FIELD EXPERIENCE WITH GROUND-SOURCE HEAT PUMPS IN AFFORDABLE LOW ENERGY HOUSING

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Abstract: The tangible end-user benefits of low energy housing are needed most at the entry level, where high energy costs can be least afforded. Yet, this sector also provides the greatest challenge in managing the associated construction cost increase. Lasting structural and behavioral changes in the marketplace are required to overcome the barriers created by an over-emphasis on first cost. A large-scale demonstration was initiated with just such a goal. This affordable housing project utilizes ground-source heat pumps, low energy construction techniques, and in some cases, on-site solar electricity production to reduce energy consumption by 60-80% from current practice. This paper discusses the creation, goals and funding of the project, reviews the energy reduction measures employed, and presents the estimated and actual results in terms of energy consumption, carbon emissions, and economics.

Key Words: ***heat pump, geothermal, ground-source, low energy, zero energy, solar, photovoltaic, affordable, low income, Habitat***

1 INTRODUCTION

Habitat for Humanity International (HFHI) is a nonprofit Christian housing ministry that has built more than 250,000 homes around the world, providing more than 1 million people with safe, decent, affordable shelter. HFHI is ranked the third largest private home builder in the U.S., completing on average more than 5,000 homes per year and another 20,000 homes per year in other countries. Although they depend on volunteer labor and donations of money and materials, Habitat is not a giveaway program. In addition to a down payment and the monthly mortgage payments, these limited-income homeowners invest hundreds of hours of their own labor into building their own Habitat house and the houses of others.

Like most HFHI affiliates, Central Oklahoma Habitat for Humanity (COHFH) has focused on minimizing the initial costs of construction to keep homeowner mortgage payments low. Their modest wood-frame single-family detached homes have traditionally been built to code-minimum insulation specifications and have utilized standard-efficiency natural gas forced-air furnaces, split-system central air conditioners, and gas-fired storage water heaters. With U.S. natural gas prices doubling in recent years, an overlooked aspect of the COHFH mission to provide affordable home ownership emerged… the monthly energy costs, which in peak months could rival the mortgage payment for their lowest-income homeowners, because the payments are based on their income level.

COHFH installed its first ground-source (or geothermal) heat pump (GHP) system in 2005, with the technical and financial support of a local GHP manufacturer. During 2006, 10 more GHP systems were installed, with 9 as part of the COHFH “Home Builder Blitz” in Spencer, Oklahoma. The Blitz homes were sponsored by a group of local professional home builders and were all constructed from start to finish in 5 days as a promotional event.

In late 2006, COHFH reached an agreement with the local GHP manufacturer to incorporate GHP systems into all of their homes on an ongoing basis, an average of 50 per year. For the

next 5 years, most of these homes will be built in Hope Crossing, a new (first phase 2007) 240 lot COHFH development located on 24 hectares in Oklahoma City. In early 2007, the local electric utility added its support to the Hope Crossing project. The additional funding provided for envelope, lighting, and appliance upgrades that were desired to further reduce the energy consumption of these homes. Thus, a private-sector collaborative team consisting of COHFH, the electric utility, and the GHP manufacturer was formed with the ambitious goal of making Hope Crossing a showcase large-scale demonstration of affordable low energy housing.

1.1 Hope Crossing Project Goals

- Install GHP systems in all homes

- Reach the lowest energy consumption feasible in all homes by using cost-effective and generally available measures such as insulation and window upgrades, and high efficiency lighting and appliances

- Track the energy consumption of all homes to establish a baseline of performance, and install a proportion of "smart" data-recording meters to develop detailed electricity demand profiles

- In a limited number of homes, integrate on-site solar photovoltaic (PV) grid-connected systems to demonstrate the benefits of zero peak energy (no net grid electricity use during summer peak periods) and eventually zero net energy (no net grid electricity use over a full year)

- Utilize this large-scale, affordable, low energy housing demonstration as a market transformation publicity tool, as a platform to generate spin-off projects with other HFHI affiliates, and as a means to attract additional COHFH donations

1.2 Hope Crossing Project Funding

The average COHFH house costs about $85,000 to build, which is also the selling price to the homeowner. However, COHFH directly provides its homeowners a zero-interest mortgage loan, so the selling price is actually received over a 20-30 year period. So, even if the costs of reducing the energy consumption of their homes were included in the selling price, they would actually be recovered slowly over many years as the mortgage was paid. For COHFH to proceed with the project, the funding for the additional costs had to be found elsewhere.

The GHP manufacturer and its local installer agreed to install the GHP systems for COHFH at the same price they were paying for a gas furnace and air conditioner. Several steps were taken to reduce the installation costs to make this more feasible:

1. Integrate the ground-loop pumping and purging valves into the heat pump to save on space required, equipment cost, and field labor content

2. Drill a single 120m heat exchange bore directly under the floor slab instead of the typical practice of drilling two 60m heat exchangers in the lawn, which requires a separate excavation step to manifold them and route the piping into the house.

These measures put the installer in a better position, but to meet the cost goal still requires the manufacturer to donate the GHP. The electric utility is funding the incremental costs for the envelope, lighting, and appliance upgrades as part of its low-income weatherization program. Both of these parties shared the costs for the 2 homes equipped with solar PV

systems. There is good justification for this level of financial support beyond the project demonstration value: it is an act of corporate stewardship, but excels over a one-time gift in continuing to provide financial and environmental benefits over many years; in addition, the project provides valuable experience in an unexplored segment of the housing market.

2 THE PROGRESSION TO LOW ENERGY

Oklahoma City is considered a mixed-humid climate that requires significant amounts of both heating and cooling, and that has significant humidity levels throughout the year. Air conditioning is considered a must in all new homes, which makes air-based distribution systems the norm. Most new homes use either a central forced-air gas furnace coupled with a split-system air conditioner, or a split-system central air-source heat pump and supplemental resistance heat. In low-cost single-story houses typical of the COHFH homes, the central duct system is usually located in the unconditioned attic, perhaps the worst possible location from an energy-efficiency standpoint.

Table 1 outlines the characteristics of the 4 types of COHFH homes that have been constructed to date, with the “Standard Gas” home being typical of all COHFH homes built up until recently. The first step taken to reduce energy consumption was to install a GHP system in this same type of home, which is designated “Standard GHP” in Table 1. Later, the envelope, lighting, and appliances were upgraded leading to the designation of “Low Energy GHP” home. Finally, 2 homes to date have been equipped with solar PV systems sized with a goal of being zero-peak, or nearly “off-grid” during the utility peak load period, which occurs during summer afternoons. In addition, these “Low Energy GHP + PV” homes should not require any grid electricity (on a net basis) to operate the GHP system over the year.

Figure 1 illustrates the major changes made to the homes in the progression from Standard Gas to Low Energy GHP + PV.

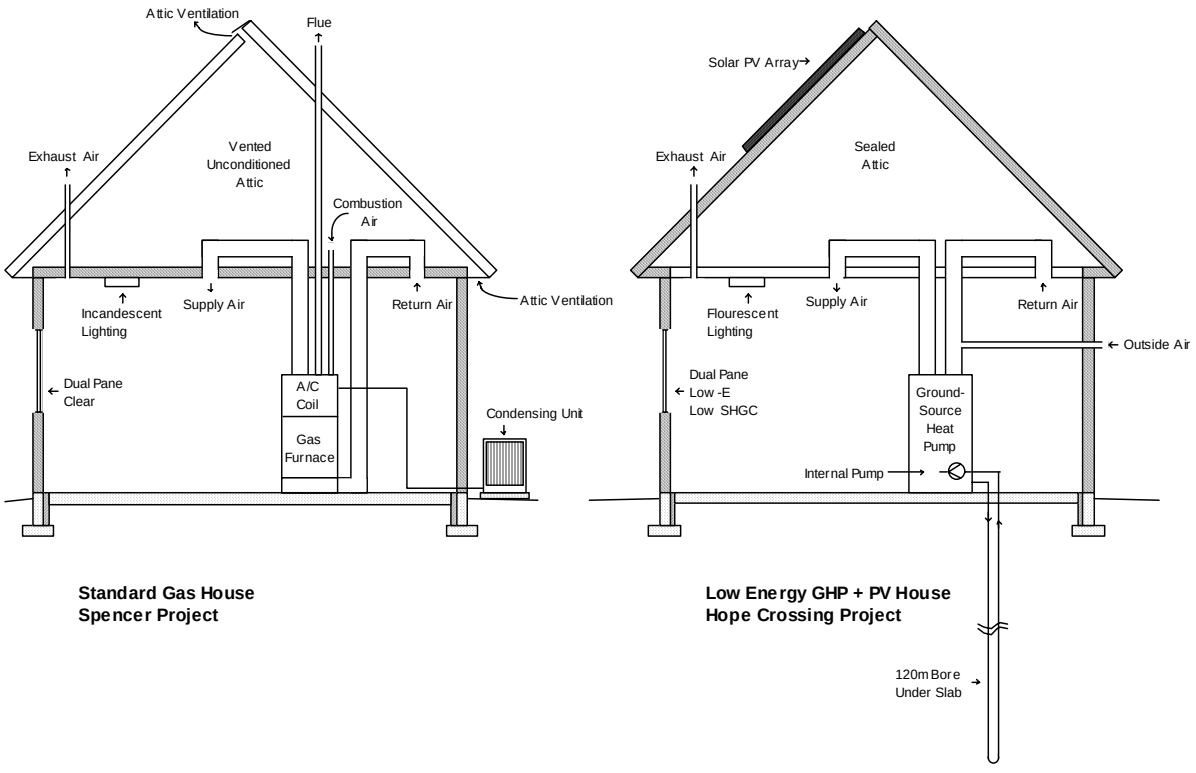


Figure 1: Evolution of COHFH Homes

Table 1: COHFF Housing Characteristics

House Type		Standard Gas	Standard GHP	Low Energy GHP	Low Energy GHP + PV
Project		Spencer	Spencer	Hope Crossing	Hope Crossing
Heating		Gas	GHP	GHP	GHP
Cooling		Split A/C	GHP	GHP	GHP
Hot Water		Gas Storage	Elec Storage[1]	Elec Storage[1]	Elec Storage[1]
Lighting		Incandescent	Incandescent	Flourescent	Flourescent
Appliances		Standard	Standard	Energy Star[2]	Energy Star[2]
Solar PV Array	DC kW				2.3
Construction		Wood Frame	Wood Frame	Wood Frame	Wood Frame
Floor		Slab on Grade	Slab on Grade	Slab on Grade	Slab on Grade
Attic		Vented	Vented	Sealed	Sealed
Insulation Type		Fiberglass	Fiberglass	Spray Foam	Spray Foam
Air Duct Location		Attic	Attic	Attic	Attic
Ventilation		Spot Exhaust	Spot Exhaust	Central Supply	Central Supply
Average Floor Area	m^2	110	110	110	110
Total Envelope UA	W/K	183	183	137	137
U-value - Slab Perimeter	$W/(m^2 \cdot K)$	1.10	1.10	1.10	1.10
U-value - Wall	$W/(m^2 \cdot K)$	0.35	0.35	0.35	0.35
U-value - Flat Ceiling	$W/(m^2 \cdot K)$	0.19	0.19		
U-value - Sloped Roof	$W/(m^2 \cdot K)$			0.26	0.26
U-value - Air Duct	$W/(m^2 \cdot K)$	0.95	0.95	0.71	0.71
U-value - Window	$W/(m^2 \cdot K)$	2.84	2.84	1.99	1.99
SHGC - Window		0.62	0.62	0.40	0.40
Natural Air Change Rate - Htg	1/h	0.78	0.78	0.30	0.30
Natural Air Change Rate - Clg	1/h	0.56	0.56	0.22	0.22
Envelope Air Leakage Rate		Untested	Untested	Tested	Tested
Air Duct Leakage Rate		Untested	Untested	Tested	Tested
Heating Load (-11°C, 21°C)	kW	8.2	8.2	5.3	5.3
Cooling Load (36°C, 24°C)	kW	6.1	6.1	4.7	4.7
Hot Water Load (55°C)	kWh/yr	3200	3200	3200	3200
Lighting Load	kWh/yr	1753	1753	701	701
Appliance Load	kWh/yr	4667	4397	3518	3518

1. GHP desuperheater assist
2. Energy Star appliances meet strict efficiency guidelines

3 ACTUAL ENERGY CONSUMPTION – STANDARD HOUSES

Monthly energy consumption during 2007 was collected from utility meter data for 16 homes in the Spencer project. The characteristics of these homes are outlined in Table 1, with 8 being of type Standard Gas and 8 of type Standard GHP. The occupancy of each house type was essentially the same, with the Standard Gas homes averaging 2.8 people, and the Standard GHP homes averaging 2.6. Figure 2 shows the total energy consumption for each house type, by month and annually, as determined by averaging the monthly utility meter data for the homes of each type.

The heating (E_H) and cooling (E_C) components of the energy consumption for each house type were derived by analyzing the monthly metered energy consumption and corresponding

monthly Degree Days (DD_H, DD_C) using linear regression. Figure 3 presents the results of this analysis, normalizing the energy consumption to remove the y-intercept, or base load component, in each case. The high value of correlation (R^2) indicates that the heating and cooling loads of the standard homes are strongly dominated by the outdoor temperature, or in effect, the building envelope.The reduction in heating and cooling energy consumption achieved by the GHP system was:

E_H reduction using GHP = 1- (E_H GHP/E_H Gas) = 1 – (.0134/.0397) = 66.3%

E_C reduction using GHP = 1- (E_C GHP/E_C A/C) = 1 – (.0145/.0284) = 48.8%

Figure 4 shows the total energy cost for each house type, by month and annually, as determined by averaging the actual monthly utility costs for the homes of each type. The reductions in annual total energy consumption (E_{Ta}) and annual energy costs ($E_{\$a}$) achieved by the GHP system were:

E_{Ta} reduction using GHP = 1- (E_{Ta} GHP/E_{Ta} Gas) = 1 – (116.2/234.3) = 50.4%

$E_{\$a}$ reduction using GHP = 1- ($E_{\$a}$ GHP/$E_{\$a}$ Gas) = 1 – ($1,023/$1,606) = 36.3%

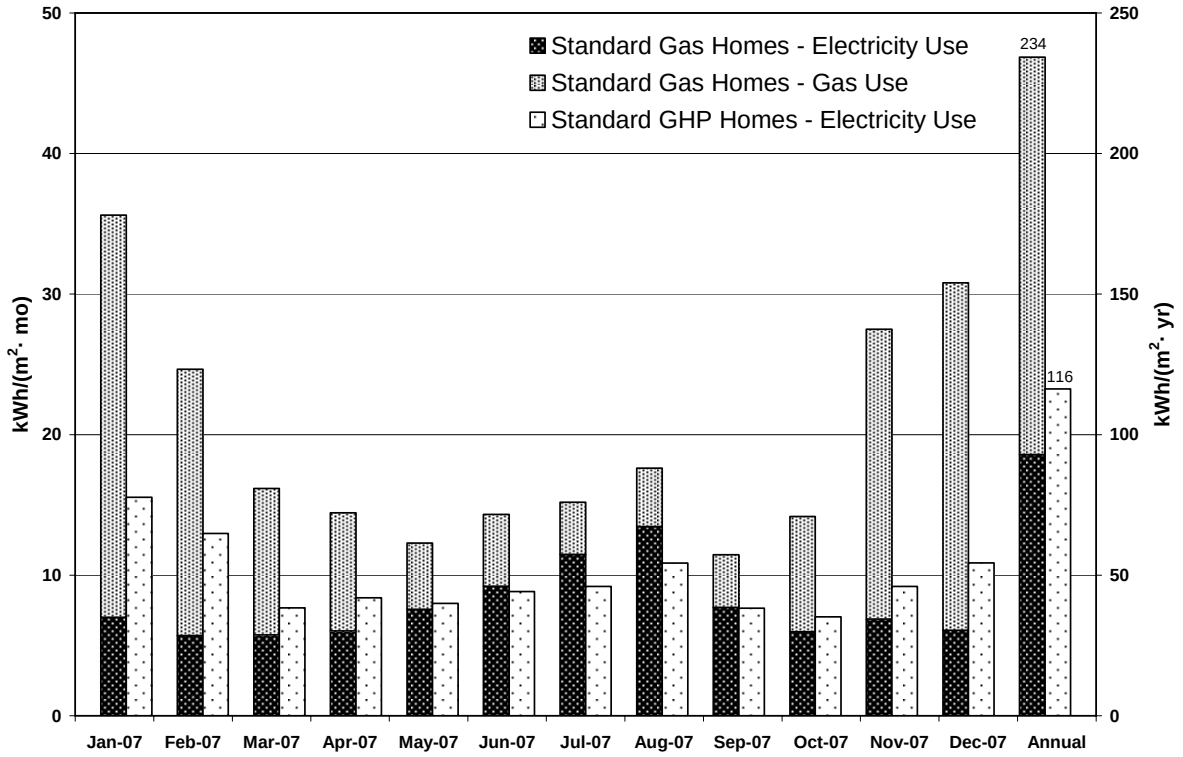


Figure 2: Average Metered Energy Consumption

Although many low energy homes were completed in the Hope Crossing project from mid-2007 onward, this did not provide an adequate time period to gather useful energy consumption data for analysis.

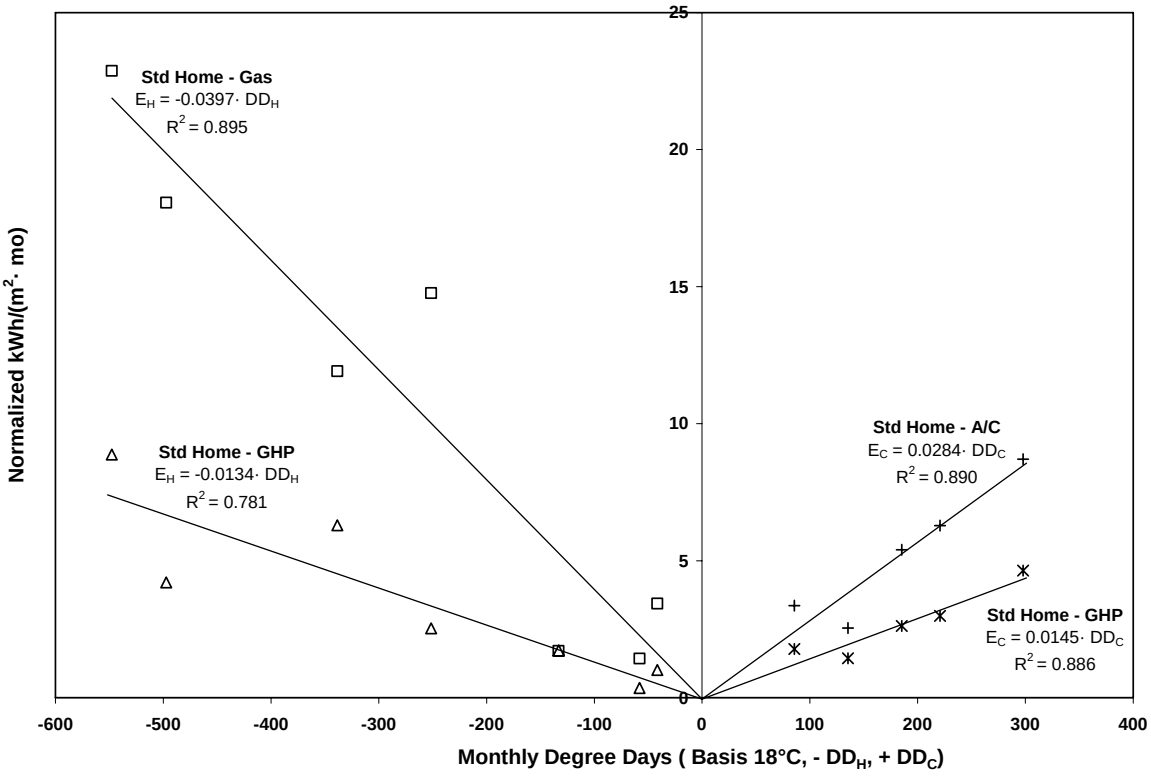


Figure 3: Derivation of Heating and Cooling Energy Consumption

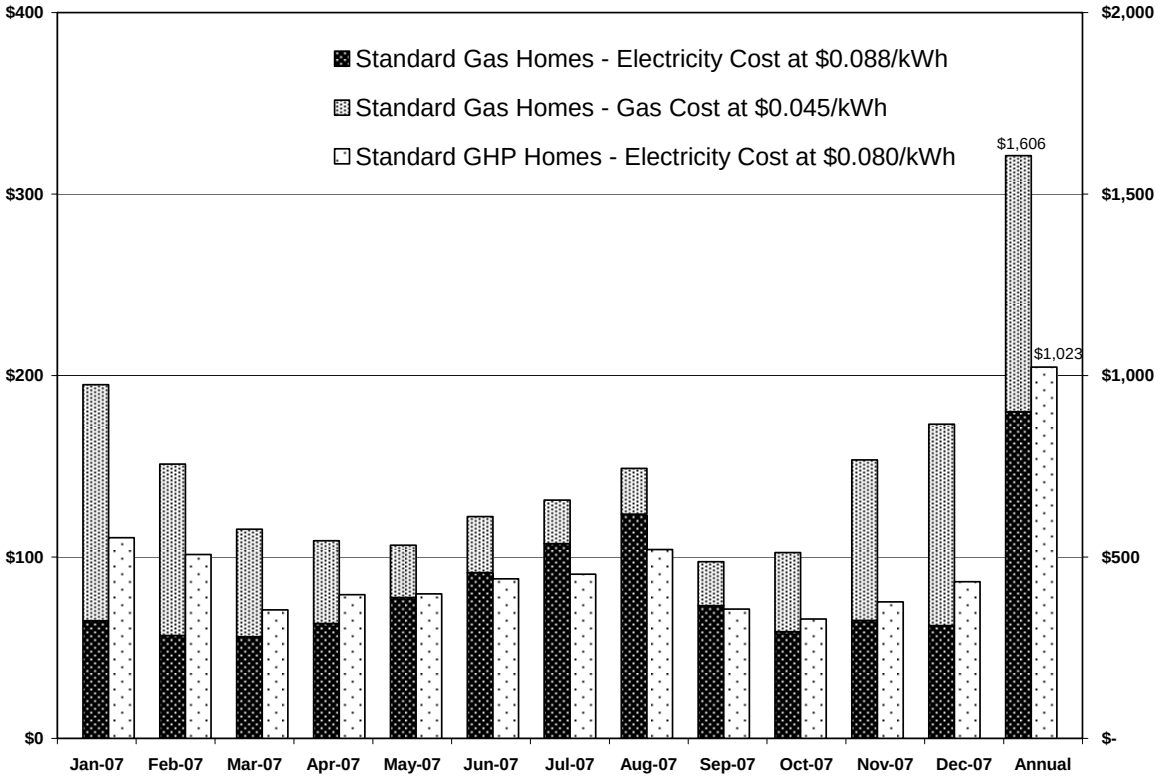


Figure 4: Average Metered Energy Cost

4 ESTIMATED ENERGY CONSUMPTION – ALL CURRENT HOUSES

Energy consumption estimates were generated as part of the project planning process in order to evaluate the benefits of GHP technology, of low energy construction modifications, and of integrating a grid-connected solar PV system. All typical end-use loads were considered in order to estimate the total energy consumption of the homes.

Benchmark hot water, lighting, and appliance loads for the standard house types were estimated using the methodology of Hendron et al. (2004). Following the benchmark procedures, the hot water load is calculated as a function of the number of bedrooms (N_{br}), the supply temperature setting, and the water mains temperature, which is assumed to vary as a function of climate and day of year. The lighting load is calculated as a function the finished floor area (FFA). The total appliance load calculated as a function of N_{br} and FFA.

In the low energy houses, compact fluorescent lighting (CFL) displaces the benchmark incandescent lighting used in the standard houses, reducing lighting energy consumption by an assumed 60%. The low energy homes also use Energy Star appliances, which are assumed to reduce benchmark appliance energy consumption by 20%.

For the GHP homes, all loads are met with electricity. In fact, natural gas distribution lines were not installed in the Hope Crossing project. For the standard homes using natural gas for heating, the hot water heater is also gas-fired, and it was assumed, based on feedback from COHFH, that 75% of the ranges and 25% of the clothes dryers were also supplied by gas. The remainder of the loads in the gas-heated homes are met with electricity.

Residential energy analysis software (ClimateMaster 2004) was used to estimate the annual energy consumption of the heating, cooling, and water heating equipment for all system types. The software uses design load calculations, annual bin weather data, and detailed equipment performance characteristics, including factors such as auxiliary energy use and cycling losses, within a modified bin method calculation. Ground heat exchanger sizing and performance modeling are also incorporated.

The annual energy output of the solar PV system was estimated using PVWATTS software (NREL 2008). The software uses hourly Typical Meteorological Year (TMY) weather data and a PV performance model that incorporates array DC rating, DC to AC derating factors, and array tilt and azimuth to estimate AC energy production (kWh) for a crystalline silicon PV system.

Figure 5 shows the annual site energy consumption obtained using the estimation methods discussed, in total and by end-use, for each of the 4 COHFH house types listed in Table 1. Houses of all 4 of these types have now been constructed. Upon review of Figure 5, it is apparent that as the energy consumption of the homes is reduced by using GHP systems and low energy construction techniques, the hot water and appliance loads become dominant. Looking ahead, there are several methods of addressing the hot water load, leaving the appliance (which includes plug) load as a major challenge.

4.1 Validation of Energy Consumption Estimates

Figure 6 compares the estimated annual energy consumption to the actual metered energy consumption during 2007 for the Spencer project homes. The estimates are calculated using an average weather year for the locale. In 2007, the annual DD_H were 13% less than in the average weather year, and the annual DD_C ran 16% below normal. The adjusted estimates in Figure 6 are corrected to correlate with the actual weather incurred during 2007. As can be seen, the estimated energy consumption for both house types is reasonably close to the actual consumption, deviating by less than 9% in the worst case after adjustment.

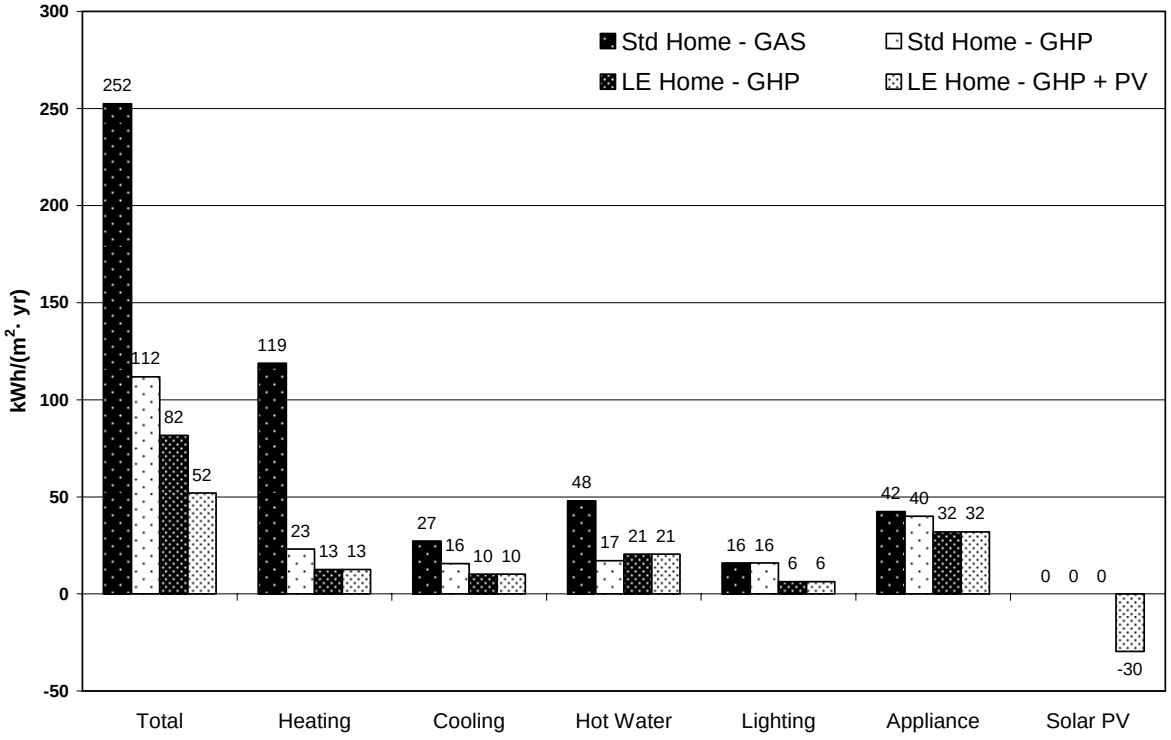


Figure 5: Estimated Site Energy Consumption by End-Use

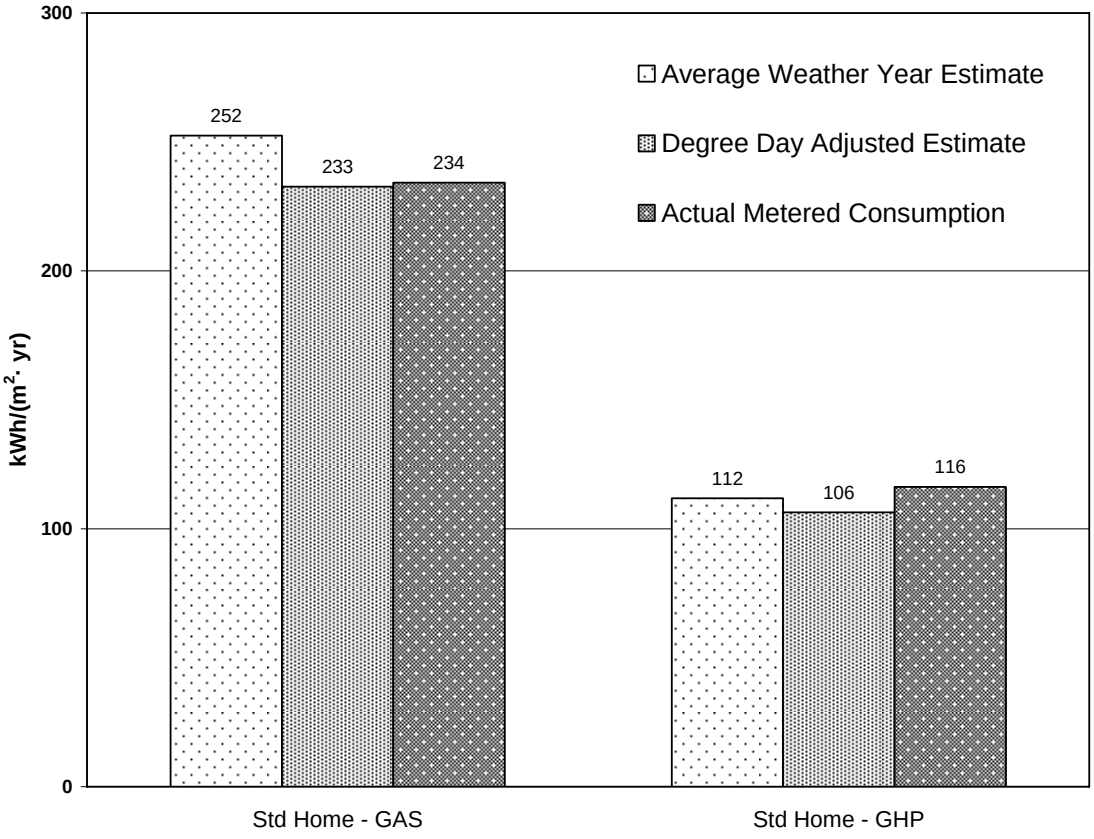


Figure 6: Estimated and Metered Total Energy Consumption

4.2 Source Energy and Carbon Emission Estimates

Source (or primary) energy consumption and carbon equivalent emissions are calculated using the annual site energy consumption estimates for each COHFH house type and factors for electricity and natural gas obtained from Deru and Torcellini (2006). For electricity, these factors account for power plant conversion inefficiencies, and transmission and distribution losses. They also include precombustion effects associated with extracting, processing, and delivering primary fuels to the point of conversion in the power plant. For natural gas, the factors account for both precombustion effects and on-site combustion emissions. The factors used are based on U.S. national averages.

Figure 7 compares the total estimated site and source energy consumption, and the associated carbon equivalent emissions, or global warming potential (GWP), for each COHFH house type. The 240 low energy GHP homes to be constructed in the Hope Crossing project will collectively save nearly 1,100 metric tons of CO_2 per year, or 22,000 metric tons over a nominal 20 year lifespan, compared to the Standard Gas homes that COHFH had been building. If all of the homes had the 2.3 kW solar PV option, another 12,000 metric tons could be saved over 20 years.

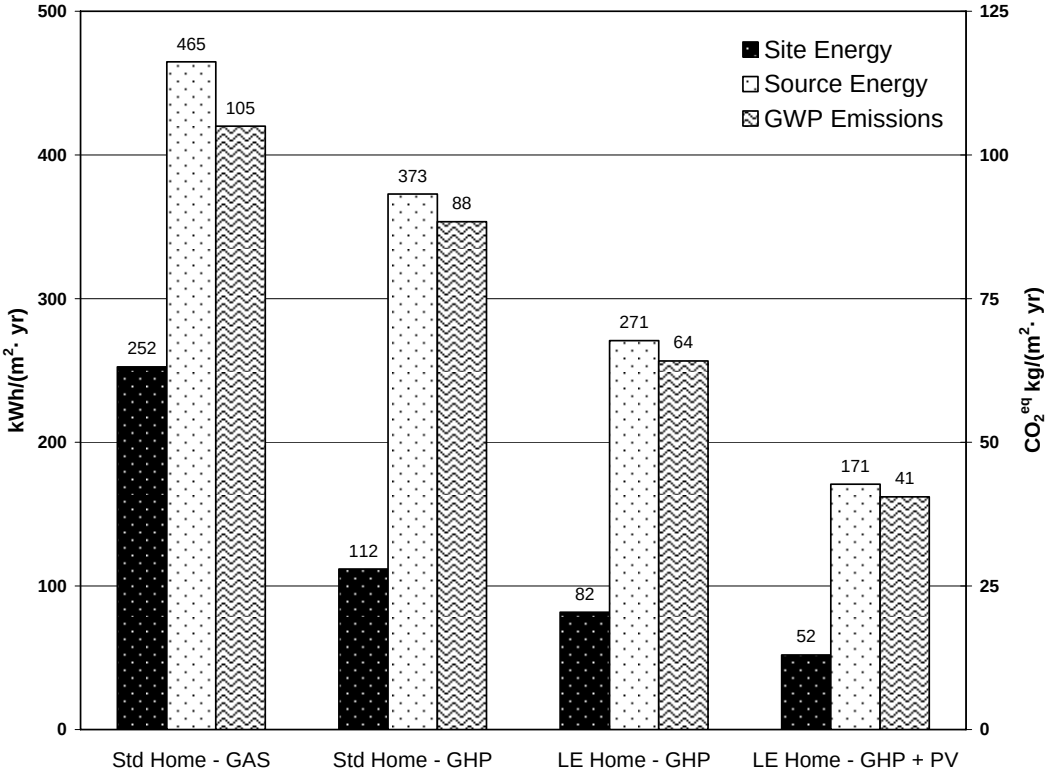


Figure 7: Estimated Total Energy Consumption and Emissions

5 FUTURE IMPROVEMENTS

Several additional improvements to the COHFH houses are under consideration:

- Advanced GHP with inverter-driven variable speed compressor and integrated full-condensing hot water modes in lieu of desuperheating (LE Home - Adv GHP)

- Advanced GHP with grid-connected solar 2.3 DC kW PV system sized for zero peak (LE Home - Adv GHP + PV)

- Full “zero- energy” home with a grid-connected 5.2 DC kW solar PV system capable of producing all the energy required for the home on a net basis over the year (ZE Home - Adv GHP + PV)

The estimated site energy consumption for homes incorporating these improvements are presented in Figure 8, with the current Low Energy GHP home as a baseline. The advanced GHP reduces the energy consumed for heating, cooling, and water heating by 34% compared with the current GHP. Note that the appliance load represents nearly 50% of the total energy consumption of the Low Energy Adv GHP home. No matter what is done to improve the envelope or thermal energy systems in these homes, the appliance and plug load will remain as the limiting factor.

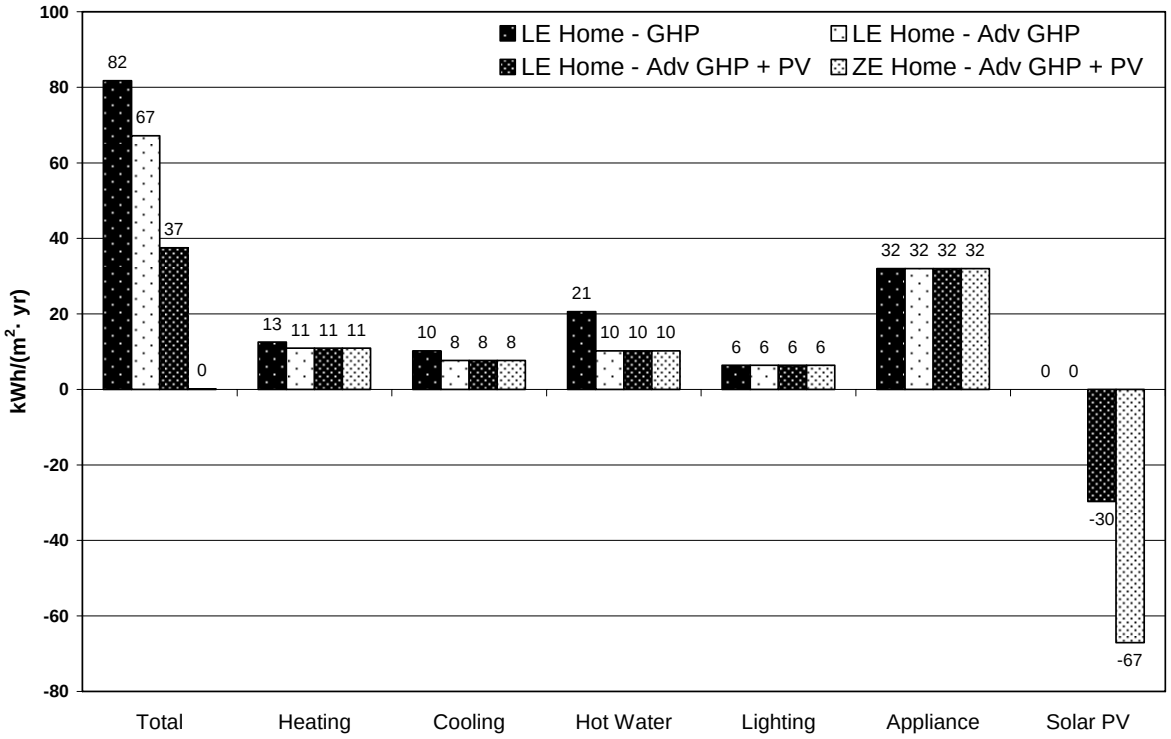


Figure 8: Estimated Site Energy Consumption by End-Use

6 ECONOMIC ANALYSIS

Table 2 provides detail on the additional investment and annual energy cost saving associated with current and future COHFH homes types relative to the benchmark Standard Gas home. The additional costs shown in Table 2 are the normal prices that any builder of COHFH scale would pay in the Oklahoma City market. They do not reflect the discounts and outright donations that COHFH is receiving. There is no valid benchmark for the price of solar PV systems in Oklahoma, so these costs were estimated using information from volume purchases in States with higher activity levels.

Figure 9 shows the return on investment (ROI) provided by each home type relative to the Standard Gas home. The ROI calculation assumes an annual energy cost inflation rate of 2%. In comparing the ROI presented in Figure 9 to alternative investments, it should be noted that energy cost savings are not taxable income, so this would be equivalent to the net

after-tax ROI of an income-producing investment. The GHP systems and the low energy construction costs provide a very favorable ROI. The investment in Solar PV is much more difficult to justify on energy cost savings alone. Providing financial benefits for the carbon emission reductions would improve the economics for all of these alternatives.

Table 2: Additional Investment and Annual Energy Cost Savings

House Type:	Standard Gas	Standard GHP	Low Energy GHP	Low Energy Adv GHP	Low Energy GHP 2.3 kW PV	Low Energy Adv GHP 2.3 kW PV	Zero Energy Adv GHP 5.2 kW PV
Additional Investment[3]:							
Heating and Cooling	$ -	$ 4,500	$ 4,500	$ 6,000	$ 4,500	$ 6,000	$ 6,000
Solar Photovoltaic	$ -	$ -		$ -	$ 15,000	$ 15,000	$ 30,000
Insulation, Lighting, Appliance	$ -	$ -	$ 2,500	$ 2,500	$ 2,500	$ 2,500	$ 2,500
Total	$ -	$ 4,500	$ 7,000	$ 8,500	$ 22,000	$ 23,500	$ 38,500
Annual Energy Cost[1,2]:							
Heating	$ 596	$ 127	$ 69	$ 60	$ 69	$ 60	$ 60
Cooling	$ 270	$ 155	$ 101	$ 76	$ 101	$ 76	$ 76
Hot Water	$ 275	$ 132	$ 158	$ 78	$ 158	$ 78	$ 78
Lighting	$ 175	$ 175	$ 70	$ 70	$ 70	$ 70	$ 70
Appliance	$ 423	$ 440	$ 352	$ 352	$ 352	$ 352	$ 352
Solar PV Contribution	$ -	$ -	$ -	$ -	$ (228)	$ (228)	$ (636)
Total	$ 1,739	$ 1,029	$ 750	$ 636	$ 522	$ 408	$ -
Annual Energy Cost Saving[3]	$ -	$ 710	$ 989	$ 1,103	$ 1,217	$ 1,331	$ 1,739

1. based on electricity at $0.100/kWh for first 600 kWh/month, then $0.050/kWh winter and $0.090/kWh summer for all kWh/month over 600
2. based on natural gas at $0.045/kWh equivalent
3. Relative to Standard Gas Home

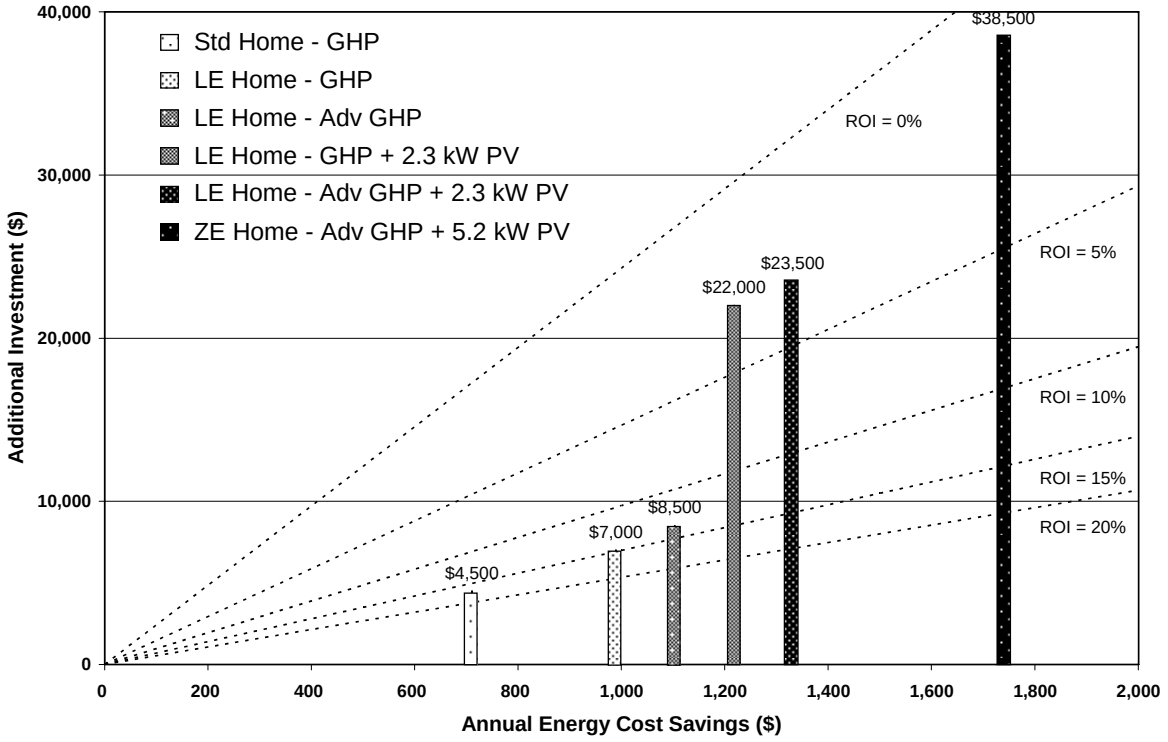


Figure 9: Return on Investment Relative to Standard Gas Home

7 CONCLUSIONS

- The total site energy consumed by the typical new COHFH home can be reduced from 50-75% through the use of GHPs combined with low energy construction techniques

- The 240 low energy GHP homes to be constructed in the COHFH Hope Crossing development will collectively eliminate nearly 1,100 metric tons of CO2 emissions per year, and 22,000 metric tons over 20 years, compared to the standard gas furnace homes typical of prior COHFH developments

- Actual annual site energy savings of 50% were obtained using GHP systems in standard homes during the first phase of this project, which led to a 36% reduction in annual energy costs

- GHPs and low energy construction are both cost-effective, providing a return on investment in the 15% range, and both are generally available in the COHFH locale

- When the energy consumption of a home is brought to these low levels, relatively small solar PV systems can be incorporated that will nearly eliminate the summer peak load imposed on the electric utility, and that will provide all of the energy required to operate the GHP system

- By using a larger solar PV system, zero energy homes are feasible, but expensive

- As the energy consumption of the home is reduced, the appliance and plug load grows to nearly 50% of the total, creating a limit on further reductions

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