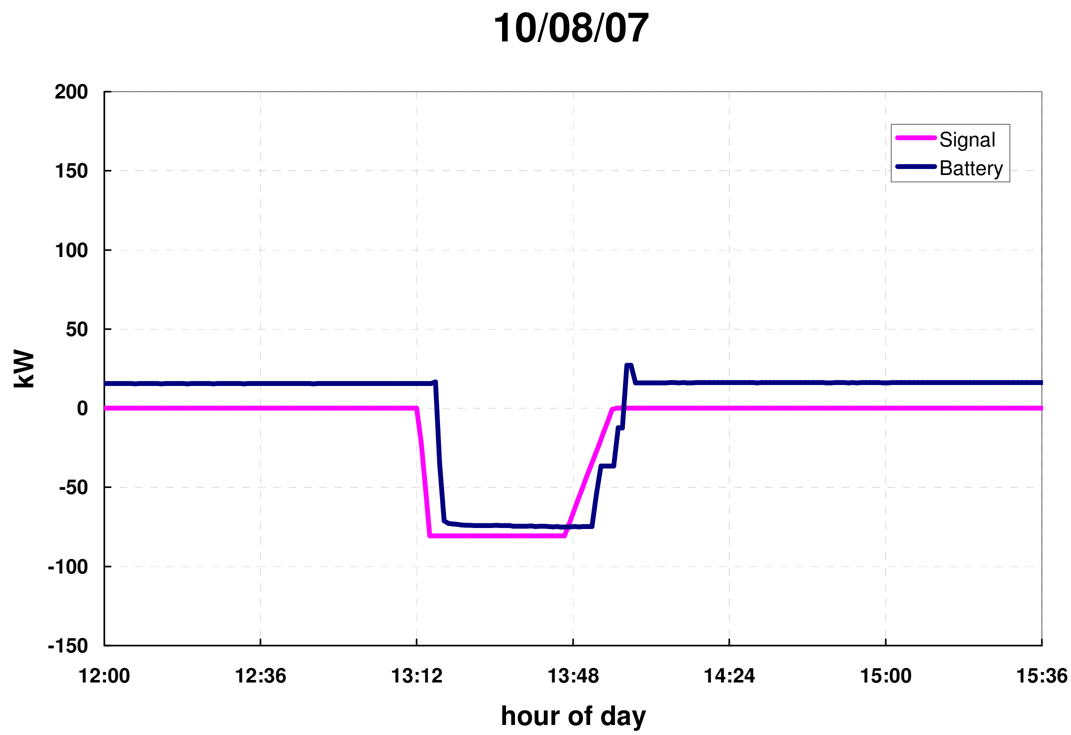

Figure A-57. Load Following Discharge 10/08/07

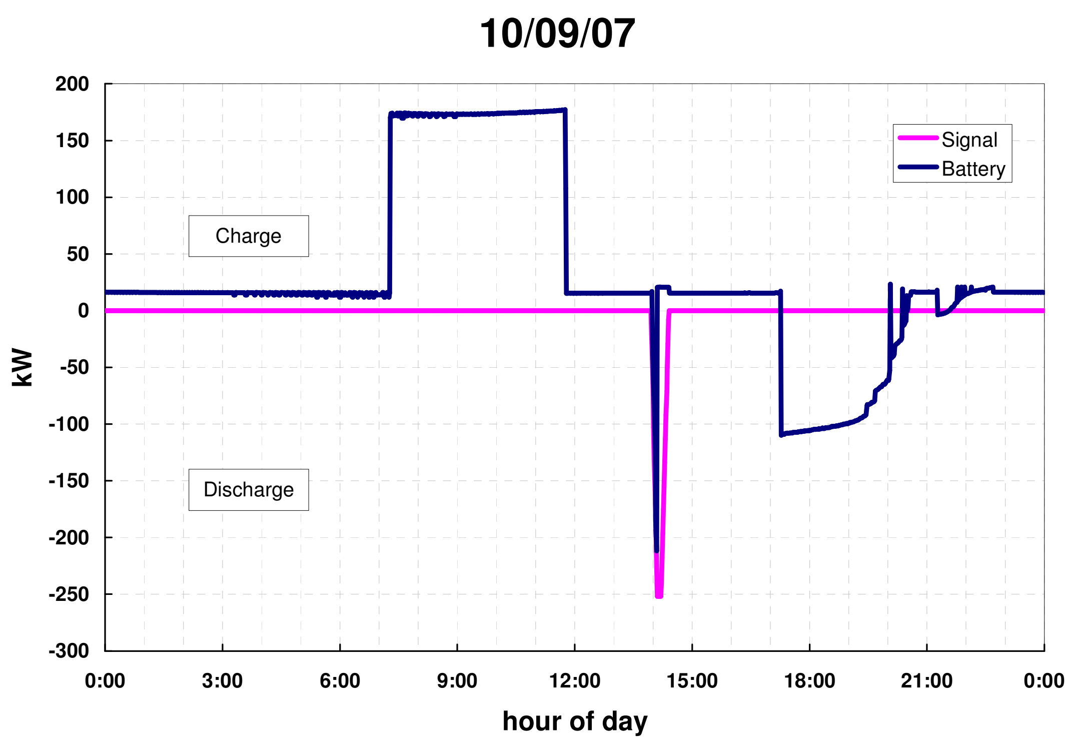

Figure A-58. Diurnal Results 10/09/07

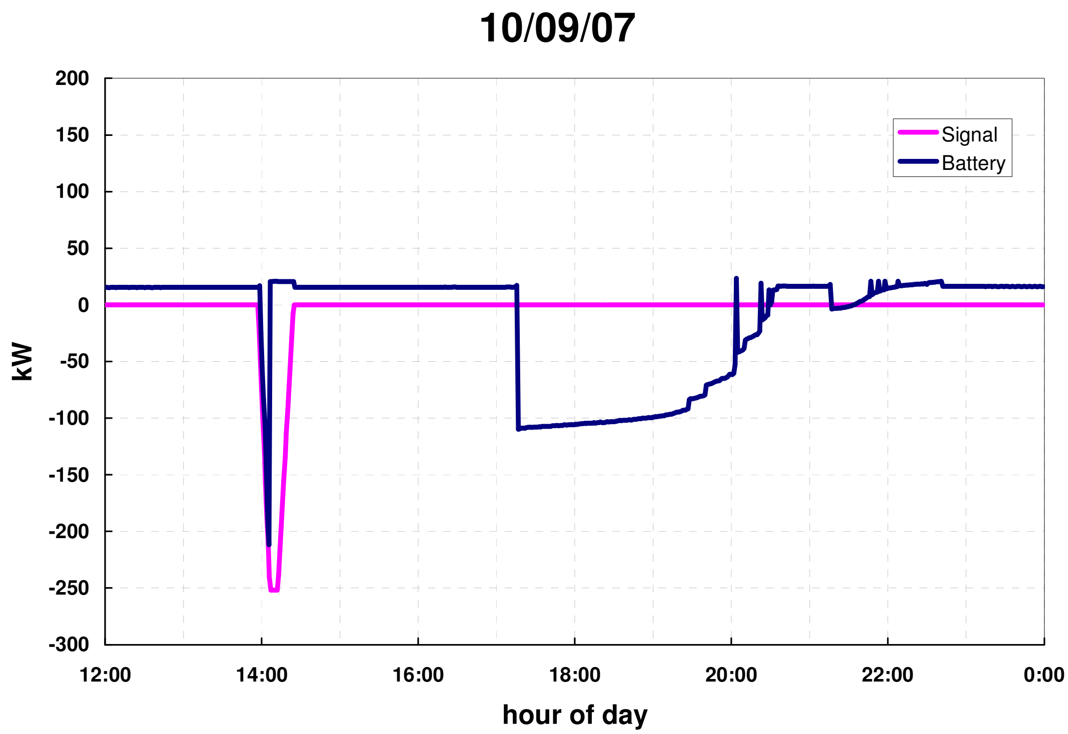

Figure A-59. Afternoon Results 10/09/07

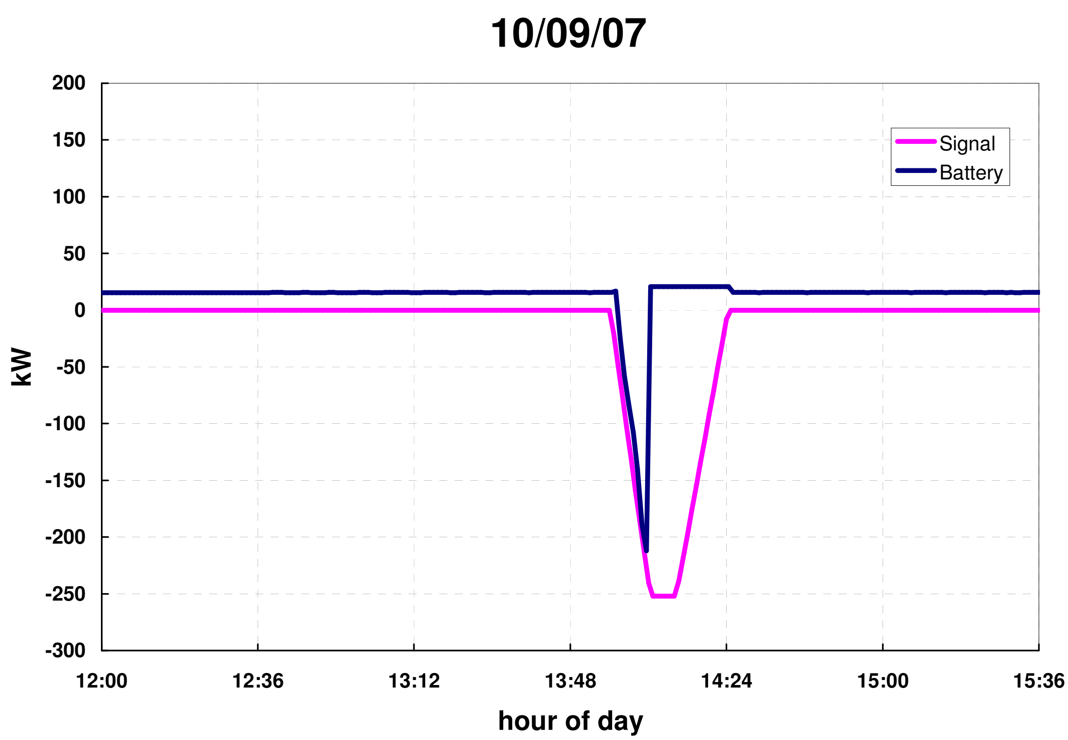

Figure A-60. Load Following Discharge 10/09/07

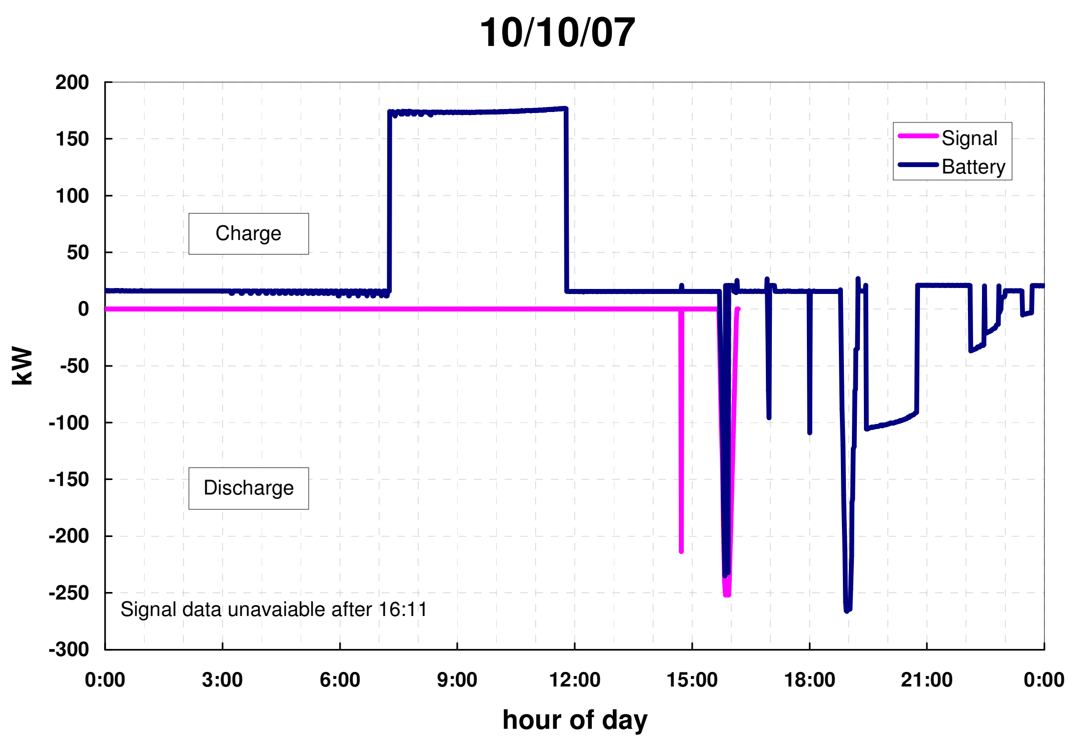

Figure A-61. Diurnal Results 10/10/07

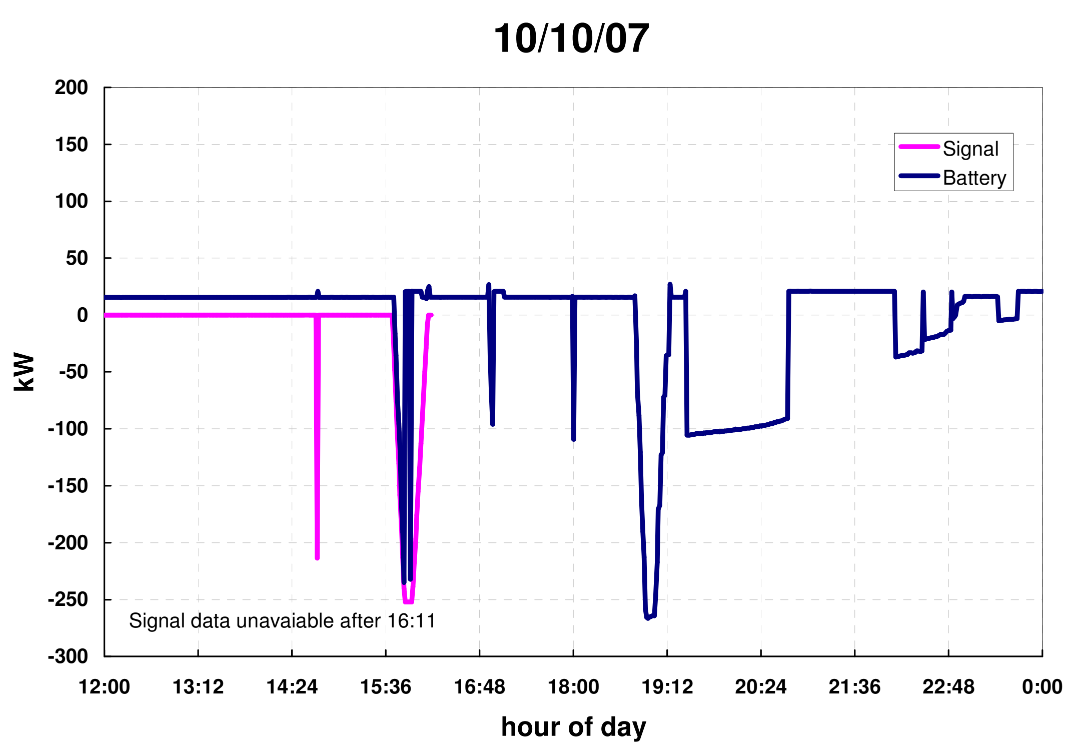

Figure A-62. Load Following Discharge 10/10/07