LI-COR greenhouse gas analyzers, including the LI-7200/LI-7500A CO₂/H₂O Analyzers, the LI-7700 Open Path CH₄ Analyzer, and greenhouse gas analyzer systems, are designed to monitor fluxes of CO₂, H₂O, and CH₄ from natural and human-managed environments. Frequently, these instruments are deployed in remote locations without access to grid power. Off-grid power sources must be used at these sites.

In recent years, photovoltaics (solar cells that convert sunlight to electricity) have become increasingly popular as energy sources which can be used in most remote locations. Off-grid photovoltaic (PV) power systems (Figure 1) consist of solar panels, batteries, electronics, enclosures, and a supporting structure. Constructing an efficient PV power system requires careful planning throughout the process, from selecting components, to placing the solar array. In this technical note, we describe some important considerations and provide guidelines for constructing an off-grid PV power source for eddy covariance flux systems.

Key PV system elements include:
- Solar panels - convert sunlight into electric energy
- Deep cycle batteries - store power produced by solar panels and provide power to instruments
- Charge controllers - protect batteries from overcharging and optimize the battery charging function
- Wires and cables - connect the electrical components

Supporting structures include:
- Panel mounting - supporting framework for the solar panels
- Battery enclosure - protects batteries and charging circuitry from environmental elements

Optional system components include:
- Combiner box - combines the output of each individual solar panel into one circuit
- Disconnects - circuit breakers that protect the various system components; one disconnect is placed between the solar panels and the batteries and another is placed between the batteries and the instruments

Designing a PV system
The main challenge for the off-grid PV system is to ensure that it can keep up with regular power demands and can provide enough power during infrequent peak periods. Keys to the design of such a system are: (1) computing power demands of the instruments, (2) evaluating how many batteries are needed to ensure operation at night and on overcast days, and (3) determining the number of solar panels that are required to satisfy power demands.

Power Requirements
The first important item to consider before designing a PV system is the power requirements of your system. Table 1 provides power requirements for some common instruments used in CO₂/H₂O flux measure-
ments. Table 2 shows the power requirements for the LI-7700 Open Path CH$_4$ Analyzer in a variety of configurations. Although Tables 1 and 2 give power requirements for normal operation, warm-up periods, and with accessories, the most important values to consider are the average daily wattage, which is determined based on the settings of each particular instrument.

Table 1. Power requirements for instruments commonly used in flux stations. Maximum power consumption for the LI-7200 and LI-7500A occurs during the warm-up period, which typically lasts about 10 minutes after the instruments are powered up.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Nominal Power Consumption (W)</th>
<th>Warm-up Power Consumption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LI-7200 Enclosed CO$_2$/H$_2$O Analyzer</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>LI-7200-101 Flow Module</td>
<td>15</td>
<td>n/a</td>
</tr>
<tr>
<td>LI-7500A Open Path CO$_2$/H$_2$O Analyzer</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>WindMaster Sonic Anemometer</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Power requirements for the LI-7700 Open Path CH$_4$ Analyzer and accessories. The cleaning cycle duration is from 10 to 120 seconds (30 seconds typically). Mirror heater power consumption is user-settable from 0 to 7.5 watts. It is only necessary to include LI-7550 power requirements if the LI-7550 is used solely with an LI-7700. Do not include the LI-7550 power requirements if it is part of an LI-7500A or LI-7200 CO$_2$/H$_2$O Analyzer.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Normal Operation (W)</th>
<th>During Cleaning Cycle (W)</th>
<th>Mirror Heaters On (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$ Analyzer</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Washer Assembly</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upper Mirror Heater</td>
<td>-</td>
<td>-</td>
<td>0-7.5</td>
</tr>
<tr>
<td>Lower Mirror Heater</td>
<td>-</td>
<td>-</td>
<td>0-7.5</td>
</tr>
<tr>
<td>With LI-7550*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>18</td>
<td>26</td>
</tr>
</tbody>
</table>

**Determine the size of the battery bank**

Batteries are needed to provide power to the system during the night and through periods with overcast skies. The size of the bank will vary with latitude and increase with the number of days the system needs to run without solar panel input. The example in Appendix A, step 7 is 4 days.

First, determine the acceptable number of days that can pass without solar input based on study site location and personal preference. The value entered in Appendix A, step 7 will equal the maximum allowable number of days you are willing to tolerate without sun power. Entering 4 days here ensures that your system will continue to operate in the design envelope without exceeding the battery discharge threshold (step 9), however, the system can and will continue to operate until the batteries are completely discharged. Note that if the batteries become excessively discharged, they may be damaged.

To compute the number of deep-cycle batteries to use in your system, follow steps 7-16. Because batteries should never be fully discharged, these examples conservatively assume that 50% is the maximum acceptable battery discharge (step 9). This number may be lower or higher depending on specific batteries. Again, this does not guarantee that battery discharge will not exceed 50% in certain circumstances.
An additional consideration is the size and weight of the batteries. Batteries with a higher amp-hour rating will be heavier than those with a low amp-hour rating. Standard batteries are either 6 V or 12 V; 6 V batteries are more portable. The best option for you depends on your study site. If you opt for 6 V over 12 V batteries and you wire them with heavy gauge cables (Figure 2), you can minimize power loss while retaining portability.

Figure 2. Battery bank in a solar system. Battery terminals are connected with heavy gauge cables and power is delivered to the system with heavy, low-resistance wires (e.g., 8 gauge). The charge controller is mounted on the left wall of the enclosure. The charge controller display/interface (lower left) is positioned for easy access and visibility.

After making the calculations in steps 7-15, round the result up to the nearest whole number (step 16). The example system would require a bank of 6 high-rated, deep-cycle batteries to operate continuously for 4 days without power input from the solar panels.

Determine the number of solar panels
Solar panels are the only elements in PV systems that actually produce electricity. Steps 17-24 in Appendix A establish the number of solar panels that are needed to power the entire system. The number of average sun hours per day (step 17) is important to determine the number of panels, and depends on the geographic location (the example here uses Lincoln, Nebraska). You can use reference websites such as:
http://www.solarexpert.com/Pvinsolation.html
or
http://www.solar4power.com/solar-power-insolation-window.html
to get solar insolation (sun hours/day) for major U.S. cities. The number of panels required will also depend on the efficiency of each panel. Enter the peak amperage of one solar panel (the example uses 7.1 amp peak panels).

After entering all the information in steps 17-23, compute the number of panels and round up to the next highest integer (step 24). The PV system configured to sample continuously near Lincoln, Nebraska, would require 3 solar panels with a peak of 7.1 amps.

System output and charge controller
A charge controller (Figure 2) regulates the power transfer from the PV array to the batteries, which prevents overcharging. In addition, it prevents the batteries from discharging into the solar array. Some charge controllers also monitor the temperature of the batteries to prevent overheating. Charge controllers may offer remote power monitoring and can show the overall operating efficiency of the system.

Advanced charge controllers, such as Maximum Power Point Tracking (MPPT) controllers, provide more sophisticated controls and can improve the efficiency of a PV system. MPPTs use feedback controls that allow solar panels to operate at maximum efficiency while charging the batteries with maximum efficiency.

Selecting the correct charge controller depends on the amp rating of the PV system, which in turn depends on the system output and rating of the solar panels. The PV systems in this example generally will produce around 375 Watts of energy (step 26), which should be enough to run the system’s equipment and charge the battery bank. This would require a charge controller capable of handling 31.3 Amps of current (step 28). Most controllers have actual ratings that are 25% larger than specified in order to handle unexpected short-term surges of current.

Other Important Considerations

Battery charge time
As an optional check on the system design, follow steps 29-32 of Appendix A to determine the number of sunny days it will take to recharge the batteries to 100% after 4 days of discharge (step 7). The number of dark days to support is determined by the design of your system. To find the total watt-hours of power generated by the solar panels each day, multiply the
output of the PV system (step 26) by the voltage of the solar array (step 27), which in our case is 12 V. To determine the excess power needed to charge the batteries (step 30), subtract the average load from the total power generated. The result of step 31 is the power needed to charge the batteries to 100%, including the battery loss factor. The total number of sunny days needed to recharge the batteries is then found by dividing step 31 by step 30. In the example, it takes 12.4 days.

**Bird deterrents**

Without a proper deterrent in place, the accumulation of bird droppings on solar panels may become a problem at your study site. We recommend setting up a deterrent system immediately to avoid this issue altogether. The best option is to create an uneven and uncomfortable landing area with the use of bird spikes. Another option is to use visual deterrents such as fake or holographic owls. Either option is humane and does not harm wildlife. There are a number of companies who offer bird control solutions; see the following websites for more information:

http://www.birdbusters.com/

or

http://www.birdbgone.com/

You can also construct your own bird deterrent using supplies that are available in most hardware stores, such as the zip-ties shown in Figure 3.

**Solar panel orientation**

Solar panels should generally face toward the solar south in the northern hemisphere and toward solar north in the southern hemisphere. The angle of inclination of the panels should be similar to the latitude of the study site near equatorial regions, but increase at latitudes that are closer to the poles, as shown in Figure 4 (e.g., at Lincoln, NE, 40.82°N, a 60° elevation angle from the horizontal plane at a 0° azimuth is ideal). You also may wish to adjust the tilt closer to horizontal in summer and closer to vertical in winter. The websites below are useful references when determining the latitude of your specific area/region:


or

http://www.srrb.noaa.gov/highlights/sunrise/azel.html

It is important to note that for some panels, shading may be detrimental to the entire system. Shading of just one (out of several dozen) PV cell in the module may lead to a total production loss of 50%. Other panels have bridging diodes, which minimize such losses. Therefore, it is crucial to be familiar with the type of PV panels being used and to avoid shading the panels regardless of their type.

**Safety considerations**

Deep-cycle batteries must be protected from the environment in a dry, well-ventilated enclosure for a number of reasons, including minimizing the risk of explosion (especially for open-cell batteries, where hydrogen can be released).

Cables and connections need to be properly chosen to handle the load in the particular PV system. All elements in the system should be carefully connected. Any losses in the system due to resistance in the connectors are more significant than in a typical home or office environment. The battery bank in a
PV system provides extremely high current and can melt/burn equipment or people very rapidly.

The solar system also must be properly grounded in order to prevent bodily injury, damage to equipment from faulty electrical components, and damage to equipment from lightning strikes. A Ground Fault Circuit Interrupter (GFCI) provides additional protection by detecting an unintended current path to ground and breaking the circuit if this occurs.

Installation by a professional electrician, particularly one who specializes in PV systems, is the most reliable choice, especially if there are specific regulations on the electrical setup and operation. However, with proper precautions, simple and reliable self-made PV systems can be successfully designed and constructed (Figure 5).

It also is important account for battery weight and study site location, as carrying multiple lead-acid batteries over long distances may be difficult.

Wind resistance
Strong winds can apply considerable force to a solar panel array. Therefore, the frame, mounting structures, and anchors must be heavy enough and strong enough to resist the force of strong winds. A concrete foundation is the most secure mount but anchoring stakes or sandbags will also work. Place the stakes or sandbags near the corners of the frame for the best anchoring.

Additional information on PV system design
Essential and optional components of the PV system are listed in Table 3. Figure 4 is a wiring diagram of a PV system that is similar to the system described in the example in Appendix A. This is one possible configuration, and components used in your system may differ from those shown in this schematic.

<table>
<thead>
<tr>
<th>Essential</th>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panels</td>
<td>DC panel</td>
</tr>
<tr>
<td>Mounting structure</td>
<td>Exterior disconnect for DC</td>
</tr>
<tr>
<td>Cables to batteries</td>
<td>Bird deterrent</td>
</tr>
<tr>
<td>Deep-cycle batteries</td>
<td>Lightning rod</td>
</tr>
<tr>
<td>Ventilated battery box</td>
<td></td>
</tr>
<tr>
<td>Battery interconnect cable</td>
<td></td>
</tr>
<tr>
<td>Charge controller</td>
<td></td>
</tr>
<tr>
<td>Fuses</td>
<td></td>
</tr>
<tr>
<td>Earth ground</td>
<td></td>
</tr>
</tbody>
</table>

There are numerous online and journal publications on the subject, as well as manufacturer-provided manuals for specific solar panels and commercial PV systems. A few useful examples of such literature are listed below.

A brief review of PV system principles is provided online by Solar4Power Advanced Energy Group at:
http://www.solar4power.com/solar-power-basics.html

Subsequent pages of this website also provide detailed discussions on the load, solar panel, and battery bank calculations. Another excellent source for general information on PV systems is the “System Design” section of the Colorado Solar Electric Company website:
http://www.cosolar.com/system_design/systems_home.htm

This page explains the differences between on-grid and off-grid systems, AC and DC types of PV systems and load estimates, and provides do-it-yourself instructions on assembling PV systems. A very detailed, step-by-step PV system worksheet calculator can be found in the guide produced online by SunWize Technology Company: Solar System Design Guides by SunWize:

This guide also contains look-up tables for the number of solar hours for a given geographic region, and for weather-related corrections on system efficiency. A number of companies conduct PV system assessment for specific cases free of charge with an equipment quote. Pricing will depend on the type of system constructed, the geographic location of the system, and which optional accessories are purchased; expect to spend $3500-$5000 USD.

Additional resources
American Solar Energy Society
(http://www.ases.org)


Figure 5. Schematic of a solar power system. With three 125 watt solar panels, this system could provide power year around to an LI-7500A Open Path CO₂/H₂O Analyzer, LI-7700 Open Path CH₄ Analyzer, Gill Windmaster Sonic Anemometer, and an Internet radio at LI-COR’s headquarters in Lincoln, NE (40.82°N, 96.68°W).
### Compute the flux system wattage

<table>
<thead>
<tr>
<th>Step</th>
<th>Instruments</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 LI-7700</td>
<td>Instrument specs</td>
<td>Watts</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 LI-7500A (includes LI-7550)</td>
<td>Instrument specs</td>
<td>Watts</td>
<td>12.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Sonic anemometer (Gill WindMaster)</td>
<td>Instrument specs</td>
<td>Watts</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Internet radio</td>
<td>Instrument specs</td>
<td>Watts</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Watts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Watts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>Watts</td>
<td>27.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Compute amp-hours per day

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Average load (power per day)</td>
<td>Multiply [1] by 24 (hours/day)</td>
<td>Watt-hours/day</td>
<td>648</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Battery loss factor</td>
<td>Assumed conservatively</td>
<td>Percent</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>System voltage</td>
<td>Instrument specs</td>
<td>Volts</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Amp-hours per day consumed</td>
<td>Divide [4] by [5]</td>
<td>Amp-hours/day</td>
<td>64.8</td>
<td></td>
</tr>
</tbody>
</table>

### Determine the size of the battery bank

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Number of dark days to support</td>
<td>Specific to region/preferences</td>
<td>Days</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Amp-hour storage</td>
<td>Multiply [6] and [7]</td>
<td>Amp-hours</td>
<td>259.2</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Depth of discharge (100% is total discharge)</td>
<td>50% is safe 80% usable</td>
<td>Fraction</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Total storage required, corrected for discharge</td>
<td>Divide [8] by [9]</td>
<td>Amp-hours</td>
<td>518.4</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Battery rating</td>
<td>Battery specifications</td>
<td>Amp-hours</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Battery voltage</td>
<td>Given</td>
<td>Volts</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Total # of batteries needed</td>
<td>Multiply [13] and [14]</td>
<td>Number</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Total # of batteries, rounded</td>
<td>Round [15] up</td>
<td>Number</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

### Determine the number of solar panels

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Sun hours per day, worst month</td>
<td>Depends on your region (Lincoln, NE; December)</td>
<td>Hrs/day</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Peak amperage of solar panel</td>
<td>Panel specifications</td>
<td>Amps</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Efficiency of charge controller</td>
<td>MPPT ~97%</td>
<td>Percent</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Number of solar panels in parallel</td>
<td>divide [18] by ([19]*[20])</td>
<td>Number</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Number of panels in series (12 V)</td>
<td>Panels are nominally 12 V</td>
<td>Number</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Total number of solar panels</td>
<td>Multiply [21] and [22]</td>
<td>Number</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Total number of solar panels, rounded</td>
<td>Round [23] up</td>
<td>Number</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
## System output and charge controller

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Power rating of the panel</td>
<td>Panel specifications</td>
<td>Watts</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Voltage of the solar array</td>
<td>Solar panel specs</td>
<td>Volts</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Controller amp rating</td>
<td>Divide [26] by [27]</td>
<td>Amps</td>
<td>31.3</td>
<td></td>
</tr>
</tbody>
</table>

## Battery charging time

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>Source of Information</th>
<th>Units</th>
<th>Example</th>
<th>Your System</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>Total power generated by solar panel per day</td>
<td>Multiply [26] by [17]</td>
<td>Watt-hrs</td>
<td>1312.5</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Power to charge batteries to 100% (including loss) from depth of discharge</td>
<td>[11]<em>[16]</em>[5]<em>(1+[3])</em>[9]</td>
<td>Watt-hrs</td>
<td>8208</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Number of sunny days to charge batteries</td>
<td>Divide [31] by [30]</td>
<td>Days</td>
<td>12.4</td>
<td></td>
</tr>
</tbody>
</table>