Power Sharing

Establishing an Off-Grid Community Microgrid

Story & photos by Chris Farmer

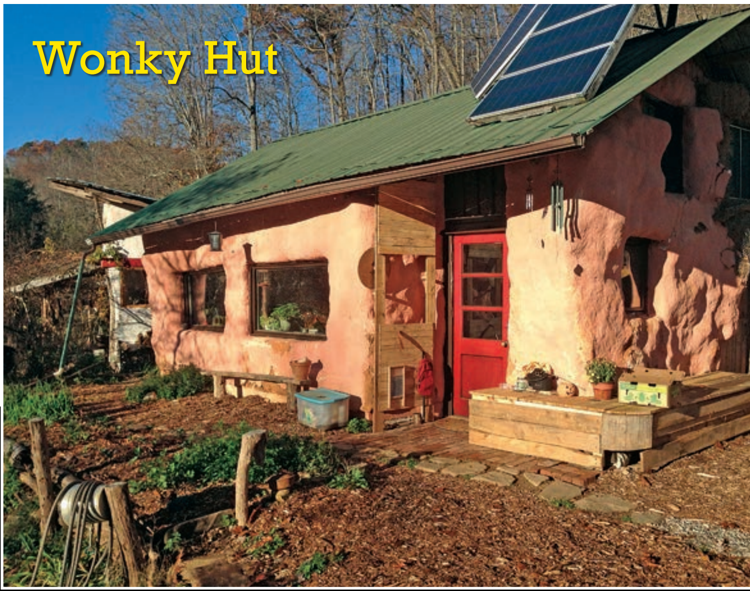
In June 2015, 22 residents of the Hut Hamlet neighborhood commissioned an 8.16 kW off-grid microgrid PV system at Earthaven Ecovillage, an intentional community outside of Black Mountain, North Carolina. The shared solar-electric system serves 10 small cabins, and the neighborhood kitchen and bathhouse. On an average sunny day, the system produces 31.5 kWh of electricity—what the average American house consumes—which is shared among the neighborhood homes.

Top: Brandon Greenstein and Chris Farmer, designers of the community PV system and custom weighted-metering system that helps in billing residents proportionally to their energy use.

Earthaven is a 21-year-old intentional community situated on 329 acres near the edge of the Blue Ridge Mountains. Presently, about 80 people live in the community year-round. Earthaven's mission is to create a village that is a living laboratory and educational seed bank for bioregionally appropriate cultures.

The entire community is off-grid, producing its electricity from several PV arrays (and two small microhydro turbines). However, after solar electricians Chris Farmer and Brandon Greenstein got repeated calls from the Hut Hamlet neighborhood residents asking them to troubleshoot, fix, or upgrade their old, owner-installed off-grid PV systems, Chris and Brandon proposed an upgrade—one state-of-the-art, code-compliant system to distribute conventional 120/240 VAC power to the entire neighborhood. While this idea technically made the most sense, the notion of sharing an off-grid power system brought up many issues:

- How to organize a group of neighbors to make decisions about creating an off-grid power system and deal with its many complexities
- What kind of entity needed to legally own the system, how to track everyone's different equity in the system, and how to leverage renewable energy tax credits
- How to equitably deal with the power system being shared among different people with different electrical loads, and different levels of consciousness about usage
- How to maintain a system with multiple owners



A few of the 10 residences powered by a central 8.16 kW off-grid photovoltaic system.

Sizing the Single System

Chris worked with the neighborhood's residents on an electrical loads spreadsheet to assess all of their existing and potential future desires for electrical loads, as some knew that they would likely want to install a refrigerator in their cabin in the next couple of years.

The great majority of loads on this system are lights; refrigerators and freezers; small plug-in loads (computers, modems, printers, chargers, and occasional small appliances, such as blenders and food processors); stereos; and a few small pumps (pressure and circulating). There are occasional larger loads of juicers, electric tea kettles and cooking plates, irons, and corded 15 A, 120 V power tools. The single largest load is the electric water heater used as a diversion load. This load is in the same building and very close to the inverter and AC distribution panel, and runs at a more efficient 240 volts (since it uses diverted excess energy, it is not included in calculations used for system sizing).

Hut Hamlet Estimated Household Loads

AC Loads	Qty.	×	Watts Each	×	Hrs. / Day	=	Wh / Day	×	Days / Wk.	÷ 7 =	Avg. Daily Wh
Laptop computers	12		30		4.00		1,440.00		7		1,440.00
Schneider XW6048 inverters	1		40		24.00		960.00		7		960.00
Chest freezer, 10 c.f.	1		–		–		740.00		7		740.00
Modem/routers	5		6		24.00		720.00		7		720.00
Lights: personal	12		15		4.00		720.00		7		720.00
Room fans	10		10		6.00		600.00		7		600.00
Washing machine	1		750		0.75		562.50		7		562.50
Small refrigerator	10		–		–		5,000.00		7		5,000.00
Phones	10		2		24.00		480.00		7		480.00
Lights: group space	4		23		4.00		368.00		7		368.00
Range hood lights	10		18		1.50		270.00		7		270.00
Blenders/food processors	10		350		0.10		350.00		5		250.00
Battery chargers	10		10		13.00		1,300.00		1		185.71
Car stereos	10		8		2.00		160.00		7		160.00
Circulating pump	1		30		4.00		120.00		4		68.57
Phone/ iPod chargers	10		5		1.00		50.00		7		50.00
Range hood fans	10		18		0.25		45.00		7		45.00
Printers/fax/scanners	10		12		0.20		24.00		7		24.00
Pressure pump	1		30		0.50		15.00		7		15.00
									Total Avg. Daily Wh		12,658.79

Twelve individual kWh meters transmit consumption data to a data logger, helping balance the energy use of residences, the community kitchen, and a diversion-load water heater.

There are no electrical space-heating loads in the neighborhood. Passive solar design and wood heaters provide space heating in each home. Tankless propane water heaters provide water heating in each cabin. Cooking is primarily propane, although some cabins now use electric tea kettles or electric burners for cooking and/or dishwashing on sunny days.

Before the microgrid was installed, the few folks who had refrigerators often had to run generators to keep their batteries charged. Only one household had the ability to run power tools. Now, all households have the ability to run refrigerators, power tools, and other large loads like juicers, tea kettles, cooking plates, and irons. There's more reliable power for all of their small loads. And now there is only one generator, which rarely has to run.

Sharing the Costs & Counting Electrons

An important factor in creating a shared power system is how to fairly split all of the capital and maintenance costs between people who have different impacts on the system. Some homes have larger electrical loads than others. Some users will forgo running large loads in the evenings during cloudy weeks, while others are simply less aware of their electrical consumption. In light of each home's varying impacts on the system, it was essential to figure out how to fairly allocate the costs among the users.

In response, Chris designed and installed a weighted metering system for the Hut Hamlet microgrid to record each household's true impact on the system. This metering system accounts for the fact that drawing energy out of the battery bank while at a lower state of charge (SOC) results in more wear and tear on the bank than using energy when it's fully charged.

The neighborhood agreed to base their monthly maintenance fees and also adjust their initial capital contributions based on the results of the metering. Initial capital contributions were determined by every household filling out an individual electrical loads spreadsheet, based on what their estimated loads would be a year or so after the system's completion. Afterward, each household's totals were summed to derive appropriate percentages.

Each household's circuit is run through a kilowatt-hour meter that sends a pulse for every 1.25 watt-hours consumed to a single BeagleBone Black microcontroller. The microcontroller checks the system's SOC as determined by a TriMetric meter in real-time, and applies a multiplier to each watt-hour based on the SOC. The multiplier is 1x for 100% SOC, but 11x for 0% SOC. The multiplier for 50% SOC is 6x. If the generator is running or has run anytime in the last 12 hours, the multiplier is automatically 11x, regardless of the SOC.

The SOC is based on what is available from the battery, instead of the full rated amp-hour capacity. In this case, a HuP Solar One 950 Ah battery was installed. Since the battery bank must not be fully discharged under normal usage, the SOC is based on 630 Ah, which keeps 34% of its capacity in reserve.

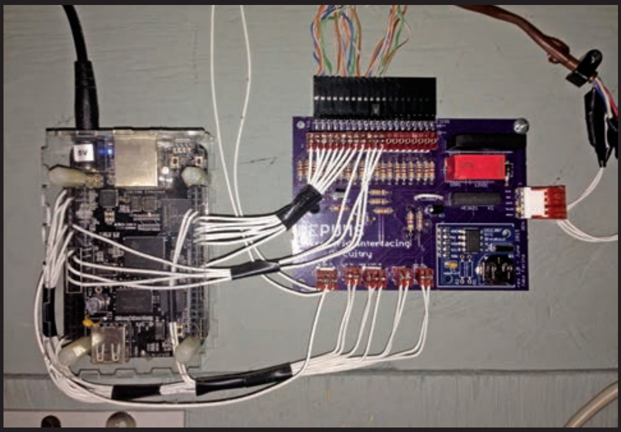
The TriMetric has been programmed for a 630 Ah battery, since that is the capacity readily available to the neighborhood. When the TriMetric reads "Minus 630 Ah" (or any larger number), this registers as 0% SOC; negative 315 Ah registers as 50% SOC; negative 157 Ah registers as 75% SOC; negative 63 Ah registers as 90% SOC; and so on.

A simple algorithm calculates the multiplier factor from the SOC percentage. The multiplier is a perfect gradation, by percentage points, between 11x (for 0% SOC) and 1x (for 100% SOC). For example, 10% SOC has a multiplier of 10x, 20% is

BeagleBone Black Microcontroller

Microcontrollers are small, affordable computers (~$55 for the BeagleBone Black) with many digital or analog input and output ports that can be used for a diversity of projects. With Ethernet, USB, and serial port connections, they can communicate with many other devices and the Internet. They can be used as programmable logic controllers (PLCs), to run, monitor, and record many types of industrial processes. Whereas PLCs are usually programmed in some more user-friendly form of ladder logic, microcontrollers are programmed in common C, C+, or C++ computer languages. Microcontrollers are cheaper and more versatile than PLCs, but do require a computer programmer.

Chris designed the weighted metering system, and the automatic generator start (AGS) program. Former Earthaven resident Jake Ferina wrote all of the computer code for the microcontroller and also designed a custom printed circuit board that serves both the weighted metering and AGS systems. These programmed microcontrollers are available from Chris for other communities that also want weighted metering systems.



Hut Hamlet Example Monthly Weighted Usage (September 2015)

Energy Use	Tribal Condo West	Tribal Condo East	Kitchen	Water Heater	Yurt-goslavia	Tudor Hut	Snake Hut	Micro Hut	Zen Hut	A-Frame	Flower Hut	Wonky Hut
Meter kWh	9.70	67.25	13.39	228.14	16.97	86.57	2.13	6.73	6.68	44.07	4.88	34.44
% of kWh	1.9%	12.9%	2.6%	43.8%	3.3%	16.6%	0.4%	1.3%	1.3%	8.5%	0.9%	6.6%
Weighted %	2.5%	16.8%	3.3%	25.8%	4.4%	21.6%	0.5%	1.7%	1.3%	10.4%	2.8%	8.8%
Double Check												
Pulses count	7,896	54,487	10,879	194,023	13,744	70,715	1,783	5,471	5,441	36,384	3,590	27,795
Pulse kWh	9.87	68.11	13.60	242.53	17.18	88.39	2.23	6.84	6.80	45.48	4.49	34.74
Pulse kWh % of meter kWh	101.8%	101.3%	101.6%	106.3%	101.2%	102.1%	104.6%	101.6%	101.8%	103.2%	92.0%	100.9%

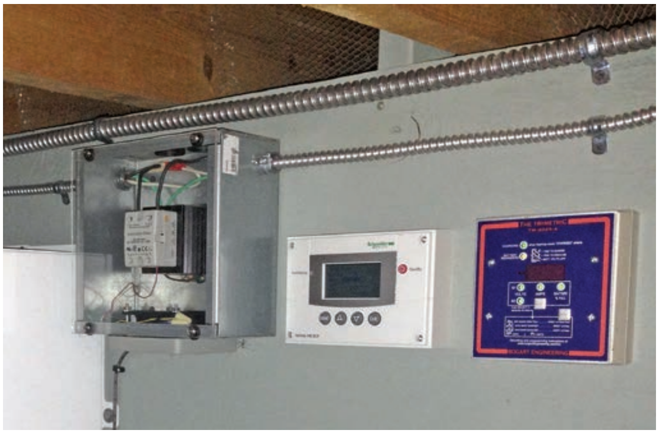
Thirty-two 255-watt Kyocera modules in eight series strings. The two subarrays are offset in relation to a road behind them, not for solar exposure purposes.

9x, 30% is 8x, 40% is 7x, 50% is 6x, and so on, up to 100%, which is 1x. It works down to the single percent accuracy of SOC, not just for every 10% (45% is 6.5x; 49% is 6.1x) Each hour, the microcontroller totals all of the weighted pulses for each household and records the data. Once a month, the data file is downloaded onto a laptop computer and inserted into a spreadsheet to calculate the monthly weighted impact for each household. The microcontroller also provides a count of pulses for the month, so that the pulses can be double-checked against the kWh meter displays.

A diversion-load relay (at left), controlled by a MidNite Solar charge controller, diverts excess solar energy to a water heater in the common area.

In the middle, a Schneider Electric system control panel for remote control and monitoring of charge controllers and inverters.

A Bogart TriMetric amp-hour meter sends battery state-of-charge data to the data logger.



Tech Specs

Overview

System type: Off-grid, battery-based solar-electric

Date commissioned: June 2015

System location: Black Mountain, North Carolina

Latitude: 36°N

Solar resource: 4.89 average daily peak sun-hours

Production: 945 AC kWh per month

Photovoltaics

Modules: 32 Kyocera KD255GX-LFB2, 255 W STC, 30.4 Vmp, 8.39 Imp, 37.6 Voc, 9.09 Isc

Array: 8,160 W total; two subarrays of 16 modules—each four strings of four modules is 121.6 Vmp, 1,020 W STC total

Array combiner boxes: MidNite Solar MNPV12-250s with MidNite Solar 300 V 15 A DIN rail breakers

Array disconnect: MidNite Solar 300 V 60 A panel mount breaker (located in the XW power distribution panel) for each array

Array installation: IronRidge ground-mount, one array faces 180°; one is 170°, both tilted at 40°

Energy Storage

Batteries: Four HUP Solar One, SO-6-85-19, 12 V 950 Ah each; 950 Ah at 20-hour rate, flooded lead-acid

Battery bank: 48 VDC nominal, 950 Ah total

Battery/inverter disconnect: One 250 A breaker per inverter

Balance of System

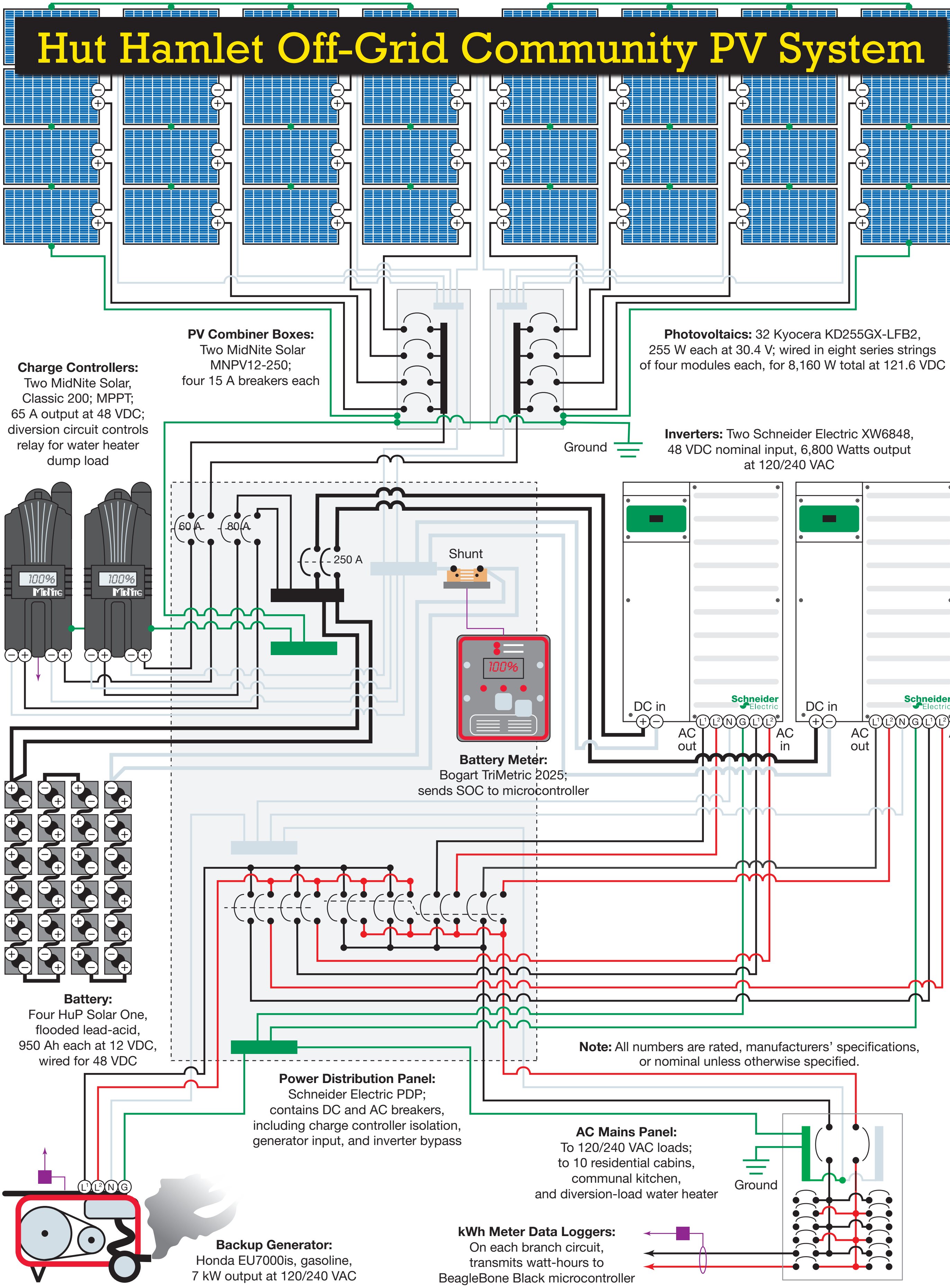
Charge controllers: Two MidNite Solar Classic 200, 200 VDC max input, 121.6 Vmp MPPT input voltage, 65 A at 48 VDC nominal output

Inverters: Two Schneider Electric XW6848, 48 VDC nominal input, 120/240 VAC output

System performance metering: 12 EKM-251DS kWh meters, BeagleBone Black microcontroller, Bogart TriMetric 2025 and Schneider Electric system control panel

Backup generator: Honda EU7000is gasoline, 7 kW, 120/240 VAC

Hut Hamlet Off-Grid Community PV System



A MidNite Solar Classic 200 MPPT charge controller for each PV subarray. One controls a relay for the water heater diversion-load circuit.

Maintaining a Shared System

A 7 kW Honda EU7000is generator turns on with an automatic generator start (AGS) system programmed into the microcontroller. This AGS only requires that the neighborhood residents regularly check the level of fuel in the generator's tank. If, after a few seconds, the generator is not yet on, the AGS stops. It tries again after 5 minutes. After several attempts, it will take an even longer break and then completely start over. The generator battery is on a trickle charger, so theoretically, the generator will keep attempting to start until someone finally hears it trying to start, and figures out that it needs gas. The neighborhood residents are fully informed that this is their biggest responsibility for maintaining the whole system (and for preventing a low-voltage disconnect from the inverters and a full system shutdown). If the battery stays above 57.6 V for more than two hours, the generator automatically turns off.

Every month, maintenance bills are sent to each user based on the weighted metering data. After two years, the user's original estimate for their percentage of impact on the system (and therefore for their original capital contribution) will be re-evaluated. All users have agreed to adjust their original capital contribution in light of the weighted metering data. Any discrepancy between their original estimate and actual usage will be reflected over time on the user's monthly bill as either a fee or a refund.

So far, everyone's weighted metering percentage has been surprisingly close to their actual energy consumption percentage. This means that everyone in the neighborhood has a relatively similar level of consciousness around the timing of their electrical consumption and that they throttle back their consumption as the batteries get increasingly drained. It is assumed that the weighted metering system encourages a high level of consumption consciousness.

Four HuP SolarOne flooded lead-acid batteries supply 950 Ah at 48 VDC—enough storage for the whole neighborhood.

Maximizing Trenching Benefits

The microgrid required about 900 feet of trench through the neighborhood, starting from the main kitchen/bathhouse, where the battery and BOS are located, to each home. Since this excavation was already disruptive to the landscape, the neighborhood decided to also use the trench to replace other infrastructure.

The Hut Hamlet neighborhood had grown in a rather hodge-podge fashion, which left phone lines trenched through the neighborhood in very nonlinear ways. These phone lines were often accidentally cut, which was annoying to both the neighborhood and to the local phone service provider.

A new master cable was run to a pedestal near the central power distribution point. The phone company supplied new phone cable that was run to each home in the same trenches as the power lines (separated by at least 12 inches). This centralized phone and power distribution allowed a neighborhood Internet network to be created, providing high-speed Internet to every user of the microgrid. The neighborhood previously had only four DSL connections, with the phone company not offering any more—the remaining hut owners were simply out of luck.

With centralized phone lines, the neighborhood was able to pool the four DSL connections in one spot, run each phone line into its own DSL router, and then run all into a load-balancing router. This router was then plugged into an Ethernet-over-powerline adapter at the power distribution point, which sends Internet signals along the power lines to the homes. Surge-protection was placed on the four individual DSL phone lines, and the Ethernet-over-powerline connection.

Now, wherever there is a power outlet on the microgrid, someone can plug in another power line adapter to access high-speed Internet service. This may not seem like a big deal to many people in the modern world, but living in the middle of nowhere, it's quite an improvement.

Two situations can trigger the generator to turn on during daylight hours:

- When the battery drops below 50% SOC and the SOC has not reached 100% in the past seven days
- If the battery drops below 25% SOC and the SOC has not reached 100% in the past four days

If the battery drops to 0% SOC, the generator automatically turns on, regardless of the history or the time of day.

Monthly bills to each user include costs for regular monthly maintenance so that a qualified person (currently, Chris) can check the system, equalize and water the battery, and perform generator maintenance. The monthly bills also include costs for accounting and for the depreciation of the entire system. Additionally, the Hut Hamlet Co-op is generating a capital fund to purchase replacement equipment when needed.

Ownership

Originally, the neighborhood wanted to own the PV system outright, instead of creating a separate entity to own the system and sell energy to the users. The group also wanted each user to be able to own differing amounts of equity in the system and take advantage of available renewable energy tax credits.

However, the issue of renewable energy tax credits forced the group to develop an appropriate legal entity to own the system. Only condominiums and housing cooperatives can pass through tax credits to their members without triggering "passive activity loss" rules with the IRS. These PAL rules state that "passive" tax credits can only be used against tax liabilities derived from "passive" income, which is narrowly defined as either rental income or income from businesses one owns but in which one doesn't actively engage (stock earnings are not included as "passive" income).

Given this situation, the users would have been ineligible to use the tax credits unless they legally formed as a housing cooperative. Fortunately, the Hut Hamlet neighborhood at Earthaven was already beginning to legally form a housing cooperative, which now owns the microgrid officially.

Organizing the Group

The Hut Hamlet hired one of its residents to facilitate the microgrid's development—to organize and schedule meetings, take and post minutes, and keep track of any unresolved issues that needed the group's attention. The neighborhood also hired legal and accounting consultants to advise on all questions involving legal entities and taxes.

The neighborhood simply added the cost of these services to the system's total capital cost, which was then allocated to users based on each household's estimated percentage of impact on the system. The weighted metering system allows these original estimates to be adjusted over time with real-world data so that everyone pays for their fair share of the system and its associated costs.

Putting Surplus Energy to Good Use

A question in any off-grid solar design is how large a battery bank to install relative to the PV array size. Too small and it's almost useless, meaning there's not enough stored energy to get you through the night or a cloudy day. Too big for the PV array, and the batteries will not adequately recharge after cloudy spells, and be in a discharged state for longer periods, reducing their longevity.

The battery was sized to give two full days of autonomy. Under no modification of consumption by the households, the depth of discharge (DOD) will likely reach 80%. If the households are in "conscious conservation" mode, the batteries DOD won't be as large—about 60%.

Hut Hamlet PV & Water Heating Systems Materials Cost

PV System*	Cost
4 HuP Solar One SO-6-85-19 12 V, 950 Ah batteries	$11,200
32 Kyocera PV modules, KD255GX-LFB2, 255 W	7,680
2 Schneider Electric Conext XW6848 inverters	6,181
Honda EU 7000is generator (not eligible for federal tax credit)	4,000
IronRidge XR racks	2,737
Schneider XW power distribution panel, connector kit, breakers	1,912
Miscellaneous electric; wire, fittings, conduit	1,480
2 MidNite Solar Classic 200 charge controllers	1,281
Shipping	1,000
10 pipes for ground mount, 2 in. schedule 40, 21 ft.	800
Concrete & rebar for footers	700
HuP battery watering kit & tank	476
4 MidNite Solar surge protectors	356
Cables for battery & inverter, 4/0	345
MidNite Solar MNPV12-250 PV combiner boxes	337
MidNite Solar breakers	332
Battery box materials (plywood, EPDM, screws, vent)	200
Automatic generator starter, custom	150
Battery pickup	150
Bogart TriMetric 2025	145
Post-hole auger rental	100
Shunt bus, to parallel 4/0 battery negative cables through shunt	28
DC Shunt 500 A 50 mV for battery	24
Total PV System	$41,614
Federal Tax Credit	-12,484
State 35% tax credit	-14,565
Grand Total, PV System	$14,565

PV Hot Water Diversion System	Cost
Marathon Lifetime water heater, 105 gal.	$1,300
Miscellaneous diversion electrical	539
Miscellaneous plumbing & other electrical	500
Mixing valve for water heater	135
Azel dual thermometer for water heater	70
Drain pan for water heater	45
SSR & heat sink enclosure (metal screw top box w/ plexi cover)	30
General miscellaneous	500
Total Hot Water Diversion System	$3,119
Federal Tax Credit	-936
State 35% tax credit	-1,091
Grand Total, Water System	$1,092

*PV system only, excludes items for distributing & monitoring individual huts

A large array can keep the batteries well-charged and provide quick recharging after cloudy spells, but electricity may be "wasted" during sunny weather—once the batteries are charged, the solar charge controller will disconnect the array to prevent overcharging the batteries.

The two 4 kW arrays were sized to max out the two MidNite Solar charge controllers and to fill out each of the two ground-mount arrays with 16 modules each. To take advantage of any excess generation, a diversion system redirects the array's excess electrical production to a conventional electric water heater, located in the kitchen/bathhouse, which provides hot water to the kitchen and bathroom sinks, a shower, and a bathtub. This provides the neighborhood with a freeze-proof solar water heating system, and essentially gives them two solar systems—a solar-electric and a solar hot water system—in one.

The Hut Hamlet's PV system diverts excess PV energy to a Marathon 105-gallon 240 VAC electric water heater. The water heater is turned on and off by a 240 VAC solid state relay. The relay's DC coil is controlled by the 12 VDC output from the MidNite Solar Classic charge controller's auxiliary terminals. The relay can turn the water heater on and off many times a second, and the inverters are robust enough to handle the loads. The auxiliary output is not triggered by a constant voltage setpoint, but instead by the in-the-moment charge setpoint—which differs, depending on the battery's charging stage (bulk, absorb, float, or equalize) and battery temperature. The diversion starts at 54 V when the battery is in float, but starts at 58.4 V when in absorb, and even higher when in equalization.

The water heater's thermostat is set at its maximum temperature (150°F) to store as much excess energy as possible, providing some hot water for showers and dishwashing through the night and into the next morning. (The Marathon tank has 2.5 inches of insulation, so there's very little standby loss.) The water heater uses a mixing valve to temper outlet water with cold water to prevent scalding water from reaching fixtures.

The neighborhood kept their existing tankless propane water heater as backup to the solar-electric water heater. Fortunately, they already had a model that can take pre-heated water as an input. The solar water heating system is freeze-proof, as there isn't any exterior plumbing.

Energy Futures

The Hut Hamlet microgrid is completely solar-powered at this time, but future plans are to incorporate a microhydro system if it takes on new members with additional electrical loads. The neighborhood has a good hydro resource (three different upstream hydro turbines serving other homes are each making more than 500 watts, continuous). Even one turbine could produce about 12 kWh a day—regardless of cloudy weather. A hydro plant's continuous output would be incredibly helpful getting the neighborhood through cloudy stretches when there's little or no PV input.

Before the microgrid, many Hamlet residents had barely enough electricity for a light and a laptop. The new plan, which took many months and many minds to work out, has been running smoothly—and the future of power in the Hamlet looks bright!