Table of Contents

Table of Contents continued on the **next page**

Click on the chapter head or subheading page number to go to the section or chapter

TOC

Table of Contents

Table of Contents continued on the **next page**

Click on the chapter head or subheading page number to go to the section or chapter

TOC

Table of Contents

Click on the chapter head or subheading page number to go to the section or chapter

Introduction

Converting solar energy to electricity via photovoltaic cells is one of the most exciting and practical scientific discoveries of the last several hundred years. The use of solar power is far less damaging to the environment than burning fossil fuels to generate power. In comparison to other renewable energy resources such as hydro power, wind, and geothermal, solar has unmatched portability and thus flexibility. The sun shines everywhere. These characteristics make solar power a key energy source as we move away from our fossil fuel dependency, and toward more sustainable and clean ways to meet our energy needs.

The sun is a powerful energy resource. Although very little of the billions of megawatts per second generated by the sun reaches our tiny Earth, there is more than enough to be unlimited in potential for terrestrial power production. The sunlight that powers solar cells travels through space at 186,282 miles per hour to reach the earth 8.4 minutes after leaving the surface of the sun. About 1,368 W/M^2 is released at the top of the earth's atmosphere. Although the solar energy that reaches the Earth's surface is reduced due to water vapor, ozone layer absorption and scattering by air molecules, there is still plenty of power for us to collect. Harvesting photons for use in homes, factories, offices, vehicles and personal electronics has become practical, and economical, and will continue to increase in its importance in the energy supply equation.

Introduction

In my opinion, the most exciting aspect of photovoltaic power generation is that it creates opportunities for the individual power consumer to be involved in the production of power. Even if it is only in a small way, you can have some control of where your energy comes from.

Almost anyone can set up a solar panel and use the power – independent of the grid and other "powers that be." Batteries and supercapacitors for the electronic devices that we use on a daily basis can be recharged by this natural and renewable energy resource. Doing so cuts down on pollution and makes life better for everyone. Practically every aspect of our lives will be touched in a positive way by the increasing use of solar electric power.

Solar Cells

Solar cell basics

A solar cell is a solid state semiconductor device that produces DC (direct current) electricity when stimulated by photons. When the photons contact the atomic structure of the cell, they dislodge electrons from the atoms. This leaves a void which attracts other free available electrons. If a PN junction is fabricated in the cell, the dislodged photons flow towards the P side of the junction. The result of this electron movement is a flow of electrical current which can be routed from the surface of the cell through electrical contacts to produce power.

The conversion efficiency of a solar cell is measured as the ratio of input energy (radiant energy) to output energy (electrical energy). The efficiency of solar cells has come a long way since Edmund Becqueral discovered the photovoltaic effect in 1839. Present research is proceeding at a fast clip to push the efficiencies up to 30% and beyond.

The efficiency of a solar cell largely depends on its spectral response. The wider the spectrum of light that the cell can respond to (the spectral response), the more power is generated. Research is ongoing to develop techniques and materials that can use more of the light spectrum and thus generate more power from each photovoltaic cell.

The reflectivity of the cell surface and the amount of light blocked by the surface electrodes on the front of the cell also affect the efficiency of solar cells. Anti-reflective coatings on cells and the use of thin electrodes on the surface of cell faces help to reduce this loss of photonic stimulation.

Another factor in cell efficiency is the operating temperature of the cell. The hotter a cell gets, the less current it produces. Inherently, solar cells in use get hot, so it is important to have them mounted in such a way that they are cooled as much as possible to keep current production at its maximum.

Silicon is the most widely used material for solar cells today, though this is changing as thin film amorphous technologies are achieving greater efficiencies using materials such as gallium arsenide, cadmium telluride and copper indium diselenide.

Amorphous cells

There are basically two categories of amorphous cells: high efficiency non-silicon thin film amorphous, and low efficiency silicon amorphous. Both types of amorphous cells are manufactured using physical vapor, chemical vapor or electrochemical deposition techniques. These compounds are usually deposited on low cost substrates such as glass, stainless steel, or a polymer.

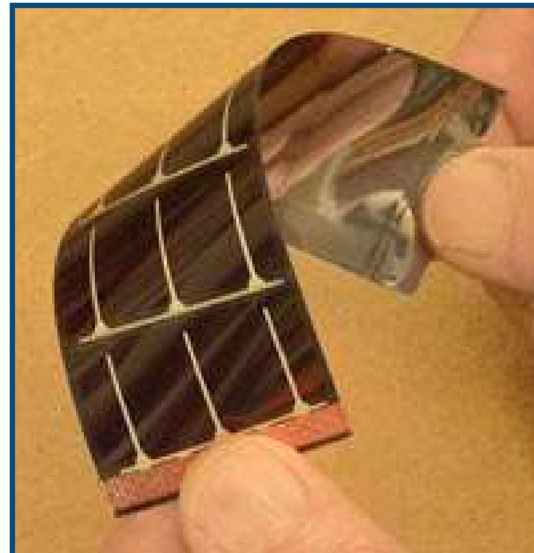
Low efficiency amorphous silicon cells are generally used for trickle charging batteries and low power needs. They are not recommended for serious power systems when space is at a premium as their efficiency at present ranges from 4% to 8%. Although silicon amorphous panels are not as efficient as mono, poly, and non-silicon thin film, amorphous silicon panels produce more power under scattered, diffuse, and cloudy conditions. They are more responsive to the blue end of the light spectrum which is dominant under these conditions. If you live in an area with a lot of cloudy weather, you may wish to use silicon amorphous. Generally, under light cloud cover, silicon amorphous panels are more efficient, but they require about twice as much space to produce the same amount of power as silicon crystalline cells.

Amorphous panels are less expensive to manufacture, and thus to buy. However, the price savings need to be considered along with the cost of more rack material, more space and more wiring. This can add up. Most solar installers would not recommend amorphous silicon panels for a home power setup, but would recommend them for installation in commercial buildings where the look of amorphous panels blends well into the architectural aesthetic and there is plenty of facade and roof surface available. This concept is currently called BIPV, Building Integrated Photovoltaics.

Non-silicon thin film amorphous cells are generally high output. Some types can reach efficiencies of up to 25%. They are excellent choices for all power applications, however at present they are more expensive than other types of cells available.

Flexible solar cells

Polymer based amorphous flexible solar cells are interesting in that you can attach them to backpacks and articles of clothing like jackets or hats. They are handy for special applications like model building, planes trains, dirigibles, balloons and model rockets for high altitude experimentation, robotics and in general where you need flexibility to mount them on curved surfaces. These are available in either low efficiency silicon or high efficiency non-silicon thin film.



Amorphous flexible solar cell

Crystalline solar cells

There are two types of crystalline solar cells: polycrystalline and monocrystalline.

Crystalline solar cells are produced mainly by the Siemens process, the Czochralskie process, and ribbon process. In the Siemens process, trichlorosilane, or silane is fed along with hydrogen into a chamber in which slender rods of electronic grade silicon are heated to over 1000°C. This process produces a polycrystalline ingot.

In the Czochralskie process, silicon chunks are heated to over 1000°C and a seed crystal is put into the melt and raised slowly while being rotated. The silicon solidifies and forms a single crystal growth. This produces a monocrystalline ingot.

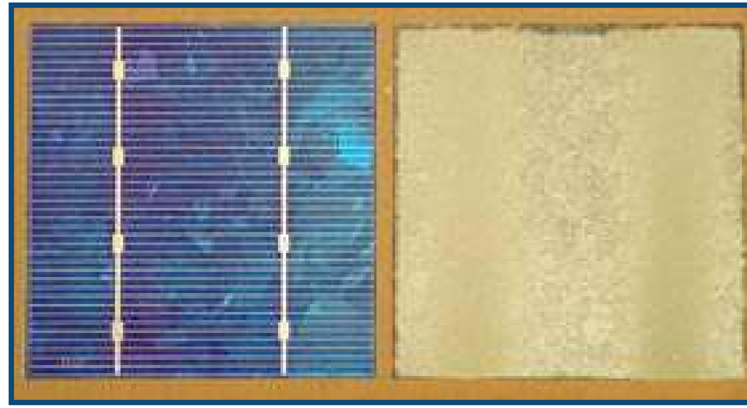
Another method is the ribbon forming process in which strings are pulled through a container of molten silicon. The molten silicon solidifies between the strings and forms a continuous ribbon.

In each process, after the crystal is formed, it must be cut into wafers and/or cut to size, polished, etched, and a PN junction formed. Then, the front electrodes and back contacts are applied. Finally, an anti-reflective coating is applied.

In this book we will focus on the use of polycrystalline and monocrystalline solar cells for building solar panels because they are easy to work with, are most readily available in the secondary market, and provide a good power output that is cost effective.

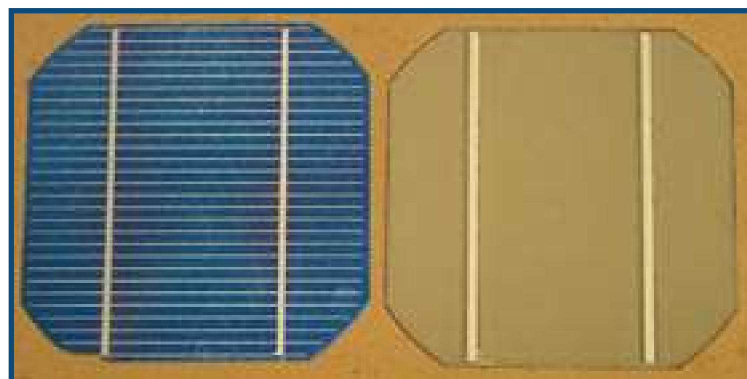
Monocrystalline and polycrystalline cells

Polycrystalline and monocrystalline cells generally have an efficiency of 8% to 15%. Of these two types of silicon cells, the single crystal (monocrystalline) cell produces more current from a given area of exposed surface than the same area on a polycrystalline cell. Single crystal cells are also more expensive to manufacture. This is of course reflected in the cost of the cells to the end buyer.



Magnified surface of polycrystalline cell

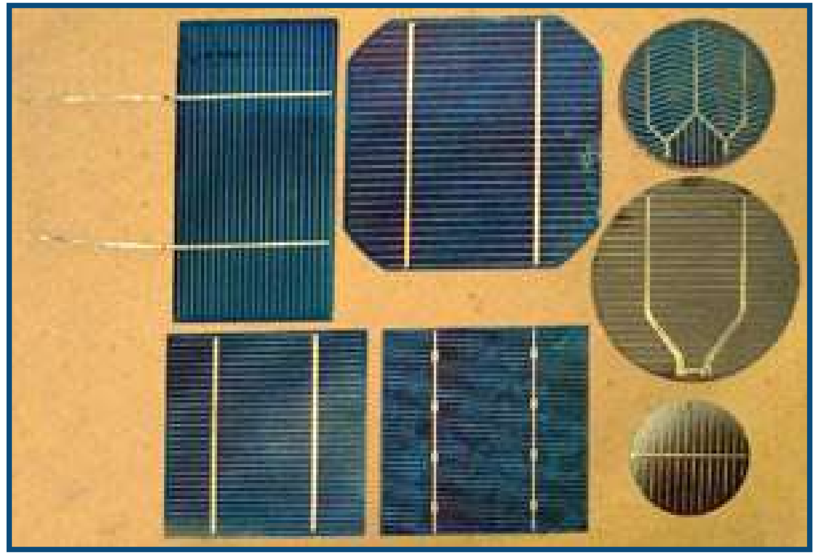
Polycrystalline cell, above; Monocrystalline cell, below



TOC

Either of these types of cells is fine for the construction of solar panels, but if you want to get the most power from a given amount of space, use monocrystalline cells.

Both poly- and mono-crystalline cells come in several shapes and many sizes. The basic cell shapes are round, square, pseudo-square and rectangle. Cells can be cut to just about any size needed by the manufacturer.



Various solar cell shapes. Top left to right, rectangle, pseudo-square; three round cells on the right; and bottom left, two square cells.

New cells vs. old-style cells

The structure of photovoltaic cells has changed over time. They are becoming thinner, which makes them less expensive to make since the manufacturer can get more cells from a given amount of silicon and other active materials in the ingot, ribbon, or deposition process. The cells are now easier and less costly to manufacture, but they are much more fragile and delicate than the older cells, and require much more care in handling and soldering.

The electrode contacts are also becoming thinner. The older cells, usually round in shape, have heavy solder contacts on the front side of the cells, and the backs are usually totally covered with solder. Cells made today have just thin lines or spots of solder that are usually vapor deposited or silk screened onto the cell.

Above, older style cells, with solder covering the backs; below, newer cell with six solder spots on the back.

Solar cell output

Solar cells all produce about 0.5 volts, more or less, no matter how large they are. However, the size of the cell does affect the current output. The larger the surface area of the cell, the more current it will produce. A 2" square cell will produce less current than a cell that is 4" square, all other parameters being equal. This is important to consider when you design panels for a specific purpose. If you need a lot of battery charging power (amps), your panels should have high current output cells. If your power needs are minimal and/or you live in a fairly sunny climate, you can do well with lower current cells.

Cells with high current output are generally more desirable; but, the higher the current output, the more they will cost. High current cells will recharge batteries faster in less than perfect solar power conditions, such as in a climate prone to cloud cover, or during winter months when the sun is low on the horizon and less light is available daily. So, seasonal and local climate conditions should be considered when selecting the cells to use for building a panel.

Another very important consideration is how much energy will be drawn from the batteries on a daily basis, and thus how much the batteries are being drained, and how much time will be required to recharge them each day.

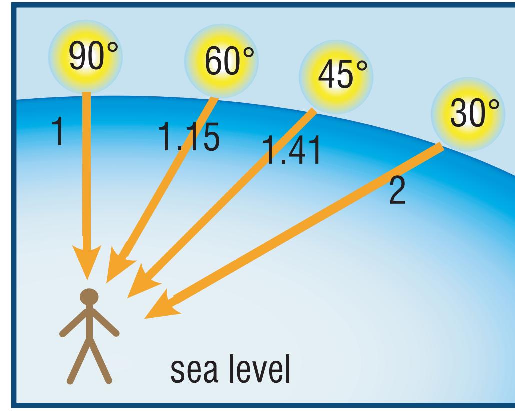
Watt rating of solar cells

When looking for solar cells, notice that a voltage rating and a current rating (amperage) is given. These figures are called open circuit voltage and short circuit current ratings. If you multiply the current by the voltage you will get the watt power rating of the cell. For instance, a cell with a voltage rating of 0.5 volts and a current rating of 4 amps is rated as a 2 watt cell.

Generally cells range from milliamps on up to 6 amps output. For most practical projects a 1 to 4 amp cell will suffice. Two to three amp cells are more commonly used and are the most readily available at a decent price.

Testing solar cells

Solar cells are tested by the manufacturer with artificial light under what is called AM1 conditions. AM stands for air mass. Air mass is the amount of air the photons have to travel through before they reach the surface of the earth at sea level. Air mass 1 is when the sun is directly overhead at sea level. The energy available to the solar cell at AM1 is equivalent to about 1kW/m^2.



Air mass conditions

Match solar cell output

You need to test each and every cell that will be used in your panel. If you are dealing with off-spec cells, the cells must be grouped into categories of high, medium, and low output. If you include a low output cell in a panel with cells that are higher output, the low output cell will bring all the other cells down to its lower rating. They don't have to all have the same dead-on output, but they should be in the ballpark for what you want the panel to produce. One cell that is of very low output can deprive you of a lot of energy from the other cells.

Cells can be tested in the sun on a very clear day. The ideal time to test cells outdoors is during the summer when the sun is at its highest point around the solstice, and at solar noon. This gets you the closest to AM1 conditions. However, you can test your cells using the sun at any time of the year. If you do this, take into consideration that the output from the cells will be less than their peak output under ideal conditions.

Stand for testing solar cells

Any light conditions can be used to tell how well the cells perform in comparison to each other, since you don't need to know their peak output for matching. The comparison of each cell's output to the others is really the critical issue.

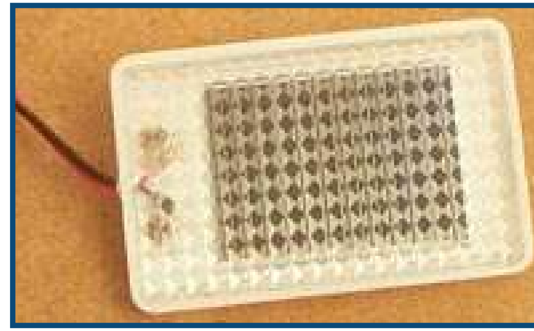
Tools for testing solar cells

To test the cells you will need a multimeter that gives a current (amperage) reading and a voltage reading. All multimeters have these two readings available. It's also useful to make a stand that will hold the cells at the same angle as the sun above the horizon, and that can be pointed in the direction of the sun. You can just hold the cells with your hands, but this can be clumsy.

My testing stand has a piece of copper clad circuit board to lay the cells on. With this arrangement I can connect the multimeter with the back of the cell simply by touching the multimeter probe to the copper on the circuit board. With this method, however, you have to be sure that the contacts on the back surface of the cell connect well with the copper on the board.

To take a reading, touch the negative probe to one of the cell fingers on the face of the cell and touch the other (positive) probe, to the back of the cell (or the copper surface of the circuit board if you are using one). The cell should be facing in the direction of the sun and at the sun's angle. Take both the voltage and current reading for the cell, and write it down. Proceed similarly with the other cells, grouping them as you go along.

Test all of your cells on the same day. If you test the same cell on two different clear days, you may get quite different readings, although conditions one day might appear to be the same as the other day, there can be a significant difference in available sunlight due to the level of aerosols present. Particulates, moisture, general pollution, and pollen all affect cell output readings. With repeated observations, you will be able to discern the aerosol levels in the atmosphere.



Calibrated solar cell

Using a calibrated cell

One way to measure light intensity when working with solar cells and panels is to use a calibrated cell. This is simply a photovoltaic cell that has been exposed to artificial AM1/full sun (1kW/m2) condition light, and the output marked on the back of the cell. The calibrated cell can be used to indicate what percentage of AM1 conditions you have when testing other cells and panels. For instance, if the current output of the calibrated cell under AM1 conditions is two amps, if you get a reading of one amp, it indicates that light conditions are 50% or ½ AM1.

To test cells using a calibrated cell, write down the calibrated cell reading and then write down current readings for the cells being tested. This will indicate what your cell output is for a specific light condition. Since the output of a silicon solar cell is linear you can extrapolate from this reading what your cells will output at different percentages of AM1.

A calibrated cell can be purchased from one of the suppliers listed in the suppliers list on page 137. They are also excellent for comparing the performance of different types or lots of cells that you may have so that you can discern which cells to use for different projects.

When testing single cells with a calibrated cell, you need a fixture like the test stand shown on page 13 to hold both the calibrated cell and the cell being tested at the same position and angle to the sun. This can be as simple as a flat board.

TOC

Solar Panels

Solar panel output for different applications

Most simple series connected solar panels are rated into three categories:

- 15 to 16 volts – usually 30 to 32 cells per panel
- 16.5 to 17 volts – 33 to 34 cells per panel
- 17.5 to 21 volts – 35 to 36 cells per panel

15 to 16 volt panels are referred to as self-regulating panels because they do not produce enough voltage to overcharge batteries, which results in gassing. For this reason they do not require a charge regulator as the other panels do. This reduces the cost and maintenance of a system. These are referred to as battery maintainers, and are excellent to use in small system with one battery if the system does not have much of a power drain. Electric fences, and other low power applications that have limited energy use can use these types of panels.

16.5 to 17 volt panels are adequate for full fledged powers systems in locations that generally get a lot of sun year round, such as the US Southwest.

The preferred panel for most solar charging applications is a 35 to 36 cell panel which delivers from 17.5 to 21 volts open circuit voltage. A 36 cell panel is recommended for very hot climates in order to offset power output loss from high temperature. They also compensate for voltage drop in systems with long wire runs.

I usually construct panels with 36 cells for basic 12 volt lead acid battery charging. One of the great advantages of building solar panels is that they can be built to exactly the voltage and current needed for your project by adjusting the type and quantity of cells.

Solar panel ratings

Solar panels are rated in many different ways. The ratings provide a baseline to project what the power output could be under a variety of different conditions. Some of the designations that manufacturers use are Wp (peak watts) and Pmax (maximum power).

If you use off-spec cells in your panels you will not know where a panel will land in the IV or voltage current curve until it is finished and you can test it. Each cell in the panel may output slightly different voltage and current, and they will all be added or subtracted together for the whole panel's output.

When the finished panel is tested, you will have a better, although still not perfect, reading of its output. The reason it will not be perfect is that you will probably not be testing the panel under laboratory conditions where temperature and light intensity are absolutely controlled. This is not too much of a concern since most laboratory panel tests do not reveal real working conditions, anyway. Very few panels will see laboratory AM1 conditions in service, nor will they be

TOC

in the constant even temperature on which the ratings are based. So, remember that there is a discrepancy between real life working conditions and the rated output of commercial panels.

The truth is you will never know how a panel will perform until it is installed in the system where it will be in service. The output of a particular panel or array depends a lot on the battery load. Each type of battery acts differently and has different internal resistances and so on. The variables go on and on. In a tropical location with lots of sun you might think a panel would be near optimum output, but in fact heat above a certain point usually reduces performance as output is temperature sensitive.

Designer watts

In designing panels with off-spec and blemished cells you will only be concerned with what we call "designer watts." Designer wattage is simply the open circuit voltage multiplied by the short circuit current. Panel designers use this figure to rate the components used in the panel and peripheral components

For instance, if a panel delivers about 20 volts open circuit and 3.5 amps short circuit current, the designer wattage would be 70 watts. The system components must be able to handle 70 watts, at 3.5 amps and 20 volts.

A panel rated at 70 designer watts will in fact probably give you about 54 watts in real use. This is a ballpark figure and will vary depending on the efficiencies of the cells as well as other conditions mentioned.

Finding and choosing cells for solar panels

Each type of cell has its own individual characteristics. Don't mix cell types in a single panel – each panel should consist of only one type of cell.

Getting to know your cells can save you a lot of money and aggravation in the long run. In practice I have never had a cell I could not work with, but for big projects it is good to settle in with a cell whose working characteristics are familiar to you.

Different suppliers may offer the same cells, but at very different prices. It pays to look around for the best price. That being said, the quality of the cells and good customer service can be more valuable than low price alone.

TOC

Suppliers have different price break points and you should inquire about these. For instance, a cell will be reduced in price at a certain quantity. Even if the quantity is more than you need, the price break may be big enough that you would spend less money and get more cells.

Solar cells are fragile and it is important to know about replacement policy and procedure if your cells arrive broken from shipping. Some carriers only insure up to a certain amount, so if your purchase exceeds that amount, get extra coverage for replacement – it's worth a few extra dollars. Do not buy cells from anyone if shipping is not insured, or they will not provide replacements for cells broken in shipping, when the cells are not being sold as broken cells.

Tab and bus ribbon

Tab and bus ribbon

Tab ribbon is used to connect solar cells to each other in series or parallel fashion. Tab ribbon is narrower than bus ribbon. Tab ribbon is usually the same width as the silvered fingers on the faces and backs of solar cells. Bus ribbon is used to connect strings of series or parallel connected cells to other strings of cells, and for leads from the strings of cells to the power takeoff box. Bus ribbon can also be used to connect cells to each other in parallel.

Tab and bus ribbon is simply flat copper foil that has been coated with a thin layer of tin or tin/lead mixture. Copper foil is highly conductive and flat which makes it an excellent choice for soldering to cell terminals (fingers). Stranded wire can also be used to connect the cell terminals, but is not as pliable and easy to work with as foil.

For tab ribbon, a thickness of .003" usually suffices. It is quite pliable and tends to stick to the finger surfaces well. The .005" works well for higher current cells, but is stiffer and not as pliable as .003". This does not usually present a problem. Although differences are small, .003" solders faster since the heat transfer is faster through the thin material. The .005" is a little slower to solder to terminals. Overall, the .003" is easier to use.

See page 111 for a discussion about making your own tab and bus ribbon, and other options for connecting cells.

E. Jordan Brooks has tinned tab and bus ribbon cut to any length, width and thickness. (There is a minimum order and cutting fee.) You will have to call them for current pricing and minimum length requirements. They are cost effective and appropriate for larger orders, however even for smaller projects they are recommended even if you have to order more than you need. They produce a quality product and you can get exactly the sizes you need

Other companies listed starting on page 138 offer tab ribbon on their web sites in small quantities, which is great for building just one or two panels.

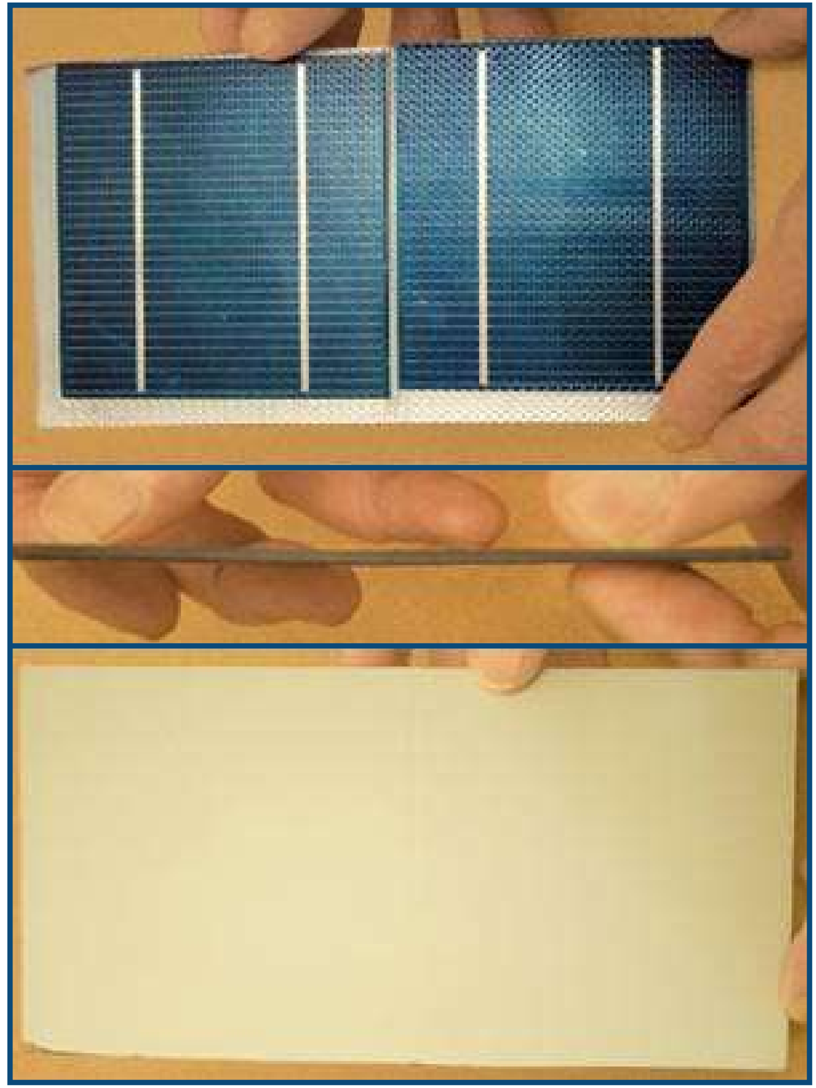
Occasionally tab and bus ribbon is available on popular web auction sites, so you may wish to check on this possibility.

Panel frames

There is a wide variety of materials that can be used for photovoltaic panel construction. These factors are important to consider when you choose panel materials:

- Weatherability and durability of materials
- Method of construction
- Cost of materials
- Easy availability of materials.

Panel frame materials must be able to withstand temperature extremes, moisture ingress,



Commercial panel front, side and back

wind, and precipitation. They must be rugged enough to protect the cells during handling, and protect them from physical impact when the panels are installed. The panel frame should be able to withstand hail, snow loads (in some areas) and wind pressure. Of course, if the panels will not be exposed to the elements on a daily basis, such as if they are portable and only used occasionally to charge batteries, or to demonstrate photovoltaics, then you can get away with using a wider variety of inexpensive materials.

Two very important considerations for choosing panel materials are thermal resistance and moisture resistance.

Thermal resistance

Panels are normally subjected to very high temperatures and very low temperatures. Daily and seasonal temperature fluctuations can warp the structure of the panel permanently if proper materials are not used.

Temperature changes cause materials to expand and contract, and different materials will expand and contract at different rates. Different materials fastened together either mechanically or by bonding (with adhesives, for instance) will tend to disengage from each other if they are expanding and contracting at significantly different rates. Allowances need to be made for this movement, and particular attention should be given to longevity of bonding materials.

Low temperatures can make some substances brittle, and contraction can cause some material to crack and disengage from other materials whose rate of contraction is different.

High temperatures can soften materials, which can cause some materials to physically decompose, which can degrade the structure and performance of the solar panel.

Moisture resistance

Fog, dew, rain, and melting snow all subject panels to moisture, so moisture resistance is critical for panel construction. If a material absorbs moisture, it will tend to warp over time and will draw moisture to the cells and electrical connections inside the panel. This can cause failure of the panel.

Bonding agents for solar panels must have decent moisture resistance ratings, and mechanical fasteners need to resist corrosion. Methods of mechanical fastening must allow contraction and expansion of the materials used. All parts need to work and move together, so connections need to have a degree of flexibility. We use Silicone II as a bonding agent because it has excellent flexibility in conditions of thermal expansion and contraction, and it makes a good seal against moisture.

UV resistance

Another factor to consider is UV degradation. Some materials do not stand up when exposed all day and every day to ultraviolet rays from the sun. They will decompose, which allows moisture, heat and cold to finish the job and deconstruct your panel.

In considering weatherability, cost, and easy availability, our choice has been to use silicone, aluminum, Plexiglas or polycarbonate and fiberglass. These materials, although not the very best options, are the best when considering cost and easy availability.

Glass in solar panels

A number of materials can be used to cover solar panels. The best material for this is low iron tempered glass. It has good light transmission qualities (about 91%), does not break readily and is more abrasion resistant than plastic. However, tempered low iron glass is expensive. You cannot buy tempered glass and cut it to size – it will shatter if you try to cut it. You have to order the exact size that you will need for your panels. Regular window glass has very poor light transmission qualities (about 83%) for solar cells and is not recommended. It will also shatter easily with hail. Tempered glass is about five to six times stronger than regular window glass.

Plexiglas in solar panels

A good compromise between cost and light transmission characteristics is Plexiglas. Plexiglas is an acrylic (polymethyl-methacrylate or PMMA, also known as Lucite and Acrylite). Plexiglas weathers extremely well for solar panel use. It has 92% light transmission, and a high strength to weight ratio. Although it has a softer surface than glass, with proper care Plexiglas panel covers will last a very long time.

When cleaning Plexiglas covers, it is important to first run water down the surface liberally to rinse the grit away and then wipe the water off gently with a rag – if you wipe the dirt, you will scratch the Plexiglas and compromise its light transmission. Do not use chemical cleaners of any sort with Plexiglas – just plain water.

Properly cared for, Plexiglas will last an extremely long time. It is also readily available at most hardware stores where they will cut it to size, or you can cut it yourself with a Plexi cutter. It is easy to drill and cut, and is inexpensive compared to other options. Brands such as Plaskolite Optix, which is available at most hardware stores, are UV stabilized to protect from yellowing and come with a ten year warranty.

Solar panel backing and sides

I prefer to use readily available materials for the other main components of the panel frame. All are available at most hardware stores:

- Aluminum for panel backing, side bars, and channel clips
- Silicone bonding agents
- Stainless steel nuts and screws
- Fiberglass screen to electrically insulate the cells from the panel backing

Using these materials and proper panel construction techniques will give you panels that will last for many years.

The benefits of long screws

The screws that hold your panel together can be longer than the thickness of the panel. This way, they protrude out the back to provide an easy way to secure the panel on a rack or similar structure. It also makes it easy to create space for air flow behind the panel to help cool it. The cooler the panel, the better the efficiency of the cells and also less degradation of all of the panel materials. This adds up to a longer panel life.

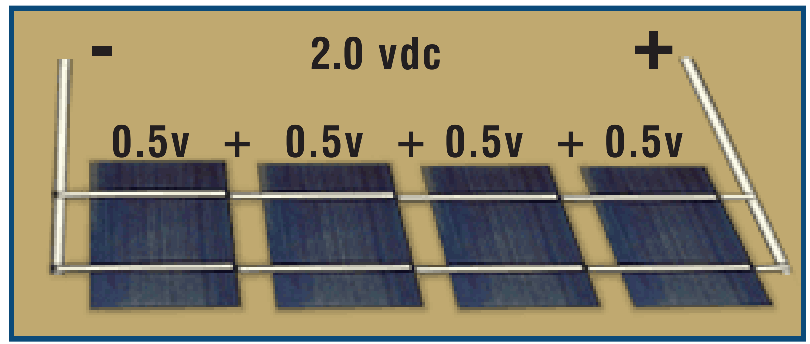
TOC

Planning the panel wiring – series and parallel connections

Solar cells have positive and negative leads or output terminals. They are not marked with a "+" for positive leads and a "-" for negative leads. The face of the cell (the blue colored side that faces the sun) is the negative side and the back (the other side) is the positive side.

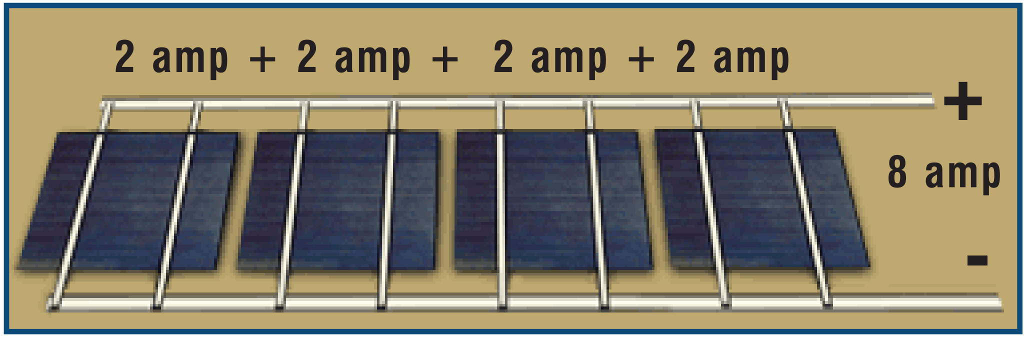
Solar cells are usually connected together in strings. In the examples given below, each string consists of four cells, and the panel consists of five strings of cells connected together.

Cells in strings can be connected to each other in series, which adds the **voltage** of each cell; or they can be connected to each other in parallel, which adds the **current** of each cell.



A string of solar cells connected in series. Voltage is added.

A string of four .5 volt 2 amp cells connected in series will have an output of 2.0 volts and 2 amps at the end leads. To connect cells in series in a string connect the back of one cell to the face of the next cell, and so on.



A string of solar cells connected in parallel.
Amperage (current) is added.

The same four cells connected in parallel will have an output of 8 amps and .5 volts. To connect cells in parallel in strings, connect the back of one cell to the back of the next cell and connect the faces of the cells together. In other words, the positive side is connected to the positive side of the next cell and the negative side of each cell is connected to the negative side of the next cell.

Customizing panel output

Most commercial solar panels consist of strings of series connected cells. In turn, the strings are connected to each other in series. The panel projects detailed here use this same kind of wiring configuration: series/series. However, different combinations of connections between the cells and the connections between the strings can be used to customize panel output.

For example, to get a total panel output of 2.0 volts and 8 amps, the cells can be connected in parallel/series. To do this, the four cells in the example strings are connected to each other in parallel to add up the amperage of the cells; then the strings are connected to each other in series to add up the voltage of each string. In this way custom panels can be made to output the exact voltage and current needed for a given application.

The details of constructing such a panel, with photos and illustrations, can be found in Build A Solar Hydrogen Fuel Cell System. These particular panels were designed to give a low voltage at about 20 amps current and are used specifically to power electrolyzers to produce hydrogen. Although your application may be different than powering electrolyzers, these instructions will give you a foundation for correctly connecting and constructing series/parallel panels for your own purposes.

Voltage and distance to the battery

For most commercial panels, high current cells are used and are connected in series to produce enough voltage to charge a 12 volt battery system. Of course, cells can be can be configured to make 24 volt and 48 volt panels. Higher voltages allow a greater travel distance with less voltage drop, and thus less system loss. For a run from panel to battery that is 100 feet or more, you may want 24 volt panels. For a run that is 300 to 400 feet, 48 volt panels might be a better choice.

Panel arrays and connections

For some purposes it may be better to build smaller 12 volt panels. They are not unwieldy and oversized, so one person can handle them easily. Two 12 volt panels connected together in series can be used for a 24 volt system, or four 12 volt panels in series for a 48 volt system.

For more current, you can connect four panels in this way: make two pairs of panels by connecting each pair together in series; then connect the two pairs to each other in parallel. Batteries are connected in the same way to create battery banks customized to produce the voltage and/or amp hour capacity desired for your solar system. For more detail about this, see Solar II which shows how to set up panels and battery systems once you have built your panels.

Panel size and shape

You can make panels with as few cells as you like, or with many cells, to suit your particular needs. Panels can also be made in any shape imaginable. This can be handy if the panels must fit into a particular area and not be too obtrusive; or for that matter, if you want them to stand out and make an architectural, or aesthetic statement.

Preparing and connecting solar cells

Choose and inspect your cells carefully

As noted previously, solar cells are available in a variety of types and sizes. The prices vary, depending on the supplier and the output of the cell. When you purchase your cells, you should also ask for dead or broken cells. These are good to use to practice soldering and to get a feel for handling the cells. However, do not use any cells that seem a bit substandard for your panel. Cells that have hairline cracks may appear to be functioning well when you test them initially, but when the panel is exposed to the weather there will be contraction and expansion that can break such cells. If this happens after you have your panel built and sealed, the panel will not work. The entire panel would have to be taken apart to replace the bad cell. So, avoid this problem by carefully inspecting all the cells you are going to use before you solder them together for a panel, and stabilize any cracks in the cells if you are going to use cells with cracks.

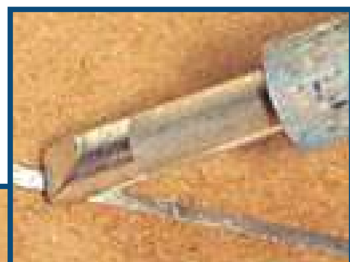
When working with PV cells, remember to be gentle with them. They are brittle and crack very, very easily. In particular, when soldering, there is a tendency to apply too much pressure by leaning on them. Also, solar cells are heat sensitive, so it's important to get a feel for how to solder the connectors to them without damaging the cells with too much heat.

Preparing the tab ribbon

Commercial tab and bus wire comes lightly tinned, but more tinning is needed on the areas where the tab or bus will be soldered to a cell or other tab or bus ribbon. The idea is to avoid having to resolder tabs that don't stick for lack of tinning.

Melt some solder on the tip of the hot soldering iron.

Tinning is very simple. Take some solder and melt it on the soldering iron when it is up to heat. Then, coat the areas of the tab or bus that will later connect. You do this by rubbing the iron tip with the solder on it along the length of the tab ribbon you wish to coat. Try to get a smooth layer with no bumps. Do not tin the tab where it will be crimped.



Apply the tinning to the tab ribbon

TOC

Flux

Applying flux with a pen before soldering tab ribbon to the cells

When attaching any tab ribbon to a cell, or tab ribbon to bus ribbon, always use flux. This cleans and prepares the surfaces to be bonded and will allow the solder joint to form. If you do not use flux, many of your joints will not form and adhere. This is not always the case, but most of the time it is.

Flux comes in several different forms, but over the years I have come to use flux pens exclusively. Flux pens are like felt tip pens, except that you first push the spring loaded tip against a surface for the felt to soak up some flux from the body of the pen. Do not push the felt tip against the cell surface to charge the flux pen tip. This would likely crack the cell.

Push the felt tip against another surface, then apply it to the cell. Then, apply the felt tip of the pen to the area you will solder. You only need to do this on one of the surfaces to be joined.

When soldering, flux just before you solder a particular piece. For cells, I flux one finger (or the soldering points for one tab ribbon) on the cell just before soldering the tab to the cell.

You do not need much flux at all – just enough to cover the surface lightly, but thoroughly. Always replace the cover of the flux pen immediately after each time you flux a finger or tab or bus ribbon. If you leave the cover off you will lose the volatile constituents of the pen and you will have to buy a new one.

Other forms of flux (such as paste) can be used, but they are more difficult to apply well. To do the job quickly, and to be sure the solder joints hold, use the flux pen exclusively.

Do not use acid flux. Use only rosin type such as listed in the parts section. Acid flux will corrode the connections. For all electronics and electrical applications, use a rosin flux.

Soldering

Soldering is easy once you know a few tricks of the trade. If you can, use a soldering station with a digital readout and temperature control. Inexpensive units can be purchased from the suppliers listed starting on page 137. Although just about any soldering iron will do the job, the tips of temperature controlled units will last much longer, which saves money in the long run. They will also maintain the exact soldering temperature needed.

Soldering iron with digital readout and temperature control

TOC

Soldering tips

The best kind of soldering tip for this work is a screwdriver or chisel tip. Get a few different sizes and keep a spare tip on hand of the size you use most. Get a tip that will fit the size of tab ribbon you will be using. The better you match the size of the tip to the surface that will be soldered, the better the solder job will be.

Basic soldering tools

Soldering technique

When using a soldering iron, always coat the tip with a light layer of solder between each soldering task. For instance, to attach two tab ribbons to one side of a cell, solder one ribbon on, and before you put the iron down to position the other ribbon for soldering, wipe each side of the chisel face on a wet sponge. Then, coat the tip with solder by wiping each side of the tip on the edge of a piece of solder wire. Both the cleaning and the coating help to protect the tip from oxidation and corrosion.

Before soldering the other tab to the cell, touch the point of the iron to the solder wire again and get a little more solder on the iron tip before applying it to

Soldering tab ribbon on the face of the cell.

the tab ribbon. This is important. Soldering irons basically don't work very well unless they can conduct the heat through a layer of solder from the surface of the iron tip to the surface of tab or bus that is being soldered. You can solder without doing this, but it makes a huge difference in speed and efficiency and getting a proper connection.

Since you coat (tin) the iron between each solder, it may not be necesary to coat again before soldering, but I prefer to. Much depends on how much solder is on the iron from the previous protective coating after the most recent solder. There should not be too much solder on the tip; but there should be enough to conduct the heat effectively and to avoid corrosion of the tip.

The most common problem encountered is not using flux or enough flux, and/or not keeping the iron wet with solder. Another is not putting enough solder on the tab or bus ribbon for the second tinning. You do not need very much, but it must be sufficient.

Types of solder

On most solar projects I use a 60/40 solder. 60/40 means that the solder consists of 60% tin and 40% lead. It remains solid to about 361°F, and turns liquid at about 374°F. I like to set my iron at as low a heat as possible so that the tip will last longer, usually about 376°F. This varies, depending on the project.

On some cells a silver alloy finger is deposited, but other alloys are also used. Usually a lead-free silver solder will work on all of these. This type of solder usually has about 3% to 4% silver content, and is supposed to be better for fingers with silver content, but I have found that 60/40 works fine on just about any cell. Lead free alloy solder is available with or without silver. The lead-free alloys have higher melting points, but do have the advantage of not containing lead. If you purchase a spool of lead-free solder, ask what the melting temperature is. When soldering, it is wise to use a fan to pull the fumes away from the soldering station.

Building a solar panel

With just a few basic tools and good construction technique, you can fabricate a panel that is comparable to, or even better than a commercially manufactured panel.

Once you are comfortable with the basics (after producing your first panel), you can improvise and work with different materials and design ideas that will improve the looks and performance of your PV panels. You'll be able to build custom-crafted panels for any climate or site.

Except for the PV cells, tab and bus ribbon, the materials needed for solar panel construction are usually readily available at any local hardware store. URLs of companies that sell PV cells, and tab and bus wire can be found starting on page 137.

Following is a simple overview of the tools and materials needed as well as the calculations and some basic construction techniques needed to design and construct a simple series/series wired solar panel. You will find more detailed photos of the solar panel construction process, and some variations starting on page 60.

TOC

Materials for the panel

- PV cells
- Tab ribbon (narrow)
- Bus ribbon (wide)
- Aluminum bar stock ¼" x 1"
- Aluminum sheet (rigid)
- Plexiglas
- Nylon or plastic screen
- Fiberboard for layout board
- Screws and nuts (stainless steel)
- Solder
- Clear silicone rubber caulking
- Junction box
- 2-position barrier block (barrier strip)
- Electrical tape
- Epoxy

Tools needed

- Soldering iron with screwdriver type tip
- Caulking gun
- Paint brush to spread caulk
- Hacksaw
- Exacto knife
- Screwdriver
- Pencil
- Ruler
- Drill
- Multimeter

Figuring panel output

For illustration purposes this project will use a 4" square single crystal cell that puts out .89 watts. Remember that although the current rating or amperage of each cell can vary, a single PV cell, no matter how large or small, will only put out .5 volts (half a volt). Watt output is equal to volts x amps, so for example, .5v x 1.78a = .89 watts.

Most panels, for a variety of design reasons, contain 32 to 36 individual cells. A 36 cell panel gives more voltage than a 32 cell panel. The higher voltage is useful if you are designing a panel for a location that tends to have a lot of cloud cover, as the panel can produce more watts with less sun.

Calculate the number of cells you will need

Figure out how many cells add up to the voltage you want from the panel. In this project, we will use 32 single crystal cells, each .89 watt and 4" square. This will make a solar panel that, with full sun, will put out 16 volts at almost 2 amps. That’s more than sufficient to charge a 12 volt battery supply system.

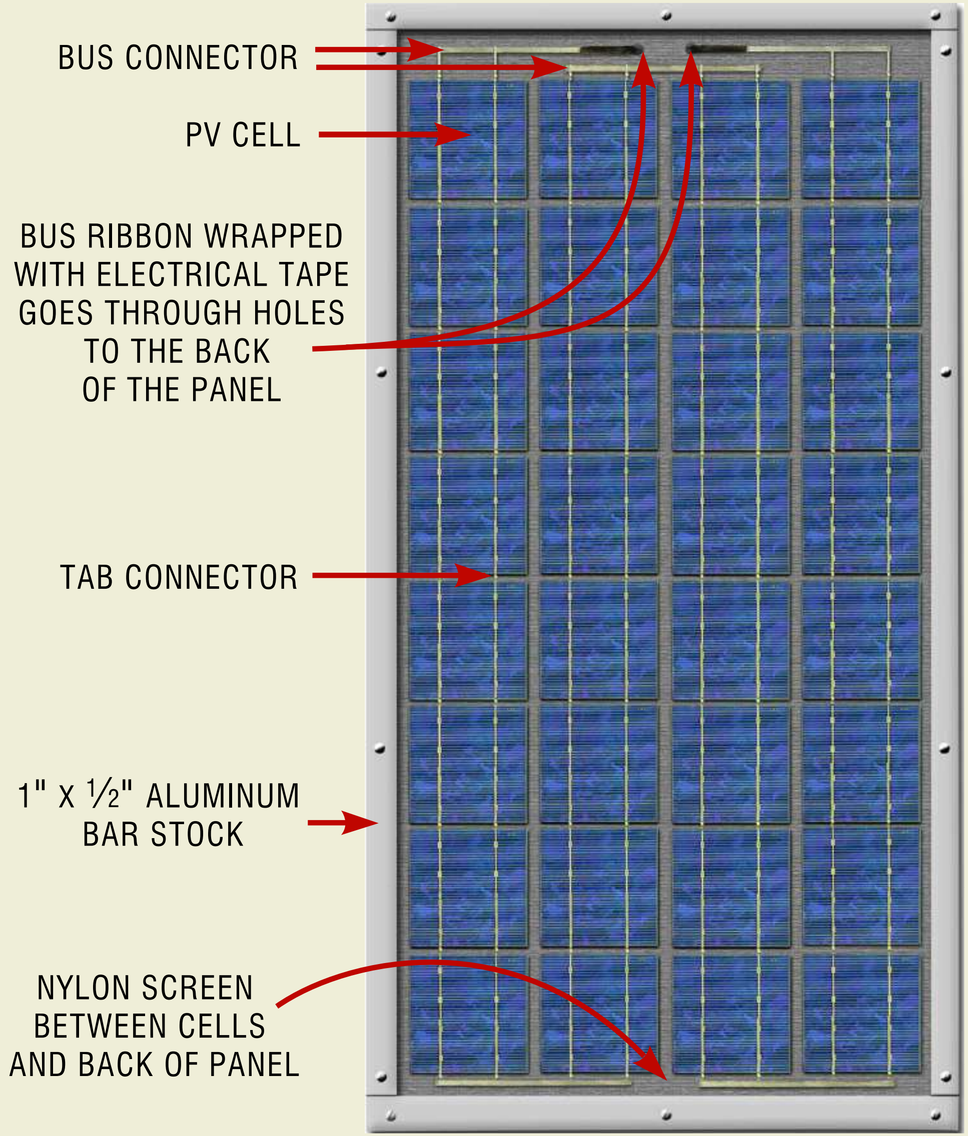
Plan the panel layout

We now know the output of the panel (16v) and the size of the cells (4"), so next we plan the panel layout. Since we will use 32 cells, we can lay them out in a pattern of 4 across and 8 down (4 strings of 8 cells each: 8 x 4 = 32).

Any layout will work, but this is a typical size and an efficient way to use the space. One of the advantages of building your own PV panels is that you can make them any size or shape you wish, even triangles or circles. This can be handy if you are designing custom panels for places where the typical rectangular panels won't fit, and if you have particular aesthetic considerations. However, a basic rectangle or square is the configuration you will usually be working with.

TOC

Panel layout



Over-all panel length

To figure the panel length, multiply the number of cells in a row times the length of the cell:

8 cells x 4" = 32"

In addition, we want a ¼" space between the cells, so we multiply the space times the 7 spaces between the 8 cells in a row:

¼" x 7 spaces = 1¾"

This panel will be framed with 1" wide and ¼" thick aluminum bar stock to connect the aluminum sheet metal back and the Plexiglas front cover. The width of the bar stock (1") must be added to both the top and the bottom:

2 bars x 1" = 2"

Allowance must also be made at the top and bottom of the panel for the bus and tab connectors between the end cells and the bar stock. A clearance of ¾" at the bottom and 1" at the top is sufficient. That gives us a clearance total of:

¾" + 1" = 1¾"

So, we add together these four subtotals: the total length of the cells + space between cells + frame allowance + top and bottom clearance; or

32" + 1¾" + 2" + 1¾" = 37½"

Thus, the total length of the panel needs to be at least 37½". We will round it up to 38". The aluminum sheet and the Plexiglas should be this length.

Total panel length = 38"

Over-all panel width

To figure the width, first multiply the number of cells in a row times the width of the cell:

4 cells x 4" = 16"

Again, we need a ¼" space between the cells, so we multiply the amount of space times the number of spaces between the cells in a row:

¼" x 3 spaces = ¾"

We also need the bar stock allowance (1") added to the right and left sides:

2 bars x 1"= 2"

There will not be tab and bus connectors to accommodate on the right and left sides, so a ¼" clearance between the bar stock and each end of the cell row will be sufficient:

2 x ¼" = ½"

Add each of the subtotals together: the total width of the cells + total space between cells + frame allowance + right and left clearance, or:

16" + ¾" + 2" + ½" = 19¼"

So, the total width of the panel needs to be at least 19¼". We will round it up to 20". The aluminum sheet and the Plexiglas should be this width.

Total panel width = 20"

TOC

Bar stock length

Four pieces of bar stock are needed for the frame. Two should be 20" (the full width of the panel) for the horizontals, and the two verticals cut to 36", which is the length of the panel minus the allowance for the two horizontal bars:

38" - 1" - 1" = 36"

Cut the tab ribbon

Next, cut the tab ribbons which will connect the cells to each other and to the bus strips. To calculate the length: we are using 4" cells, so for each cell we need 4" of tab on the cell face and 4" on the next cell's back. There is ¼" space between the cells, plus there should be ¼" extra to crimp between the cells. So, the tab ribbon should be cut into 8½" lengths:

4" + 4" + ¼" + ¼" = 8½"

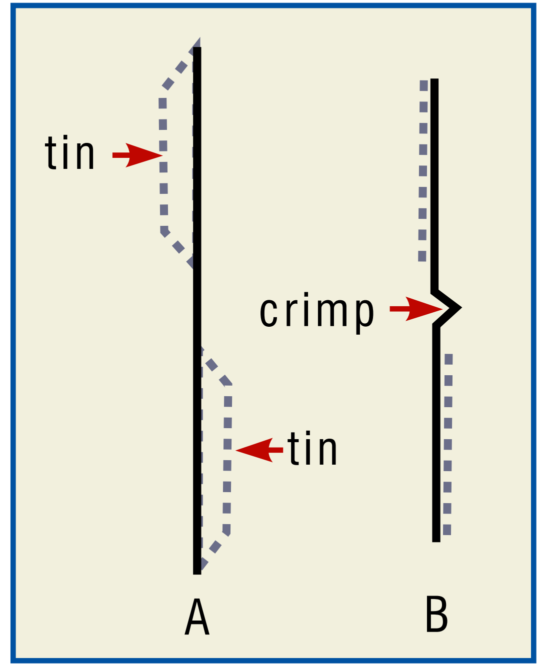
TOC

Two lengths of tab ribbon are needed for each cell, so for a 32 cell panel, 64 strips of tab ribbon (2 x 32) are needed.

Total of 8½" tab ribbon strips needed = 64

Prepare the tab ribbon

The two areas of the tab ribbon that will be in contact with the PV cells are tinned to prepare for soldering, 4" from each end of the tab ribbon, but on opposite sides (see diagram). Tinning is simply melting solder against the soldering iron tip, and then transferring it to the tab ribbon. This covers the tab ribbon with a layer of solder that melts and attaches the tab to the cell when you run the hot soldering iron along the tab ribbon.



Side view of tinning and crimping the tab ribbon

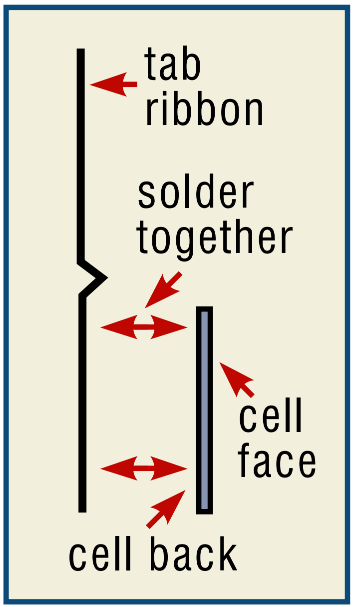
Tinning

To tin the tab ribbon, apply solder to the first 4" of the facing side of the tab ribbon. Then, flip the tab ribbon over and apply the solder to the back side, covering 4" from the end opposite the first end that you tinned. The middle of the tab ribbon should have ½" that is free from tinning on either side, and this center portion will be crimped (diagram, B). The end product will be a piece of tab ribbon tinned on one side and end for 4“, and on the opposite side and end for 4". The reason for this is that cells connected in series are connected from the face side (negative) of one to the back side (positive) of the next.

Crimp the tab ribbon

Crimped tab ribbon

Crimp the tab ribbon with needle nose pliers, or a small BBQ stick for a form. The crimps should be no more than ⅛" high and should be positioned midway between the cells but not touching the cells. The crimp reduces the stress on the soldered connections as temperature changes cause the cells and tab to contract and expand. This helps keep the connections intact, and lengthens the service life of the panel.



Solder the tab ribbon to the cell back

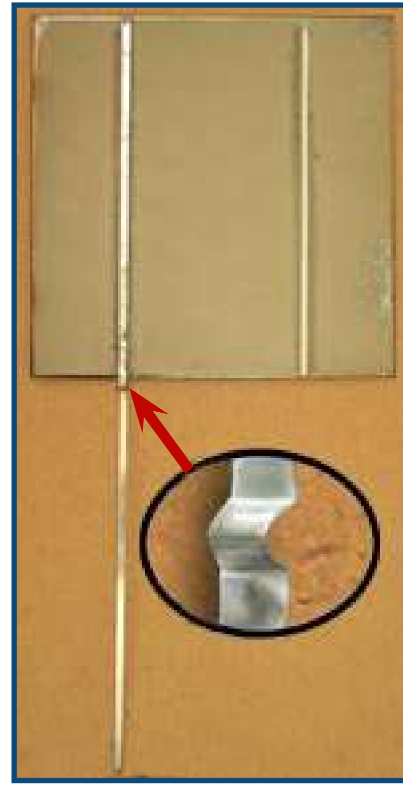
Attach the tab ribbon to the cells

When the panel is completed, each cell will be attached to 4 pieces of tab ribbon: 2 pieces soldered to the back or positive side, which is silver-colored, and 2 pieces soldered to the face or negative side, which is blue. But, to begin with, just solder two pieces of tab ribbon to the back of each cell (see diagram at left). The cell-to-cell connections will be soldered together later.

TOC

Building a solar panel

There are soldering strips on both the back and face of each cell. The tab ribbon should be soldered to these strips. (Some cells have smaller separate soldering points, but the operation is basically the same.) To solder, place the tinned side of the tab down on one of these strips on the back of a cell and roll the soldering iron tip across the top of the tab ribbon for the entire length of the cell.



A tab ribbon soldered to one finger on the back of a cell. Note that the crimp points toward the cell face.

It is a good idea to practice this first on some dead cells to get the knack of it if you have never soldered PV cells before. It's not difficult to do, once you've tried it a few times. It is very important to keep the iron moving – don't let it stop. Keep it constantly moving along the tab surface as the tinning melts so that the cells are not destroyed by the heat. It is also important not to apply too much pressure to the cells as you solder, as they crack easily.

Soldering tab to cell back

While soldering, keep the tab ribbon in its proper place with a piece of wood, or an Exacto knife or

TOC

similar tool, but be careful not to crack the cell. This can be tricky as the bus ribbon is apt to move out of alignment. With practice, you will get a feel for this. It is really very simple to do – after a few tries, you'll find that you can tab cells quite fast, and get them straight.

Pre-tabbed cells

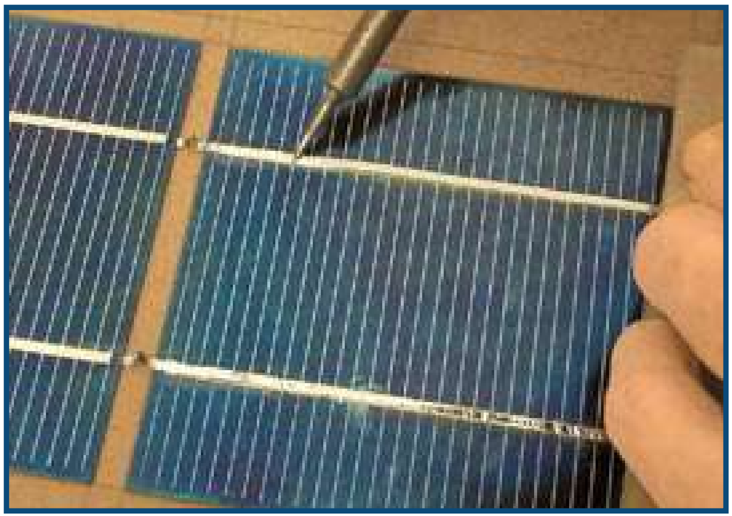
If the cells you purchased came with tab ribbon already soldered to the **face** of each cell, a different approach is needed for using layout templates and connecting the cells. This is discussed starting on page 83.

Make a layout template

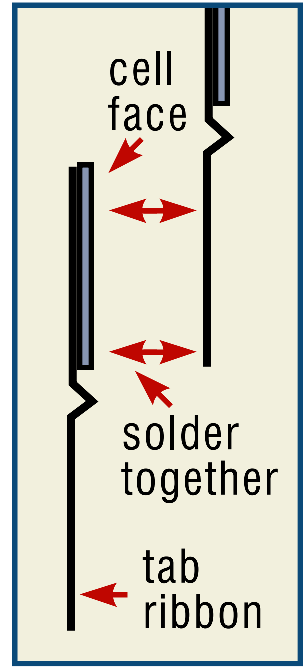
After each cell has 2 tab ribbons soldered to its back, it is time to make a layout template. Cut a sheet of fiberboard to fit inside the sidebars of the panel, which in this case is 36"x 18". With a pencil and ruler, draw the layout for the cells and tab and bus connectors. (Use one cell as a template to make the outlines.) Place each cell on an outline. This will help to get a straight and even spacing. The fiberboard template will also be used later as a “peel" to lift the entire assembly of connected cells intact and slide them into place on the panel.

Solder the cells together

The cells will be soldered together in place on the template. The tab ribbons connected to the back (positive) of each cell are soldered to the face (negative) of the next cell in the string (see diagram at right and photo below).



Solder the tab ribbon to the face of the next cell

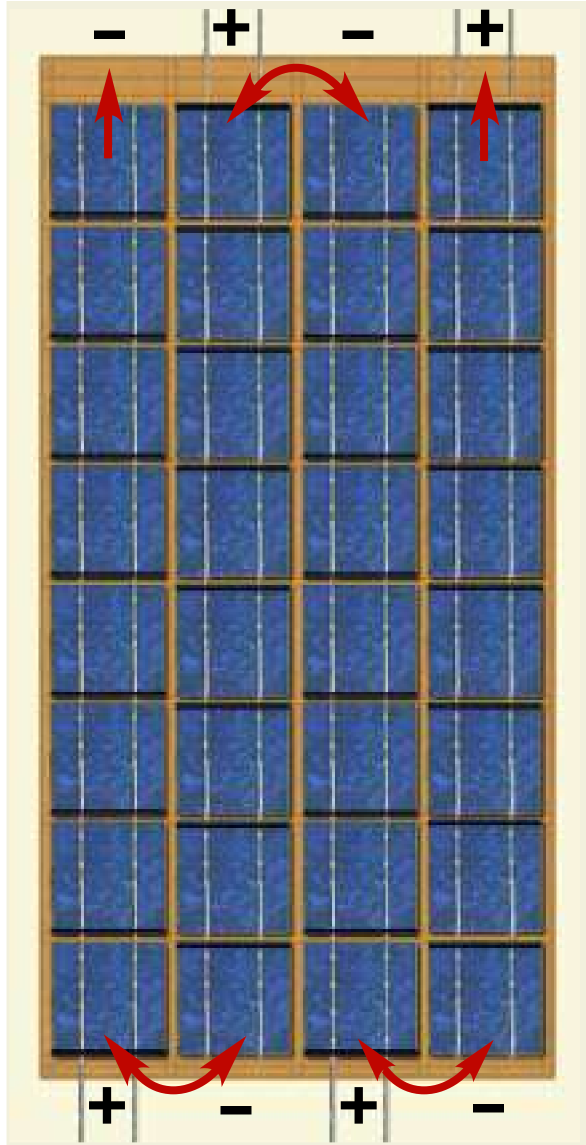


Solder the tabbed cells together (side view).

Place each cell into position on the template and solder it to the face of the next cell to form 4 strings of 8 cells per string. On each string, one end will have 2 long tab ribbons extending out from the back of the cell. This is the positive end of the string.

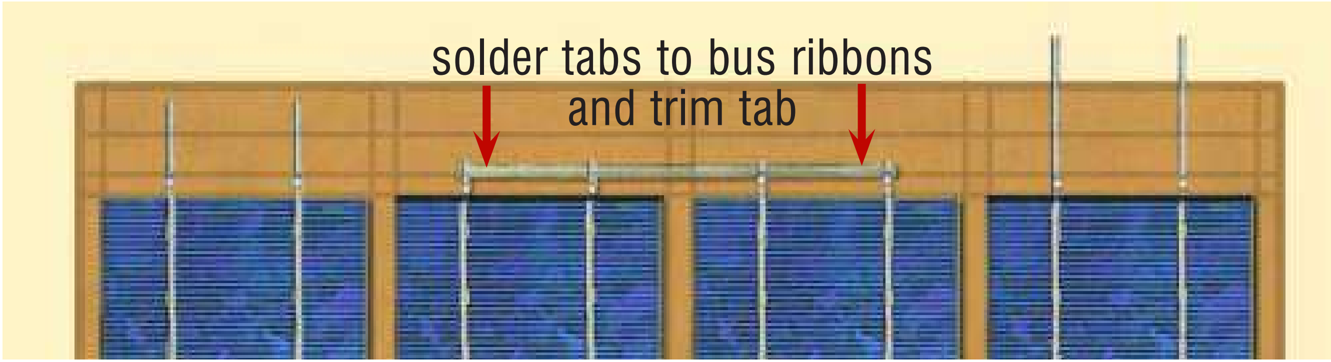
The other end of the string will be a cell with no tab ribbon connected to its face. This is the negative end of the string.

Note that the strings of cells must alternate in direction, as shown at left, so that they can easily be connected in series (positive to negative). The red arrows indicate how the strings will be either connected together, or connected to the negative or positive bus ribbon leads for the entire panel.



Strings of solar cells laid out on the template

TOC



Once the strings are all laid out correctly, solder tab ribbon to the cell faces on the negative end of each string. Then, solder the tab ribbon to the bus connectors to connect the strings, and trim the tab, as shown in the diagrams above (panel top) and below (panel bottom). The connections for the two corner cells at the top will be made after the cells are placed on the panel backing, so don't trim the tab connectors for those cells.

Prepare the panel structure

To prepare the structural parts of the panel, drill holes in the bar stock, Plexiglas and aluminum backing sheet for screws and nuts. Put 3 to 4 holes on each side. Use only stainless steel screws and nuts so they won't rust from exposure to the weather. The screws must be at least long enough to pass through the Plexiglas, bar stock and aluminum sheet stock. Using longer screws can be useful for mounting the panel later.

Drill two additional holes in the center top of the aluminum sheet backing (but clear of the bar stock allowance – see diagram at left). These are for the positive and negative takeoff bus ribbons that go through the panel to the terminal box on the back. The holes should be close enough for the two takeoffs (bus ribbon connectors) to come out on the back of the panel, inside the junction box.

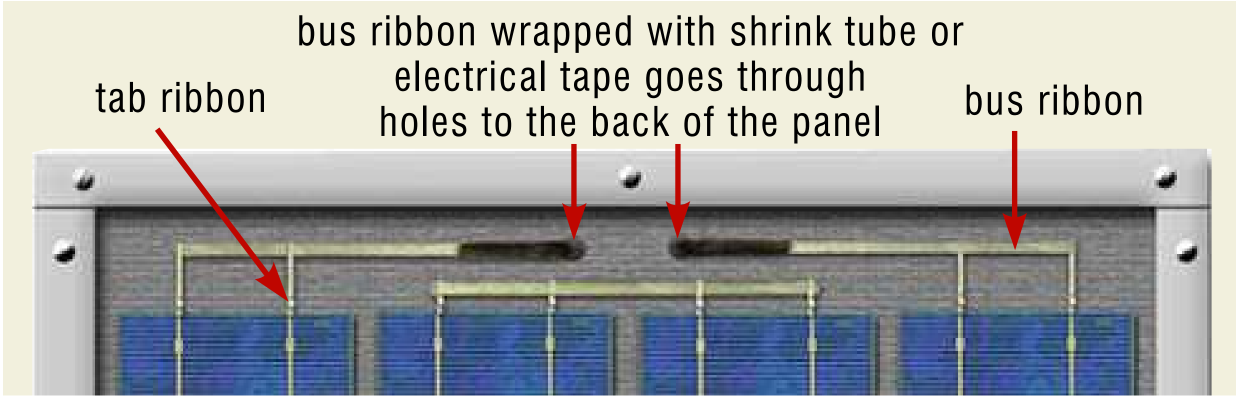
Panel back with side bars in place

Attach the screen

Now, take a piece of nylon or fiberglass screen and cut it to fit inside the bar stock edges on the sheet metal backing (36" x 18"). This provides electrical insulation for the cells and connectors. Without this insulation, the panel will short out. If you use a non-conductive backing such as Formica or plastic, you don't need the screening. Spread a thin layer of silicone caulk on the aluminum backing with a brush, and place the screen on it, pressing it firmly and evenly in place. The screen should not extend under the side bars. Let it dry 24 hours before placing the cells on the panel backing.

Place the cells on the panel

Next, put the cells in the prepared bed and position them on your panel. To do this, lift the assembled cells with the fiberboard template and gently slide them into place on the screen on the panel. When you are satisfied with their placement, put a little dab of silicone caulking on the edges of each cell to hold it to the nylon screen. Don’t use too much silicone, and don’t cover the entire edge – just a dab on two edges will suffice. When this is dry, it will hold the cells in place.



Attach the tab ribbons to the bus ribbons

Now the tab ribbons are attached to the bus ribbons for the power takeoffs (see illustration above). Measure out a piece of bus ribbon long enough to connect to the top corner cells and go through the takeoff holes. Leave plenty of excess so that you have enough bus ribbon to easily make the connection to the junction box. (You can always cut the excess later.) Slip a small piece of fiberboard or wood between the screen and the connections so that as you solder, you do not melt the screen, which could create a short in the panel later. Solder the tabs to the bus ribbon. One of the two upper corner cells should have the tab ribbon connecting the cell to the bus ribbon from the face of the cell (negative), and the other upper corner cell will have the tab ribbon connecting the cell to the bus ribbon from the back of the cell (positive).

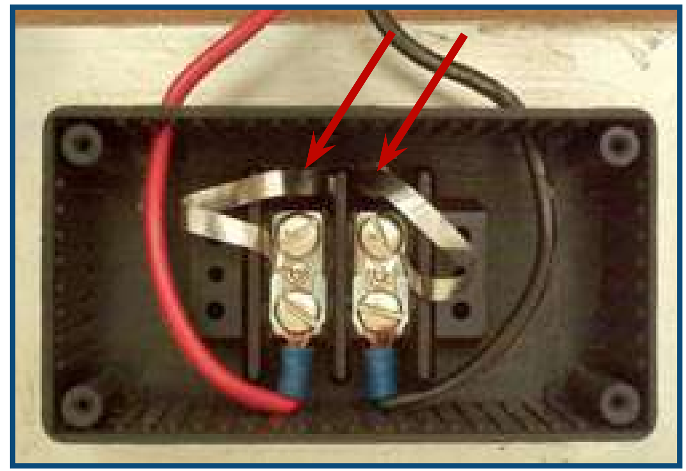
Cut a generous length of bus ribbon for the power takeoffs

Insulate the bus connectors

After you have made all the connections, wrap electrical tape or apply shrink tubing around the portion of the bus ribbon that will be pushed through the sheet metal backing, as in the illustration on the previous page. Be absolutely sure that the bus ribbon will not make an electrical contact with the sheet metal. Slip the insulated bus ribbon through the holes.

Junction box

To make the junction box, use a small plastic project box and a terminal block. If using the little blue project boxes from Radio Shack, be sure to file off the plastic molded knobs on the bottom so that you have a good flat surface to glue to the sheet metal panel back.



Bus ribbon comes through holes in the panel into the junction box at the back.

The box will protect the connections from the weather, and will be applied to the top center of the back of the PV panel, covering the 2 holes you drilled through the panel to accept the bus ribbon. Drill 2 holes in the junction box to match the 2 holes in the panel. (See above, and illustration on previous page.)

Epoxy the terminal block to the inside of the box. To make neat connections, drill a hole in the end of each bus ribbon to fit over the screw connector in the terminal block. You can, of course, use whatever method of connecting that you wish, whether banana jacks, screws and nuts, or hard wire.

After gluing the terminal box onto the surface of the panel, apply silicone caulk around the edges of the box which are in contact with the panel back. This is very important in order to make your terminal box thoroughly waterproof, as any leak into the terminal box or panel can create a short. There is more detail about installing the junction box starting on page 75.

Test the panel

Test your panel before you fasten and seal the Plexiglas cover onto it. Connect the output to the terminal box and test the panel in full sunlight with a multimeter. If everything checks out well, you're ready to cover and seal the panel.

Seal the panel

To seal the panel, put a thick bead of silicone caulking on the surface of the sidebars that will be against the panel, and place them on the panels, lining up the screw holes. Caulking the surfaces of contact between the sidebars and the Plexiglas and aluminum sheeting will ensure a waterproof panel. If you experi-ment a little beforehand, you will be able to lay out just the right sized silicone bead so that when you squeeze the layers together, the silicone will cover an approximately 1" strip of surface area fairly neatly. Screw the Plexiglas, side bars and aluminum backing together tightly. Wipe up any excess silicone immediately to make neat edges, as it is difficult to remove the silicone once it has set. Make sure that all possible openings and places where different panel parts come together are well caulked to avoid moisture problems which can cause panel failure or erratic performance.

Connect your output wires to the terminal box, and the panel is complete.

A small solar panel array project

To show the panel building process in more detail, following is an illustrated account of the fabrication of four simple series connected panels. These were used as the PV power source for the complete photovoltaic system discussed in Solar II. In some cases, alternative construction techniques and materials are shown, but mostly this next section is an elaboration of the process described in pages 40-59.

The Solar II project specifications

Goal: make 4 solar panels to provide a simple backup power supply during power outages, and for daily use to supply power for a few lights and small electronic appliances.

Physical characteristics of cells used: off-spec, cosmetic blemishes, chipped, very thin. This particular lot of cells had tab ribbon already soldered on negative face of cell, so there was no need to cut tab ribbon – half the soldering work was essentially done.

Number of cells needed for project: 144

Electrical characteristics of cells used: 0.54 volt 3.6 amp

Panel and array output: Each panel is 36 cells with an output of about 70 watts using open circuit voltage and short circuit current for output determination. The array of four panels outputs a total of 280 designer watts.

Panel layout and dimensions

Photovoltaic cell size: 3 3⁄16"h x 5 15⁄16"w

Sidebars: ¾" wide and ⅛" thick

Horizontal layout: 4 strings of solar cells:

4 cells x 5 15⁄16"	23¾"
2 sidebars x ¾"	1½"
2 spaces from sidebars to cells x 1⅛"	2¼"
3 spaces between cells x ½"	1½"
total panel width	29"

Vertical layout: 9 cells per string of cells

9 cells x 3 3⁄16"	28 11⁄16"
2 sidebars x ¾"	1½"
space from top sidebar to cells 2½"	2½"
space from bottom sidebar to cells 1 5⁄16"	1 5⁄16"
8 spaces between cells x ¼"	2"
total panel height	36"

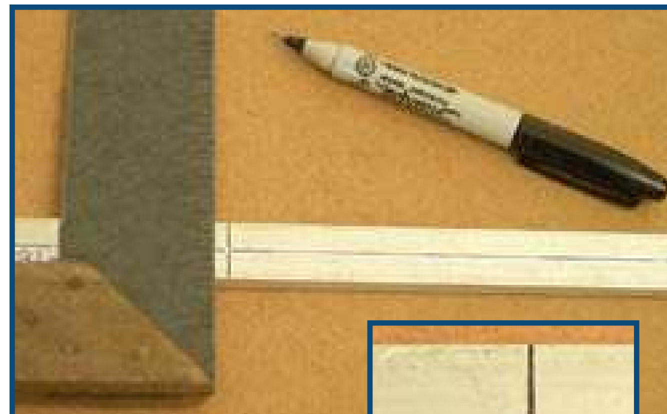
So, dimensions for the whole panel, the aluminum sheet panel backing and Plexiglas cover are 29" x 36".

Horizontal sidebars are 29" long. Vertical sidebars are 34½" long (36" minus 1½", the width of the two horizontal sidebars).

The bus ribbon (3⁄16" wide) connecting the strings in the panel at the bottom is centered between the bottom sidebar and the edge of the cells. At the top of the panel, the bus connecting the strings, as well as the power takeoffs, can be placed as desired in the 2½" space between the sidebars and cells.

Panel sidebars

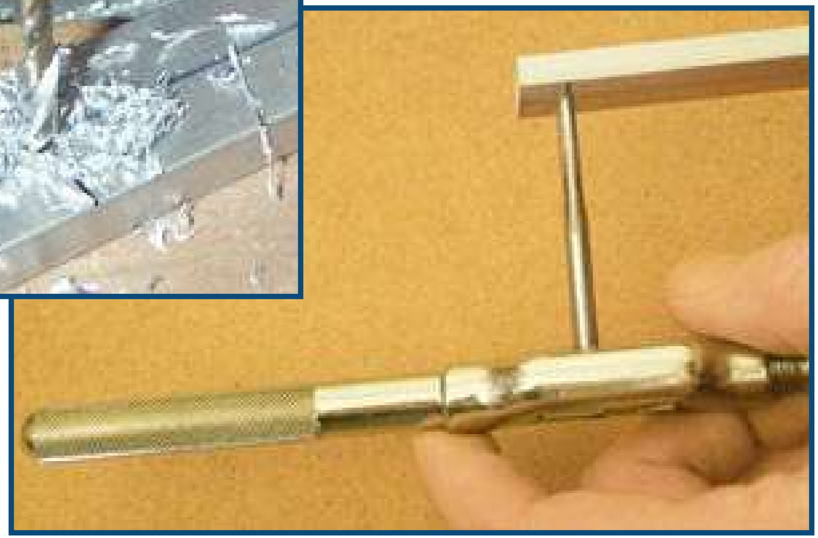
- Aluminum bar stock $\frac{3}{4}$" wide and $\frac{1}{8}$" thick is cut to length for the sidebars. Each panel has two horizontal sidebars 29" long, and two vertical sidebars 34$\frac{1}{2}$" long.



- The sidebars are measured and marked for drilling in the center of the bar stock width.
  - For the horizontal 29" sidebars, the holes are at $\frac{3}{8}$", 9$\frac{3}{4}$", 19$\frac{1}{4}$", 28$\frac{5}{8}$" measured from one end.
  - For the vertical 34$\frac{1}{2}$" sidebars, the holes are at $\frac{3}{8}$", 8$\frac{13}{16}$", 17$\frac{1}{4}$", 25$\frac{11}{16}$" and 34$\frac{1}{8}$" measured from one end.
- Pilot divots are drilled at the hole marks.

TOC

Panel construction



▲ Sidebars are drilled and tapped for 10-24 screws with a #26 drill, and a 10-24 tap, in the center of the bar width.

Side bars, drilled and tapped.

Panel backing

The panel backing consists of a 29" x 36" piece of aluminum sheeting, 1⁄16" thick. Twenty holes are drilled in the aluminum backing sheet: eighteen are for screw fastening; and two for the power takeoff bus ribbon to junction box on the panel back. The sidebars are used as templates for the screw fastening holes along the sides of the panel backing.

- ▲ 29" side bar is laid on one 29" side of the panel backing
- ▲ A pilot divot is drilled with a #26 drill.

Panel construction

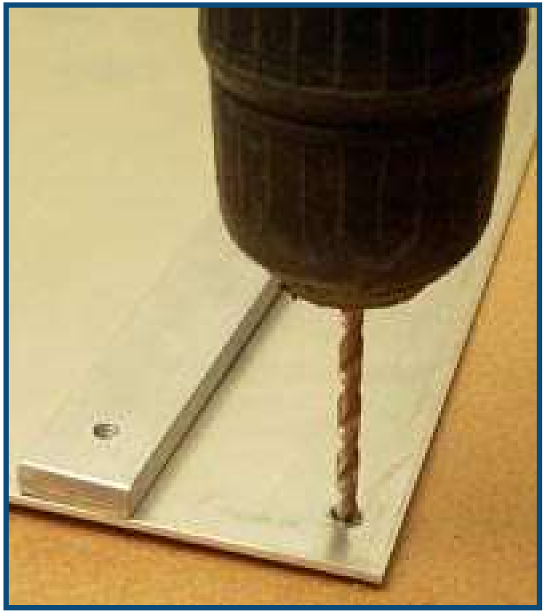
▲ The sidebar is removed and the first hole is completed with a 7/32" drill bit, using the divot as a drill guide.

▲ The hole is reamed.

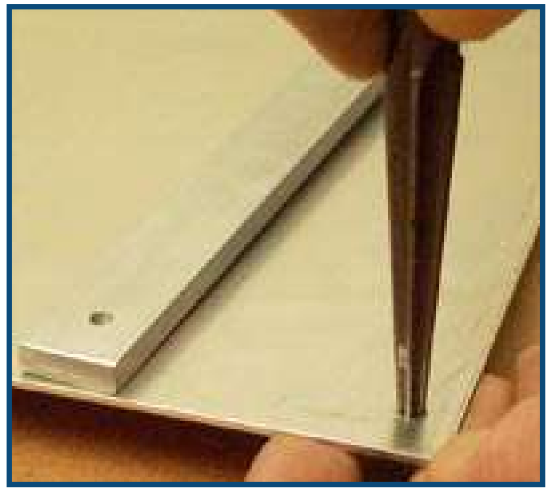
▲ With the first hole finished, the side bar is put back in place and a screw is attached through the side bar and back plate to hold them in place

TOC

▲ The pilot divot for the hole furthest from the first hole is drilled.



▲ The bar is swung aside to finish drilling the second hole.



▲ The hole is reamed.

▲ The bar is swung back into place and a screw goes through the second hole to hold the side bar and plate.

▲ Pilot divots are drilled in the two remaining holes

▲ The side bar is removed and the hole drilling and reaming is completed.

▲ After all the holes are drilled for the first sidebar, the first side bar is attached to the panel backing with screws and nuts in to hold it in place.

▲ The process is repeated with each of the 34½" vertical bars, and finally with the other 29" horizontal bar, leaving each bar in place once its holes are completed, until all the holes are completed.

Cutting the Plexiglas

▲ Plexiglas sheet is cut to 29" x 36":

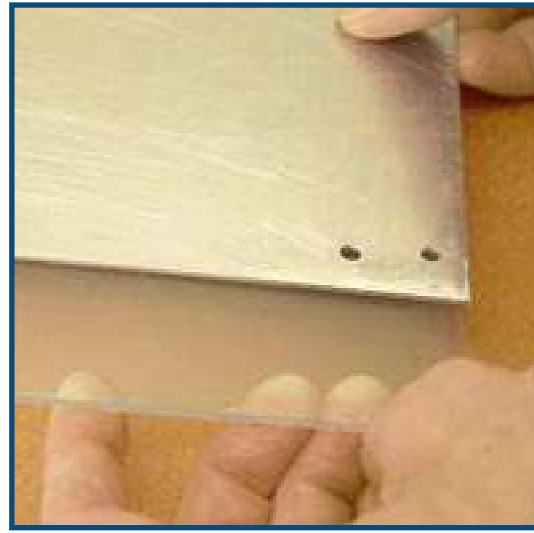
▲ The cut is marked.

▲ The cut is scribed with a plastic cutter.

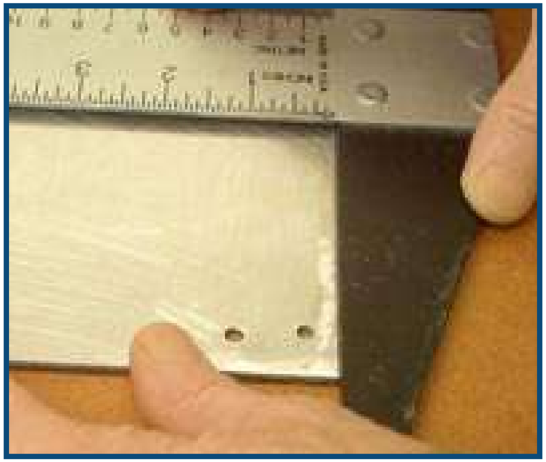
▲ The cut is aligned on a long straight edge and broken.

Drilling the Plexiglas

- ▲ The screws holding the sidebars to the panel backing are removed.



- ▲ Plexiglas panel cover is laid on the work surface.



- ▲ Panel backing is laid on top of the Plexiglas sheet and aligned.

- ▲ Using the holes in the panel backing as a guide, pilot holes are drilled in the Plexiglas sheet.

▲ Panel backing is removed.

▲ The holes in the Plexiglas are widened with a reamer or a larger drill bit. This allows the Plexiglas to expand and contract during temperature changes. Otherwise, it will likely crack. Cracks can be repaired, but definitely should be avoided.

Plexiglas must be held down if it is free drilled. Otherwise, it tends to ride up the drill and crack. It is easy to forget this while drilling. Clamping the work-piece before drilling avoids this problem.

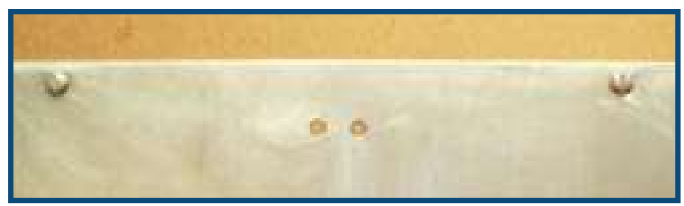
Drill Plexiglas, backing and sidebars together

An alternative way to do the drilling is to drill the sidebars, panel backing and Plexiglas all at the same time:

- ▲ Panel back is laid on a work surface.
- ▲ Plexiglas sheet is laid on top of the panel back.
- ▲ Marked sidebars are laid in their proper positions on top of the Plexiglas.
- ▲ The layers are aligned and clamped together.
- ▲ All of the holes are entirely drilled at once through the three layers – sidebars, Plexiglas and panel backing.

This method helps ensure proper hole alignment between all the parts.

Output holes



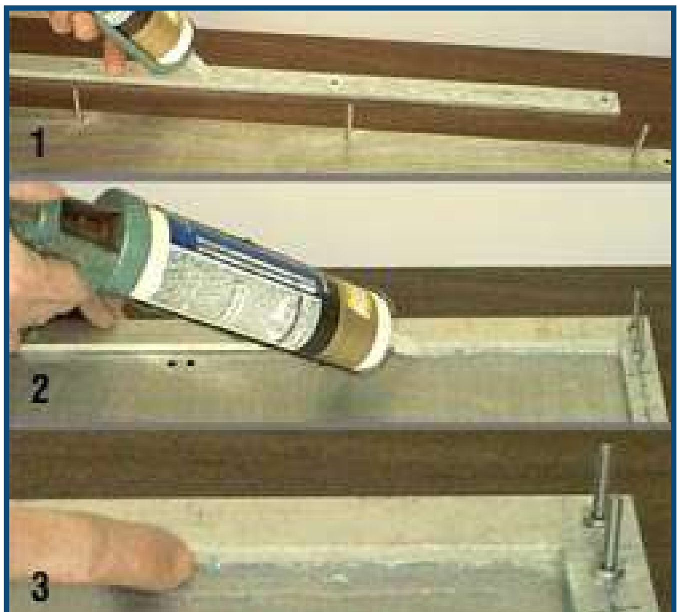
Two $^{9}/_{32}$" holes are drilled near the top of the panel back for the bus ribbon entry to the junction box. For this project, each of the two hole centers are situated $1\frac{1}{8}$" from the panel top and $14^{5}/_{32}$" from either side.

TOC

Attach sidebars to backing

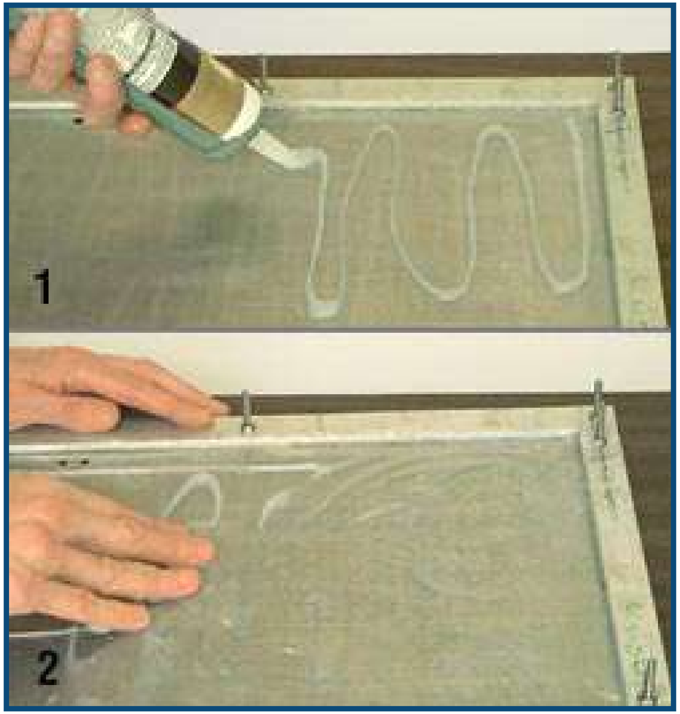
The sidebars are glued to the panel back with GE Silicone II:

- ▲ The inside of the panel backing, and the sidebars on both broad surfaces, are sanded to create a better surface for silicon bonding. All parts are washed and dried after sanding.



- ▲ A bead or two of silicone is laid along each sidebar, and the sidebars are placed in position on the panel backing.
- ▲ The screws are put in the sidebars to hold them in place while the silicone dries. Nuts are added to the screws to keep the sidebars tight to the panel backing. (After a few days, when the silicone has cured, the screws and nuts will be removed.)
- ▲ Another bead of silicone is laid along the corner of the inside of the sidebars and the panel backing.
- ▲ The bead is smoothed with a finger or other tool.

TOC



Attach screen to backing

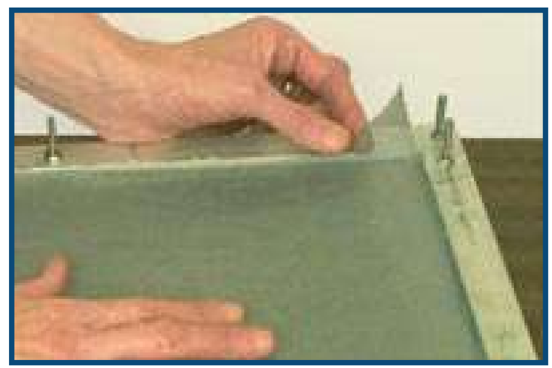
Fiberglass screen is glued to the panel backing to insulate the cells from the backing.

▲ A piece of fiberglass screen is cut to 29" x 36".

▲ The inside of the panel backing is coated with silicone between the side-bars and spread evenly in a thin layer.

▲ Screen is laid onto the panel backing and pressed into the silicone.

▲ Screen edges are trimmed at the sidebars with a razor.



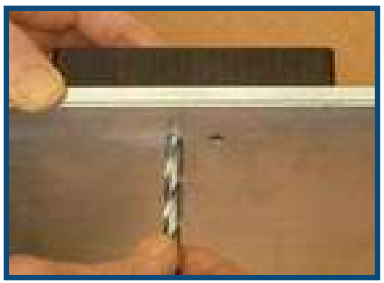
- The screen is cut at the two output holes at the top of the panel with a hole punch or Exacto knife.

- The silicone is allowed to cure for 24 to 36 hours.

Junction box

Two holes are drilled in the junction box, matching the hole positions on the back of the panel.

▲ Junction box is centered on the front side of the panel under the top space bar so that, for this project, the sides of the box are about 12 5/32" from either side edge of the 29" wide panel.

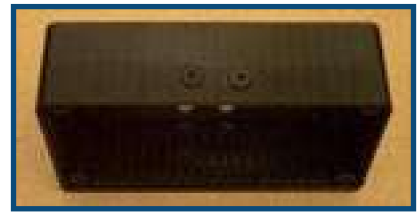


▲ The bus ribbon entry holes are marked on the box by holding it securely and inserting a 9/32" drill from the back side of the panel through the panel output holes. The drill is twisted a little by hand into the plastic box to make a pilot divot.

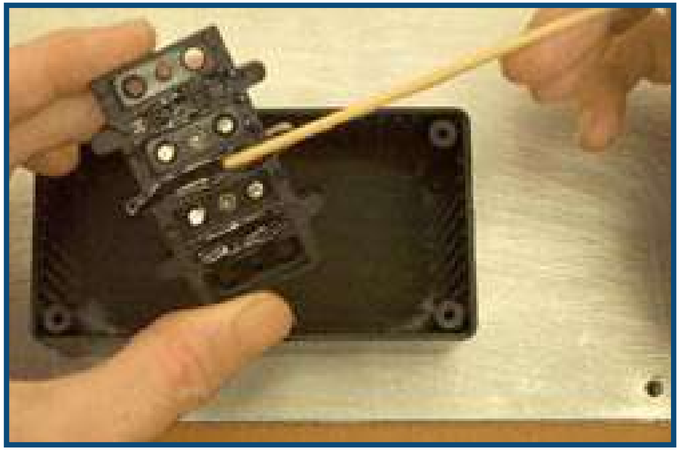
- Junction box is removed from panel backing and the two bus ribbon entry holes are drilled with a $^{9}/_{32}$" bit.

- Two more holes are drilled with a $^{9}/_{32}$" bit in the side of the junction box for power takeoffs to exit the box.

- Two rubber grommets are inserted into the power takeoff exit holes to prevent moisture from seeping into the connections.

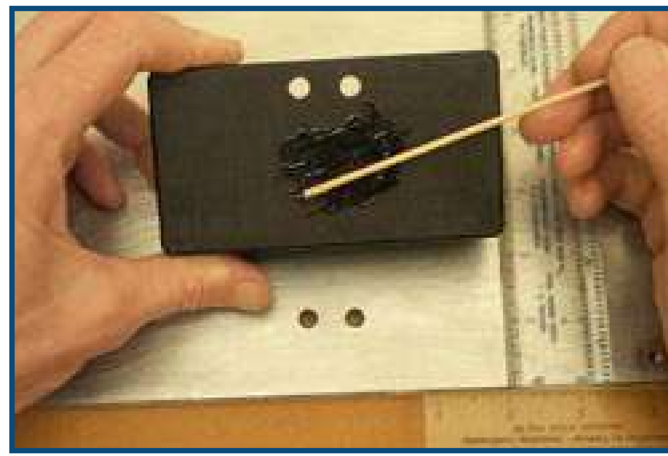


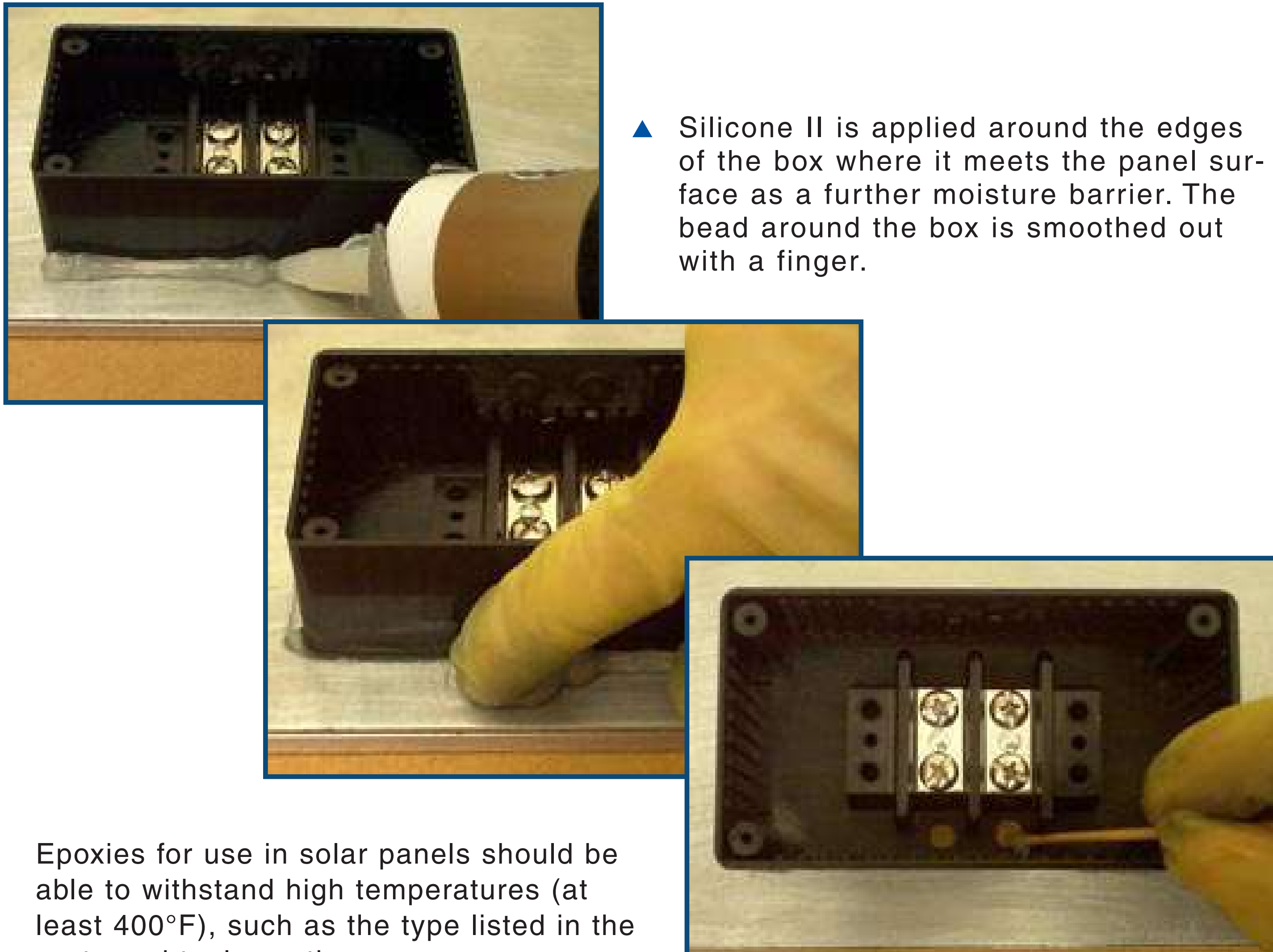
- Terminal block bottom and junction box inside are sanded on the surfaces where they will mate, and the sanding debris is cleaned; and the same for the outside of the junction box where it will be glued to the panel back, and the panel back. Any plastic manufacturer's marks or mold protrusions are removed with a file so that the surfaces can mate.



▲ Epoxy is applied to the bottom of the terminal block and the block placed inside the junction box, centered so that the screw connectors match up with the holes.

▲ The side of the junction box that will abut against the panel is coated with epoxy, and the junction box is applied to the back of the panel by aligning the holes in the box with the holes in the panel. Box is aligned and allowed to dry for 24 hours.





▲ Silicone II is applied around the edges of the box where it meets the panel surface as a further moisture barrier. The bead around the box is smoothed out with a finger.

Epoxies for use in solar panels should be able to withstand high temperatures (at least 400°F), such as the type listed in the parts and tools section.

Tab and bus ribbon

The cells purchased for this panel project had tab ribbon already attached to the negative surface (face) of each cell, and the leads were long enough to fully attach to the positive surface (back) of each cell next to it in the string. This saved some soldering time. All that was necessary was to solder the tab ribbon of any particular cell to the bottom positive side of the next cell in the string. For this reason, each string of cells only needed two pieces of tab ribbon to be cut and placed on the positive back of the last cell of each string.

For each panel, eight 6" pieces of tab ribbon (48") were needed, thus for the four panels in the array project, 192" (16'). If the cells had not had the tab ribbon attached, the project would have required a total of about 160 feet of tab ribbon – each string would require 120"(10'), and each panel would require 480"(40') of tab ribbon.

About 66" (5½') of bus ribbon is needed for each panel. (Four panels would require 22'). The power connection takeoffs were 13" long and the string interconnects were about 9½" in length. There are two power interconnects and three string interconnects in each panel. This would be 54½" per panel, or 218" for four panels.

Panel construction

Tinned .005 thick copper foil is used for both the bus wire and tab wire, Copper foil can be purchased and then cut into appropriate sized strips and tinned for final use (details beginning on page 111). The width of the tab ribbon depends on the width of the cell fingers. These cells fingers are 1⁄16" wide, so a 1⁄16" or 3/32" tab ribbon can be used. The bus ribbon is cut to 3⁄16" width.

Coating interior panel parts

GE RTV 615 optically clear silicone is used to coat the top of the cells (see details about encapsulants on page 117). For this particular panel with 3"x 6" cells we used 6.7 grams of part A and .67 grams of part B. The silicone is cut with Xylene for ease of application. An extremely thin coating is all that is needed. You can use from about 33⅓% to 20% silicone.

The 615 silicone is also applied between the sidebar tops and the Plexiglas, as it is optically clear and looks better than using GE Silicone II for this purpose. The 615 is used full strength here (not cut with Xylene). Coating the top of the side bars of each panel required a mixture of 13 grams of part A and 1.3 grams of part B.

For both applications (cell coating and side bars) the 615 silicone is de-aired before use, as shown beginning on page 119.

A coat of GE Silicone II is used to adhere the screen to the inside of the panel back. It is also applied between the side bars and the aluminum panel backing to act as a gasket, and to coat the edges of the completed panel to seal it.

Cell preparation

As discussed earlier (starting on page 12), before soldering cells, each cell is tested to ensure that it is working within the operating parameters for the panel. The performance of the whole panel will be no better than the performance of the lowest output cell in the panel.

Before the cells are soldered into strings, they are inspected carefully for dirt and any debris that can be removed. If off-spec blemished cells are being used, there may be some imperfections that cannot be removed. If the aesthetic appearance of the panel is a concern, make the cells look as nice as possible at this stage. Solvent can be used to clean cell surfaces, but it is not advisable to use very much, because the solvent can damage any silk screened fingers on the cell. Clean cells sparingly and with caution. Most cells that I have worked with do not require any cleaning other than a light dusting with a dry rag.

Some cells, such as the ones used for this project, come with tab ribbons already attached to one side. Most will come with no tabs attached, so the appropriate length of tab ribbon must be attached to the two fingers of either the backs or the faces of each cell. Choose either faces (negative) or backs (positive), and attach the tab ribbon to all the cells the same way.

Tab ribbon length

Each tab ribbon must run the whole length of the cell finger and be long enough to cover the measured space between that cell and the cell it will be attached to, as well as the length of the finger on the cell that it will be attached to. Each tab is crimped in the space between cells so that the tab can expand and contract without pulling away from the cells as the temperature changes, so allowance for the crimp is also included in the tab length.

The tab is coated (tinned) where it will be soldered to the cell fingers. No solder should be on the part of the tab that will be in between cells because the solder makes the tab stiffer and will reduce its flexibility – which makes it less able to expand and contract with temperature changes. It is important to not have solder in the crimp of the tab ribbon between the cells.

Soldering tab ribbon to the cells

The cells for this project had tab already attached to the faces. If this was not the case, at this point the tab ribbon would be attached to the cells. See pages 34-39 and 47-50 for a discussion of this process in detail.

Cell layout template boards

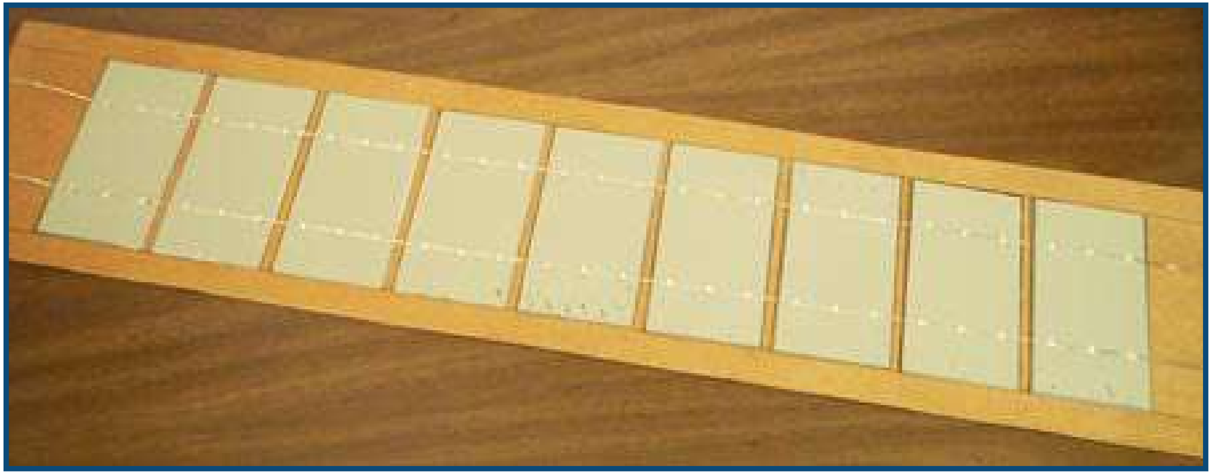
Three boards composed of any stiff material such as Formica, fiberboard, Plexiglas or plywood are used for cell layout. The board dimensions are dependent upon the panel and cell dimensions.

Two of the layout boards are 36"x 8". One board is used to solder the cells into strings. (The larger layout board can be used for this purpose also.) A template is drawn on the string board for nine cells with the calculated space between each cell included in the template. The second 36"x 8" board is used to turn the strings over and transfer them to the large board.

The large board is cut to fit exactly into the frame of the panel with the side bars on. For this project its dimensions are 27½" x 34½". This board is a template and layout surface for soldering the strings of cells together. It is also used as a peel to slide the soldered strings into place onto the panel frame.

To make this full template, lines are drawn on the board marking the locations of the tops, bottoms and sides of each of the cells. Positions are also marked for the bus ribbons that will connect the strings to one another.

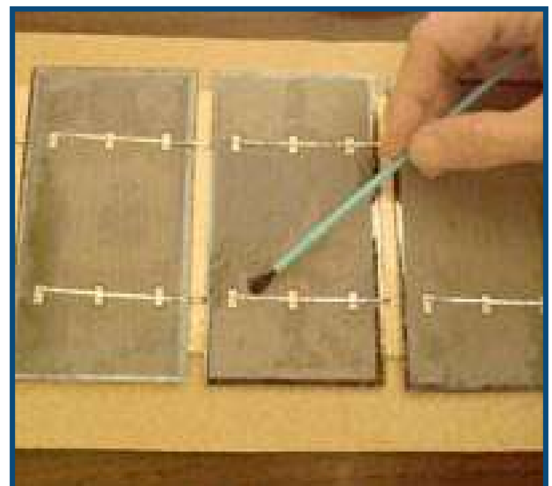
String construction



String layout board for soldering the cells together

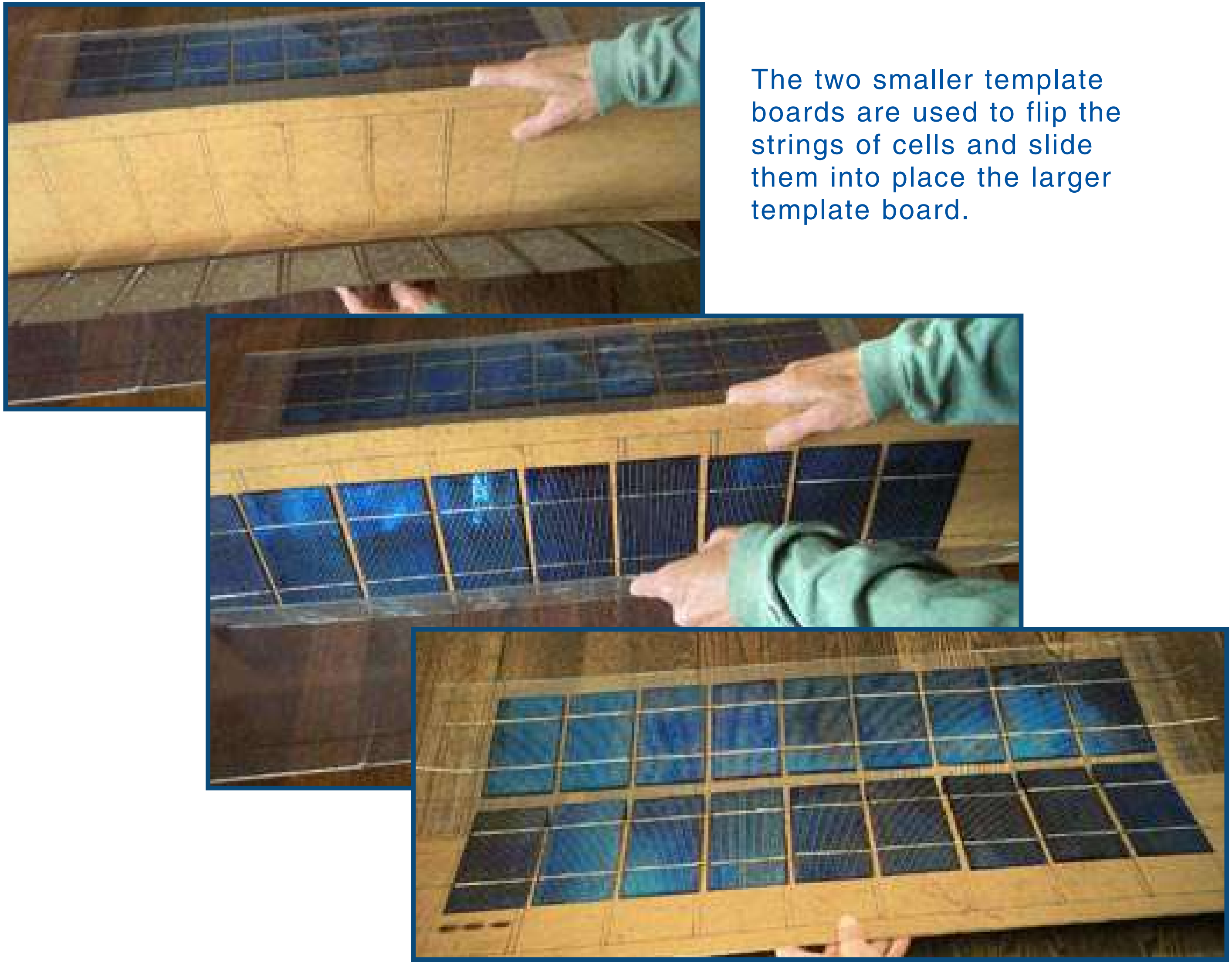
A string board makes it easier to lay the cells out correctly, quickly solder them, and flip the string over so that it will be face up on the large template.

For this project, after the string connections for each string are made, the backs of the cells in the string are coated with silicone and allowed to dry.



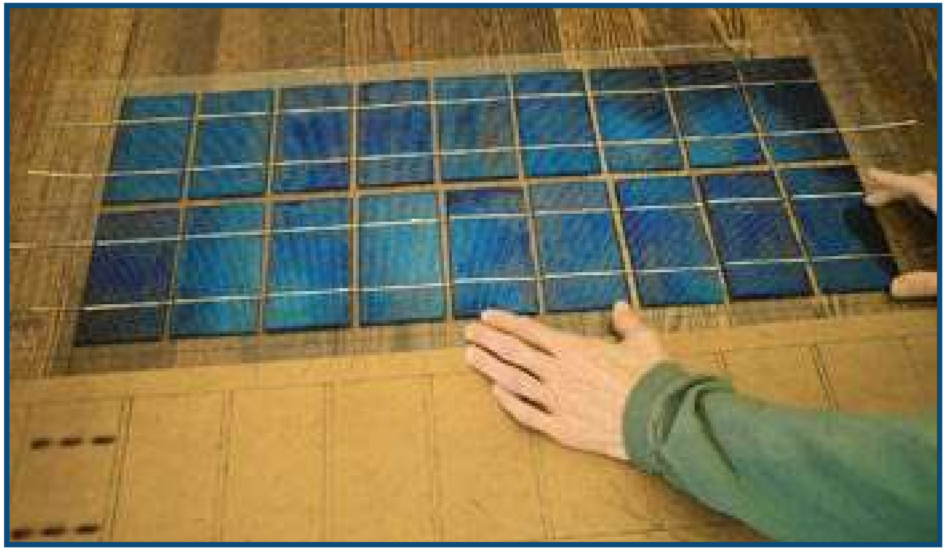
Coating the backs of the cells in a string with silicone.

Panel construction



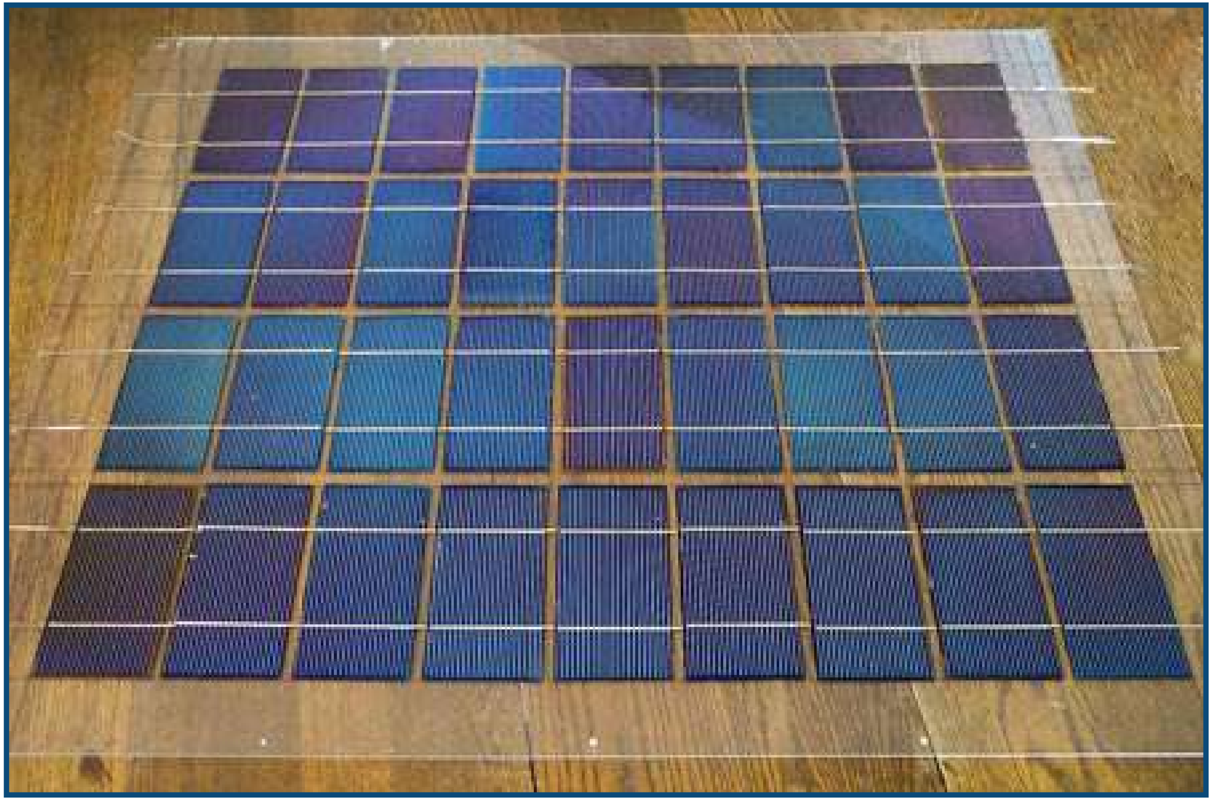
The two smaller template boards are used to flip the strings of cells and slide them into place the larger template board.

TOC



Placing a string of cells on the larger template

The finished string is then transferred to the main template board, using the second 36"x 8" board to flip the cells and slide them into place. Moving the strings by this method prevents putting stress on the delicate cell connections when the soldered strings are moved.

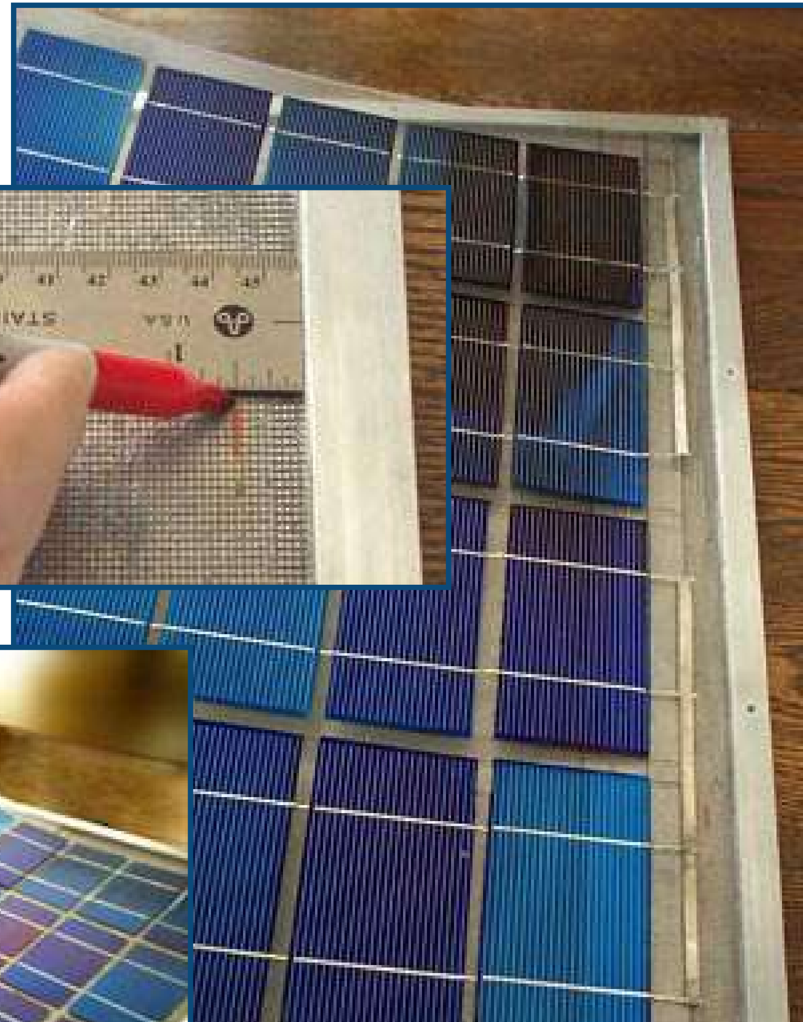


The strings of cells are aligned on the larger template, and are ready to be connected with bus ribbon.

Each string is positioned on the main board, and the strings are connected by soldering the string tabs to bus ribbon.

When all the strings are connected, the whole assembly is peeled (slid) onto the panel frame. (See illustrations next page.) Any needed position adjustments are made so that the strings are correctly placed in the panel.

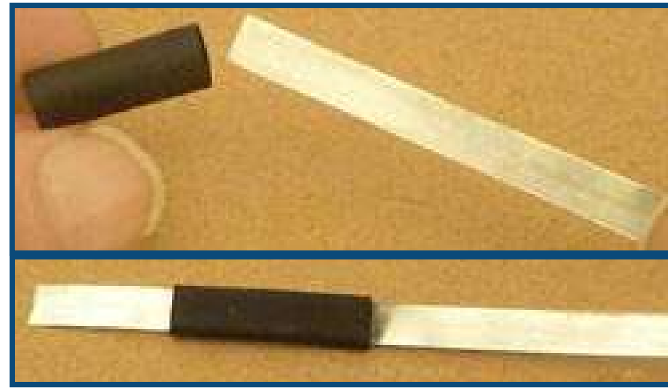
Panel construction



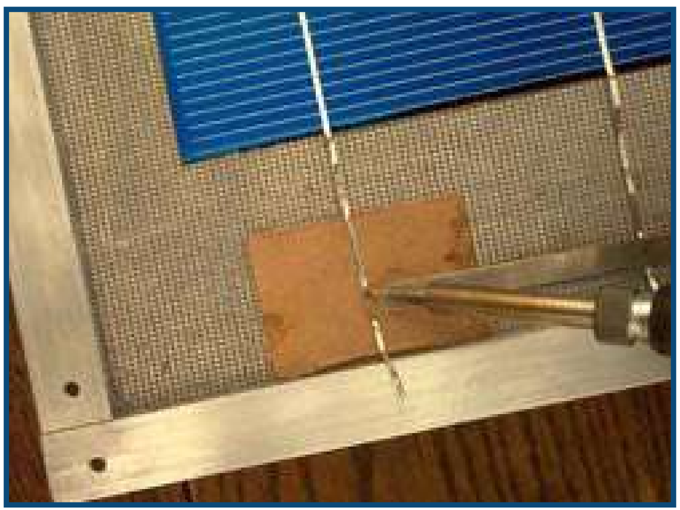
The position for the bus ribbon is marked at the bottom of the panel, and used to line up the template to slide the connected strings of cells into place. Once aligned, the template is gently pulled out from under the cells.

Panel construction

The two power takeoff bus ribbons are placed where they will be soldered, and marked for shrink tube. The shrink tube is positioned so that it will insulate the bus wire totally from the edges of the metal holes on the back plate as the bus enters into the plastic junction box.



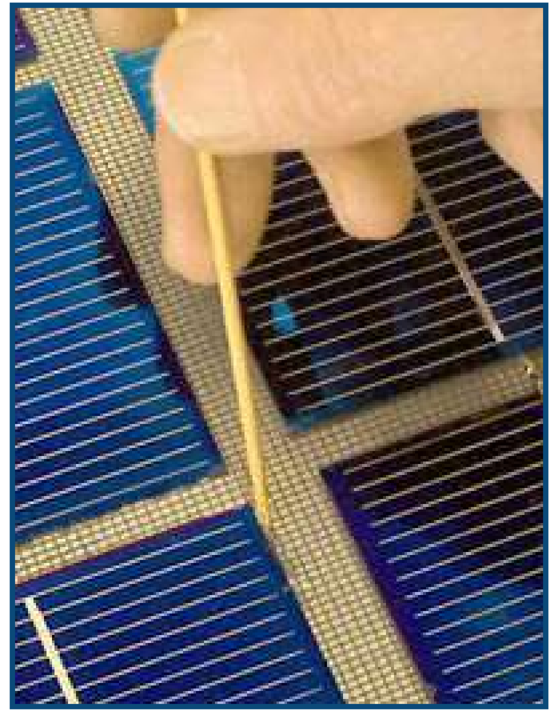
The shrink tube is placed on the bus wire as marked and heat is applied.



The takeoff bus ribbons are positioned on the panel, and soldered to the tabs. Then, the insulated bus ribbon is pushed through the holes to the box at the back of the panel.

TOC

Panel construction



Silicone is applied to the cell edges to hold them in place

The cell assembly is secured to the panel back by gluing the right and left side edges of each cell into position on the panel backing.

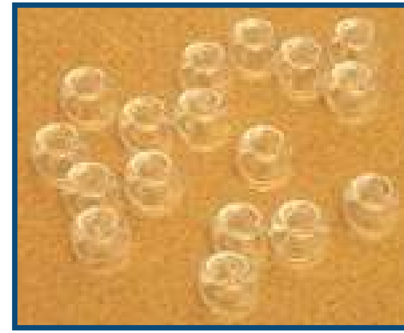
Silicone is squirted onto a paper plate and a stick is used to apply a bead where the right and left edges of the cells come together with the back plate. Usually there is a small space between the cell and the back plate. The silicone is tucked under the cell to get complete coverage and good adhesion. This process takes a little time and patience but is vitally important to secure the cells adequately to the panel backing.

After the cells are glued to the panel backing, silicone is applied to the underside of the bottom and top bus ribbons wherever this can be done without pulling the cells up.

The bus ribbon is lifted slightly from the surface of the panel back to apply silicone. After the silicone is applied to the underside of the bus ribbon, the bus is pushed down gently to adhere it to the panel backing.

The bus ribbon sometimes has slight bends that make it pop up from the surface of the panel backing. Small objects can be used as weights to hold down the bus ribbon while the silicone cures.

At this point, spacers are glued at intervals between the cells to hold the Plexiglas cover up and away from the cells. If the spacers are not used, the Plexiglas cover will bend inward and can crack the cells. For small spans (small panels) the spacers are not necessary, but panels of this size require them.



Plastic beads are used as spacers to keep the Plexiglas cover from touching the cells

Transparent plastic pony beads (from any craft supplier) were used for spacers. Usually nine beads per panel will suffice. The pony beads have two flat ends. One of these flat ends abuts the Plexiglas cover and the other is adhered to the panel back surface. These beads had to be filed down a little to fit the space. If the spacers/beads are too thick, they will bow the Plexiglas a little and throw off the hole alignment for attaching the cover to the rest of the panel.

The beads are attached to the surface of the back plate between the cells with a dab of silicone on the bottom of the bead. The silicone is allowed to cure for at least 24 hours before moving on to the next step.

TOC

If the cells are going to be coated with optical grade silicone this is the time to do it. A complete discussion of using the optical grade silicone can be found on page 117. The silicone is applied with a brush to the cell faces and also to the tops of tab and bus ribbon for insulation. Let this dry and cure completely before installing the Plexiglas cover.

Coating the cell faces with optical grade silicone.

Plexiglas cover


The tops of the sidebars are coated with silicone before placing the Plexiglas cover

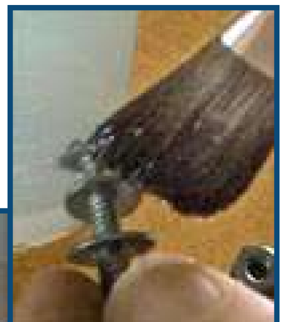
A silicone sealant is applied to the top of the sidebars that the Plexiglas will rest on. One or two beads along the length of the surface should be fine. If there is too much, it will ooze out when the Plexiglas is pressed onto the sidebars. On the other hand, if there is too little silicone there will not be a complete seal where the Plexiglas is in contact with the side bars. The idea is to get a tight seal, which is necessary to weather proof the solar panels.

Either the inexpensive Silicone II grade or expensive optical grade silicon can be used. The Silicone II grade will not look as good for this application. The optical grade is extremely clear and will not show. The Silicone II provides great adhesion so if the looks of the panel are not important, then Silicone II is the best option. If panel clips are used, most of the sidebars will be covered up anyway. The viscosity of the Silicone II is better than the optical silicone for this purpose – it is not as flowy and cures faster. If optical grade silicone is used for this purpose, do not cut it with Xylol because it should be as thick as possible.

TOC

Panel construction

As soon as the tops of the sidebars are coated, the Plexiglas is set in place on top of the sidebars, and aligned by matching the screw holes.



Coat each screw with silicone, insert a small washer on the screw and place the screws in the holes from the Plexiglas side of the panel.

On the back of the panel, place another small washer on each of the screws, then place and tighten the nuts. Coat each screw/washer/nut assembly on the back of the panel with silicone for a good weather seal. Let this cure for twenty four hours.

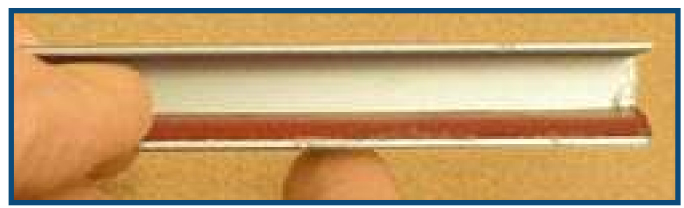
Panel clips

Panel clips are made from aluminum channel. They mechanically hold the panel cover, sidebars and back together; and ensure the integrity of the panel during contraction and expansion due to temperature changes. Over time, the cycles of temperature change can loosen adhesives and allow moisture to enter the panel. This can degrade the panel's electrical performance. Panel clips are not necessary, but strongly suggested.

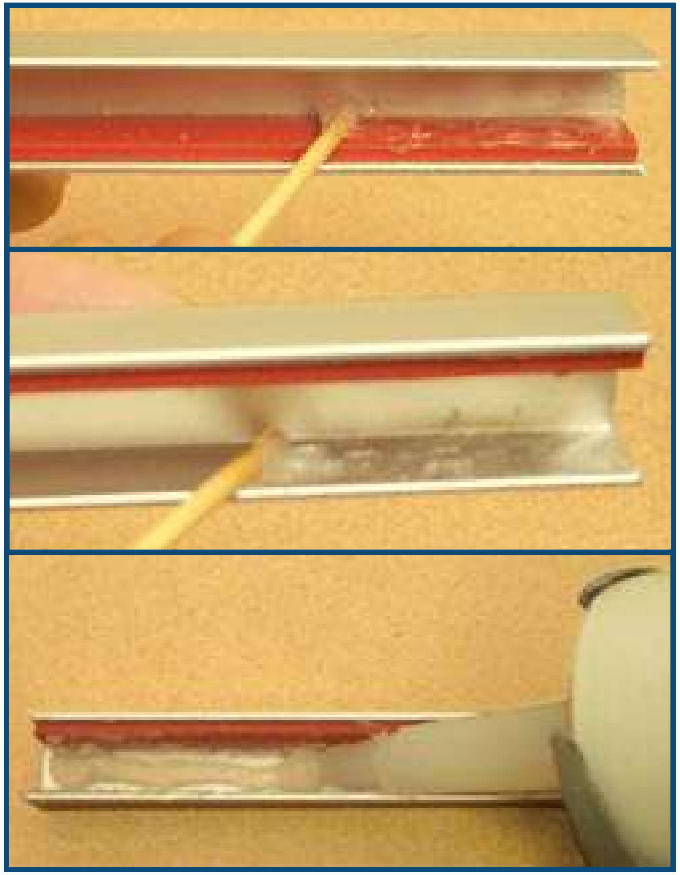
An alternative to clips would be to fabricate one channel strip for each panel side with slots or holes in the channel for the screws and washers.

For these four panels, twenty-four 8 13⁄16" pieces and thirty-two 8" pieces are cut from six ½" inside dimension stock aluminum channel pieces. Three 6' and three 8' long pieces of stock were purchased, which gave the exact amount needed.

Twenty four $8\frac{13}{16}$" pieces and thirty two 8" pieces of ½" wide, $\frac{3}{32}$" thick silicone rubber strip were cut. The silicone rubber strip is a gasket which is inserted and glued to one leg of the channel. The gasket leg will be placed on the front of the panel. The strips are glued in with silicone.

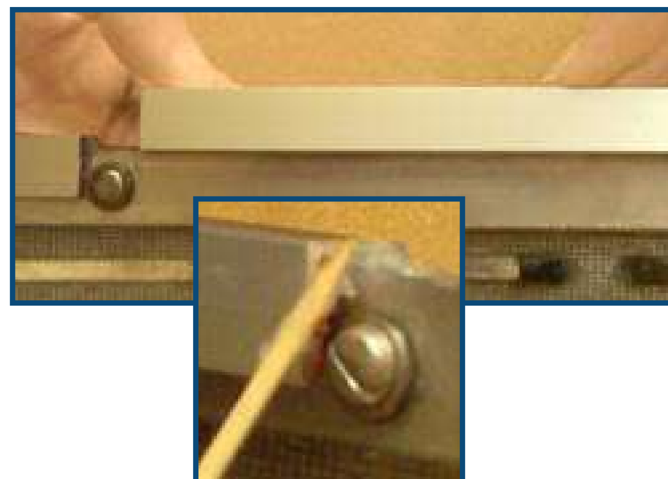


Panel construction



When the strips are dry, the inside side channel legs are coated with silicone and a bead of silicone is run down the base of the channel.

The clip is then pushed over the panel edges in the spaces between the screws. When the clip is put on the panel, the silicone bead inside the clip will seal the edges of the panel.



Two of the completed panels, ready to be mounted.

Purchasing and working with solar cells

Purchasing solar cells can be a whole study in itself. There are numerous primary and secondary suppliers. Primary suppliers are the actual manufacturers of the solar cells. Usually they require large quantity purchases. However, some primary suppliers also provide graded, non-graded off-spec, and cosmetically blemished cells in small quantities at a very good discount.

Secondary suppliers purchase either off-spec cells or standard non-defective cells from the manufacturers and resell them.

You can put together a list of current photovoltaic cell suppliers and contact them to find out what their minimum order and price is for standard cells; and if they supply off-spec cell or cosmetically blemished cells. You can find some very good prices in this manner if you are willing to put the work and time into it.

Both primary and secondary suppliers have a variety of products available, from standard fully functioning cells to off-spec and blemished, or chipped and cracked and broken.

Many secondary suppliers offer grab bags of broken cells; however, I would advise caution before buying these for serious or large projects. Cutting and trimming cells and getting them back into shape is extremely time consuming and thus can become more expensive than buying standard perfect cells if you take into account the labor involved in prepping the cells. Please read the following section about repairing solar cells before buying broken cells.

Off-spec or cosmetically blemished solar cells

Off-spec or cosmetically blemished cells are fine for any project where appearance is not important and exacting performance standards are not an issue. All of the cells I have used over the years have been cosmetically flawed and/or off-spec and my panels have performed as well and lasted as long as any commercial panels. I have panels that I built in 1993 using the same construction methods described in this book. They are still ticking and doing very well considering the Vermont weather they have had to endure.

Cosmetically blemished cells can:

- Have cell contact fingers incorrectly applied
- Be off color
- Have chips around the edges
- Lack anti-reflective coating.

Most cosmetically blemished cells have about the same output as non-defective cells – they just have minor flaws which make the final product not readily saleable. Cells that have chipped edges usually do not present major problems and are fine to work with.

Off-spec cells are cells that do not meet the panel manufacturer's exacting voltage and/or current output requirements for inclusion in their solar panels. Off-spec cells vary just enough from the particular manufacturer's specifications to not be appropriate for sale. Most are quite close to the output of standard non-defective cells.

Some primary suppliers will grade the defective cells, whether blemished or off-spec, into categories of output and sell them priced on that basis. On the other hand, some just bunch them all together as seconds and offer them for sale at one price, whatever the defect.

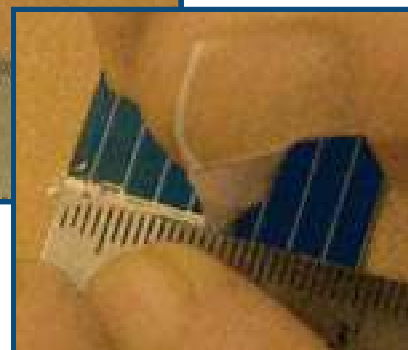
Repairing solar cells

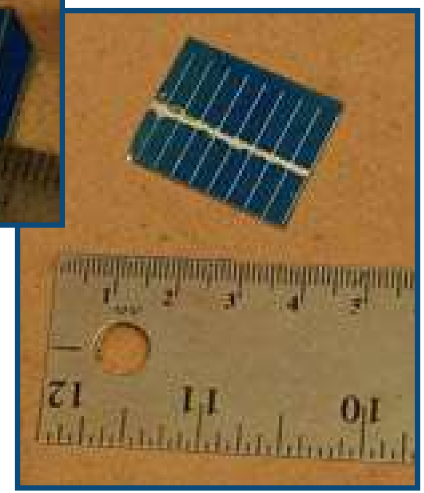
Some cells can be repaired if they have cracks but are still more or less intact. Cells can have hair line cracks that, if tapped slightly would break them into two or more pieces. With such cells, you can apply silicone to the length of the crack on the back (positive side) to reinforce the cell.

I apply a coating of silicone II to the back (positive) side of most cells after soldering the tabs on, whether or not they have cracks. This strengthens the cells. Optically clear silicone can then be applied to the face of the cell along a crack line to strengthen the front. Silicone II can also be used on the face. It is not optically clear, but the small amount that would be used along the crack line it will not affect the cell that much. When applying silicone to either the face or back, do not cover the tab fingers with silicone as this can prevent making a good connection when you solder the tab to the cells.

Another repair option is to use epoxy along any fault lines. This produces a more rigid connection, and is not as desirable as using silicone because the epoxy lacks flexibility. Use a higher temperature type epoxy and try to find one that is a bit more flexible. There are many types of epoxies available from various industrial suppliers. Generally a well stocked hardware store will have a number of different types of epoxies available in small quantities for experimentation.

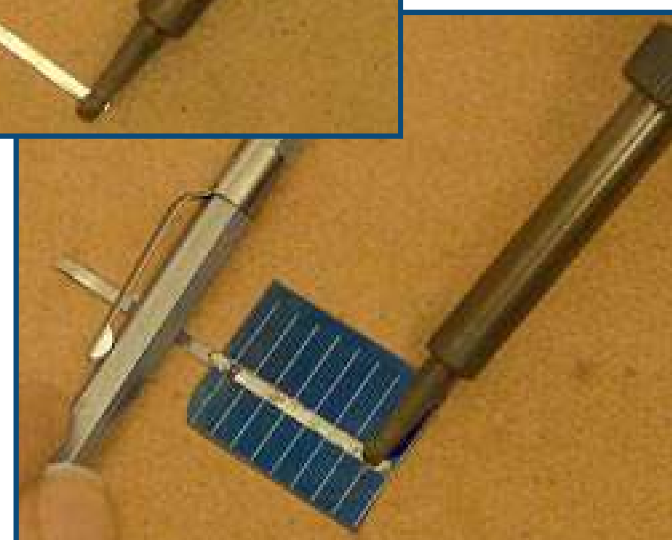
Creating cell fingers





Some cells, or pieces of cells if you are working with broken cells, will have the solder finger totally missing. A solder finger can be added by drawing it with a conductive epoxy pen. After you have drawn a finger, let it dry for 24 hours, and apply flux.

TOC



Then, add solder to some tab ribbon by tinning the iron and rubbing the solder along the tab, building up a little bit of solder. This tab can then be soldered to the newly created finger. These connections will be delicate, but they can work well with careful handling.

TOC

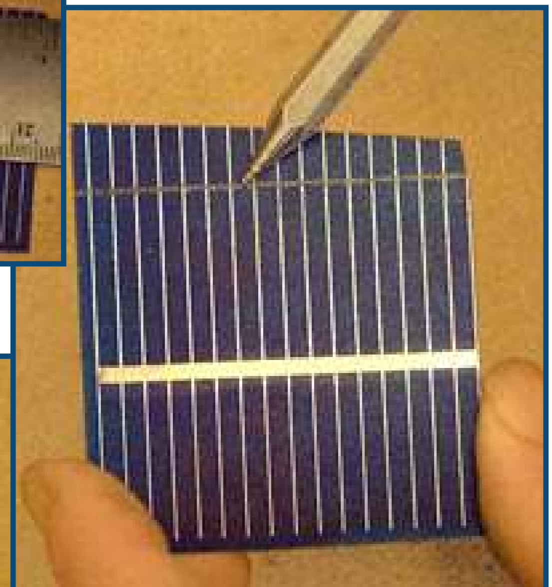
In some cases you can simply flux the line where the old solder finger used to be and then lay a trace of solder down that line with the iron without using the conductive epoxy. The key is to experiment with different methods – you never know what will or will not work until you try. Different cells have different tolerance of repairs.

If the cells will only be used for demonstrations and/or will be used exclusively indoors, you can simply apply some scotch tape to the back (positive) side of the cell where the crack line is. You can also use water glass (sodium silicate) to patch cracks. This forms a good bond. It is quite clear with only a very faint yellowish tint, so it can also be used to coat the entire front of the cell if you wish. The only problem is that sodium silicate is water soluble so the cells must not get wet. The water glass is an excellent glue to hold the backs of the cells to just about any surface. Conductive tape is also useful for binding cracks.

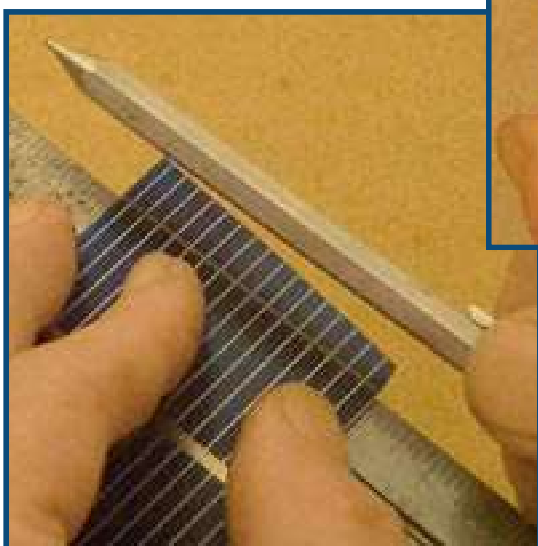
Piece of a solar cell with repaired finger and tab ribbon

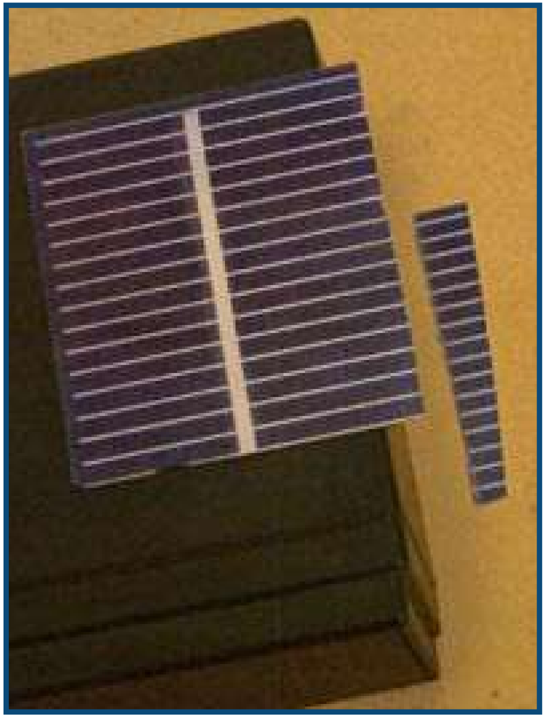
Using broken solar cells

Broken cells are a challenge. Cutting a silicon cell evenly is not an easy task.



The best cutting method I have found to date is to use a diamond tipped scriber with a ruler. Use the ruler as a guide and simply scribe along the ruler's edge, gently rubbing the tip along the cut back and forth until you cut about half way through the cell. Then, line up the cut line on the 90° edge of a flat surface and quickly snap the piece off. It is like cutting glass, but more





delicate. It takes a little practice. Thicker cells are generally easier to cut than thinner cells as they have less tendency to break off unevenly. Adjust your cutting technique according to the cell type.

Cutting cells is labor intensive. If the cells do not have to have perfect, smooth edges, you can just match up broken pieces of about the same size and connect them as is. It may not look as neat, but the time saved could be well worth it.

When working with a batch of broken cells, group them according to size and then test the biggest and smallest of the same group to get a reading of the current range. Write the readings down, as well as the number of cells in the group so that you can access this information later.

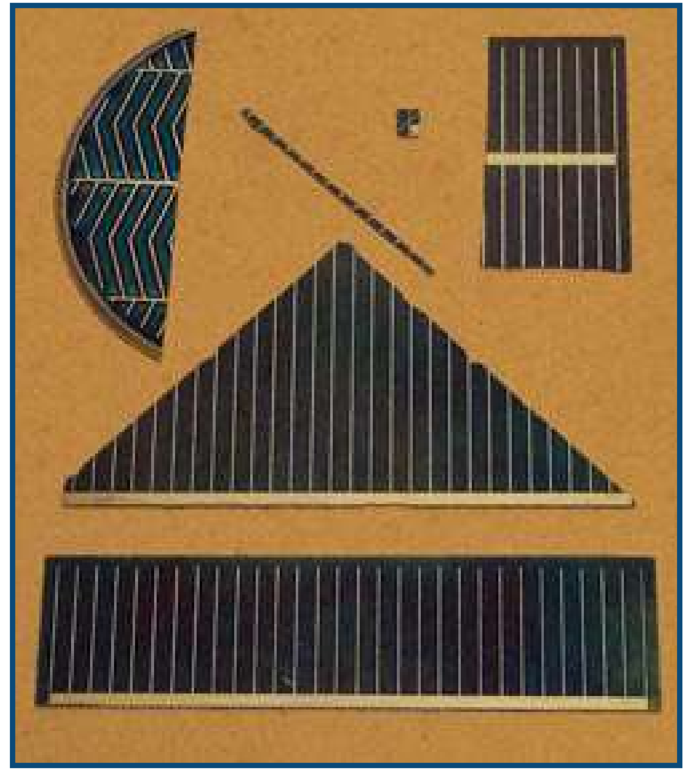
If you are an educator and are considering using an inexpensive batch of broken cells for student projects, consider this. Silicon is glass-like and small shards

easily get into the skin as splinters. It is not advisable for young children to be cutting cells. If you are working with young children, you may want to cut the cells yourself, attach the tabs, and then coat them with silicone to minimize accidents from shards of silicon.

It is good practice for anyone cutting cells to wear gloves, and be attentive to the powder from scribing, and to silicon shards. After cutting, make sure all debris is cleaned from any work surface.

Working with broken cells can be a bargain – or not. For instance, if fingers have to be added to many of the cells, the cost of conductive epoxy must be considered – and the same for any other materials used. You may discover in practice that it is actually cheaper to buy whole cells. Cell chip lots come with different levels of problems. Some are easy to work with and some are not. The best thing is to buy a small lot, then if that lot is workable, you can order more of the same type of cells.

Broken cells lots are great to work with to practice and hone your soldering technique and gain experience and confidence handling cells. They are also good for some smaller projects and in some cases will work well in larger projects.

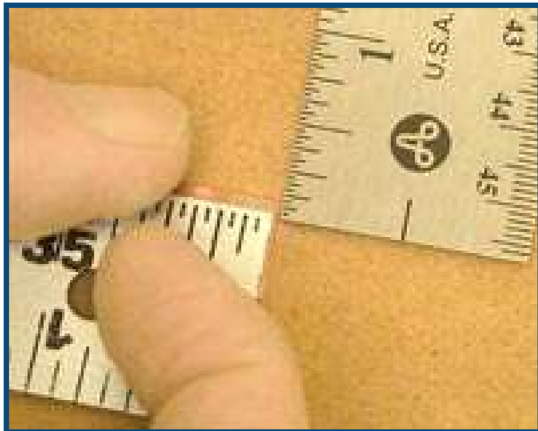


Shapes cut from broken cells

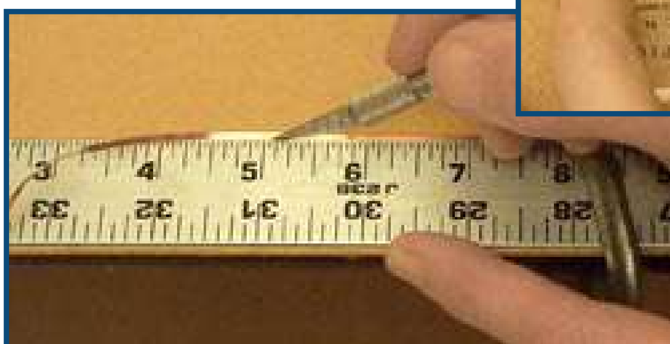
Making tab and bus ribbon

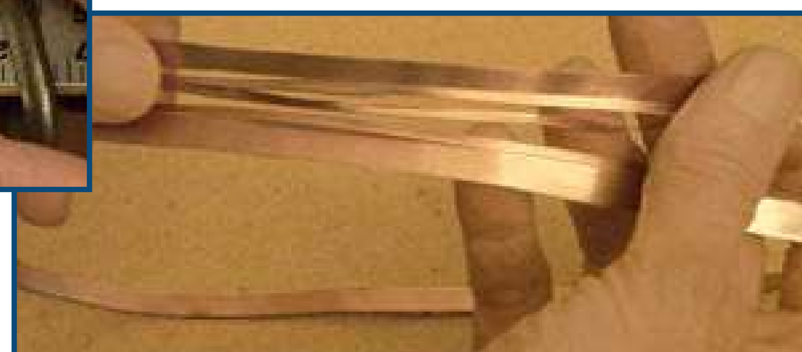
Tab and bus ribbon can easily be cut from .003" or .005" copper foil with a sharp pair of scissors, a rotary cutter, or a paper cutter. McMaster-Carr has copper foil in the thickness needed for tab and bus ribbon applications. This is the most effective way to make tab and bus ribbon. Simply go to their web site and type in copper foil to see the selection available for your needs.

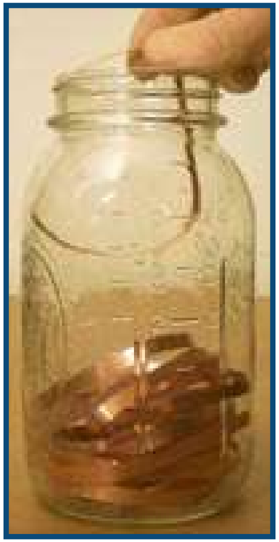
Making tab and bus ribbon



Cutting tab and bus ribbon





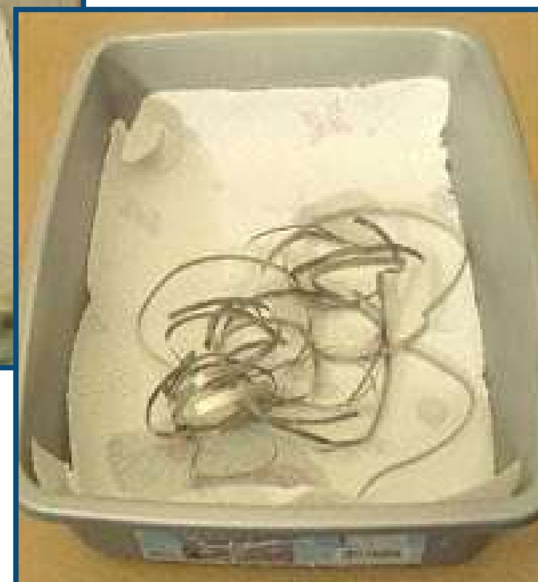


Tinning the cut foil

Commercial tab and bus ribbon normally comes tinned to make the foil easier to solder and reduce corrosion. To tin the copper foil that you have cut for tab and bus ribbon, the strips can be immersed in a heated solution of Tinnit, as illustrated here.

Top left: cut foil is placed in a quart sized canning jar. Bottom, left to right: boiling water is added to Tinnit in a pint jar, and stirred to make a solution; the jar of foil strips is placed in a heated water bath, and the solution is poured onto the foil strips.

One pint of the solution will cover about 600 square inches of foil. So, for a 100' roll of ½" wide foil, two pints of Tinnit is needed to coat both sides of the ribbon with a 0.0004" plate. The solution will usually last about six months if stored in a jar that does not have a metal lid.



The foil strips are left in the Tinnit solution in the heated water bath until they turn silver in color. Then, they are removed from the solution and allowed to dry.

TOC

Later, when assembling the panel, the parts of the tab or bus ribbon surfaces that will be soldered will again be tinned, but with a soldering iron. This extra tinning with the soldering iron is a necessary step for good adhesion of the tab ribbon to the cells.

Instead of using a tinning solution, the cut copper foil can be tinned by simply melting some solder on the soldering iron as is done for the second tinning, but in this case the soldering iron is run down the whole length and both sides of the tab or bus to apply a coating to the entire ribbon.

Other options for connecting cells

There may be circumstances where a quick connect is needed for classroom demonstration, and test purposes, without the need to solder connections. Simply attaching copper foil tab and bus with clear tape will work. However, remove the tape slowly when you are done so that the cell does not crack. A tape that has a mild sticking quality would be more appropriate rather than a tenacious forever-stick type. Plastic paper clips can also work in a pinch.

Small gauge stranded wire can be used instead of tab and bus ribbon for connections. This has to be tinned with a soldering iron so that the wire will adhere well to the fingers of the cell.

Making tab and bus ribbon

The copper foil tape that is used for stained glass can be purchased in various widths and can be substituted for tab and bus ribbon. To give it more current capacity and to allow for soldering, double it back on itself with the sticky side inside, which gives you two clear sides of copper foil to be used as tabs or bus. This then has to be tinned.

Another connecting method is conductive epoxy. This is expensive, but it eliminates all soldering – and solder fumes.

Using conductive tape also eliminates soldering. Current can flow through the adhesive layer of this tape. 3M #1182 has adhesive on both sides which is perfect for connecting cells in series. The tape can also be doubled up for more current carrying capacity. 3M also has a conductive tape #1245 with the adhesive on one side and pre-tinned tapes such as #1183.

I have not used these alternatives except for quick demonstrations and class projects, and cannot vouch for the durability of these methods in the harsh conditions that a working solar panel is subject to. For this reason I cannot recommend them, but you may wish to experiment with them.

Encapsulants

Encapsulants form a barrier around the cells and tab and bus ribbon. This electrically insulates the positive output from the negative output. Any moisture that gets inside the panel is thus blocked from creating a conductive bridge that would leak current and degrade the cells' output performance or short them. Encapsulation is not necessary, but it adds to the integrity of the panel.

There are two types of encapsulants that are widely used for this purpose: EVA (ethylene vinyl acetate) and silicone. In commercial panel production the cells of the panel are covered with a sheet of EVA which is thermally bonded to the cells in a vacuum chamber. Silicone is usually injected or sprayed over the cells in a vacuum chamber in commercial production.

I have not worked with EVA so I cannot provide any information about its use. I have used silicone and find it easy to work with.

The backs of the cells in the panel array can be coated with any type of silicone, but the faces of the cells need to be coated with a two part RTV (room temperature vulcanization) optically clear silicone.

Do not confuse what is called clear silicone with optically clear silicone – they are quite different. Do not cover the faces of the cells with any clear silicone that is not optically clear as it will reduce the light transmission, resulting in drastically lower cell output and poor performance. If you cannot use the optically clear silicone, it is best to not use an encapsulant.

Silicone has excellent thermal expansion characteristics. It remains elastic as it heats and cools in the demanding conditions that solar panels are subject to, and moves with the other panel components. GE 615 silicone has a temperature range from -75°F to 400°F which makes it a reasonable choice for solar panel operation in a wide variety of climates.

Silicone encapsulation is a good addition as a last line of defense against moisture, but it is not a substitute for a Plexiglas or glass panel cover. Silicone is too soft and can pit and become worn with abrasive particles blowing in the wind and general weathering.

There are several optically clear silicones on the market. I have worked with GE 615 and have found it more than satisfactory for these purposes. You may want to research and investigate other brands of optically clear silicone for comparison.

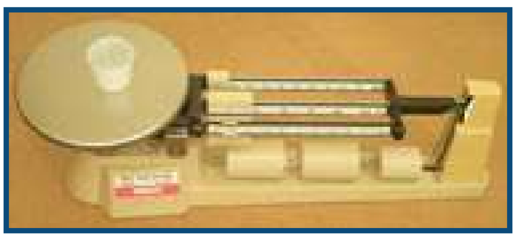
Generally, optically clear silicone is expensive, so you will want to use it sparingly. I have experimented with cutting the RTV GE 615 with xylene and this works well for applying thin films. The cells do not have to be encapsulated in a thick layer. A very thin layer is sufficient to provide the insulation needed.

RTV GE 615 is a two part silicone, which means you mix the A and B components. For this particular product the mixing ratio is 10 parts A component by weight to 1 part B component by weight.

De-aerate the silicone

When you mix the A and B components, air will be trapped in the mixture. This appears as many tiny air bubbles. You have to de-aerate the mixture (remove the bubbles from the silicone). This can be done with a hand operated or motorized vacuum pump. McMaster-Carr has a simple hand operated vacuum pump kit with a vacuum jar and stopper, which is convenient for this purpose. For mixing the A and B mixture, use a container that allows enough room for the frothing that will occur as the mixture is de-aerated, and fill the mixing container to no more than one third full. You can use the jar that comes with the vacuum pump kit for the AB mixture, and do a larger batch, but start out with a small amount and proceed with subsequent batches based on your observation of the process.

To de-aerate,



▲ Weigh the mixing cup, then weigh out the appropriate amounts of parts A and B into the mixing cup.

▲ Mix the A and B

▲ Place the cup in the vacuum jar

▲ Put on the cover on with the stopper and vacuum hose

▲ Pump down to about 29 hg

TOC

As you pump the air out, notice that the silicone froths and rises. The frothing will subside after about two minutes, when the de-aerating is finished.

- Let the air back into the vacuum cup and remove the lid. The mixture should be bubble-free, as shown at left.
- Pour the silicone mix into a glass container to prepare for cutting with xylene.

Cutting the silicone

In a glass container, mix xylene into the silicone mixture and stir thoroughly. This lowers the viscosity and makes it easy to spread on the faces of the solar cells with a small brush. Any size brush you are comfortable with will do. The more you cut the silicone with xylene, the easier it is to spread an even, thin layer.

Experiment with different percent solutions of silicone and xylene by mixing small batches and testing on cells for spreadability to suit your needs.

1 part silicone with 1 part xylene = 50% solution

1 part silicone with 1½ parts xylene = 40% solution

1 part silicone with 2 parts xylene = 33⅓% solution

TOC

Test each of these to see what thickness works for you. A very thin coating is all that is needed as long as coverage is thorough. The xylene evaporates quite quickly and will lose viscosity, so work fast when coating the cells, or cut the silicone mixture with more xylene for more workable time.

At room temperature the mixture will cure in about seven days. You can speed up the curing time by applying heat; however the xylene is highly flammable, toxic, and explosive. You must let it evaporate off before applying heat to the mix. Do not work with xylene without proper safety equipment, filter, respirator, etc., and do not work with this material near a source of ignition. Follow all recommendations on the available MSDSs for these chemicals.

As stated, applying heat will greatly accelerate the curing time. At a temperature of 302°F the silicone will cure in about 15 minutes, at 257°F it will cure in about 45 minutes. At 212°F it will cure in 1 hour. At 149°F it will cure in 4 hours. At 77°F it will take 6 to 7 days to cure.

It is best to work with and cure these materials outdoors. Curing in the sun outdoors accelerates the curing process and also allows the toxic fumes to dissipate. Xylene (also known as xylol) is a common lacquer thinner and can be purchased at any local hardware store.

When the cell surfaces are tack free, the silicone has cured.

If you do not wish to de-aerate the silicone mixture, you can simply cut with xylene. This will allow entrapped air bubbles to release as the lowered viscosity allows freer air movement. There will still be some trapped air, but not as much as there would be if you do not cut it with xylene. If you do not wish to cut with xylene and do not wish to de-air, there will be bubbles, but as the silicone mixture is applied to the cells many of the bubbles will dissipate; however there will be more bubbles than if you cut the mixture with xylene.

Again, it is not necessary to use an encapsulant, but it does help to preserve the electrical integrity of the panel when moisture and condensation is a concern. If you seal the outside edges of the finished panel well with silicone, and have constructed the panel in a dry warm atmosphere, you will probably not have any major problems with condensation or moisture invasion.

The solar electric system

With the addition of rechargeable batteries, the panels you have constructed can be used as a constant power supply for a variety of applications. You can either use 12 volt DC appliances which are readily available from RV and alternative energy suppliers, or purchase an inverter to change the DC to AC so that you can run most AC powered home appliances. The greater your power requirements, the more panels and batteries you will need.

Although this book is concerned strictly with panel construction, following is a very brief discussion of the other components needed to complete a photovoltaic system. Details of all these other system components, how to size a solar system for your needs, and construction techniques for a small home power supply can be found in the e-book Solar II.

Diodes

If a solar panel or array is going to be connected to batteries as part of a small power system, be sure to include a diode. There is a reversal of current flow when no or very little current is coming from the panels to charge the battery. The diode prevents the current in the battery from leaking back into the panel when the sun goes down. Always install a diode!!

Any Schottky diode rated at or above 30 amps at around 50 volt (PIV) will suffice for these four panels, and remember to put the striped end of the diode towards the battery on the positive lead. Most regulators (charge controllers) include a diode, so if you install a purchased regulator, you will not need another diode.

If you use a diode alone, remember that most silicon diodes have a voltage drop of 0.7 volts. To reduce this loss, use a Schottky diode which has a voltage drop of only 0.3 volts. It's not strictly necessary, but it will help to reduce system losses. More about diodes is in Solar II.

Charge controllers

A voltage charge controller is needed to keep an even keel on the battery charging process and to prevent excessive gassing. A battery will start excessive gassing at around 15 volts. The charge controller ensures that the batteries will not be damaged by overcharging.

For some purposes a controller may not be needed, for instance if you are there to watch for overcharging, and the battery is constantly being used and depleted. Also, if you are using self regulating panels (very low output) you will not need one. I have some second hand batteries and self regulating panels that I use without a diode for short field trips, but I am always there to monitor them, so I don't really need a regulator for them. I simply use a knife switch to disconnect the panel at night to prevent reverse flow. On the other hand, the batteries that I use for home power backup are on a charge controller.

Solar II has more detail about construction and use of charge controllers.

Cables and connectors

The wiring from the panel to the battery should be the proper gauge to handle the current rating of the panel or panels. If you have a long wire run, it is best to use larger diameter wire than you need, so that voltage drop will be minimized. If you are going to run the cable underground or have it exposed to sunlight outdoors, it must be rated for that purpose and UV resistant, such as type TC or UF. You can give extra protection to buried cable by inserting it in PVC tubing for its underground stretch.

Battery connections to equipment should be secure. Do not use alligator clips, as they are easily knocked off. Any outside connections should be sealed from the weather. Solder all connections (except battery terminal connections) and cover them with heat shrink or electrical tape, and cover them with clear silicone rubber caulk to prevent moisture from seeping in .

Generally 10 or 12 gauge zip wire will be sufficient for most small systems with a very short run. Wire runs, wire ampacity and more, are discussed in detail in Solar II.

TOC

Batteries

If you are going to use your panel with a battery for a regular power supply, use deep cycle batteries such as golf cart or forklift as they have the longest life. Marine batteries can also be used, but they are not as good as deep cycle batteries because their plates are not as thick. They are a workable compromise if you can not readily obtain deep cycle batteries. However, avoid using automobile batteries as they are not designed to take the depth of discharge this kind of system demands. If you are a really hard-core do-it-yourselfer, you can even build your own batteries.

Maintain the system by checking the battery water level (keep a bottle of distilled water on hand) and check the batteries' state of charge once a month. Battery capacity can be monitored in several ways. The simplest is to hook up a voltmeter to the battery terminals to get a reading of the battery's voltage. In general, if a battery's no load voltage goes below 12 volts, you should give it a rest and let it charge up again before using your system. If the battery is old, it may not maintain or hold a charge for very long. Types of batteries, maintenance and sizing of battery systems are discussed in Solar II.

Fuses

There should always be a fuse between the positive battery terminal and the appliances the system powers. This fuse should be rated higher than the current draw of the appliances. Miniature circuit breakers (MCBs) can also be used. Detailed instructions on fuses are in Solar II.

Mounting panels

In planning to set up your panels outside, there are several factors to consider. Ground-mounted panels need to be off the ground, and mounted on a platform, rack or pole. The bottom of the panel should be above the greatest height of snow accumulation for your area. Also, panels act like sails, so they need to be secured to withstand high winds. Lightning is also a concern for PV systems. Panel frames and mounting racks should be grounded to reduce the chances of lightning damage.

Solar panel location

Panels should face true south without any partial or full shadows. If a portion of a panel is shaded at a certain time each day, be sure to have a bypass diode on the panel. If at all possible, site solar panels in areas that do get full sun all day. More information on siting and using bypass diodes can be found in Solar II.

Orientation

For maximum performance, solar panels should be mounted at an angle. Depending upon how your panel is mounted, you may keep it at a permanent angle, or adjust it throughout the year to take full advantage of the sun. The rule of thumb for figuring the angle for your location is latitude plus or minus 15°, according to the season. For instance, my location is about 45° north latitude, so for a permanent year-round angle I would mount my panels tilted up to 45° from horizontal, and facing true south. In this location, to get maximum power in the winter, the angle should be 45° plus 15°, or 60°, and for maximum power in the summer, the angle should be 45° minus 15° or 30°. Although such adjustments might seem bothersome, they do make a considerable difference in the charging time for the batteries.

Panel maintenance

Panel surfaces should be cleaned periodically of dirt, pollen, and dust. Use just a damp rag. Don't use soap, as it creates a film on the panel surface which cuts down on the sunlight reaching the cells. Remove snow and ice from the panels as well, but use tools that will not scratch the Plexiglas. Clean and clear surfaces will keep the panels operating at peak efficiency.

Last but not least, make sure that your PV installation conforms to all safety and electrical codes for your place of residence. Some areas require consultation with an electrician before installation, or may have zoning regulations for panel siting.

Materials and tools

TOOL	PART #	SUPPLIER
Wire crimping tool		Electronics supplier
Wire cutters		Electronics supplier
Solder, 60/40 or silver		Electronics supplier
Soldering iron, or soldering station		Electronics supplier
Drill		Hardware store
Screwdriver		Hardware store
Cobalt steel jobbers' twist drill bit, heavy duty, wire gauge size 26, 3" L, 1⅞" L flute	#3033A238	McMaster-Carr
Machine screw size high-speed steel hand tap taper, 10-24, H3 pitch diameter, 4 flute	#2522A671	McMaster-Carr
7/32 drill bit		Hardware store
Plastic sheet cutter		Hardware store
Reamer		Hardware store
Pliers		Hardware store
Hacksaw or cutoff saw		Hardware store
Triple beam scale (optional)	WLS3455	Sargent Welch

MATERIAL DESCRIPTION	SUPPLIER	PART #	QUANTITY
300 VAC/VDC terminal block 2 circuits, .69" center-to-center, 65 amps	McMaster Carr	7527K22	1 per panel
18-8 SS pan head slotted machine screw 10-24 thread, 1½" length. Can also use 1¾" or 2" depending on preference	McMaster-Carr	91792A251	Pack of 100
18-8 Stainless steel machine screw nut 10-24 screw size, ⅜" width, ⅛" height	McMaster-Carr	91841A011	Pack of 100
Plastic case, 4.7" X 2.6" X 1.55"	All Electronics	1591-CSBK	1 per panel
18-8 Stainless steel large OD flat washer 10 screw size, 13/64" ID, ½" OD, .033"-.047" thick	McMaster-Carr	90313A200	Pack of 100
Acrylic (Plexiglas) or polycarbonate sheet, 3/32" thick, 29" X 36" or as needed	McMaster-Carr or hardware store		1 per panel

Materials and tools

MATERIAL DESCRIPTION	SUPPLIER	PART #	QUANTITY
Aluminum sheet, 1⁄16" thick, 29" x 36" or other as needed	McMaster-Carr or sheet metal shop		1 per panel
Alloy 6061 aluminum rectangular bar ¼" thick x ¾" width x 6' long	McMaster Carr	#8975k27	2 - 6' lengths per panel
Alternative washers 18-8 stainless steel SAE flat washer #10 screw size, 7/32" ID, ½" OD, .036"-.065" thick	McMaster-Carr	#96659A104	Pack of 100
Alternative washers 18-8 stainless steel SAE flat washer #8 screw size, 3⁄16" ID, 7⁄16" OD, .036"-.065" thick	McMaster-Carr	#96659A103	Pack of 100
Fiberglass insect screening medium, gray, .011" wire, 36" width, 25' Length	McMaster-Carr	#1017A31	as needed
Rubber grommets, ⅛" ID, 11/32 OD, groove diameter ¼", groove width 1⁄16", 3⁄16" thick	Hardware store		2 per panel

Materials and tools

MATERIAL DESCRIPTION	SUPPLIER	PART #	QUANTITY
Shrink tube, ¼", ⅞" long	Electronic, electrical supplier, hardware store		2 pieces per panel
GE Silicone II sealant, clear	Hardware store		About 1 tube per panel
GE RTV 615 optically clear silicone	Circuit Specialists	RTV615-1P	1 pint (for 4 panels)
Xylene (xylol) solvent	Hardware store		1 pint (for 4 panels)
Clear plastic pony beads ¼"	Craft store		8 per panel
Silicone rubber strip 3/32" thick, ½" width 36" long	McMaster Carr	7665K12	4 per panel
Aluminum channel, ½" inside dimensions for both legs and base.	Hardware store		3 6' and 3 8' long pieces, (for 4 panels)

Materials and tools

MATERIAL DESCRIPTION	SUPPLIER	PART #	QUANTITY
Copper foil .003", .004" or .005 thick, ½" width, 100' rolls	McMaster Carr	.003" #9053K12 .004" #9053K13 .005" #9053K14	as needed
Copper foil tape w/conductive adhesive, one side, ½" wide x 6 yards long (optional)	McMaster-Carr	#76555A712	as needed
Copper foil tape, non-conductive, one side adhesive (optional)	Stained glass supply		as needed
3M 1181 one sided conductive adhesive tape, ½" wide, 18 yard lengths (optional)	SPI Supplies	#05012A-AB	as needed
3M 1182 two sided conductive adhesive tape, ½" wide, 18 yard lengths (optional)	SPI Supplies	#05085A-AB	as needed
Flux pen or other form of flux	HMC Electronics	186FP Mildly activated rosin, type RMA	2 pens or as needed

Materials and tools

MATERIAL DESCRIPTION	SUPPLIER	PART #	QUANTITY
J-B Weld Epoxy, Max temp. 500°F or similar, 2 oz. tube	McMaster Carr	#7605A11	1
Tinned copper bus and tab ribbon	E. Jordan Brooks Co Inc.	Contact them	as needed
Calibrated solar cell (optional)	Solar World	CC 2X 4	1
Flexible solar cells (optional)	Solar World	See online catalog	
Solar Cells	Plastecs	See online catalog	