Very Low Energy Homes in the United States: Perspectives on Performance from Measured Data

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Very Low Energy Homes in the United States:
Perspectives on Performance from Measured Data

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Abstract

We present measured annual performance data from a dozen recent-vintage very low energy homes in North America. Many of the designs combine greater energy efficiency with solar electric photovoltaic power in an attempt to create Zero Energy Homes (ZEH). We also provide measured data from the first home constructed to the German *Passivhaus* standard in the United States. Several projects either exceeded or come very close to true net zero energy when evaluated over a year.

The data indicate that very low energy use buildings can very readily be achieved in North America. Annual energy use half that or less than standard housing can be achieved for an equivalent cost of $0.10/kWh from the efficiency investment. In general, the better cost effectiveness seen from energy efficiency measures indicates that greater investment in conservation should be a prerequisite to installation of solar water heating and solar electricity in Zero Energy Homes. However, over emphasis in efficiency is also possible. This suggests that optimization tools such as *BEOp*t, which characterize both renewable resource performance and that also of specific combinations of energy efficiency measures, will best guide designers to locate the most economically favorable mix to reach an energy neutral level.

Keywords

Low energy homes, zero energy homes, monitoring, *Passivhaus*, energy performance

The Residential Sector in Perspective

Currently, the residential sector in the U.S. uses approximately 20 quadrillion Btu of site energy per year; this amounts to approximately 20% of all energy use in the nation and 27% when confined to the non-transportation sector. Moreover, American households consumed fully 35% of all national electricity production (3,660 Billion kWh) and strongly depend on natural gas for heating [1].

Further, supplying energy to the residential sector in the U.S. generates fully 18% of its greenhouse gas emissions. Despite technological improvements in refrigerator, furnace efficiency and energy codes improving insulation, many American lifestyle changes have put higher demands on heating and cooling resources. For instance, the average size of homes built in the United States has increased significantly, from 1,500 ft^2 (139 m^2) in 1970 to 2,300 ft^2 (214 m^2) in 2005. The two-person household in a large home has become more common, as has central air conditioning: 23% of households had central air conditioning in 1978 that figure rose to 55% by 2001. Also, miscellaneous electric end-uses in households since 2000 has been rapidly expanding, largely offsetting efficiency gains in the conventional end-uses of heating, cooling and water heating.

Recent electricity shortages in California, growing U.S. dependence on foreign energy supplies with oil prices over $130 per barrel, and the greatly expanding threat of global warming underscore the critical need to address the efficiency of residential energy systems. Since the twin energy crisis of the 1970s, first passive solar, then superinsulation and now zero energy homes have provided increasingly refined means to create a new generation of very low energy housing.

History of Low Energy Residential Buildings

Interest in reducing energy use in buildings began in the U.S. just before World War II with work at the Massachusetts Institute of Technology on solar heated structures. This lead to the construction of four successive research structures ending with the M.I.T. Solar House IV built in 1958-1959 with 60 m^2 of active solar collectors which took care of 57% of measured space and domestic water heating in 1960-61 [2]. Similar work was done on solar air collector systems by Löf during the same period in Denver, but with less attractive savings [3].

With the twin energy crises in the 1970s, a flurry of activity developed means to reduce energy use in U.S. homes. Contrary to the complication and expense of active solar heating approaches as seen in the MIT and Colorado houses, of the initial activity was to utilize passive solar heating for buildings. Passive solar design aimed to use insulated south-oriented glazing systems with direct gain, indirect gain (e.g. Trombe walls) and attached sunspace features. All configurations featured interior thermal mass to maintain interior thermal comfort while reducing the requirement for active heating and cooling systems [4]. The added cost of passive solar design with appropriate insulation was estimated in 1984 at approximately \$50 - \$150/m^2. A compendium of seventy monitored passive solar homes reported an average 70% savings in measured auxiliary space heating [5]. However, many aggressively glazed passive solar homes suffered summertime over heating and often required night-insulation for windows unless wide temperature swings in cold climates could be tolerated. Moreover, gradually within this research, researchers deduced that reducing building cooling and heating needs though energy conservation and balancing this with solar elements could achieve the lowest energy use at lower incremental cost [6]. In cold and cloudy climates it was also realized that substantially better insulated buildings could achieve much lower energy use than conventionally insulated structures [7]. This led to the advent of superinsulated homes.[1]

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[1] The term "superinsulation" was coined by Wayne Schick at the University of Illinois at Urbana-Champaign who was part of the team simulating the performance of the *Lo-Cal* house.

In 1976 a computer simulation team at the Small Homes Council at University of Illinois Urbana that developed a design called the *Lo-Cal* house, evaluated using the climate of Madison, Wisconsin [8]. The house was never built, but its design features were highly influential. The key design facets of superinsulated homes were high insulation levels for ceiling, walls and floor (typically R-60, R-30 and R-20 or greater), very tight air construction and sun-tempering, with most of glass located on the south side of the building. Ventilation was provided by an air to air heat exchanger and target auxiliary design heat loads were a fraction of the size of ordinary furnaces.

In 1977, sponsored by the National Research Council of Canada, the cube-shaped *Saskatchewan House* was built in Regina, Saskatchewan. With an air to air heat exchanger for ventilation and no furnace installed, it was the first house to publicly demonstrate the value of superinsulation. The Saskatchewan House had an incremental cost of approximately $6,000 in 1982. In 1979, the *Leger Superinsulated House* was built in East Pepperell, Massachusetts with an annual natural gas heating cost of only $50 [9]. It had a more conventional appearance than the *Saskatchewan House* and widely influenced builders [10]. In 1984, three 223 m^2 superinsulated homes built in Great Falls, Montana were extensively monitored. Even in a climate with 7,600 heating degree days, measured average resistance electricity use was only about 4,500 kWh or 20 kWh/m^2 [11].

A number of superinsulated houses were built over the next few years, but interest subsided as energy prices dropped in the 1980s. One weak point of the technology concerned the great attention to detail required for airtight construction and also the over-ventilation of some schemes using heat recovery ventilators. Within both the passive solar homes movement and that for superinsulation there remained the key issue that while heating energy use was reduced, cooling, water heating and the plethora of other home energy end uses were not addressed.

Zero Energy Homes

Throughout the late 1980s, the cost of solid state solar electricity production through photovoltaics declined in price such that the possibility of using the solar resource for house-level distributed generation became increasingly feasible. In the early 1990s the Florida Solar Energy Center undertook a simulation exercise that looked to examine whether it was possible to aggressively reduce all home energy end-uses (cooling, heating, water heating, refrigerators, lighting and appliances) such that with photovoltaic electricity it might be possible to realize a annual zero net energy load [12]. Called the "Minimum Electricity Building," the exercise estimated that it might be possible to reduce total electrical load in a hot climate by two-thirds and heating and cooling by up to 80%.

To evaluate the real-world potential, two highly-instrumented homes were built in Lakeland, Florida in 1998 – both with the same floor plan and constructed by the same builder. One of these was of conventional construction and served as the project control. The experimental building, called "PVRES," included all the features anticipated in the simulation exercise (Figure 1). The goal was to determine the extent to which advanced energy efficiency technologies can reduce the demand for electricity in Florida homes. Features included interior duct system with a high efficiency heat pump, better wall insulation, a white reflective roof system, solar water heating and efficient interior appliances and lighting. Over one year, the PVRES home used 6,960 kWh of electricity and had a PV system production of 5,180 kWh. For the same year, the Control used 22,600 kWh. The measured a yearly energy savings due to the differences in the energy efficiency of the two homes of 70%. Adding in the PV system production showed the PVRES house's net energy use (electricity from the utility) for the entire year was only 1,780 kWh– a reduction in energy use of 92% relative to the control.

Figure 1. *Lakeland Zero Energy Home (PVRES), view from SW and aerial view.*

Moreover, the project showed that virtually zero net utility peak coincident demand was possible. As shown in Figure 2, the summer peak demand of all net end-uses in the occupied ZEH was above and below zero on the hottest summer day while air conditioning alone was 4.7 kW in the control home.

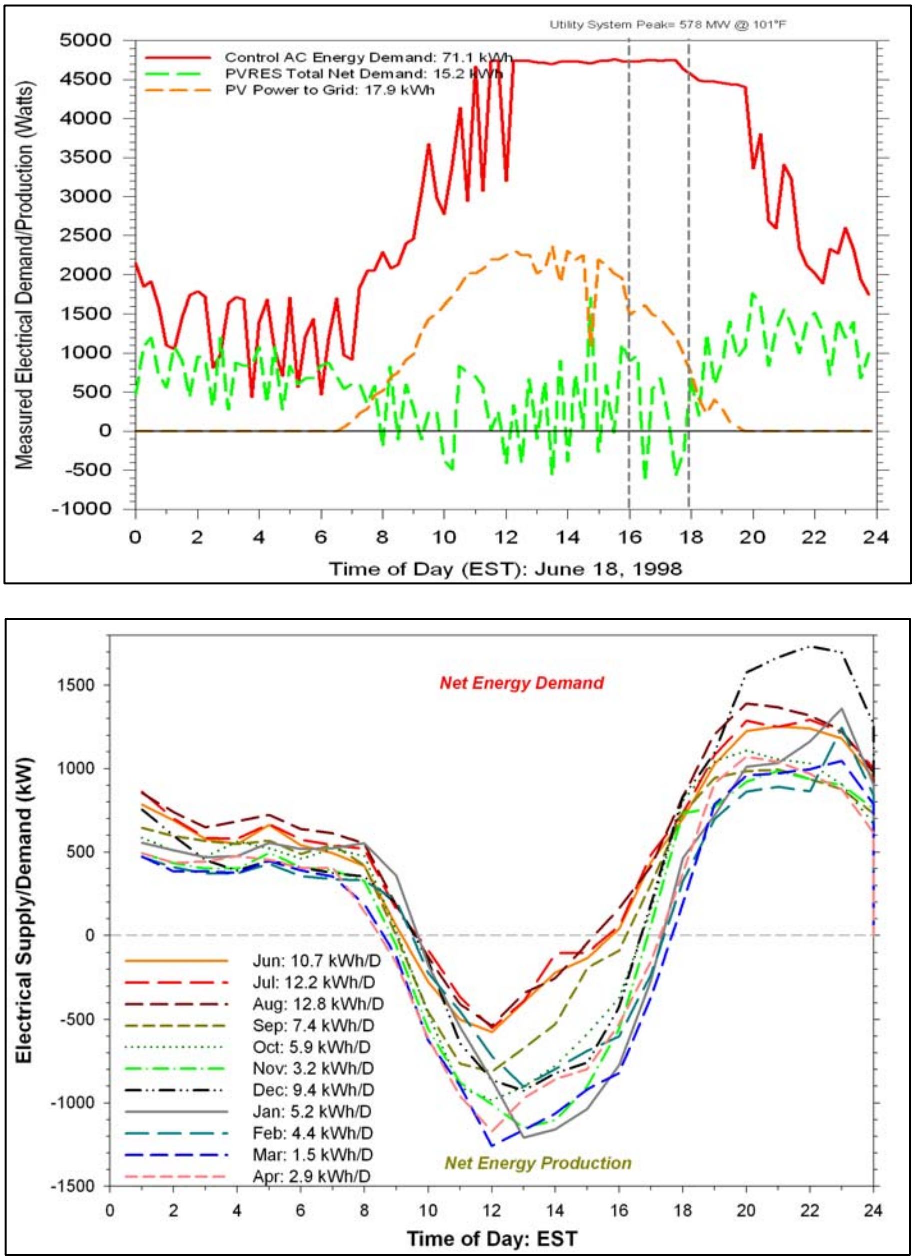


Figure 2. Upper plot – *Net electrical demand of control, solar PV output and PVRES house on summer peak day*. Lower plot – *Long-term Lakeland electric demand by month*

So successful was the project that it became the flagship for a new program for the U.S. Department of Energy: Zero Energy Homes. Within the concept, a combination of active and passive solar features with superinsulation and high efficiency appliances and overall load minimization is used with solar power generation to effectively lower annually net energy requirements to zero. Since the original zero energy project there have been many noteworthy zero energy homes constructed, some exceeding the performance of the original. Below we summarize some noteworthy projects.

In Washington D.C. in 2001, a 2,800 square foot (268 m^2) modular ZEH called the “Solar Patriot” or Hathaway home [13] was created to demonstrate potentials in a mixed climate. The home featured better insulated walls and foundation with low-e windows and high efficiency appliances and lighting throughout. An advanced geothermal heat pump was installed to further lower space conditioning loads with an evacuated tube solar water heating system. A 6 kW PV system was installed with the objective of reaching zero energy on an annual basis. The performance of the all-electric home was monitored in considerable detail. Total measured electricity consumption in 2002 was 10,585 kWh against the 7,510 kWh produced by the PV system. Although short of zero energy, the detailed monitoring of the home produced a wealth of information about the technologies and methods needed to achieve zero energy. For instance, it was determined that greater investments in efficiency than actually installed were likely warranted to further reduce space heating needs. Also, “other” energy use from home electronics and other plug loads were fully 23% of the energy use in the house. Figure 3 shows the measured consumption of various end-uses in the house versus the PV energy produced. Annual net energy consumption was only 3,075 kWh (11.8 kWh/ m^2). Incremental cost for the construction was approximately $20,000 for efficiency and HVAC improvements with another $39,000 for the PV and $7,000 for the solar water heating system.

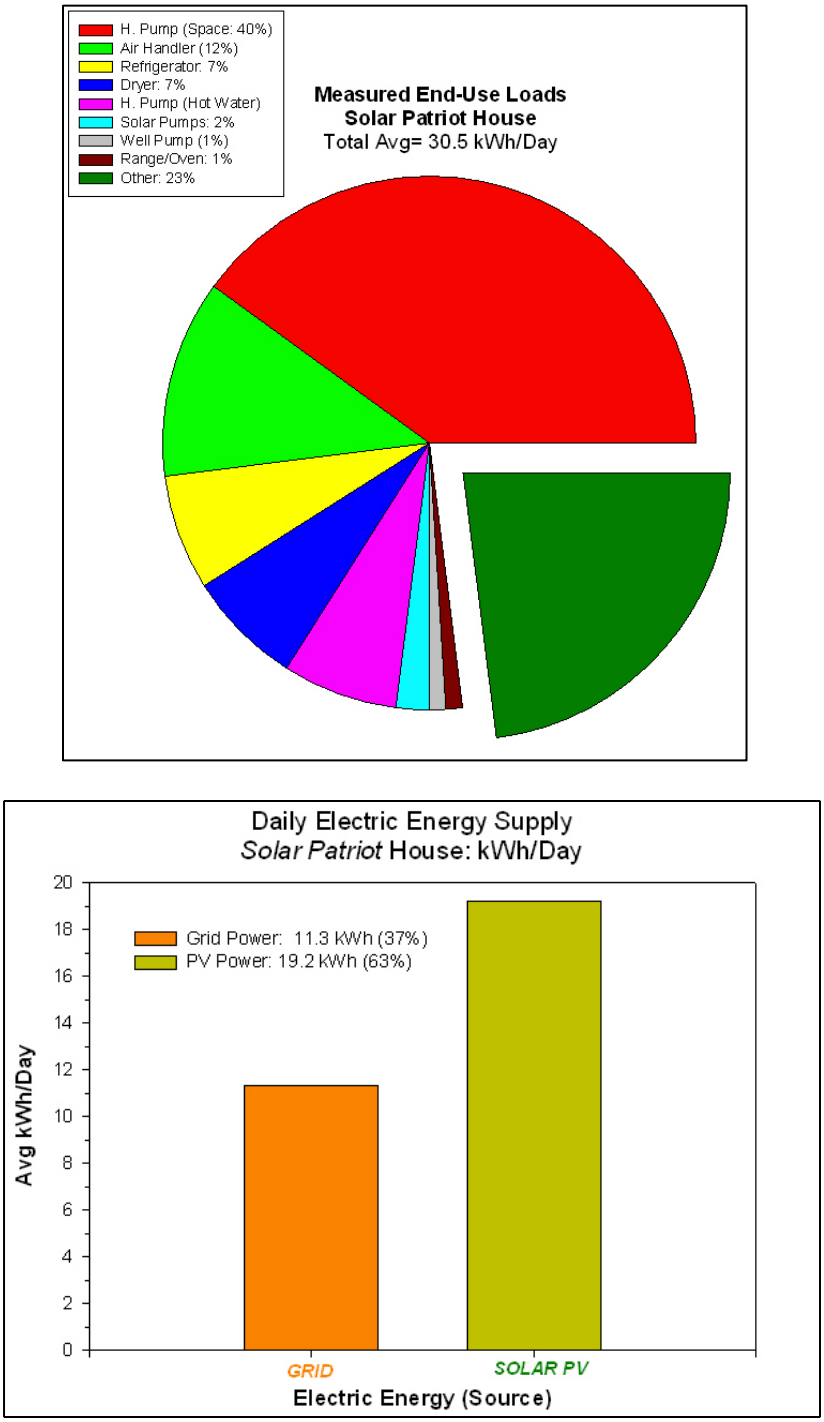


Figure 3. *Monitored annual performance of "Solar Patriot" house in 2003 showing end-use consumption and net energy purchased from the grid.*

In Livermore, California a 3,079 ft^2 (286 m^2) ZEH was designed by Davis Energy Group and built by Centex Corp in 2002 [14]. The home featured fairly high levels of insulation in a moderate climate, but included an innovative night cooling system (*NightBreeze*) using outside air introduced by the duct system, high performance windows with window shading, and attic radiant barrier, extensive use of tile with perimeter insulation and highly efficient appliances and lighting. Heating was provided by a hydronic loop using a tankless gas water heater. Cooling as provided by the *NightBreeze* with compressor cooling backup. The home also included a dynamic energy feedback system that allowed occupants to see how much energy their home was using against the energy being produced by the PV system. Performance of the house has been very good. In 2004, the 3.6 kW PV system produced more electricity (4,890 kWh) than the house used (4,380 kWh) so that net electricity consumption was negative: -510 kWh. Very little compressor cooling was ever needed even in the hot conditions near California's Central Valley. In Figure 4 each point on the lines represents the average 15-minute electrical demand by time of day for 2004.

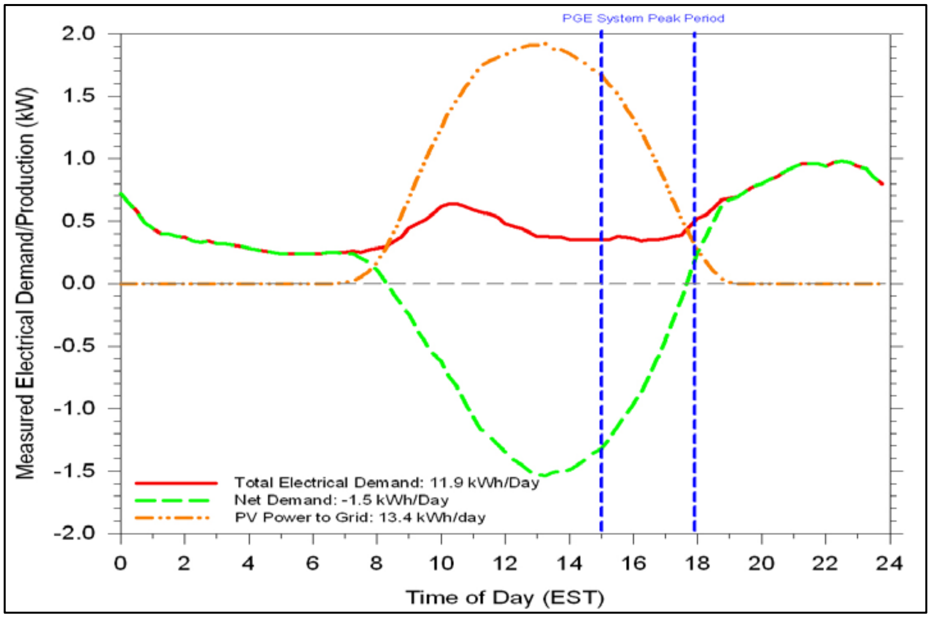


Figure 4. *Long-term performance of Livermore ZEH 2003-2004 showing total, solar and net end-use demand averaged over a 24-hour period. Utility peak is shown on the plot as vertical lines.*

However, natural gas consumption totaled 699 therms a year – likely due to excess heat loss in a hot water circulation loop. With that accounted for annual energy consumption equivalent was only 19,971 kWh or 70.6 kWh/ m^2. Incremental cost for the construction was approximately $26,000 with another $40,000 for the PV and solar water heating systems without California-specific rebates.

In Lenoir City, Tennessee, Oak Ridge National Laboratories has constructed five successively more advanced small near zero energy homes from 2002 - 2005 within a Habitat for Humanity development [15]. The project has been more impressive in that it has been done with small, affordable homes done while steadily improving performance, reducing costs and all the while evaluating a variety of efficient building methods and technologies such as:

- Heat Pump Water heater linked to the Refrigerator for heat recovery
- Unvented Crawl space controlled by the thermostat for supplemental space cooling and dehumidification in the summer and serve as a radon mitigator in the heating mode
- Ground Source Heat Pumps using foundation heat recovery
- Structural Insulated Panels throughout
- Interior duct system within the insulated envelope
- High performance windows, efficient appliances
- Grey water waste heat recovery system

The first home built in 2002 had a net energy input after solar production of 84 kWh/ m^2 at an incremental costs of $54,000 whereas the 5th home constructed in 2005 had dropped net consumption to 33.9 kWh/ m^2 while reducing added costs to $48,000.

In 2003, an innovative hot-climate design ZEH was built at Armory Park del Sol in Tucson, Arizona by John Wesley Miller. The all-electric 1,720 square foot home featured good insulation, solar control windows, a reflective roof and interior ducts with a high efficiency cooling system. One unique feature was the use of 120 ft^2 of flat plate solar collectors with 220 gallons (852 L) of storage that was to be used both for water and space heating. Measured performance over 2005 was quite good, although the solar thermal system fell short of expectations. Total electricity consumption was 8,786 kWh and the 4.2 kW PV system produced 7,207 kWh in Tucson's sunny climate. Figure 5 summarizes performance measured over a second year of monitoring. Net consumption was only 1,578 kWh for the year or 9.9 kWh/ m2. The total cost of the system was $46,100 of which $34,000 was for the PV and solar water heating system.

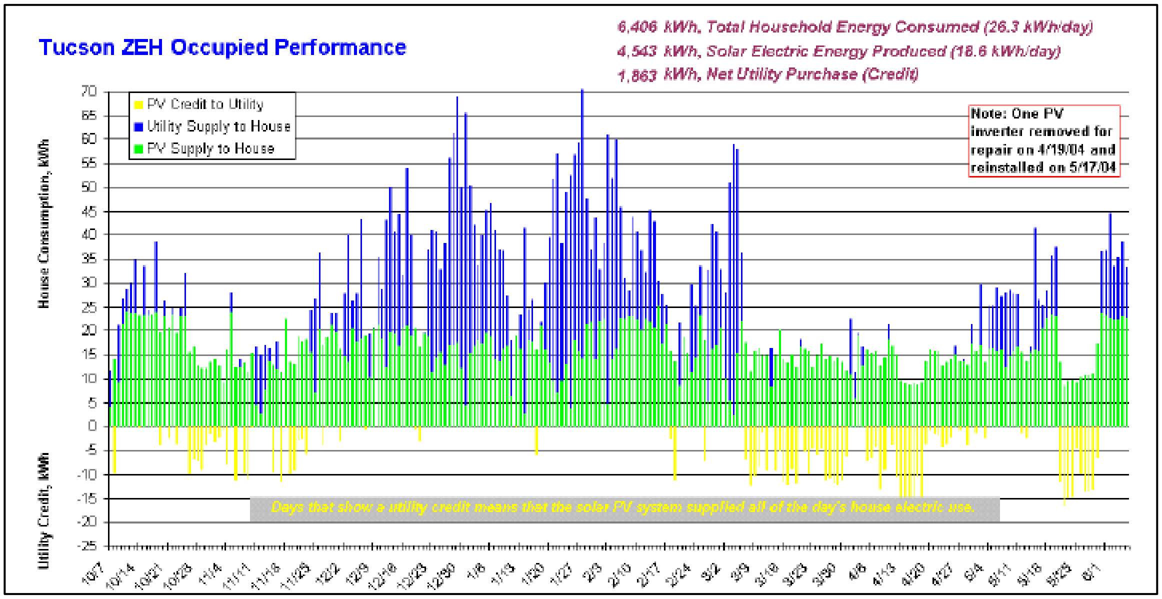


Figure 5. *Measured performance of Armory Park del Sol showing PV electricity supplied to the home, PV sell back to the utility and utility supply to the home.*

Perhaps the most impressive recent ZEH project has been a small 1,280 square foot (119 m^2) Habitat for Humanity home in Wheat Ridge, Colorado, as conceived by the National Renewable Energy Laboratory (NREL) [16]. The small home was superinsulated with R-60 ceiling, R-40 double stud walls and R-30 floor insulation (Figure 6). Ventilation is provided by a small heat recovery ventilator. Very high performance low-e solar glass with argon fill and a U-factor of 0.2 was used for the east, west and north faces with a higher transmission U-factor 0.3 glass used for the south exposure. The home used a 9 m^2 solar collector with 757 liters of storage, backed up by a tankless gas water heater. The home was mated with a 4 kW roof-top PV system.

Figure 6. *Habitat for Humanity Wheat Ridge ZEH.*

During a year of data collection stretching from April 2005 to the end of March 2007, the PV system produced 1,542 kWh more than the electricity used in the home even though blizzards reducing PV output were experienced in January 2007.

It is interesting to note that some 60% of the electricity use in the home was for non-appliance, non-lighting miscellaneous electric loads. Only 57 therms of natural gas were used during this period. The excess electricity produced on site helped displace the natural gas use on a source energy basis. The net site energy requirement for al fuels of the home over the period was 1.1 kWh/ m^2 – very close to zero. The total incremental cost of the project was $42,500 including $32,000 spent for the PV system and $7,100 for the solar water heating system. The incremental cost of the efficiency measures was only about $3,400 due to savings in the elimination of a typical full scale furnace as would be found in a comparable building.

One of the most collectively compelling evaluations to date, Premier Gardens, is a community level project in Sacramento, California. This project saw 95 entry level homes constructed varying from 1,285 to 2248 square feet built with high levels of energy efficiency: R-38 ceiling insulation and R-13 to R-19 wall insulation, tank-less gas water heaters, high efficiency gas furnaces, tightly sealed ducts buried in the attic insulation, fluorescent lighting in all permanent fixtures. The Premier homes also included 2.2 kW of PV on each house. A unique element of the project was that across the street from the development was a similar housing project constructed by a similar builder without the higher efficiency measures or solar power. Samples of homes in both developments (average 169 m^2 in size) were monitored by Sacramento Municipal Utilities District (SMUD). The measurement showed that the homes averaged 34% lower gas consumption and 16% lower electricity use without solar power production being considered. With the PV included, the homes averaged 54% lower electrical demand – particularly evident during summer peak periods as shown by the comparative data for July 15, 2005 (Figure 7). During the year of data collection, the homes in the nearby “control” development annually used 454 therms of gas and 7,770 kWh of electricity against 277 therms and 7,066 kWh for the Premier Homes. When solar electricity production is included (3,329 kWh), the consumption in the monitored sample averaged 70.1 kWh/m^2. This was less than half the consumption of typical SMUD homes which used 144 kWh/m^2. Incremental cost of the homes (not including the California PV buy-down) averaged $18,836.

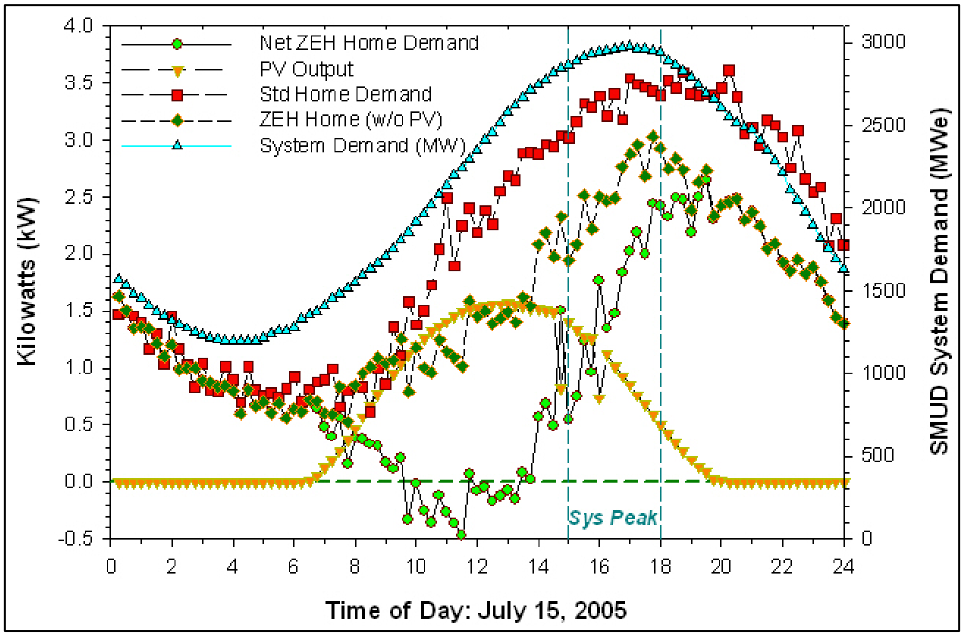


Figure 7. *Average total, solar and net demand of non-ZEH and PrestigeGardens ZEH communities near Sacramento: peak summer day in 2005.*

It must be emphasized that here we have highlighted a number of the more successful near zero energy home projects with monitored data. Given increasing interest, many more are currently under construction and/or monitoring.

Smith-Klingenberg Passivhaus

The *Passivhaus* concept is a European design strategy for achieving very low energy buildings based on optimizing both first cost and operational costs. It was developed in

Germany in the late-1980s by Dr. Bo Adamson and Dr. Wolfgang Feist, owing a large part of its origins to the superinsulation concept in the U.S. a few years before it [17]. However, there are important differences: the *Passivhaus* concept emphasizes the economic advantage of improving the building conditioned envelope to a point where a furnace becomes unnecessary, the need for eliminating all thermal bridging in construction, compact designs to minimize exterior surface area and extremely air tight construction with tiny heating systems integrated into the ventilation air distribution system and of designating specific performance targets along with software calculation of the levels required to reach those target. The specific targets are a space heating energy use no more than 15 kWh/ m^2 and a total primary energy consumption of 120 kWh/m^2.

While many Passive houses have been constructed in Germany and Austria, the first one built in the U.S. was constructed in Urbana, IL in 2002-2003. The many construction features of the 1,200 square foot (111 m^2) Smith/Klingenberg house are summarized in the attached summary (Figure 8).

Figure 8. *Smith-Klingenberg Passivhaus.*

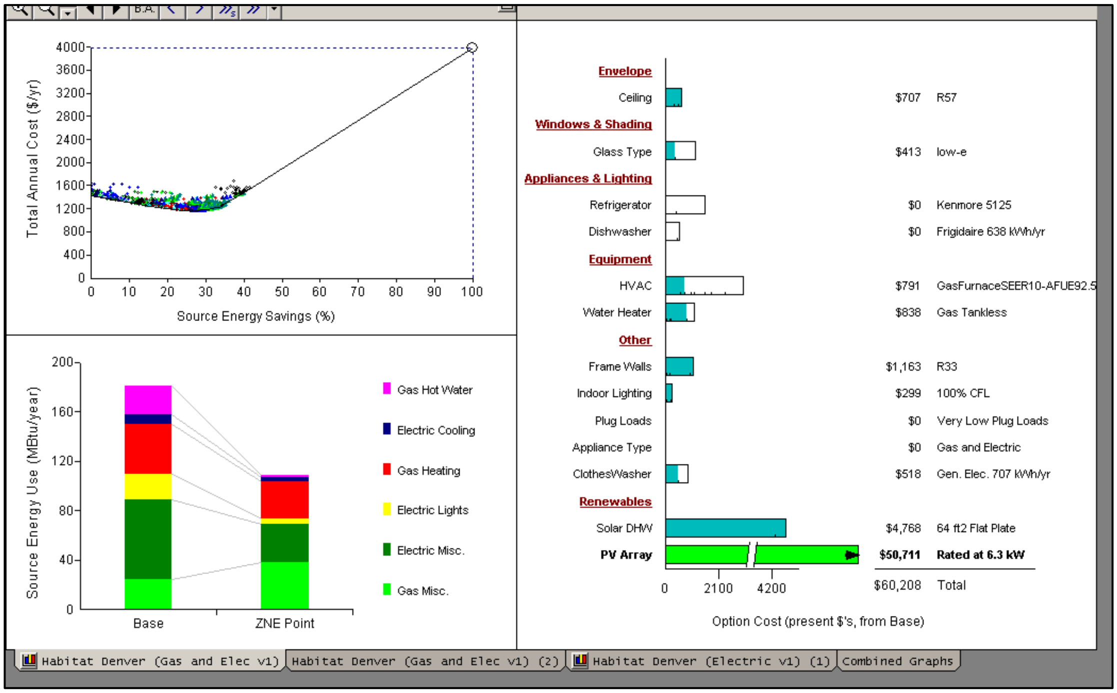
The annual total electricity consumption was 4,350 kWh (39 kWh/m^2 or 118 kWh/m^2 of primary energy). Annual electricity consumption for heating was 1,065 kWh for the twelve month period between February 2005 and February 2006. On a unit area basis this translate to 10.7 kWh/m^2 well below the limit of 15 kWh/m^2 set forth in the Passive House Standard. The estimated incremental cost of the house was approximately \$18,000 or \$162/m^2. Since the performance of PV systems is highly predictable, it can be shown that with 3.8 kW PV system near Chicago, Illinois, the Smith *Passivhaus* would become a Net Zero Energy Home as well. Within one of the plots, we estimated performance based on the added \$32,000 for such a PV system.

Summary of Zero Energy Homes and *Passivhaus* Conceptual Models

It can be readily seen that both the Zero Energy Home and *Passivhaus* concepts have some unique hazards within each approach. In general, both require very aggressive energy conservation measures to reach their goals. However, ZEH homes, given the ability to add on photovoltaics, can readily suffer under-investment in energy efficiency and over emphasis of renewable systems unless engineering simulations are run in the design process and best building envelope choices are made during construction. The author’s personal experience with this process suggests that compromise within the building process is the greatest hazard.

On the other hand the *Passivhaus* concept risks overinvestment in conservation if a point is reached in the optimization process where adding solar electricity is a lower cost option than adding the next unit of insulation or air tightness. While the elimination of the heating system is a specific goal within that design process, that explicit step function in the cost optimization curve should be explored in a consistent fashion in the evaluation process.

Both approaches remain difficult and costly to achieve – particularly for standard building practice and standard appliances. This is precisely why the *BEOpt* software has been developed by the National Renewable Energy Laboratory within the *Building America* research process. As shown in Figure 9, it allows specific evaluation of each tradeoff in the locus of conservation options on the least cost curve [18].



Envelope		
Ceiling	$707	R57
Windows & Shading		
Glass Type	$413	low-e
Appliances & Lighting		
Refrigerator	$0	Kenmore 5125
Dishwasher	$0	Frigidaire 638 kWh/yr
Equipment		
HVAC	$791	GasFurnaceSEER10-AFUE92.5
Water Heater	$838	Gas Tankless
Other		
Frame Walls	$1,163	R33
Indoor Lighting	$299	100% CFL
Plug Loads	$0	Very Low Plug Loads
Appliance Type	$0	Gas and Electric
ClothesWasher	$518	Gen. Elec. 707 kWh/yr
Renewables		
Solar DHW	$4,768	64 ft2 Flat Plate
PV Array	**$50,711**	**Rated at 6.3 kW**
	$60,208	Total

Figure 9.*Original analysis of Wheat Ridge ZEH using BEOpt software to evaluate a wide parameter field of competing options.*

Based on the performance of the homes detailed here, the *Passivhaus* and Wheat Ridge efficiency levels are generally closer to the global optimum than that seen in many ZEH projects to date.

To show how the various low energy homes compare, we have prepared three data summary plots.[2] Figure 10 shows how the cost of each project compares with the level of energy savings obtained from efficiency measures. The baseline homes are shown in red squares with savings shown from measured data (green triangles) for each of the projects. It is noted that costs are generally modest for efficiency measures in the homes – save for some of the more aggressive of the ORNL research projects.

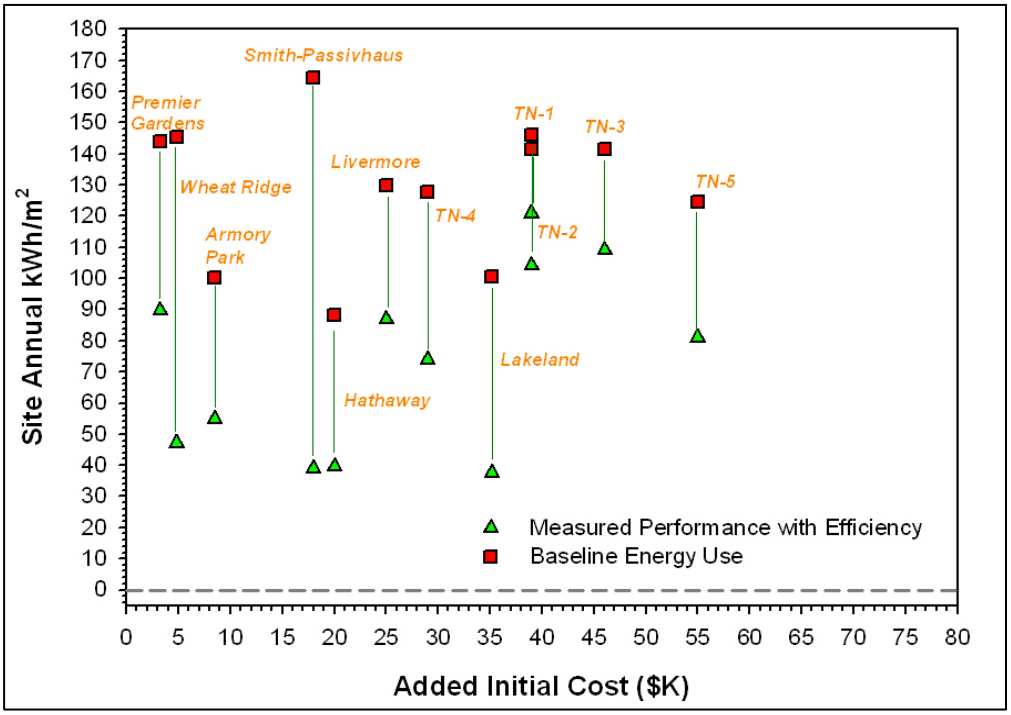


Figure 10. *Performance of efficiency measures in low energy homes.*

A second plot, Figure 11, shows similar data to that above with the costs and performance of the solar electric PV systems included. The PV costs are shown without rebates. The baseline building is shown by the red squares, the efficiency measures by the green triangles and the solar PV by the yellow circles. This data shows that the costs of PV adds another $20 - $40K to the project costs and with generally lower savings than those achieved from the efficiency measures.

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[2] We caution that the data from the houses are from very different climates, differing sized homes and with varying degrees of added cost due to the research elements inherent in each.

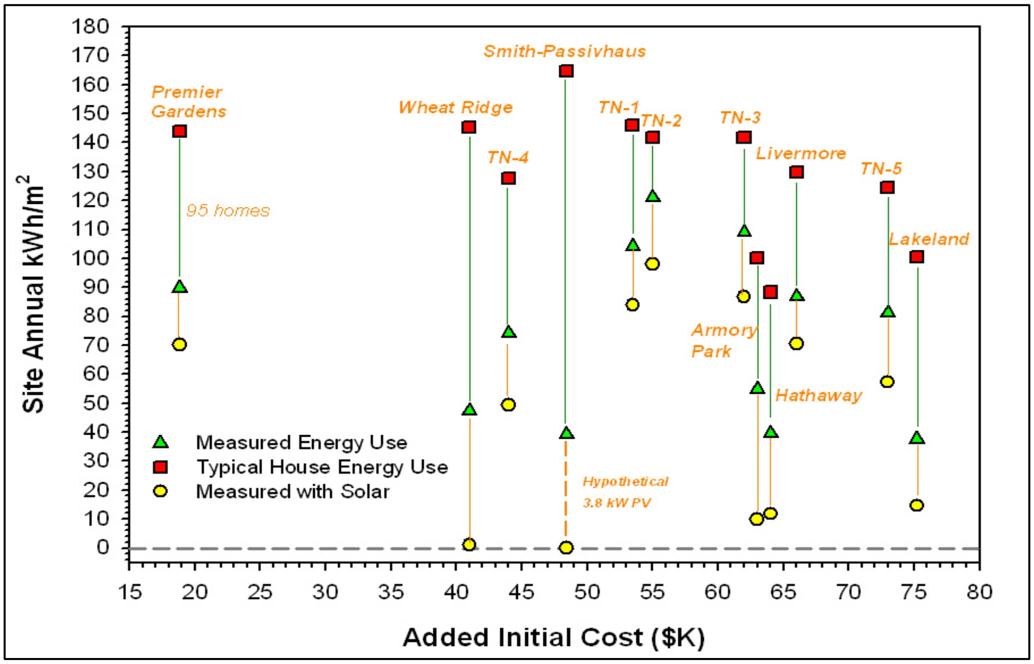

Figure 11. *Summary of energy performance of twelve advanced Zero Energy Homes around the United States.*

Figure 12 shows how the added costs for the efficiency and solar systems compare when the incremental costs for these elements are amortized at a 4% real discount rate over 30 years (annualized capital recovery factor = 0.0578). We then estimate the cost of conserved energy for the efficiency and PV sides of the achieved building performance. Most often the efficiency measures are more cost effective than the popular PV segments and hence remain a key prerequisite of any successful very low energy use programs. For instance, this argues for greater effort to improve energy efficiency within conventional Zero Energy Home designs such as the *Hathaway House*. On the other hand, over investment in efficiency or selection of more expersive options can mar potential economics. An example of this is the emphasis of more costly structurally insolated panels (SIPs) and ground source heat pumps in the ORNL ZEH projects versus the lower cost double-stud wall construction used in the NREL Habitat project.

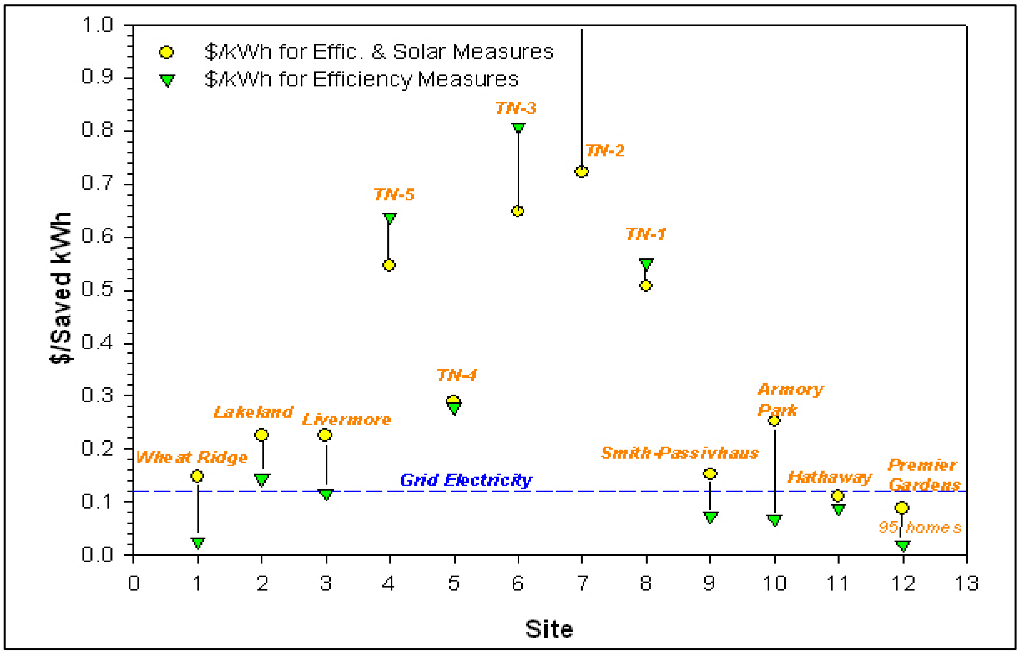

Figure 12. *Cost of conserved energy for efficiency and solar elements in low energy homes.*

Community Scale Efforts

Beginning in 2001, three other builders in California (Shea Homes, Clarum Homes and Grupe Homes) and one in Arizona (John Wesley Miller) have built entire communities of high performance homes with photovoltaic systems similar to the Premier Homes project. Bill analysis data for Shea Homes show 54% annual energy savings on a whole house basis (for homes with the 2.4kW PV system) compared to communities of adjacent homes [19]. Buyers of such near ZEH homes are also very happy with their utility bills. For instance, the average monthly utility bills for the John Wesley Miller *Armory Park del Sol* community of 97 homes in Tucson, AZ has been less than $16/month.

One of the most significant findings is that all four California builders report that their near ZEH homes sell much faster than conventional ones – a highly desirable attribute for builders. Grupe Homes has provided recent data showing an estimated savings of $13 million for their 144 home near ZEH community (*Carsten Crossings*) from the fact that the NZEH homes were are selling twice as quickly as the competition. Also, so successful has been the *Premier Gardens* project in California that Sacramento Municipal Utilities District has developed a utility program based on this model with over 4,000 such homes under contract with eight different builders.

Claiming the Potential

Based on thirty years of research effort, we already know much about how to reduce energy use in our homes. This was convincingly demonstrated in an early ZEH project in Lakeland, Florida where two houses were built, one standard and the other efficient with photovoltaics. We used off-the-shelf technologies and reduced measured energy cooling use by 75% and total energy use by 93% once the solar electricity was counted [20]. As seen in this summary, other such homes have been built, but surprisingly few given expressed public interest in reducing greenhouse gas emissions.

Economics is at least partly to blame for our torpid progress. Standard thinking often evokes a faulty time horizon for personal decisions with societal consequences. Since most may only live in a house for an average of seven years, unless a technology or innovation pays for itself in half that time, most tend to dismiss it [21]. Why should an investor pay for the benefits inherited by another person buying their home? The answer is, of course, that the person buying that home is ourselves. Another economic failure is the perceived lack of valuation of energy efficiency features in resale – a real estate valuation gap that may be remedied by an expanding data base of such homes in California. There is also another limitation of classical micro-economics: uncertainty is not properly accounted within a typical life-cycle cost approach. True, the sensitivity analysis and risk assessment techniques can be applied to its static framework, but these studies belong to the rarified world of academia [22]. Financial and energy planners don't want a Monte Carlo derived range of probabilities; they want a single answer. We demand that the complex estimation be made simple – simple enough where our assumptions may paint us in to a hopelessly inadequate position.

To place this in perspective, one need only recall the difficult progress on policy matters ranging from fuel efficiency standards for automobiles to SEER minimums for air conditioners where payback and lifecycle costs dominate the evaluation rather than the possibility that foreign oil dependence or peak electricity demand could become crushing problems. Moreover, excess CO_2 production and global climatic damage might be exacting a planet-level illustration of Garret Hardin's "Tragedy of the Commons [23]."

Economics forever looks at the future as if it is a reflection of the past – a flawed myopia. Yet, the energy picture will constantly change such that targeting based on present position is prone to underachieve what might be vital. Put another way, the economic downside of making our homes more efficient than economically justified in the future is much less catastrophic than a world where energy prices suddenly rise and we find ourselves still housed in buildings that are too expensive to operate.

Recently, however, there have been encouraging signs. The *Passivhaus* movement in Europe along with the explosion in renewable energy power production there, are promising [24]. In the U.S, large-scale developments with near ZEH homes such as those seen in California illustrate both the potential and means for much more wide spread transformation towards advanced energy-efficient housing in the 21st century.

Summary

In general, the presented research data above would suggest that while genuine research challenges remain, very low energy use buildings can very readily be achieved in North America. In general, the greater cost effectiveness seen from energy efficiency measures in this evaluation indicates that greater investment in conservation should be a prerequisite to installation of solar water heating and solar electricity in Near Zero Energy Homes. The same data also would reveal a tendency towards underinvestment in energy efficiency relative to renewable energy in many previous projects and the need to re-emphasize the efficiency element.

Collective political will may be the more difficult issue than the research data to support the tasks. Very low energy buildings, both new and existing, are fully within our grasp if society deems their achievement a national priority.

Acknowledgements

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Exemplary Low Energy House Performance Summaries

Site Designation: Lakeland Zero Energy Home
Location: Lakeland, FL
Contact: Danny Parker (Dparker@fsec.ucf.edu)
Year of Construction: 1998
Conditioned Floor Area: 2,425 ft2 (225 m^2)
Measured Annual Total kWh: (all end uses) 6,960 kWh; 19.1 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: 54 gallons of propane used (5.16 x 106 Btu; or 1,511 kWh heat equivalent)
Year of Measurement (12 month period) July 1 2001 - June 30, 2002
Normalized Total Annual Energy Use: 37.6 kWh/ m^2
Annual kWh Solar Electric Production: 5,180 kWh
Net Electricity Use: 1,780 kWh (4.9 kWh/Day)
Normalized Net Energy Use: 14.6 kWh/ m^2
Primary Design Features (Energy Efficiency): highly reflective roofing, interior duct system, low-e solar control windows, efficient lighting and appliances; high SEER heat pump; exterior wall insulation
Primary Design Features (Renewable Energy): solar water heater; 4 kW PV system (2.7 kW facing south; 1.3 kW facing west)
Estimated Incremental Cost of Construction: $35,200
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): $40,000
Other Project Comments: PV costs would be approximately 20% lower ten years later; also better cooling systems are now available and lower cost wall options. Control home of the same size without features use 22,600 kWh for the same year (100 kWh/m^2 and roughly 300 kWh/m^2 for primary energy consumption).
Project Weblink:
http://www.fsec.ucf.edu/en/research/buildings/zero_energy/lakeland/index.htm

Site Designation: Livermore ZEH
Location: Livermore, CA
Year of Construction/Renovation: 2002
Conditioned Floor Area: 3080 ft2
Measured Annual Total kWh: (all end uses) 4367 kWh
Measured Annual Natural Gas Therms: (All end uses) 699 therms
Year of Measurement (12 month period) 2007
Annual kWh Solar Electric Production: 4658 kWh
Primary Design Features (Energy Efficiency):
-R-10 slab edge insulation
-2x4 walls with cellulose insulation
-R-38 ceiling insulation (cellulose)

-Radiant barrier roof sheathing
-House & ducts tested for tightness (SLA~3, <6% duct leakage)
-5/8" drywall and 50% hard surface floors (for mass)
-Low E2 windows (~0.34 U & SHGC)
-Exterior window shading (trellis) on east and south, deep patio on west
-Tankless water heater (0.82 EF) and on-demand hot water recirculation
-NightBreeze integrated ventilation cooling, heating & AC (two variable speed fan coils served by tankless water heater)
-SEER 13 A/C

Primary Design Features (Renewable Energy):
-3.6 kWdc Astropower modules, 3 inverters (3 strings)
-48 ft2, 80 gal. solar water heater (closed loop, antifreeze), PV powered brushless pump

Estimated Incremental Cost of Construction:
If Centex had been charged for the added components, incremental costs would likely have exceeded $25,000. PV modules were provided and installed by AstroPower (currently GE). The solar water heater was donated and installed by Solahart, and Rinnai donated the tankless water heater.

Estimated Incremental Cost of Solar Features: (include both solar hot water and PV) These were donated. The solar water heater would likely have cost ~$5,000 and the PV system $18,000 after rebates.

Other Project Comments: The house has been continuously monitored for over five years. The owners have yet to be charged for electricity usage. The house has been reported on in several reports.

Contact: David Springer, Davis Energy Group
Project Weblink: www.davisenergy.com,
http://www.fsec.ucf.edu/en/research/buildings/zero_energy/livermore/

Site Designation: Hathaway Zero Energy Home
Location: Purcellville, VA (outside Washington DC)
Contact: Paul Norton (Paul_Norton@NREL.gov)
Year of Construction: 2001
Conditioned Floor Area: 2880 ft^2 (268 m^2) in two stories on unconditioned basement
Measured Annual Total kWh: (all end uses) 10,585 kWh; 20 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period): January - December 2002
Normalized Total Annual Energy Use: 39.5 kWh/m^2
Annual kWh Solar Electric Production: 7,410 kWh

Net Electricity Use: 3175 kWh (8.7 kWh/Day)
Normalized Net Energy Use: 11.8 kWh/m^2
Primary Design Features (Energy Efficiency): Ground source heat pump, R-38 attic insulation, R-19 walls + R5 sheathing, and interior duct system, High performance solar control low-e windows, efficient appliances, compact fluorescent lighting
Primary Design Features (Renewable Energy): 6.0 kW PV system (facing south on 5/12 pitch roof), solar hot water with evacuated tube collectors, 80 gallon storage and geothermal heat pump auxiliary backup
Estimated Incremental Cost of Construction: $20,000
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost ~$39,000 for PV, $7,000 for solar hot water
Project weblink: http://www.nrel.gov/docs/fy05osti/37731.pdf, http://www.ert.net/solarhome/chapters.htm

Site Designation: ZEH5-two-story (2600 ft^2) Zero Energy Home
Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2005
Conditioned Floor Area: 2,632 ft^2 (245 m^2)
Measured Annual Total kWh: (all end uses) 10995 kWh; 30.1 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) Jan 1 2007 – Dec. 31, 2007
Normalized Total Annual Energy Use: 44.9 kWh/m^2
Annual kWh Solar Electric Production: 2697 kWh
Net Electricity Use: 8298 kWh (22.7 kWh/Day)Normalized Net Energy Use: 33.9 kWh/m^2
Primary Design Features (Energy Efficiency): foundation geothermal heat pump system, ZEHcor wall, Structural Insulated Panel roof and above grade walls, air-tight construction, ASHRAE 62.2 mechanical ventilation compliant, reflective raised metal roofing, interior duct system, High performance windows, efficient lighting and appliances, exterior foundation wall insulation, walkout lower level
Primary Design Features (Renewable Energy): solar water heater; 2.2 kW PV system (facing south on 4/12 pitch roof)
Estimated Incremental Cost of Construction: $30,200
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): $18,000
Other Project Comments:

Site Designation: ZEH5-one-story (1240 ft^2) Zero Energy Home
Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2005
Conditioned Floor Area: 1232 ft^2 (115 m^2)

Measured Annual Total kWh: (all end uses) 9323 kWh; 25.5 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) Jan 1 2006 – Dec. 31, 2006
Normalized Total Annual Energy Use: 81.1 kWh/m^2
Annual kWh Solar Electric Production: 2739 kWh
Net Electricity Use: 6584 kWh (18 kWh/Day)
Normalized Net Energy Use: 57.3 kWh/m^2
Primary Design Features (Energy Efficiency): foundation geothermal heat pump system, ZEHcor wall, Structural Insulated Panel roof and walls, air-tight construction, ASHRAE 62.2 mechanical ventilation compliant, reflective raised metal roofing, interior duct system, High performance windows, efficient lighting and appliances.
Primary Design Features (Renewable Energy): solar water heater; 2.2 kW PV system (facing south on 4/12 pitch roof)
Estimated Incremental Cost of Construction: $54,676
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): $18,000
Other Project Comments:

Site Designation: ZEH4 Zero Energy Home
Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2004
Conditioned Floor Area: 1200 ft^2 (112 m^2)
Measured Annual Total kWh: (all end uses) 8286 kWh; 22.7 kWh/DayMeasured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) Dec 1 2005 – Nov. 30, 2006
Normalized Total Annual Energy Use: 74 kWh/m^2
Annual kWh Solar Electric Production: 2763 kWh
Net Electricity Use: 5523 kWh (15.1 kWh/Day)
Normalized Net Energy Use: 49.3 kWh/m^2
Primary Design Features (Energy Efficiency): Heat-Pump Water Heater, Air-source SEER 17 heat pump system, Structural Insulated Panel roof and above-grade walls, Precast insulated concrete panels for the walkout lower level, Cool-coating applied to the exterior surface of the exposed above-grade lower level panels, air-tight construction, ASHRAE 62.2 mechanical ventilation compliant, reflective metal roofing, interior duct system, High performance windows, efficient lighting and appliances.
Primary Design Features (Renewable Energy): 2.2 kW PV system (facing south on 4/12 pitch roof)
Estimated Incremental Cost of Construction: $27,816
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost $15,000

Site Designation: ZEH3 Zero Energy Home
Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2003
Conditioned Floor Area: 1082 ft^2 (101 m^2)
Measured Annual Total kWh: (all end uses) 11014 kWh; 30.2 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) March 1 2004 – Feb. 28, 2005
Normalized Total Annual Energy Use: 109 kWh/m^2
Annual kWh Solar Electric Production: 2241 kWh
Net Electricity Use: 8773 kWh (24 kWh/Day)
Normalized Net Energy Use: 87 kWh/m^2
Primary Design Features (Energy Efficiency): Geothermal Heat-Pump with a desuperheater connected to the Water Heater, Air-source SEER, Structural Insulated Panel roof and above-grade walls, Insulated unvented crawl space, Infrared reflective pigmented coating applied to raised metal seam roof, air-tight construction, ASHRAE 62.2 mechanical ventilation compliant, interior duct system, High performance windows, efficient lighting and appliances.
Primary Design Features (Renewable Energy): 2.0 kW PV system (facing south on 6/12 pitch roof)
Estimated Incremental Cost of Construction: $45,728.40
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost $16,000

Site Designation: ZEH2 Zero Energy Home Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2003
Conditioned Floor Area: 1082 ft^2 (101 m^2)
Measured Annual Total kWh: (all end uses) 12207 kWh; 33.4 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) April 1 2004 – March 31, 2005
Normalized Total Annual Energy Use: 120.9 kWh/m^2
Annual kWh Solar Electric Production: 2305 kWh
Net Electricity Use: 9902 kWh (27.1 kWh/Day)
Normalized Net Energy Use: 98 kWh/m^2
Primary Design Features (Energy Efficiency): Heat Pump Water heater linked to the Energy Star Refrigerator and the Crawl space controlled by the thermostat to provide supplementary space cooling and dehumidifing in the summer and serve as a radon mitigator in the heating mode, SEER 14 2-speed compressor Heat-Pump Air-source, Structural Insulated Panel roof and above-grade walls, Insulated unvented crawl space, ASHRAE 62.2 mechanical ventilation compliant, interior duct system, High performance

windows, efficient lighting and appliances.
Primary Design Features (Renewable Energy): 2.0 kW PV system (facing south on 6/12 pitch roof)
Estimated Incremental Cost of Construction: $39,357.80
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost $16,000

Site Designation: ZEH1 Zero Energy Home
Location: Lenoir City, TN
Contact: Jeff Christian (ChristianJE@ORNL.gov)
Year of Construction: 2002
Conditioned Floor Area: 1056 ft^2 (98 m^2)
Measured Annual Total kWh: (all end uses) 10,216 kWh; 28 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) March 1 2003 – Feb. 29, 2004
Normalized Total Annual Energy Use: 104.2 kWh/m^2
Annual kWh Solar Electric Production: 2006 kWh
Net Electricity Use: 8210 kWh (27.1 kWh/Day)
Normalized Net Energy Use: 84 kWh/m^2
Primary Design Features (Energy Efficiency): Heat Pump Water heater linked to the Energy Star Refrigerator and the Crawl space controlled by the thermostat to provide supplementary space cooling and dehumidifing in the summer and serve as a radon mitigator in the heating mode, SEER 13 Heat-Pump Air-source, Structural Insulated Panel roof, walls and the floor, Unvented crawl space, ASHRAE 62.2 mechanical ventilation compliant, interior duct system, High performance windows, efficient appliances, Grey water waste heat recovery system.
Primary Design Features (Renewable Energy): 2.0 kW PV system (facing south on 4/12 pitch roof)Estimated Incremental Cost of Construction: $39,198
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost $14,500

Site Designation: Armory Park del Sol ZEH
Location: Tucson, AZ
Contact: Joe Wiehagen, NAHB, Jwiehagen@nahbrc.org
Year of Construction: 2003
Conditioned Floor Area: 1718 ft^2 (160 m^2)
Measured Annual Total kWh: (all end uses) 8786 kWh; 24.1 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) None
Other Energy Source Use: None
Year of Measurement (12 month period) 2005 – 2006
Normalized Total Annual Energy Use: 54.9 kWh/m^2
Annual kWh Solar Electric Production: 7207 kWh

Net Electricity Use: 1578 kWh (4.3 kWh/Day)
Normalized Net Energy Use: 9.9 kWh/m^2
Primary Design Features (Energy Efficiency): High efficiency 2 speed air conditioner, R-41 ceiling under white reflective roofing, R-14 exterior insulation over filled concrete blocks, interior duct system, high performance windows, efficient lighting and appliances.
Primary Design Features (Renewable Energy): 4.2 kW PV system; 120 sqft solar thermal collectors with 220 gallon storage for DHW and space heating; electric resistance backup
Estimated Incremental Cost of Construction: $9,500
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): PV cost $42,000

Site Designation: Smith/Klingenberg Passivhaus
Location: Urbana, IL
Contact: Katrin Klingenberg (katrin.klingenberg@e-colab.org)
Year of Construction: 2002-2003
Conditioned Floor Area: 1200 sqft (111.5 sqm)
Measured Annual Total kWh: (all end uses) 4350 kWh or 39 kWh/sqm and year (of that 10.7 kWh/sqm and year are for space conditioning)
Measured Annual Natural Gas Therms: (All end uses) 0
Year of Measurement (12 month period) 2005
Annual kWh Solar Electric Production: 0
Primary Design Features (Energy Efficiency): Superinsulation, airtightness 0.6 ACH @50Pa, passive solar, HRV with 100' Earth tube air intake for pre-warming in winter, cooling/dehumidification in summer, triple pane, argon filled low-e windows with insulated fiberglass frames, multi lock doors and windows, concrete slab on grade finished floor
Primary Design Features (Renewable Energy): 0
Estimated Incremental Cost of Construction: approx. $15 per sq ft
Estimated Incremental Cost of any Solar Features: 0
Other Project Comments: First US passive house project to be entered into the first English version of the PHPP (Passive House Planning Package)
Project Weblink: e-colab.org

Site Designation: Wheat Ridge ZEH
Location: Wheat Ridge, Colorado (near Denver)
Contact: Paul Norton, Paul_Norton@NREL.gov
Year of Construction: 2005
Conditioned Floor Area: 1280 ft^2 (118.9 m^2)
Measured Annual Total kWh: (all end uses): 3585 kWh
Measured Annual Natural Gas Therms: (All end uses): 57 Therms (1670 kWh)
Year of Measurement (12 month period): April 2006- March 2007
Annual kWh Solar Electric Production: 5127 kWh
Net Electricity Use: -1542 kWh (-13.0 kWh/Day)
Normalized Net Energy Use: 1.1 kWh/m^2

Primary Design Features (Energy Efficiency): (list) superinsulation (R-60 ceiling, R-40 walls, R-30 floors), U=0.3 windows; ERV; tankless gas DHW auxiliary, direct vent ductless gas heater in home, CFL used for lighting throughout, Energy Star clothes washer and dishwasher
Primary Design Features (Renewable Energy): (list) large solar DHW system with 200 gallon (757 l) storage; 4 kW PV system
Estimated Incremental Cost of Construction: $3,443
Estimated Incremental Cost of Solar Features: (include both solar hot water and PV): $39,068
Other Project Comments: One of the first buildings to prove their attainment of zero energy on an annualized basis. When calculations are based on source energy, consumption was -24% given the excess electrical production.
Project Weblink:
http://www.eere.energy.gov/buildings/building_america/cfm/project.cfm/state=CO/city=Wheatridge/full=Colorado/project=Habitat%20for%20Humanity%20-%20NREL%20ZEH/ID=3690/floor_plan=4700%20Carr%20St%20Plan%20-%201130%20sq.%20ft#house

Site Designation: Premier Gardens Homes
Location: Rancho Cordova, CA, (near Sacramento)
Contact: Rob Hammon, BIRA/CONSOL (rob@ConSol.ws)
Year of Construction: 2003, 95 homes of which 18 were monitored
Conditioned Floor Area: Avg 1770 ft^2 (164 m^2)
Measured Annual Total kWh: (all end uses) 7,066 kWh; 19.4 kWh/Day
Measured Annual Natural Gas Therms: (All end uses) 277 Therms
Other Energy Source Use: None
Year of Measurement (12 month period) 2004
Normalized Total Annual Energy Use: 89.8 kWh/m^2
Annual kWh Solar Electric Production: 3,329 kWh
Net Electricity Use: 3,737 kWh (10.2 kWh/Day)
Normalized Net Energy Use: 70.1 kWh/m^2
Primary Design Features (Energy Efficiency): High efficiency SEER 14 air conditioner, high efficiency furnaces (AFUE=0.91) R-38 ceiling, R-13 to R-19 wall exterior insulation, ducts buried in attic insulation, high performance windows, 100% fluorescent lighting.
Primary Design Features (Renewable Energy): 2.4 kW PV system
Estimated Incremental Cost of Construction: $3,200
Estimated Incremental Cost of any Solar Features: (include both solar hot water and PV): $15,636
Comment: Compared to monitored adjacent community (Cresleigh) without features which showed 10% higher electricity use (7770 kWh) and 64% higher gas consumption (454 Therms). Electricity use is 17% lower than PGE average for houses this size (8550 kWh); gas consumption is 49% lower (540 Therms)
Weblink: http://media.pennnet.com/documents/Solar+data.pdf