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Evaluation of a 50-W Stand-Alone Photovoltaic System

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Abstract: A stand-alone photovoltaic system was set up at the Colorado State University in Ft. Collins, Colorado to mimic the needs of a remote cosmic-ray detector. A 50-W crystalline silicon solar panel connected to a series-interrupting pulse-width modulation controller was used to charge a marine deep-cycle battery. The battery was continuously discharged trough a constant load of 30 Ω. The current from the solar panel to the battery, battery voltage, solar panel and air temperature during the charge and discharge processes were monitored for several weeks in June and July. To gain information about temperature effects, the battery and control electronics were stored first at room temperature and then in a temperature controlled chamber at 0°C.

Introduction

A common stand-alone photovoltaic system consists of a solar panel, storage batteries and control electronics. Solar power is often the only power source. Therefore, a highly reliable system is desirable. Stand-alone systems are mostly used in areas, where access is difficult and therefore maintenance should be kept as low as possible. For the Pierre-Auger Project to detect high-energy cosmic rays, about 1500 stand-alone photovoltaic systems will be set up in the Argentinean high plains. Each system will power one particle detector with an approximately invariant power consumption of 10 W. Excessive cloudy periods or less solar radiation during the winter, will lead to a deeper discharge of the batteries. To prevent total discharge the detector can be switched to a low power suspend mode. The whole system in Argentina will be exposed to varying weather conditions, especially variations of temperature.

A photovoltaic system, that resembles those designed for the use in Argentina, was set up on the University campus. The ongoing charge/discharge processes were monitored over several weeks in June and July with all of the equipment, except the solar panel, stored at a constant temperature of 25°C for a period of four weeks, then changed to 0°C. By disconnecting the solar panel the battery was discharged to the lowest allowed state of charge, in that way a worst-case simulation was performed; this forced the system to switch to the low power suspend mode and the recovery process afterwards was monitored.

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Setup

The installations in Argentina [1] will be setup with two solar panels and two batteries in series, which gives a nominal net voltage of 24 V. The estimated power consumption is 10 W; this is equivalent to an average current output of 0.42 A. The battery's capacity will be sufficient for running the detectors for 10 days without discharging them significantly below 50%. A prototype 24-V system has been set up at Fermilab.

For Colorado State test setup, only one battery connected to one solar panel was used (net voltage 12V). The power consumption was also halved to take into account the changed storage capacity and solar panel wattage. The current throughout this system, however should be the same as in a 24 V system. The battery size was deliberately reduced from 180 Ah to 55 Ah to bring down discharge times and in that way enable data collection that includes more frequent shut downs. It is important to keep in mind, that the battery used was new and the effect of aging will reduce the capacity of the batteries used in Argentina. An overview of both systems is given in Table 1.

	Solar Panels	Batteries	Load Current	Charge Controller
Fermilab Setup for Argentina	2 x 60Watts, In series	2 x 180Ah, gel-cell lead acid, In series	0.42 A	Solarex SRX-6/24
CSU Test Installation	Siemens SM50-H Crystalline silicon 50 Watts	Interstate HD-24DP Deep cycle/cranking 55Ah	0.42 A	Morningstar - SunGuard PWM-one step Rated for 4.5A

Table 1: Fermilab and CSU test setups

Figure 1 shows the setup of the test installation at the Colorado State University in Ft. Collins, CO (latitude 40.6°). The solar panel is mounted on the roof at an angle of 45° (Figure 2).

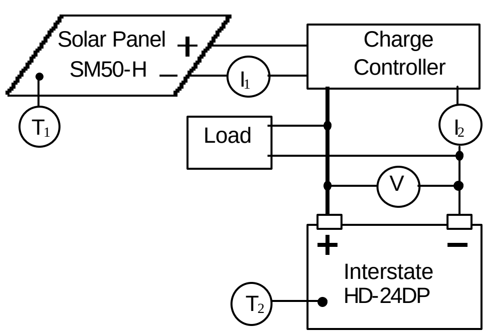


Figure 1: general design, test setup

Figure 2: 50W Panel (122 cm by 33 cm)

The controller, battery, and equipment for data collections were placed in the laboratory below the solar panel. 14 gauge wires with a length of about 30 ft ($R_{total} \approx 0.14\ \Omega$) connect the solar panel to the charge controller (Figure 3). The charge controller is a series interrupting pulse-width modulation (PWM) controller. Once the battery voltage reaches the regulation set point, the controller starts to disconnect/connect the battery with a constant frequency of 340 Hz.

The temperature of the solar panel was measured with a copper-constantan thermocouple attached to the backside of the solar panel (Figure 4). A thermocouple to analog converter amplified the thermocouple voltage to an output signal of 1 mV/°C. All signals were measured with a built in "Lab-NB" Data Acquisition Board using the LabView™ program development application.

Figure 3: Moringstar Charge Controller (5 cm square)

Figure 4: Thermocouple attached to the backside of panel

In the beginning a small engine starting battery was used, but the capacity of this battery was insufficient and after a few test cycles one of the cells short-circuited due to being too deeply discharged. A deep cycle marine battery, with a rated capacity of 55 Ah (Table 2), replaced the engine starting battery.

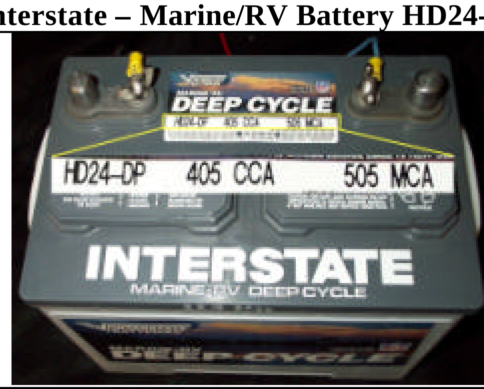
DieHard Gold - Garden Tractor Battery.	**Interstate – Marine/RV Battery HD24-DP**
	
Physical size: 7.5" x 6.5" x 5" Capacity: 340 CCA Definition "CCA": "The discharge load in amperes which a new, fully-charged battery at 0°F can deliver for 30 seconds and maintain a voltage of 1.20 volts per cell or higher." Capacity in Ah: 10 (estimated)	Physical size: 10" x 8" x 7" Capacity: 405 CCA, 505 MCA Definition "MCA": "The discharge load in amperes which a new, fully charged battery at 32°F can deliver for 30 seconds and maintain a voltage of 1.20 volts per cell or higher." Capacity in Ah: >55 (manufacturer's value: 11.6 h at 5 A)

Table 2: Comparison of the batteries used

Battery - Interstate HD24-DP

Self-Discharge Rate

The self-discharge rate of the fully charged battery was measured over 30 hours, after the battery had relaxed for 10 hours in advance of the measurement. The self-discharge rate was found to be about 32 mV/day at 25°C and about 28mV/day at 0°C (Figure 5). These values are higher than found in "Handbook of Batteries" [2] and can only be applied to a fully charged battery, but most of the time the battery will be in a fully charged state. It should be a good upper limit.

Temperature Coefficient

A linear approximation in the range of 0-25°C yields the thermal coefficient for the battery voltage, a value of about 1.8 mV/K (Figure 6).

The charger regulation voltage is temperature compensated by –28 mV/°C. With decreasing temperature, the regulation voltage of the charge controller increases. The purpose is to compensate for the higher internal resistance during the charging process when the battery is at a lower temperature.

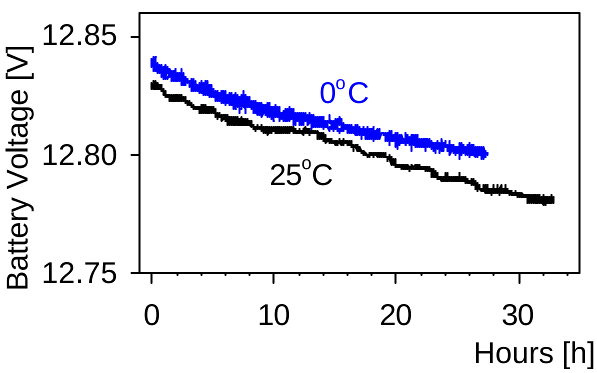


Figure 5: Self-discharge Rate

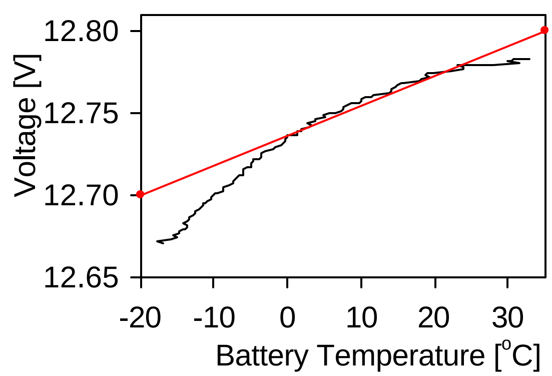


Figure 6: Voltage vs. Temperature

Discharge Profile

The discharge profile (Figure 7) of the battery was measured with a load of 30 Ω and a current of 0.42 A. To measure the open circuit voltage, the load was disconnected, for 5 minutes every 20 minutes. After an initial period, both the open-circuit and the operating voltages decreased quite linearly. For estimating the state of charge (SOC) the values in Table 3 have been used. These values were derived from the data given for marine batteries in the "Handbook of Batteries" [2]. The capacity of a battery depends on the rate of discharge. The battery used was rated for 55 Ah with a discharge current of 5 A. With a smaller load current, the available capacity of a battery is higher. This explains why the amount of charge taken out of battery was higher than the amount that could have been expected with the 55 Ah rating. Our criterion is that the battery should not be discharged lower than 40%, or about 12.2 V open-circuit at room temperature.

State of Charge	Battery Voltage
100 %	> 12.64 V
75 %	12.44 V
50 %	12.26 V
25 %	12.08 V
0 %	< 11.90 V

Table 3: SOC vs. Voltage (open circuit at 25°C)

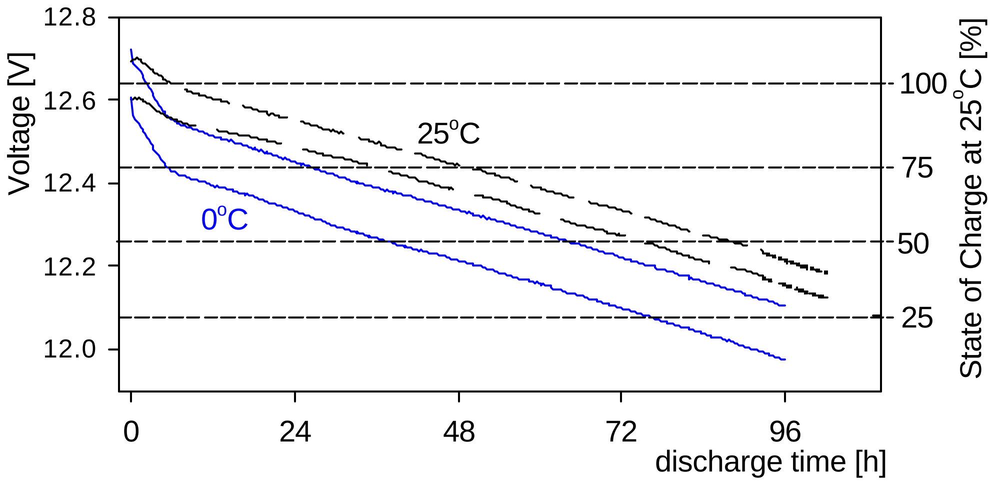


Figure 7: discharge profile, Interstate HD24-DP

The difference between the open circuit voltage and the voltage with a load current of 0.42 A was about 60 mV at 25°C and 120 mV at 0°C. These values depend on the battery and have to be measured with the batteries which will be actually used in Argentina. The rate of discharge seems to be the same at 25°C and at 0°C. The rate is small enough so that there is no significant influence of the temperature on the discharge rate.

The open circuit voltage is usually not available during operation; therefore the shut off voltage has to be determined by taken the voltage measured during operation, corrected by the temperature effect (1.8 mV/°C) and by the voltage drop, that occurs when a current is drawn from the battery (60-120 mV, depending on the temperature).

Solar Panel - SM50-H

IV-measurement

Before the panel was mounted on the roof an IV-curve was measured (Figure 8). The panel was at a temperature of 25°C and faced directly towards the sun.

Date: 03/07/2000 Time: 10:00 am

I_{sc} = 3.82 A
V_{oc} = 19.07 V
Max. Power: P_{max} = 47.8 W
Fill Factor: FF = 0.66

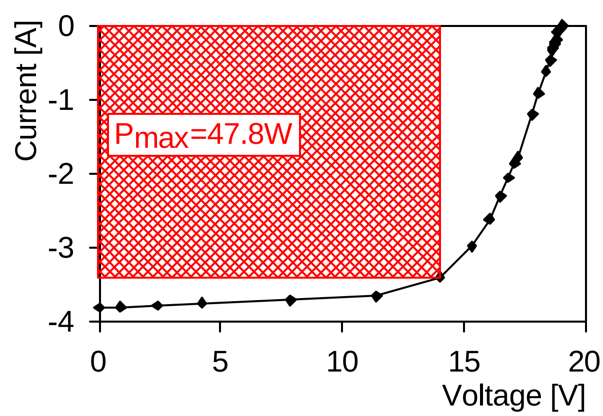


Figure 8: IV-Curve, SM50-H

Open Circuit Voltage and Short Circuit Current

Open circuit voltage and short circuit current were measured for several days (Figure A1 of Appendix, page 12). Short-circuited the panel operates at a voltage of 0V and delivers the maximum current. Connected to the charge controller and the battery, the solar panel operates at the charging voltage and the current is always less than the short circuit current. By integration of the current over time, the available charge for the day can be calculated. The maximum available charge on a sunny day was found to be 24 Ah in the short-circuited mode. The highest charge available on sunny days, while the solar panel was connected to the charge controller and therefore was operating at the charging voltage of about 12.5 to 14 V, was about 20 Ah. Figure A1 in the Appendix shows the current available on a cloudy and a sunny day, the panel open-circuit voltage and what it would be at a constant 25°C (-48 mV/°C correction), and the panel and air temperature profiles.

Data collection

Overview

The following signals were continuously monitored:

- Peak and average current from the solar panel to the charge controller. This is the input current (I_1 in Figure 1) to the charge controller and is within the available accuracy equal to its output current (I_2 in Figure 1).
- Voltage across the battery's terminals (V in Figure 1)
- Voltage on the charge controller input terminals (not displayed in the daily data plots)
- Temperature of the solar panel (T_1 in Figure 1)
- Air Temperature (data taken from the Ft. Collins Weather station, 0.2 miles from the solar panel)

If the voltage across the battery is lower than the regulation set point, a continuous current will go to the battery (current 1 in Figure 9). Once the voltage reaches the regulation set point the charge controller will enter the PWM-mode and start to open and to close the circuit with a constant frequency of 340 Hz (current 2 in Figure 9). The current signal is sampled over 20 periods and the peak value and the average value (current 3) are derived from the data. The peak current represents the current that is available from the solar panel at that time.

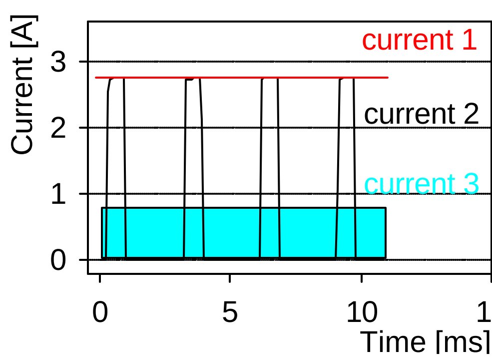


Figure 9: PWM-mode – current flow

The PWM-mode leads to an average current that is lower than the peak current. By modulating the pulse-width, the average current is controlled by the charge controller to maintain the regulation voltage across the battery's terminals. Integration over the peak current gives the amount of charge available on one day. The integration over the average current gives the amount of charge, which was used for charging the battery and/or the load resistor.

Days #	Bat. Temp.	Changes to normal setup	start date end date
1 - 12	25°C	-	5/24/00 6/4/00
13 - 16	25°C	disconnect solar panel, discharge through load	6/10/00 6/14/00
17 - 27	25°C	-	6/15/00 6/26/00
28 - 37	0°C	-	6/26/00 7/5/00
38 - 41	0°C	disconnect solar panel, discharge through load	7/8/00 7/13/00
42 - 52	0°C	-	7/14/00 7/24/00
53 - 60	25°C	-	7/15/00

Table 4: different setups

A summary of the days, when the system was running, is shown on page 13 in Figure A2 of the Appendix. Within the time displayed, some changes in the setup were made (Table 4). The upper graph shows the charge that was going to or was coming from the battery on each day. On most of the days excessive charge, which was not used because of the charge controller was switching to the PWM-mode, was available. The middle graph shows the voltage at midnight of each day and indicates the changes in the state of charge.

Daily Data Plots

On pages 15, 16 and 17 typical plots for a sunny, a partly cloudy and a very cloudy day are shown. The current plot shows the current, which is available from the solar panel, the current going from the charge controller to the battery and the load current. If the current going from the charge controller to the battery is larger than the load current, the battery is getting charged. If the current to the battery is smaller, the battery is getting discharged. On the bottom of each page a summary of the most important numbers is given. The term "fully charged" means that the battery was charged until the charge controller switched to the PWM-mode. In the current plots this corresponds to the time, when the available net current starts to differ from the used net current. Some charge went to the battery on every day, even when the battery was nominally fully charged on the day before (see day 5-12, Figure A2). The amount varies between 0.6-2 Ah and depends mostly on the time the system was running in the PWM-mode on this day and for how many previous days it was fully charged. The current going to the battery in the PWM-mode was about 0.42 A when the battery was fully charged for the first time (day 4) and dropped to about 0.25 A on the ninth day of being fully charged (day 12). The current going to the battery at the end of the PWM-mode on each day is plotted in Figure 10. The change from day to day correlates with the time the system was in the PWM-mode on that day.

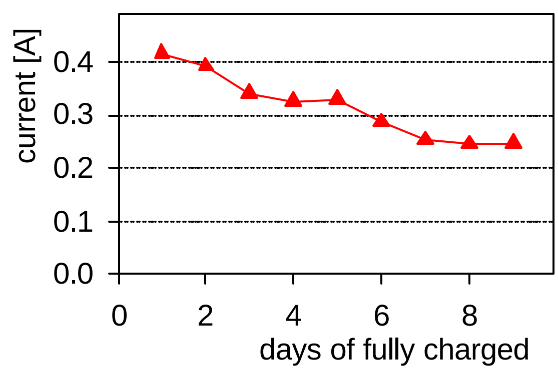


Figure 10: end-current of PWM-mode

Sunny day (Figure A4 in the Appendix, page 15):
There was more charge available on this day than was going to the load. The battery state of charge did not change that day, because the battery was fully charged both that day and the one before (see day 9 Figure A2, page 13). When shortly before noon the battery voltage reached the set point of the charge controller (13.9 V at 25°C) the current quickly dropped to an almost constant value going partly to the load and partly to the battery. The size of the current, which goes to a nominally fully charged battery, depends on the type and size of the battery and decreases very slowly with time, because the battery is additionally charged at a very low rate. The maximum current from the panel was 2.59 A. Compared to the maximum short circuit current of 3.3 A (Figure A1, page 12), this seems to be low. But the panel is operated at the battery charging voltage and not at short-circuit. Temperatures of about 50°C were reached on that day and on other days they reached more than 60°C. The highest power output of the panel on this day was 2.59 A*13.9 V = 36 W.
The available current plot shows a cosine distribution in the time from 7:00 am to 7:00 pm (daylight saving time). From sunrise to about 7:00 am and after 7:00 pm until sunset the diffusive solar radiation delivers a small current. The load current was almost constant and varied only very slightly due to the change in the battery voltage over the day.

Partly cloudy day (Figure A5 in the Appendix, page 16):
The available charge was still more than what was needed for the load resistor. The state of charge did not change over the day. This is day 7 on the summary plot on page 13. The maximum current available on a partly cloudy day is usually higher than on cloudless days, because of scattering effects in the clouds, which lead to higher solar incident flux for a brief time. The highest value on this day was about 3.49 A, but it was available for only 2 minutes.

Cloudy day (Figure A6 in the Appendix, page 17):
On this day only 4.3 Ah were available from the solar panel and 9.8 Ah went to the load. The battery lost 5.5 Ah of the stored charge and the battery voltage, taken at midnight each day, dropped by 0.17 V. At the end of the day the battery reached almost the shut-off voltage of 12.15 V and it actually shut off at 12:32 am on the next day (see below "worst case simulation").

Worst-case simulation

Shut-off:
To force the battery to a lower State of Charge the solar panel was disconnected until the shut-off voltage of 12.15 V was reached. The amount of charge taken out of the battery was about 40 Ah and afterwards the solar panel was connected again and the recharge process started (day 17). The bad weather on day 18 forced the system into the low power suspend mode at 12:32 am on day 19. If the Argentinean system goes into the low power suspend mode, the power consumption will drop to a very low value, which would allow a central control station to stay connected via radio transmission for many additional days. In the test setup the load was disconnected and the power consumption dropped to zero.
Our criterion for reconnecting the standard load to the battery was that the charge necessary for one day (10 Ah) had gone to the battery. This would enable the system to run at least 24 h after it switched on again even without any solar incident flux and toggling between the on and off state would be prevented. At 12:43 pm 10 Ah of charge went to the battery so that the load was switched on again.

Recovery:
The disconnection of the load on day 19 and a cloudless sky on that day allowed the battery to recover 15 Ah. In days 19-25 (see Figure A2), a total of about 40Ah were recovered, the same amount that was drawn in the forced discharge (days 13-16) and the battery reached the fully charged state on day 23 for the first time again. Figure A3 on page 14 shows the continuously integrated current during the recharge process. The daily discharge and recharge cycle is overlapped with the long-term recovery process. Once the battery is fully charged the daily cycles are within a range of ±3Ah. The change over the day is the amount of charge displayed in the summary plot (Figure A2).

As previously mentioned, every day the battery is in a fully charged state, some charge will go to the battery, and the current in the PWM-mode drops each day. The amount of this current can be used as an additional indicator for the state of charge. On days 4-12 the voltage in the PWM-mode and after the PWM-mode stopped was always the same. A comparison of the voltages at midnight on the days 4-12 (see Figure A2) delivers the same result, that the charge that went to the battery in the PWM-mode does not affect the battery voltage, but the amount of charge can be estimated by the current which goes to the battery in the PWM-mode. Days 7 and 25 have two things in common: Both days had been preceded by several days in PWM-mode, so there was excess charge available, and the current in the PWM-mode was approximately 0.33 A. The charge going in and out of the battery on the days 8 to 23 is a cumulative +7 Ah. This is probably partly due to the loss in self-discharge of the battery and partly to the increased capacity described in Ref. 2 that occurs on deep-cycle batteries after the first few cycles.

Running at 0°C

In this experiment the battery and the charge controller were put in a temperature controlled chamber at 0°C. Charge controllers can come with no temperature compensation, with a built in temperature compensation, or with an external temperature sensor. The charge controller in the test setup operates with a built in temperature compensation of –28 mV/K. For every degree of decrease in temperature, the regulation set point is increased by 28 mV to compensate for the higher internal resistance of the battery. Figure A7 on page 18 shows a sunny day with the battery and the charge controller cooled down to 0°C. The higher voltage, which is needed to drive the charging current in the battery, lowers the available charge considerably to about 15 Ah instead of 19-20 Ah (see summary plot on page 13). In a field installation the solar panel would also be at a lower temperature, and this would increase the solar panel output and make up for some of the loss due to the higher voltage that is needed. Once the system went to the PWM-mode there is a difference in the current profile. At room temperature, the current will drop within 1.5 h after being fully charged to an almost constant value when it reaches the regulation set point (Figure A4, page 15). At 0°C however, the current decreases more slowly after the voltage reaches the higher set point. The PWM-mode current still decreases with every day at the fully charged state but at a lower rate. The important point about 0°C operation, as shown earlier in Figure 7, is that there is no significant decrease in time that the load current can be drawn from the battery, but the shut-down voltage needs to be adjusted.

Recommendations

Monitoring

Reliability of a stand-alone photovoltaic system requires monitoring and control. There are different levels of importance in the parameters that are usefully monitored. Level 1 is most critical.

Level 1 (minimum):

Estimate the state of charge only by taking data every 5-60 minutes to avoid deep discharge.

- Battery Voltage
- Battery Temperature

Level 2 (recommended):

More information is collected about the state of charge by monitoring the integrated current in and out of the battery and hence its state of charge. A current record gives information about possible deterioration of the solar panel or partial shading. In the case of a constant load, or constant power consumption, the load current does not have to be monitored. Data should be taken every minute, because the incident solar flux can change within a short time.

- Current from the solar panel
- Current to the load (if load is not constant)
- Charge in Ahs going from/to the battery daily

Level 3 (additional information):

Monitoring the PWM-mode current gives additional information about the state of charge. This kind of information is more difficult to utilize, because it varies with the history of the battery and strongly with the temperature. The air and solar panel temperature, available current and solar panel voltage monitoring allows very good evaluation of the solar panel and a slow decrease in panel performance may be determined early.

- Current in PWM-mode (calculated from a sampled waveform)
- Air Temperature
- Solar Panel Temperature
- Available Current (calculated from a sampled waveform)
- Solar Panel Voltage

To best ensure long-term reliability it would be useful to install level 2 monitoring in most systems and level 3 monitoring in a few systems. This would enable a central station to monitor and track the deterioration of individual solar panels and batteries, and over time to better document solar conditions on-site and the failure rate of the components.

About the intended setup

The intended setup for the detectors in Argentina include two batteries and two solar panels in series operating at a nominal system voltage of 24V. Having batteries in parallel would be an advantage, if a failed battery could be detected and disconnected automatically. Changing to a setup with smaller batteries in parallel (a total of four) might be reasonable. The failure of one battery, in a parallel arrangement, allows the system then to operate for some time before it has to be shutdown (i.e. the whole summer). A higher number of smaller batteries in parallel would be more reliable and similar in cost, and probably easier to install and replace in an environment that is difficult to access. In case that there will be only batteries in series it might be useful to change to a setup using four 6 V batteries instead of two 12 V batteries. The 6 V batteries will be only half the weight and easier to install and replace. Thirty kilograms is a reasonable target.
Parallel panels might also be helpful, since a single panel could deliver some energy so that the system will be able to run longer than 10 days after a failure. On the other hand the reliability of solar panels is generally high and getting an arrangement of 30 W panels is not practical. But in case that the system electronics might be operated at 12 V, parallel panels (2 x 60 W) would be the logical configuration.

There are some more things to mention regarding charging a vented battery:

- The regulation set point of the used charge controller was relatively low. Setting this point to a value of about 14.4 V would not harm the battery nor would it increase the maintenance.
- Several times a year (at least once every 3 month) the battery should be charged to a higher voltage so that the bubbling from the generated gas will stir the electrolyte and reduce the effect of stratification. Simply bypassing the charge controller with a relay, if the charge controller does not offer this function, could give the increased voltage for a controlled period of time.
- Vented batteries may require occasional addition of deionized water, especially if bubbling is excessive. There are ways to electronically monitor fluid level, but we are not aware of a commercial product, which is especially designed for the use with lead-acid batteries.

Regarding sealed gel-cell batteries (valve regulated lead acid VRLA):
The maintenance is considerably lower than using vented batteries. Refilling with water, stirring, and equalization charges are not necessary. The reduced maintenance and increased reliability could make up for the higher price. The process of battery selection should include a reasonable estimate of maintenance and replacement cost.

References

1. The Auger Collaboration, "The Pierre Auger Observatory Design Report", 2nd edition, March 1997, pp. 187-189
2. David Linden, “Handbook of Batteries”, 2nd edition, McGraw-Hill, Inc. 1995

Appendix

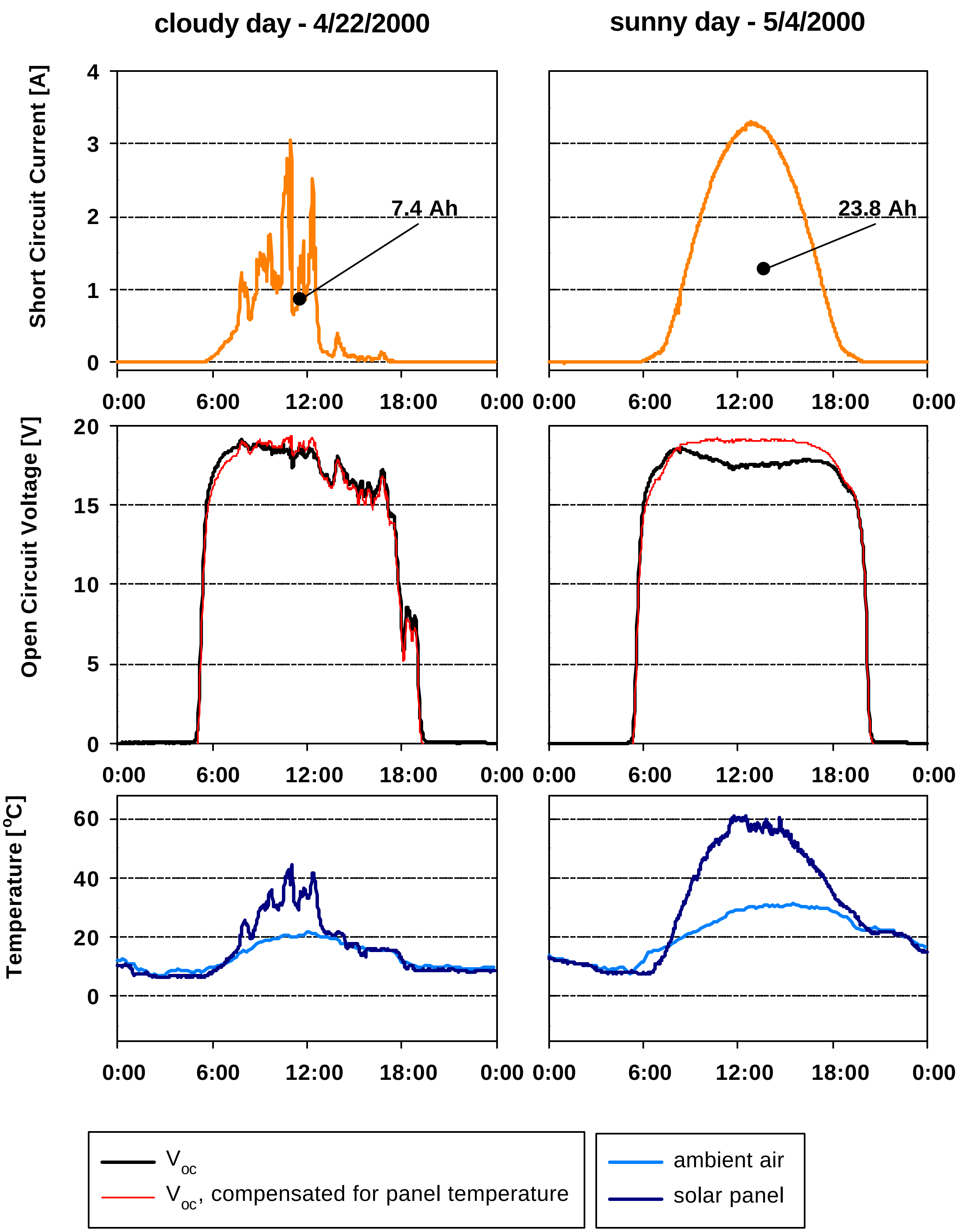


Figure A1: short-circuit current and open-circuit current

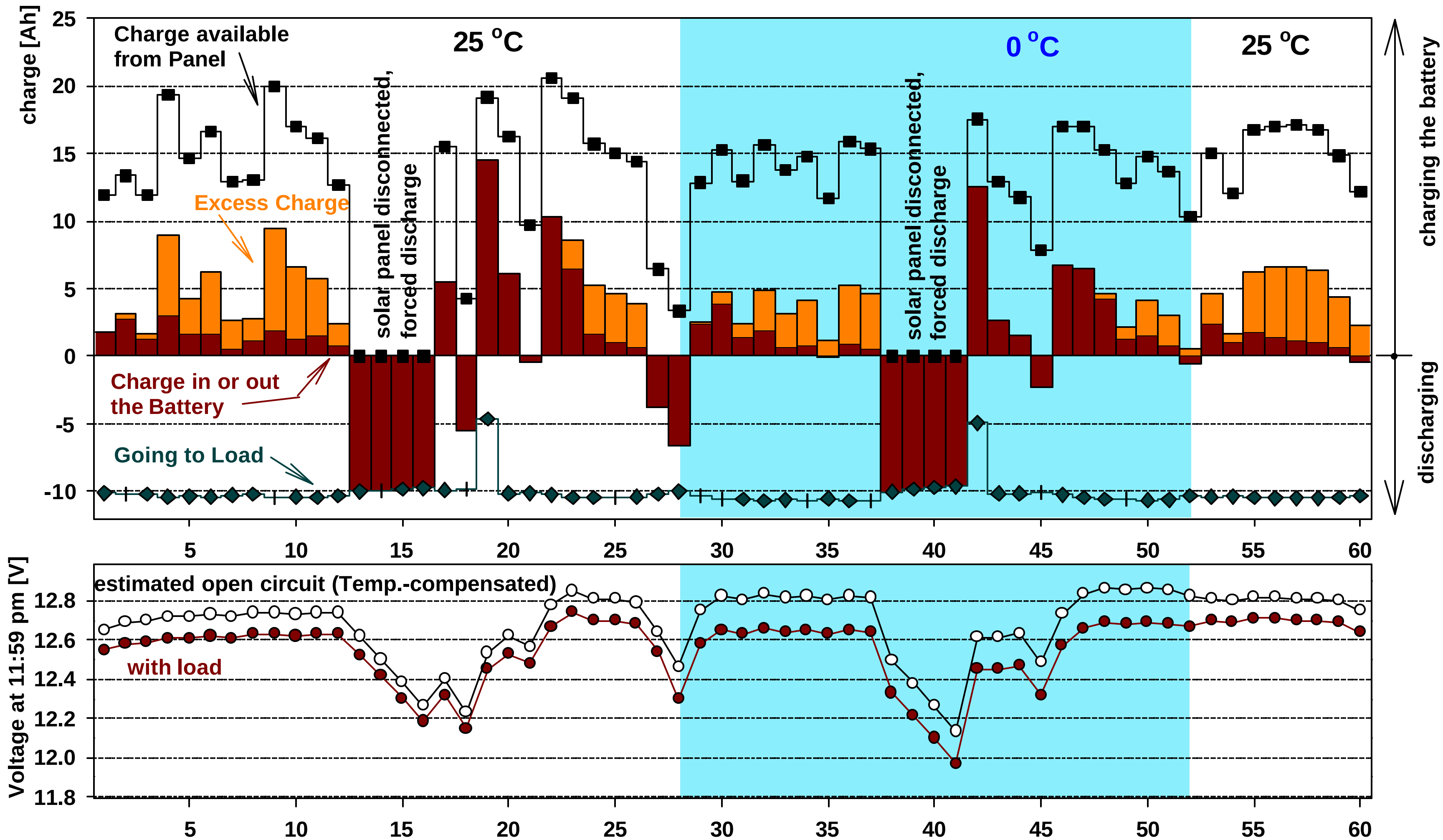


Figure A2: summary of daily-average data

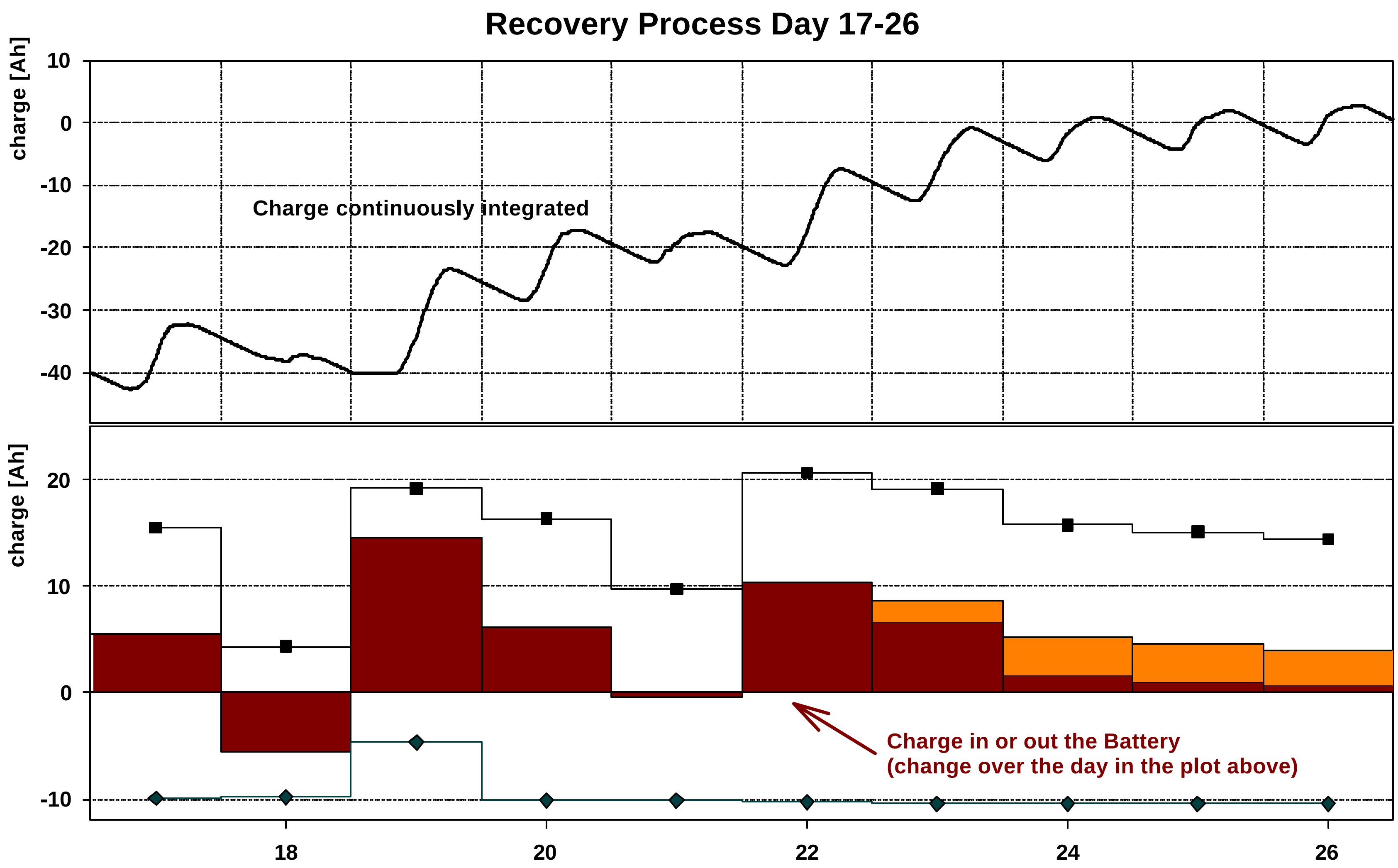
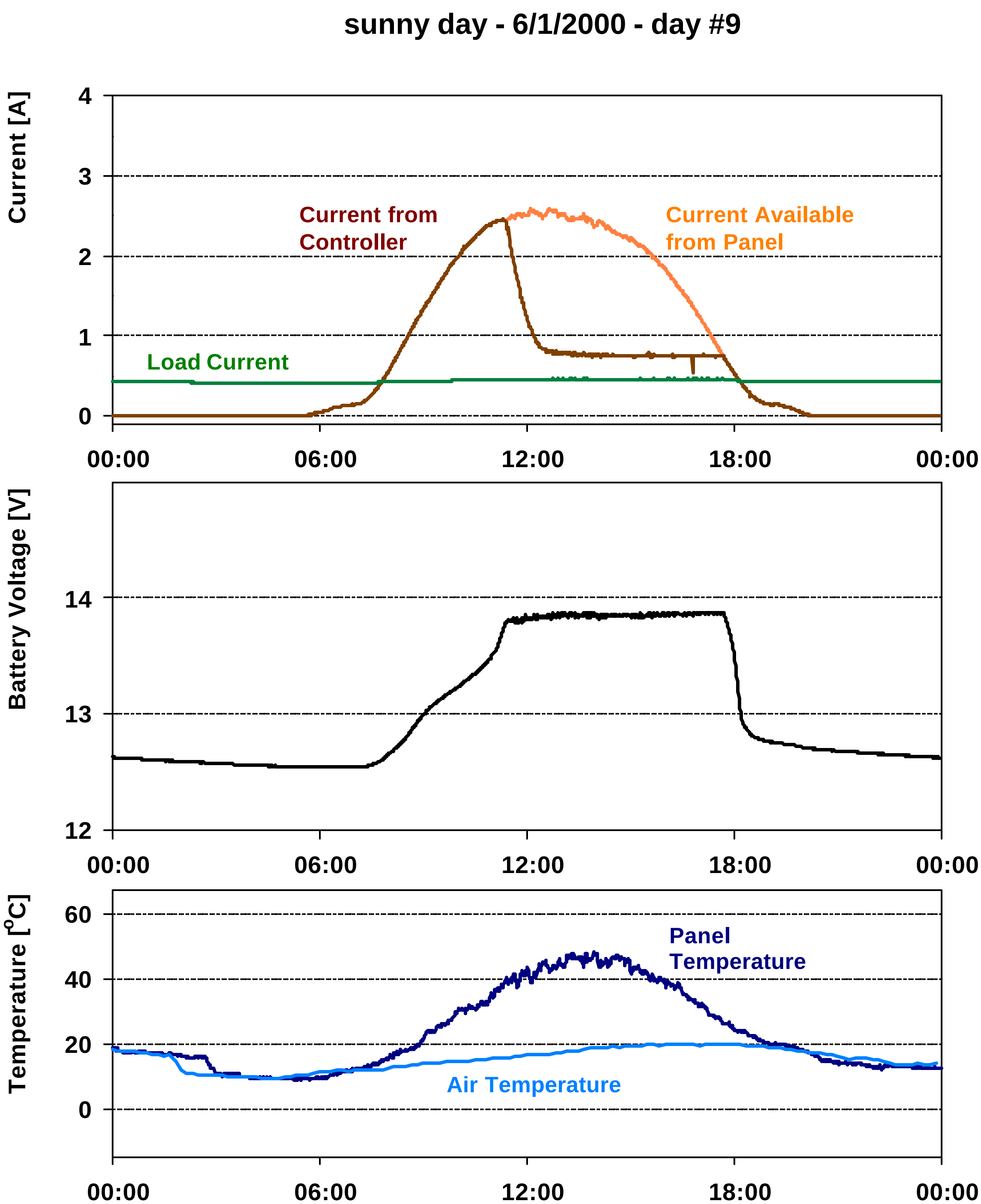
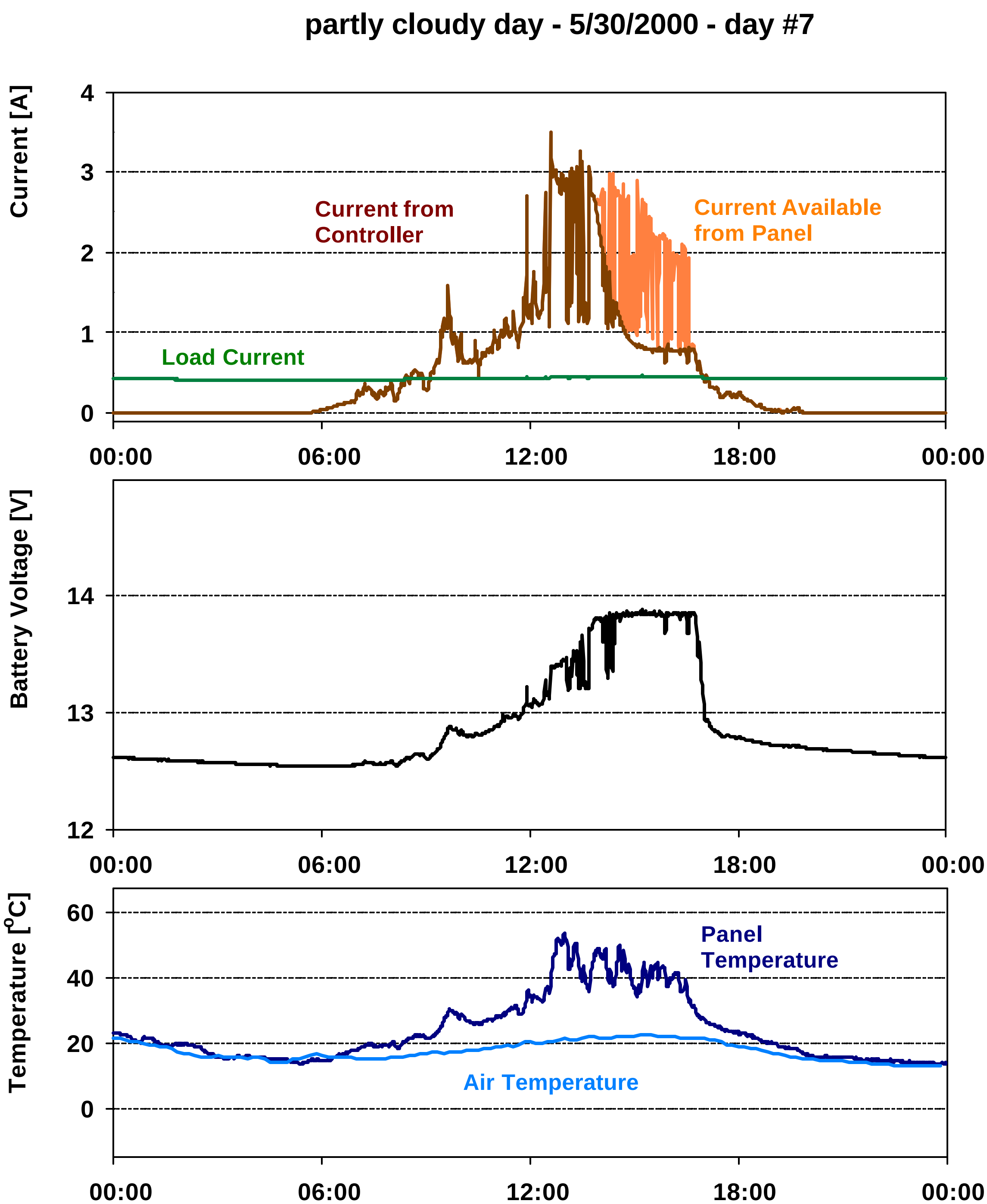


Figure A3: Recovery Process



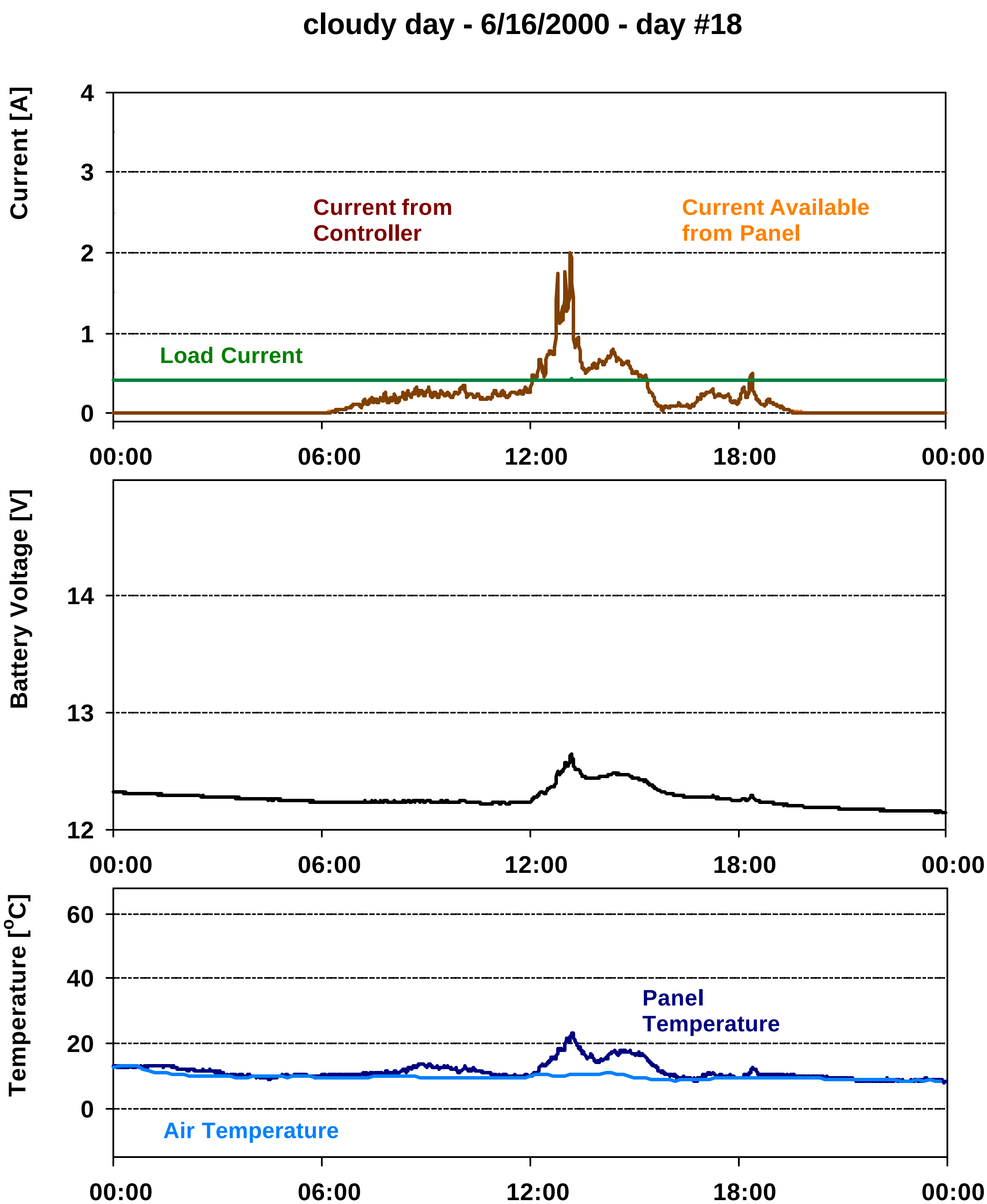
charge to battery:	1.9 Ah	max. battery voltage:	13.88 V	max. panel temperature:	48.4 deg C
charge to load:	10.4 Ah	min. battery voltage:	12.54 V	min. panel temperature:	8.8 deg C
excess charge:	7.6 Ah	change in battery voltage:	0.0 V	max. current:	2.59 A

Figure A4: daily data plot – sunny day



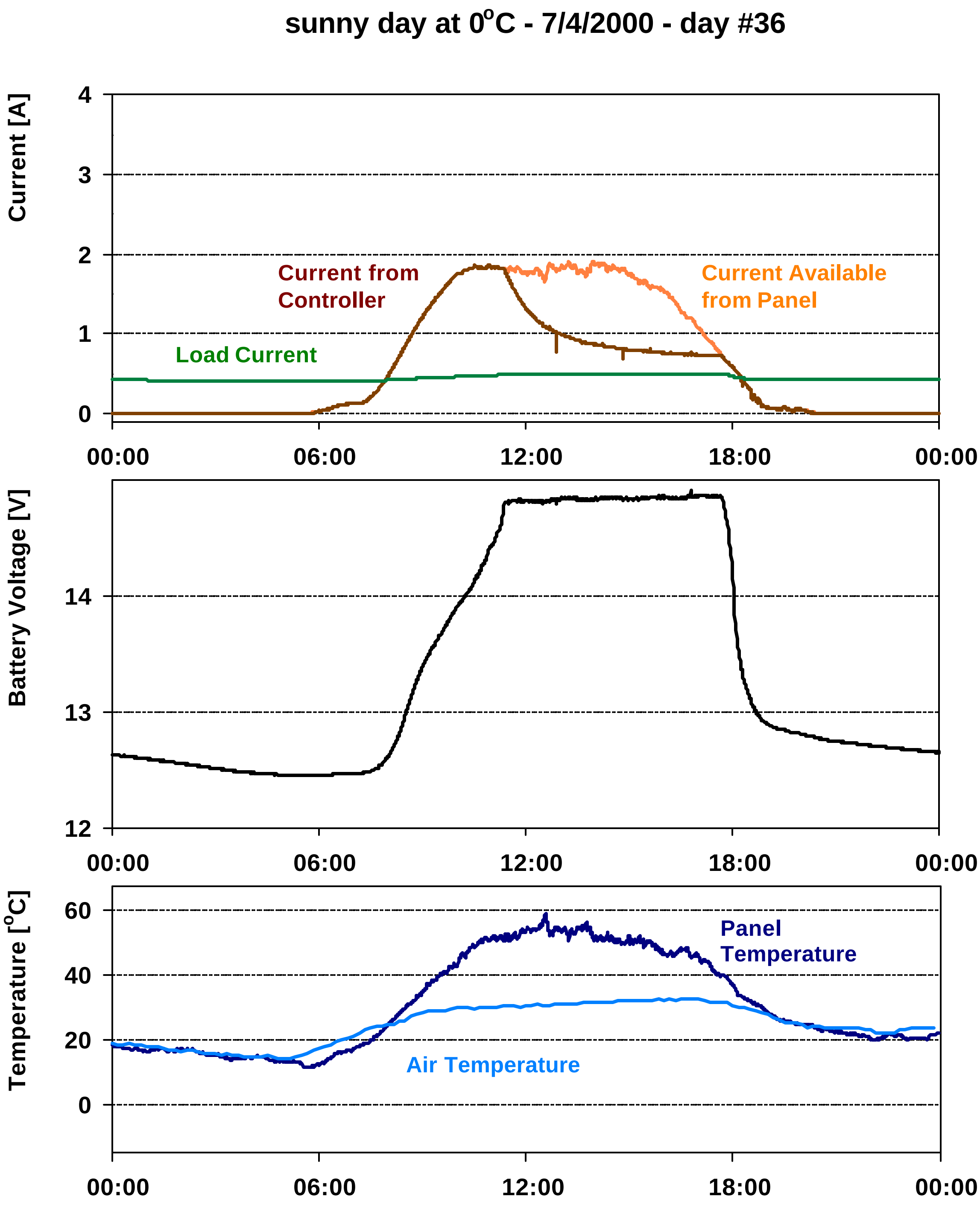
charge to battery:	0.6 Ah	max. battery voltage:	13.88 V	max. panel temperature:	53.9 deg C
charge to load:	10.3 Ah	min. battery voltage:	12.54 V	min. panel temperature:	13.4 deg C
excess charge:	2.1 Ah	change in battery voltage:	0.0 V	max. current:	3.49 A

Figure A5: daily data plot – partly cloudy day



charge to battery:	-5.5 Ah	max. battery voltage:	12.65 V	max. panel temperature:	23.3 deg C
charge to load:	9.8 Ah	min. battery voltage:	12.15 V	min. panel temperature:	8.2 deg C
excess charge:	0.0 Ah	change in battery voltage:	-0.17 V	max. current:	2.0 A

Figure A6: daily data plot – cloudy day



charge to battery:	0.9Ah	max. battery voltage:	14.90 V	max. panel temperature:	58.9 deg C
charge to load:	10.7Ah	min. battery voltage:	12.44 V	min. panel temperature:	11.3 deg C
excess charge:	4.3Ah	change in battery voltage:	0.02 V	max. current:	1.91 A

Figure A7: daily data plot - running at 0°C