Executive summary on backup power and solar energy options.

People living in rural areas might want backup power for critical loads such as CPAP machines, oxygen concentrating devices and communications systems. Backup power for refrigeration can cost more money than the value of the food in the refrigerator; ditto for freezers, unless they are very large. Either can maintain cold for 12-24 hours without electricity. Backup heat is usually provided most cheaply by wood or a propane stove. Electricity storage for modest loads is typically accomplished with inexpensive golf cart batteries. Charging these batteries can be by means of solar electric panels (photovoltaic or PV), a gas engine generator set or even by means of a trickle charger that was plugged into the grid prior to the power outage.

People living in rural areas also have few options when it comes to heating their space or domestic hot water. Most common are propane, heating oil, electricity and wood. Electricity is typically the most expensive, with propane/ oil occasionally costing more but typically costing 2/3 as much as electricity. With the collapse of oil prices in 2015, propane now costs about 1/3 as much as electric resistance heat. Those are dollar costs. The reader is left to explore and quantify the external costs.

Sunlight can be used to make electricity or heat. Solar thermal panels are somewhat less expensive per unit of heat produced, only produce heat and can be placed on a roof or on a ground mount that is ideally within 100 feet of the intended heat load. These produce 3-4 times as much heat energy per square meter of panel area when compared to PV and produce the most heat energy per dollar of equipment on large size systems. They are the best choice if one's goal is to heat their home or other large heating loads such as DHW for seven teenage daughters. They are no longer cost competitive for modest uses such as domestic hot water for 2-3 people in a single family home.

Sunlight to make electricity is much better known than solar thermal and in the last two years has overtaken the latter as a cost effective means of providing domestic hot water for homes. This is due to its lower Installed Cost. PV--> DHW is a very simple system. Cost of panels, racks and installation is low due to competition and standardized components. Energy storage is via an off-the-shelf electric water heater that is typically installed adjacent to existing hydrocarbon water heaters. Siting of PV arrays is not critical though line losses and cable costs grow with distance. 200 Yards should be considered a practical limit.

It's reasonable to use PV and solar thermal systems on the same property. I frequently ask: “How much backup power would you want if it was free, because using the PV to provide your DHW saved enough money to pay for the system?” Battery storage is not free, nor are inverters. Battery costs are proportional to the average daily power consumption and inverter cost proportional to the single largest load. Powering a CPAP machine and communications equipment via two golf cart batteries and a 250 watt inverter would cost less than $500 beyond the cost of the PV panels. Note that the PV array would allow one to support this load indefinitely. Batteries + inverter to power a well pump is more expensive, but the costly PV array is exactly the same.

PV panels used to power Pete's electric water heater have a total nameplate rating of 1.2kW. This array has provided all but 3.1 kWh of my DHW needs since August 9 when it went on-line. PV panels now cost $1/ watt for made in USA panels, with a similar $1/ watt cost for racks. 2KW of PV is a reasonable guess at the power needed to provide DHW for two people. Aquilla Solar tells me that $3/ watt for installed and ready to go PV systems is a good budgetary figure. PV is cheap enough in 2015 that it makes economic sense to use it for DHW, and that it's available for backup electricity, well that's a bonus. 2KW is a huge backup power system, but if it pays its own way, then why not?

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Grid defection or load defection seems to be the topic of the hour, especially with the advent of really affordable photovoltaic panels brought to us by makers in the USA, Canada and the orient. In 2015 photovoltaic panels cost about 1/6th as much per watt as they did in 2001. More PV is being added to the grid each year. Officials often express concern that the grid might not be able to handle more renewable or non-dispatchable energy. Nobody expects that the grid in the US will be as robust as it is in advanced nations such as Spain, where: “Overall 27.4% of Spain's electricity was generated from wind and solar in 2014.” (Spanish Electrical Report via Wikipedia) Or that we can ever do what Germany accomplished on July 25, 2015: “Renewables Make Up 78% of Germany’s Power Consumption in an Afternoon.” (from http://www.greentechmedia.com) There is good news though. We can put more PV in service without even connecting to the US' fragile electrical grid. Many states in the US still do not have net metering laws and others have net metering with fees that are excessive for the small system owner. These laws are irrelevant when we power DC appliances direct from PV panels, and our electric bills get reduced by OUR avoided cost, not by the utilities' avoided cost.

For those of us whose only options for domestic hot water (DHW) are propane, oil or electricity, PV provides an excellent opportunity for load defection. Defecting from the propane or heating oil grid is just as noble as defecting from the electric grid. Electric water heaters can be powered by direct current, straight from the PV panels, with no batteries, no inverter and no grid-tie. Ouch!, I can hear your protests from here. You say inverters are cheap and I should just grid-tie. A friend in the biz here at La Crosse told me: “When I checked around retail prices they are still in the 48-65 cents a watt range.” “So I did verify the costs with the electrician and the engineer and you are right on target. If you can get away with not using the inverters you could probably increase the size of your array by 50% or more.” Xcel Energy and other utilities in southwest Wisconsin charge $400- 1,200 for the bi-directional meter plus $7.00 per month to be grid-tied. My point is that one doesn't have to pay any of these fees to take advantage of cheap PV for uses such as DHW which run perfectly well on DC.

Isn't solar thermal better suited for domestic hot water? It's true that at one time, solar thermal was a tenth or less of the cost of PV. At about 50 cents per watt, solar thermal is still cheaper than PV, but not by enough to offset its higher installation cost and the cost of a coil-in-tank hot water storage tank. A PV based DHW system using an electric water heater for storage and the resistance element as the functional equivalent of the heat exchanger is cheap in comparison. PV for DHW is very much a DIY project. Like myself, you can even use the electric water heater you already have.

How does PV for DHW work? Doesn't my electric water heater require AC? It does if it is a heat pump water heater. Electric resistance water heaters can be run on AC or DC, however the thermostat in an AC water heater will not survive for long on DC. Alternating current has zero voltage 120 times a second so any arcs created when opening a switch are readily extinguished. This is not true with DC. One needs either DC rated switches or DC solid state relays.

Why do I need switches or relays at all? It's not like the PV array will heat the water all that hot. Oh yes it will! Just like the electric elements installed in your water heater at the factory, PV powered elements can heat the water with no limit on the temperature it will reach. Sufficient sunshine and lack of use of hot water can result in the water reaching 175 degrees or more, causing the temperature & pressure relief valve to open. This should not be relied upon as a temperature control device!

My own solution is a simple on-off controller that I built within the fused safety disconnect box near my water heater. (There is also a safety disconnect outside on the ground mounted array.) Inside the enclosure is a solid state relay (SSR) and a DIN rail power supply to power the SSR. Don't worry, these are both off-the-shelf items that can be bought from an industrial supply or even from sellers on ebay. The wires that previously powered the bottom element of the electric water heater have been re-routed to the little gray power supply shown at left. This is no problem as the same wires that once conducted 4,500 watts to the resistance element are now conducting 7 watts to the power supply. Just as before, when the water in the bottom of the tank is cold, the thermostat switches on and when it's hot, it switches off. Now it is switching on and off the 7 watt power supply, which controls the relay to turn the PV array on and off. After several sunny days, or a day or two of being away from home, the built-in thermostat in the water heater will open, which shuts off the little power supply, and opens the SSR which prevents any more PV electricity from reaching the heating element.

How can this work when the water heater is rated 4,500 Watts and I have only 1.2kW of PV?" The water heater element draws 4,500 Watts only when it is powered by 240 volts AC or by 240 volts DC. The name "240 VAC" is given to a voltage source that varies in sine-wave fashion between 0 and 340 volts and then cycles from 340 to 0 to -340 volts, but it delivers the same power to a resistance heater as 240 volts DC. For the purpose of calculating power, so-called 240 VAC is identical to 240 VDC. If you powered this same water heater with 120 volts AC or DC, it would draw 1,125 Watts. *Is this enough to heat water?* Yes it is, though it will take longer than when powered by 240 volts. *Will 48 volts work?* Yes, though the same element that was rated 4,500 watts at 240 volts now delivers only 4,500 (48/240) x (48/240)= 180 watts. In mathematical terms, watts is proportional to voltage squared.

For the purpose of designing a system, it will be more useful to rate a resistance element in ohms than in watts. You can measure ohms with a digital volt meter or you can calculate it like this: Ohms = (rated voltage x rated voltage)/ watts. Resistance = (240 x 240)/ 4,500= 12.8 ohms. Notice that this has nothing to do with AC or DC. All of the off-the-shelf water heater elements are perfectly suited for use with DC. AC thermostats are Not suitable for use with DC!

Can I wire my PV panels to my water heater any way I want? No, but any PV panels will work for this purpose. PV panels have ratings of voltage at maximum power(Vmpp) and amps(Impp) at maximum power. My Siemens SP-75 panels are rated at 17.0 Vmpp(volts) and 4.4 Impp(amps). The values of 17.0Vmpp and 4.4 Impp are both reached when the panel is driving a load of 17.0/ 4.4= 3.86 ohms in bright sunshine. With a load of one ohm, the amps would be a little higher and volts would be much lower. We want the product of amps times volts to be maximal. We don't care about amps or volts by themselves; we care about the product of amps x volts-- watts. Operating at a resistance of

Vmpp/ Impp is what allows us to achieve maximum power. Four panels in series makes 4 x 17.0= 68 Vmpp and the same 4.4 Impp. Four panels in series are suited for driving a load of 68/ 4.4= 15.4 ohms. That's pretty close to the 12.8 ohm resistance of the water heater element, but only 4 x 75= 300 watts. 8 of these SP-75 panels in series produces 136 volts; two of these 8 panel strings in parallel produces the same 136 volts but at 8.8 amps, both maximum power ratings. 136/8.8= 15.4 ohms, the same as one set of four panels in series.

That's it. Your introduction to power engineering and impedance matching is complete. The arrangement of panels in the PV array or specifically, the ratio of Vmpp / Impp needs to reasonably match the resistance of the heater element. There are different size (wattage) heater elements and one can use different series/ parallel arrangements of PV panels. One only has to figure this out one time. Thereafter, the power production is optimal on a sunny day and is decent on bright overcast days. On heavy overcast days when solar thermal produces zilch, I get a few tens of watts from this 1.2kW array. It is on these days one would want a higher resistance element in the tank, to prevent pulling the array voltage down so low. In a future article, I'll describe the design and construction of a MPPT controller that will keep the PV array voltage optimal, regardless of the sky conditions.

How much PV is needed to power a water heater for my family? The author lives alone and has an array with 1.2kW nameplate of panels. This seems to be plenty to provide hot water for all my uses and to overcome the standby losses as this is a tank type water heater. The same water heater which has been here since 2007, now powered by PV. Its 50 gallon capacity is enough to get me through two days of heavy overcast. The water heater's top element is still connected to the grid, with the upper thermostat set to 120 degrees. The bottom element can be set as high as 150 F, but please install a thermostatic mixing valve to temper the extremely hot water which it can produce. Without a temperature limiting control, the PV can heat the water to unsafe temperatures. Be sure to use a temperature limiting control or switch off your array before going on vacation. I installed an hour meter on the top element so I know that it has not been used this summer. It will certainly be needed during the extended overcast we get in November and December. I am guessing that 1.8kW of PV would be plenty for two people and possibly 3.0kW for four people-- and a larger water heater/ storage tank. Sizing renewable energy systems has never been an exact science, depending so much on site, climate, energy use, etc.

There are many considerations in choosing solar thermal or PV for DHW. For a larger family and/ or for space heating, solar thermal will be less expensive. Available space and distance to the most favorable site is an important consideration. Line losses between a ground mounted solar thermal array and in-home storage tank can be significant. For my PV array, running at 136 volts and 8.8 amps, 240 feet out and 240 feet back, using #8 copper wire, the calculated voltage drop is 2.4 volts, or less than 2% power loss. The cost of cables + sheath is a bit over $1/ foot for my PV array; I was lucky to get down to $10/ foot for my solar thermal array when I installed it in 2009.

Either solar electric or solar thermal is a good step in getting off the energy grid controlled by others. For ease of installation, and lower cost on smaller systems, PV is the easy winner. For physical size, solar thermal is more compact, requiring a third as much area in cold climates and perhaps a quarter as much area in extremely hot climates. PV panels are more efficient in cold weather; solar thermal is more efficient in warm weather. The advantage of PV for DHW is its lower installed cost on single family home sized systems and that it can readily be tapped for backup power. How much backup power would you want if it was free, because using the PV to provide your DHW saved enough money to pay for the system? Pete Gruendeman gruendeman@att.net