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SUBJECT: EVALUATION OF SOLAR PANELS' ABILITY TO CHARGE BATTERY-POWERED AIR SAMPLING PUMPS

In field studies related to fumigant flux measurements, the Department of Pesticide Regulation (DPR) has used SKC Aircheck PCRX air sampling pumps with attached sorbent tubes. DPR has employed 12 V rechargeable batteries to power the air sampling pumps. These batteries need to be changed every 24 hours to maintain constant power supply. Changing batteries so frequently is time consuming and can lead to pump failure due to improper battery recharging, damage to connectors from frequent handling, and loss of samples. To ensure a constant power supply to the pumps and minimize the number of times required to change batteries during field studies, DPR investigated using solar panels to recharge the batteries during the day time. DPR tested solar panels configured to provide three different levels of power: 4.5, 9, and 18 W. Each solar panel configuration was connected to a battery that powered two pumps set at their field maximum flow rate (1500 ml/min). DPR used a Campbell 21X datalogger to record the battery voltage changes for each configuration continuously for 336 hours (14 days) and the charge-discharge from the batteries during day and night time. The results of the study indicate that solar panels were able to maintain the power supply of the battery at an optimum level for 4 to 5 days, as long as the solar panels provided at least 18 W. A single 4.5 W solar panel adequately charged a single 12 V battery assigned to power both the Campbell 21X and 23X during the 336 h study.

Material and Methods

Solar Panels

DPR preferred small size solar panels so that they would fit easily onto metal posts where pumps can be installed as well. Therefore, DPR purchased BP SX405M solar panels (BP Solar, San Francisco, CA), due to their small physical dimensions (L: 251 mm (9.9"); W: 269 mm (10.6"); D: 23 mm (0.9"). The solar panel consists of a high-efficiency photovoltaic module using silicon nitride monocrystalline silicon cells connected in series, which produces a maximum power of 4.5 W (Picture 1). Table 1 gives the electrical characteristics of the solar panel.

To test its ability to recharge the battery that typically powers two air pumps, staff connected the solar panel(s) to the battery. In this study, DPR used three power levels for charging the batteries: 4.5, 9, and 18 W. To accomplish these power levels, staff connected one, two or four solar panels in a parallel style to create the 4.5, 9, and 18 W power outputs, respectively. In parallel style, the voltage of each panel remains the same and the amperage (current) of each panel is added. Thus, by connecting in parallel style, we could obtain 0.27, 0.52, and 1.08 A current for 4.5, 9, and 18 W panels at their maximum power, respectively (Table 1). None of the solar panel configurations had a voltage controller, which regulates the current from the solar panel array to the battery to provide optimum current control during charge. To get the most power from the solar panels, we faced them in the south direction that captures the most sun. In principle, the solar panels should be tilted from the horizontal at a degree equal to latitude of our location (Sacramento 38^{o} N) minus 15 degrees in summer. In our study, we titled our solar panels using bricks to approximate angle of 10-20 degree (Picture 6).

Air sampling pump
DPR selected the SKC Aircheck model PCXR8 air sampling pump (SKC, Eighty Four, PA) (with an adjustable flow rate of 5 to 5000 ml/min) in this study. In the first set of experiments, two pumps were connected to each configuration of solar panels and battery. Each pump was set at a flow rate of 1500 ml/min, which is typically the highest flow rate for these pumps in field studies. A total of 6 pumps (three pairs) were used to run the experiment. To simulate resistance under field conditions, sorbent tubes were attached to the inflow inlet of the pumps. In the second set of experiments, six pumps (three pairs) were used with one pump at 50 ml/min and the other pump in each pair at 1500 ml/min. These flow rates simulate field-sampling conditions for 1,3-dichloropene and methyl isothiocyanate.

Datalogger and connections
To measure the performance of the solar panels for charging and discharging the batteries, DPR used a Campbell 21X datalogger (Campbell Scientific, Logan, UT) to continuously record all battery data during the study period. A second Campbell 23X datalogger used to record solar radiation (W/m^2) measured with a Pyranometer at 1-minute intervals. Both dataloggers were powered by a separate 12 V battery (35 mAh) connected to the own 4.5 W solar panel for recharging. Staff created a datalogger program using Edlog software embedded in the datalogger-controlled software PC400 (Campbell Scientific, 2011) (Appendix I). This datalogger program was measured discharge-recharge in millivolt (mV) from the batteries and battery voltages in volt (V) units at 5-second intervals and stored data in 5-minute averages. This datalogger can measure voltage between ±5000 mV. To measure 12 V battery voltages, a voltage divider terminal input module was constructed by connecting one 10 kΩ and one 100 kΩ resistor in a serial form on the black terminal strips (Figure 1 and Picture 2). These voltage dividers produce output that 1/11 of the original voltage (Campbell Scientific, Inc., 2007). This allows a voltage up to ± 50 volts to be measured on a 21X Datalogger within ± 5000 mV range. The batteries were connected to voltage divider as a single-ended measurement input for datalogger

measurement (Figure 1 and Picture 3). A total of three batteries were connected to this voltage divider for measuring their voltages (Figure 2).

Study set up

This study was conducted between August 14 and 30, 2012 at warehouse facility in West Sacramento. We conducted two sets of experiments: (1) The battery charging performance of the solar panels at different power levels was tested while two air pumps were in operation at a rate of 1500 ml/min; and (2) to investigate effect of different air pump rates on the current draw from the brand new batteries while they were being charge with solar panel at different power levels.

First set of experiments

In the first set of experiments, the charging performance of the solar panels was tested by running two air sampling pumps simultaneously at a rate of 1500 ml/min at each power level. All batteries in this first set of experiments have been in use for at least 8 years.

To charge the batteries powering two air sampling pumps, staff set up solar panels into three different power output configurations by using a combination of 4.5 W solar panels. A single solar panel produces 4.5 W power at its maximum output. The 4.5, 9, and 18 W power outputs were created by using one, two, and four solar panels, respectively. To measure discharge-recharge characteristics of the solar panels during day and night, a resistor block set-up was built by connecting three-10 W 3.3 Ω resistors with a 5% tolerance (NTE 10W3D3) in parallel resulting in a total of 1.2 Ω resisting unit to the ground (-) side of the batteries (Picture 4, Figure 2). The discharge-recharge (mV) was measured connecting differential channel measurement terminals (red lines in Figure 2) of the 21X datalogger (see details for differential channel measurement in CR 21X manual) where the voltage difference between the high and low inputs was read (Campbell Scientific, Inc., 1995). If the measured voltage is negative, it indicates that the battery discharging. If the measured voltage is positive, the battery is charging. Each solar panel configuration was connected to its own battery unit that was fully charged at the beginning of the experiment. In turn each battery was connected to two air sampling pumps (shown by brown dashed lines in Figure 2 and Picture 5). Each battery was connected to the datalogger via a voltage divider with a single-ended connection (see details for single channel measurement in CR 21X manual), which means the positive lead connected to the High (H) or (L) terminal of the datalogger and the negative lead connected to the Ground (G) terminal of the datalogger through a voltage divider (Figure 1) (Campbell Scientific, Inc., 1995). The datalogger and voltage divider initially were placed into a weatherproof enclosure to protect the instruments (Figure 2). Then all connections shown in Figure 2 were made to set up the study (Picture 6).

Second set of experiments
In the second set of experiments, we used the same experimental set up as in first set of experiment. The main objective of this part of experiment was to investigate effect of various flow rates of air pumps on current draw from a set of brand new batteries. Before starting the second set of experiments, the eight years old batteries were replaced with brand new batteries. Rechargeable batteries have a cyclic service life reflecting deterioration in their ability to hold a charge after many recharge cycles. The cyclic service life of a battery is the period until it drops to 60% of its rated capacity (Campbell Scientific, Inc., 2010). In our case, old batteries have already fulfilled their cyclic service. These experiments on the new batteries involved testing different flow rates and numbers of pumps operating: (a) one pump set at 1500 ml/min; (b) one pump set at 50 ml/min; and (c) two pumps, one set at 50 ml/min and the other at 1500 ml/min. Each experiment ran for approximately two hours. The charge-discharge rate (current draw) by solar panels from batteries was recorded for approximately 20 hours after pumps were stopped.

Results and Discussion

The first set of experiments
At the start of the study, batteries were fully charged. Figure 3 shows voltage changes in the batteries connected to the solar panels and two air sampling pumps operating at rate of 1500 ml/min. The pumps were started immediately after batteries were fully charged by their corresponding solar panels. The pumps operated continuously until they stopped due to low voltage in their batteries. Interestingly, both pumps connected to the 18 W solar panels stopped (came to hold) first after approximately 5 days (141.5 hours after the study started). This might be caused by a higher discharge rate at night when solar panels are not able to charge batteries, instead causing a higher current draw from the batteries (Figure 4). Only one pump was on hold or stopped around 149.5 hours in the 4.5 W solar panel set up, even though 18 W and 4.5 W batteries show similar voltage output (Figure 3). Other explanations for differences in when the pumps stopped are maybe the operational characteristics of the individual pumps, such as condition of valves. These older batteries may also have differed in their ability to hold and receive charge. There were insufficient samples for statistical evaluation. The pumps at 9 W solar panel set up were still operating until they were turned off at 153 hours. Regardless of the power solar panel set up, the voltage of batteries continuously dropped until the threshold value was reached, where pumps could not be operated. After turning off the pumps, the batteries were charged via solar panels almost a week. The battery connected to the 4.5 W solar panel (Figure 3, blue solid line) did not reach its original voltage of 12 V or higher within a week; it seems that its capacity diminished due to exceeding its operational life.

The batteries for powering the dataloggers kept their operational voltage throughout the study. These two batteries were connected to a separate 4.5 W solar panels which sufficed to maintain charge for each battery (Figure 3). Figure 4 shows the charge-discharge of the batteries using different powered solar panels. The night time voltage drain from the battery connected to the

18 W solar panel was the highest at the 600 mV compared to 400 mV for the 4.5 and 9 W configurations. DPR expected that voltage drain from the batteries would stay close together, as shown by the batteries connected to the 4.5 and 9 W solar panels. However, the excess battery drainage during the night due to the solar panels can be prevented by using voltage regulator. As expected, the charge of the batteries was correlated with the power of the solar panels (Figure 4). After turning off the pumps, the batteries showed net charges during the day, depending upon the solar radiation and small discharge due to current drain through all solar panel configurations during the night (after 153 hours in Figure 4).

The second set of experiments

At the beginning of this set of experiments, the new batteries were charged for four hours and then solar panels were shortly disconnected to prevent overcharging until the new flow rate of the pumps (50 ml/min) adjusted (Figure 5). This second set of experiments started with connecting solar panels to the corresponding batteries, thus observing peaks at the battery voltages just before starting tests with running pumps at 33 hours (Figure 5). The dramatic changes in the battery voltage were not observed due to short duration of the tests. However, relatively small changes in battery voltages during experiments with pumps set at different flow rates are shown in Figure 5 (insert) and its corresponding discharge trends in Figure 6 (insert). The single pump operating at rate of 1500 ml/min did not cause a drastic change in battery voltage whereas the discharge rates of all test subjects presented similar values (Figure 6, “a”). The experiment with flow rate of 50 ml/min drew more power from the batteries as expected because of more resistive operation on the diaphragm of the pump (Figure 6, “b”). Running the experiment with two pumps, one set at a rate of 50 ml/min and the other at 1500 ml/min, caused more draw from the battery (Figures 5 and 6, “c”).

Conclusions and future work

The results in this memorandum will serve as a base study for future works required to make more solid statements on the performance of solar panels for charging batteries. Moreover, the results of this study suggested that the batteries can be used for up to five days before they need to be replaced, when powered by solar panels. The system performs best using new batteries, as shown in the second set of experiments. The single 4.5 W solar panel set-up did not supply enough power to maintain operations at optimum conditions. Although the 9 W solar panel configurations presented better operational data, tests suggest that at least an 18 W solar panel configuration in combination with a voltage regulator will supply the required operational power demand for up to five days. However, to make above statement more reliable, DPR will plan to conduct another study investigating performance comparison of running pumps on brand new batteries connected to solar panels and with no solar panels. This will serve us better for quantifying the probabilities of pump failure with and without use of solar panels.

References

Campbell Scientific, Inc. 1995. 21X Micrologger operator's manual. Revision: 8/95. Logan, Utah.

Campbell Scientific, Inc. 2007. VDIV10.1, VDIV2.1 Voltage Divider Terminal Input Modules: Instruction manual, Revision: 5/07, Logan, Utah.

Campbell Scientific, Inc. 2010. Power supplies. Revision: 10, Logan, Utah.

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Table 1. Electrical characteristic of SX 405M solar panel.

Characteristic	**(1) STC 1000W/m^2**	**(2) NOCT 800W/m^2**
Maximum power (P_{max})	4.5W	3.2W
Voltage at Pmax (V_{mpp})	16.5V	14.7V
Current at Pmax (I_{mpp})	0.27A	0.22A
Short circuit current (I_{sc})	0.3A	0.24A
Open circuit voltage (V_{oc})	20.5V	18.7V
Module efficiency	6.7%	
Tolerance P_{max}	±10%	
Nominal voltage	12V	
Efficiency reduction at 200W/m^2	<5% reduction (efficiency 6.3%)	
Limiting reverse current	0.3A	
Temperature coefficient of I_{sc}	0.105%/ ^{o}C	
Temperature coefficient of V_{oc}	-0.360%/ ^{o}C	
Temperature coefficient of P_{max}	-0.45%/ ^{o}C	
(3) NOCT	47±2°C	
Maximum series fuse rating	1A	
Maximum system voltage	50V	

(1): Values at Standard Test Conditions (STC): 1000W/m^2 irradiance, AM1.5 solar spectrum and 25ºC module temperature.
(2): Values at 800W/m^2 irradiance, Nominal Operation Cell Temperature (NOCT) and AM1.5 solar spectrum.
(3): Nominal Operation Cell Temperature: Module operation temperature at 800W/m2 irradiance, 20ºC air temperature, 1m/s wind speed.

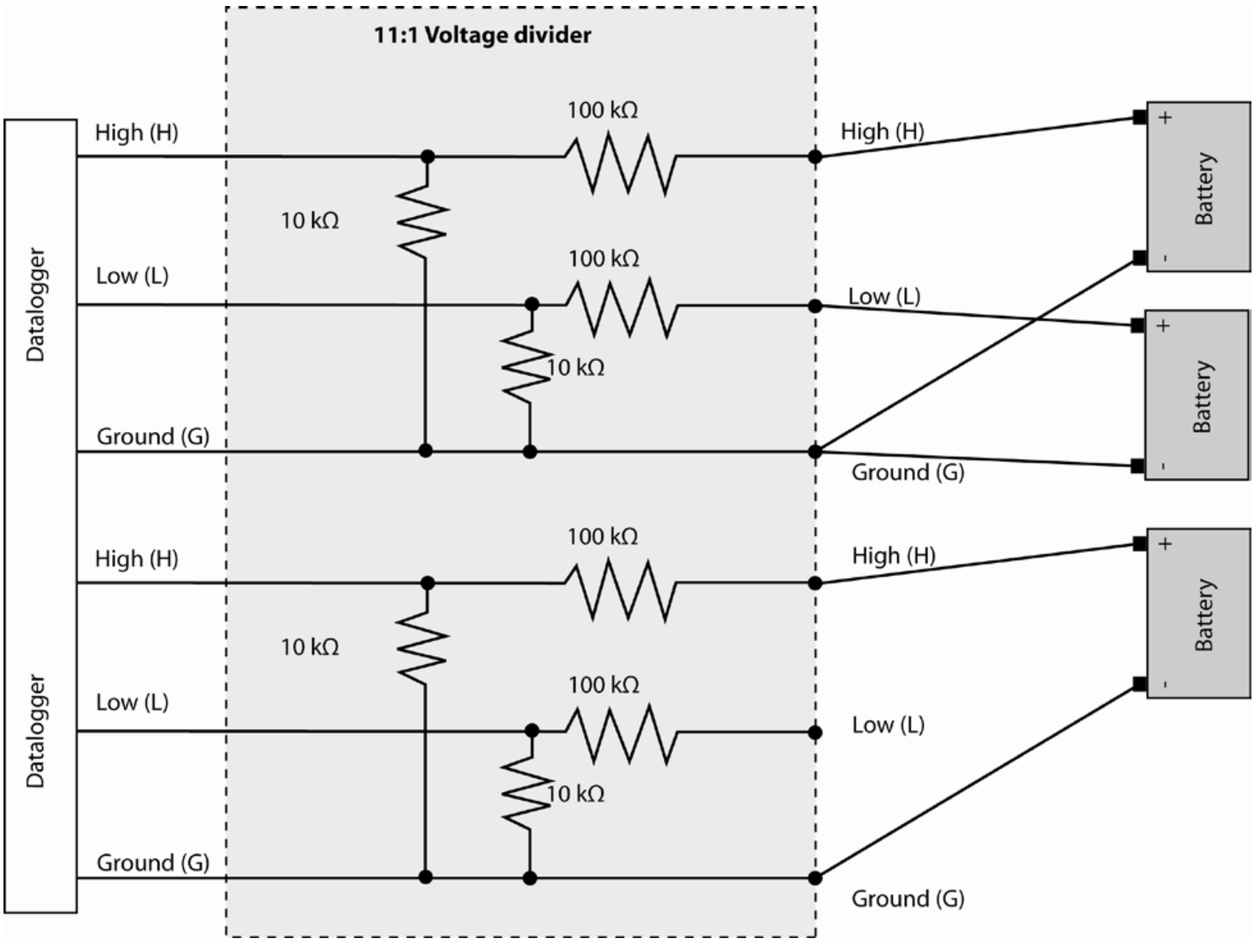


Figure 1. Schematic of 11:1 Voltage divider with connections to datalogger and tested batteries (Adapted from Campbell Scientific, Inc., 2007).

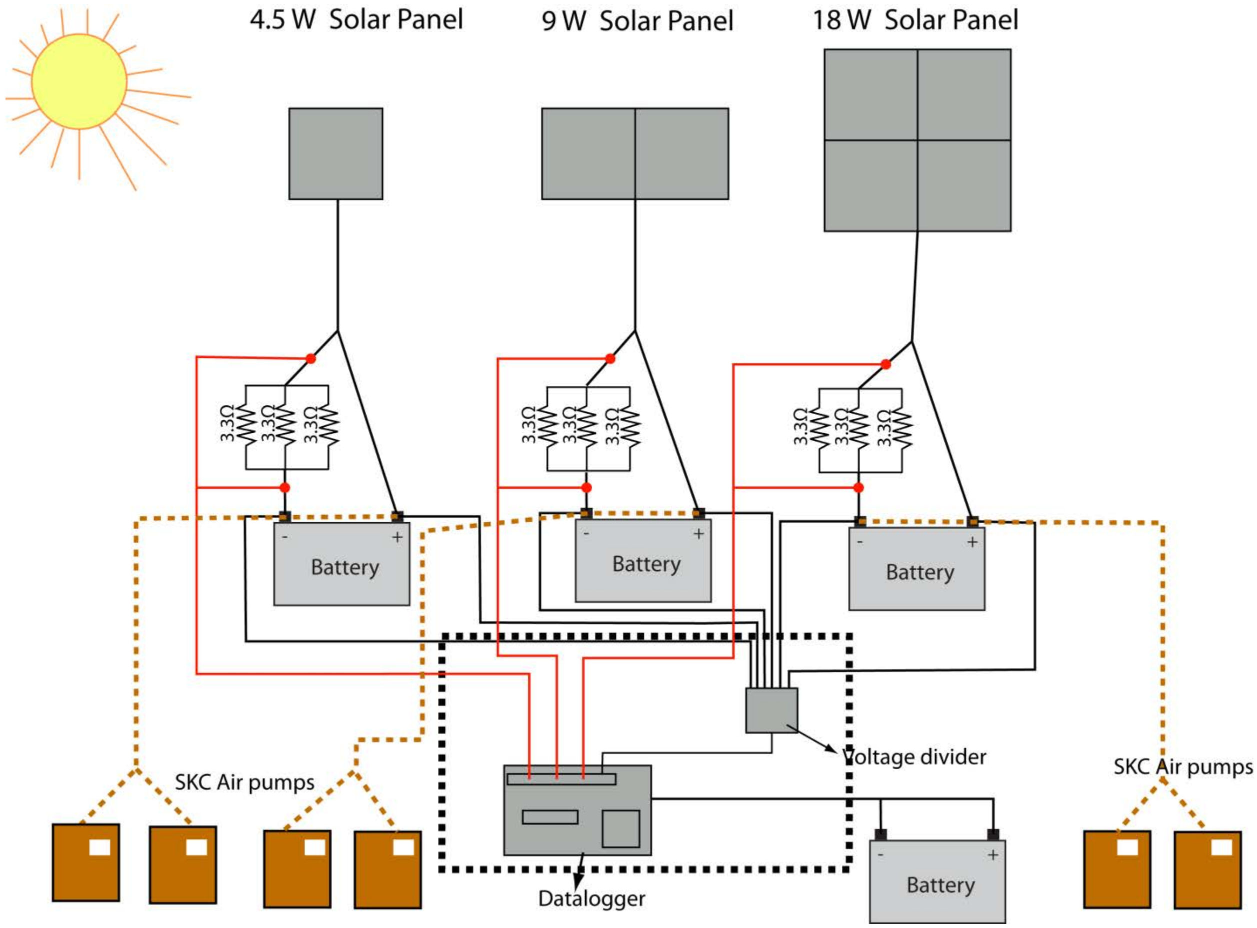


Figure 2. Schematic of study set up for monitoring solar panel performances. Heavy black dashed line represents weather proof enclosure. Light brown dashed lines represent connection between battery and air pumps. Red lines are connected to differential channel measurement terminals of datalogger whereas black lines coming from batteries connected to the solar panels are connected to the single channel measurement terminals of datalogger.

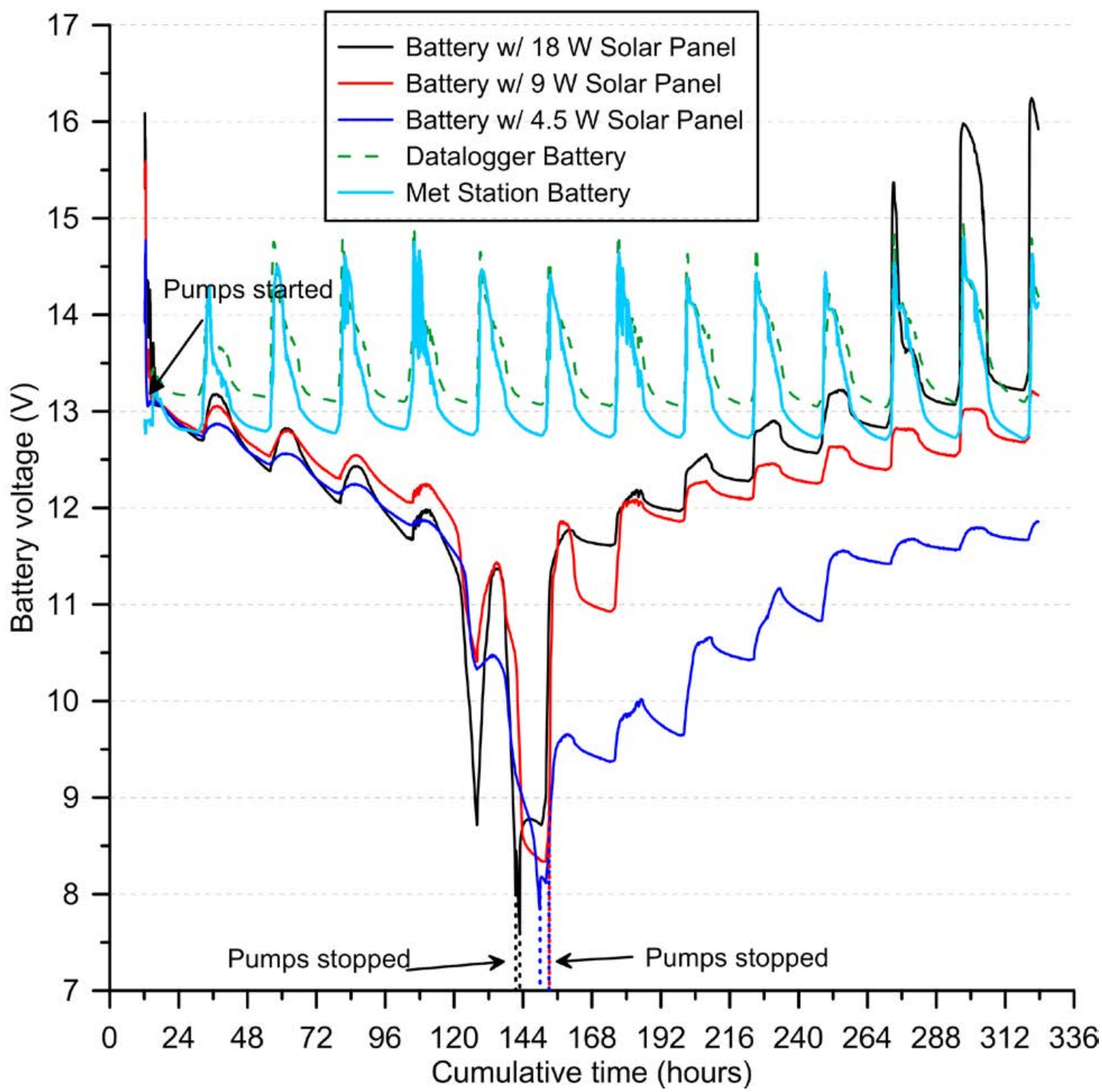


Figure 3. Battery voltage changes with operating two air pumps at a rate of 1500 ml/min and after air pumps were stopped at 153 hours.

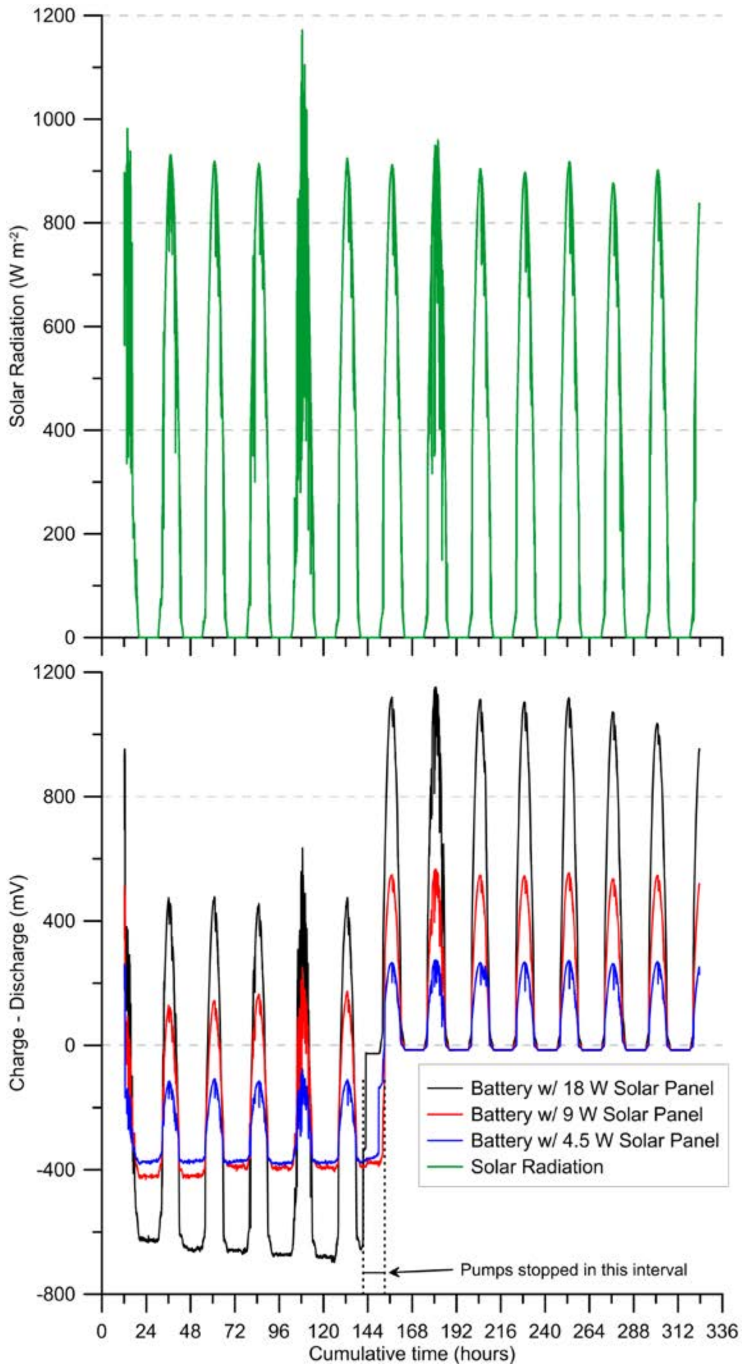


Figure 4. Charge-discharge (mV) of the batteries at corresponding solar radiation ($W\ m^{-2}$) with operating two air pumps at a rate of 1500 ml/min and after air pumps were stopped at 153 hours.

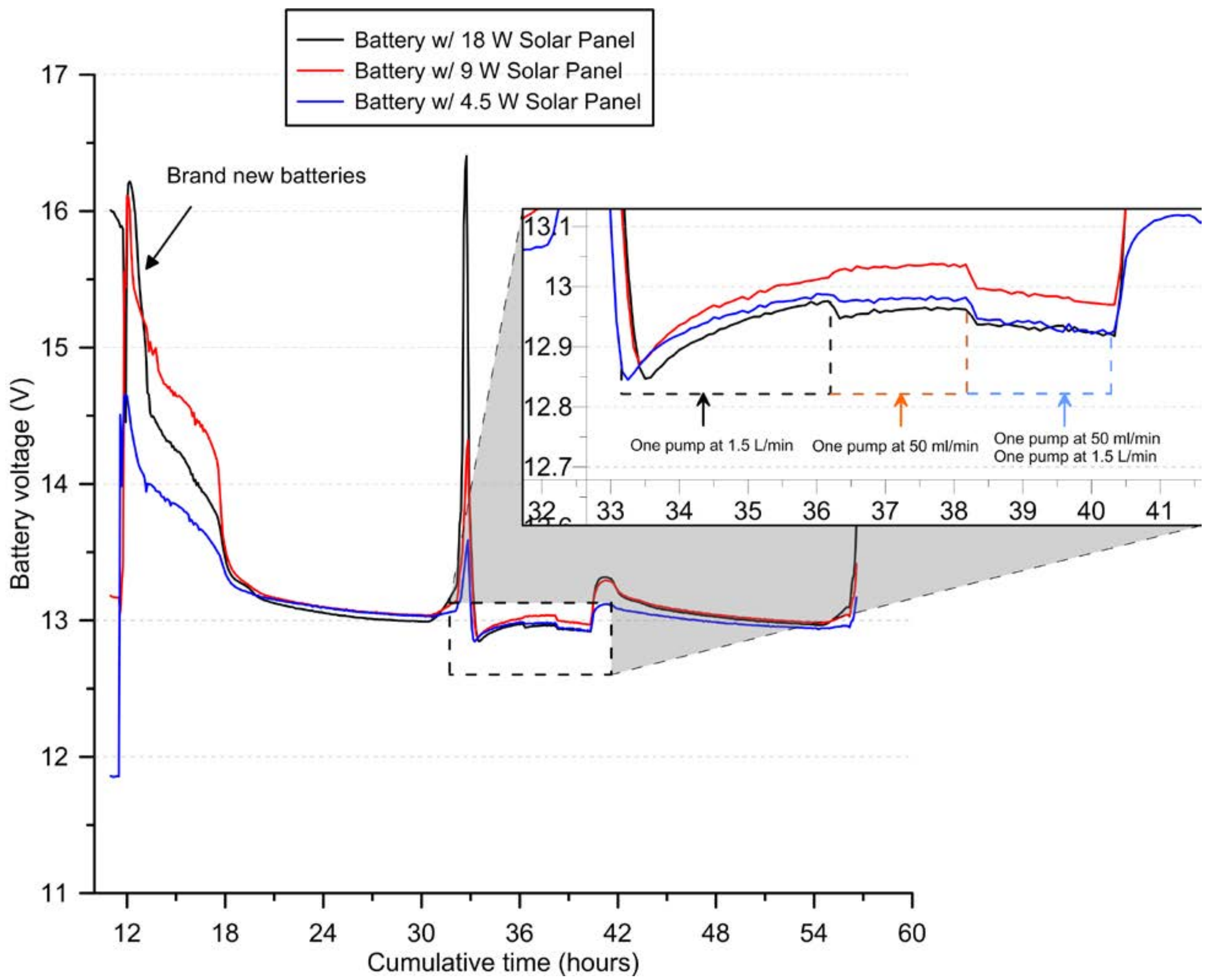


Figure 5. Battery voltage changes after changing into brand new batteries and applying different pumps flow rates (insert): single pump at flow rate of 1500 ml.min, single pump at flow rate of 50 ml/min, and combination of one pump at flow rate of 50 ml/min and one pump at flow rate of 1500 ml/min.

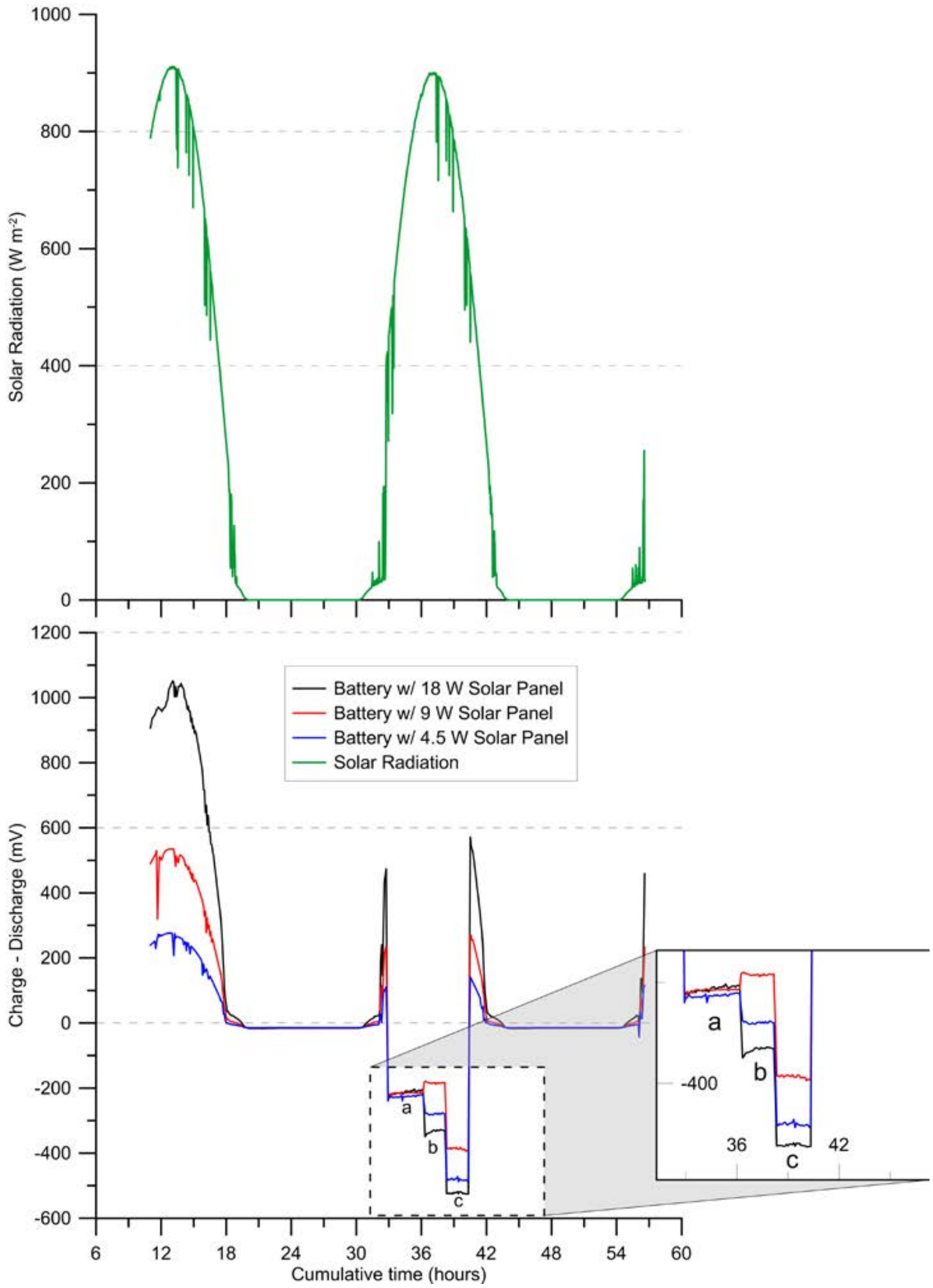
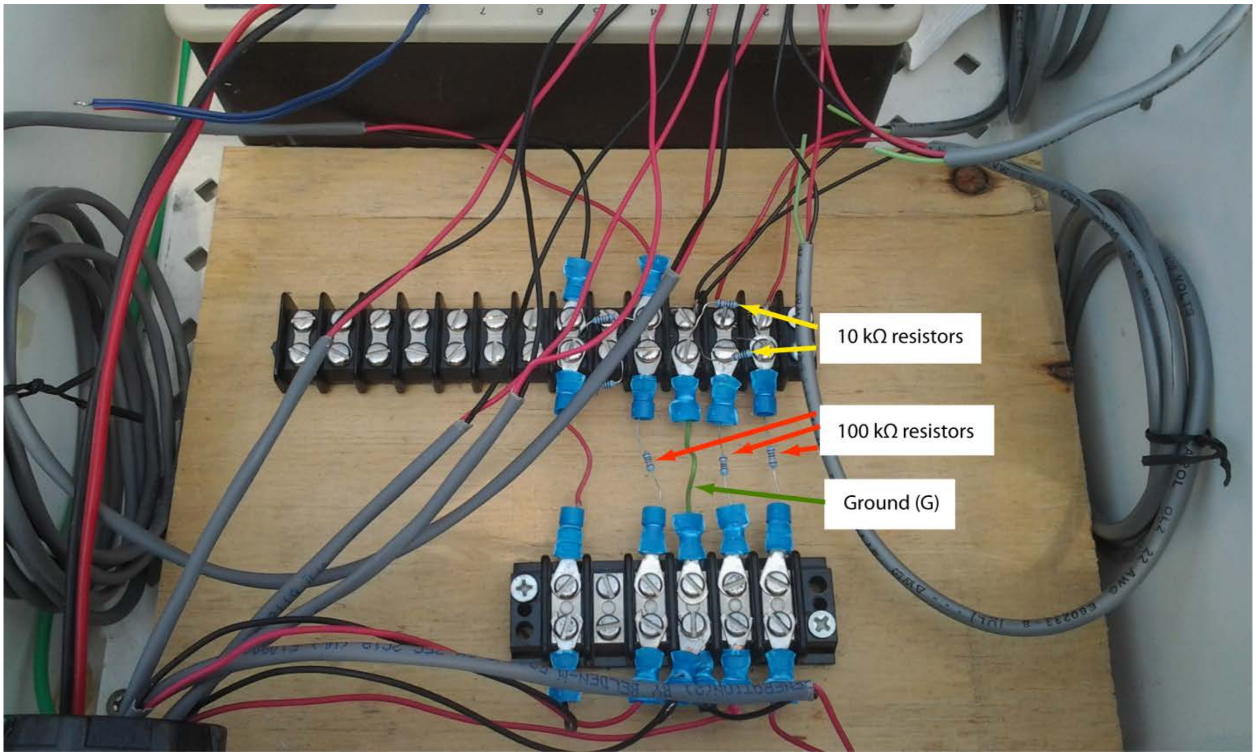
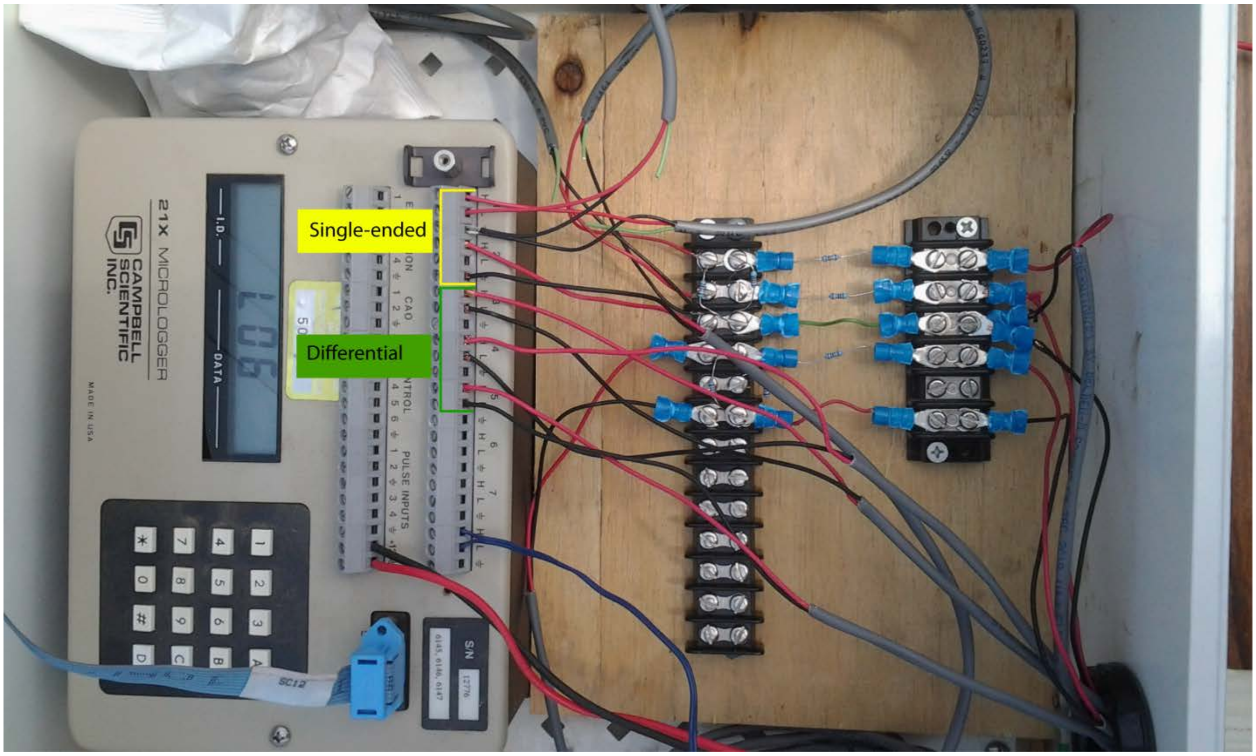


Figure 6. Solar radiation changes and charge-discharge from batteries after changing into brand new batteries and applying different pumps flow rates (insert): (a) single pump at flow rate of 1500 ml.min, (b) single pump at flow rate of 50 ml/min, and (c) combination of one pump at flow rate of 50 ml/min and one pump at flow rate of 1500 ml/min.

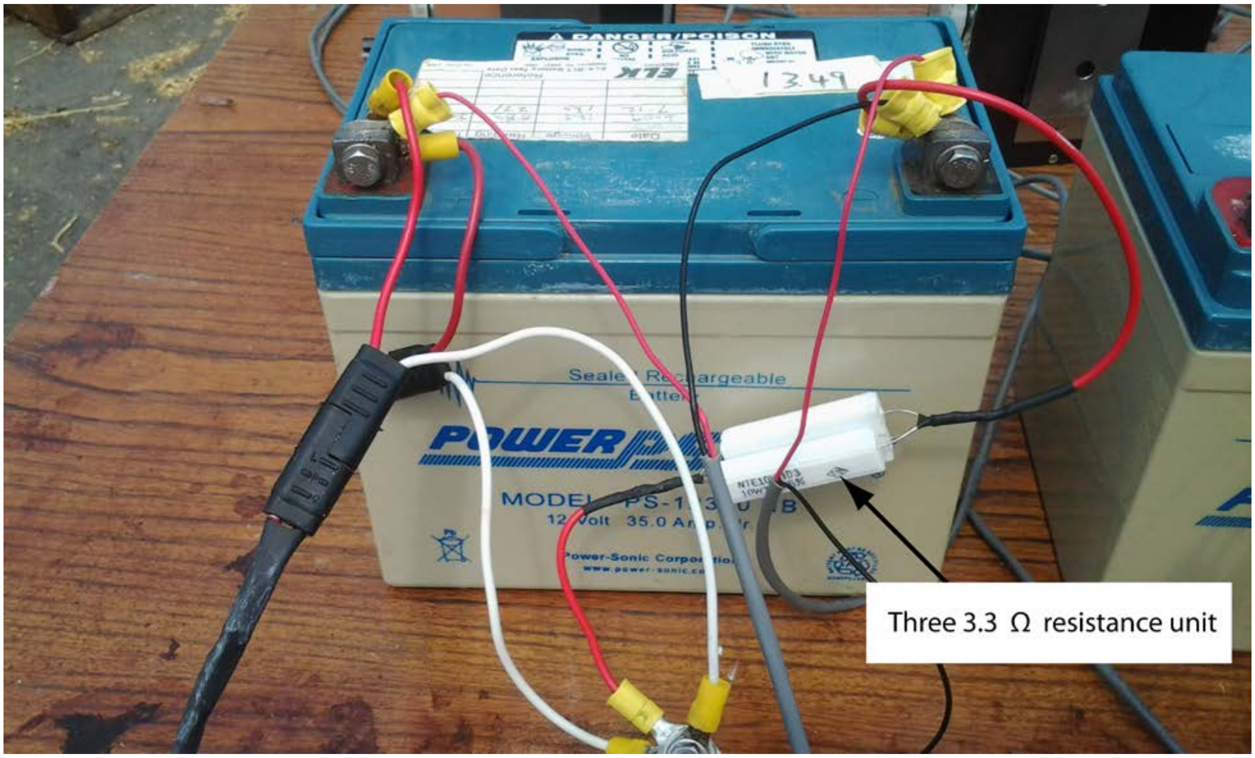
Picture 1. SX 405M 4.5 W Photovoltaic module (solar panel).



Picture 2. Built voltage divider by connecting 10 and 100 kΩ resistors in a serial way on the strips.



Picture 3. Connections of single-ended and differential measurements for battery (V) and discharge – recharge (mV) voltages, respectively.



Picture 4. The total of 1.2 Ω resistance unit with three 3.3 Ω resistors connected in parallel.

Picture 5. Batteries connected to the two SKC Aircheck pumps.

Picture 6. The study set up.

SolarPanelTest.csi

```
;{21X}
;
*Table 1 Program
  01: 5         Execution Interval (seconds)

1:  Volt (SE) (P1)
 1: 3        Reps
 2: 5        5000 mV Slow Range
 3: 1        SE Channel
 4: 1        Loc [ Batt1_1   ]
 5: 0.0110   Multiplier
 6: 0.0      Offset

2:  Volt (Diff) (P2)
 1: 3        Reps
 2: 5        5000 mV Slow Range
 3: 3        DIFF Channel
 4: 4        Loc [ Solar_1   ]
 5: 1.0      Multiplier
 6: 0.0      Offset

3:  Batt Voltage (P10)
 1: 7        Loc [ LogBat    ]

4:  If time is (P92)
 1: 0        Minutes into a
 2: 5        Minute Interval
 3: 10       Set Output Flag High

5:  Real Time (P77)
 1: 0110     Day,Hour/Minute (midnight = 0000)

6:  Resolution (P78)
 1: 1        High Resolution

7:  Average (P71)
 1: 7        Reps
 2: 1        Loc [ Batt1_1   ]
*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```