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Design and Performance of the Van Geet Off-Grid Home

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DESIGN AND PERFORMANCE OF THE VAN GEET OFF-GRID HOME

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ABSTRACT

The Van Geet home near Denver, Colorado, demonstrates the successful integration of energy conservation measures and renewable energy supply in a beautiful, comfortable, energy-efficient, 295-m^2 (3,176-ft^2) off-grid home in a cold, sunny climate. Features include a tight envelope, energy-efficient appliances, passive solar heating (direct gain and Trombe wall), natural cooling, solar hot water, and photovoltaics. In addition to describing this house and its performance, this paper describes the recommended design process of (1) setting a goal for energy efficiency at the outset, (2) applying rules of thumb, and (3) using computer simulation to fine-tune the design. Performance monitoring and computer simulation are combined for the best possible analysis of energy performance. In this case, energy savings are estimated as 89% heating and cooling, 83% electrical, and nearly 100% domestic water heating. The heating and cooling energy use is 8.96 kJ/ºC·day·m^2 (0.44 Btu/ºF·day·ft^2).

KEYWORDS

Residential, off-grid, high performance, passive solar.

INTRODUCTION

The Van Geet home near Denver, Colorado, serves as a prime example of the potential effectiveness of energy conservation measures coupled with renewable energy supply in a modern residence. The remote location, with no utility connections available, and the owner/builder's interest in renewables have motivated an ambitious design. Also, the research homes portion of the Building America program [1] has provided energy engineering throughout the design, construction, and performance evaluation phases. The house was engineered as a system using hourly simulations. It won a first place ASHRAE Technology Award in 2001 for Alternative and Renewable Energy Use [2].

The significance of this project is the successful integration of numerous energy conservation and renewable energy features into a beautiful, comfortable, and very energy-efficient home. The integrated design includes a tight, well-insulated thermal envelope, passive solar heating, natural cooling, active solar water heating, high-efficiency electrical appliances, and a photovoltaic (PV) hybrid electrical power system. In addition, some lifestyle adjustments by the energy-conscious occupants also contribute to the energy savings. In this paper, the effects of occupant behavior are reported separately from the effects of the building design.

In addition to describing the house and its performance, this paper also documents the design process, which proceeds in stages from the initial concept of the house through the final design and performance evaluation. Additional details of this project, which cannot be included here due to limited space, are described in our technical report [3].

NOMENCLATURE

K	Thermal conductance in SI units, W/m^2K
R	Thermal resistance in I-P units, ft^2·hr·ºF/Btu
RSI	Thermal resistance in SI units, K·m^2/W
SHGC	Solar heat gain coefficient: the fraction of the solar energy incident on a window that enters the building
U	Thermal conductance in I-P units, Btu/ft^2·hr·ºF

DESIGN PHILOSOPHY

The design process demonstrated here includes (1) setting a goal for a low-energy building before the design begins; (2) designing the house as a single package where the components work together; and (3) tailoring the design for the local climate. This approach of climate sensitive, whole house, passive solar design has evolved over the past 20 years, along with the development of computer simulation tools to aid in the design process. In housing markets where production builders use a few floor plans and replicate them many times, the use of simulations to optimize performance is very appropriate.

DESIGN PROCESS

The design process began in June 1995. Initial design constraints included the following:

- The desired floor plan
- Comfort
- A remote site with no utility connections
- Economy: Minimize energy costs (thermal and electrical)
- Environmental impact
- Low operation and maintenance requirements desired
- Garage to be kept above freezing.

At this site, 2,835 m (9,300 ft) above sea level in the Rocky Mountains, the climate is cold and sunny, with 5,346 heating ºC·days (9,623 ºF·days) and 0 cooling degree-days. The cost of extending the electrical power grid 2.4 km (1.5 miles) to reach the home was estimated as US$100,000. Thus, it is very cost-effective to feature high-performing passive solar heating, active solar hot water, and photovoltaic electrical systems. Liquefied petroleum gas (LPG) is used for backup heat, backup hot water, backup electrical generation, and cooking.

The initial energy design proceeded based on rules-of-thumb for low-energy building design, such as:

- Simple, compact envelope design (low surface-to-volume ratio)
- Long east-west axis
- Most of the glazing area on the south side
- Significant thermal mass within the thermal envelope
- Ample insulation on the exterior
- Low-emissivity glazings.

This design minimizes space-conditioning loads by using a good thermal envelope and passive solar design, including thermal storage. Windows dominate the south façade for solar gains and daylighting. Behind some of the south-facing windows are opaque, masonry, thermal storage walls, known as Trombe walls[1]. These serve to store solar heat and delay its delivery into the home approximately six hours. The Trombe wall sections are positioned near the corners of the walls so they do not diminish the scenic views and open feeling of the home. They are also inconspicuous from the outside, as they resemble adjacent windows. High-mass exterior walls serve to store solar gains in the winter and stabilize indoor temperatures in the summer. The exterior walls are constructed of dry-stack concrete blocks with 12.7-cm (5-inch) expanded polystyrene insulation attached on the outside.

After laying out the envelope, the internal heat loads were minimized by specifying fluorescent and compact fluorescent lighting and low-energy appliances. This, along with the cool climate, allows for the use of natural ventilation as the primary cooling system. Solar collectors heat water for domestic use. Electricity is supplied by a PV/battery/LPG hybrid system.

One important indicator of a passive solar design is the annual solar radiation incident on the south glazings compared to the annual heating load. In this case, the annual average radiation incident on the south façade is 158 W/m^2 (or 3.80 kWh/m^2·day), and the total south aperture area (including windows and Trombe wall sections, excluding the garage) is 39.4 m^2 (424 ft^2). Thus, the average incident solar amounts to 6,225 W (186 MBtu/year). The building loss coefficient is estimated as 329 W/K (624 Btu/ºF·hr.) With 5,346 ºC·days (9,623 ºF·days) per year, the annual average heating load is 4,819 W (144 MBtu/yr). Comparing these two numbers, the solar load ratio (SLR) is 6,225/4,819 = 1.29 (186/144 = 1.29). That is, the incident solar is about 29% more than the annual heating load. Of course, some of the incident solar radiation is reflected or absorbed by the glass or vented when it is not needed. Computer simulations are needed to analyze these details. However, if the SLR were much less than one, the solar could not meet the load regardless of other details. If the SLR were, say, 1.5 or more, significant overheating could occur unless shades or other devices were used to control solar gains.

Another important indicator of the design is the amount of thermal storage, or heat capacity, compared to the load. In this home, the thermal mass[2] is estimated as about 72.2 MJ/K (38 kBtu/ºF.) All of this heat capacity is enclosed within the thermal envelope (the insulation), which enables it to be effective in stabilizing indoor temperatures. Mass that is outside of the insulation does not have the same effect. When this heat capacity is divided by the building loss coefficient of 329 W/K (624 Btu/ºF·hr), the quotient is about 61 hours or 2.5 days. This is the building time constant. Of course, the effect of the thermal mass depends on where it is located in the house and numerous other factors. Again, computer simulations are needed to analyze these effects in detail. However, the time constant does provide a simple indication of the amount of thermal storage. Because this house has a time constant of several days, it is capable of storing heat from one day to the next, and this is an important aspect of why the house works well. A much smaller time constant, such as 0.5 days, would indicate that the building is not capable of storing much energy from one day to the next, regardless of other design details.

In the spring of 1996, the rough initial design was fine-tuned through a parametric analysis of its features, using SERIRES [4]. SERIRES is a thermal network computer simulation model that is intended for analyzing the energy performance of residences that may incorporate passive solar

[1] For further information on Trombe walls, see http://www.nrel.gov/buildings/highperformance/trombe_walls.html.

[2] This thermal mass does not include the concrete slab, for reasons discussed in the Envelope section. It consists of the exterior walls described in the same section.

design features. SERIRES can analyze complex thermal systems including Trombe walls, energy efficient windows, and other technologies for heating and cooling a home. The mathematical solution technique uses forward finite differences with time steps of 1 hour or less. SERIRES has been well tested through experimentation and practical use and is one of the benchmark programs for the International Energy Agency [5] testing procedure, BESTEST [6]. SUNREL [7] is a newer, upgraded version of SERIRES that has also been tested satisfactorily using the BESTEST procedure. This model became available and was used during the later stages of the Van Geet project (see below). Upgraded features in SUNREL include a more flexible input structure; a more sophisticated model for advanced window systems; algorithms to handle shading by overhangs and side fins of finite length; and a comprehensive routine for infiltration and natural ventilation, driven by temperature and wind effects. TMY weather data for nearby Boulder, Colorado, were adjusted for the site elevation of 2,835 m (9,300 ft) for design purposes. Using simulation, the house was optimized for the climate in which it is located.

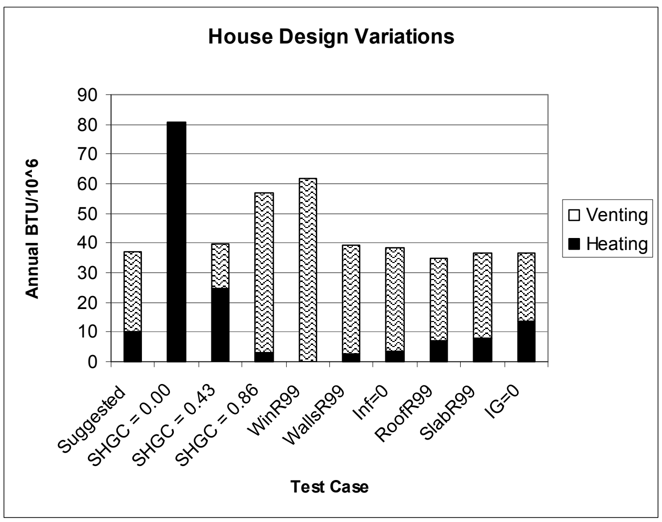

Figure 1. Parametric simulation study of house design features

The sensitivity of energy performance to various building design features is illustrated in Figure 1. The purpose of this parametric study is to help fine-tune the house design, by identifying the features that have the greatest impacts on energy performance. The solid, lower portion of each bar in the graph indicates the annual auxiliary heating energy. The textured, upper portion of each bar indicates excess energy that must be vented to prevent overheating. The first bar, labeled "Suggested," represents the suggested design resulting from this parametric study. Other bars in the graph represent hypothetical variations on that design. Each of these hypothetical cases is based on an extreme value of a parameter that may not be physically realistic; this serves to indicate an upper limit on the effect of varying that parameter. The results are interpreted as follows:

- **Suggested.** This represents the suggested building design, based on the results of this parametric study. The house as actually built is somewhat different.
- **SHGC = 0.00, 0.43, and 0.86.** The window solar heat gain coefficient (see Nomenclature section) was set to three successive values. SHGC = 0 represents windows that do not let any solar energy through the glass. SHGC = 0.86 represents a single pane of clear glass (a practical upper limit on solar transmission). Energy performance is obviously very sensitive to this parameter, in terms of both heating and cooling. See additional comments below.
- **WinR99.** The window R-Value is set to RSI-17.4 (R-99, $K\approx0$, $U\approx0$), virtually eliminating heat loss through the windows. This reduces the auxiliary heating load to zero while greatly increasing the overheating, emphasizing the importance of this parameter.

Based on the results for SHGC and WinR99 (above), a great deal of emphasis was placed on the windows. The south-facing window area and the amount of thermal mass were both increased (to the levels discussed above). South glazing was selected to maximize the solar gain, while minimizing heat loss—a low-e coating and a high SHGC (0.65).[3] The south glazing was sized such that no backup heat would be required on a sunny day and one following cloudy day. Windows on the north, east, and west façades were located and sized to provide adequate natural ventilation and daylighting, without causing unnecessary heat loss in the winter or overheating in the summer. The simulations showed that these windows should have a low-e coating and a lower SHGC (0.40).

- **WallsR99.** The wall insulation R-Value is set to RSI-17.4 (R-99), virtually eliminating heat loss through the walls. The auxiliary heating load is rather sensitive to the wall insulation R-value. A value of RSI-3.5 (R-20, K=0.28) was selected, based on diminishing returns as more insulation is added.
- **Inf=0.** The natural infiltration rate of outside air into the house is set to zero, representing a building that is airtight. A rate of 0.25 ACH was assumed in the "Suggested" case, although it is hard to predict this rate very accurately prior to construction. The parametric study shows that making the building tighter would be effective in reducing the auxiliary energy consumption. However, a lower ventilation rate would raise indoor air quality concerns. Thus, efforts were made to construct a very tight house while providing for controllable ventilation through the use of operable windows.[4]
- **RoofR99.** The roof insulation R-Value is set to RSI-17.4 (R-99), virtually eliminating heat loss through the roof. This slightly decreases auxiliary heating. However, the design for the roof already includes 30.5-cm (12-inch),

[3] This was selected as the highest SHGC commercially available with a low U-value.

[4] A blower-door test conducted in January 1999 indicated 948 liters/s (2,008 cfm) at 50 pascals; ELA = 723 cm^2 (112 in^2); and an annual average natural infiltration rate of 0.34 ACH.

RSI-6.7 (R-38, K=0.15) batt insulation, and it would be difficult to increase this.

- **SlabR99.** RSI-17.4 (R-99) insulation is added underneath the slab floor, in addition to the 5.1-cm (2-inch) slab edge insulation that is already included in the design. This only slightly reduces the auxiliary heating. Slab insulation was not installed.[5] (See discussion in next section.)

- **IG=0.** Internal heat gains from occupants and appliances were set to zero. This slightly increases the auxiliary heating and decreases the overheating. High-efficiency lighting and refrigeration were already included in the design, for the sake of electrical energy efficiency. No further measures are indicated by this result.

The resulting passive solar design for the occupied space includes 77% direct gain and 23% Trombe mass storage walls. (Including the garage, the split is 71% direct gain and 29% Trombe wall.) Construction drawings were prepared based on the simulations.

Figure 2. View of home from the southwest, showing the significant south-facing glazing for passive solar heating and the solar hot water collectors in the foreground. The 1,000-watt photovoltaic array east of the house is not shown in this view. (NREL PIX 08226)

ENVELOPE

A view of the home from the southwest corner is shown in Figure 2. Additional photos and floor plans are shown in the technical report [3]. The conditioned space floor area is 295 m^2 (3,176 ft^2) including the third floor loft; the garage is an additional 54.7 m^2 (589 ft^2), for a total area of 350 m^2 (3,765 ft^2). The first floor features a family room, two bedrooms, bath, laundry room, mechanical room, and a two-car garage. The second floor consists of a great room with cathedral ceiling, kitchen, dining room, master bedroom suite, fourth bedroom and bath. This floor is the main living space of the family. It is mostly daylit and heated by direct gain solar power. A wood-burning stove is located between the great room and the kitchen.

Key features of the design include the following:

- A simple, compact envelope design with a low surface-to-volume ratio
- Insulation levels in the walls and roof (see above)
- U-factors (K=1.74, U=0.31) and low-E coatings for the windows.

Some construction details are as follows:

The exterior walls of the house consist of dry-stack 8-inch concrete masonry units (CMU). Every third cell is reinforced with steel and filled with concrete. In the Trombe wall sections, all the cells are filled with concrete. The exterior of the block is finished with 12.7 cm (5 inches) of expanded polystyrene and covered with a synthetic stucco finish. The inside of the house is finished with plaster.

Below grade, the exterior of the 0.91-m (3-ft) deep stem wall is insulated with 5.1 cm (2 inches) of polystyrene.

A 10.2-cm (4-inch) thick ***concrete slab*** constitutes the floor on the lower level of the house. It was intended that this thermal mass would store heat from sunlight entering through the south glazing and impinging on the slab. However, no insulation was installed underneath the slab. The house occupants have covered the slab with a carpet to mitigate the discomfort of the cold floor. Evidently, heat losses from the slab to the ground are rendering the slab useless as a heat storage component. Fortunately, this house performs very well in spite of this feature, because of the ample thermal mass in the exterior concrete block walls with exterior insulation. As a lesson learned, slab floors intended as heat storage components in future projects should be insulated.

The roof above great room, kitchen, and dining room, with a 6/12 pitch, is insulated with RSI-6.7 (R-38, K=0.15) batts in 36-cm (14-inch) TGI trusses spaced 61 cm (24 inches) apart. In the roof above the bedrooms, with a 4/12 pitch, insulation was blown into the prefabricated trusses, for an estimated net thermal resistance of RSI-7 (R-40, K=0.14).

The windows are double-pane, with a low-emissivity coating. On the south façade, they are K=1.76 (U=0.31) and SHGC=0.65. On other façades, they are K=1.70 (U=0.30) and SHGC=0.40. These windows are an off-the-shelf product, purchased from a major manufacturer.

HEATING AND COOLING

The thermal design of the house, resulting from the parametric study described above, includes the following features:

- Direct gain passive solar (10% of floor area)
- Trombe wall (3% of floor area)
- High mass exterior walls
- Natural cooling
- Wood stove

[5] Heat loss to the ground is the subject of very complex analysis. Both SERIRES and SUNREL lack a sophisticated model of this phenomenon. Thus, the effect of slab insulation may have been underestimated in this analysis. See Deru and Kirkpatrick [8,9] for a treatment of this topic.

- Hydronic backup heating system (LPG)
- LPG range and clothes drier.

A mechanical cooling system is not needed in the Van Geet home for the following reasons:

- Cool climate. There are 0 cooling degree-days, and the monthly average temperature never exceeds 16ºC (60°F). Throughout the year, the ambient temperature never exceeds 27ºC (80ºF);
- Ample thermal mass. The house cools off overnight, and the thermal mass helps to keep the house cool during the warm or hot days;
- Reduced internal gains. High-efficiency lighting and refrigeration help to reduce the amount of heat generated within the house.

The natural ventilation (in the form of operable windows) was designed into the open floor plan as the primary cooling system. The windows were sized and located for cross-flows and stack effect[6] to provide ample natural ventilation. As discussed above, windows with low SHGC were used on the east and west walls to minimize solar gains in the summer. The insulating and temperature-retaining properties of the high-mass walls further control the temperature in the home.

In passive solar design common practice, overhangs are often used to shade the south glazings from the summer sun to avoid overheating. In this case, modeling indicates that overhangs are not necessary, due to the combination of the cool weather, large thermal mass, and steep summer sun angles. (This was later confirmed by the occupants and the collected data.) The minimal advantage of overhangs in the summer was deemed to be outweighed by the unwanted shading that would diminish solar gains in the spring and fall seasons. In a climate with warmer summers, overhangs should definitely be considered.

Performance Evaluation. A combination of monitoring and modeling was used to achieve the most accurate and meaningful analysis of energy performance possible. Monitoring is important because it provides real data on actual building performance. On the other hand, modeling is useful for:

- Calculating the *total* auxiliary (non-solar) heating energy required, including LPG (which was measured), firewood, and losses from the solar domestic hot water (DHW) system (which can only be estimated);
- Evaluating occupant behavior effects separately from building performance;
- Evaluating performance for a typical weather year, rather than an arbitrary year; and
- Comparing the actual building to a standard code reference case.

[6] "Stack effect" refers to air movement that is driven by the difference between indoor and outdoor temperatures. Warmer air flows out of upper windows, while cooler air enters the house through lower windows.

Thus, in this study the measured data were used to calibrate the model, and then the model was used to analyze performance. The SUNREL model, discussed above, was used for this purpose.

As energy conservation enthusiasts, the Van Geets are happy to use energy-efficient appliances and to wear sweaters around the house with lowered the thermostat settings. This affects the performance of the house, which would be somewhat different with a more conventional family living in it. In order to distinguish the performance of the house from the behavior of the occupants, two separate comparisons are made:

1. The Van Geet home is compared to a standard reference case at the time of construction (1995 Model Energy Code [10]), assuming the same conventional occupant behavior (thermostat setpoints and internal heat generation) in both homes. This comparison credits the *house* with 77% energy savings for heating and cooling.

2. In order to evaluate the energy-conscious lifestyle of the occupants, the actual behavior of the occupants was used in the model. The difference between this and the previous case indicates the contribution lifestyle makes to the energy savings. This comparison credits the *occupants* with an additional 12% energy savings, for a total heating and cooling reduction of 89% when compared to the MEC reference case.

These quantities are illustrated in Figure 3. Figure 4 shows measured building performance for a period of one week in January 2000. For this week, the outdoor temperature was near the long-term monthly average of -6.3ºC (20.7ºF). Backup heat was used to keep the north bedroom at 18.3ºC (65ºF) each night. During a period of three rather cloudy days, backup heat kept the master bedroom (on the south side) above 15.6ºC (60ºF), while the less-used family room on the lower level was allowed to cool off to 12.8ºC (55ºF).

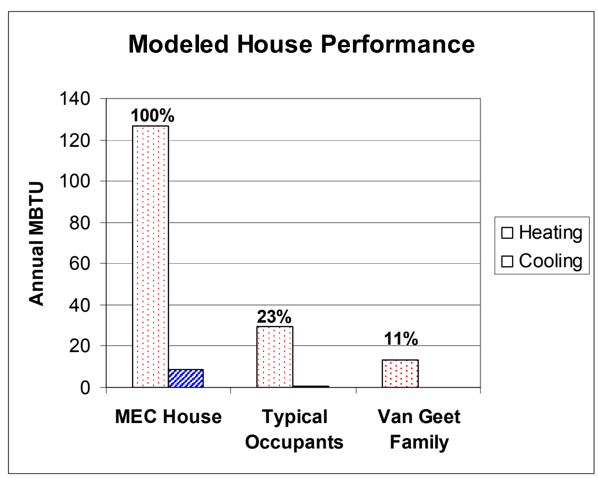

Figure 3. Heating and cooling energy savings attributed to house with "typical occupants" and with the Van Geet family's more energy-conservative lifestyle

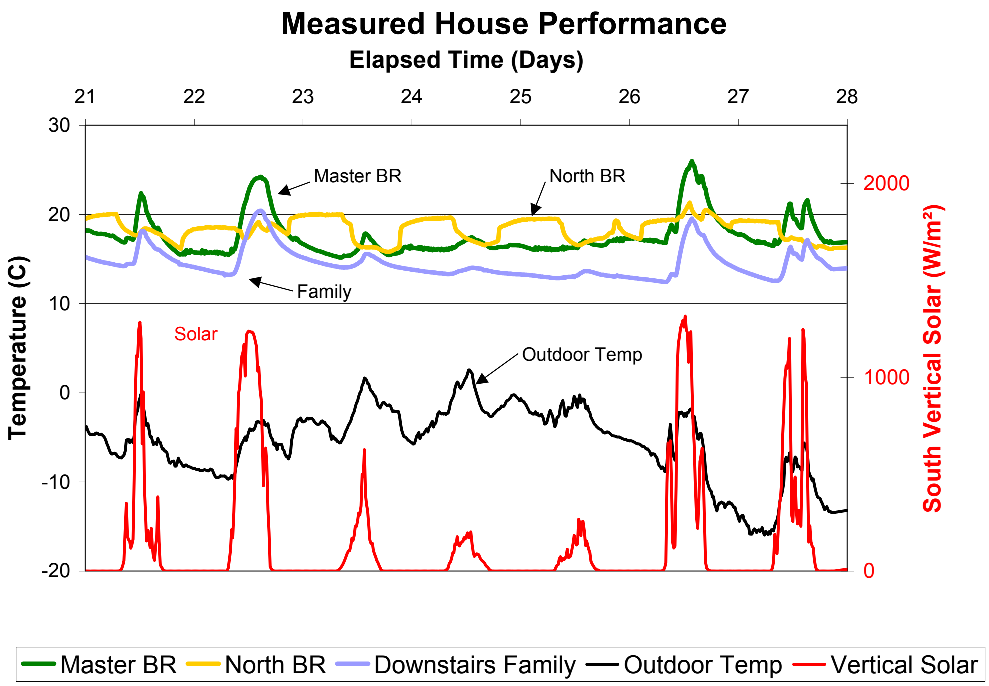

Figure 4. Sample of measured performance data for the fourth week of January 2000

SOLAR DOMESTIC HOT WATER SYSTEM

Domestic hot water (DHW) is heated by an active solar system with LPG backup. Four flat-plate solar collectors are used, for a total collection area of about 11.1 m^2 (120 ft^2). These are mounted on a freestanding structure just southwest of the house (see Figure 2) for easy maintenance access and optimal solar exposure, at a tilt angle of 55° from horizontal (latitude +15º). Pumps powered by a dedicated PV system (visible above the collector array in Figure 2) circulate a solution of propylene glycol through the collector, underground piping,[7] and heat exchangers in two 303-liter (80-gallon) tanks for heat storage. Each tank has a built in heat exchanger. The glycol solution flows through the tank heat exchangers in series, in counterflow to the DHW. The 25-W dedicated PV system powers the DC pumps directly, creating a self-regulating system with no additional controls. A 151-liter (40-gallon) LPG water heater, with sealed combustion, is plumbed in series with the two solar storage tanks to provide supplemental heat as needed.

During the year of data collection, the backup water heater tank was a net energy loser; i.e., the tank losses exceeded the LPG usage, and the water leaving the tank was on average cooler than the water entering. Because of this condition, the owner/occupant has turned off and valved off the backup water heater in order to avoid the tank losses. Now, the solar water heating is so effective that only on rare occasions, during extended cloudy periods in December or January, is the backup water heater used. Performance data on this mode of operation were not collected. However, based on the owner/occupant's account, it is evident that the DHW is heated nearly 100% by solar energy.

[7] The piping is 1.9-cm (¾-inch) copper with 2.5-cm (1-inch) foam insulation.

ELECTRICAL SYSTEM

The stand-alone hybrid electrical power system includes:

- Nominal 1000-W amorphous silicon PV array, with a maximum power point tracking (MPPT) charge controller
- Nominal 42.7 kWh battery bank; the effective capacity is 7.8 kWh, or 58 hours of average load
- 4 kW inverter
- 7.5 kW LPG engine-generator set (genset).

The total electrical load, including a well pump, high-efficiency lighting and refrigerator, and other appliances amounts to 3,240 Wh/day or 1,183 kWh/year.

As with the thermal system, the performance evaluation is based on a computer model that was calibrated against data from the data acquisition (DAQ) system. The model was developed by Barley [11]. It is a quasi-steady-state model, in which it is assumed that all quantities, including the genset on/off control function, are constant over each 1-hour time step. The model is run for 8,760 hours to simulate 1 year of

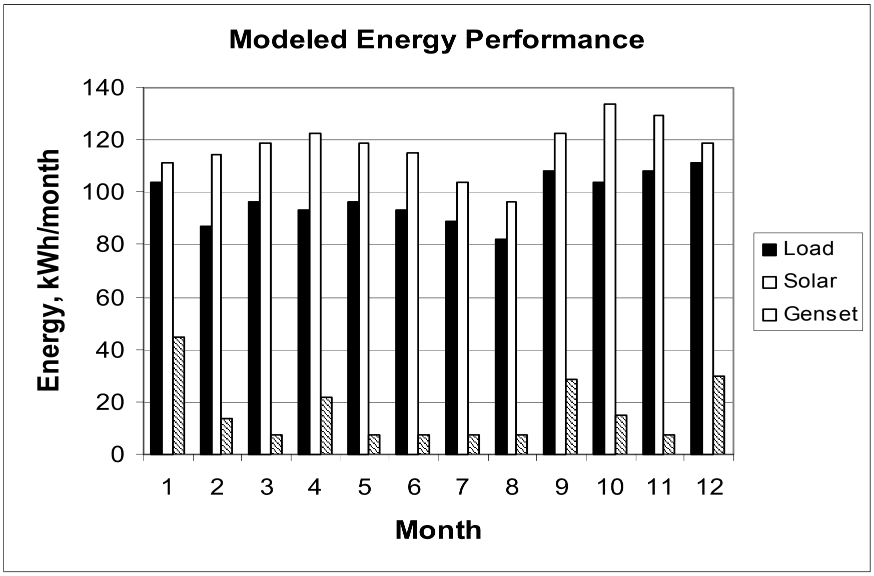

Figure 5. Modeled monthly energy performance of the electrical system

system operation. The dispatch strategy was modeled by starting the genset when the battery state-of-charge (SOC) falls to 50% and running it until the SOC reaches 80%. This approximates the manual control that was implemented by the owner-occupant. The model was calibrated against the measured LPG usage of 76.3 m^3 (2,696 ft^3) of gas, or 236 liters (62.3 gal) of liquid, during the period of Dec. 9, 2000 through April 3, 2001, when the current genset was running on LPG and the DAQ system was operating.[8]

The model predicts that in 1 year, the genset starts 28 times, runs 84 hours, produces 197 kWh of electricity (which is 17% of the total load), and consumes 443 liters (117 gal) of LPG. Monthly energy totals are shown in Figure 5. In the figure, the solar totals represent energy *available* from the PV array; this includes energy that was not actually generated, because of regulation of the PV array to avoid over-charging the batteries. It also includes losses in the battery and inverter. It appears in the figure that the load varies with the available PV power, perhaps reflecting the occupants' lifestyle of using more electricity when solar power is available.

Speculation about the performance of this home in a *grid-connected* application is as follows. The batteries and genset would be eliminated from the system. The PV array would generate 1,400 kWh/yr. If all of this were converted to AC with the assumed average inverter efficiency of 85%, 1,190 kWh/yr would be available to meet the loads. The total annual load was measured as 1,183 kWh/yr. Thus, this system would approximately break even on energy exchanges with the grid. In this perspective, the energy generated by the genset in the stand-alone system is seen to compensate for losses in the system, including PV power that could not be utilized because of limited storage capacity.

Subsequent to this analysis, the Van Geets have installed a new, energy-efficient, horizontal-axis washing machine. This is expected to further improve the performance of the electrical system.

CONCLUSIONS

The design process that is demonstrated here worked well; this includes the following:

- Planning for energy efficiency from the start
- Initial design based on rules of thumb
- Good solar load ratio and building time constant
- Parametric modeling to fine-tune the design.

In this case, energy savings are estimated as 89% heating and cooling, 83% electrical, and nearly 100% domestic water heating. The heating and cooling energy use is 8.96 kJ/°C·day·m^2 (0.44 Btu/°F·day·ft^2).

Overhangs are not needed in this case due to the cold climate (0 cooling degree days), high thermal mass, low internal gains due to energy-efficient electrical appliances, and high summer sun angles. In many other situations, overhangs would be recommended.

Concrete slab floors intended as heat storage components should be insulated.

A combination of monitoring and modeling is deemed to provide the best possible performance evaluation.

[8] When the original LPG genset failed, it was replaced with a larger, gasoline-powered generator. This was run on gasoline for several months before it was converted to LPG. Thus, we only have about 4 months of data on the fuel usage of the current generator.

ACKNOWLEDGMENTS

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13. ABSTRACT *(Maximum 200 words)* The Van Geet home near Denver, Colorado, demonstrates the successful integration of energy conservation measures and renewable energy supply in a beautiful, comfortable, energy-efficient, 295-m^2 (3,176-ft^2) off-grid home in a cold, sunny climate. Features include a tight envelope, energy-efficient appliances, passive solar heating (direct gain and Trombe wall), natural cooling, solar hot water, and photovoltaics. In addition to describing this house and its performance, this paper describes the recommended design process of (1) setting a goal for energy efficiency at the outset, (2) applying rules of thumb, and (3) using computer simulation to fine-tune the design. Performance monitoring and computer simulation are combined for the best possible analysis of energy performance. In this case, energy savings are estimated as 89% heating and cooling, 83% electrical, and nearly 100% domestic water heating. The heating and cooling energy use is 8.96 kJ/ºC·day·m^2 (0.44 Btu/ºF·day·ft^2).

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