EHS/MCS Refugee Hut Design

by

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I have significant sensitivities to cell phone and WiFi signals, 60 Hz magnetic fields, and many foods and drinks. I have Electromagnetic HyperSensitivity (EHS) and Multiple Chemical Sensitivity (MCS). I want to build a small house, reasonably adequate for one or two people, on some property I own in the town of Rockvale, Colorado (about 40 miles southwest of Colorado Springs). This document is my attempt to design such a small house, or what might be called a refugee hut. I am sharing my design with the hope that others in the EHS/MCS community will find suggestions for their own building plans and also for others to make suggestions for improvements in my design.

Many codes have been developed over the past 50 or 75 years that deal with various aspects of house design, including the National Electrical Code (NEC), the Uniform Building Code, the International Building Code, and the International Residential Code. A state, county, or city may pass a law or ordinance requiring new construction to follow one or more of these codes. There may be additions (e.g. snow load) to reflect local conditions. The primary emphasis is safety. For example, if the guidelines in the NEC are followed carefully, the numbers of electrocutions and electrical fires will be minimal.

Codes do not deal with health issues, whether human, animal, bird, or insect. Some of us become quite ill from 60 Hz electric fields and/or 60 Hz magnetic fields. It seems obvious to me that we need a house operating exclusively on DC. I suspect that a large majority of electrical inspectors would hesitate to approve such a house.

Codes also do not deal with economic consequences. I know people who are disabled by EHS who are trying to survive on a \$700 per month disability check. They need a place to live that costs no more than \$300/month, in a place with low cell phone signal strength, and at least 100 feet from the nearest neighbor (who might be using electronic equipment that radiates too much). I have 40 acres in a box canyon with room for a few cabins. I have not raised this particular issue with the local planning and zoning office, but assume for the moment that they say I must install a flush toilet and connect to town water. That means I will need a septic system costing \$10,000, a water meter costing \$6,000, a monthly fee of \$50, plus cost of water used, plus plumbing costs inside the house. Assume also that I get a reasonable rate of return on investment if I rent the cabin at 1% of construction cost, ignoring the value of the land. That means that an allowable cost for a cabin with a composting toilet, renting for \$300/month, would be \$30,000. I think it might be possible to build a Tiny House for this amount. A cabin with a flush toilet would have to rent for \$250/month because of the \$50/month for the water system. The allowable budget for the cabin would then be \$25,000 - \$10,000 - \$6,000 = \$9,000. I would not have the nerve to ask anyone for \$250/month for the shack I could build for \$9,000!

A rule that every dwelling unit have a flush toilet certainly 'feels' good, but has the consequence that no housing can be built at the necessary price point, so people are forced to become unsheltered/homeless. They park their vehicle in a National Forest, moving every two weeks as required by local law enforcement. Their lives are unpleasant. Locals threaten them and steal their supplies. They poop in the forest, possibly impacting other users of the National Forest. 'Feel Good' rules have very real consequences!

As a nation, we have made progress in reducing discrimination against Blacks, homosexuals, etc. but still discriminate against the poor by our use of codes. At some point the Blacks had to engage in civil disobedience, to refuse to move to the back of the bus, to call attention to their plight. I think we are at that point now, where those with EHS and/or MCS will refuse to abide by the laws, codes, rules, ordinances, and interpretations that injure us.

One problem with the current system is that there is no obvious path to appealing a decision by a code inspector. We might talk to the county commissioners, the town board, or a lawyer, but in most cases we would be asking non technical people to make technical decisions. We could use something like a Small Claims court where everyone could present their case before one or more technical people and receive a ruling with some legal standing. If this court ruled in favor of my cabin with a composting toilet, then I could go ahead and build it, and reduce the homeless population by one.

This design is for a cabin for me. I will use a composting toilet to save the money for a septic system and water meter, but otherwise I will spend whatever is necessary to have a nice place to live and to show off to visitors who are EHS.

Building a house for the electrically sensitive requires some knowledge of electricity. You should expect to learn about volts, amps, and ohms. You should learn the difference between power (watts) and energy (watt hours), and use the terms correctly (saves considerable confusion and misunderstanding). DC is easier to understand than AC. There are no imaginary numbers, $\sqrt{-1}$, differential equations, trig functions, or reactive power in DC, like appear regularly in AC. If you made a B or better in your high school freshman algebra class, you should have no problem understanding my design.

ON GRID OR OFF GRID?

It is 1170 ft from the nearest power pole to the center of the hut. For a few thousand dollars the power line could be extended to the hut and I could enjoy all the benefits of a central electric supply. I have decided to not do so, but to just use photovoltaic panels. The hut will have batteries for lights and electronics but will not have an inverter (a device that converts DC to AC).

There was a battle called "The War of the Currents" fought in the early 1890s between Thomas Edison and Nikola Tesla. Edison had developed a DC system and Tesla had patented an AC system. The battle was fierce! Edison took the position that AC was inherently dangerous to human health. He would go to county fairs, catch a stray dog, and electrocute it on stage with AC. He once even electrocuted an elephant! He persuaded the New York State Legislature to adopt electrocution (by AC) as the method of executing criminals rather than hanging. But society went with the lower cost and greater convenience of the AC power grid, ignoring the safety aspects. The Tesla system is universally used today. We accept the accidental electrocutions as part of the cost of doing business.

I believe Edison was right about 60 Hz electricity being dangerous, not only for electrocutions but also the low level (and probably accumulative for many of us) effects of 60 Hz electric fields and 60 Hz magnetic fields. AC electricity has not been universal for all that many years. My parents and I moved into a house with electricity when I was 11 years old. I distinctly remember the satisfaction of having a better source of light for reading than the coal oil lamps we had used up to that time. So we are quickly reaching the point where *all* the elderly have been exposed to 60 Hz electric and magnetic fields their *entire* lives. If the accumulative effect of these fields has negative health effects, we would expect life expectancy to decline, along with the quality of life of the elderly. I believe we are seeing exactly that in this country! People blame this decreased life expectancy on all sorts of causes: increased use of drugs, obesity, pesticides, herbicides, cell phones and WiFi, etc. I will not argue against any of these having a significant effect, but we should not ignore the 60 Hz electric and magnetic fields.

If I am right, then continued use of 60 Hz electricity would be as stupid as continuing to smoke after seeing convincing data about lung cancer. We need to shift entirely to DC. DC has both electric and magnetic fields, but mankind has been living in dc fields for thousands of years without obvious ill effects. The earth has a net negative charge which causes a vertical electric field on the order of 100 V/m, directed downward. The earth's magnetic field is on the order of 500 milliGauss (mG), used by many lifeforms (including man) for navigation. Many with EHS have significant problems with 60 Hz electric fields above 1 V/m and magnetic fields above 3 mG, but no problem at all with the much higher dc fields.

The plan is to avoid all 60 Hz voltages or currents as much as possible. If electric motors or pumps are necessary, and they produce fields at frequencies above, say 10 Hz, then these devices should be separated a maximum distance from the living space.

This design is for an all electric hut. I want it warm in the winter and cool in the summer, with good thermostats. I want a refrigerator and a means of cooking. I want a computer with a good (wired) Internet connection, and a phone using Voice Over Internet. I want electric lights capable of at least 100 to 200 lux. I want to take a hot shower like my on-grid brethren. And I would like it to make sense economically.

My motivation is survival (and then reasonable comfort) rather than minimal cost, but a quick look at the numbers might be of interest. I pay almost $3000 per year electric bill for an 1500 ft^2 house on the Rockvale property. There is an economic concept called present value or present worth regarding the amount of cash in hand right now that is equivalent to this string of payments. This is used to calculate the monthly mortgage payment when you buy a house. The present value of $3000 per year for 20 years at 6% interest is $34,410. If the cost of the installed solar panels and batteries is less than this amount, then the economic decision would be to go off grid. There are other motivations (health, in case the grid goes down for an extended time, save the planet, etc.). But the point is that there is a chance that I will enjoy better health at a *lower* energy cost than if I were living in the existing Rockvale house.

RESEARCH REQUIRED FOR A 120 VDC SYSTEM

A quick search of the Internet failed to turn up an off grid residence that used a 120 VDC battery bank and no inverter. Standard battery bank voltages are 12, 24, and 48 VDC. The big box stores do not carry circuit breakers that are UL rated for 120 VDC. There are manufacturers specializing in the solar business (e.g. MidNite Solar) who fabricate and sell such breakers for about $20, so the research here will just consist of monitoring the performance of the commercially available circuit breakers.

There is an industry group, Emerge Alliance, that is building equipment to convert part of the commercial load from AC to DC. They are working on 12, 24, and 380 VDC, but not on 120 VDC as far as I can tell.

The bigbox stores do not carry switches rated for 120 VDC, at least at a reasonable cost. Mouser carries a toggle switch rated at 16 A, 250 VDC for about $11. The standard AC wall switches may also be used, but only for currents so small that switch failure is highly unlikely. If I want to use a 120 VAC hotplate for cooking, I will need to modify it so the thermostat controls only a control signal to a solid state relay, rather than the main current through the heating element.

SIZE AND LAYOUT

Size and layout are mostly a function of one's personal taste. Nothing is inherently good or bad about choosing 1600 ft^2 over 800 ft^2 or 400 ft^2. I chose an outside dimension of $20' \times 40'$ for the living portion, split into a combination living and kitchen area, a bedroom with walk-in closet, and a toilet/shower room. This is an experimental structure so there needs to be adequate space for experiments. I chose to attach a $10' \times 24'$ utility room on the side of the living space. This is unheated space for batteries, water heaters, pumps, and instrumentation.

WATER

Town water is available near the last power pole. It would be technically feasible to trench a pipe from the existing water supply to the hut. Water pressure is low at the connection point, barely enough for the adjacent house. It would not be enough to reach the hut without the addition of a booster pump. Town water is relatively expensive (I think $6000 for a meter and then $50/month plus water usage). My plan is to collect rainwater for house water usage. I might install the water storage tank about 100 feet above the cabin elevation, on the side of the mountain. Battery power would be used to pump the water uphill, but this would provide a constant water pressure in the hut.

SEPTIC

The town of Rockvale does not have a central sewage treatment plant. Everyone is on a septic system. Colorado has recently changed the rules on septic systems, making them more expensive. Certainly the water required for flush toilets is a problem here in the high desert. I have read the book *The Humanure Handbook* by Joseph Jenkins (both the second and third editions) and agree fully with him that it is better to compost our humanure and use the resulting compost on our gardens. One poops in a five gallon bucket, covers the poop with sawdust for odor control, and dumps the bucket on a compost pile when full. He has walked the walk, raising a family in Pennsylvania using this technique. He claims there has never been a documented case of disease transfer while using compost toilets. I had a 62 year old woman with severe EHS and MCS live in my shop for two months, and used a compost toilet for that time without complaint. Jenkins acts as a resource person for government bodies considering how to best handle our 'waste', and comments that some states (Arizona, California) are relaxing their requirements for flush toilets in favor of compost toilets. This hut will use a compost toilet.

GRAY WATER

Also known as grey water, this is the household output from showers, washers, and the like. It is distinguished from black water, the household output from flush toilets and garbage disposals. There are the usual bureaucratic rules, but it is generally legal to use in wetlands, on gardens, etc. I plan to install three plastic drain pipes under the concrete slab, one from the floor drain in the utility room, one from the shower and vanity in the bathroom, and one from the kitchen sink, draining to daylight on the downhill side of the hut. This area will be a small garden after the removal of rocks and the addition of rabbit manure and compost.

LIGHTING

I will consider only electric lighting in this building. Fumes from propane lamps, coal oil lamps, candles, etc. are simply unacceptable in a tight space. There are two competitors, incandescent and light emitting diode (LED). Incandescent can be considered the 'gold standard'. It has minimal impact on those with EHS, even those who are also photosensitive. However, LEDs use about one fourth the power to produce the same amount of light. Solar panels are getting cheaper, but batteries are not. Lighting is needed primarily when the sun is not shining, so the power must be stored in batteries. We can buy a given amount of solar panels and batteries for an LED system or four times as many solar panels and batteries for the same light levels with incandescent bulbs. The difference is significant in terms of cost, space, and maintenance, so we need to look carefully at LED lighting.

LEDs are available in two forms: bulbs that are direct replacements for 120 VAC light bulbs, and adhesive backed strips that operate on 12 or 24 VDC. I have investigated both forms in some detail. My shop is lit with LED bulbs and both bulbs and strips are in regular use in my home. Some LED bulbs produce large amounts of dirty electricity, so obviously I do not use those. Clean LEDs seem not to affect me to any significant degree.

I see comments on the Internet about people who *are* affected by LEDs. I assume this is due either to accidentally using the dirty LED bulbs, or to a reaction to the LED light spectrum. (LEDs tend more toward blue light and incandescents more toward red). My guess is that well over half the EHS population will feel fine while using clean LEDs so I will proceed with that choice.

I do not want to use an inverter because of the 60 Hz fields and the dirty electricity produced by inverters. Lighting voltage must therefore come from batteries. This voltage will vary with the state of charge and whether the batteries are being charged or not. We therefore are looking for LED bulbs that work on DC, and over an appropriate range of voltage.

In July 2020 I tested 19 different bulbs, 3 by ACE, 1 by Cree, 3 by EcoSmart, 2 by Feit, 3 by Great Value, 1 by Green Light, 5 by Phillips, and 1 by Satco. All worked with minimal variation in light intensity from 110 VAC to 140 VAC. Eleven maintained a fixed light intensity down to 100 VAC. All bulbs worked for 140-160 VDC. One EcoSmart, both Feit, 2 Great Value, and 3 Phillips bulbs worked for 110-160 VDC.

I also tested for dirty electricity by plugging a Stetzer meter into the same 120 VAC circuit with a bulb. The background Stetzer reading was about 40 Stetzer units. Fifteen of the bulbs did not change the Stetzer reading by more than 3 or 4 units, except for one Phillips bulb that increased it by 15 units. One of the Feit bulbs increased the reading by 400 units, one of the Great Value bulbs increased it by 150 units, one of the Phillips bulbs increased it by 240 units, and another of the Phillips bulbs increased it by 80 units. These four bulbs were rejected from further consideration.

There were four bulbs that worked down to 110 VDC and had relatively little dirty electricity; the Ecosmart A6A19A100WUL01, the Feit A1600/830/10KLED/6, the Great Value A191011, and the Phillips 9290011351A. The Phillips bulb increased the Stetzer reading by 15 units, enough for concern but not enough for automatic rejection, especially if the first three bulbs were not available.

At 120 VDC the Ecosmart used 13.9 W and had a light intensity of 2161 lux/W, the Feit used 11.4 W and produced 2471 lux/W, the Great Value used 13.5 W and produced 2420 lux/W, and the Phillips used 12.7 W and produced 2762 lux/W.

I have done tentative designs for both the 24 VDC strips and the 120 VDC bulbs. The 120 VDC design is presented here and the 24 VDC design in a later section.

My shop has a room of 86 m^2 that has 11 LED bulbs in the ceiling, all rated at 100 W equivalent or about 1500 lumens. These are connected to a battery bank of 16 Nissan Leaf modules in series. I try to maintain the terminal voltage between 120 and 130 VDC. Power input and light output of the bulbs are nearly constant over this voltage range. At 125 VDC the current is about 1.06 A, for a power of (125)(1.06) = 132.5 W. In an eight hour day, the energy consumed is (132.5)(8) = 1.06 kWh.

If all the lumens were radiated downward, the light intensity would be (11)(1500)/86 = 192 lux. Measured lux level at chest height is between 60 and 140 lux. (Some of the lumens are directed to the side or up, rather than down toward the floor.) This measured level is acceptable for most activities. I use a floor lamp or table lamp when more light is necessary. I will probably install 6 fixtures in the hut living room, area 31 m^2. The light level in the hut with all 6 bulbs on, and all light directed toward the floor, would be (6)(1500)/31 = 290 lux. These bulbs will be wired on four switches so lower light levels can be selected.

The bedroom, bathroom, and walk-in closet will have two bulbs each. I will assume that I will have two 100 W equivalent LED bulbs on for 16 hours per day. The lighting load (e.g. the Great Value bulb) would then be (2)(13.5)(16) = 0.432 kWh per day or (2)(13.5/120)(16) = 3.6 Ah per day. I will need a battery bank with a low voltage (a design discharge state) of perhaps 110 to 115 VDC, and a high voltage (the design voltage while being charged just before reaching the maximum charge state) of perhaps

130 VDC.

The availability of LED bulbs that work on 120 VAC and also on 110-150 VDC allows the use of 'conventional' wiring equipment, the same 14 or 12 gauge wire and the same light fixtures and bulb sockets. We just have to use light switches rated for 120 VDC. Replacement bulbs are available from big box stores, but have to be selected from an approved list.

120 VDC COOKING

I use a rice cooker to prepare breakfast, a small hotplate to fry eggs for lunch, and a popcorn popper for a Sunday evening snack, all counter top appliances that typically operate on 120 VAC. I might use a slow cooker to warm food for the evening meal. The cookers and hotplate all must be modified to operate on DC. They all have a bimetallic strip that expands and contracts with temperature changes to close and open electrical contacts. These contacts are guaranteed to fail if used with DC. What must be done with each device is to rewire it with the contacts controlling a solid state relay, which in turn will operate the heating element.

I will probably need to use a different plug on the modified cooker so it cannot be plugged into a standard 120 VAC socket. There are dozens of different plug and socket possibilities, but the ones built for the American market tend to be expensive because of the small quantities manufactured. I may use British plugs and sockets, hopefully available on Ebay. I bought a lot of 10 UK plugs, fused, 13 A, 250 VAC there on 3/17/21 for $55 including tax and shipping. I did not see the mating sockets on Ebay for that day. I did find five switched double sockets on amazon.co.uk for £11 plus tax and shipping.

I have no problem in eating directly from the can or jar. On a gloomy winter day with the batteries not at full charge, I would just cook less or not at all. But for budget purposes, I will estimate using a 300 W rice cooker (or equivalent hot plate or slow cooker) for one hour per day. This contributes 0.3 kWh or 2.5 Ah.

REFRIGERATOR

I enjoy gardening and enjoy eating what I grow. My sensitivities are such that I need to eat organic as much as possible. I want to store my own garden produce for as long as possible into the fall and winter. A good way to do this is to ferment the vegetables (like making sauerkraut). I made several different batches of fermented vegetables for the first time in the summer of 2020. I liked the flavor and texture, and have no argument with the widely held opinion that this is healthy. My problem was that after about a month of setting in a space at 75^o the batch turned an ugly shade of brown and smelled worse. A fair amount of work had gone to waste.

After that, when the 7-10 days of fermentation process was finished, I put the product in half gallon glass jars in a small refrigerator. While refrigerated, the product lasted nicely until March. Nothing spoiled, so it might have lasted until the new harvest if I had prepared more of it. Therefore I am inclined to put a large refrigerator in the cabin, to store food on a seasonal basis as well as what is needed between weekly trips to the grocery store.

The specific model of refrigerator is not critical to the design of a cabin, so I will just pick one at random. The website www.solarpanelstore.com carries 24 VDC SunDanzer refrigerators and freezers. The largest refrigerator, the DCRF450, \$1799, has 10 ft^3 in the refrigerator and 5 ft^3 in the freezer. They claim 0.55 kWh per day in a 70^o space and 0.89 kWh per day in a 90^o space. A 120:24 DC to DC converter will be necessary.

DC TO DC CONVERTERS

Historically, off grid housing has been 12 VDC, 24 VDC, or even 48 VDC (but not 120 VDC), so manufacturers have responded by building 24 VDC refrigerators and swamp coolers. Some laptop and desktop computers need 12 VDC. We might wire the house with three sets of wires, one pair carrying 120 VDC, another pair with 24 VDC, and a third pair with 12 VDC. This gets complicated and expensive quickly! Or we can use a DC to DC converter wherever we need 12 or 24 VDC.

A well built DC-DC converter will have minimal ripple on the input and output voltages. More filtering can be added if necessary. It the device radiates energy into space it can be put in a metal box. I think they can be made to work for almost all of us who are EHS. I am in the process of evaluating three DC-DC converters purchased recently so I can report a few observations about them.

The first converter was purchased on Ebay for about \$20. The case has "Intelligent DC-DC Converter, 48/60/72/94/120 to 12 VDC 180 W, output current 15 A maximum, red input line, yellow output line, black earth line" printed on it. There is no company name, no website, and no spec sheet. I connected it to the desktop computer in my lab, a Jetway NF9N Intel Celeron N2930 Mini-ITX Motherboard w/12 VDC-in on-board power, purchased 5/3/16 for \$159.95. Input power to the converter is only about 16 W at 125 VDC. If efficiency were 80% the power into the computer would be about 13 W, or less than 10% of 'rated' power. The losses of 3 W or so are dissipated into space from the case of the device. There is no provision for adding an external heat sink. I observed one spot on the case at 120^oF when the room temperature was about 65^oF. I would say that an 'honest' rating would be about 30 W rather than the claimed rating of 180 W. Even though it is badly overrated I think it is a good choice for this particular application. I striped the three wires coming out of the case, soldered red and black to a two wire cable to the battery, and yellow and black to a short length of cable to a power plug to the computer (salvaged from an old power supply), and covered the solder joints with heat shrink tubing. The process was quick, easy, and cheap. The converter will hopefully last for a long time at this low power level.

Then I bought two 100 W converters from Mouser for about $100 each. There is a Cincon CHB100-110S12 with a 12 VDC output and a Murata IRQ-24/4.2-T110N-C with a 24 V output. The Cincon is a half-brick size (about 2.3 by 2.4 inches) and the Murata is a quarter-brick size (about 2.3 by 1.2 inches). These are standard size packages that make it easy to mix and match converters, heatsinks, and enclosures by different manufacturers. Both have an aluminum plate on one side with metric M3 screw holes that accept M3 screws that attach a heatsink. Documentation for one converter mentioned part numbers for mating heatsinks, the other did not. Once you decide what size converter to buy, you type in the Search box something like "quarter brick heatsink kit". That gets you a heatsink, some M3 screws, and a sheet of plastic that helps the heat transfer between converter and heatsink. Mouser had quarter and half brick heatsink kits for $5 or $6 each.

Both converters have a trim pin. One can connect a pot between the two output pins with the wiper connected to the trim pin, to adjust the output voltage by ±10%. I do not expect to need this capability. The converters are close enough to 12 or 24 VDC with the trim pin unconnected.

ELECTRONICS

There are at least three different ways to get power to our computer and monitor: (1) Just plug the 120 VAC power cord into a 110-140 VDC outlet, (2) Buy equipment with a native DC input and use a DC-DC converter to convert down from the battery bank voltage, or (3) Buy equipment with a native DC input and install a separate PV panel, battery, and wiring system for that voltage.

For option (3) it would be technically possible to use an electrical cable like 12/2 with ground, let the black be 120 VDC, the white be 12 VDC, and the bare be the return for both voltage levels. There may be an issue with two different voltage levels in the same box. There may be a problem with voltage drop. The 12 gauge wire might be too small to carry the current. We would have to find a different style socket and plug to distinguish between 12 VDC and 120 VDC. The problems are significant.

While it is possible to buy a 12 VDC monitor (or TV), it is not easy. Websites typically do not show the actual input voltage of the device. There is a market for TVs and monitors in recreational vehicles, of course, and these typically work on 12 VDC. These need to be ruggedized to withstand the potholes and temperature and humidity variations in an RV, which may double or triple the price. This heavy duty construction is not really needed in our case. Also, it seems that the 12 VDC inputs are restricted to smaller sizes, perhaps up to 32 inches. I use a 40 inch Hisense TV as a monitor in my lab (with direct 120 VAC input) in my lab and would hate to downsize.

If option (1) works it would make life simpler for us. I tried it with my Hisense 40H3E TV and it worked fine for DC voltages between 110 and 140 VDC. The input power was about 38 W at 140 VDC, increasing to about 39 W at 110 VDC. I have no way of knowing what fraction of monitors and computers will work on a DC input, but my guess is that most will be fine. I think that most (if not all) 120 VAC input power supplies for monitors, TVs, and computers immediately rectify the AC to DC, with a peak of $120\sqrt{2} = 169$ VDC. A DC:DC converter then follows the rectifier, to get 3.3, 5, 12, etc. volts for circuit operation. The only way to find out if a device works on DC is just to plug it in and see what happens. On occasion this would burn up the TV power board. I can buy a replacement power board for this TV for $29 from www.shopjimmy.com, so it may not be too great a loss if the experiment fails.

The Hisense 40H3E TV being used as a monitor has a nominal input power of 38 W. Adding my desktop with a measured power input of 16 W gives a total of 54 W during hours of operation. If we assume 12 hours/day operation, the daily energy requirement will be 0.65 kWh.

SWAMP COOLER AND PUMPS

Evaporative coolers (swamp coolers) work quite well in the high desert, at much less power than a conventional air conditioner with a compressor. For several decades the off grid and recreational vehicle community has provided a market for units that work directly on 12 VDC or 24 VDC. I bought a 1424XP Solar Chill evaporative cooler (24 VDC) from Southwest Solar in 2012. It now provides cooling for a 1500 square feet house on my Rockvale property. Power comes from two 12 V PV panels in series, connected to four 6 V T-105-RE lead acid batteries located on the floor of the coat closet in the house. It has worked quite well.

I found one website carrying the 1424XP in 2021, www.warehouseappliance.com, for $1054 plus shipping. This unit has a 14 inch diameter fan and consumes 38 W at low speed and 52 W at high speed. It is rated at 1000 cfm and should cool 800 square feet at 'higher elevations'. They also handle the 1824XP, 18" fan, 53 or 73 W, 1500 cfm, for $1192, and the 2424XP, 24" fan, 80 or 250 W, 3000 cfm, for $1639.

If we assume 8 hours per day of operation at high speed for the 1424XP, we will need $(52)(8) = 416$ Wh $= 0.416$ kWh per day in hot weather.

In cold weather there will be a need for a pump to circulate hot water through the PEX tubing in the slab, another pump to blend stored hot water with return water to get the proper temperature for the circulation water, and ventilation fans. Ideally, these would all operate directly on 120 to 130 VDC, but because 120 VDC is not a 'standard' voltage, it may be simpler to use 120:24 dc-dc converters for the swamp cooler and other pumps and fans.

HEATING OPTIONS

Heating options include wood, propane, passive solar (sunlight through south facing windows onto the thermal mass of a concrete floor), solar thermal (direct heating of water in solar receivers, and photovoltaic. Wood is a common heat source for off grid cabins. There is not enough biomass growing on my 60 acres to supply a wood stove long term, but I am sure that wood can be acquired from area sawmills or tree trimming crews. I would like to put a dozen or more similar cabins on this property and wood smoke from all these cabins would definitely lower the air quality in the gulch. The main argument for me is that I might want to live in this cabin past the age of 85 or 90, when handling wood is no longer physically possible. I also do not like the dust and ash that are associated with a wood fire. So wood is rejected.

Propane is also a common choice for off grid cabins. One can heat with it, cook with it, and even use it for refrigeration. It works for us old geezers! I have never experienced any reaction from propane fumes. But I know people who are extremely sensitive to propane. They need to isolate the propane appliances from the air in the living quarters, perhaps cooking outside, or using strong exhaust fans. This is a research hut, hopefully safe for a large fraction of the EHS and MCS population. Propane is a known problem to some of us, so it is rejected.

Passive solar has been well known for many years. It is easy to find guidelines on the Internet for the size of the south facing windows and the amount of overhang necessary to shade the windows in the warm months. It requires a bit of management to work well, such as closing curtains at night to prevent heat loss back outside. It also requires some tolerance for a diurnal temperature swing of 5-6^{o}F or more from late afternoon to early morning. And the house will cool off significantly after a couple of days of cloudy, cold weather unless there is some form of backup heat. I do not do well with wide diurnal temperature swings and do not want to put in any backup heating system so passive solar is rejected.

Solar thermal was a bit of a fad 40 years ago. I just do not see very many people using it today, suggesting it does not live up to its hype. I have tried resurrecting old technologies in research projects in the past, and found out that they were dead for a reason. Without further discussion, solar thermal is rejected.

Using photovoltaic (PV) panels for space heating is a relatively new concept. Just a few years ago, PV panels would have produced space heating at a cost perhaps ten times as much as one could heat space with wood or propane. But PV panel costs have dropped to where it is thinkable to do it. There are plenty of research opportunities regarding heat storage, smart thermostats, etc. so this is the technique I will try.

HEAT LOSS AND INSULATION

How many PV panels are needed to heat the hut? This depends on the heat loss through the building exterior and also on my tolerance to how many days per year the building temperature dropped below some desired level. It will take more panels to keep the hut temperature above 65^{o}F except for one day in ten years, than to keep the hut temperature above 55^o except for ten days per winter. I think I will go with the minimum number of panels and just move into the grid connected shop or house if the hut gets too cold.

It will also take more panels to heat a poorly insulated building. There is a direct correlation. I can either buy more panels or buy more insulation. We have enjoyed cheap energy in the USA for many years, so the common practice has been to put in minimum insulation to save on the initial cost, and let the poor house buyer pay larger monthly utility bills. The building codes specify minimum insulation levels well below what is easily achieved. I think I will go with a well insulated or even superinsulated hut, at least R25 for the walls and R50 for the ceiling.

One way of reaching R25 or R30 for the walls is to build a double wall. In my case this will be a standard 2×4 wall with 24" spacing on the exterior, then one (or maybe two) 2" sheet of foam insulation, then another 2×4 wall with the studs offset by 12" from the studs of the first wall to prevent thermal bridging through the studs. There will probably be fiberglass batts between the wall studs, or perhaps blown in cellulose. With nailers and metal siding, the overall wall thickness will be on the order of one foot thick. The interior space of the living portion of the hut will be about $18' \times 38' \times 8'$. The gross wall area is $(2)(18)(8) + (2)(38)(8) = 896$ ft^2. There will be one door of standard $3' \times 6'8$" size or 20 ft^2. There will be three windows of about 12 ft^2 each or a total of 36 ft^2. The net wall area is then $896 - 20 - 36 = 840$ ft^2. The ceiling area is $(18)(38) = 684$ ft^2.

The heat loss through a building component is

$$Q = \frac{A}{R}(T_{in} - T_{out}) \tag{1}$$

where Q is the rate of heat transfer through the material in BTU/hr, T_{in} is the inside temperature in ^{o}F, T_{out} is the outside temperature, A is the area in ft^2, and R is the R value of the material. I will be using the notation in the book *Modern Hydronic Heating, Third Edition* by John Siegenthaler. This hut will generally resemble the Morton building recently built on my property. The R values that Morton listed for their construction were 38 for the ceiling, 21.3 for the walls, 3.5 for the double glazed windows, and 1.67 for the doors. I will assume R60 for the hut ceiling, R30 for the hut walls, and the Morton values for the windows and door. I will also assume a target indoor temperature of 65^{o}F.

Another important heat loss is due to infiltration or leakage. Siegenthaler gives an equation for this, Eq. 2.8, as

$$Q_i = (0.018)(N)(V)(\Delta T) \text{ BTU/hr} \tag{2}$$

where 0.018 is the heat capacity of air, N is the number of air changes per hour, V is the interior volume of the heated space in ft^3, and ΔT is the inside air temperature minus the outside air temperature in ^{o}F.

The long term average temperature for Canon City in December and January is 33.75^{o}F. I hope to have a hut with several days of heat storage, so a selection of $T_{out} =$ 30^{o}F might be adequate for design purposes. This yields a $\Delta T = 35^o$F.

The various heat losses are calculated as

$$Q_{walls} = \frac{840}{30}(35) = 980 \text{ BTU/hr} \tag{3}$$

$$Q_{ceiling} = \frac{684}{60}(35) = 399 \text{ BTU/hr} \tag{4}$$

$$Q_{windows} = \frac{36}{3.5}(35) = 360 \text{ BTU/hr} \tag{5}$$

$$Q_{door} = \frac{20}{1.67}(35) = 419 \text{ BTU/hr} \tag{6}$$

$$Q_i = (0.018)(0.4)(18)(38)(8)(35) = 1379 \text{ BTU/hr} \tag{7}$$

Siegenthaler shows in his Fig. 2-15 that $N = 0.4$ air changes per hour is appropriate for the "best" construction.

The sum of the above heat losses is 3537 BTU/hr, or 84888 BTU/day, or 24.9 kWh/day. That is, we need our PV panels to provide an average of 24.9 kWh/day to meet our average heating needs during periods when the inside to outside temperature difference is about 35^{o}F and Q_i is in the neighborhood of 1400 BTU/hour.

I report elsewhere (MortonEff2021.pdf) about efficiency tests on my Morton building. It has no exhaust or ventilation fans, only baseboard electric heat. Windows are kept tightly closed through the heating season. It seems to me, and not contradicted by my test results, that Q_i for this type of building is almost entirely due to wind blowing through cracks in the building. Q_i can therefore be neglected in calm conditions. The differential air pressure from outside to inside is actually due to the square of the wind speed. My guess is the 0.4 air changes per hour will be reached at a wind speed of about 20 mph for a well build building.

The average wind speed here is well under 20 mph, so a loss of 1379 BTU/hr (7.9 kWh/day) may be pessimistic by as much as a factor of four. A value like 2 kWh/day might be more realistic for estimating purposes. That would give a heating loss of 19 kWh/day rather than 24.9 kWh/day. So we need to select solar panels that will provide a minimum of 20 to 25 kWh/day over the lifetime of the panels. Panel output declines with age, from 100% when new to perhaps 80% after 25 years. If we really need 20 kWh/day, we should design for a minimum of 20/0.8 = 25 kWh/day. We will start the design process looking for 25 kWh/day, and round up as needed.

SOLAR PANELS

Photovoltaic (PV) panels have gotten cheap in the last few years, so are being installed in large numbers, including by homeowners. One would assume that the Big Box stores would carry at least one or two brands and several of the popular sizes. But that does not seem to be the case. One surfs the Internet, orders a particular panel, and waits for delivery by a semi truck. (The appropriate panels are too large/awkward/fragile to ship by UPS). They come on a pallet that weighs over a thousand pounds. The truck will deliver a pallet to a commercial address (that has a fork lift) for perhaps $150 or to your home for perhaps $300 (or more depending on distance shipped).

I identified six manufacturers that have at least some manufacturing capability in the USA or Canada. These are

1. Heliene Solar, Ontario
2. Mission Solar, San Antonio
3. Seraphim, Jackson, Miss.
4. Silfab Solar, Washington State
5. Solar Tech Universal, Florida
6. Sun Spark Technology, California

I decided to use Mission Solar panels for the first cabin. Other manufacturers will be tested when additional cabins are built.

Solar panels for solar power plants rated at a few kW or more are mostly made of either 60 or 72 cells in series. The individual cells are typically squares about 6 inches on a side. The 72 cell Mission Solar MSE385SR9S, 385W, 78.7” $\times$ 39.68” $\times$ 1.58” (close to 2 m by 1 m), V_{oc} = 48.53 V, V_{mp} = 40.84 V, I_{sc} = 9.993 A, I_{mp} = 9.426 A, efficiency = 19.11%, 52 pounds, had a list price of $270.00 at www.solarpanelstore.com on 3/3/21, or 270/385 = $0.7013/Watt. The Mission Solar MSE345SX5T is rated 345W, 1748 $\times$ 1054 $\times$ 40mm, (68.82” $\times$ 41.5” $\times$ 1.57”), V_{oc} = 41.00 V, V_{mp} = 33.37V, I_{sc} = 10.92A, I_{mp} = 10.34A, efficiency = 18.7%, 44.8 pounds, list price $192.00 on 4/10/21 at www.thepowerstore, or 192.00/345 = $0.5565/W. The 60 cell panel is shorter, lighter, easier to handle, and less expensive per kWh produced.

Solar panels are undergoing continual improvement so model numbers and precise performance measures change frequently. It is always good practice to get multiple bids. In the Fall of 2020, I spent some time on the Internet and decided to try the Mission Solar brand. I got several quotes from different vendors for 10 panels, and the Solar Panel Store in New Castle, Colorado gave the best price. Then in March, 2021, I decided to buy a full pallet (26 panels) of the MSE345SX5T. The Solar Panel Store bid $238.95 per panel or $6212.70 total (plus shipping). I asked one other vendor, The Power Store, Alvarado, Texas, for a quote. They bid $179.40 per panel or $4664.40 total (plus shipping of $464.37) or 179.40/345 = $0.52/W. I am not sure why the difference was that great. Perhaps a year from now, the industry would have adjusted itself to where the Solar Panel Store would give the best price. The point is that a little price shopping can save you some money.

The pallet was delivered surprisingly quickly. They announced Monday that it was loaded in San Antonio, Texas. It got to Colorado early Tuesday and to my lab Wednesday morning, by FexEx Freight. The semi did not carry its own fork lift. The driver used a hand operated lift like those seen at auto repair shops. His semi was parked with the rear aimed up hill, so he asked me to help him push the pallet out once he lifted it off the floor of the truck. We rode the truck lift gate up to floor level. He maneuvered the pallet to where it was almost falling off the rear end on the lift gate. We rode the lift gate down. The pallet was now partly on the gravel driveway and partly on the lift gate. He then just drove out from under the pallet.

I can remember teaching about alternative energy some 30 years ago, when solar panels cost about $10/W, and telling the class that if the panels ever got to $1/W, they would be economically competitive. It appears that day has finally come.

The rated power output is obtained at standard conditions of 1 kW solar radiation per m^2 and the panel aimed directly at the sun.The power output drops with increased cloudiness, increased angle to the sun, and increased ambient temperature. The power output may exceed the rated value slightly on a cold, clear day, especially if there is snow on the ground.

It is possible to build trackers that keep the panels pointed at the sun, but at this low price for panels, the small amount of extra energy would not begin to pay for the tracker.

For fixed panels, the power output at any moment is given by the solar radiation in W/m^2 times the cosine of the angle between the normal to the panel and the sun times the panel area in m^2 times the efficiency. Using spherical trigonometry to determine the angle can be a bit tedious. The National Renewable Energy Laboratory (NREL) has written a nice online program to do this, available at pvwatts.nrel.gov. You enter the tilt and the azimuth of the panel and it gives you the monthly average integrated solar radiation on the panel surface in $kWh/m^2/day$. Just multiply by the efficiency and the area of the PV cells and you have the desired daily energy production. The solar radiation for the months of November-March is about 5.6 $kWh/m^2/day$ on average.

The area of the MSE345SX5T is $(1.748)(1.054) = 1.842$ m^2 The estimated daily output is then $(1.842)(0.187)(5.6) = 1.93$ kWh/day. To get a total of 25 kWh per day we would need $25/1.93 = 13$ of the 60 cell panels. We will continue with the design process of how many of what size panel to buy in a later section.

Note that solar panel degrade during use. The warranty on the the MSE345SX5T is "Degradation guaranteed not to exceed 2.5% in year one and 0.7% annually from years two to 30 with 80.7% guaranteed in year 25." Panels that produce 25 kWh per day when new will produce closer to 25(.807) or about 20 kWh per day in year 25. This makes life interesting for the system designer! Should we design a system that barely meets requirements when new, or one that comfortably exceeds requirements at year 25?

BATTERIES

The most common battery for electric energy storage has been the lead acid battery. I bought four 6V Trojan T-105-RE deep cycle batteries in 2013 that are still in service. They supply 24 V for a swamp cooler. If discharged slowly (100 hours from full charge to full discharge) they are rated at 250 Amp Hours. The nominal energy content is then $6(250) = 1500$ Wh $= 1.5$ kWh. But to get long life, one should never fully discharge a lead acid battery. Trojan has prepared a table of the expected number of discharge cycles during a lifetime versus the Depth of Discharge (DoD), shown in Table 1.

If the battery is discharged $(0.8)(1.5) = 1.2$ kWh each day, and recharged fully, it

DoD	Cycles
20%	4800
30%	3500
40%	2600
50%	2000
60%	1600
70%	1300
80%	1200

Table 1: Lifetime cycles versus Depth of Discharge for T-105-RE.

will last 1200 cycles or 1200/365 = 3.3 years. On the other hand if it is discharged only (0.2)(1.5) = 0.3 kWh/day, it will last 4800 cycles or 13 years. The cost of battery ownership might be defined as the initial cost of the battery divided by the product of *usable* energy times the expected number of cycles. The T-105-RE was priced at about $200 each on www.alte.com on 3/4/21, making the ownership cost 200/(0.3)(4800) = $0.139 per usable kWh cycle.

The cost of a twenty battery string (to get a voltage of (20)(6) = 120VDC) would be about $4000. The usable energy would be (20)(0.3) = 6 kWh. Note that we can exceed this number during emergencies, say 2-3 days per year, without shortening the lifetime significantly.

The weight of the T-105-RE is 62 pounds, far more than I can lift. It is a flooded battery, requiring an inspection a few times per year to check the water level and add distilled water as necessary. Individual battery voltages also need to be checked. If the voltages differ by an excessive amount, an equalization process can be performed to bring them back into line.

The efficiency of a flooded lead acid battery is on the order of 88%. That is, about 12% of the energy put into the battery is lost as heat and chemical reactions.

Lithium ion batteries have emerged as an alternative to lead acid batteries in recent decades. There are many different chemistries, including lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), lithium manganese oxide ($LiMn_2O_4$), and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$). Large numbers of lithium ion batteries are made for consumer electronics and for electric vehicles. Several companies, including Battle Born, KiloVault, and SimpliPhi, make lithium ion batteries for the renewable energy market.

The Battle Born BB10012 100 Ah, 12 V, $LiFePO_4$ battery (www.alte.com) lists for $949. The weight is 30 pounds, the efficiency is 99%, and they claim 5000 cycles at a 80% DoD. The ownership cost is then \$949/(1.2)(0.8)(5000) = \$0.1977 per kWh cycle. This is 42% higher than the ownership cost for the T-105-RE, but the BB10012 has several features that must be considered in this decision. It is more efficient (99% compared with perhaps 88 to 90%) so we might need fewer solar panels. It needs zero maintenance over the entire lifetime. It needs no ventilation (does not emit fumes of any kind). It weighs half as much so I might be able to install it myself. It has a sophisticated Battery Management System (BMS) built in to the battery to protect it from shorts, overcharging, excessive discharging, unbalanced cells, etc. I consider it to be a quite reasonable choice for those willing to pay for good quality and long life with minimal malfunctions.

The cost of a 120VDC string of these batteries would be \$9490, more than double the cost of the equivalent T-105-RE string (\$4000). The usable energy is also higher, 9.6 kWh versus 6 kWh.

Those with some technical ability may want to consider buying used lithium ion batteries, either the 18650 cell used in laptops or batteries from an electric vehicle. Search YouTube for Tesla Powerwall and you will find many examples. Using cells from dead laptops would require the testing and connecting literally thousands of these cells. I looked at the time required to do this and decided to try recycled electric vehicle batteries first.

The battery in an electric vehicle is under warranty for a certain number of years and/or a certain number of miles. If the effective battery capacity drops below say 70% of the capacity when new, the manufacturer will replace the battery bank. The old batteries are either shipped to a recycling center or made available to the off grid community. With a reasonable DoD, these old batteries could easily function nicely in an off grid setting for another 10 or 15 years.

Early versions of the Nissan Leaf had a battery bank of 48 modules. Each module contained four cells in a series parallel configuration. Therefore the full battery pack has 96 cells in series. The pack voltage, the individual cell voltage, and the voltage for 16 modules in series is shown in Table 2 for States of Charge (SoC) from 0% to 100%.

I bought 24 modules from www.greentecauto.com on 7/13/2020 at a list price of 8 modules for \$470 or \$58.75 each. When new, their rating was 7.6 V and 64 Ah. The average capacity was about 43 Ah when removed from service. The 43 Ah was measured by discharging the fully charged module from 8.3 V to 5 V at a 20 A rate. The module will survive this heavy discharge but life will be longer with less aggressive treatment. Table 2 appears to be a more realistic definition of a 'proper' voltage range for long life. We redefine the available capacity for module voltages between 7.2 V and 8.2 V as 100% capacity. This will be less than the 43 Ah value by 10% or 15%, but is

SoC	1 cell	16 modules	48 modules
100%	4.1	131.2	393.6
95%	4.075	130.4	391.2
90%	4.05	129.6	388.8
80%	4.0	128.0	384.4
65%	3.925	125.6	376.8
50%	3.85	123.2	369.6
30%	3.75	120.0	360.0
20%	3.7	118.4	355.2
10%	3.65	116.8	350.4
0%	3.6	115.2	345.6

Table 2: Battery voltages for various states of charge for Nissan Leaf

closer to what we might expect on a daily basis.

If we assume a capacity of 38 Ah and a nominal voltage of 7.6 V, the energy content per module is (7.6)(38) = 290 Wh or 0.29 kWh. The energy content of the entire battery pack would be (16)(0.29) = 4.64 kWh. We will also assume a life of 5000 cycles, same as the Battle Born. Life might be less. My guess is a life of at least 2500 cycles. The cost per rated kWh (also usable kWh in this case) is $58.75/((0.29)(5000)) = $0.0405/kWh, comparing very favorably with the equivalent Battle Born ownership cost of $0.1977/kWh.

It is seen from Table 2 that 16 modules in series produces a voltage range between 115.2 V and 131.2 V, very similar to the allowed voltage range of 114 VAC to 126 VAC for our nominal 120 VAC systems. I connected 16 of my 24 modules in series and connected them to a circuit of 11 overhead bulbs in my shop. All bulbs are 100 W equivalent LED bulbs that work nicely over a voltage range of perhaps 100 VDC to 150 VDC, constant power input and constant light intensity output. The total current to the circuit is 1.06 A at a voltage of 127 VDC. The bulbs are turned on for about 8 hours/day while I am in my shop. Daily energy use is on the order of (127V)(1.06A)(8Hr) = 1.077 kWh.

When the voltage drops to about 120 VDC I connect the module bank to a string of four Renogy RGN-300D-G1 solar panels in series, that are mounted on the south side of my shop. These are 60 cell panels, V_{mp} = 32.2 VDC, V_{oc} = 38.8 VDC, I_{mp} = 9.32 A, and I_{sc} = 9.71 A, nominal 300 W each or 1200 W total. This is a direct connection, no MPPT electronics producing dirty electricity.

The claimed efficiency for the Renogy panels is 0.1844 and the active area is about

1.46 m^2. Assuming an average daily solar intensity of 5.6 kWh/m^2, the average daily output of the four panel string would be (4)(0.1844)(1.46)(5.6) = 6 kWh/day.

My guesstimates for lighting, cooking, refrigerator, and electronics in the cabin add to 0.43 + 0.3 + 0.55 + 0.65 = 1.93 kWh per day. The maximum available from 16 modules was estimated above at 4.64 kWh. This suggests that 16 modules could supply all the electrical needs of the cabin for 4.64/1.93 = 2.4 cloudy days.

We now have to make a decision. Are we comfortable with the idea of the battery going dead after a couple of days without sun, or do we buy another 16 modules to put in parallel with the first 16? This extends the period to 4.8 days without sun. It also reduces the depth of discharge and extends the life of the batteries. I personally am more comfortable with the longer period and will be getting the additional modules. At a cost of \$90 per module, this increases the battery pack cost by (90)(16) = \$1440.

Our string of four solar panels provides an average of about 6 kWh/day, so on a typical day, they would provide 1.93 kWh to the battery bank. The remaining 4.07 kWh would then be wasted. This surplus capability is necessary for recharging the battery after a cloudy period. Suppose we have 3 cloudy days. The battery is down by (3)(1.93) = 5.79 kWh. The fourth day, the solar panels provide the load of 1.93 kWh and are additionally able to recharge the battery by 5.6 - 1.93 = 3.67 kWh. The battery is still down by 5.79 - 3.67 = 2.12 kWh. The battery will be fully recharged on the next day, assuming good sunshine, so we are prepared for the next cloudy period.

CHARGE CONTROLLER

I built my own battery charge controller around the Arduino Mega 2560. The circuit that is being controlled is shown in Fig. 1.

PV+ and PV- are the terminals from the series string of photovoltaic panels. Electrically the panels are a long string of diodes that would tend to discharge the battery at night. Diode D1 prevents this from happening. Switch S1 isolates the panels and S2 isolates the battery while maintenance work is being done. Both S1 and S2 are large knife switches used in the Power Lab at Kansas State University back in the days before OSHA.

The resistor marked INA260 is actually a 2 mΩ current sense resistor for the precision INA260 current and power monitor, available from Adafruit.com. The INA260 is mounted as a daughter board on the data logger board which in turn is mounted on the MEGA 2560. It works for voltages up to 36 VDC and currents up to 15 A. The PV+ open circuit voltage can be over 150 VDC so a voltage divider is necessary to get a proper voltage VBUS to the voltage input circuit of the INA260. One then multiplies VBUS by the inverse of the voltage divider ratio, in software, to get the actual voltage.

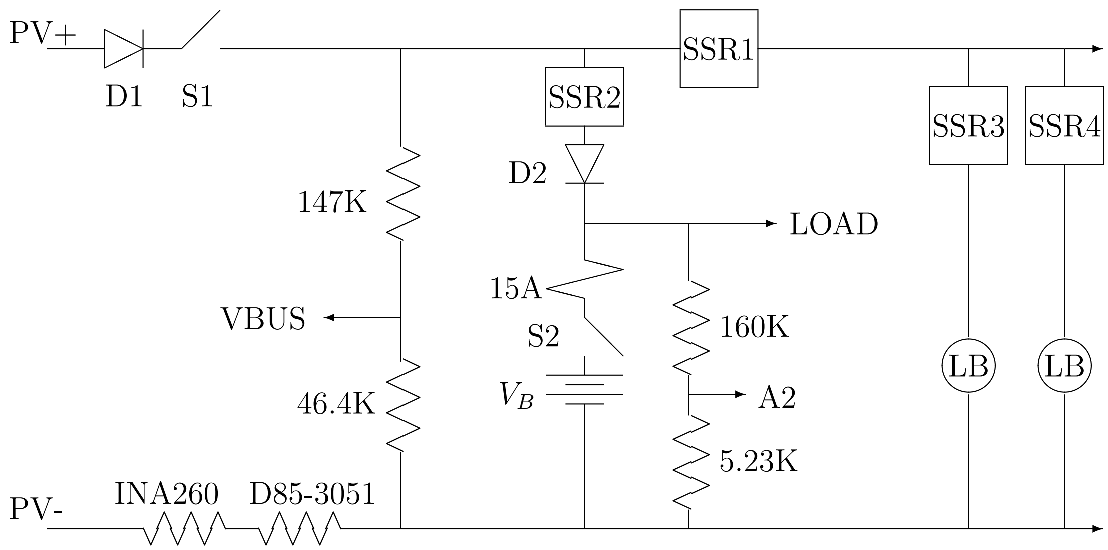

Figure 1: Charge Controller.

The resistor marked D85-3051 is the current sense resistor for a Chinese panel meter, rated at 200 VDC and 10 A. One can apparently use an external voltage divider and an external current shunt to get other ratings, but the one page user guide (one side English and the other Chinese) was vague about how to actually do it. It is independent of the Arduino, hence allows monitoring of PV voltage and current without the computer being turned on.

The boxes marked SSRx are solid state relays, which will be discussed later. In my lab there are a total of nine SSRs in parallel (SSR3 through SSR11), each controlling an incandescent light bulb, marked LB in the circles. An old electrician retired and gave me a large stock of 52 W and 200 W, 130 VAC, bulbs. I mounted five of the 200 W and six of the 52 W bulbs on the wall above the file cabinets, for a nominal load of about 1300 W when all are on. The nominal maximum power of the PV panels is 1200 W under standard conditions, but this can be exceeded under unusual circumstances (very cold with snow on the ground reflecting sunlight onto the panels).

PV panels are basically constant current sources for a given level of solar radiation (think one electron per photon). They supply this current at load voltages ranging from zero (a short circuit) to V_{mp}, the maximum power voltage. Above this voltage the current declines rapidly until it reaches zero at V_{oc}, the open circuit voltage. The output power VI increases almost linearly from zero voltage to V_{mp}, then declines rapidly back to zero. We get the most possible energy from our panels if we are able to change the load to maintain the load voltage at about V_{mp}. When the solar radiation drops by a factor of one half, the current drops by the same amount, and the resistance must be doubled to keep the voltage at the right value. The Mega 2560 connects and disconnects light bulbs until the voltage is in the general range of 110-130 VDC. It calculates power, then connects a 52 W bulb. If the new power is greater than the old power, the bulb is left connected. Otherwise it is again disconnected. I believe this process gets us within a few percent of the optimum energy production for a given set of PV panels.

The battery supplies power to the overhead lights (eleven 100 W LED bulbs) and other loads like the monitor, hot plate, etc. at the junction marked LOAD. The 15A fuse will hopefully prevent a catastropic discharge of the battery if the load develops a short. If switch S2 is opened while the battery is being charged, the LOAD voltage will rise to the 140-150 VDC level from the charging voltage of perhaps 125-130 VDC. The LED bulbs are happy at 150 VDC, which is not necessarily the case for other loads.

The Arduino Mega 2560 reads the PV panel voltage from the INA260 and the battery voltage V_B with the Mega on-board analog to digital converter (ADC). When V_B drops below some selected value, say 123 VDC, the Mega turns SSR1 off and SSR2 on, to charge the battery. When V_B rises above say 128 VDC, the process is reversed. SSR1 is left off during warm weather months when no lab heating is required.

It is important to note that solid state relays only block current in one direction. Consider the case where the battery is fully charged, SSR2 is off and SSR1 is on, as well as some of the SSRx, and the sun goes down. Without a diode D2, battery current will flow up through SSR2 and discharge the battery through the incandescent bulbs LB.

USED BATTERY AVAILABILITY

In July 2020 www.greentecauto.com had plenty of Nissan Leaf batteries at a price less than $60 per module. This was not the case in February and March 2021. They showed a Gen 1 Nissan Leaf module for $80, Out of Stock, and one lot of 48 Gen 1 modules for $2800, Out of Stock. Ebay had one seller on 3/5/21 with Gen 1 modules for $90 each. Apparently the supply has dried up.

I checked on www.car-part.com for Nissan Leaf 2012 model battery with battery warmer. They listed 19 battery packs with a price range of $2500 to $4500, with the nearest one 475 miles away.

One option to get batteries would be to buy a functional electric vehicle that is no longer under warranty, say from www.craigslist.com, with batteries at the 70% capacity level. We drive it to the nearest junk yard and ask for a bid on the vehicle when it is missing its battery pack. We drive the vehicle home, put it up on jacks, and drop the battery pack. We then push the vehicle onto a trailer, haul it back to the junk yard, and collect a few hundred dollars for it. If we have extra modules left over, we keep them for spares or sell them on Ebay.

A second option would be to call the local junk yard every week or two, and ask about the availability of an electric vehicle battery pack.

A third option would be to buy an EV at auction. This could be a challenge. In Colorado and many other states, it is not legal for an individual to buy a car at some of the auctions (the ones with the most cars). One has to hire a broker, who buys the car and then resells it to you, for a fee of course. The car shows up at your front door on a flat bed truck. You take out the battery pack and take the remainder of the vehicle to the local junk yard. There are also public auctions where I can buy a car. I will be attending some of these in the coming months.

One might be able to get less expensive batteries by buying a wrecked vehicle at auction. The insurance company has determined it will cost more to repair than its value after repair, so it is titled as a junk vehicle and is sold at auction for whatever spare parts can be salvaged. I am concerned that the wreck might have damaged the batteries. The damage could be delayed, such that an internal short would appear weeks or months later. There have been reports of fires with some battery chemistries. Caution should be exercised.

On 6/3/21, I called the local salvage yard to ask about electric vehicle battery packs. They had just acquired a 2017 Chevy Volt with 17,000 miles on it, and offered the battery pack for $2500 plus tax. The nominal energy content (100% depth of discharge) is 18.4 kWh. The age and mileage are such that little degradation has occurred, so we can do simple calculations using the rating when new. The cost per rated kWh is $2500/18.4 = $136/kWh. This compares with the cost of the Trojan battery mentioned earlier of $200/1.5 = $133/kWh. The longer life and better efficiency of the Lithium ion batteries suggest that the Volt battery pack at that price at least has the potential of being a 'good deal'.

They did not take personal checks so I pulled out my debit card, which was declined! It turned out that my bank imposed a $2500 limit on my card, even though there was ample cash in the account. After a half hour on the phone and Internet, I managed to get it paid for. After they had their money, they pulled the vehicle into their shop to remove the battery pack. First order of business was to remove a large jumper that electrically separated the battery into two sections, then wait two hours for the capacitors in the invertor to discharge. They called about four hours later, that the battery pack was ready to be picked up. I backed up to an open garage door with my Ford F-150. The pack was on a sturdy cart. Four strong guys picked up the 400 pound lump and put it into the pickup.

The individual Lithium ion batteries are mounted on a steel plate and then covered with a fiberglass cover. The cover is “tee” shaped, about 38” across the “top” portion (outside dimension including flanges) and 65” tall. There are seven clusters or packs where individual cells are packaged together as a unit. Cells are connected in a 96S-2P format, 96 cells in series and another 96 in parallel, for a total of 192 cells. I measured the weight of one cell as 19.5 oz, so the weight of 192 cells is 234 pounds.

The cells are heated in cold weather, and cooled in hot weather, by a liquid cooling system. The cells are approximately 6.45” wide by 9.15” tall. The plus and minus plates are a thin foil tab and extend out the “top” of the cell. The cells are nested into plastic forms that contain two manifolds for carrying the coolant. There are thin metal plates that are sandwiched between the cells that carry coolant from one manifold to the other. Each cluster is a sandwich of cells, plastic forms, and metal plates pressed together with enough force to prevent the coolant from leaking.

Construction of a cluster proceeds by placing two cells adjacent to each other in parallel (plus to plus and minus to minus). One polarity is spot welded to a copper foil connected to a terminal. The other polarity is spot welded to one side of a U-shaped copper foil the same length as the cell tab. Then two more cells are placed adjacent to the first two, but oriented plus to minus. The two tabs touching the other side of the U-shaped foil are then spot welded to it. We move to the other side of the cluster and repeat the process.

There are three clusters of 16 double cells, containing (3)(16)(2) = 96 cells, and four clusters of 12 double cells, containing (4)(12)(2) = 96 cells, in the Gen II Chevy Volt battery. I found it challenging to find authoritative values for maximum and minimum cell voltages on the Internet. One site (www.schultzengineering.us) selected 390 and 335 VDC as the ‘extreme’ limits for long life operation, keeping away from the knees of the charge curve, and then 380 and 340 VDC as the ‘safe’ limits for really long life. This translates to 4.06 and 3.49 VDC per cell ‘extreme’, and 3.96 and 3.54 VDC per cell ‘safe’. Two clusters of 16S-2P cells can be connected in series (combined 32S-2P) to have a voltage range of 113.3 to 126.7 VDC for ‘safe’ operation. This is the same cell configuration as what I have been testing with the Nissan Leaf modules. Early results suggest that this is a good voltage range. LED light bulbs are happy. Cookware modified to work on DC should be indifferent to whether the voltage is 120 VDC or 120 VAC. This means that one third (64 out of 192) of the cells in the Chevy Volt battery can be immediately reused in my off grid system.

The three clusters in the top of the ‘tee’ are bolted together with long bolts, which must be removed to separate the clusters. The top of each cluster is held together in a fixed spacing by the spot welded connections. The bottoms of the clusters expands due to the pressure of assembly. I then put in two lengths of quarter inch all thread bolt into each cluster to provide some stability. The liquid coolant leaks out during this process, making a mess. I did the disassembly outside in the back of my old pickup. The coolant looks and feels like a light weight oil but evaporates cleanly from concrete floors that it drips on.

The remaining 128 cells must be disassembled down to the individual cell , then reassembled into appropriate packages. A series connection of 32 single cells weighs 39 pounds, which most of us can lift, so it makes sense to put the 128 cells into four packages. Each of these 120 VDC batteries has half the energy content of the 120 VDC battery removed without this disassembly earlier.

The 12 double cell clusters would have a nominal terminal voltage of about 48 VDC, hence might be used 'as is', without separation into single cells and spot welding back together. I have another application involving eight 100 W PV panels, approximately 20 V and 5 A each, connected series parallel in the rack as 80 V and 10 A. I need 120 VAC at that site to run an air compressor. I can buy a combination inverter/charger, such as the MidNite Solar MN3548DIY, which will both charge a 48 V battery from the existing PV panels, and generate 120 VAC as needed. It would probably make me ill if I had to be near it for any amount of time. but in this case, I can turn it on and run to a place where the fields are low.

If I use any of the 12 double cell clusters as 48 V batteries, and also want one or more 32 single cell packs for 120 V battery use, I will have unused cells taking up space on a shelf. For example, if I use two of the 12 double cell clusters in parallel for running the air compressor, that uses $(2)(12)(2) = 48$ cells, leaving $128 - 48 = 80$ cells. I can make two 32 cell 120 VDC batteries, which leaves 16 cells unused.

HEAT STORAGE

We have chosen to not have energy storage in the form of a wood pile or propane tank. There are two other methods of storing energy, in batteries or in thermal mass. As we have seen, batteries are expensive, have a relatively short life, and generally require considerable care in charging and discharging. I have decided to use thermal mass rather than batteries. In our situation, the best thermal mass is water.

Home Depot sells a 1000 gallon water storage tank for $756 plus shipping. Dimensions for the Chem-Tainer TN6974IW-GREEN are 69 inch diameter and 74 inch height. If I choose a double door access to the utility room, nominal dimensions 72 inch by 80 inch, I should be able to get this tank into the utility room, and perhaps even to replace it if necessary. PV panels can be connected to resistive heating elements in this tank to heat the water. The hot water can then be pumped through PEX tubing in a concrete slab to heat the hut.

Water weighs 8.344 pounds per gallon, so 1000 gallons weighs 8344 pounds. It takes one BTU to raise the temperature of one pound of water one degree Fahrenheit, so at 130^{o}F the tank holds 500,000 BTU more than at 70^{o}F. This is the same as 147 kWh. If we got zero power from our panels for several days, it would take 147/19 = 7.7 days to lower the water temperature to 70^{o}F.

The tank will be rated at some maximum temperature, above which the plastic will become soft. We will need to measure the water temperature and disable the PV connection at some point.

The tank will be well insulated inside an unheated utility room. Losses through the insulation will be helpful in keeping the utility room at a moderate temperature (at least above freezing).

The concrete slab itself is a large thermal mass. I calculate that it requires 2.73 kWh to change the slab temperature 1^{o}F. So if we had a long period with zero power from the panels, the hut and slab temperature could be maintained at the desired level for 7.7 days by water heat storage, and then would drop only 19/2.73 = 7^{o}F the following day due to concrete heat storage.

HYDRONIC SYSTEM THERMOSTAT

I personally have no experience with hydronic heating. Information on the Internet suggests that it is a very nice system regarding the thermal comfort of the house occupants. The 'standard' practice is to have a boiler that heats water to a desired temperature, perhaps 20^o above room temperature, before it is circulated through the PEX tubing. The circulation pump is on a good fraction of the time, even up to continuous operation. We cannot use the hot water in the main storage tank directly since it might be 80^{o}F above the room temperature. Water that hot would overheat the room and might even fracture the concrete slab due to thermal shock. We will need to have a smaller reservoir, perhaps 20 or 30 gallons, and a circulation pump connecting it to the main tank. A second circulation pump will pump water from this reservoir through the PEX system.

PEX comes in sizes from 3/8th inch to 1 inch or more. I arbitrarily chose the 1/2 inch size. According to Siegenthaler, flow rates for 1/2" PEX should be kept between 1.2 and 2.4 gpm (gallons per minute). The maximum allowable length of 1/2"PEX in underfloor heating is 300 ft. I assume that two circuits will be needed in this floor, or a maximum of 600 ft of PEX. This length of 1/2" PEX holds 11.54 gallons of water (96.3 pounds). A circulation pump that pumps at a rate of 2.4 gpm is able to replace the entire 11.54 gallons in 11.54/2.4 = 4.8 minutes. If the 11.54 gallons was originally at 90^{o}F and cooled to 70^{o}F it would have transferred (96.3)(20) = 1926 BTU = 0.565 kWh to the concrete slab and on to the hut interior. To transfer a total of say 25 kWh to the hut the pump would need to operate about 25/0.0565 = 44 times per day, for a total of about 3.5 hours per day.

This will require a *very* sophisticated thermostat. I anticipate measuring the indoor temperature, outdoor temperature, main tank water temperature, reservoir water temperature, and maybe wind speed (infiltration loss), and inputting these numbers into an Arduino Uno microcontroller. It could easily take an entire heating season to get the computer program working properly.

Only one of the two circulation pumps would be operating at a given time. A tentative control logic would be the following. When the PEX pump is off and the reservoir water temperature is below 85^o, the reservoir pump is turned on, until the reservoir temperature reaches 90^o. When the room temperature drops below 70^o, the PEX pump is turned on for a fixed period of time, say the time to replace all the water in the PEX tubing with warmer water (4.8 minutes). We wait a minute or so to allow the reservoir to stabilize and measure its temperature. If below 85^o the reservoir pump is turned on and the reservoir is charged for the next cycle. We wait for perhaps five minutes after the PEX pump turned off, or about 10 minutes after the warmer water was first introduced into the slab, to allow the room air temperature a chance to increase after the start of the warmer water. If the room temperature is still below 70^o, another pump cycle is started. Otherwise, we wait until there is another call for heat.

If we assume each of the two pumps operates 3.5 hours per day, and the required power is 40 W each, the pumps require $(2)(3.5)(40) = 280$ Wh = 0.28 kWh per day. This would increase the battery load from our calculated 1.93 kWh/day to 2.21 kWh/day.

PV PANEL DESIGN FOR LIGHTING

For lighting, cooking, and electronics, I selected four of the 60 cell panels connected in series. This gives a maximum power point of $4V_{mp} = 4(33.37) = 133.48$ V, very close to the 100% SoC for a Nissan Leaf battery pack of 131.2 V. A direct connection of PV panels to battery pack (no MPPT controller) will result in the PV panels operating close to the maximum power point as the batteries approach the 100% SoC point. Four of the 72 cell panels connected in series would have a maximum power point of $4V_{mp} = 4(40.84) = 163.36$ V. The PV panels are current limited, so there is no problem with connecting the four panels to a battery at 130 VDC. The panel voltage will obviously match the battery voltage of 130 V. The current will be about the same, so the power production of the PV panels will be reduced by about $133.48/163.36 = 0.82$. We get the same power production from either the 60 cell or the 72 cell panel, so the price differential between the two panels would be wasted.

Once we select four of the 60 cell PV panels for this application, we need to mount them on some sort of rack. This might be a roof mount, a ground mount, or a mount on the south side of a building (using the wall of the building as a large part of the mount structure). These panels are used all year, so a tilting capability is desirable, to optimize energy production. My first cabin has the wrong orientation for a roof mount. I will reserve the wall mount space for PV panels used just for the heating season, such that there is no need to adjust the tilt. That leaves us with a ground mount rack.

I assume there are dozens of companies selling DIY racks suitable for four 60 cell panels, but a quick search of the Internet did not reveal them to me. There are hundreds of Youtube videos about ground mount racks, but I was unable to find one that dealt with rack design issues. So I decided to try designing a four panel rack. Design criteria include static and dynamic strength, expected life, availability, ease of assembly, and cost.

The first choice is wood versus steel (or maybe aluminum). The solar panels have an expected life of 25 years or more, so the rack should last at least as long. About half of the Youtube videos are of wood racks, so wood is commonly used. It is my guess that wood will not last as long as properly treated metal. Morton Building has been making pole barns for over a hundred years, using treated lumber in the ground. They are now bragging about "getting the lumber out of the ground", using a concrete or metal footing, so even the experts are shifting away from planting wood in the ground. Treated lumber has been treated with some very undesirable chemicals, which can be assumed to leach into the soil and air around the posts. So I decided to use steel.

There is a supply house for metal products a few miles away, selling tubing in longer lengths and lower cost than Home Depot. I decided to use square tubing, two inches on each side, for no particular reason. The supply house carried five different weights of 2" tubing: 16 gage/24' long, 14 gage/20', 11 gage/24', 3/16" wall thickness/20', and 1/4" wall thickness/20'. My guess is that the 11 gage will be satisfactory. (*The Manual of Steel Construction, Eighth Edition*, American Institute of Steel Construction, uses the spelling 'gage' rather than 'gauge'.)

My tentative design is shown in Fig. 2. We are looking from the south toward panels fully tilted toward vertical. Tubing pieces A and D are 8' long, and section C is 12' long, conveniently cut from 24' sticks with minimal waste. Section A is planted about 3' into the ground, putting the midpoint of the rack about 5' above ground. At the top of each post A is a hinge connecting to the horizontal member C. The PV panels are bolted to the members D at four places per panel. Members D are bolted to member C where they cross.

I once built a large steel Savonius wind turbine, and learned the lesson that dynamics can destroy a machine that is very conservatively designed using statics. A gust of wind that hits the two panels on the right will tend to rotate the rack around a vertical axis. A single post in the middle of the rack will experience torsion and the whole rack will

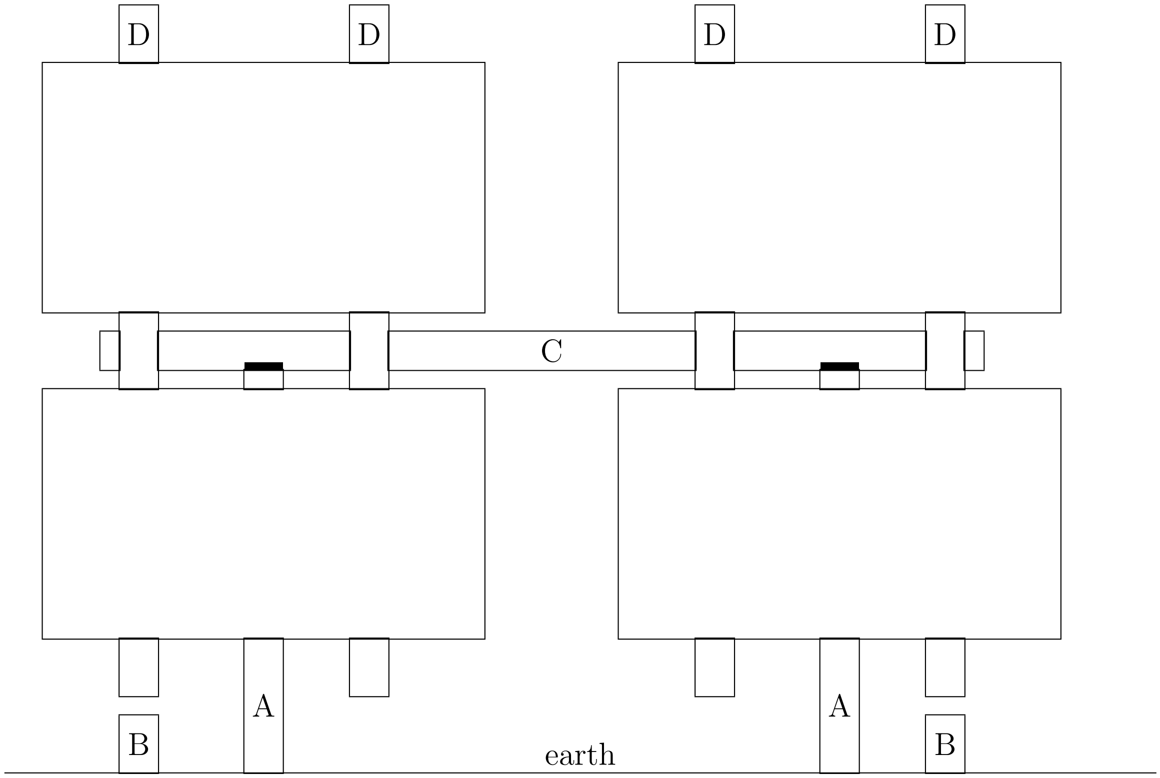

Figure 2: Rack for four PV panels.

oscillate around the post. Having two posts A will reduce this oscillation.

There will also be oscillation around member C. To damp this oscillation we will use two posts B, set toward the south from the plane of the posts A. To adjust the tilt we grab the bottom of the members D and pull toward the south and up. The bottoms describe a quarter circle as the tilt changes from vertical to horizontal. When the panels are at the desired tilt, depending on latitude and season, we somehow block them to temporarily hold that tilt while identifying a point on the ground directly under the member end, and finding the distance from member end to ground. We move the panels from this position to vertical or horizontal to get them out of the way while digging a post hole at the marked locations. We cut pieces of tubing the exact length to reach from the bottom of the post hole to the bottom of member D. Member D is bolted securely to member B and a sack of Quikcrete is poured into the post hole. This will reduce the oscillations around member C.

This tubing is ungalvanized and unpainted, hence will rust. There is always the possibility of galvanic action between the tubing and the surrounding soil, as well as chemical reaction with the soil. The tubing may last longer than wood, but will still rust and decay until it too fails. I suspect the time to failure will be well over 25 years in this dry climate, but, for the sake of appearance, I think I will paint all the tubing members. I will use a good quality oil based primer and final coat, similar to what is used to paint restored tractors.

PV PANEL DESIGN FOR HEATING

We now need to do a design for PV panels connected to electric heating elements in the hot water storage tank to heat the water. The basic concept is shown in Fig. 3. Each panel is shown as a single diode directed downward. The figure shows four panels connected in series and three sets of four panels then connected in parallel. We could have up to seven panels in series. The number of parallel strings would be selected to meet the total energy requirements.

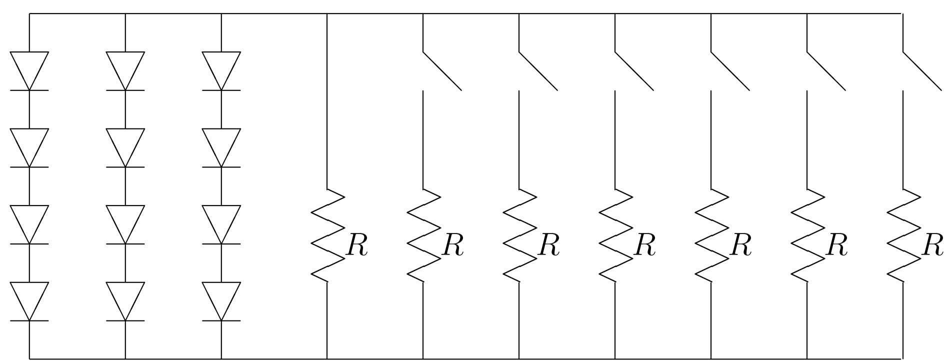

Figure 3: PV panels and water heater elements.

We have already decided to use four of the 60 cell panels for charging batteries, so there is an incentive to continue with the same size panel if possible. The 60 cell panel is less expensive per watt, and lighter (easier to handle) than the 72 cell panel (at least for the Mission Solar panels).

The switches shown in Fig. 3 are DC solid state relays. The actual switch will be a MOSFET or perhaps an IGBT, able to both turn on and turn off a direct current. Many solid state relays are made with Triacs, which can turn on a direct current but cannot turn it off. (Triacs are AC switches, depending on current going to zero to bring the switch to the off state.) A DC solid state relay should have a + on one terminal and a - on the other. We must watch for both adequate voltage rating and adequate current rating of these relays.

Fig. 3 shows six switches/relays. This number will vary as we try to load the PV panels in an optimum fashion.

Crydom has been a major manufacturer of solid state relays. Typing ‘crydom’ on

Ebay resulted in about 6500 hits. Prices seemed to range in the \$10 to \$20 range. The company is listed on www.digikey.com and www.mouser.com as Sensata-Crydom. The name printed on the relay is still Crydom, as seen on these websites. Prices on these websites are in the range of \$80 to \$120 each, for quantity 10.

I have also used MGR solid state relays (270 hits on Ebay) and unbranded (just SOLID STATE RELAY printed on the package). Four of these non-Crydom relays have failed during testing, sometimes when I am fairly confident I was not exceeding the ratings. All four failed shorted (always on regardless of the control voltage). The voltage rating for these relays is 220 VDC. If we want a higher voltage rating, or a more realistic current rating, we need to select Crydom (or perhaps a brand I am not familiar with).

Home Depot has a 240 V 1500 W water heater element available for \$6.15 each. The nominal resistance is

$$R = \frac{V^2}{P} = \frac{(240)^2}{1500} = 38.4 \quad \Omega \tag{8}$$

I calculated earlier that I needed at least 19 kWh/day for heating. I then noted that power output of solar panels degrades with time, so to get 19 kWh/day at the end of the PV life, I needed perhaps 25 kWh/day when new. Many assumptions were made to arrive at estimated energy productions of 1.58 kWh/day for the 60 cell panel and 1.96 kWh/day for the 72 cell panel if operated at, or close to, V_{mp}. Operating at a lower voltage reduces the energy production proportionally. We would have to increase the number of panels to compensate for lower energy production per panel.

Table 3 shows computations for seven different configurations, 4, 5, 6, and 7 of the 60 cell panels in series, and 4, 5, and 6 of the 72 cell panels in series.

Panel	NV_{oc}	NV_{mp}	$\frac{NV_{mp}}{38.4}$	El	R	I	config	panels
4×60	164.56	131.88	3.43	11	3.49	37.8	4P4S	16
5×60	205.70	164.85	4.29	7	5.49	30.05	4P5S	20
6×60	246.84	197.82	5.15	5	7.68	25.76	3P6S	18
7×60	287.98	230.79	6.01	4	9.6	24.04	3P7S	21
4×72	194.12	163.36	4.25	7	5.49	29.78	4P4S	16
5×72	242.65	204.20	5.32	5	7.68	26.59	3P5S	15
6×72	291.18	245.04	6.38	4	9.6	25.52	3P6S	18

Table 3: Design options for PV panels.

The nominal open circuit voltage for four of the 60 cell Mission Solar panels in series is 4(41.14) = 164.56. The solid state relays will certainly see open circuit voltage from time to time, so must be rated at this voltage or greater. The 220 VDC MGR and unbranded relays will work for four and five of the 60 cell panels in series, and for four of the 72 cell panels in series. If we decide to go with more panels in series, we will need to select a rating of at least 300 VDC.

The fourth column in Table 3, $NV_{mp}/38.4$, is the current that would flow in a 38.4 Ω heating element when NV_{mp} is applied. The relay must be rated for this current or more. Crydom makes a D4D07 (300 VDC) rated at 7 A for $73.33 (each, quantity 10, at Mouser), a DC400D10 rated at 10 A for $95.48, and a DC400D20 rated at 20 A for $111.08. A relay with a higher current rating would be expected to operate at a lower temperature, which might extend its lifetime. The 7 A relay might work fine for 30 years, but my gut says to go with a higher rating if at all possible. The MGR and unbranded relays I have are rated at 10 A, which might be optimistic.

The power input to a heating element is $VI = 131.88(3.43) = 452$ W for the first row in Table 3. We will assume this power can be supplied for 5 hours per day on average, making the daily energy production $5(452) = 2.26$ kWh per element. We would need $25/2.26 = 11$ heating elements to get our total of 25 kWh from the panels to the water tank.

Suppose I have 11 heating elements connected in parallel. The net resistance is $38.4/11 = 3.49\ \Omega$. If the voltage were 131.88, the current from the panels must be $131.88/3.49 = 37.8$ A. The panels are current limited and cannot provide more than about I_{mp} when the voltage is near V_{mp}. Four strings of panels in parallel can provide $4I_{mp} = 4(9.40) = 37.6$ A, very close to the 37.8 A needed, so 16 panels, 4 parallel strings of 4 panels in series, 4P4S in shorthand, should work.

We then repeat the process for six other combinations of series and parallel for 60 and 72 cell panels. The second line in Table 3 is for five of the 60 cell panels in series. The higher voltage means each heating element will absorb more power (V^2/R) so fewer elements will be needed (7 instead of 11). Seven elements in parallel have a resistance of 5.49 Ω, so the required current is $164.85/5.49 = 30$ A. The possible current from three strings of panels in parallel is $3I_{mp} = 3(9.4) = 28.2$ A. Since three strings in parallel cannot provide the required 30 A, we have to put another string in parallel, making the total number of panels $(4)(5) = 20$.

When we examine the case of six panels in series, the increase in voltage lowers the required current to 25.76 A, which is less than $3I_{mp}$ so three parallel strings is enough. The required number of panels is $(3)(6) = 18$.

It appears to me from my testing on the Charge Controller, discussed earlier, that a system of 9 or 10 relays is about the minimum number to give reasonable confidence that we are close to the optimum or peak load. Looking at Table 3, only the 4×60 configuration requires more than 9 relays. The others require between 4 and 7 relays, making switching that is too coarse.

It thus appears that our first panel configuration of 4S4P is the best. I would put 12 heating elements in the tank, one connected direct (no relay), and eleven connected via relays. I might decide to use 13 elements, with 2 elements in series for one of the relays, or 14 elements, with 2 relays controlling a double resistance/half current resistor to give even finer control when near the optimum point.

We will need 16 panels for space heating and 4 for battery charging, a total of 20. Mission Solar ships this particular panel as 26 panels per pallet. I bought a full pallet of 26 panels so I have 6 spares. I could immediately parallel 4 panels with the battery charging bank if my load had grown. Or if my heating calculations were not very good I could add 4 panels to the space heating bank. There could be issues with mixing different panels, and the probability of having the exact same panel available even five years in the future is low, so having spares is a prudent practice. We always need to be mindful of Murphy's Law. Lightning, hail, rifle bullets, foul balls, etc., just might lower the performance of a panel enough to justify its replacement.

DOMESTIC HOT WATER

I need to be able to wash clothes on site, to avoid MCS issues with detergents. According to the Internet, cold water can be used to wash clothes, with these possible exceptions: polyester fabrics, cold water below 60^oF, and a 'cheap' detergent that will not dissolve completely in 60^oF water. I have worn polyester pants for decades. They wear like iron so I consider them good value. I suppose I could switch to cotton blue jeans, at least for periods of time when energy for heating water is scarce.

I plan to use rainwater as my water supply, which, during the winter, will enter the holding tank as snow melt, less than 40^oF. Even in warm weather, rain in this dry climate will cool the air off by perhaps 20^oF, so we would not get much water into the storage tank at greater than 60^o. The holding tank will be in the unheated utility room, which could easily drop below 60^oF in the winter.

The detergent that I find to be kind to my skin and also kind to my garden watered by graywater might not dissolve well at 60^oF. For design purposes, I think I need to assume using some hot water for clothes washing.

I also need hot water for the occasional shower. As a very crude estimate, I will assume I need 10 gallons of hot water for each shower and for each load of wash. The worse case would be in the winter when the holding tank might drop as low as 40^oF. The energy required to raise 10 gallons of water from 40^o to 120^oF is $(10)(8.344)(120-40) =$ 6675 BTU = 1.96 kWh, or about 2 kWh.

I already have a large hot water tank for space heating, but this should not be used for domestic hot water (DHW) because the temperature may be well above 120^oF, high enough to quickly burn flesh. There is a separate mix tank and a small pump to get perhaps 20-30 gallons to the right temperature for hydronic heating, say 90^oF. I could install a second mix tank and pump with a thermostat set for 120^oF, but this hot water would be unpressurized. Hot and cold water lines in the cabin need to have pressures on the order of 40 psi.

A reasonable choice seems to be a standard 30 gallon electric hot water heater. On 3/18/21 Home Depot had 30 gallon heaters with 3800 W elements for $379 or 4500 W elements for $389. One element is located in the upper third of the tank, to heat that fraction of the water. It has a thermostat with a single pole, double throw configuration. When water in the top third of the tank is at or above a set temperature, the thermostat sends 240 VAC on to the single pole, single throw thermostat for the bottom element, which then allows the bottom element to turn on, and heat the water in the bottom two thirds of the tank.

Cold water enters the tank at the bottom and hot water leaves from the top. There is minimal mixing in the tank so the water is stratified by temperature. When the top thermostat senses cold water, the entire tank is cold. The top element heats just the top third of the water, making hot water available at the faucet more quickly than if only the bottom element was used to heat the entire tank. Using 10 gallons of hot water in a shower will lower the temperature in the bottom third of the tank, causing the bottom element to turn on. This wiring scheme means that the top element turns on only when all the hot water is used. The bottom element would therefore do almost all the heating (and therefore is usually the element that fails in on grid situations).

The nominal resistance of a 240 VAC, 3800 W element is $(240)^2/3800 = 15.2\Omega$. If I connect the element to my bank of 16 solar panels used for space heating, with a terminal voltage of $4V_{mp}$, the current is $133.48/15.2 = 8.8$ A. This is getting close to the 10 A rating of my unbranded solid state relays. If the failure mode of a solid state relay is open circuit, then I have no hot water until I trouble shoot the system and replace the relay. However, if the failure mode is short circuit, as seems to be common, then power continues to be applied after the set temperature is reached. Eventually the overflow valve on the heater will open and spray hot water on the floor of the utility room. I may want to spend a few dollars more and get genuine Crydom relays rated at 20 or 25 A for this application.

So exactly how do we wire a 240 VAC electric hot water heater so it will work with

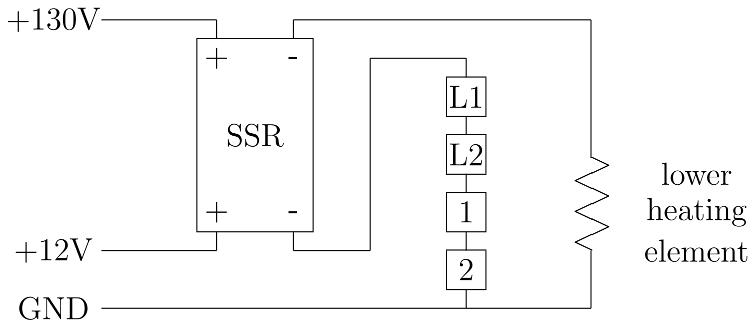

Figure 4: Water heater wiring.

four 60 cell PV panels in series (a nominal 130 VDC)? I am fairly confident that the heater switches are mechanical, a spring loaded construction that will 'jump' from on to off and back as the temperature changes, and will not interrupt 130 VDC. They will interrupt a 12 VDC current limited signal, however. Therefore I will try using the built-in thermostats in the water heater to control the on/off signal to the solid state relay (SSR) that handles the heavy current, as shown in Fig. 4.

All electric water heaters are supplied with a high limit control switch that removes power if the water temperature reaches 170^o or 180^oF. This is a double pole switch that opens both legs of the 240 VAC supply. It is the top portion of the upper thermostat. $L1$ is a screw terminal that accepts the heavy wire coming from the AC breaker box. It is possible that some brands will not have a physical terminal $L2$. It might be that the connection between $L2$ and pin 1 of the upper thermostat is made internally, so there is no way to make an external connection work. If that is the case, I would probably skip this second level of protection, and just use the switch between pins 1 and 2 of the lower thermostat.

There is no battery in this circuit (except perhaps the +12 VDC supply), so we only heat water when the sun is shining. If we are worried about efficiency, we could turn the +12 VDC supply off at night.

The lower heating element will consume about 20% of the 16 panel output at full sun. During low sun conditions, this will over load the panels and really drop the low light efficiency. We should probably disconnect the water heater from the solar panels at less than about half sun. During the warm months, the space heat water tank will be turned off so the water heater will be the only load. Efficiency concerns will become irrelevant. At full sun the voltage will be close to the open circuit value. At 39 volts per panel (156 V total) the power consumed by the lower element is about 1600 W. It would take slightly over an hour to heat the water used by a shower or laundry.

The 16 panels used for space heating are not needed at all for six months of the year. Most days in the winter an extra load of 2 kWh/day for one shower or one load of wash will not affect the power budget of 19 kWh/day for heating at an average outside temperature of 30^{o}F. My guess is that for only 10 days per winter will the 2 kWh/day make a difference. Rather than buy additional panels for DHW, I am inclined to take fewer showers and not wash clothes on those few days.

LED STRIP LIGHTING

I will use 120 VDC for lighting in this cabin, but another cabin with another set of constraints might see 24 VDC being chosen. This would be especially true if we were to use propane for space heating, hot water, and cooking.

Advantages of using a 24 VDC battery bank rather than a 120 VDC bank include the following:

1. We need fewer batteries.

2. There is a safety issue. Touching 120 VDC with one hand while the other hand is grounded can kill, while touching 24 VDC would probably not even be noticed.

3. Using LED strips uniformly across the ceiling gives an uniform light intensity across the room, as opposed to LED bulbs which have dark spaces.

I installed LED strips in one bedroom of my house in Rockvale several years ago and liked them so much that I thought they would soon become commonplace, readily available at Walmart. That has not happened, so one still needs to buy strips at places like Ebay. There are many brands, which appear and disappear rapidly. Not all will clearly specify all the important parameters. I notice that the company ABI is still operational over a period of years, and makes an acceptable product at an acceptable price. At the time this design was prepared, the particular strip I wanted was not available on Ebay, so I had to go to the website of their parent company at www.jacobsparts.com. They accepted my order, but later informed me they were out of stock and refunded my money. I was unable to immediately find an equivalent strip elsewhere, so was ‘forced’ to go to Plan B, the use of 120 VAC LED bulbs. I will leave the LED strip design in this document for those who would like to try it.

The particular strip I selected was the ABI LSL-EX-2800K. It has 600 LED chips on a 10 m long strip. The chips are 5 mm by 5 mm, referred to as a 5050 chip. The light production is 11 lumens/chip. The power rating is 3 A, 72 W for the 10 m strip operating at 24 VDC. A strip producing (11)(600) = 6600 lumens at 72 W has an efficiency of 6600/72 = 91.7 lumens/watt. By comparison, I have some Sylvania double life soft white 100 W incandescent bulbs rated at 1580 lumens, or 1580/100 = 15.8 lumens/watt. The LEDs yield 5.8 times the light for a given power input.

The wiring diagram for a strip is shown in Fig. 3. The battery voltage varies from about 24 VDC at night to a little over 29 VDC when charging. Daytime operation of the LED strips might not be advisable for a couple of reasons. The light output will increase with voltage, perhaps 20% to 30% as the voltage increases from 24 to 29 VDC. This variation with the charge cycle might be objectionable to viewers. Also operating above rated voltage lowers operating efficiency and shortens the LED strip lifetime. My best guess is that operation will be acceptable (lifetime 10 years or more, light intensity variation not very objectionable).

A 24 VDC strip has 600 diodes in 10 m, or 6 diodes in 10 cm. Each 10 cm portion has 6 diodes and three 62Ω resistors in series (shown as a single 186 Ω resistor in Fig. 3.). Each 10 cm segment is in parallel with every other 10 cm segment. A full 10 m long strip would have 100 of the series diode strings shown in Fig. 2 in parallel. If the rated current for the whole strip is 3 A, then the rated current for one segment is 3/100 = 0.03 A. Current flow through a diode increases exponentially with the voltage across it, so series resistors are added to prevent catastrophic failure.

The left end of the diode string is permanently connected to the positive terminal of the battery bank. The other end is connected to the negative terminal through the switch M_1, a power MOSFET (metal oxide semiconductor field effect transistor). This allows the total length of heavy copper wire to be kept to a minimum, thereby improving efficiency.

A second reason for using a MOSFET is more subtle, but may be even more important than the efficiency improvement. Light switches available at the local hardware store are not UL rated for switching direct currents. Switching a current off always produces a small arc between the opening contacts. A 60 Hz alternating current goes through zero 120 times per second, which always eliminates the arc in a properly functioning switch. A direct current has no zero crossing, so the arc tends to last longer, which degrades the contacts. A switch turning off 5 A DC will fail sooner than one turning off 5 A AC. And it is not impossible that the failure mode will involve a continuous arc, which would be a definite fire hazard. Using devices that are not rated for the application is a *bad* idea. The electrical inspector might not stop you, but the fire hazard should.

A mechanical switch is still required, to turn on a MOSFET by applying a voltage to the MOSFET gate. The mechanical switch in Fig. 3 also switches DC, but slightly less than 1 mA rather than the several amps required by the LEDs. (The gate of the power MOSFET is essentially a high quality capacitor that draws almost no current once charged so all the current flows through the 10K and 20K resistors.) This tiny current is enough to 'wet' the switch contacts, but far below the amplitude necessary to sustain an arc or cause a fire. A standard hardware store AC switch should last significantly longer while switching 1 mA DC than while switching several amps AC.

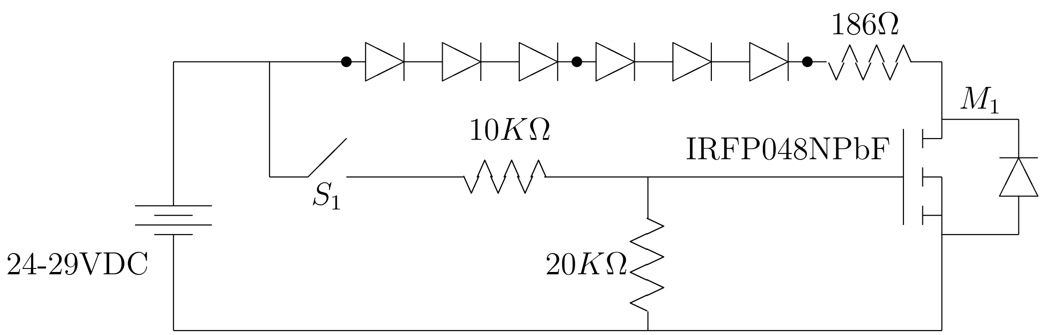

Figure 5: LED switching circuit.

The gate voltage of this MOSFET is limited to 20 V, which requires the 10K and 20K resistor combination to reduce the 24-28 VDC battery voltage to less than 20 V.

The power MOSFET needs to have an 'ON' resistance as low as possible to maintain high efficiency in the circuit. The IRFP048NPbF will withstand 55 V while 'OFF' and is rated at 64 A while 'ON'. The nominal resistance is 0.016Ω. There is nothing sacred about this particular MOSFET. The cheapest 50V MOSFET rated for at least 15 or 20A should do fine.

We are now ready to do a lighting design and power budget. Two terms need to be defined. The *lumen* (lm) is the "total" light radiated by the bulb. It may be called the luminous flux or the luminous power. The *illuminance* is the light incident on a surface, in lm/m^2 or lux. It is recommended that a family living room have at least 50 lux. Hallways and toilets in an office building should have 80 lux. Working areas in an office building should have 320 to 500 lux. Very detailed work may require 2000 lux. I personally like a well lit space, in the 200 to 500 lux range.

The analysis is reasonably straight forward. One finds the area of a room in m^2, multiplies by the desired lux to get the desired lumens, then divides by the lumens per diode to get the required number of diodes, then divides by 60 diodes per meter to get the required length of LED strip. Or one can guess at the number of full strips that naturally fit in a room and check the resulting illuminance.

The cabin under design has four rooms: bathroom 5.2 m^2, closet 4.2 m^2, bedroom 13.0 m^2, and living/kitchen 39.3 m^2. The bathroom will naturally accommodate 3 strips of 2 m length each, or 360 diodes. If no lumens were absorbed by the walls, and each diode produced 11 lumens, the illuminance would be

$$F_{bath} = \frac{360)(11)}{5.2} = 760 \quad \text{lux} \tag{9}$$

Some lumens are absorbed by the walls and other surfaces so the effective illuminance will be lower than this number. I have not seen any Internet guidelines for what this fraction is. My one data point for a room with this lighting system installed in 2014 suggests a factor of about 0.5. That means the bathroom illuminance would be about 380 lux. (Hopefully between 300 and 500 lux. This factor is not easy to calculate.) This range feels about right to me.

The closet naturally could use two strips of 2 m each. The theoretical illuminance is

$$F_{closet} = \frac{(240)(11)}{4.2} = 630 \quad \text{lux} \tag{10}$$

I will consider two strips of 4.2 m each for the bedroom. The total number of diodes is (2)(4.2)(60) = 528. The theoretical illuminance is

$$F_{bed} = \frac{(528)(11)}{13.0} = 450 \quad \text{lux} \tag{11}$$

The living/kitchen can accommodate 5 strips of length 7 m each. The number of diodes would be (5)(7)(60) = 2100. The theoretical illuminance is

$$F_{living} = \frac{(2100)(11)}{39.3} = 590 \quad \text{lux} \tag{12}$$

I expect to put two strips on one switch and three strips on a second switch, so I can operate at 235 lux, 355 lux, or 590 lux.

At an absolute minimum I would want the living/kitchen two strips on for 16 hours/day on cloudy winter days. The power would be (14 m)(7.2 W/m) = 100 W. The daily energy would be 1.6 kWh. Four Trojan deep discharge batteries hold about 6 kWh total at this current discharge rate, but only half is available if we want the batteries to live a long life. So the proposed system will supply minimal lighting for two days with zero sunlight for charging. I think this level will work for me. If I know the batteries will not last until the sun comes out, I can switch to flashlights or walk to the shop which is on the grid.

We saw earlier that the PV panels I am looking at will produce an average of 1.93 kWh/day, or slightly greater than the minimal 1.6 kWh/day for lighting that was just calculated. It will take some management, but I think this will work.

PROTECTION AND GROUNDING

There is no obvious need for fuses or circuit breakers in the water heating circuit since the panels are current limited. We just need to make certain that all wiring is rated at 125% or so of the short circuit current of the panels. The battery circuit, on the other hand, must have circuit breakers to reduce the hazard of an electrical fire. These must be rated for DC. There are some exciting videos on YouTube of AC breakers catching on fire after failing to interrupt a DC current! MidNite Solar has a good selection of 150 VDC breakers, the MNEDC series at $22 and the MNEPV series at $18. They also sell a breaker box, the MNEDCQUAD, for $68, that holds 4 breakers. We could have a breaker for 120 VDC lighting, and another for 120 VDC cooking.

A casual reading of the National Electrical Code suggests that the NEC might not require a connection from some part of the battery circuit to earth ground. Nothing is immediately obvious to me as to why a ground would improve safety. The PV panels will be mounted in a grounded rack, which will be a target for lightning. If the photovoltaic portion of the panels are not grounded, there will be less tendency for a lightning strike to follow the wiring into the cabin.