Sustainable Electrical Power at Living Energy Farm
How to Build it Yourself

Alexis Zeigler, January 16, 2018, DRAFT

This document is intended as a primer on the sustainable use of electrical power, primarily the use of electricity from photovoltaic (PV) panels. We have found that we can support a very comfortable lifestyle with minimal energy demands. It is critical that the principles of wise desing ***preceed*** any considertion of the installation of energy sources, PV or otherwise. See http://livingenergyfarm.org/techdocs/greenbuild2.pdf and http://livingenergyfarm.org/raff20.pdf for a review of those design principles.

Reader Assumes Risk

The reader should beware that we use electrical systems at Living Energy Farm in an unorthodox manner. We will do our best to explain the risks involved, but the reader, in pursuing this document further, does hereby fully indemnify and hold harmless Living Energy Farm and the author from any harm to persons and/ or property that might result from any attempts of the reader to implement any ideas or practices explained in this document. You are pursuing these practices at your own risk.

Electrical Risks

In electrical code, anything below 48 volts in considered "low voltage," and is not considered to present much of a hazard of shock or electrocution. Certainly, a single car battery at 12 volts DC or a single solar photovoltaic (PV) panel, usually at 35 volts DC or less, does not pose a shock hazard. However, if you tie two PV panels in series (we will explain that shortly), you will have 60+ volts. That voltage poses a risk of electrical shock. At Living Energy Farm (LEF), we use a lot of 180 volt DC equipment. Voltages that high pose a serious risk of electrocution. (My sister's ex-husband was killed by a 48 volt stage lighting wire. Under specific circumstances, even modest voltages can be dangerous.) If you do not have experience assembling higher voltage systems, be get help from more experienced electricians. Always make sure the power source is disconnected or turned off before you work on any electrical system. Buy proper test equipment (volt meter, aka VOM, multimeter, clamp meter), and learn how to use it. Volt meters can usually be found for $20 or less at any hardware store. Beware than any meter that sits around for a long time may suffer from a weak battery. A meter with a weak battery may give erroneous and unpredictable readings. Always test your meter against a live circuit before you test a circuit that you presume to be deactivated.

Battery Risks

While a single low-voltage battery cannot electrocute you, it does have a very high ampacity, meaning it can generate a lot of heat. Short circuiting a single battery can melt wires, make sparks fly, and start fires. Any battery system *must* have a fuse or DC circuit breaker attached to it. Circuit breakers are best, but if you are building on the cheap, at least use an inline fuse. Either way, make sure the fuse/ breaker size is appropriate for your wiring sizes. There are numerous online wire size calculators that are very helpful. Beware that trying to power heavy loads (motors, any heating or mechanical device) over long distances with low voltage will not work very well and will subject your wiring to heavy loading and possible overheating. Higher voltages work much better for powering motors and other heavy loads.

Installing Photovoltaic Panels

For solar water heating, winter heat is at a minimum, and there is a surplus of heat in the summer. Our winter sun angle at this latitude (Virginia) is near 30 degrees, so the maximum efficiency in wintertime is achieved by a solar hot water panel at 60 degrees from horizontal (with the ground).

With photovoltaic panels, sometimes people tilt the seasonally. If you want to do that, you will need an adjustable rack. If you want a stationary rack, then a good tilt for all-around performance is about 30 degrees from horizontal. You want them pointed south, but it does not need to be a perfect south. A bit east or west of south (15 degrees or less) does no harm efficiency wise. If you want power earlier or later in the day, you can tilt the panels east or west. Make sure they are bolted down well enough so the wind will not damage them.

Basic Electrical Princples

Electricity is an extremely complex phenomena. Any metaphor that attempts to explain all of its manifestations will fail at some point. That being said, general household and PV electrical systems can be understood employing a metaphor of pressurized water. If you imagine a pipe carrying pressurized water toward a turbine (a waterwheel used to do work), the pressure represents voltage (V), and the volume represents amperage (A). If you think of how much work the turbine can do, it could do the same amount of work with either higher pressure and lower volume, or higher volume and lower pressure. That work is represented by watts, which is volts X (times) amps. 1 volt X 10 amps = 10 watts = 10 volts X 1 amp. This equation is true for AC or DC power. The size of the pipe (wire) will restrict the volume (amps) that can easily flow through the wire. Try to push too much volume through too small of a wire, and the wire gets got. That is inefficient, and possibly dangerous. It is easier to move more power through a smaller (cheaper) wire with higher voltage (pressure).

As our metaphorical water moves through a pipe, the friction of the water rubbing on the inside of the pipe, and the resistance to flow of the turbine itself, are called just that -- resistance. Material that passes electricity easily, like copper wire, has low resistance. Resistance causes some of the energy in the electricity to be converted to heat. An incandescent light bulb (the old fashioned kind) has a lot of resistance. That resistance limits the amount of electricity that can pass through the bulb, and converts most of the energy passing through to heat (about 95%) and the remaining 5% is turned into light. More resistance means less energy will pass through an electrical device. Higher voltage means more pressure, which will force more energy through an electrical device. Each device is designed to handle a certain amount of energy. Voltage higher than a particular device is designed to handle would force through too much energy, and damage a device.

Electrical Units (Metaphorical)

Voltage = Pressure

Amperage = Volume

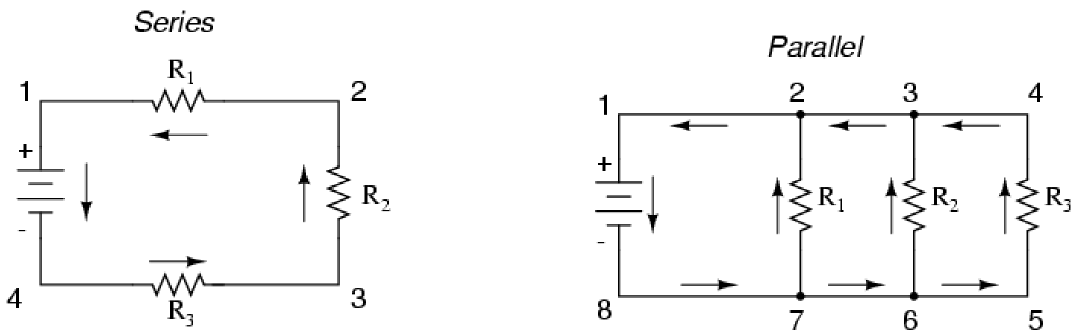
Watts = Volts X Amps = Work that can be done. Watts, or kilowatts, can be mathematically calculated as horsepower as well, useful for understanding what motors you can run with a particular power source.

Resistance = Resistance to flow, restricts the amount of energy that can flow through a wire or device, and causes electricity to be converted to heat/ and or mechanical power. The symbol for resistance is a little horseshoe, called ohms.

Watt-Hour (or kilowatt-hour, kwh) = the amount of work that can be done in an hour. This is what the power company measures with the meter outside your house.

Amp-Hour (Ah) is the unit used to rate batteries. This tells how much amperage flow over time a given battery (or set) can support, independent of voltage. Once you add voltage into the calculation, then you will know the number of watts, or how much actual work can be done. So a 12 volt car battery is rated for about 300 AH, at 12 V that 3600 Watts for one our or 360 watts for 10 hours, etc. The problem is that car batteries only actually deliver a tiny fraction of their AH rating. Nickel iron (NiFe) batteries radically outperform car batteries (or deep-cycle lead acid batteries). See below.

Series and Parallel Circuits



Understanding series and parallel circuits (illustrated above) is important. The symbol on the left of each drawing is the power source. The "Rs" are resistors, or devices that use electricity. The terms series and parallel apply to both energy production circuits (several solar panels) or to energy using circuits (the wiring in your house.)

In an energy producing circuit, a series circuit adds voltage while amperage remains constant. Our main power supply at LEF is 6 - 30 volt PV panels in series. 6 X 30 = 180 volts. Each panel has about 8 amps output, and so does the whole series circuit. We also run some irrigation pumps with 24 V motors. In that case, we use two 30 V panels in parallel. In a parallel circuit, the voltage remains the same while the amperage adds up. A 24 V DC motor is perfectly happy running at 30 V. If we put the panels in series and tried to run 24 V motors at 60 V, the motors would be damaged. Whether your panels are hooked in series or in parallel, the wattage (total power output) remains constant.

In energy using parallel circuits, the voltage remains constant at each energy using device. This is the way your house is wired. Every device, large and small, has the same voltage available (120 V AC).

In a series circuit, the voltage has to push its way through each "resistor" (which means each device using electricity). The resistance compounds. I'll skip the math. All you need to know is that when you put any kind of device in series with another, you generate a lot of resistance. Each device gets a reduced voltage. Mostly, series energy using circuits are not used.

It is important to understand that, in keeping with our voltage = pressure metaphor, electricity always pushes its way into the low pressure/ low voltage parts of a circuit and kind of just puddles there. This is true in both parallel and series circuits. Back in the old days, PV panels had a monolithic interior design. A single bird dropping would create a low-voltage spot. All of the electricity from the PV panel would flow to that spot and create heat. The output of the panel would drop dramatically. Modern PV panels are better, but even a small amount of shading dramatically reduces their power output. You can put your hand in front of a large PV panel, and even though you may only cover 10% of the panel, you may reduce the output 50% or more.

Because of the tendency of electricity to "puddle," you cannot use different kinds of batteries in the same circuit. If you have a flashlight that uses several batteries, and you mix strong batteries with a weak one, as soon as you turn on the flashlight, most of the electricity goes from the good batteries towards the low-voltage puddle in the weak battery. Your batteries die quickly and your light does not work very well. The same is true of large batteries. You cannot mix different sizes or kinds of batteries, or old and new batteries, effectively. Nickel iron batteries (NiFe) are an exception to some degree, as they maintain their strength for a long, long time. Even then, one would want to pay close attention to setting up a circuit mixing older and new NiFe batteries.

The puddling effect of electricity also means that it is not wise to mix different kinds of PV panels in a power production circuit. It may work, but it will not be efficient. Different panels will have different output voltages, and the electrical output will puddle in the weaker panels.

Electrical Polarity

Many, not all, electrical circuits have a polarity, denoted by + and - signs. With household current, the + side is usually the black wire, and it is the hot wire -- the one that can hurt you. (With high voltage and industrial AC, all wires but the ground are hot.) With DC systems, black is - and red is +. With most DC motors, you can reverse direction of the motor by swapping + and - wires. When you look at your voltmeter, the black lead should be attached to the plug labeled "com," for common. The red wire should be connected to a plug with numerous symbols, including V. When you test a live circuit with a digital meter, if you put the red wire on the + side, you will get a positive number. If the number on the screen has a negative sign (like - 240), then you have the red wire on the negative side. Reverse and test again. Labeling the + side with red electrical tape is often a good idea.

LEF's Unique Electrical Systems

I) Lighting with Nickel Iron (NiFe) Batteries

Our intention at LEF is to live with the ideas we espouse. Lots of ideas seem great on the laboratory countertop, only to prove unworkable in real life. When we started LFE, we wanted to be able to build the main house quickly. We set up an inverter tied to 2 lead-acid batteries. The batteries were only $100 or so each, and together they had a rated ampacity of 600 ah. (Meaning they should be able to put out 100 amps for 6 hours, or any variation of amps and hours that multiplies to 600.) We also purchased an experimental set of NiFe batteries rated at 100 ah. As we were finishing the kitchen, which is separate from the main house, we attached the lead-acid batteries to our DC LED lights. The DC LEDs are fantastically efficient, using only about one-tenth as much electricity to produce the same amount of light as an incandescent bulb. Still, after only a couple of years, the capacity of the lead-acid batteries starting dropping. The lights went dim.

As we started to consider taking LEF abroad, we decided to attach our experimental NiFe set (which cost $1000), even though we knew they were too small. Our 100 ah NiFe set was wired to the house (which has a lot more lights than the kitchen) as well as the kitchen. Miraculously, the lights have never gone dim. The NiFes are 7 years old to date, and show no sign of weakening. The performance of the NiFes radically exceeds the comparative amp-hour rating of lead-acid batteries.

This paper addresses electrical specifics, not general design issues (which we discuss elsewhere). That said, one should keep in mind that LEF's electrical design is very, very different than conventional off-grid design. We store electricity for lighting only. See http://livingenergyfarm.org/raff20.pdf for an explanation of our design. Trying to use a 100 ah NiFe set in a conventional off-grid design would probably be expensive and disappointing. For an explanation of the historic suppression of NiFe technology in favor of more consumerist approaches, see http://nickel-iron-battery.com/

Our NiFe set is wired in series. With NiFes, each cell is nominally 1.2 volts. Ten cells make a nominal 12 V set. If you are thinking of setting these up yourself, beware that NiFes have a different charge voltage than other batteries. Each NiFe cells charges at about 1.65 V per cell. They are much, much more tolerant of high and low voltages than other batteries. To charge NiFes, you can either find cells that match the charge needs of your set, add or subtract cells to increase or decrease the needed charge voltage, or use and MPPT charge controller to change the voltage. Our NiFe set at LEF uses a single 250 watt PV panel which puts out 30+ volts. We use an MPPT controller. With a lower voltage panel, you can also use a Xantrex C-series controller, which has NiFe settings, but you would need a nominal 12 V panel. We ran our NiFes for several years on a smaller panel (100 watt) with no charge controller at all. You have to add water more often that way, but it works. Doing that with a big PV panel might not be such a good idea.

LEF's Unique Electrical Systems

II) Daylight Drive with High Voltage DC

Electrical grids in the mainstream are dominated by centralized power generation and AC power because such a setup is profitable for power companies, and AC power travels well over long distances. (High voltage, that is.) Solar PV panels generate DC power, which does not travel long distances very well (though high voltage DC does fine over a few hundred feet.)

While AC has an advantage in moving down a wire efficiently, all AC equipment is very inflexible in its power requirements. DC motors have tremendous flexibility. At LEF, we set up our 180 V 1400 watt PV rack in part because that is a standardized industrial DC voltage. (Other standard DC voltages include 12, 24, 48, and 90.) We have since wired many motors to run off of that same solar rack. Sun come up, motors run, sun goes down, motors quit. It's that simple. We can run motors on cloudy days. We can even run motors that exceed the total presumed output of the solar rack. The motors simply speed up and slow down as the power supply fluctuates.

If you want to do this kind of thing yourself, this is what we have learned. First of all, 180 V DC power is more dangerous than the 120 V AC in your house. All wiring should be done to standardized AC standards. Avoid contact with live wires just like you would in your house.

We have spoken to numerous professional electricians about how to properly fuse and mange floating voltage DC power. Mostly, we get blank stares. You certainly MUST have fuses and/ or breakers suitable to your wire sizes.

With motors that spin freely, such as blowers, they are trouble free. Turn them on and off as you please. With motors connected to heavier loads (in our case, grain grinder, compressor, any shop tool that is working against a load), you can't run them in very low light or if the system is overloaded. In these circumstances, even though less electricity is available, excessively low voltage causes the motors to struggle. The modest amount of power starts turning into heat. In spite of the fact that our solar rack has an 8 amp output under full sun, we have melted many 20 amp switches in low light conditions. If a motor is struggling, turn it off, unplug it. Do the work some other time. We have also way oversized our main switches. We use 30 amp fused lever-arm disconnects at critical points. These cost about $60 each. Avoid turning on and off motors in very dim light. In low light, the DC power acts like an arc welder and instantaneously melts 20 amp switches.

We use industrial brush motors. Cheap, small DC brush motors are to be avoided. The heavier industrial brush motors hold up fine. If you run them hard, you will need to replace the brushes once every few years, which is not hard to do.

Brushless motors are available in low voltages, but not in 180 V DC (so far, though the good quality submersible pumps use brushless motors). Brush motors need maintenance. Brushless motors last long time, but are not repairable.

All that said, our daylight drive system allows us to do a lot of work. We run our main well, cut wood, grind grain, wash laundry, and run a host of shop tools. It's really a great system. Over time we will hopefully find a more systematic way to manage it (and stop melting switches...).

LEF's Unique Electrical Systems

III) Charging Cell Phones, Laptops, and Other Electronics

Our original conception of LEF was that we would not have personal electronics on the property. In thinking about taking our model to nonindustrial countries, we realized that we would need to provide that service. For us, we have access to many kinds of media and resources. Many people around the world have a cell phone connection and nothing else. At first, we tied an automotive cigarette lighting plug into the 12 V NiFe set. That worked great, but it would put our lighting in competition with people's gadgets. One of the big problems with conventional off-grid design is that it is, like grid power, a linear system. If a conventional off-grid system is overloaded, or if those miserable lead-acid batteries weaken, the whole system shuts down. LEF's DC microgrid is a multi-linear system. The whole thing can never fail. But we don't want to be in a position of browbeating people to not charge their gizmos off our NiFe battery set in the winter when solar resources are meager. Also, our MPPT controller (that drops the 34 volts coming from the PV panel to 16.5 volts for the NiFes) cost over $300. We wanted a cheaper way to charge devices directly off of PV panel. We talked to numerous companies providing MPPT devices. They all said that their devices have to be attached to a battery system to operate.

Then we found a simple, cheap solution. DC to DC converters are easily available and cheap (ebay). We got one for $30, connected it to a PV panel, and now we charge as many gizmos as we want (more or less) daylight drive, just like we like it. We have learned that not all "car chargers" are created equal. Some chargers made to charge laptops (and other devices) in a car work great, some don't.

We have USB converters that plug into the cigarette lighter plugs connected to the DC to DC converter, so now we charge lots of things on USB cables. Most USB-charged devices are standardized. Some need their own special charger, and get grumpy when connected to the wrong charger. If you remember the discussion about electricity and its tendency to puddle, putting to devices next to each other at the same charging station can result in the stronger battery being dumped into the weaker battery. One way to avoid this is to put a diode in each positive wire. A diode is an electrical one-way valve that only lets electricity flow in one direction. A diode will prevent a device from pulling electricity out of another device attached to the same charging station.

LEF's Unique Electrical Systems

IV) Re-cording Cordless Tools

We have made great use of abandoned cordless power tools. People throw them away all the time because a new tool does not cost much more than a new battery for the old tool. (Yet another example of consumerism.) For us, we take the old tools, take the battery pack apart, and take out the batteries. Then we connect an extension cord to the battery pack. We plug that cord back into our NiFe set. Cordless tools are made to run at 18 V, but they run fine at 12 V or 24 V. With voltages that low, you can't run power consuming tools like a circular saw on a long cord. But drills are fine, even on a long cord. Having mobile tools to compliment or heavy, stationary daylight drive shop tools has proven very helpful for us.

LEF's Unique Electrical Systems

V) Universal Motors

Another intriguing option for playing with daylight drive electricity is based on the awareness that power tools made to run on household 120 V AC current are actually "series wound universal" motors. The "universal" part means that they are brush motors that run on AC or DC. Our system is set up at 180 V DC. A universal motor plugged into that kind of voltage will try to spin very fast, and may not last a long time. Our nominal 180 V system is actually closer to 240 V at full sun. A nominal 90 V DC system would have an actual voltage close to what a (corded) power tool would want. The solar rack would need to be large enough to supply adequate amperage. And we have not worked with this enough to make any promises. Proceed at your own risk.