Geo Heat Pump Performance Achieves Zero Net Energy In The Northern Sierra

Bill Martin
California Geothermal Heat Pump Association

Keywords: *Geo Heat Pumps, Ground Heat Exchanger, Horizontal Slinky® Loop, GHEX, Energy Efficient, Zero Net Energy, Net Energy Metering.*

ABSTRACT

The rural town of Quincy, Plumas County, California, is in the upper Feather River Watershed of northeastern California in a 5,852 heating-degree day[1] climate with ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) winter and summer design temperatures of +10°F and +93°F, respectively (and record extremes of -24° and 114°). Its arid sub-climate east of the Sierra Nevada mountain crest is influenced by the Great Basin. This results in wide *diurnal temperature swings* in May and September that run up to 50°F nighttime lows to daytime highs.

As a 41-year resident who was tired of burning kerosene or propane and cutting firewood, I decided to design and build a home based on renewable thermal energy and solar electricity. In this all-electric residence's first operational year under NEM (Net Energy Metering), it exported 1,503 more kilowatt hours to its electric utility than it consumed, even though its geo heat exchanger occupied what I sardonically refer to as "the world's worst soil."

This project does not represent the early adoption of a *new* technology because it's more a blend of existing conventional building approaches and HVAC (Heating, Ventilating, and Air Conditioning) technology that already exists. However, it serves to demonstrate a path in support of _Beneficial Electrification_, a buildings and infrastructure policy shift that capitalizes on electricity as the cleanest accessible "fuel," producing no emissions.

Electrically-driven refrigerant compression (via a geothermal heat pump) is the most efficient means of concentrating thermal energy for _delivery to_ **or** _rejection from_ buildings. The differences are striking when utilizing the earth for this heat source/heat sink as compared with air-based technology, and they are highlighted within this paper. I have lived in homes with both types, but I prefer a geothermal (or *ground source heat pump*) by far. This paper features the engineering, construction, and performance proof for that.

---

[1] A degree day is the total number of hours that the outdoor temperature is above or below 65°F ÷ 24. Those hours below a 65° average are counted as HDD (heating degree days) and those above a 65° average are CDD (cooling degree days). HDD and CDD are most often expressed as annual totals.

TABLE OF CONTENTS

1. INTRODUCTION

It's said that *"If you want to learn how to do something, prepare to teach someone else how to do it!"* That's pretty much what happened to me as I commenced to build my first home at age 29. Mistakes are made along the way, but the goal is to correct them and make fewer of them in the future. My cousin, a veteran of many remodels and new-home builds says, *"You never get 10 out of 10 on any construction project, but you keep struggling to hit a consistent 9.5."*

Part of what makes success possible is an awareness of past mistakes. Another is the ability to plan (in the right order). You can't decide on a roof structure until you know the perimeter and foundation dimensions. You can't build the house foundation without knowing about sub-grade penetrations and utility conduits. Extensive planning can catch conflicting design elements *before* they are committed to final architectural drawings, and that provides greater confidence that no changes will be necessary after construction begins. Building inspectors will catch any remaining errors, providing a margin of safety for all occupants.

Many who build a new home make the mistake of focusing more on aesthetics and capital costs than the operational costs. It's not just the mortgage payment, it's the utility bill (which diminishes one's ability *to carry* that mortgage). The same rubric applies to tall walls full of windows and vaulted ceilings. Aesthetically pleasing as those may seem, R-values[2] to protect against thermal losses and gains there should not be ignored entirely. Style may need to take a backseat to function, or you should at least go in with your eyes open.

Recently, I saw a property for sale on the Multiple Listing Service for $4.7 million. It was in a tony area of timbered mountains, surrounded by a golf course. Stylish. Heavy wood-and-stone architecture, soaring ceilings with clerestory windows toward views in every direction. But its

---

[2] R stands for *resistance* to thermal energy transfer. The opposite is *conductance*, (U-value) that we use to calculate quantities of thermal transfer through a building's envelope. $1 \div R = U$ (in Btu/sf/hr/°F)

6,500 square feet was heated with expensive forced-air propane and there was NO AIR CONDITIONING, just a few ceiling paddle-fans. Was that poor thinking and planning? I'd have to say yes.
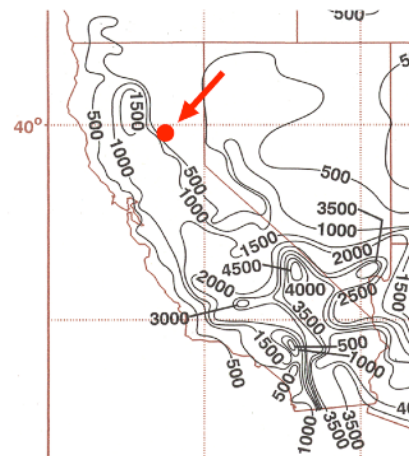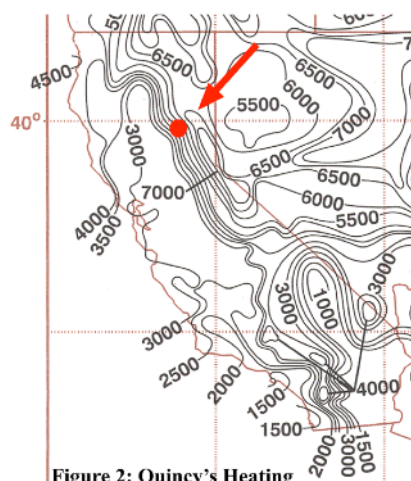
This paper tells the story of my quest for *"thermal comfort on the cheap,"* a favored phrase of mine to describe planning for a building based first upon performance. That allows for investing in style elements where you can without having to absorb excessive operating costs from heating or cooling. This approach can provide a clearer path to long-term affordability for homeowners.

Figure 1: Quincy is the county seat of Plumas County, at 3,500 feet, located NW of Lake Tahoe.

The remainder of this paper will feature optimized performance of my Quincy residence/office. It blends my interest in fighting climate change, my focus on renewable energy, my love for refrigerant compression technology, and my desire for low utility bills.

I have lived in Quincy since 1971, a spot located in Climate Zone 16, my state's most challenging zone for heating any building. The 30-year average for Quincy's degree days by NOAA (National Oceanic and Atmospheric Administration) is 5,852 HDD and 500 CDD. Our record low is -24°F, our record high 114°F. Quincy is a lopsided example of a *heating dominant* climate. Phoenix, Arizona, is a *cooling dominant* climate. Oklahoma City, Oklahoma, with roughly equal tallies of HDD and CDD, is a *balanced* climate. There is nothing disadvantageous about paying attention to thermal protection of inside space with high R-value components for the building envelope in *any* climate.

Figure 2: Quincy's Heating Degree Days are 5,852 annually.

Figure 3: Quincy's Cooling Degree Days are near 500 annually.

2. How can zero net energy[3] (ZNE) be attained with solar PV and underground dirt?

A less common path to ZNE would be if a person built an off-grid home but never used a generator for back-up power. This would necessitate electrical energy storage that would come in the form of a Lithium-ion dry battery (usually mounted on a wall) or an array of Lead-acid batteries. Both store direct current (DC) amperes gathered as a result of solar PV, a wind turbine, a mini-hydro turbine, or all of those.
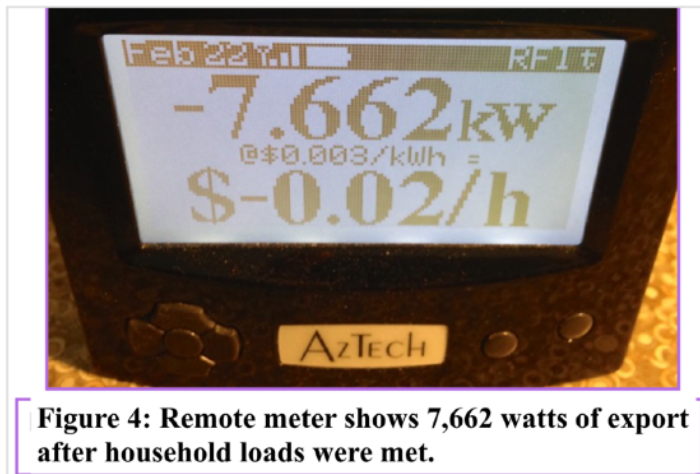

Figure 4: Remote meter shows 7,662 watts of export after household loads were met.

An inverter[4] would be required to change these DC ampere hours of storage into alternating current (AC) of the kind used to power standard household plug loads. Off-grid homes are rarely carbonless because thermal loads are substantial consumers of electrical current. Even with hot water, cooking, and refrigeration handled by a fossil-flame source, precise sizing/storage planning is still needed to see that electric loads can be satisfied by renewable electricity.

The predominant path to ZNE is a grid-connected home, usually involving a Net Energy Metering[5] (NEM) contract with the electric utility. The advantage compared to off-grid is that any amount of renewable power the customer chooses to deploy is less critical for ensuring that electrical loads are always met. The utility serves as one's battery, thereby eliminating battery expense and owner maintenance. At night or during cloudiness, consumption creates a deficit that can be reversed. You can pull five or 15 KW[6] of load from the utility on Thanksgiving afternoon, but make it up tomorrow or later in the year. Sizing of the renewable generation can be expanded to include storage for an electric-only or plug-in hybrid electric vehicle so that

---

[3] In all states *but* California, zero net energy means that the (overall) annual energy requirement to supply a building is equal to or less than the energy that is gained from the site itself. On-site electricity comes from renewable sources (nearly always solar photovoltaic). A heat pump is the mechanical equipment that delivers heating and cooling—and, in the case of geo heat pumps, water heating, as well.

[4] Electricity is normally not a "stored" resource, but with DC storage, an inverter can become one's own custom power plant with 99% efficiency. It makes sine wave current (on demand) that is more precise than that from an electrical utility.
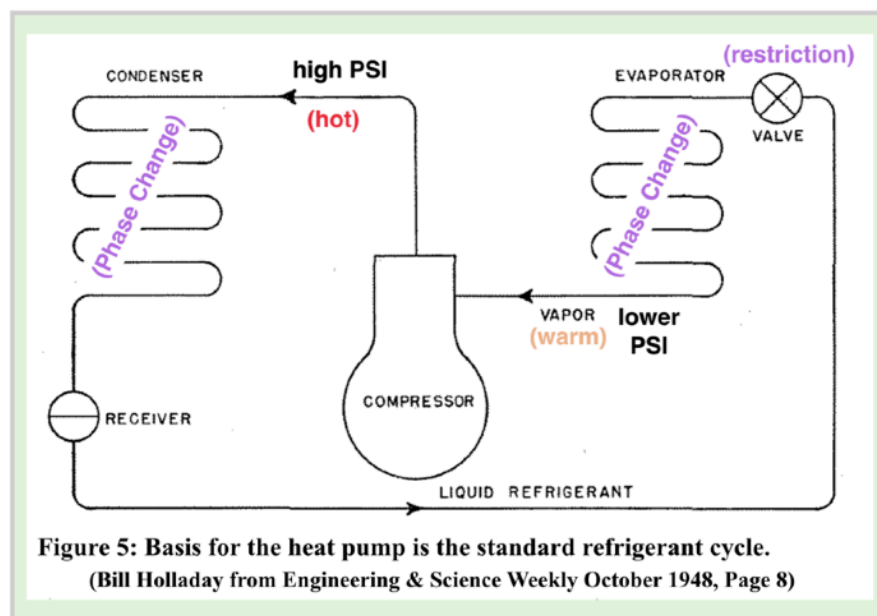
[5] NEM is an arrangement where kilowatt hours can be *pulled from* the utility or pushed back through the meter and *exported to* the utility for credit. Net consumption is billed and paid on a single date each year. If the utility sells power in increasingly expensive tiered prices, large exports can earn high credits that (as in the case of the Quincy ZNE house) offset heavy winter use at lower prices.

[6] One KW of electrical load represents an instantaneous demand of 1,000 watts. A standard electrical resistance-powered water heater would pull 4.5KW whenever it operates.

renewability can extend to transportation. That concludes the means of creating electric fuel for a carbonless building in attempting to achieve ZNE.

The second portion of this segment involves the means of adding or subtracting thermal energy from the interior spaces of a building. The only technology that's all-electric and can provide both heating *and* cooling is a heat pump. Perhaps, unknowingly, you are already familiar with one-way devices that are cousins to a heat pump. Consider the common refrigerator-freezer and the vehicle air conditioner. Your kitchen refrigerator is surrounded by 70°F air and yet it keeps one of its sections at 38° and another at 0°. Your car's interior may hit 80° before you reach for the air conditioner. Outside it might be over 95° while under the hood it may be 135-150°. *How is it possible* to receive cold air under such conditions?

All of these appliances operate on a technology called refrigerant-compression, except that a heat pump can *reverse* its refrigerant flow, making BOTH heating and cooling possible with the same equipment. As seen below, heat pumps have been around for awhile. Lord Kelvin[7] (1824-1907) theorized and experimented with the means by which refrigerant-compression occurs. Others have perfected the design.

Figure 5: Basis for the heat pump is the standard refrigerant cycle.
(Bill Holladay from Engineering & Science Weekly October 1948, Page 8)

In the diagram above, you can see that the refrigerant path passes through an *evaporator* in order to become a gas that can be successfully superheated inside the compressor. The high pressure hot gas passes the *condenser*, where it gives up its heat, becoming a liquid. Whatever thermal media has surrounded the *evaporator*, enough of its thermal energy was transferred to the refrigerant to accomplish a phase change from liquid-to-gas.

_____

[7] Lord Kelvin (William Thompson of Scotland) was responsible for creating the temperature scale that bears his name, for establishing the Second Law of Thermodynamics, and was instrumental in designing the first trans-Atlantic undersea telegraph cable.

Phase changes are the heavy lifting in thermodynamics. Refrigerants are custom designed to evaporate and condense at a certain target temperature depending upon their equipment's intended use. For heating, high amounts of thermal energy are consumed to *evaporate* the refrigerant and high amounts are *released at the condenser.* This is the heat source/heat sink relationship. During cooling, your house provides the heat for evaporating the refrigerant. The refrigerant compression cycle[8] does not *create heat,* it only concentrates and *transfers* it.

Heat pumps have three loops. The outside loop (#1) interacts with refrigerant at a heat exchanger that either evaporates refrigerant or condenses it. The refrigerant loop (#2) is located inside the heat pump. The inside loop (#3) transfers heat between the refrigerant and the conditioned air. The two heat transfer structures (*evaporator* and *condenser*) remain stationary. The refrigerant loop's reversing valve is what can change the direction of the refrigerant between them.

With an *air-source heat pump[9]* (ASHP) in the heating mode, the evaporator is an outside, air-fed fan coil, and the condenser is an inside fan coil through which a ducted air loop (#3) cools the hot refrigerant gas back to a liquid, distributing that heat through in-home registers.

With a *ground-source (or Geo) heat pump[10]* (GHP) in the heating mode, the *evaporator* energy comes from an underground liquid loop (#1) known as a geothermal heat exchanger (GHEX). It is designed to provide water at a temperature between 35 and 85°F from depths up to 600 feet. There is adequate seasonal delivery and absorption of solar energy by the earth to maintain these temperatures (this has nothing to do with hot rocks or steam).
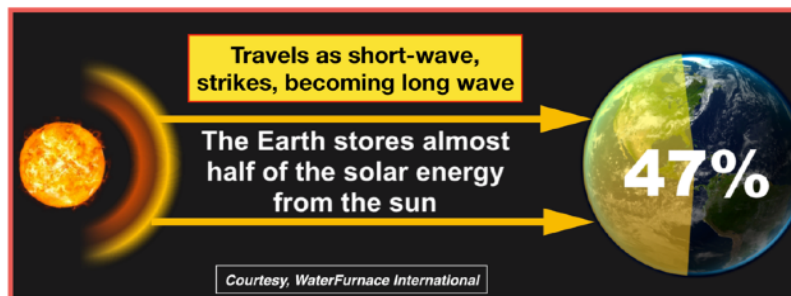

Figure 6 & 7: Resources for geo heat pumps are worldwide, less remote/random than hot rocks or steam.

---

[8] The refrigerant-compression cycle might use 48° dirt to create 145° refrigerant to heat a house to 72° while a fossil furnace burns fuel for a 3,000° flame for the same end result. Efficiency?

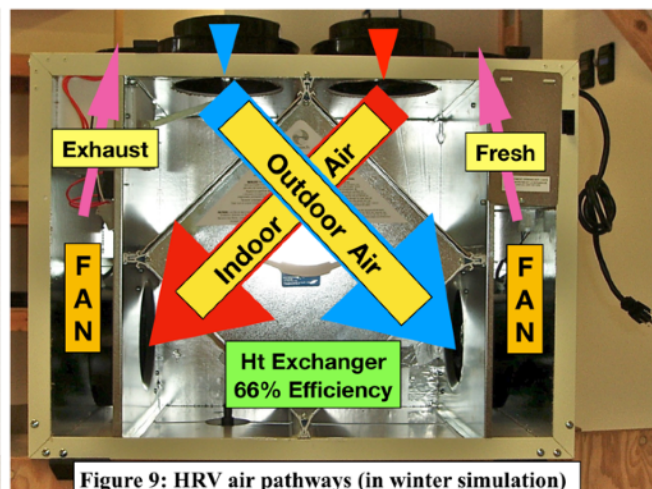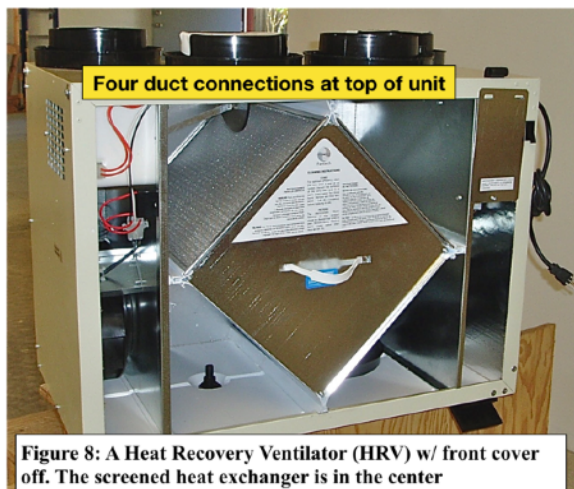[9] ASHPs pass refrigerant through a fan coil to use air as a *heat source* **or** *heat sink*.

[10] GHPs pass refrigerant through an internal heat exchanger connected to an underground liquid loop called a geothermal heat exchanger that provides closed loop water as a *heat source* **or** *heat sink*.

3. Building construction techniques to minimize heating and cooling loads.

In the last four decades as interest in energy conservation has grown, residential homes have become better armored against convective heat loss by fighting the *infiltration[11]* of outside air. Though they haven't yet equalled the performance of a Thermos® bottle, they have brought out some negatives that high occupancy commercial buildings do not experience. Commercial buildings are required to import 15 cubic feet per minute (CFM) of fresh air per hour per average occupant. This increases heating/cooling loads, but it ensures comfort and respiratory health.

Recently, residential buildings have caught on by installing heat recovery and energy recovery ventilators (HRVs and ERVs). These ventilating devices use a heat exchanger to maintain 66% of existing temperature by using exhaust air to pre-condition incoming fresh air. This means one could avoid the incoming noise and dust of opening windows. It also means that ventilation can be scheduled.

The subject house of this paper uses an HRV that *imports* fresh air through a duct leading from an upper gable wall to its heat exchanger and from there to the ducted return air stream that leads to the heat pump[12]. *Exported* air also goes to the heat exchanger before heading, via ducting, to an exhaust port in an upper gable wall. The two air streams do not mix. Both HRVs and ERVs can be installed completely separately from a ducted HVAC system.

Figure 8: A Heat Recovery Ventilator (HRV) w/ front cover off. The screened heat exchanger is in the center

Figure 9: HRV air pathways (in winter simulation)

The last tactic in the battle to stop infiltration heat loss in new construction is the use of a vapor barrier, located over wall framing and under drywall (or other wall covering). Fiberglass batts that are faced with paper or aluminized paper serve this purpose by minimizing air flow. They also stop the loss of interior humidity in winter, which would otherwise reduce the comfort of occupants, creating a need for higher thermostat settings.

---

[11] Infiltration brings outside air inside through gaps and cracks around windows and doors; sometimes through wall areas poorly insulated or ceiling penetrations of lighting or vent stack perimeters.

[12] By synchronized controls, the heat pump runs its circulating fan only at low speed to boost the fresh air through ductwork and all three zones, unless a zone thermostat is calling for heating/cooling.

My favorite method (used on the Quincy ZNE house) was to use 6-mil polyethylene sheeting, draped and stapled before drywall covered those insulated walls. Next, we move on to the remaining two paths of heat loss/gain. They are *radiation* and *conduction,* (the largest).

Radiation heat transfer can take place from any surface of a conditioned building. If a building's envelope surface is warmer than surrounding air, there will be a loss, dependent on a difference in temperature between the two, called delta T (Δt). This is the smallest heat transfer mechanism.

Let's prove it in a way you'll remember by getting down and dirty. Normal human interior temperature is 98.6°F. Outside skin temperature at limb extremities is more like 87.5°F. Now, imagine two naked human bodies standing two feet apart in air that's 65°F. They have little radiation heat transfer between them because of no Δt, but from each to the air, the transfer by radiation is driven by a differential of at least 12 degrees. Only if one of them had a hyperthermic body temperature of 60°F would radiation between them increase like their previous radiation loss to open air. But, cause them to embrace and *conductive* heat transfer between them would far exceed radiative transfer between them or to anywhere else. This is because of having created a direct pathway for *conduction* with a significant Δt.

You've probably seen one of those infrared photographs from a sensing device that shows the outside skin of a conditioned building in blues, yellows, and reds. This is an energy auditor's tool that picks up heat energy coming from surfaces of a building envelope. The image illustrates total energy transfer, although we know that conduction is the largest component unless this building's envelope is constructed of single-pane glass. The infrared scope is also useful for a before/after comparison after retrofit treatments. Color changes will hint at success without your having to wait for the utility bill. Over many such measurements, an energy auditor may develop over time an increased certainty for predicted savings from varied retrofit treatments.

Builders of new structures have fewer mysteries due to codes and standards that require minimal insulation compliance before permits are issued. The standard new home requirements seem to continually ratchet up, and a common means of measurement for that is the HERS[13] Index.

Figure 10: The HERS rating system

Let's get back to our largest heat loss/heat gain challenge, that of *conduction*. From the inside skin of your home's interior to the outside air is the path of heat loss and gain that we prioritize. The best remedy against this transfer is appropriate insulation. The rule of diminishing returns holds true here. Insulating the wall, ceiling, or floor envelope assemblies to R-90 will not be cost effective (unless you're building a habitat at the South Pole). And if your target is zero net energy, there needs to be a balance to your
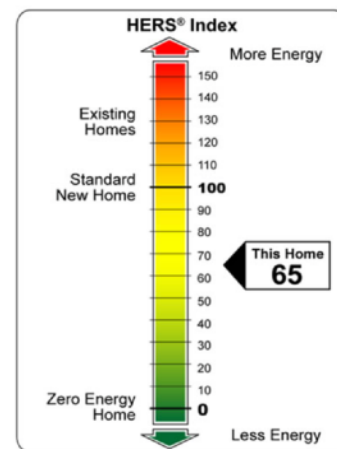
---

[13] Home Energy Rating System. With a HERS score of 65, a new home performs 35% better than the (current) standard home energy efficiency requirement.

hunger for insulation with the need to access renewable on-site electricity. Even in the climate of Fairbanks, Alaska (with its annual HDD of 13,800), a super-insulated home design would probably stop at R-60 ceilings, R-40 walls, and R-30 floors.

By comparison, the Quincy ZNE house has envelope assemblies of R-51 ceilings, R-33 walls, and R-30 floors. Those floors were built on 11 7/8" deep truss joists on 16" spacing and were stuffed conventionally with R-30 batts from below using "lightning rods"[14] for support with no vapor barrier. Let's now focus on the walls and ceiling before we move on to attic ventilation.

I had experience with rock wool, scattered fiberglass "nuggets," blown cellulose and fiberglass, and various kinds of wet foam and foam sheathing products. However, I discovered a favorite treatment for walls and ceilings and a professional installer who was willing to do the work. Though the unheated, 1800 square feet of garage space received R-22 fiberglass batts with vapor barriers along perimeter walls, the remainder of the home's 3,265 square feet of conditioned space was built with a wide-plate, double offset stud wall system that made room for an R-30 blown fiberglass fill with no conduction path except at top and bottom plates, where the framing was 2"x 8" softwood (providing only an R-1.25 rating per inch of thickness).
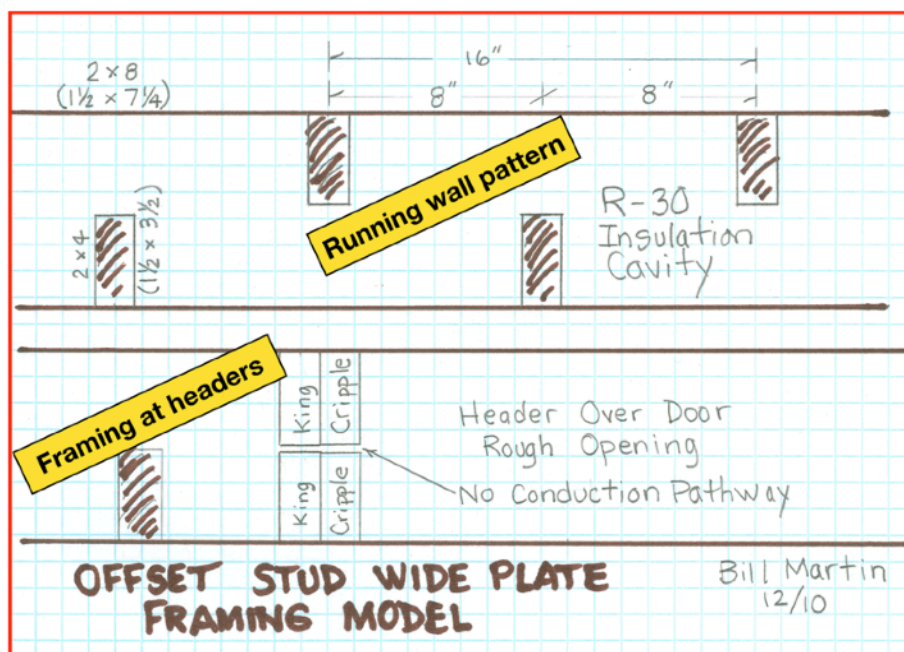

Figure 11: Author's wide plate, double offset stud wall.

This design minimizes heat loss or gain because no inside wood framing member can carry thermal energy directly *by conduction* to the outside air or from it to the interior. The product chosen for walls was Johns Manville's Spider®, a blown fiberglass applied with a water-based mastic to help with self-adhesion and attachment to the inside of exterior sheathing.

---

[14] Spring steel wire with sharp ends cut longer than the truss pocket, pushed into an arched position.

The installation truck (with a large van box) had a powerful blower fed by a chopper that fluffs densely baled fiberglass, sending it through a 4-inch flexible hose. The application nozzle at the exit becomes a rectangular opening, the top and bottom of which carries a small tube of sprayed coagulant, allowing the fiberglass to become adhesive to itself and the surface it meets in the wall cavity.

Figure 12: Clearing excess insulation to ready for 6-mil poly sheeting for R-33 assy.

Application continues until the insulation's thickness exceeds the inside surface of framing. Then, an electrically-driven, spinning squeegee shaves the excess which falls to the floor, creating quite a volume. But a second hose with a powerful vacuum consumes the excess, dumping it back in the truck's chopping hopper, returning as newly applied insulation. Therefore, there is no waste in this process.

Figure 13: Blowing dry fiberglass to R-49 in attic.

Fiberglass insulation blown into the attic is a slightly different material. It does not receive a mastic spray. It doesn't have a nozzle fixture other than to be directionally guided by the installer's gloved hand, and none of it is waste that returns to the truck.

Before the ceiling or wall insulation applications began, paper ruler guides were stapled from the bottom of the ceiling's truss chords upward into framing so that the installer had a depth reference. At the same time, ventilation baffles (shown in both figures above) were stapled in place so that insulation could be blown deeply against them without compromising incoming soffit ventilation air entering the attic. After those preparations were completed, the construction sequence continued—blowing and shaving the walls, stapling 6-mil polyethylene to the inside of the walls, installing ceiling and wall sheetrock, and then taping and texturing. Finally, the attic over conditioned living space was insulated to R-49 and that over garages to R-30.

Fresh-air ventilation from an HRV was not the only critical air flow in this house. The other was exterior ventilation to-and-through the attic space, for two reasons. First, fresh air from outside is

usually drier than an attic space, and keeping the insulation as dry as possible ensures its maximum performance. Second, moving a large volume of air through the attic and outward through continuous roof ridge venting is a sure-fire way to keep attic temperatures lower and to cycle them down by the next morning. Fireproof vent strips run in horizontal soffits under truss-end eaves, and they allow air to pass upward through bored holes in tall Frieze blocks between raised heel trusses over load-bearing walls.
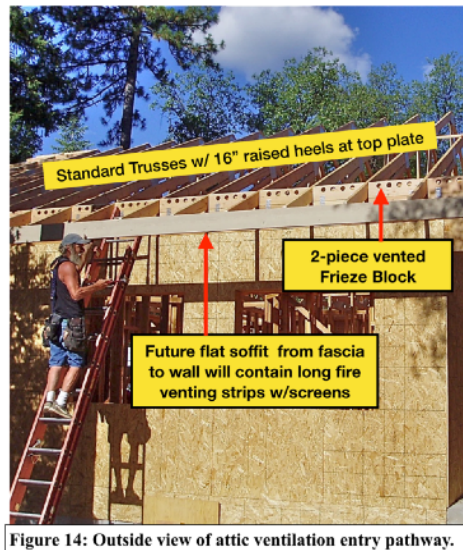

Standard Trusses w/ 16" raised heels at top plate

2-piece vented Frieze Block

Future flat soffit from fascia to wall will contain long fire venting strips w/screens

Figure 14: Outside view of attic ventilation entry pathway.

Future 4-foot long aluminized paper baffles from bottom of holes will protect a pathway for venting air above deep insulation fill

Load bearing wall carrying raised heel trusses. Two-piece 16" tall Frieze blocks each carry four 2" diameter vent holes
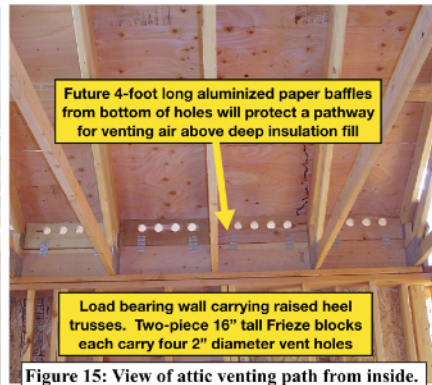
Figure 15: View of attic venting path from inside.

There is an electric thermistor located mid-level in the tallest attic space that continually measures temperature and plots this with other thermal data from around the building to a server on the Internet.

On the hottest days of summer when the attic briefly approaches 130°F, the *convective draw* from eaves and through ridge venting reaches its peak flow because of a wide Δt. By next morning, the attic temperature and the outside air temperature are usually equal. Sometimes the attic is slightly less. The majority of the earliest attic temperature drop may be from convected ventilation. But remember that large, flat surfaces (such as the roof) will radiate heat to a cooler night sky if it is cloudless. In summer, the Quincy microclimate provides plenty of both.

I used an attic exhaust fan in a 1977 house, rigged to run on either excess temperature or humidity. It was an early mistake, demonstrated by an inadequate pathway for incoming and outgoing air. Continuous ridge venting at roof peaks was not used and was nearly unknown at the time. Button vents *should have been used* in the upper roof surfaces. A passive system with adequate inflow and outgo will thermo-siphon increasing air through the attic as its Δt increases over outside air without fans and electricity consumption. Currently, there is a variety of continuous ridge venting available, and roofers are well-versed in its use.

There are other advancements that can be a tremendous help in fighting summer heat build-up and in reducing discomfort and/or air conditioning costs. There is roof sheathing that carries a radiant barrier on its underside that will keep heat build up in the sheathing and roofing materials but largely

Escape gap for continuous ridge venting (cap) to convect attic air out in favor of eave-Frieze block incoming air
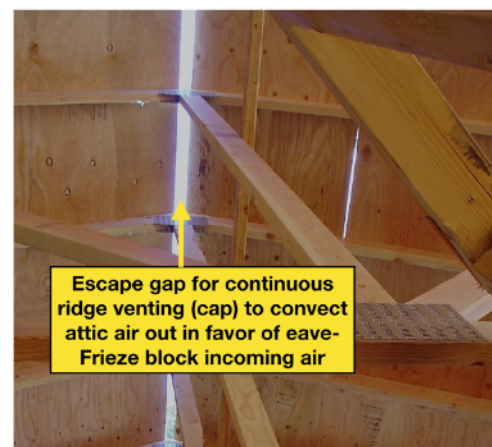
Figure 16: Upward view of continuous ridge preparation

out of the attic. When this house was begun (2012), the differential cost between this product and standard roof sheathing was 30%. That was too costly for a wide, single-story structure with

complicated roof and gables that consumed (400) 4'x8' sheets of plywood. The alternative was "cool roof" shingles.

They look like any three or four-tab composition shingle, but the surface granules have been soaked in a chemical with unique spectral qualities. Standard shingles will reflect only 9% of incoming radiation, depending on color. Cool roof shingles will reflect 28% and (through long-wave radiation) emit 70% of the heat that remains.

Figure 17: The Quincy ZNE house has 30" overhangs and 9 gables.

Convective venting in winter has been shown to lower the attic temperature somewhat, but keeping insulation drier than it would otherwise be is a compensating factor. The thicker the attic insulation, the greater the time delay until the inside ceiling is affected by changing temperature.

The last element of defense for a thermal envelope is glazing (windows), which can range from high performance and expensive, to lesser performance at lower cost. Fortunately, standards set by the National Fenestration Rating Council and local building codes make the choice a bit easier. I chose an effective performer in a type I prefer—insulated vinyl.

This was not a passive solar house, so solar transmission was cut to .20 to save furniture and keep excessive radiation out. Visible transmission of .47 maintains outward visibility but provides more privacy when a window curtain is open. A U-value of .28 is good but remains over nine times as conductive as the R-33 wall assembly in this house (curtains or shades not counted). Argon-filled space and a coating for anti-emissions on the inside of each pane (double-E coated) has become the standard approach in most windows.
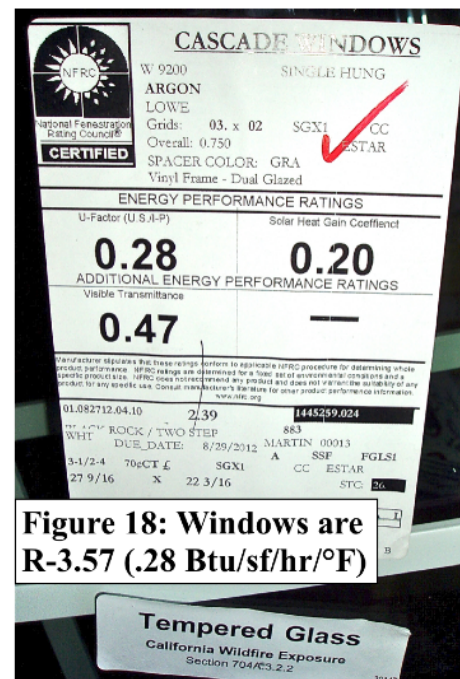

Figure 18: Windows are R-3.57 (.28 Btu/sf/hr/°F)

That concludes a review of this house's thermal envelope. Building it above minimum standards pays off in comfort and savings. Those savings come from smaller mechanical equipment for heating and cooling, pulling less electrical power. Having made strong efforts to minimize thermal loads, we are now ready to specify the HVAC equipment that will satisfy them.

4.   Geo Heat Pump (GHP) specification and sizing to the building's loads.

The ASHRAE winter design temperature of +10°F was used to calculate heating load of the subject house, and produced an hourly load estimate of 17,000 BTUs per hour. When HRV operation for four hours per day was added, the load came to 19,000 BTU/hr. This guided the choice of a ducted air, dual-speed GHP model[15] rated at 36,000 BTU/hr. on high (3-tons[16]) and 24,000 BTU/hr. on low (2-tons).

This was a very small heat pump for a conditioned space of this size, producing a maximum of only 1,350 cfm (cubic feet per minute). Pushing all this out of 19 floor registers simultaneously as one zone would feel more like a "draft" than a "flow" of conditioned air. Also, a single-zone approach would necessitate a centrally located thermostat in a very wide/long single-story building. It would suffer lots of perimeter cooling before that thermostat started up the GHP. For this reason, a three-zone, three-thermostat arrangement was chosen.

This GHP's thermal output (Figure 19) is possible, provided that entering water temperature (EWT) to the heat pump is equal to or warmer than the nameplate

Figure 19: The Quincy ZNE house's 3-ton 3-zone heat pump in heating simulation.

testing temperature of 32°F in 3-ton operation or 41°F in 2-ton operation. Lesser loop temperatures would yield less output.

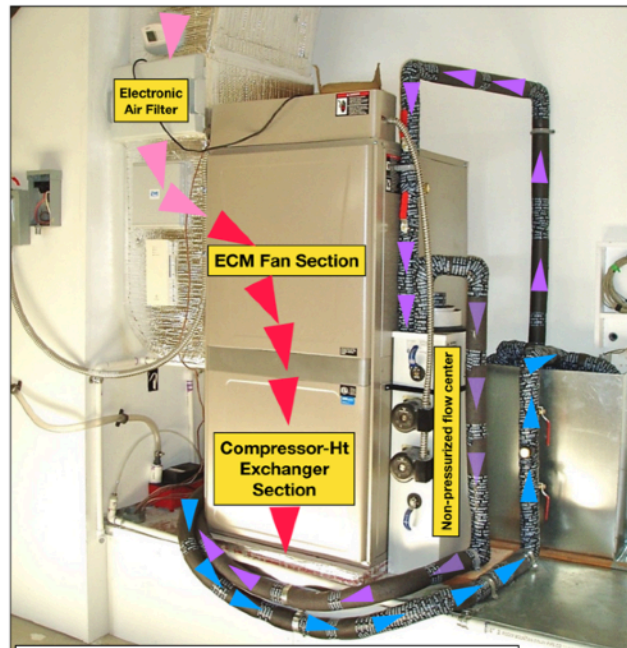That brings us to a major part of the story of the Quincy ZNE house—its GHEX in some of the least helpful underground strata that can be found. The land here was purchased before this construction was considered, so an alternate location with deep, uniform moist silt was not an option. The GHEX became the critical element of this entire project and encouraged me to conduct an operational testing regimen[17] that has demonstrated the effectiveness of my choice of GHEX. The local driller (for a vertical GHEX) was expensive and ceased geo drilling shortly after this construction began.

---

[15] Enertech GXT-036 water-to-air geothermal heat pump with a non-pressurized closed water loop.

[16] A ton of heating or cooling is equal to the Btus necessary to completely melt a block of 2,000 pounds of ice that is at a temperature of 32°F. It has been a common HVAC quantifying term for decades.
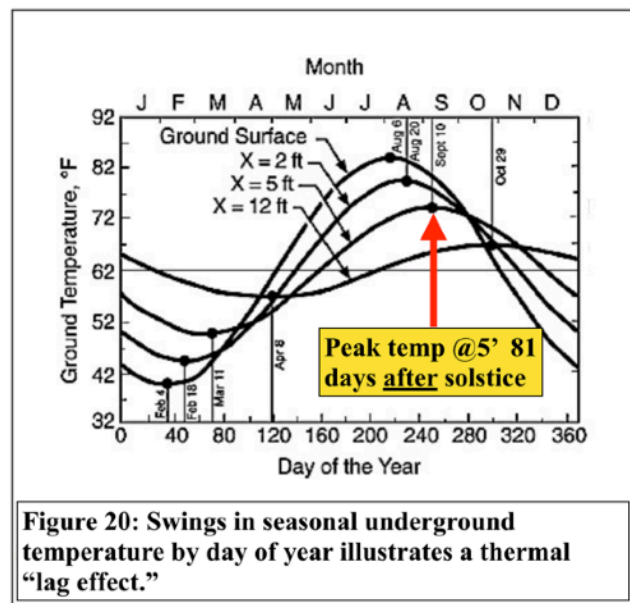
[17] 48 bi-weekly tests during live operation between November and April have spanned four years.

5.   Ground heat exchanger (GHEX) engineering for adequate thermal conductivity.

The hydrogeology of this alluvial fan location at the bottom of a north-facing canyon, extending to 7,000 feet is a challenge. A nearby well (60 feet away) had an average depth to water of 30 feet, and this was likely to carry cool water for much of the winter heating season due to snowmelt.

While it should be acknowledged that Figure 6 credits an even distribution of the sun's radiation to underground storage, local hydrogeology at my homesite could diminish that thermal availability. Subject to cost considerations, a 200-foot deep, vertically-drilled borehole with a single U-bend pipe loop encased in grout is the gold standard. This is because once you account for seasonal temperature change, there is no variation below 25 feet, meaning that nearly 90% of the GHEX is inside an unchanging thermal strata. In this case, that 90% might have been cold water.

Ultimately, I chose a horizontal Slinky® deployment of (4) 800 ft x 3/4" HDPE[18] heat exchange pipe loops at seven-foot depth based on consultations, calculations, and what appeared to be a too shallow, catastrophically short-looped[19] installation 150 feet away that burned out its heat pump's compressor in the first winter. The compressor was replaced, but now the homeowner burns wood, only enjoying a geo air conditioner during summer months. That outcome gives the industry a black eye. It could have been avoided by a properly sized GHEX, or by enabling plenum-mounted strip heaters.

Figure 20: Swings in seasonal underground temperature by day of year illustrates a thermal "lag effect."

Short-looping is potentially the most vulnerable "Achilles' Heel" threatening GHP longevity and interior comfort.

Now, for a comparison with the ASHP situation. If an ASHP operates in difficult heating conditions, its compressor simply runs longer, pushing more air against the outside heat exchanger to satisfy its thermostat's set-point. If that's not enough, strip heaters can help out (as they do during defrost cycles at the outdoor coil). Both additions of resistance electric heating drop efficiency, and runs up the electric bill.

---

[18] High density polyethylene pipe with wall/diameter ratio of 11 (SDR-11).

[19] Too little pipe (295' per ton) to exchange with earth and feed the GHP with adequately warm EWT.

Heat exchange via an underground pipe wall against dirt can only access a few feet outbound of what it is in contact with. Over a short time period, there is a limit to how much heat can be gathered or rejected in this fixed-exchange territory. Short looping guarantees that the closed water loop GHEX will run hotter and hotter under stiff cooling loads and cooler and cooler under heavy heating loads, thus over-working the GHP's compressor. Run times could become continuous. Adequate loop length for a GHP is far more critical than the unlimited open air available to the ASHP.

The short looped homeowner with a compressor failure had a 3-ton heat pump with a GHEX pipe length of 295 feet per ton at an average four-foot depth. My 3-ton heat pump GHEX was fed by 1,067 feet per ton and was three feet deeper. Circulating loop water in a GHEX is 3,000 times as dense as the air that feeds the outdoor coil of an ASHP. This boosts conduction between the GHEX and the strata it lives in, but that won't serve as a benefit if the pipe is seriously short looped.

The vertical white box in Figure 19 is a two-pump flow center that feeds nine gallons per minute to the GHP's internal heat exchanger. This closed loop, 3,200 foot GHEX carries a 116-gallon mixture of 80/20 water/methanol that heads underground and returns in 11 minutes. When running on low capacity (2-tons as it does 95% of the time in winter) loop water departs the GHP's heat exchanger 3° cooler than it arrived.

Running on high capacity (3-tons) in winter, loop water departs 4° cooler than it arrived because the heat exchanger is extracting more energy from it. This water restores its temperature through *Δt-powered conduction* during its next pass underground. The lowest EWT recorded in this system during testing was 35.2°, and the 48-test session average over four winters has been an EWT of 43.3°. This means, considering 95% of run-time on low capacity, the GHEX has fed the GHP's internal heat exchanger at or above nameplate temperature specifications.[20] It should be noted that for much of the period of winter heating, EWTs were *above* nameplate assumptions, likely more than compensating for brief periods of 3-ton operation below the standard EWT of 41°F.
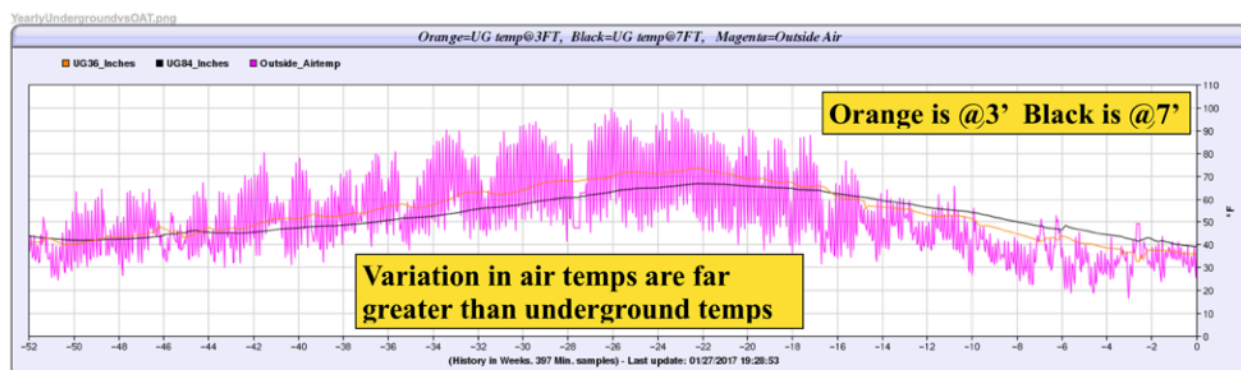

Figure 21: Outdoor air temps and underground temps for year ending 1-27-17.

---

[20] ISO Standard 13256-1 (International Organization for Standardization) is based on Part Load EWTs of 41°F for heating and 68°F for cooling with ground loop-based heat pumps.

Regardless of how close EWTs track to the ISO standard's target temperatures, Figure 21 *proves* that at the Quincy ZNE house, the 7-foot GHEX depth is working easily to feed its geo heat pump, while an ASHP would struggle from the greater variation of outside air temperature.

The most helpful factor in a horizontal GHEX deployment is when the system is spread out over the greatest available land area.
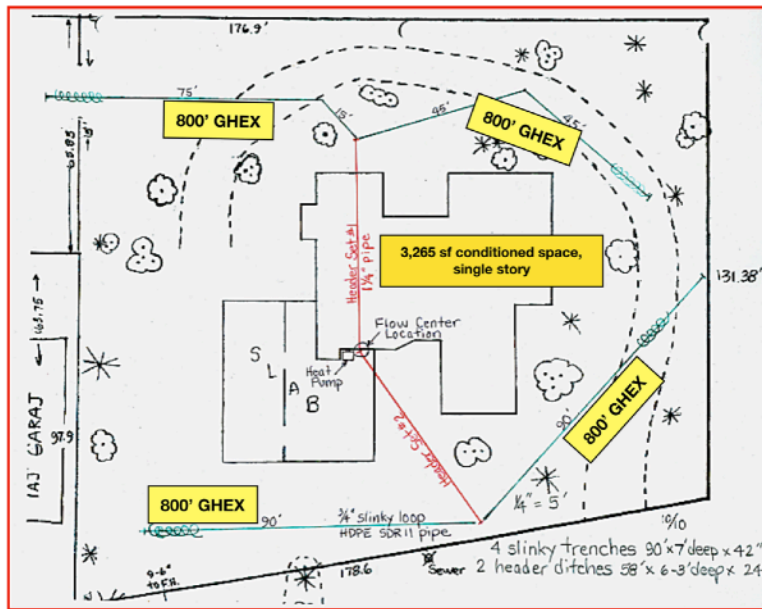

Figure 22: Plan view: house, lot, GHEX

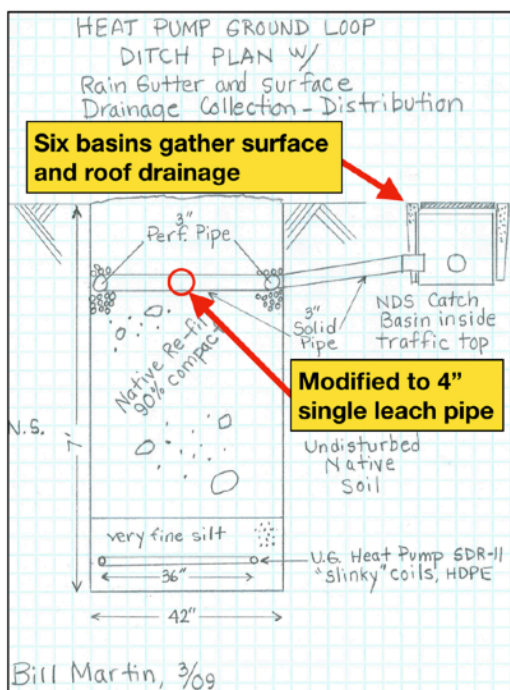Figure 23: Bedding the Slinky® within a fine silt sandwich.

Figure 24: Trench design X-section

With a poorly conductive soil and a Mediterranean climate whose heaviest precipitation falls after the beginning of the heating season, it was necessary to take steps to keep this GHEX's loops moist for maximum conduction.

This was accomplished by packing the GHEX within a one-foot layer of fine silt (mine stampings) that would make better contact with pipes than coarse sand and pebbles and that could retain moisture better. Figure 24 shows the early plan to send gutter and surface water into drain rock via leach pipe to transfer any rainwater for this purpose.

By calculation, one inch of rainfall on this large roof surface produces 300 gallons of water that is sent directly where it's useful to the GHEX.

6.   Ground loop testing and thermal performance at the Quincy ZNE house.

As featured previously, the GHEX-to-underground interface is where the *"rubber meets the road"* in receiving a GHP system's potential. Testing that followed installation was necessary to better understand utility costs, partly because as the designer-owner-builder of this house, I am a curious sort and partly because I am an advocate for GHP technology.

Testing has been performed on Saturday mornings during GHP operation for four years to date. There have been 12, two-week intervals over each year's heating season. A two-month sample and a table of yearly summaries follows in Figures 25 and 27. All numeric temperatures are generated by thermistors, uploaded continuously and plotted into graphs as in Figure 27.

Date	Time	OAT (Outdoor Air Temp)	EWT (Entering Water)	LWT (Leaving Water)	◊t (Temp Difference)	EAT (Entering Air Temp)	LAT (Leaving Air Temp)	HWIN (Hot Water to DSH)	HWOUT (Hot Water from DSH)	R1< dsh (Compressor Gas)	R2> dsh (post-DSH Gas)	°F3ft (Ground Temp)	°F7ft
2/20/16	7:35	37.5	40.5	37.5	3.0	68.0	85.9	107.7	110	142.7	117.5	43.3	42.4
	7:40	37.4	40.4	37.4	3.0	68.2	85.9	108	110.4	144.2	118.1	43.3	42.4
avg. EWT=	7:45	37.4	40.3	37.3	3.0			110.6	145.2	118.4	43.3	42.4	
40.3	7:50	37.4	40.3	36.1	4.2	100% Compressor		111.3	146.7	122.2	43.2	42.4
1.3	7:55	37.5	40.2	36	4.2	68.8	88.5	108.7	111.6	147.6	122.7	43.2	42.4
3/5/16	7:20	46.2	42.2	39.2	3.0	69.0	86.5	87	90.5	145.6	105.5	47.6	43.6
	7:25	46.2	42.2	39.2	3.0	69.1	87.0	89.2	Shower in use	107.1	47.6	43.6	
avg. EWT=	7:30	46.5	42.1	39.1	3.0	69.2	87.1	89.9	93.5	146.6	107.6	47.8	43.6
42.1	7:35	46.7	42.1	39.1	3.0	69.4	87.2	90.4	94	147	108	47.8	43.6
1.8	7:40	46.8	42.1	39.1	3.0	69.5	87.3	90.8	94.4	147.2	108.3	47.8	43.6
3/19/16	7:10	38.1	44.2	40.9	3.3	67.7	85.0	96.0	97.2	125.1	104.8	45.9	45.8
	7:15	38.4	44.0	40.8	3.2	68.1	86.9	97.0	99.6	135.6	109.3	45.9	45.8
avg. EWT=	7:20	38.5	43.8	40.7	3.1	68.5	87.2	97.2	100.0	141.0	111.1	45.9	45.8
43.8	7:25	38.4	43.6	40.4	3.2	68.8	87.3	97.6	100.5	142.4	111.7	45.9	45.8
1.7	7:30	38.6	43.5	40.4	3.1	68.9	87.3	98.1	101.1	143.6	112.4	45.9	45.8
4/2/16	6:30	40.1	44.2	41.1	3.1	69.5	88.4	96.7	100.0	145.4	112.2	47.5	45.3
	6:35	40.0	44.1	41.0	3.1	69.5	88.5	97.2	100.3	145.8	112.5	47.5	45.3
avg. EWT=	6:40	40.0	44.1	41.0	3.1	69.6	88.6	97.7	100.8	146.2	113.0	47.5	45.3
44.1	6:45	40.0	44.0	40.9	3.1	69.7	88.6	97.8	101.0	146.6	113.2	47.5	45.3
0.2	6:50	40.5	43.9	40.9	3.0	69.7	88.7	98.4	101.5	146.8	113.6	47.5	45.3

Figure 25: 2 months' loop performance testing at the Quincy ZNE house.

In the column labels above, HWIN and HWOUT refer to a "DSH." This stands for the De-Superheater. It is a secondary heat exchanger between the hottest compressor gas output and a pumped, potable water pre-heat circuit that, during the heaviest heating of the winter, regularly exceeds an output of 120°F. It also performs the same function in summer.

Also shown above are two red boxes highlighting anomalous situations. The first (100% compressor) shows the difficulty of keeping the GHP operating at only 2-tons, even if heating

isn't necessary. The unit over-responds to my efforts between two thermostats to keep the unit going, but holding at only 67% of capacity. The increased Δt appears as 4.2°. The second ("Shower in use) is the result of newly introduced cold water from the utility (47° this time of year) when an unannounced shower begins just as testing does. Temperature recovery during the testing period can be seen.
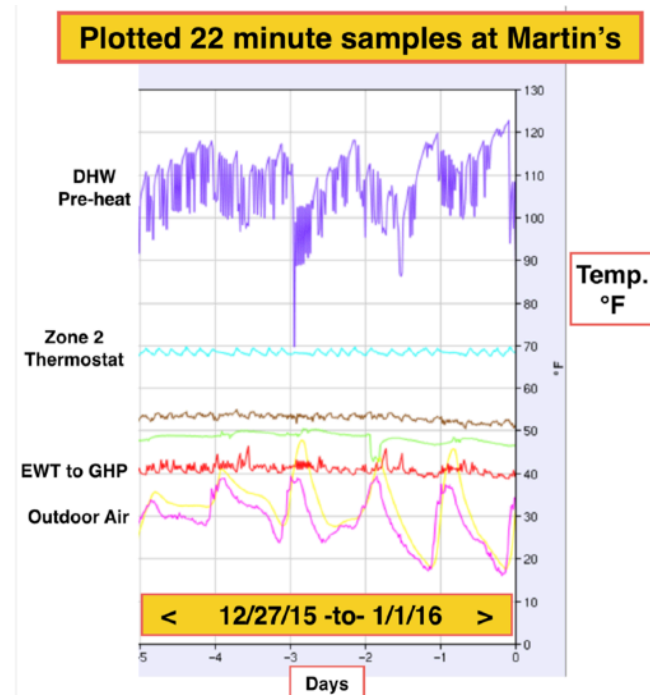

Figure 26: Five days of GHP operation in '15-'16

Figure 26 shows the gap between outdoor air temperatures (OAT) and EWTs, steady Zone 2 temps, and warming hot water in the pre-heat tank.

Figure 27 shows a summary of the most critical temperatures tracked during four years of testing. The results are good (and somewhat predictable). A comparison of rows 88, 90, and 91 in Figure 27 illustrate that the *highest* average EWT (45.6°) produced the *lowest* average hot water from the de-superheater (101.8°) during the warmest average OAT test temperature. This is appropriate, since thermostats stayed satisfied longer, calling on the GHP for less run-time, making fewer gallons of hot water.

By contrast, the same data from those rows, located in column J, show the *reverse* run-time relationship to hot water production.

	Column	G	H	I	J
	Yearly Average Winter Heating Performance Summary				
Measured by thermistors All Values in °F		48 tests over 2014-2018			
Nov -to- Apr *Tests Bi-weekly, Saturday mornings*		14-15	15-16	16-17	17-18
First Underground Temperature @7 feet		///////	///////	56.1	56.0
Last Underground Temperature @7 feet		///////	///////	43.2	44.2
First test Entering Water Temp (EWT)		56.3	57.4	52.6	51.8
Last test EWT		46.4	44.1	42.2	43.6
Average test EWT		45.6	44	41.9	41.8
Min test EWT		40.9	38.9	35.2	36.3
Average Outdoor Air Test Temp (OAT)		35.9	33.9	31.9	30.7
Average Hot Water Out of De-superheater		101.8	104.3	110.8	111.6
Success in a heating dominant climate requires beneficial Entering Water Temperatures (EWT)		NEM Yr #1	NEM Yr #2	NEM Yr #3	NEM Yr #4

Figure 27: Heating season EWT testing over 4 winters.

7.   Annual "True-up" billing and utility charges at the Quincy ZNE house.

Copious engineering and testing means little until one looks at utility costs. A choice was made to put enough solar PV on the roof through an NEM inter-tie to push toward ZNE. The focus of this paper is on the GHP system, so we will not discuss the Solar PV installation. But the full story can be found on the CaliforniaGeo website at: **https://www.californiageo.org/geothermal-heat-pump-installations-in-california/geoexchange-in-a-zero-net-energy-home/**
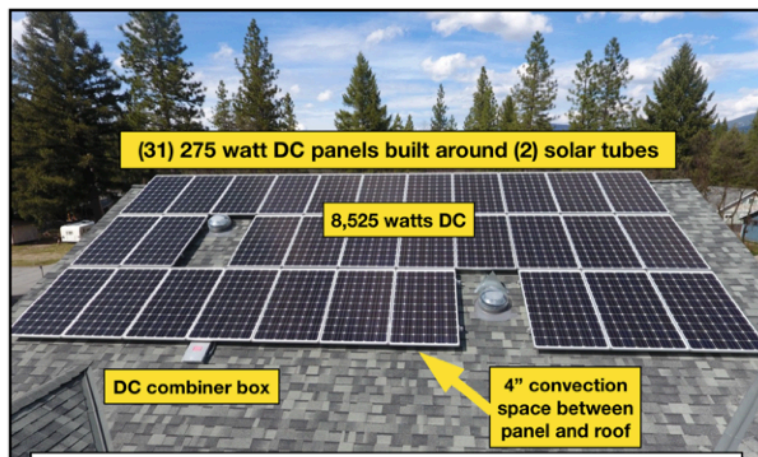

Figure 28: Solar PV array on the Quincy ZNE house.

This 8.5 KW DC array is rated as 7.4 KW (AC) by California Energy Commission methods.

Once-a-year, "True-up Billing" is what an NEM rate provides. In three complete True-up periods to date, the results were as follows:

> • Year 1   Zero Net Energy (plus) exporting 1,503 Kwh *more than* actual use. This was the last of a five-year drought period in California. Less heating load and more sunshine-based electricity to export at peak summer tiered rates for credit.
>
> • Year 2   952 Kwh net use but *zero cost* due to on-peak exports for credit.
>
> • Year 3   2,608 Kwh net use due to near-200% of annual rain/snow, reducing temperature and solar production. Net yearly cost total of $76.06 *($6.34 per month)*.

These varied results during only three years' performance are much like planning a house for a utility bill of $100/month without being able to predict teenager hot water use and lights left burning—examples of user consumption uncontrolled by building design.

The vanity of *hoping for* ZNE every year and missing it may seem worrisome, but missing by only six bucks a month in Year 3 isn't tragic. Here are Figures 29 and 30, illustrating the NEM details of Year #1, with comment to follow:
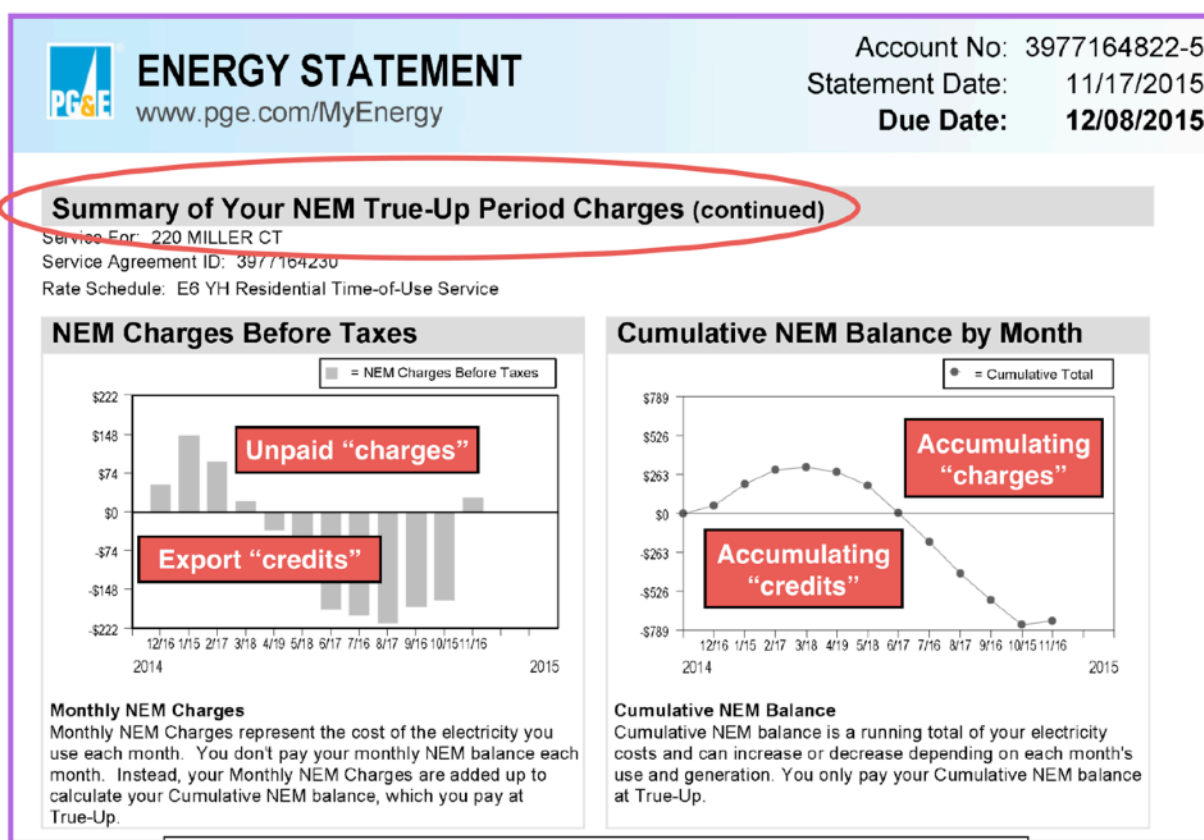

Figure 29: Graphic summary of True-up in Year 1

Summary of Your NEM True-Up Period Charges

Service For: 220 MILLER CT
Service Agreement ID: 3977164230
Rate Schedule: E6 YH Residential Time-of-Use Service

Summary of NEM Charges

Bill Period End Date	Net Peak Usage (kWh)	Net Part Peak Usage (kWh)	Net Off Peak Usage (kWh)	Net Usage (kWh)	NEM Charges Before Taxes	Estimated Taxes	Total NEM Charges
12/16/2014	0	50	291	341	$51.39	$0.10	$51.49
01/15/2015	0	183	869	1052	146.54	0.30	146.84
02/17/2015	0	159	539	699	95.99	0.20	96.19
03/18/2015	0	129	9	138	20.71	0.04	20.75
04/19/2015	0	79	-332	-253	-32.94	-0.07	-33.01
05/18/2015	-144	-87	-196	-427	-92.74	-0.12	-92.86
06/17/2015	-322	-213	-129	-664	-185.40	-0.19	-185.59
07/16/2015	-333	-263	-81	-677	-196.22	-0.20	-196.42
08/17/2015	-354	-238	-161	-753	-211.28	-0.22	-211.50
09/16/2015	-326	-204	-109	-639	-180.27	-0.18	-180.45
10/15/2015	-277	-223	-117	-617	-167.48	-0.18	-167.66
11/16/2015	-58	13	342	297	26.91	0.08	26.99
TOTAL	-1814	-615	925	-1503	-$724.79	-$0.44	-$725.23

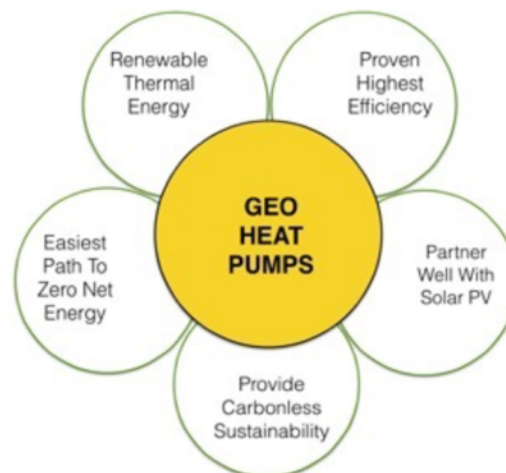| -1814 Export during Peak	-615 Export during part-Peak	-1503 Exported during year	$725 annual credit lost at True-Up

Figure 30: Month-by-month Year 1 NEM results.

In the first True-up year, the Quincy ZNE house did better than ZNE in two ways. There was a $725 credit for the power exported throughout the year and a $53 credit for excess generation, *neither of which* resulted in cash-back due to utility policy. The $725 was an instant (pre-promised) loss at the moment of True-up. The excess generation credit of $53 was rolled into the next year's billings, helping to offset the continuous utility charges of $11/month for an NEM connection.

We had two thoughts on this. Use more power (as the utility would prefer) or make plans to buy an electric or plug-in hybrid vehicle to absorb credit being generated. As can be seen from the boxed text above, wide variation in the power consumption-to-export ratio over just three years has kept us away from that plug-in hybrid for now.

8.   SUMMARY.

The Quincy ZNE House proved itself in its first year. Time will tell how close it can come to a repeat. One thing is clear. This carbonless residential building, using common and available technology, can be replicated *or even improved* by anyone. Consider the potential reduction in greenhouse gas emissions and the expansion of sustainable buildings!

Consider if the same path were followed by large, single-family and multi-residential developers and for commercial buildings across the country. People often need a *market signal* to take action on something that benefits their self-interest. If the content of this paper was news to you, then think about what might happen when a larger slice of the population comes to understand the potential of geothermal heat pumps. Homebuilders might begin to offer GHP installations as a serious option. An increasing number of satisfied customers would expand it from there.

The Blossom of Sustainability