Net-Zero Performance

Year 1

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In the February 2011 article "Heading for Zero—Smart Strategies for Home Design" (*HP141*), I described the design and computer-modeling processes for our passive solar, net-zero energy home. The design followed the German Passivhaus philosophy. Now, after a year of performance data logging, we can see how close the house came to our design goals and modeling.

We have two adults and two children in the household. Our home, called Heliospiti (Greek for "sun house"), is an all-electric house of 3,180 square feet, with a slab-on-grade foundation, and is located at an elevation of 7,000 in Monument, Colorado. According to the Western Regional Climate Center (wrcc.dri.edu), this area averages 6,324 heating degree-days and 149 cooling degree-days per year—a heating-dominated climate. The shell consists of R-49 double-stud walls, an R-67 roof, and an R-21 insulated concrete slab main floor for thermal mass.

The Accurate Dorwin windows are triple-pane, argon-filled. On the south side, we specified windows with a high solar heat gain and low U-factor; north windows have a very low U-factor; and there are no windows on the east or west sides. The house is oriented with its long axis east–west to maximize solar gain on the south face. To take the house from simply being a high-efficiency passive home to a net-zero energy home, we installed a 4.5-kilowatt grid-tied photovoltaic (PV) system and a solar hot water (SHW) system with three 40-square-foot collectors.

The passive solar design meets all of our space-heating needs, using a 4-inch-thick polished concrete floor and 11/4-inch-thick gypsum walls as the primary thermal mass. A passive solar wall based on "Build a Solar Heater…for $350" (*HP109*) heats the thermally isolated wood shop and garage. A single Mitsubishi Mr. Slim variable-compression minisplit air-source heat pump provides backup space heating. An UltimateAir RecoupAerator energy recovery ventilator (ERV) provides balanced, efficient ventilation. The incoming air for the ERV is passively preheated by a 100-foot-long, 10-foot-deep Rehau earth tube.

Overall Performance

Our home's energy performance is monitored through a variety of devices. Mountain View Electric Association, our electric utility, provides a net meter that displays the home's net energy consumption (or production). Internet-based software from Enphase Energy provides detailed production data for individual PV modules. I installed a four-channel Onset Hobo data logger to track the temperatures of outdoor and indoor air, the concrete slab, and the earth tube air as it enters the house. Internet-based software from Nissan tracks the daily and total recharging energy required for our Leaf electric vehicle (EV).

So how did the house perform overall? For the 314 days before the EV's first recharge, the house produced an excess of 2,981 kilowatt-hours (kWh), averaging 9.5 kWh excess per day. The large surplus was intentional—our long-range goal was to produce enough additional electricity to charge an EV and still remain net-zero. While it is premature to say if we met that goal, the initial numbers look promising. During its first 61 days, the Leaf consumed an average of 6 kWh per day. When subtracted from our average excess production, this still resulted in a surplus of 3.5 kWh per day. So far, our goal of net-zero was exceeded, even including EV charging.

Air Tightness

The physics behind modern building science clearly shows the large impact of building tightness on energy efficiency. This has led to the extremely low air leakage allowance by the Passive House Institute. Through meticulous attention to sealing during construction, our house tested at 0.40 air changes per hour at 50 Pascals pressure difference between the inside and outside (ACH50)—33% tighter than the 0.60 ACH50 Passive House limit. And with an effective leakage area (ELA) of 15.4 square inches, it was 20% better than the ELA design goal of 19.3 square inches that we had initially set for construction.

Using closed-cell spray foam (usually intended mainly for its insulating properties) on the inside face of all wall and roof sheathing also played a big part in the home's airtightness. Every wall bottom plate was sealed with a double bead of caulk and a thick rubberized sealer was used between the sill plates and concrete. Every door and window rough opening, and every electrical and plumbing penetration, was sealed with spray foam or caulk. After a 3-inch-thick layer of spray foam was applied to the walls, and before installing the 9 inches of blown fiberglass and the drywall, I conducted a blower door test and used a thermal camera to locate and repair any air leaks. Finally, other than the energy recovery ventilator, there are no fans that vent to the outside—no clothes dryer ducting, or range hood or bathroom vents.

Space Heating

The graph on the following page tracks a particularly cold week in December when the highs and lows for the week were below long-term averages. It shows data for outside, inside, earth tube air, and slab temperatures, in two-hour increments.

Mechanical Heating. After compensating for the passive solar contribution, Energy-10's predicted annual requirement for mechanical heating was 5,954 kBtu (thousand British thermal units). But we never turned on the minisplit heat pump, and burned only 1.9 cubic feet (0.015 cords) of hardwood molding scraps in a 63% efficient wood heater, which provided 187 kBtu. However, these five one-hour fires were lit for ambiance, not comfort, and we had to open windows to avoid overheating the house.

Earth Tube. Perhaps the most positive surprise is the performance of the 100-foot-long, 8-inch-diameter earth tube, which preheats incoming ERV air in winter and pre-cools the air in summer. This ECOAIR earth tube system has an antimicrobial interior coating, and sealed joints to prevent moisture and radon infiltration.

During design, we had no data on the thermal transfer rate from the ground to the tube air, and the Energy-10 computer model did not include earth tube energy input. So to err on the safe side, I simply ignored the contribution of the earth tube during initial modeling. But the temperature graph shows a fairly significant earth tube contribution. Even with low outside temperatures in the single digits, the incoming tube air maintained a fairly constant 48℉ to 49℉. The three temperature spikes on the earth tube air line were due to turning off the ERV and opening some windows to moderate interior temperatures before we installed window coverings. With the ERV turned off, the air in the tube at the temperature sensor begins to rise to interior air temperatures.

Taking one data point in late December, the outside air temperature was 14.8℉, the air temperature in the tube at the house inlet was 48.3℉, and the measured airflow through the 8-inch-diameter tube was 64 cubic feet per minute (cfm). Using the heat delivery rate equation, we estimate the earth tube was producing 2.3 kBtu per hour:

Btu/hr. = sT (℉) × 1.08 (Btu/(hr. × cfm × ℉)) × airflow (cfm)

Btu/hr. = 33.5 × 1.08 × 64 = 2,316 Btu/hr. (2.3 kBtu/hr.)

The Energy-10 model predicted a peak heating load of 4.5 kBtu per hour with passive solar gains included. This indicates that, for temperatures in the teens, the earth tube provided approximately 50% of the predicted peak heating load (although the peak load occurs at the design temperature of 5℉).

Another indication of the passive solar contribution to the heating demand was that, with no mechanical backup heating and temperatures as low as -4℉, the coldest interior temperature through the winter was 63℉ on two mornings, just before sunrise. By 10 a.m. on those mornings, the temperature was above 68℉.

Solar Hot Water Heat Coil Loop. The original plan was to tap excess heat capacity from the solar hot water storage tank to heat ERV supply air through a water-to-air heat exchanger in the ERV supply duct. We purchased all of the components and installed the heat exchanger, but did not connect it when it became clear that the house was meeting all of its heating load with just passive gain.

Space Cooling

Chimney Effect. The Colorado climate provides cool, dry nights through the summer, so we had no trouble meeting 100% of our cooling load through passive means, even with a week of record-high temperatures (in the mid-90s). The house includes a central open staircase that serves as a thermal chimney. At night, we open three small lower-floor windows on the north and south faces, and two windows at the highest point at the top of the stairwell. The convective chimney effect, plus north-south prevailing winds, pull cool air across the concrete floor and exhaust hot air through the upper windows. If we properly time closing the windows in the morning, the house does not get hotter than 76℉, since the thermal mass floor moderates the temperature. On the couple of occasions that we delayed closing the windows until mid-morning, temperatures reached 80℉ inside . With the low humidity and the occasional use of an Energy Star-rated ceiling fan, however, even these temperatures feel very comfortable.

Energy Recovery Ventilator. The RecoupAerator ERV has an “econo-cool” mode that shuts off energy transfer between incoming and exhaust air. Combined with the earth tube inlet, the ERV supplied comfortable, cool air during days that were too hot to ventilate the home via the windows.

Overhangs. Roof overhangs were designed to block most of the high summer sun, but allow maximum heat gain in the winter. We were in the second week of August before the sun started to appear on the windowsills, and into September before the sun reached the concrete floor at midday.

Domestic Hot Water

The goal of producing 100% of our hot water demand year-round with SHW was met. The backup electric element has not been used. The 120-gallon Vaughn storage tank with three SunEarth EC-40 collectors kept the water at an average temperature of 165℉ in the winter, peaking at 170° + in January and February. The average summer temperature was between 140℉ and 150℉ due to collector high-temperature limits. The lowest temperature at the top of the tank was 128℉ during a rare three-day period of cloud cover and fog.

The SHW system is an unpressurized, indirect drainback design with distilled water as the heat-transfer fluid. Three roof-mounted (39° pitch) SunEarth collectors form the heart of the system. A 15-gallon drainback tank sits in a conditioned attic, 10 feet below the top of the collectors. A Vaughn 120-gallon, dual-heat exchanger tank provides storage and backup electric water heating. A Caleffi iSolar Plus controls the system.

Hot water production is only one side of the efficiency equation—distribution and demand is the other. Every inch of hot water line in the house is insulated with 3/8-inch-thick foam pipe insulation, and we installed high-efficiency water appliances and plumbing fixtures (see “Water Conservation” sidebar).

Solar Electricity

The grid-tied PV system has 20 Sharp 224-watt modules, with each connected to an Enphase 190-watt microinverter. Total rated output, given the nominal limits (see below) of the microinverters, is 3.8 kW. We mounted the modules on our standing-seam metal roof using nonpenetrating SolarMount S5! clamps to secure the rails.

A key element in the design process was to estimate the system’s energy production. The graph on the following page shows the system’s month-by-month predicted production (generated by NREL’s PVWatts program) and actual production to date. I used a 0.82 total DC-to-AC derate factor instead of the default 0.77 derate, due to the better efficiency of the microinverters compared to a central inverter. With the exception of October 2011, the actual energy production exceeded the predicted values. October’s lower production values were due to a failed roof-mounted disconnect switch, which took out 10 modules’ production over 10 days.

Electrical Consumption

The table below shows the house’s predicted and actual electrical usage. As part of the design, we measured appliance energy consumption using a Watts Up? Pro energy meter, used Energy Star specifications for the appliances we expected to install, and estimated lighting consumption based on the number of fixtures and our expected usage. We estimated consumption for the well pump, solar hot water circulation pump, and the ERV based on component specifications and national consumption averages.

After eliminating backup space and water heating, the remaining actual electrical load was close to our predictions. However, some specific estimates were off by quite a bit. We underestimated SHW circulation pump consumption by 183 kWh per year. We overestimated the well pump consumption, having based it on a water consumption of 120 gallons per day—our actual average is about 36 gallons per day. We also overestimated the electric clothes dryer's consumption because we are using a "solar dryer" (outdoor clothesline) much more than anticipated. Our total electrical consumption, excluding the EV, averages 338 kWh per month. The EV has raised this average to 521 kWh per month, which is still much less than the average U.S. home's 920 kWh per month.

EV Energy

The energy our EV would consume was the most critical, yet most difficult, amount to predict. It would be the household's largest energy consumer. We did not know which vehicle we would purchase or what our driving patterns would be, and there was precious little manufacturer data on recharging consumption. Our prediction was based on published Chevy Volt charger specs and an assumption that the EV would require a full charge every night. Charging consumption from empty to full is higher for our Nissan Leaf compared to the Volt specifications, but it is consuming less than predicted, since full discharges are rare.

During its first 61 days with us, the Leaf consumed 366 kWh for an average of 6 kWh per day. We are eager to see how this will play out over the course of a year. Of course, with only two months of EV data under our belts, it is difficult at this point to make a long-term consumption prediction.

Challenges

Solar Hot Water. Even though the system met all of our hot water demand, the Taco pump is undersized. The low flow rate causes the collector to overheat, which in turn shuts down the system daily, except during cloudy weather. The other sign that the pump is undersized is the 55°F temperature difference between the collector inlet and outlet. Ideally, there would be only a 20°F difference. The installed pump should be able to provide a 6 gallon per minute (gpm) flow rate (2 gpm per collector) with the 10-foot head from the drainback tank to the top of the collector, but only provides 2.5 gpm. I suspect that the 12 or so 90° elbows are introducing excessive pipe friction, which is creating the 15-foot effective head—and low flow.

However, provided that the system continues to meet 100% of our demand, and we do not need the SHW system for backup space heating, it's unlikely we will replace the pump, since the pump that meets the 15-foot head requirement uses twice as much energy as the current pump.

Solar Electricity. For 10 days in October and five in January, we lost 10 modules' worth of PV production (about 11.0 and 8.8 kWh per day, respectively). The fault was finally traced to a failed 240 VAC rooftop disconnect. After switching to an air-conditioner-type heavy-duty disconnect, the problem was eliminated.

There was another inverter-related problem we were aware of during the system's design. At the time of installation, the Enphase M210 microinverter was not available, so we used the M190s that Enphase specified for our Sharp 224-watt modules. These inverters (rated at 190 watts) have a maximum output power of 199 watts, which means that, under ideal conditions, module output would be clipped at 199 watts rather than 224 watts. Our high elevation and low temperatures may be contributing to more clipping than expected—it happens three to four days per week.

Finally, a minor issue is snowfall that sticks to the modules longer than anticipated. Even with their 39° tilt, the modules don't shed snow for at least two days if snowfall is greater than 2 inches—and they are too high to be swept. One advantage of microinverters, however, is that as the snow melts unevenly, individual modules start producing electricity rather than an entire string remaining shut down until all of the snow melts.

Space Heating. In hindsight, our 10 kBtu per hour Mitsubishi minisplit heat pump was probably overkill as backup—although staying warm was a key design area where we did not want to come up short. Any future backup heating needs (they were zero for this first year) could have been handled by a small 1,500 W to 2,000 W electric heating element in the supply trunk of the ERV, and cost much less.

Conclusions

Energy design by computer modeling is only an approximation and can never completely account for variations in occupant behavior and lifestyle. Still, our Energy-10 modeling predictions came very close to reality. There is still much to be learned as we monitor the house's performance over the long term. We can safely say, however, that we demonstrated that the Passivhaus philosophy works well, and that builders can achieve tremendous energy-efficiency improvement with just a change in techniques and a modest increase in cost (see “Cost Comparison” sidebar).

Comfort and safety are very important, too. A home like ours is not for a “hands-off” family that insists on the narrow 68°F to 72°F comfort range that Americans have grown accustomed to since the widespread use of air conditioning. A passive solar home requires getting used to slightly wider temperature swings, and requires hands-on participation to occasionally open and close shades and windows to maintain comfort.

We also were pleased that humidity problems did not occur. Because of our dry climate, we purposely used an ERV for ventilation, rather than a heat recovery ventilator, because an ERV also transfers humidity between incoming and exhaust air. This worked extremely well—throughout the winter, the house remained between 25% and 35% relative humidity, the heart of the comfort zone in cold weather.

The challenges of detailed design and frustrations during construction began fading the moment we watched the electric meter run backward—and at the first of many 0 kWh electricity bills—and the first time the outside temperature dipped below 0°F, but we could sit in a 72°F house, with no heater turned on. It has been a fun and worthwhile adventure!

Access

Jim Riggins is the owner and principal analyst of EnerSmart Energy Solutions (enersmartenergy.com), a Building Performance Institute (BPI) building analyst, EPA WaterSense home inspector, and a Residential Energy Services Network (RESNET) certified home energy rater. Jim and his wife Elise showcased Heliospiti in the 2011 Pikes Peak Tour of Sustainable Buildings to show the benefits of affordable energy-efficient construction to the Monument and Colorado Springs, Colorado, communities.

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