

San Francisco Bay Area Net Zero Urban Infill

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Some technologies incorporated into this prototype include higher R value walls than typically used in this mild climate, high performance windows, excellent airtightness, a heat pump water heater, drainwater heat recovery, and a residential-scale economizer. The data collected to date indicate that the building is on track to achieve net zero performance.

Several obstacles arose during the construction and commissioning of the building, which provided some useful lessons on integrating advanced technologies. Another design constraint was that the builder wished to have an all-electric house: both for 'perceived net zero performance' (all measured in electricity), and due to restrictions of California net metering laws. An analysis was conducted to assess the relative cost-effectiveness of various building enclosure and mechanical measures.

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ABSTRACT

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INTRODUCTION

A startup builder in the San Francisco Bay Area has a goal of producing factory built/modular houses with net zero energy performance. Their first prototype was a 1540 sf (143 m²), two-story, two bedroom, urban infill townhouse design; it achieved a USGBC LEED Platinum rating, and was awarded the 2009 Green Builder Home of the Year Award. The authors provided design guidance and analysis under the Department of Energy’s Building America program. The prototype has been in operation for roughly a year, and has been extensively monitored, providing information about its net zero performance, and the contribution of its various sub-systems.

The building was designed as a grid-tied net zero energy building (NZEB)—specifically a net zero site energy building (as defined by Torcellini et al. 2006), meaning that renewable energy produced at the building site offsets all energy consumption of the building. As it is all-electric, this building is also by definition net zero source energy.

The site is in a very mild climate (Oakland CA, Zone 3C, 2880 HDD 65° F/1600 HDD 18° C/435 CDH 74° F), resulting in minimal space conditioning energy demands, and therefore reducing the renewable energy input required to achieve net zero energy. Interestingly, this mild climate challenged typical cold-climate assumptions on the most valuable enclosure upgrades.

An all-electric design was chosen by the builder. This was done primarily to make the building’s net zero performance indisputable (if achieved), based on simple metering of electrical use. In addition, although net zero source energy buildings

are a valid approach (burning fossil fuel on site, and generating excess renewable energy to offset this use), California net metering laws at the time made this approach economically unfeasible. These laws stated that net excess generation at year's end was forfeited to the utility, thus discouraging oversized photovoltaic arrays; however, this law has since changed.

DESIGN AND BUILDING SPECIFICATIONS

Enclosure

The builder chose modular construction for quality control and climate-controlled construction reasons. The opaque assembly values are insulated substantially above code levels. For instance, California Title 24 (CEC 2008) calls for R-13 (RSI 2.3) cavity insulation in wood frame walls, which would result in an opaque wall R value of about R-8 (RSI 1.4) when thermal bridging is accounted for. In contrast, the chosen wall (which included 1”/25 mm XPS insulating sheathing) was R-25 nominal/true R-19 opaque wall (RSI 4.4/RSI 3.3). The windows are high performance units (two layers of glass + film; essentially triple glazed); the use of spray foam throughout resulted in very good airtightness (2.7 ACH 50). The insulated and sealed crawl space foundation was chosen for experimentation using semi-active control of the thermal mass contained within the foundation. However, this resulted in added cost, due to both the foundation design, and also site seismic and soil issues. In addition to energy concerns, moisture management and durability were high priorities of the design team. Some durability features shown in Figure 1 include subsill pan flashings under all windows, and ventilated rainscreen cladding.

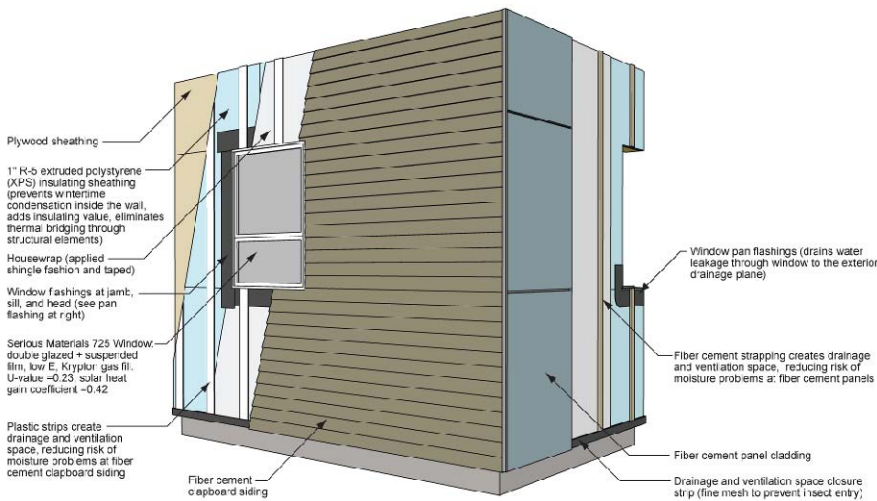


Figure 1 Exterior view of typical building enclosure assemblies

Table 1. Building Enclosure Characteristics

Component	Description	Performance Characteristics
Roof/Ceiling Assembly	Low density (0.5 PCF) urethane spray foam filling ceiling joist cavities (tapered 9.5”-15”/240-380 mm); compact assembly	Average insulation value R-43 (RSI 7.6)
Above-Grade Walls	Wood frame 2x6 advanced framing 24” (610 mm) o.c. Low density (0.5 PCF) urethane spray foam in stud bays 1” (25 mm) extruded polystyrene sheathing exterior	R-20 + R-5 nominal values (RSI 3.5+ RSI 0.9); R-19.2 (RSI 3.4) whole wall R value
Frame Floors	Low density (0.5 PCF) urethane spray foam in joist bays	R-22 nominal (RSI 3.9)
Foundation	Sealed insulated crawl space; 1-1/2” (38 mm) extruded polystyrene on crawl space walls; 1” (25 mm) XPS under slab	R-7.5 walls (RSI 1.3) R-5 slab (RSI 0.9)
Fenestration	Pultruded fiberglass frame windows with double glazing + suspended film (effectively triple glazing)	U=0.23 (RSI 4.3) SHGC=0.42
Infiltration	1150 CFM 50 (543 l/s)/ 4.4 ACH 50 targeted value (2.5 sq in leakage area per 100 sf of envelope area)	728 CFM 50 (344 l/s) 2.7 ACH 50 final tested value

All R values in ft²·°F·h/Btu; CFM 50=cubic feet/minute @ 50 Pa; ACH 50=air changes/hour @ 50 Pa

Mechanical Systems

As discussed above, an all-electric design was chosen by the builder. Therefore, space conditioning was provided by a high-efficiency air source heat pump: the site was not amenable to a ground source heat pump and such a unit would have been significantly more expensive with modest energy savings in this climate zone. Given the mild climate of the Bay Area, a residential-scale economizer was installed. It was built with off-the-shelf components and a custom controller which would open a damper from the return to the exterior, open a roof-mounted skylight for relief air, and run the air handler (under favorable weather conditions).

Domestic hot water was provided with an add-on heat pump water heater on an electric resistance tank; this is discussed in more detail later. In addition, a drainwater heat recovery unit was installed; however, given the crawl space geometry, this unit could only capture waste heat from the second floor shower and sink drains (i.e., not the first floor drains).

The original ventilation design was a heat recovery ventilator (HRV), drawing exhausts from both bathrooms, and supplying to the upstairs hallway. The design intent was to have a 33% duty cycle for general ventilation, with high speed ventilation controlled by a bathroom timer switch. However, in operation, the selected unit proved to be unreliable and too loud for occupant acceptance. After several iterations, ventilation was provided by the customized controller, operating the air handler and economizer motorized damper, to provide distributed ventilation (i.e., central fan integrated ventilation, as discussed by Rudd and Lstiburek 1998). Bathroom exhaust, though, was still provided by the installed HRV.

All installed lighting is compact fluorescent or LED; all major appliances and most lighting fixtures are Energy Star qualified. The townhome design limited available fenestration for daylighting; a skylight was used over the central stairwell, providing well-distributed daylighting.

Table 2. Mechanical System Characteristics

Component	Description	Performance Characteristics
Heating & Cooling	Air-source heat pump split system; horizontal air handler located in conditioned crawl space	16 SEER/9.5 HSPF
Domestic Hot Water (original)	Air-source heat pump water heater (add-on unit) mounted on 40 gallon/150 liter electric resistance tank water heater	2.11 EF nominal for heat pump alone; 0.92 EF resistance tank
Domestic Hot Water (replacement unit)	50 gallon/190 liter integrated heat pump water heater (heat pump with tank) in garage (ventilated space)	2.35 EF nominal
Domestic Hot Water	Drainwater heat exchanger for second floor drains	-
Ductwork	Sheet metal and insulated flex, located within conditioned space (crawl space and interior walls)	133 CFM 25 total (17%) (11.8 l/s) 0 CFM 25 to exterior
Ventilation	Central fan integrated ventilation using economizer damper and fan cycling controller	170 CFM @ 5 min. on/25 min. off (17% runtime) = 30 CFM (14 l/s)
Ventilation (abandoned system)	Heat recovery ventilator connected to bathrooms (exhaust) and second floor hallway (supply)	153 CFM exhaust, 70 CFM supply, no HVI rating (% recovery)
Lighting	All compact fluorescent and LED lighting	-
Appliances	All Energy Star (refrigerator, dishwasher, washing machine)	-
Renewable energy	5.4 kW _p rooftop photovoltaic array (24×225 W _p panels with 5000 W AC inverter)	-

CFM 25=cubic feet/minute @ 25 Pa

Renewable energy was generated by a roof-mounted photovoltaic array (5.4 kW_p), which covered roughly half of the available roof area. This system was sized to meet expected loads under typical operating conditions.

Design Process and Simulations

The best design practice for net-zero energy houses is to maximize conservation measures, and then to add renewable energy sources to offset the remaining loads. Some steps in this process are described below, including the use of building

energy simulations to inform decisions, economic analysis, domestic hot water choices, and designing for the variability of homeowner operation. One of the most common measures includes optimization of solar orientation; unfortunately, due to lot restrictions and the townhome design, this was not available as a measure.

Parametric Simulations and Net Zero Optimization. This house was analyzed with parametric simulations in a DOE-2.1E-based software package (Energy Gauge USA, Parker et al. 1999). The initial reference building was the Building America Benchmark, which is intended to capture typical mid-1990’s construction (Hendron 2007); incrementally changes were then added, as shown in Figure 2. The graph shows annual source energy consumption, divided by end-use load (heating, cooling, domestic hot water, lighting, and miscellaneous end use loads).

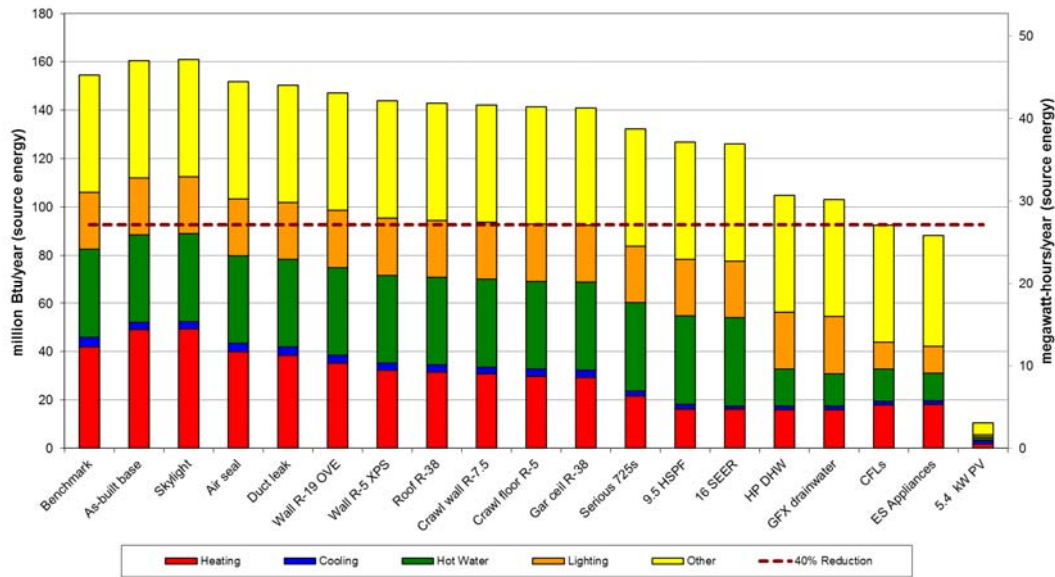


Figure 2 Parametric simulations of prototype house, using DOE-2.1E based simulation

It is immediately clear that the mild climate of the San Francisco Bay Area minimizes enclosure (heating and cooling) loads, which comprise only roughly 1/3 of the total for the Benchmark case. Furthermore, all of the enclosure improvements combined (opaque wall R value, fenestration, airtightness) result in only a 15% improvement relative to the Benchmark.

Similarly, the space conditioning equipment upgrades have a small effect (4% improvement). The largest improvements are in domestic water heating at 14% (as the Benchmark “base case” uses electric resistance water heating), and the installation of compact fluorescent lighting (7%). Of course, an economic balance should be struck between conservation measures and renewable energy; Proskiw (2010) described a framework for this evaluation similar to what was used here. This system involves an “Energy Conservation Measure Value Index,” which divides the incremental cost of the measure by the annual energy savings. The ECM Value Index for any measure can then be compared to the ECM Value Index for the renewable energy system. The installed cost of the PV array was \$8/W_p (circa 2009) without rebates, and roughly \$4/W_p including state and Federal incentives. Using the latter cost, some of the worst performers proved to be the heat recovery ventilator and high performance windows. In addition, several of the opaque assembly insulation upgrades provided lower Value Indices than the PV system. All of these issues were a function of the mild climate, which minimizes the need for environmental separation between exterior and interior.

Domestic Hot Water and Fuel Choice. The choice of an all-electric house proved to be an obstacle to overall energy efficiency when selecting domestic hot water equipment. To demonstrate the effect of equipment choice, a matrix was generated of nominal efficiency levels (energy factor/EF) for typical options (Table 3). A “Relative Site Consumption” value was calculated by taking the reciprocal of the energy factor. Then, the site consumption was multiplied by source energy factors for the US average power grid (1.092 gas; 3.365 electricity), as given by Deru and Torcellini (2007), resulting in a “Relative Source Consumption.”

Table 3. Normalized Source Consumption of Domestic Hot Water Options

Unit	Fuel Type	Nominal EF, Typical	Relative Site Consumption	Relative Source Consumption
Gas Storage Tank, Typical	Gas	0.60	1.67	1.82
Electric Storage Tank, Typical	Electricity	0.90	1.11	3.74
Tankless, non-condensing	Gas	0.80	1.25	1.37
Tankless, condensing	Gas	0.90	1.11	1.21
Heat Pump Water Heater	Electricity	2.11	0.47	1.59

This exercise demonstrates that an electric heat pump water heater has lower nominal source energy efficiency than many of the gas-fired tankless/instantaneous water heaters commonly available on the market. These two equipment options have comparable installed costs: this suggests that a tankless gas heater is a better choice for reducing source energy use. Admittedly, recent work demonstrates that tankless water heaters have lower installed efficiencies than rated values when realistic draw schedules are used (Burch et al. 2008). However, heat pump water heaters also have performance below their nominal rated value, given their partial dependence on electric resistance heating (typically an option to recover from large draws). Of course, the relative performance will change as grid source energy factors change regionally and over time.

Occupant-dependent effects and targeting net zero. One fundamental issue when sizing the photovoltaic array for this building was that occupant behavior causes tremendous variations in energy consumption. Parker et al. (1996) reported variations (from highest to lowest user) of a factor of 3:1 in identical houses; others have reported similar results (see Parker et al. 1996). In addition, miscellaneous end use loads (MELs) dominate over enclosure loads, as shown in Figure 2 (roughly 50%). Unfortunately, MELs are highly variable, increasing overall variability. The builder therefore faced a dilemma: either (a) size the system for “normal” occupancy, and run the risk of not meeting net zero targets (which would have adverse effects on their reputation), or (b) oversize the system (resulting in greater first cost for the home), and also run the risk of overproducing electricity and forfeiting the excess production to the utility company. In the end, the builder chose the former approach, assuming that anyone choosing to buy a net zero house would exhibit low consumption behavior.

TESTING AND PERFORMANCE RESULTS

Short-term testing and long-term data monitoring were done in this prototype house. The monitoring data has been providing a wealth of information, including submetered energy consumption for end uses, photovoltaic system output, heat pump water heater performance, and the effectiveness of the drainwater heat recovery system.

Economizer

The use of a residential-scale economizer may be considered questionable: unlike commercial buildings, houses are typically enclosure-load dominated, resulting in fewer hours requiring cooling at low ambient temperatures. However, although the desired response to overheating at moderate outdoor temperatures is homeowner operation of windows (ventilation cooling), thermostats often operate compressor-based cooling before occupants notice and respond. Therefore, one can argue that automating this mechanism has several advantages: it allows for ventilation cooling while the house is unoccupied (thus avoiding overheating), it addresses poor occupant understanding of temperatures and enthalpy, and addresses potential security risks of open windows. Given the large number of hours during which ventilation can be used to provide cooling in the Bay area climate, a residential economizer has a better chance of success here.

This system was implemented by installing a large (14”/356 mm diameter) duct from exterior to the return with a motorized damper; a motorized skylight was used to provide pressure relief; both components were connected to a custom controller. When the system was run in economizer mode, outdoor airflow was 170 CFM or 80 l/s (total system airflow was ~750 CFM or 354 l/s), with an air handler fan energy use of 120 W. This airflow efficiency could be combined with interior-exterior temperature difference, along with the heat shed to the airstream by the air handler fan (120 W or 410 Btu/hr), to calculate net cooling efficiency at various conditions:

- $\Delta T=10^{\circ}\text{ F}/5.6^{\circ}\text{ C}$ (65° F out/ 75° F inside): 11.9 Btu/(W·hr)
- $\Delta T=13^{\circ}\text{ F}/7.2^{\circ}\text{ C}$ (65° F out/ 78° F inside): 16.5 Btu/(W·hr)
- $\Delta T=15^{\circ}\text{ F}/8.3^{\circ}\text{ C}$ (60° F out/ 75° F inside): 19.5 Btu/(W·hr)

In comparison, DX cooling (as calculated from manufacturer’s specifications) operated at 15.5 to 16.6 Btu/(W·hr). This indicates that DX cooling is more efficient than the economizer at indoor-outdoor temperature differences up to roughly $13^{\circ}\text{ F}/8.3^{\circ}\text{ C}$. This is partially due to the geometry of the dampers: commercial economizers can draw all airflow from exterior through the fan by closing off the interior return damper. In contrast, economizer mode with this system draws air from both interior and exterior. The air handler fan measured efficiency (6.2 CFM/W or 2.9 l/s·W) was much higher than typically assumed values of ~ 2.5 CFM/W or 1.2 l/s·W (see Ueno 2010). However, since only a fraction of the air handler draw was from exterior, the net efficiency of the economizer was 1.4 CFM/W or 0.7 l/s·W, resulting in relatively low delivery efficiency. To achieve significant energy savings, an economizer must have an air system configured to deliver outdoor air at an efficiency of 5-10 CFM/W or 2.3-4.7 l/s·W. In addition, while commissioning the system, substantial duct leakage was observed; this issue was later remedied. However, this indicates that a residential economizer has a risk of being a major source of duct leakage to exterior, which would have negative impacts in both heating and cooling seasons.

Domestic Hot Water Heat Pump

Long-term monitoring measurements of electrical energy use for the domestic hot water heat pump and resistance element (separately), DHW flow volumes, and water temperatures (allowing calculation of thermal energy delivered by the DHW system) were taken. These inputs could be used to calculate an “in service energy factor (EF)” (dividing thermal energy output by electrical energy input); note that this is a site (not source) measurement. Daily average values were calculated and graphed against DHW consumption (liters/day) in Figure 3. The data sets include heat pump operation alone, and combined operation of heat pump and electric resistance; the latter mode was inadvertently used, and resulted in the two systems “fighting” against each other, and reduced efficiency.

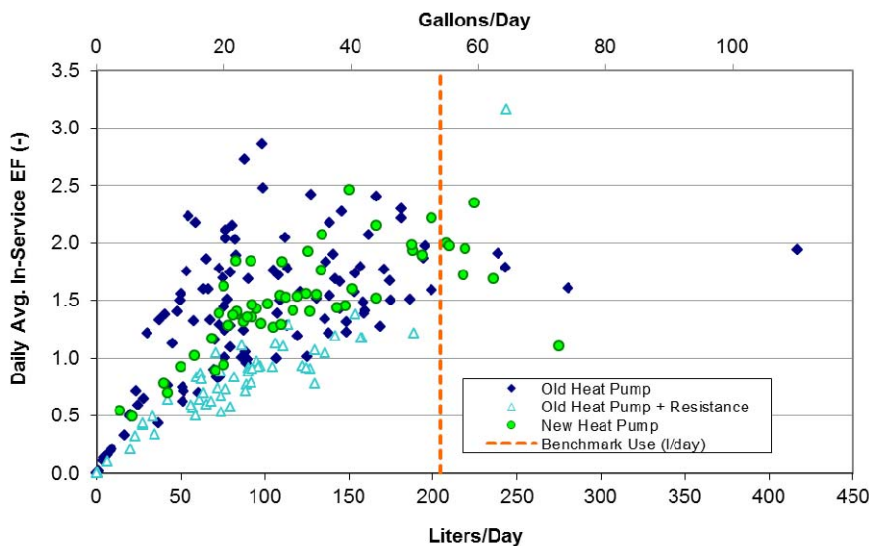


Figure 3 Domestic hot water consumption (liters per day) vs. daily average “in-service energy factor”

One trend is that the “in-service EF” is a function of water use: this is logical, given that small daily draws result in a greater proportion of energy use as standby loss. Furthermore, this is consistent with the behavior of heat pumps: larger draws result in a greater “slug” of cold water, which would improve heat pump efficiency. In addition, the “typical” (Benchmark) daily hot water use is plotted, showing that the occupants are very low consumers. While the heat pump was

operational, “in service EF” was typically in the range of 1.0 to 2.5, with the intercept at “typical” daily usage near 2.0. The overall average values were 1.4 for heat pump operation, and 0.8 for heat pump + electric resistance operation.

The simultaneous operation of both heat pump and resistance heat eventually resulted in equipment failure of the add-on heat pump unit; the unit was replaced with an integrated DHW heat pump system with a higher rated EF (2.35 vs. 2.11). Data for this replacement unit (“New heat pump”) is plotted for January and February in Figure 3.

Drainwater Heat Recovery System

Short-term testing of the drainwater heat recovery/heat exchanger system (HX) was conducted; a % recovery was calculated based on the temperatures shown in Equation 1. If the mass flow rate (\dot{m}) from the shower head and the flow through the heat exchanger are equal, the % recovery can be calculated from temperatures alone (although flow rates were measured). Temperatures were measured using thermistors ($\pm 0.4^\circ\text{F}/0.2^\circ\text{C}$) attached to pipe surfaces and covered with insulation; a data acquisition system was used to ensure that steady-state conditions had been reached. Measurements were taken at several delivered hot water temperatures (133°F and $111^\circ\text{F}/56^\circ\text{C}$ and 44°C).

$$\% \text{ recovery} = \frac{\text{energy recovered}}{\text{energy required}} = \frac{\dot{m} \cdot (T_{in\ HX} - T_{out\ HX}) \cdot C}{\dot{m} \cdot (T_{DHW@tap} - T_{mains}) \cdot C} = \frac{(T_{in\ HX} - T_{out\ HX})}{(T_{DHW@tap} - T_{mains})} \quad (1)$$

Under all test conditions, calculated steady-state recovery was 19%. One early concern was that the use of cast iron DWV pipe would inhibit recovery due to thermal mass effects; however, steady state was reached in 5-6 minutes. Another interesting result was that shower water cooled noticeably from the shower head to the drain, e.g., from 130°F to 109°F (54°C to 43°C). This is likely due to evaporative cooling as the droplets travel through the air; it has the effect of reducing available heat for the drainwater heat exchanger system.

Overall Performance

Net zero energy performance was considered a key goal for this prototype: it is a core goal for the builder, given that “zero energy” is part of the company’s name. The monthly submetered consumption and PV production are graphed in Figure 4, with monthly HDD/CDD for Oakland, CA.

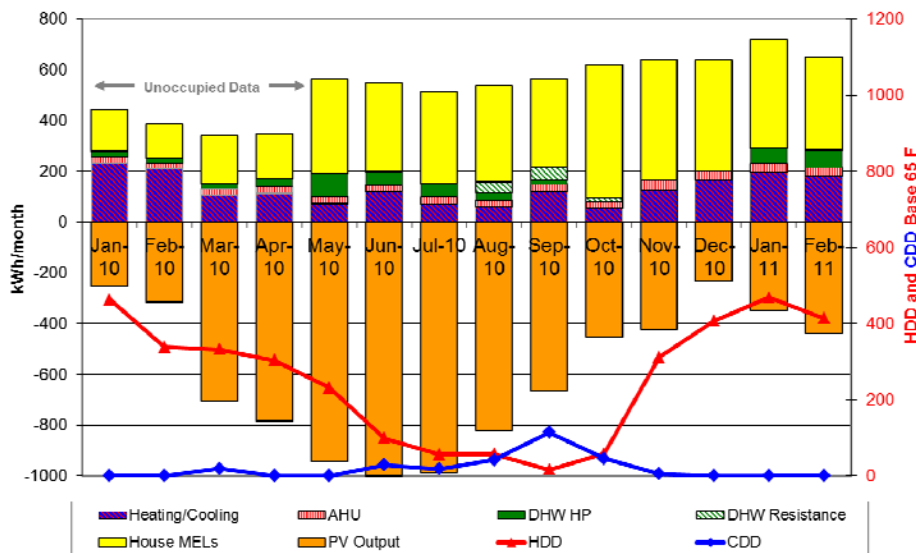


Figure 4 Monthly submetered energy consumption of prototype, with PV production and HDD/CDD

Note that the first four months of operation were unoccupied, as reflected by the lack of significant DHW and MEL consumption. August data shows the inadvertent use of electric resistance water heating, and October onwards shows the loss of submetering due to the replacement of the water heater.

The data collected to date indicate that the building has achieved net zero performance to date: 7506 kWh consumed, and 8367 kWh generated by PVs. The building has generated roughly 11% excess relative to consumption. For the past year, these figures are 6678 kWh consumed/7798 kWh generated (17% excess). In addition, the house has achieved net positive energy costs.

CONCLUSIONS

Monitoring of a prototype townhome in the San Francisco Bay Area indicates that net zero performance has been achieved to date. Of course, occupant behavior has a major effect, and credit must be given to conservative operation of the house. Several subsystems were found to be less cost-effective than the addition of further renewable energy resources; this is also a function of the low rebated system cost ($\$4/W_p$) for photovoltaics at the time of construction.

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About this Report

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