LESSONS LEARNED: GREEN BUILDING DESIGN TECHNIQUES FOR OFF-GRID LOCATIONS

Dan Fink[1]

INTRODUCTION

Over 25 percent of the world's population lives without access to electricity from a utility-supplied grid [1]. In underdeveloped and developing countries, the reason is primarily a lack of government-sponsored utility infrastructure due to the high cost of power line extension. In developed countries, power line extension costs are again the primary factor in lack of a grid connection, as in most cases the end user must foot the bill for such improvements. In the United States, power line extension can cost over $50,000 per kilometer [2], so the cost of an off-grid electrical system that uses renewable sources to charge a large battery bank for energy storage can compare favorably to that of grid extension—but not always.

However, both the design and implementation of such off-grid renewable energy systems differ greatly from more common grid-tied applications, where the utility grid is used as "battery" with which the system can buy and sell electrical energy from and to the utility as needed. Energy efficiency and conservation are paramount in all off-grid renewable energy system designs, as these measures extend at low cost the hours or days of autonomous operation time before a backup power source (usually an internal-combustion generator) must be used for battery charging during periods of no input from renewable solar, wind, or hydroelectric sources.

The techniques used in designing and operating an off-grid building can seem extreme compared to the norm, and provide a whole set of new challenges if the retrofitting of an existing structure is required. But the lessons learned from these experiences are quite relevant to modern buildings in urban and suburban areas, as the goal is the same—first reduce energy consumption through efficiency and conservation, rather than simply increasing energy production. With off-grid systems, the payback from these measures simply has a more immediate effect. And at the end of the day, non-electrical energy efficiency measures prove to be at least as effective as electrical ones.

KEYWORDS

off-grid design, electrical efficiency, energy efficiency, efficient heating, efficient lighting

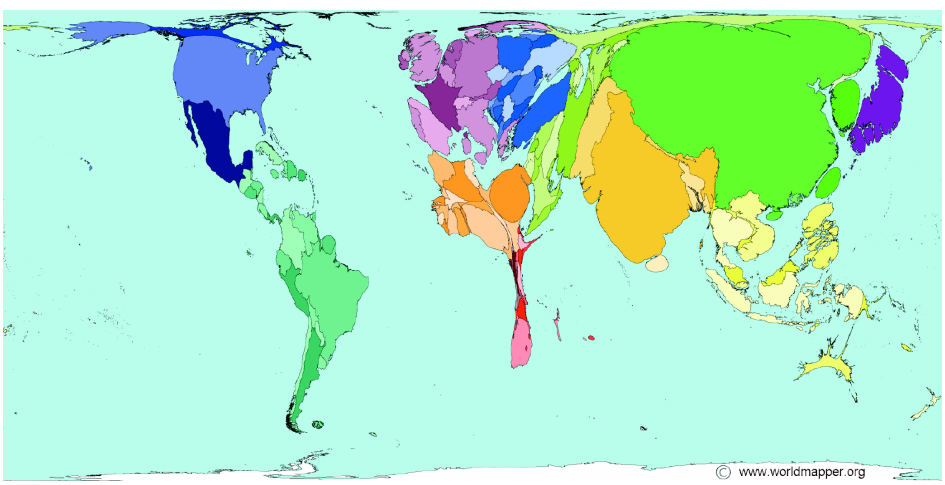


FIGURE 1. Worldwide access to electricity. Territory size shows the proportion of all people with some electrical power in their homes living there. Copyright SASI Group (University of Sheffield) and Mark Newman (University of Michigan).

1. Buckville Energy Consulting LLC, www.buckville.com, danfink@buckville.com.

A BRIEF INTRODUCTION TO OFF-GRID ENERGY SYSTEMS

All off-grid energy systems consist of equipment in three primary areas: energy production, energy storage, and energy conversion.

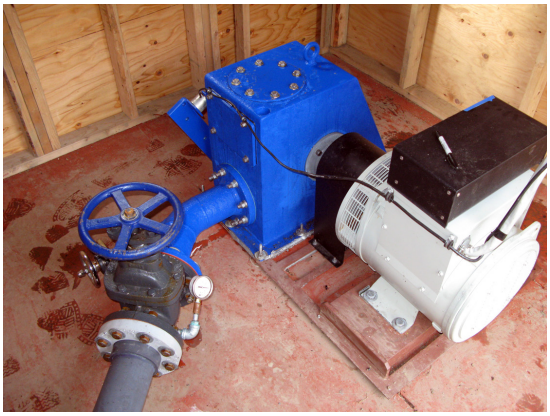
Energy Production

- *Sun:* Solar is by far the most common energy source deployed in off-grid locations, and can be used to produce electricity, heat water, and heat air. Arrays of photovoltaic (PV) modules convert solar radiation directly into direct current (DC) electrical energy for battery charging using no moving parts, and can achieve a service life of over 25 years. Solar hot water collectors heat an exchange fluid, which is then used to heat water for domestic use and space heating. Solar hot air is usually provided by large, efficient windows, though collectors can be retrofitted if a structure is not oriented correctly for optimum heat gain via windows.
- *Wind:* While wind energy is often deployed successfully in remote and rural areas, it has proven to be problematic in urban and suburban situations [3]. Wind speed near the ground is very slow due to friction, and also turbulence from obstructions—the standard in the small wind industry is that any wind turbine should fly no less than 30 feet above any obstruction within 500 feet in any direction to assure maximum speed and smooth, laminar flow [4]. Most U.S. counties and municipalities have strict building codes that limit tower height to under 40 feet, which is generally not high enough to be clear of trees and other buildings to assure good performance and reasonable payback time on the investment. Rooftop turbines perform even more poorly [5].
- *Water:* Hydroelectric energy is relatively simple and inexpensive to harvest, but very few locations have the resource available for significant energy production. If a large drop (head) is not available, a large flow is needed. The minimum head for significant energy production (about 200 watts) is about 1.5 meters with a flow of 35 liters per second [6]. Submerged or floating generators that rely on a river's speed are impractical below 6 knots due to the large size needed to capture such slow flows, and higher river speeds are rare [7]. When deployed at a location with a good resource,

Two 1.6-kilowatt photovoltaic arrays on pole mounts. Copyright Doug and Sheryl Keator, Simply Solar LLC.

A three-meter diameter small wind turbine on a 15-meter tower, properly sited above the tree line. Copyright Rex and Lavonne Ewing, Pixyjack Press LLC.

A 5-kilowatt hydroelectric generator. Copyright Peaks to Prairie Power.



though, hydroelectric energy can be extremely effective because of its steady, round-the-clock nature.

- *Internal combustion:* Nearly all off-grid systems use an internal-combustion generator as a backup source during times of no sun, no wind, and low water. Generators can be fueled by gasoline, diesel, propane, natural gas, or bio-fuels. Fuel prices and fuel transport costs combined with intensive and expensive regular maintenance schedules and the need for spare parts make the cost of energy from internal combustion far higher than any renewable source when deployed at any off-grid location.

Small, 2.8-kilowatt internal combustion backup generator. Copyright Honda Power Equipment.

Energy Storage

Storage for thermal energy has been used effectively by humans for thousands of years, and is a simple process. A thermal mass is heated, usually by the sun, and then releases heat at night or when needed. Thermal masses in modern structures generally consist of stone, concrete, sand, or water, with water giving the greatest flexibility because it can be moved easily where needed with pumps.

Storage for electrical energy is far more complicated and problematic. In 2010 the only practical and affordable means of electrical storage for an off-grid structure remains lead-acid batteries, which have changed little since their widespread implementation in the early 1900s. A battery bank large enough to power an efficient off-grid home for three to four days of autonomy when no renewable sources are operating can weigh well over a tonne and cost thousands of dollars [8]. Worse, batteries wear out with use. The predicted service life of a typical off-grid battery bank is only six to ten years before replacement is needed.

New developments in large-capacity storage battery technology abound—for example, the nickel-metal-hydride and lithium-ion cells used in new electric vehicles—but these technologies remain far too rare and expensive for off-grid deployment (compared to current lead-acid technology) due to the large storage capacity needed for long autonomous periods. As production increases, prices drop and "smart utility grids" are implemented world-

Off-grid battery bank. Courtesy of DOE/NREL.

wide; newer battery technologies will become cost-effective. A future energy storage solution will likely be hydrogen with fuel cells, but again the technology is not yet available or affordable for the typical home or small business owner.

Energy Conversion

Battery banks can store energy only in the DC form, with the most common configurations for off-grid systems being 12, 24, or 48 volts. Photovoltaic modules produce electricity in the DC form, but are wired, when possible, in high-voltage arrays ranging from 65 to 600 volts. Wind and hydro turbines generally produce three-phase alternating current (AC), but at frequencies and voltages that can vary rapidly with the resource. But, common household electrical appliances and lighting fixtures all use single-phase, 60 hertz, 120 volt AC in the United States, and 50 hertz, 240 volt AC in Europe. Conversion equipment is needed on both the input and load sides to provide compatible energy for the end user.

- *Photovoltaic controllers* convert (usually) high-voltage DC from a PV array down to the proper voltage for battery charging, while also protecting the battery bank from overcharging, which can quickly damage it.
- *Rectifiers, diversion load controllers, and diversion loads* are used with wind and hydro turbines to first convert three-phase AC output to DC for battery charging, then to protect the battery bank from overcharging by diverting energy to air or water heating elements when the batteries are fully charged and no more energy can be stored.

Control center and battery bank of a large off-grid system. Courtesy DOE/NREL.

- *Non-islanding grid-tie (utility-interactive) inverters* convert high-voltage DC from a PV array or turbine directly into single-phase AC for domestic use and possible sale to the utility. No battery bank is involved.
- *Off-grid inverters* convert electrical energy stored at 12, 24, or 48 volt DC battery bank voltage to the single phase AC "house current" used by common lights and appliances. Off-grid inverters may also have grid-tie capabilities, but always require a battery bank as the energy source.

OFF-GRID VERSUS ON-GRID SYSTEM SIZING

The average American homeowner uses 11,040 kilowatt-hours of electrical energy each year at a cost of $1,214 [9]. Household energy consumption in Europe averages approximately half that; however, electric rates are approximately double [9] Well-designed off-grid residences can allow their owners to consume only one quarter to one half the average American electrical usage.

In locations with favorable rates paid for energy by the utility due to feed-in tariffs, net metering laws, and Federal, State, and local incentives, the daily, monthly, and yearly input from energy sources is often designed to be far larger than the home's average use [2]. This allows the sale of surplus energy back to the utility and turns the system into a profitable venture after the initial cost is paid off. And the slower the energy produced is used by homeowner, the faster the payback time and the larger the profits.

Not all areas have such favorable laws, and there are many variations. In many locations, the system owner is given favorable rates for energy produced to offset energy used, but is not paid for surplus energy produced. The monthly utility bill can reach zero, but never negative. In these situations the energy sources should be sized closely to the average consumption, as any surplus is given to the utility at no charge. Some utilities offer plans where the surplus differential between their maximum production (summer) and minimum production (winter) is "banked" over a rolling 12-month period for the end user.

Off-grid system sizing is performed with similar considerations in mind, but there are more com-

plications. Surplus energy is not always wasted, as it can be diverted to air or water heating elements—but the inefficiency is so great that impact on heating loads is minimal. Since there is no utility grid from which to pull energy when renewable sources are not producing, off-grid systems must rely entirely on that fragile, expensive battery bank that is prone to damage if over-discharged. In some cases, the off-grid system is sized so that during the two to three months where insolation is lowest, a certain number of hours of internal combustion generator use each week is planned for. Instead of the monthly and annual average insolation figures used for on-grid system design, worst-month insolation is primary in off-grid system design. The use of internal combustion engines is always avoided, but it can be inevitable in such cases.

OVERVIEW OF OFF-GRID LOAD SELECTION

Load selection for off-grid buildings is a critical process of the entire site design, and often functionality is sacrificed for energy efficiency and minimum instantaneous load. With utility power, the maximum load is governed only by the size of the wiring and breakers in the structure. With an off-grid inverter, maximum total load can range from only 300 watts in very small systems to 5,000 watts, with some inverters "stackable" with multiple units to increase capacity beyond that.

Energy efficiency in off-grid homes is of extreme importance due to the fragility and high cost of battery banks, and the high cost of internal combustion generation. If the owner of a typical American suburban home with no green features wanted to cut all ties with the utility and install renewable energy sources plus a battery bank, the cost could be so prohibitive as to be impractical, and the investment payback time could range into multiple decades.

Load selection is a fundamental area where lessons learned from off-grid system design can be quickly and immediately implemented into urban and suburban green building design.

HVAC LOADS

Space heating and cooling loads comprise over 43 percent of the energy consumption of the average American home [10], with the balance between heating and cooling changing with latitude and climate. This high percentage makes these loads critical in conservation efforts when utility power is not available.

Heating

Off-grid systems almost never employ electric space heaters as a primary or even secondary building heat source, as the high wattage draw over a long period of time would require an extremely large and expensive battery bank for times when renewable sources are not available. The only exceptions occur in the very rare cases where a large wind or hydroelectric turbine is operating, and excess energy is diverted to heating elements so as to keep the turbine loaded at all times, a requirement with such systems [4]. With smaller turbines and PV, the possible heat from diverted energy is insignificant compared to the total heating load, and does little to help the total heating situation.

Common central forced-air gas furnaces are also only rarely employed off the grid, even those running on gas. Propane in small or large tanks is usually the only gas available off the grid, and both the delivery costs and the gas itself are more expensive than natural gas, which in more developed areas is delivered from a central source at the utility by underground pipes. The blowers in typical central forced-air heating systems are also a large electrical load that must run whenever the furnace is operating.

Instead of these more common heating techniques, more efficient solutions are usually employed in off-grid situations. In-floor radiant heating systems can be fueled by a gas boiler, direct solar hot water heating, wind and hydroelectric diversion loads, or a combination of these. Because each room of the dwelling has a separate floor heating zone, spaces that are occupied infrequently can be kept at minimum temperature, which can be quickly raised when the space is in use. Thermal mass is built into the floors, with the heat circulation pipes embedded within. Small, wall-mounted propane heaters combined with ceiling fans can accomplish this same zone effect, though not as efficiently as in-floor systems. In more remote areas fuels such as wood, wood pellets, corn cobs, and other biomass are frequently burned in both central and localized heat distribution systems.

The least expensive and most common heating options for off-grid structures employ direct sunlight, large insulated windows oriented for maximum insolation and thermal masses such as Trombe walls. While this direct heat input may not cover the entire structure's heating loads at all times of year, it can lower heating loads substantially. If the structure is not oriented correctly for solar heat gain through windows, solar air heating panels can be retrofitted; however, these are not as efficient as windows, and require electricity for fans and sensors.

Sealing and insulation, while not heat sources, can prevent a significant amount from being wasted. Almost all off-grid structure designs incorporate well-sealed and well-insulated doors, windows and skylights, and high R-values of insulation throughout the building. In very cold climates, nighttime insulated window shades are often included in the total heating system design.

Cooling

Typical air conditioning units, whether central or window-mounted, present the same problem of high wattage and long run times as do electric and forced air heating, and are rarely if ever deployed in off-grid systems. Evaporative cooling systems ("swamp coolers") can be very efficient, but are most effective only in dry climates—a big advantage of traditional air conditioning units is that they remove large quantities of moisture from the air.

Unfortunately, few efficient cooling options exist for consistently hot, humid environments. Geothermal HVAC systems show the most promise, but the excavation required, up-front costs, and electricity needed for the heat pumps often make geothermal cost-prohibitive. Retrofits are possible, but are generally even more expensive than using geothermal in new construction.

Simple thermal efficiency measures like those used for heating (sealing, insulation) can also be of great help in lowering cooling loads. Additional measures such as insulated window shades to block unwanted solar heat and the proper design of roof overhangs to block direct sunlight during times of year when it is undesired, can also be effective. However, the off-grid implementation of cooling systems still remains far more problematic than that of heating.

WATER HEATING LOADS

Domestic water heating makes up about 12 percent of the average American's home energy consumption [10]. This makes it another very significant area in selecting loads for an off-grid system. Traditional electric hot water heaters with tanks are rarely if ever installed off the grid, and even tank hot water heaters using gas are uncommon. Since hot water is only rarely needed during a typical day, efficient on-demand water heaters using either propane or electricity are used almost exclusively. While the load from an electric on-demand water heater is high, usually near 1,500 watts, the time of use is generally short, such as for a shower, dish washing, or clothes washing.

Solar water heating systems can be excellent solutions for reducing water heating loads if local insolation is ample. Even if the stored water has not been raised high enough in temperature for the intended end use, on-demand heaters expend less energy when raising pre-heated water to the proper temperature. After domestic hot water demands have been met, surplus solar hot water can be diverted into a structure's in-floor radiant heat system. And the electrical loads involved for pumps and sensors in solar hot water systems are minuscule.

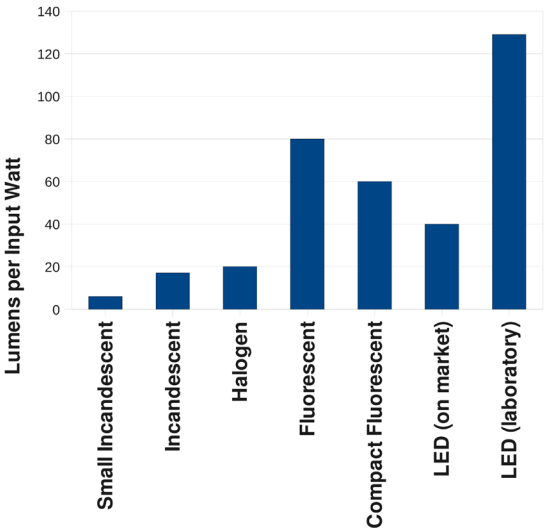
LIGHTING LOADS

Eleven percent of the average American home's energy consumption is used for lighting [10]. In off-grid structures only the most efficient lighting systems are employed. Traditional incandescent lighting is rarely if ever used, and slightly more efficient halogen bulbs are used only in outdoor situations in cold climates, where low temperatures can drastically reduce the output luminosity of compact fluorescent lights.

Standard fluorescent lighting (FL) still provides the best efficiency (luminous efficacy) of any lighting technology commonly used in homes and businesses, at about 80 lumens per watt including ballast losses [11]. Commonly deployed in off-grid structures, these fixtures are often used for lighting large indoor spaces, with smaller models used as task lighting, for example, under cabinets in kitchens. Disadvantages include the long, narrow form factor and a limited selection of color temperatures.

Compact fluorescent (CFL) lighting is the most common type deployed in off-grid systems. While

FIGURE 2. Luminous Efficacy Comparison. Dan Fink, Buckville Publications LLC.



their efficiency of 45 to 60 lumens per watt (including ballast losses) trails behind FL lighting [11], most CFL bulbs will fit into common, inexpensive fixtures designed for incandescent bulbs, simplifying both new construction and retrofits. Many color temperatures are available.

Light emitting diode (LED) lighting is rapidly gaining in market share, especially with off-grid systems. LED light output is highly directional and therefore ideally suited for task lighting, but problematic for lighting large areas. Other disadvantages include high cost, and the fact that LEDs require regulated low-voltage DC current for operation, which means that conversion from 120 VAC house current is required. A variety of color temperatures are available.

The luminous efficacy of white LED lighting has been a cause of confusion amongst both homeowners and off-grid system designers for years now. Claims of 100 lumens per watt and above from LED manufacturers are common; however, these do not tell the whole story—these figures are laboratory measurements of lumens per *radiated* watt. The important figure for off-grid building designers is instead lumens per *input* watt, which takes into account the total energy use of the LED. The most efficient LEDs available in early 2010 can produce 80–129 lumens per input watt [12], which surpasses FL lighting. However, new LED technology takes years to get to market in the form of UL-listed AC lighting devices that can be purchased by homeowners or off-grid system designers, and these new technologies are not yet available on the market. Currently available LED lighting products that run on 120 VAC house current range from 20 to 60 lumens per input watt [12]. The U.S. Department of Energy's "Commercially Available LED Product Evaluation and Reporting" (CALiPER) program tests new lighting fixtures against benchmark standards, and is invaluable for anyone considering LED lighting for any application.

LESSONS LEARNED: SPACE HEATING AND COOLING, WATER HEATING, AND LIGHTING

It is always more efficient to use the sun's energy directly.

Anytime energy is converted from one form to another, there are losses. With a typical commercially-available mono-crystalline photovoltaic module in 2010, the losses in converting solar radiation energy to electrical energy range from 85 to 90 percent—about 150 watts per square meter of collector out of a total of 1,000 watts per square meter available in the sun [13]. Assuming a location near the author's, in Colorado, with a yearly average of five full-sun equivalent hours per day, average electric energy production from this square meter of collector would be 0.6 kilowatt-hours per day after industry standard 20 percent PV system derating, or 2,048 BTU per day if that energy were used to run an electric space heater.

By comparison, at that same location a one square meter window made of high-solar-gain low-emissivity glass with a high Solar Heat Gain Coefficient could provide 6,456 BTU daily [14], again assuming five equivalent full-sun hours and typical window heat gain of 1,291 BTU per hour. This is over three times the heat gained compared to using PV with electric. Of course all fenestrations lose thermal energy at night, but low-E glass and nighttime thermal blankets combined with thermal mass help reduce these losses and their effects. In climates where cooling loads dominate over heating loads, low-solar-gain low-E glass and properly-oriented

roof overhangs can be used to reduce solar gain and air conditioner run time.

The same direct solar lessons also apply to water heating. A modern, evacuated-tube solar water heating collector of one meter in area at the location used in the examples above can provide 7,278 BTU per day [15], over three and a half times the heat available from a PV collector and electric heating elements.

Lighting in off-grid buildings becomes more and more problematic as distance from the equator increases, because of the greater discrepancy between available sunlight hours in summer and winter. At higher latitudes, in addition to the problem of increased lighting loads during winter due to decreased natural light, solar energy input is also reduced during winter. Using solar energy directly for lighting is a critical concept in all off-grid system design.

Fenestrations, however, are extremely difficult and expensive to retrofit into an existing building that was designed and built without using sound natural lighting techniques. The only exception is solar tube skylights, which can be retrofitted with minimal expense and effort.

Proper building siting and orientation are critical for reducing electrical loads when off grid.

Because HVAC and lighting loads make up 54 percent of the energy consumption in a typical home, a systems approach must be taken when designing an efficient off-grid structure. Natural lighting combined with passive space heating and cooling are a major factor in the amount of electrical energy generation capacity and storage that will be needed, and such features cannot easily be retrofitted onto an existing structure. In one of the case studies presented below, the existing structure was deemed completely unsuitable for retrofitting an off-grid renewable energy system and the project was never undertaken—the homeowners instead paid the utility for power line extension.

MAJOR APPLIANCE LOAD SELECTION

In the early days of off-grid renewable energy systems in America, homeowners, electrical system

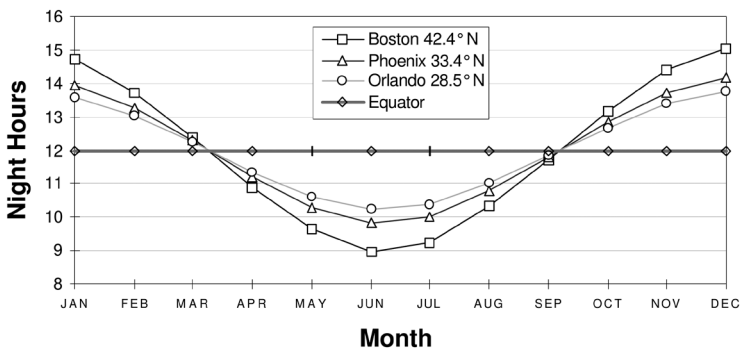


FIGURE 3. Night hours per month for differing latitudes. Source: James Dunlap, Florida Solar Energy Center.

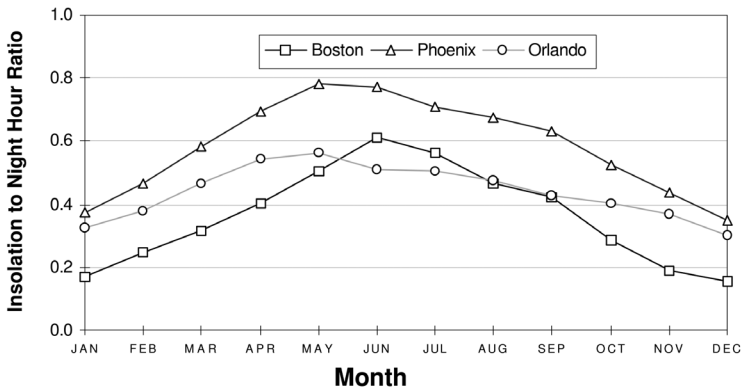


FIGURE 4. Insolation to night hour ratios for latitude tilt surfaces. Source: James Dunlap, Florida Solar Energy Center.

designers, architects, and contractors all struggled to find efficient major appliances at reasonable cost. In many cases items such as refrigerators, dishwashers, and clothes washers were ordered from Europe at great shipping expense because efficient models were simply not available in the United States—and because even these large extra costs paid back quickly due to drastically reduced energy consumption. Fortunately that situation has changed—all major U.S. appliance manufacturers now offer efficient appliances at a reasonable cost, and the Energy Star rating system provides a comparison benchmark for consumers. However, American-made appliances still tend to be larger and thus use proportionally more energy than their European counterparts.

Cooking

Electric ranges and ovens are not recommended for off-grid buildings, and propane gas is used instead. The high instantaneous wattage draw of large electric heating elements is far more than most off-grid inverters can handle, so an expensive stacked multi-inverter system would be required. And, the typically long run times of the heating elements would require an extremely large and expensive battery bank. While induction cooking systems are more efficient, their wattage draw is still high, with long run times. Even gas-fired range/ovens must be selected carefully for off-grid dwellings. Some models use an electric "glow bar" element to ignite the gas oven burner, and this element can draw over 500 watts continuously whenever the oven is in operation.

Smaller electric cooking appliances can be surprisingly efficient, and are widely deployed off the grid. Though the power draw may be up to 1,500 watts, run times are relatively short and heat is more efficiently concentrated on the food. Common examples include microwave ovens, rice cookers, small convection ovens, and toasters.

Clothes Washing and Drying

Electric dryers are also not recommended for any off-grid system due to extremely high instantaneous wattage draw and long run times. Gas dryers are used instead, and models with efficient electric motors and blowers are available. Washer efficiency is also important, and new front-loading models are designed to save both energy and water.

Dishwashers

In off-grid applications, efficient dishwashers can be installed. Most on-grid households use a dishwasher that is far larger than needed, wasting both electricity and hot water. Efficient models are now produced by U.S. manufacturers, with smaller sizes available, too. Electrical energy used by the actual washing of dishes is far lower than that used during the drying cycle, so machines in which this cycle can be skipped are always preferable. With smaller off-grid systems, dishwashers are often omitted entirely.

Refrigeration

Efficient refrigerator models are also now common from U.S. manufacturers, and Energy Star ratings make comparison easy. Refrigeration is a critical load in off-grid systems, as expensive food spoilage will occur if the battery bank is too far discharged to run the appliance. Unlike most other loads, the building occupants cannot choose what time of day the refrigerator or freezer is running to take best advantage of renewable energy input and reduce energy storage needs.

Larger off-grid dwellings generally use common full-size, efficient electric refrigerator/freezers. Smaller building and renewable energy systems often use specialty smaller, super-efficient and super-insulated refrigerators that are designed specifically for off-grid applications. The smallest systems often use propane refrigeration instead of electric.

Consumer Electronics

Televisions and computers that use cathode ray tube (CRT) monitor technology are not recommended for any off-grid system, as inexpensive LCD replacements of the same screen size can use a quarter of the energy. Plasma televisions are even more inefficient than CRTs. LED televisions simply use LEDs instead of cold cathode fluorescent (CCFL) elements for LCD backlighting, and are currently about 10 percent more efficient than CCFLs.

Most other consumer electronic devices do not cause problems in an off-grid situation. However, a large majority of them are sources of "phantom loads," which indicate energy used even when the appliance is turned off. Any device that can be turned on with a remote control or pushbutton or that uses a "wall-wart" transformer is a phantom

load. Most of these loads are small, but they add up when dozens of devices are involved.

Many off-grid homeowners reduce these loads by the judicious application of switched power strips. For example, one strip can be switched on if the desire is to simply listen to the radio. A second strip can be activated to provide power to the satellite box and television. And for full, amplified surround-sound, a third strip is activated to power the sound system and DVD player.

Multiple power strips are not particularly aesthetic in appearance, though, so many off-grid building consultants recommend deploying switched outlets at strategic locations throughout a structure, for example in the computer room and at the entertainment center. A few phantom loads, such as the digital clock on a typical microwave oven, are convenient and use little energy. But a home office full of computers, printers, scanners, and routers, all turned off, can be a significant phantom load and should be switched.

LESSONS LEARNED: CONSERVATION

Every dollar spent on conservation can save three to five dollars on the cost of a renewable energy system [16].

This figure is actually more appropriately applied to grid-tied renewable energy installations—off the grid, the conservation savings can be far higher, over $10 per watt—due to the cost, fragility, and limited service life of storage batteries. In many cases, grid-tied utility customers can make a much more effective impact on their monthly energy costs by replacing old, inefficient appliances rather than by installing PV energy sources [17]. The payback time for conservation investments can be very short compared to PV, and first-year return on investment (ROI) is almost always higher. It is entirely possible to cut the energy use of an average household in half over one year [18], with a first-year ROI of 40 to 60 percent—this compares very favorably with typical first-year ROI of 10 percent from a PV system.

Changing of habits costs little, and bad habits waste energy.

One job of the green building designer is to make good energy use habits easy and convenient for the building's occupants, whether the structure is on or off the grid. Space heating systems with multiple zones make it easy to heat rooms only when in use. Phantom loads can be eliminated with the flip of a switch. Domestic water is heated only as needed. Large intermittent loads such as dish and clothes washers can be selectively run only when renewable energy input is at a maximum, to avoid drawing energy from a battery bank.

For small off-grid businesses such as home offices, fabrication operations or remote guest lodges, habits can be more difficult to change—employees and guests often will not have a conservation ethic ingrained, and may not realize how much energy they waste daily or the financial effects of that waste for the building owner. In these cases, automated systems modeled after those used in larger businesses and offices can be deployed, for example, occupant sensors for lighting and heating.

CASE STUDIES

In the three case studies below, all locations are within a 20-mile radius, are in similar climatic zones, and have similar insolation to best show the real-world effects of green building techniques on off-grid structures.

Case Study: Northern Colorado House #1

- Location: 56 kilometers west of Fort Collins, Colorado, at 2,500 meters elevation
- Nearest electric grid: 18 kilometers
- Size: 158 square meters
- Local insolation: 4.5 equivalent full-sun hours per day, worst month average

Environmental factors considered by the designer

- Ridge top location with excellent insolation both summer and winter
- Extremely cold and snowy climate due to high elevation; cool summers; very low humidity
- Subterranean granite rock formations precluded deep foundation excavation or earth sheltering
- Small existing structure already contained underground spring water pumping system and cistern, but was not oriented to an east-west axis

Green design features implemented

- Large, tilted south-facing windows in great room (low-E, 1-inch insulated double pane) with nighttime thermal blankets, tilted for maximum winter exposure

Off-grid northern Colorado house, case study #1. Copyright Dan Fink, Buckville Publications LLC.

- Floor plan uses both rectangles and triangles to correctly orient south-facing windows, while retaining existing water pumping structure
- Floor plan and ceiling fans provide for maximum air circulation using the chimney effect during warm weather, and are the only source of cooling
- Upstairs in master bedroom, large insulated sliding glass door facing southeast, large insulated window facing southwest
- Only one very small north-facing window, plus two north-facing skylights
- Wood heat with propane backup because of steady source of firewood on property
- Wood stove is adjacent to every room of house
- Heat moved to individual rooms with small, energy-efficient fans
- On-demand, tankless propane hot water heater
- Propane refrigerator and range/oven
- Small, efficient dishwasher
- Switched outlets to reduce phantom loads

Renewable energy system

- 500 watt PV array
- 2.1 meter diameter wind turbine on tower extending 4.6 meters above roof line
- 1,500 watt inverter
- 16.8 kwh battery storage at 12 volts (8.4 kwh usable)
- All rooms wired with both AC and DC circuits as backup against inverter failure
- 6,500 watt propane backup generator
- 2.5 kwh per day energy production
- 2.2 kwh per day loads
- System cost $10,000

Lessons learned

- Large amount of natural lighting greatly decreases lighting loads.
- Tilted and correctly-oriented great room windows increase wintertime heat gain; sunlight strikes north wall of structure in winter.
- Adequate thermal mass was not implemented. Future retrofits may include cement board underlayment, tile floor, and Trombe wall.
- Tilted windows cause numerous problems with sealing and water damage, and are vulnerable to snow and ice dropping off the metal roof.
- Non-rectangular floor plan corrected window orientation, but caused wastage in building materials.
- DC load circuits were expensive and unnecessary; a backup inverter would have been cheaper.
- The wind turbine tower is too short, and turbine output is decreased by a factor of four due to slow wind speeds and turbulence.
- Propane refrigerator is expensive to run, and access for propane delivery is limited in winter. Future retrofits may include expanding PV array and installing electric refrigerator.
- System voltage of 12 volts limits and makes more costly any future expansion of electrical system with more PV and wind energy sources; 48 volt systems are far more versatile.

Conclusions

All in all, this house was a successful green building design; it was built in 1998. Maintenance of the tilted windows against water leakage is a constant problem, but allows for indoor vegetable production year-round, and vegetable production humidifies the air in a very dry climate. Passive solar heat combined with propane backup allows autonomy at low propane cost without freezing pipes when the homeowner is traveling during the winter. The wood heating system with small circulation fans greatly reduces propane costs when the home is occupied. The electrical system is adequate, but expansion will be costly due to low system voltage.

Case Study: Northern Colorado House #2

- Location: 40 kilometers west of Loveland, Colorado, at 2,200 meters elevation
- Nearest electric grid: 3 kilometers
- Size: 200 square meters
- Local insolation: 4.5 equivalent full-sun hours per day yearly average

Note: This home was a "generic" design, and was built by a contractor without any consideration for green building design features. It was wired with standard AC circuitry and appliances to run off a generator, with the thought of adding a renewable energy system later. The homeowner did not research renewable energy systems or green building techniques in advance of selecting a design. A consultant was not called in to design the renewable energy system until after the structure was completed. Because of a privacy contract in place, there are no photos of this home shown here.

Environmental factors

- Valley location, oriented east, with numerous tall trees
- Extremely cold and snowy climate due to high elevation, cool summers, very low humidity

Existing structure

- Rectangular floor plan with long side facing east
- Large east-facing windows in great room, with few windows on south side
- Large trees blocking south exposure
- Ridge top to south blocks winter sun
- Generic forced-air propane furnace and ductwork installed
- Generic electric refrigerator, clothes washer, and dishwasher installed
- Generic gas range with electric glow-bar oven installed

Renewable energy system

- A renewable energy system was never installed.
- The final cost/benefit analysis showed that extending existing utility power lines by three kilometers would cost $50,000, compared to over $70,000 for renewables, because:
  - Terrain features blocked large amounts of solar input for both heat and electricity.
  - Tall trees made cost of wind turbine tower prohibitive.

Lessons learned

- A site evaluation should have been performed before approval of the building location, orientation, and design
- Efficient appliances should have been incorporated into this new construction, to better allow renewable energy retrofits later.

Conclusions

The homeowner was extremely disappointed that the home could not be retrofitted with a renewable energy system in a cost-effective manner, but lessons were learned. In addition to the line extension cost of $50,000, the yearly energy bill is over $1,500. Had green building principles been used in siting and designing this structure, a moderately-sized off-grid renewable energy system (only slightly larger than in the first case study) could have powered it easily.

Case Study: Northern Colorado House #3, with Office

- Location: 16 kilometers west of Fort Collins, Colorado, at 2,000 meters elevation
- Nearest electric grid: 5 kilometers
- Size: 244 square meters
- Local insolation: 4.5 equivalent full-sun hours per day, worst month average

Environmental factors considered by the designer

- Ridge top location with excellent insolation both summer and winter
- Cold and snowy climate due to high elevation, hot summers, very low humidity

Green design features implemented

- Large, insulated south-facing windows throughout house
- Built of hand-hewn, locally-harvested logs for insulative qualities and low embodied energy
- Wood heat with propane-fired radiant floor backup
- Excellent thermal mass in radiant floors
- On-demand, tankless propane hot water heater can accept solar pre-heated water

Off-grid northern Colorado house, case study #3. Copyright Rex and LaVonne Ewing, Pixyjack Press LLC.

- Propane range/oven and clothes dryer
- Efficient, though standard, electric refrigerator, dishwasher, clothes washer, and other appliances

Renewable energy system

- 2,320 watt PV array
- 3-meter diameter wind turbine on a 15-meter tower, 8 meters above nearby obstacles
- 4,000 watt inverter
- 202 kwh battery storage at 24 volts (101 kwh usable)
- Evacuated tube solar domestic hot water system

Evacuated tube domestic hot water heating panel, off-grid northern Colorado house, case study #3. Copyright Rex and LaVonne Ewing, Pixyjack Press LLC.

Lessons learned

- Large amount of natural lighting greatly decreases lighting loads.
- Correctly-oriented windows greatly increase wintertime heat gain.
- Radiant floor heating systems also contain excellent thermal mass.
- Log construction provides excellent insulation R-value.
- Trees grow, so the yard-mounted PV array and wind turbine tower had to be sited to account for this.
- With a large enough renewable energy system, standard electric appliances of U.S. manufacture can be used, with the exception of gas range/oven and gas clothes dryer.

Conclusions

This house has been an exceptionally successful green building design; it was built in 1999. Passive solar space heating combined with propane radiant floor backup allows autonomy at low propane cost without freezing pipes when the homeowners are traveling during the winter. The wood heating system greatly reduces propane costs when the home is occupied. The homeowners also own a small publishing company that they operate from this location. While this requires a high load of computers and related equipment, the large amount of PV and wind input are more than adequate to power both the home office and the home.

THE FINAL LESSON LEARNED

Advances in small-scale renewable energy technology and manufacturing techniques have drastically lowered the cost of off-grid renewable energy systems to the end user over the last 10 years. But there is still no excuse for not using green building techniques in *every* structure, even in suburban and urban locations. While this exercise in off-grid design serves to point out the acute problems faced when energy must be stored and backup sources are expensive, the monthly utility cost savings from using green design techniques at *any* location are tremendous. When the additional challenges of off-grid autonomy are added, sound green building design becomes essential, not optional.

REFERENCES

1. International Energy Agency. 2005. "The Developing World and the Electricity Challenge," www.iea.org.
2. Davidson, Joel, and Fran Orner. 2008. "The New Solar Electric Home," Aatec Publications.
3. Gipe, Paul. 2010. "Small and Household Size Wind Turbines," www.wind-works.org.
4. Gipe, Paul. 2004. "Wind Power," Chelsea Green Publishing Company.
5. Warwick Wind Trials. 2008. www.warwickwindtrials.org.uk.
6. Davis, Scott. 2003. "Microhydro," New Society Publishers.
7. Ampair Corporation. 2010. www.ampair.com.
8. Ewing, Rex, and LaVonne Ewing. 2006. "Power With Nature."
9. U.S. Energy Information Administration. 2008. www.eia.doe.gov.
10. U.S. Energy Information Administration. 2005. www.eia.doe.gov.
11. Eleek Inc. 2010. "Eleek Lamping Guide." www.eleek.com.
12. Klipstein, Donald. 2010. "Lighting Information Center," www.members.misty.com/don/.
13. National Renewable Energy Laboratory. 2010. www.nrel.gov.
14. Mikelbank, Sid. 2010. "Solar Heat Through Windows." www.engineeringanddesign.com.
15. Sunmaxx Solar. 2010. www.sunmaxxsolar.com.
16. San Luis Valley Rural Electrical Co-op. 2010. www.slvrec.com/conservation.htm.
17. U.S. Department of Energy. 2010. www.energy.gov.
18. Reysa, Gary. 2009. "The Half Plan." www.builditsolar.com/References/Half/Half.htm.