An Evaluation Of Residential Energy Conservation Options Using Side-By-Side Measurements Of Two Habitat For Humanity Houses In Houston, Texas.

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ABSTRACT

This paper describes a project where energy conservation measures in two identical Habitat for Humanity houses in Houston, Texas were evaluated using side-by-side measurements (i.e., one with the energy conservation measures, one without) and calibrated simulations. The measures include shell tightening, improved A/C efficiency, modifications to the DHW heater, and solar screens. To perform the analysis both houses were instrumented with hourly data loggers for more than one year and the data analyzed using several methods including inverse methods and calibrated DOE-2 simulations. The results indicate that the efficient air conditioner performed as estimated when all confounding factors are removed using calibrated simulation. The confounding factors that needed to be normalized include: the weather conditions, differences in the life styles of the two houses, interior temperature settings, and certain omissions in the construction of the houses. This paper will discuss the project, the measurements that were taken and the results of the computer simulation analysis. The details of the efforts undertaken to calibrate the simulations can be found in a related paper by Haberl et al. (1998).

Introduction

Several new Habitat for Humanity homes have been built in a sub-division in North-East Houston as shown in Figures 1 and 2. The Energy Efficient home had a number of energy saving features incorporated into it to lower utility costs to the homeowner. Since these features also increased the price of the home, the specific objective of this project was to evaluate whether the individual energy improvement features were saving energy as expected. Previous work that has evaluated energy savings in residences have used various techniques, including the Princeton Scorekeeping Method (PRISM), Fels (1986), Fels et al. (1995), Goldberg (1986), and before-after analysis of retrofit installations, Parker et al. 1996, 1997, 1998. Protocols for monitoring energy use in residences have also been published Ternes (1987).

For this study two homes were build side-by-side which are identical in all respects except that one of the homes had specific energy saving features built-in while the other home was of standard construction. These two homes are referred to as the Energy Efficient (EE) home and the Standard Efficiency (SE) home respectively. In order to evaluate the cost-effectiveness of the individual measures, monitoring was initiated to measure the relevant parameters beginning in May 1996.

The construction plans of the two houses are identical, consisting of 1,100 ft^2 of floor area with an attic space. In each house, there are three bedrooms, a living area, a kitchen/dining area, a utility room, and a bathroom. Both the houses have forced-air, central air-conditioning with cooling provided by a vapor-compression air conditioner and heating provided by a natural gas furnace. The domestic water heating is also accomplished with natural gas. The differences in the building and equipment features of both houses, as well as the cost increase in incorporating the individual features are summarized in Table 1 which include the retrofits and estimated costs provided by Habitat for

Humanity. The $1,300 in additional energy efficiency measures can be broadly classified into four categories:

(1) shell tightening, which consists of improved duct insulation/sealing and shell tightening (both of which cost $150),
(2) window upgrades, which include single pane clear glass windows with solar screens installed at a total cost of $300,
(3) a smaller water heater placed in the attic of the EE house (versus in the utility room), which includes the roof pitch having to be increased thus costing an additional $200 (with insulated water lines) that increased the cost in total by $375, and
(4) a more efficient HVAC system, with a programmable thermostat in the EE home that cost an additional $475 (SEER of 10 in SE house and SEER of 12 in EE house).

The other major difference in the houses was the fact that the Standard Efficiency house had a gas oven and range while Energy Efficient house had a electric range and oven.

Analysis Approach

In order to analyze the effect of the energy conservation retrofits it was decided to instrument the houses with a modest suite of sensors and a data acquisition system and record hourly data through both the heating and cooling seasons. Table 2 includes a list of the channels that were chosen for monitoring. In both houses whole-building electricity use, air-conditioner electricity use, and the electricity use of the HVAC blower were recorded. In the EE house the electricity use of the kitchen was also recorded[1]. Supply and return air temperature and humidity the HVAC unit were also recorded in an attempt to ascertain the in-situ efficiency of the air conditioner. The temperature difference across the DHW was also recorded along with ambient temperature, humidity, wind, and solar radiation. Data were retrieved weekly from the data logger, inspected for data quality and loaded into a data base for later analysis. All sensors were calibrated before and after the experiment to assure that sensor drift had not occurred.

Figure 3 presents a sample of the data that was collected. It shows comparisons of the indoor return air temperature (middle graph), humidity (upper graph) and blower electricity use for both houses (lower graph) through the cooling and heating seasons. It is clearly seen from the data that the homeowners in the houses operated their homes in very different manners. In the SE house the homeowners manually set back the temperature in both the summer and winter when they went to work and the house was unoccupied. In the cooling season this allowed temperatures to approach 80 F when the house was unoccupied during the day, while in the heating season, temperatures dropped to 55 F when the HVAC was manually set back.

In the Energy Efficient house the HVAC system ran continuously for several months, which accounts for the very tight band of indoor temperatures between 65 and 72 F. The few points where the temperature dipped below 65 F represent only infrequent periods when the homeowner allowed the temperature to drop because the HVAC system had not been switched into the "heating" mode before going to bed. Humidity profiles in both houses are similar with the exception that the SE house saw wider variations in the humidity because of the wide temperature swings during the setback period. The blower electricity use profiles indicate that two speed blowers were installed in both houses with a lower speed for the heating mode. Also, in the SE plot there are bands of both zero electricity use and

[1] The Standard efficiency house used gas appliances in the kitchen.

maximum electricity use which point to the manual on/off switching that the homeowners used to shut down the system when they were are work, turning it on again when they came home. In the EE house the A/C never ran continuously for an hour or was rarely shut off for a complete hour.

Numerous site visits were also made to inspect the construction of the building and perform additional tests as needed to obtain "as-built" parameters for the simulation such as the air conditioner efficiency. Blower door tests were also conducted to ascertain the shell tightness.

Monthly Utility Bill Comparison

During the data collection portion of the project a preliminary analysis was performed on the monthly utility bills to determine if the anticipated energy savings were visible in the monthly utility bills. Unfortunately, the utility bills indicated the Energy Efficient house was consuming more energy than the Standard Efficiency house. This can be seen when one inspects Figure 4 (electricity use), Figure 5 (natural gas use) and Table 3 where it is clear that the EE house consumed considerably more electricity than the Standard Efficiency house. Natural gas use was similar at both houses.

Several additional features are also evident in the monthly utility bills that helped guide the calibrated simulation analysis. First, it was clear that the natural gas use and electricity use in both houses had strong weather dependencies which can be seen in the sloped portions of the 3 parameter change-point regressions (Kissock et al. 1993). Second, the natural gas use for both houses was well described by the 3 parameter model with R^2 of 0.96 and 0.95 for the SE and EE home. Monthly use of natural gas in the summer appears very similar for both houses which indicates that the combined impact of placing the water heater in the attic of the EE house and that electric oven-range in the SE could not be seen. The Energy Efficient house had a slightly higher change-point temperature which confirms the characteristics of the measured indoor temperatures.

On the other hand the electricity use for both houses was only partially explained by a 3 parameter model as evidenced by the R^2 of 0.64 and 0.79 for the SE home and EE home respectively. The one feature that does stand out about the differences in the electricity use in the two houses is that the Energy Efficient house used considerably more electricity for non-weather-dependent purposes (i.e., cooking, lighting, etc.) as is evident in the increased baseline use (413.46 kWh/mo for the EE home vs 299.98 kWh/mo for the SE home). This was expected since the Energy Efficient home contained an electric oven-range whereas the Standard Efficiency house had a gas range and oven.

In conclusion, a simple monthly analysis of the electricity use and natural gas use of the two houses begins to shed light on the differences in the energy use characteristics of the two houses. However, as we will indicate later, the monthly analysis was not normalized for differences in lifestyle and therefore was not useful in determining whether or not the energy conservation retrofits were saving energy as intended.

Creating A Calibrated Doe-2 Model

To create a calibrated model an architectural rendering of the input files was performed using the DrawBDL program (Huang, 1993) that sketches the actual BDL input file and hence was used to verify the placement and orientation of the building's walls, roof, windows, and doors. Table 4 presents the summary of the envelope materials and thermal properties and Table 5 presents information about the HVAC system.

The overall calibration process included: (1) confirming the building geometry with the DrawBDL architectural rendering program; (2) confirming the envelope materials/assemblies; (3) creating input parameters for space conditions using on-site data; (4) developing energy use profiles from hourly monitored, data; (5) entering the HVAC systems parameters using manufacturer's data, clamp-on measurement, hourly monitoring; and (6) fine-tuning the input data until the simulated results match measured data within an acceptable range (i.e., 5 to 10%).

The calibration process consisted of nine phases where one or more changes were made to the input file, the building simulated again and the results of the hourly simulation compared with the hourly whole-building electricity and the indoor temperatures. Table 6 shows the progress of the calibration process through each phase. Phase I represents a "first pass" at the building using information that was readily available and resulted in a simulation that had a coefficient of variation of the root-mean-square error of over 0.45 and a RMSE temperature error of 0.97 F. Each of the successive phases introduced selective changes to the input file with the resultant improvement in the RMS error of the whole-building electricity and temperature clearly evident. After the ninth phase the simulation was declared "calibrated" with a CV(RMSE) of 10.2% for the whole-building electricity and a 1.5% CV(RMSE) for the indoor temperature. Additional details of the efforts undertaken to calibrate the simulations can be found in the paper by Haberl et al. (1998). Once the computer program was declared "calibrated" it was then used to perform the analysis to determine whether or not the energy conservation measures were reducing the energy use of the Energy Efficient house.

Analyzing The Energy Savings Using Calibrated Simulation

To accomplish a savings calculation with the calibrated simulation the simulation was first "calibrated" to the basecase or Standard Efficiency house, and then the known ECRMs were added one at a time to the simulation to obtain a simulation of the Energy Efficient house with specific ECRMs added to the input file.

Selected data from the on-site measurements were used to verify the input modifications to the basecase simulation to accurately reflect the ECRMs that were installed, including the increased air conditioner efficiency, solar screens, and tightening of the structure (Bou Saada et al. 1998). The programmable thermostat, electronic ignition, increased duct/pipe insulation and DHW ECRMs were not included in the simulation analysis for various reasons. The programmable thermostat was not included because the occupant of the Energy Efficient house felt that it was too complicated for her (or her two children) to use on a regular basis. Observations of the indoor temperatures for the first few months of the cooling season revealed that the occupant was setting the thermostat at 70F and leaving the air-conditioner running continuously even when the house was unoccupied. This was one of the reasons for the unexpectedly high utility bills. To remedy this the occupant was shown how to manually turn off the system while the house was unoccupied which helped reduce her bills substantially and yet did not force her to learn how to program the thermostat. Instructions for programming thermostat were also provided.

The effect of the electronic ignition was not simulated since both of the heating units had electronic ignition. The differences between the R-4 (standard house) and R-6 (efficient house) were not insulated because much of the ductwork in both houses was completely covered with the blown-in, R-30 insulation. Finally, the impact of moving the domestic water heater to the attic in the Energy Efficient house from its normal utility room location was not directly simulated because a manual calculation indicated that the savings from decreased jacket losses in the hot attic during the summer were negligible when increased losses from the cold attic (in the winter) were also factored in (Bou Saada et al. 1998).

However, it was discovered that this ECRM can provide savings because of the removal of the opening for the flue that served the domestic water heater. This reduced infiltration was confirmed with a subsequent blower door analysis of a different Habitat house which indicated that the removal of the flue (using masking tape) that serves the DHW eliminates about 0.1 to 0.2 air changes per hour and thus serves to tighten the envelope of the house. These savings were not factored into the final simulation for reasons that will be discussed in the following section.

The procedure that was employed to calculate the savings using the calibrated simulation was as follows. First, the calibrated simulation input file for the baseline house was modified to reflect average features, including: 1) average monthly interior profiles from the measured data, 2) average weekday/weekend electricity use profiles from the measured data, and 3) the shading coefficients were set at 0.2 (basecase) to represent the shades being always opened as observed in the Standard Efficiency building and 0.1 to represent the interior shades always closed, as observed in the Energy Efficient house. Then an annual simulation for each case was run against average weather data for Houston. Table 7 lists the primary features of the "adjusted basecase" simulation input file. Table 8 shows the adjustments that were made to the input file to simulate the effect of each of the ECRMs.

Results

Table 9 and Figure 6 show the results of the analysis. In the first column of Table 9 the DOE-2 end use values from the BEPS report for the baseline simulation are shown in MMBtu for the lighting, equipment, space heating, space cooling, fans, and DHW (a constant value). Dollar values are assigned to the simulated MMBtu energy use using $23.44 $/MMBtu (electricity: lighting, equipment, cooling & fans) and $9.40 $/MMBtu (natural gas: heating & DHW). Figure 6 shows the annual costs by DOE-2 end use for the five simulations.

Changing the air conditioner efficiency. The first simulation (SEER=12) evaluated the effect of changing the efficiency of the air conditioner from an SEER 10 unit to an SEER 12 unit. Since this also represented a change in manufacturers the cooling capacity was also changed from 24,000 Btu/hr to 23,200 Btu/hr and the heating capacity was changed from 36,000 Btu/hr to 35,000 Btu/hr. This ECRM reduced the cooling electricity use by 22.0% and increased the fan electricity use by 2.9%, probably due to the smaller unit. The slight downsizing of the furnace increased the heating energy use by 2.7%, according to DOE-2. The total annual savings for the improved air conditioner efficiency represented a 9.9% reduction in the annual electricity use and a 1.6% increase in the annual natural gas use, which is a 6.9% reduction in the total utility bills, or $62.

Adding solar screens to the house. The next simulation attempted to represent observed conditions regarding the solar screens, rather than the potential for savings from solar screens. This is because on numerous visits to the site both of the houses had the interior venetian blinds closed which significantly reduces the need for solar screens. Furthermore, conversations with Energy Efficient homeowner indicated that she always kept her shades drawn for privacy reasons. Therefore, in the basecase simulation the shading coefficient was set at 0.2 and in the solar screen simulation, the shading coefficient was set at 0.1. Although this assumption effectively eliminates (and slightly reverses) the impact of the solar shades, it represents observed conditions. Therefore, the observed shading conditions decreased the cooling load by only 2.3% and increased fan energy use by 5.7%. The observed shading conditions increased the heating load by 4.1%. The total annual change for the observed shading conditions represented a 0.4% reduction in the annual electricity use and a 2.4% increase in the annual natural gas use, resulting in a 0.4% increase in the total utility bills, a increase of $3.

Tighter structure. During the numerous site inspections it was discovered that the contractor never completed the installation of the access doors to the closet that housed the HVAC unit. This had the effect of allowing a direct passage to the attic since the ceiling of the closet that houses the HVAC unit was directly open to the attic to allow for combustion air for the HVAC unit. Blower door tests on both houses under this condition resulted in more air changes per hour than the blower door could measure, which unfortunately, represented the actual condition of the Energy Efficient house for a number of months. In the Standard Efficiency house the homeowner covered the opening with a piece of 1/2" polystyrene mainly to cover up the noise that the unit was making. Therefore, the actual leakiness of the envelope in both houses could not be measured without covering the access doors with masking tape.

Blower door tests on both houses with the access doors taped showed almost identical results which were a 0.75 air change rate. Therefore, no change in infiltration was assumed for the DOE-2 simulation, which resulted in no annual savings as indicated in Table 9 and Figure 7.

Combined reduction from all the ECRMs. When SEER=12, actual window shading, and actual infiltration were combined the annual cooling energy use was reduced by 23.5%, the fan energy use remained constant, and the heating energy use increased by 1.4%. The total annual savings for the combined ECRMs represented a 11.0% reduction in the annual electricity use and a 0.8% increase in the annual natural gas use, which results in a 7.9% reduction in the total utility bills, a $71 reduction in total utility costs.

Conclusions

In this paper energy conservation measures in two identical Habitat for Humanity houses in Houston, Texas were evaluated using side-by-side measurements of identical houses (i.e., one with the energy conservation measures, one without). The only measure that could be properly evaluated with the calibrated simulation was the improved A/C efficiency. To perform the analysis both houses were instrumented with hourly data loggers for more than one year and the data analyzed using a calibrated DOE-2 simulation. The results indicate that the efficient air conditioner was the major contributor to a reduced overall utility costs of $71 per year, or about 11.0%, which is well within the range of the expected savings. When one compares the estimated costs of the ECRMs against the calculated payback as shown in Table 1 the improved air conditioner yields a 5.6 year payback.

Discussion

There are several issues that came up during the course of this study that warrant a further discussion, namely, our assumptions about the windows and the infiltration and the importance of follow-up and commissioning. First, in regards to our assumptions about the window treatments, we felt that it was best to attempt to represent "observed conditions" rather than "ideal" conditions. Therefore, we severely discounted the effect of the solar screens in the simulation. Although this is a valid representation of the existing conditions it does not provide an accurate assessment of the potential for energy savings that the solar screens could have produced. Therefore, we have eliminated the option from the payback discussion in Table 1.

Second, in a similar sense, we did not include any savings from the "tightening" of the Energy Efficient house because blower door tests on both houses with the access doors taped showed almost identical results which were a 0.75 air change rate. However, subsequent tests in a Habitat for Humanity house in Bryan, Texas showed that this number could be reduced to 0.35 air changes when one properly sealed all attic penetrations including the attic access door (i.e., the type of door that folds down to reveal the stairs that are used to climb up into the attic). Therefore, there is good potential for energy reduction if this retrofit is properly commissioned. However, since this was not observed to be the case at the Houston houses it was not simulated.

Finally, this study has also revealed that the most important "ECRM" involves the training of the occupants in the proper use of the thermostats, and the careful inspection and commissioning to make sure all systems are properly installed and working. The evidence from this study indicates that had the intervention not taken place to show the occupant how to manually turn off the thermostat, and had the occupant continuously left the thermostat on 70 F year around the energy use would have swelled to $1,334 for the basecase which represents a 149% increase over the chosen baseline assumptions. Furthermore, had the access panels to the HVAC unit never been put in place the air change rate for the house would have remained at several air changes per hour which would have increased the heating and cooling bills even more than simulated. Although there is a cost associated with the occupant training and inspections, no other ECRM that was proposed produced a $400+ annual savings -- clearly enough to pay for the training and inspections many times over.

Thoughts About The Future

As is the case with most studies, this study has generated more questions than answers. Here are a few thoughts about the future. First, a closer look at the DOE-2 calculated end- uses reveals that $366 was consumed by the lights, equipment (i.e., refrigeration, TVs, etc.) and domestic water heater which represents 41% of the annual baseline bill which was unaffected by the ECRMs evaluated by the simulation (this excludes the small savings in the DHW from moving the tank to the attic). Clearly, any future efforts to reduce the annual energy use in Habitat housing must consider how to reduce lighting loads and equipment loads.

In the houses in this study none of the fixtures in the house were "compact fluorescent friendly". Therefore, it is suggested that all Habitat houses be "compact fluorescent" friendly and that lamps be purchased and installed in the fixtures before the occupant takes possession of the house. Second, it is recommended that new, efficient appliances be purchased and installed as part of the homeowner's package. This would also help to reduce the lighting and equipment loads which represented $270 (30%) of the total annual baseline utility costs.

Second, using calibrated simulations may be the only way of analyzing certain types of retrofits. However, calibrated simulations are extremely time consuming and require considerable expertise to be able to pack weather data files, measure and input equipment efficiencies, measured air change rates, etc. -- all of which is difficult to justify under normal project time and budget constraints. Problems that were encountered with the use of DOE-2 for simulating a residence include: how to properly enter the duct losses, ground temperatures, site shading, and dual fan speeds.

Third, it appears that the placement of the HVAC unit in the attic in hot and humid climates significantly reduces the equipment life because the cold- rolled steel combustion surface remains below the attic dewpoint temperature for a significant portion of the summer (i.e., the furnace rusts to death). In most dry climates the combustion surfaces of forced-air furnaces last for 25 to 35 years. However, in humid climates where the HVAC unit is placed in the attic the combustion surfaces often need replacing in less than 15 years. This problem can be eliminated by placing the HVAC unit within the air-conditioned space. In a small structure such as a Habitat home this should also be accompanied by a supply of combustion air to the unit when the burners are firing to avoid the building up of dangerous combustion by products.

Fourth, duct leakage and duct heat gain are significant in any house where the ductwork is in the attic. This can increase heating and cooling loads by 10 to 50% depending upon the severity of the problem. Moving the ducts within the conditioned area and minimizing duct runs may be the only way of completely eliminating this problem. Furthermore, in the two houses used in this study the cabinets of the HVAC units were extremely leaky, allowing humid air to be pulled in with the return air. Moving the HVAC units with the conditioned space would eliminate the problem.

Fifth, the ceiling of the hallway is a poor place to put the attic access door or hatch from a thermal point of view, especially if the drop-down-stair-type attic hatch is used because these hatches rarely ever seal properly. Subsequent blower door tests on several Habitat houses in Bryan, Texas indicated that these hatches could be responsible for 0.1 to 0.3 air changes per hour, depending upon the size of the crack around the edge of the hatch. Moving the hatch to a porch and using a lock might help to eliminate this problem in a vented attic. Moving the attic insulation from the floor of the attic to the underside of the roof and sealing the attic would also help to eliminate this problem.

Finally, preliminary results of indoor-outdoor CO_2 tests indicate that levels above 1,500 ppm are not uncommon in well-sealed Habitat houses, especially in the summertime when the temperature driven air infiltration is low. This problem becomes worse as one tightens the building's envelope. Use of a fan-driven air-to-air heat exchanger, or use of a properly installed outside-air intake louver may help to eliminate this problem.

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Table 1. Energy saving features of Houston Habitat for Humanity homes.

Building Feature	Standard House	Energy Eff. House	Cost	Simulated Savings	Payback
Improved Insulation and Shell Tightening					
Ceiling Insulation	R-30	R-30	-		
Wall Insulation	R-13-16	R13-16	-	Not	
Duct Insulation/Sealing	R-4/tape	R-6/mastic	$100		
Air Infiltration				evaluated.	
Sealing Ext. Envelope					
Window Upgrades					
Type	Single pane	Single pane	-		
Frame	Aluminum	Aluminum	-	Not	
Shading Coefficient	Clear	Clear	-	evaluated.	
Solar Screens	No	Yes	$300		
Water Heater Placed in Attic					
Type	40 gallon, natural gas	29 gallon, natural gas	-		
Location	Conditioned space	Attic	$100	Not	
Electronic Ignition	No	Yes	-		
Insulated Lines	No	Insulate lines	$75	evaluated	
Roof Pitch	-	Increased pitch	$200		
More Efficient HVAC System					
AC Type	10 SEER, 2 ton	12 SEER, 2 ton	$400	$71	5.6
Heating Type		80% AFUE elec. ignition	-		
Thermostat	Non-programmable	Digital programmable	$75	Not eval.	
Other					
Ceiling Fans	Livingroom + bedrooms	Livingroom + bedrooms	-		
Attic Ventilation	Ridge/soffit vents	Ridge/soffit vents	-		
Total ECRMs					
		Grand Total	$1,300	-	-

Table 2. List of installed monitoring equipment.

House Metering	EE home	SE home	Device	Units
Whole-building electricity use	Y	Y	digital Watt trans.	kWh/h
Air conditioner electricity use	Y	Y	"	kWh/h
Electric oven electricity use	Y	N	"	kWh/h
HVAC blower electricity use	Y	Y	"	kWh/h
Attic dry bulb temperature	Y	Y	1000 Ohm RTD	^{0}F
Indoor/return air dry-bulb temp.	Y	Y	"	^{0}F
Indoor/return air relative humidity	Y	Y	thin film RH sensor	% RH
Indoor/supply air dry-bulb temp.	Y	Y	1000 Ohm RTD	^{0}F
Indoor/supply air relative humidity	Y	Y	thin film RH sensor	% RH
DHW supply water temperature	Y	Y	1000 Ohm RTD	^{0}F
DHW cold water feed	Y	Y	1000 Ohm RTD	^{0}F
Outdoor Weather Station				
Global solar radiation	Y	Q_{sol}	PV-type pyranometer	W/m^2
Air relative humidity	Y	RH_0	thin film RH sensor	% RH
Wind speed	Y	v	contact anemometer	mph
Air dry-bulb temperature	Y	T_0	1000 Ohm RTD	^{0}F

Table 3. Statistical Parameters for the 3 Parameter Models. These tables display the statistics of the 3 parameter change-point models that were used to analyze the monthly utility bills for both houses. The upper table shows the statistics for the electricity use and the lower tables show the statistics for the natural gas use.

Electric model cooling statistics

Cooling	SE House	EE House
Slope	20.68	40.95
Intercept	299.98	413.56
CV(RMSE)	24.1%	21.5%
RMSE	102.80	142.75
R^2	0.64	0.79

Natural gas model heating statistics

Heating	SE House	EE House
Slope	-3.68	-2.69
Intercept	16.82	14.22
CV(RMSE)	13.9%	15.7%
RMSE	4.07	4.41
R^2	0.96	0.95

Table 4. Envelope material/assembly of the Simulated Energy-Efficient House

Component	Assembly (out-in)	Thickness ft	Conduct. Btu-ft / hr-ft^2-F	Density lb / ft^3	Sp. Heat Btu / lb-F	R-Value hr-ft^2-F / Btu
Roof	Fiberglass shingles					0.21
	Plywood 1/2"	0.0417	0.0667	34	0.29	-
Ceiling	Blown insulation 18"	1.5	0.025	6	0.20	-
	Frame, wood 3.5"	0.2917	0.0667	32	0.33	-
	Gypsum board 1/2"	0.0416	0.0926	50	0.20	-
Wall	Vinyl siding					0.0004
	Styrene 1/2"	0.0417	0.0200	1.8	0.29	-
	Plywood 1/2"	0.0417	0.0667	34	0.29	-
	R-11 batt insulation*	0.2957	0.0250	6	0.20	-
	Gypsum board 1/2"	0.0416	0.0926	50	0.20	-
	*) for the studs, wood 3-1/2" is used instead of the batt insulation					
Floor	Concrete 4"	0.3333	0.7576	140	0.20	-
	Linoleum tile	-	-	-	0.30	0.21
Doors	Metal sheet	0.0050	26.0	480	0.10	-
	Polyurethane 1.25"	0.1042	0.0133	1.50	0.38	-
	Metal sheet	0.0050	26.0	480	0.10	-

Table 5. Summary of the HVAC systems in the Standard and energy-efficient houses.

SYSTEM	Standard-efficient house	Energy-efficient house

1. Cooling	Goodman
	Model # CK24-1B (outdoor)
	# U-30 (indoor)
	SEER = 10
		Carrier
		Model # 38BR024-30 (outdoor)
		# CD5BA024 (indoor)
		SEER = 12

2. Heating	Goodman
	Model # GNP 050-3
	Input = 45,000 Btu/hr.
	Output = 36,000 Btu/hr.
		Resco
		Model # GB1AAV024045, C series
		Input = 44,000 Btu/hr.
		Output = 35,000 Btu/hr.

3. Water heater	Rheem Model # 21V40-7 Natural Gas Input 34,000 Btu, 40 gallon	State Model # PRV-30-NOLSO Natural Gas Input 28,000 Btu, 29 gallon

Table 6. RMSE and CV(RMSE)[2] of whole-building electricity use and indoor temperature from adjusting input parameters, for the period of March 17-31, 1997

Phase	Input Parameters	RMSE and CV(RMSE) of WBE	RMSE and CV(RMSE) of Temp
I	Fan = 0.36 kW, no HVAC curve-fit, no custom weighting factors, air changes = 0.3, floor conductance = 0.7576	0.52 kWh (45.71%)	0.97 F (1.43%)
II	Fan = 0.36 kW, with HVAC curve-fit, no custom weighting factors, air changes = 0.3, floor conductance = 0.7576	0.54 (49.31%)	1.02 (1.48%)
III	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3, floor conductance = 0.7576, light furniture	0.43 (32.32%)	0.91 (1.39%)
IV	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3, floor conductance = 1.0147, heavy furniture	0.38 (25.37%)	1.17 (1.58%)
V	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.4 ACH, floor conductance = 1.0147, heavy furniture	0.30 (15.71%)	0.95 (1.5%)
VI	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3 ACH, floor conductance = 1.0147, heavy furniture	0.30 (15.71%)	1.0 (1.46%)
VII	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.3 ACH, floor conductance = 1.0147, heavy furniture, adjust other load	0.25 (10.84%)	1.0 (1.46%)
VIII	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.75 ACH, floor conductance = 1.0147, heavy furniture, adjust other load	0.25 (10.62%)	1.0 (1.46%)
IX	Fan = 0.36 kW, with HVAC curve-fit, with custom weighting factors, air changes = 0.75 ACH, floor conductance = 1.0147, heavy furniture, adjust attic infiltration rate and ceiling weight	0.24 (10.24%)	1.03 (1.48%)

Table 7: Summary of the input parameters for the basecase and adjusted simulations.

ADJUSTED SIMULATION USING HOURLY WBE, MONTHLY N.G., AND FIXED WINTER/SUMMER INDOOR TEMPERATURES
• Geometry: drawings • Envelope: Detailed thermal properties w/ Custom Weighting Factors. • Attic is a separate space • SC = 0.2 (blinds observed to be always open) • Infil. = 0.75 ACH • SEER = 10 (EIR=0.3412) • Cool cap. = 24,000 • SH-cap = 17,200 • Heat cap. = 36,000 • Heat-FIR = 1.25 • Supply CFM = 750 • Supply kW = 0.5 • Thermostat: • Developed average daytype profiles of interior temperature for each month. • Internal electricity use: Develop ave. daytype profiles from hourly data

[2] The hourly RMSE of Whole-Building Electricity is in kW, RMSE of indoor temperature is in degree F.

Table 8: Summary of the input parameters for the SEER=12, solar screens, tight structure, an all strategies.

STRATEGY	ADJUSTED SIMULATION USING HOURLY WBE, MONTHLY N.G., AND FIXED WINTER/SUMMER INDOOR TEMPERATURES
HVAC: SEER = 12*	• EER, kW, Cool-cap from manf's data (EIR = 0.2843) , Cool Cap = 23,200 Btu/hr, SH-cap = 16,500 Btu/hr, Curve-fit = manf's data., supply kW = 0.45 (meas.), heat cap = 35,000 Btu/hr, Heat HIR = 1.25 (manf).
SOLAR SCREEN*	• SC = 0.1 (blinds observed to be always closed)
TIGHT STRUCTURE*	• Inf. Rate = 0.75 ACH (measured)
ALL STRATEGIES	• SC = 0.1 • Infil. = 0.75 ACH, SEER = 12 (EIR = 0.2843), Cool Cap. = 23,200 Btu/hr, SH-cap = 16,500, Heat cap. = 35,000, temp setting (avg.mon.profiles), no natural ventilation.

*Each ECM was applied to the base case (standard efficient house) separately.

Table 9: Adjusted simulation results. This table shows the adjusted simulation results that reflect the calibrated simulation run at average measured temperature profiles for the baseline house.

	BASELINE (MMBtu & $)	SEER=12 (MMBtu & $)	SOLAR SCREEN (MMBtu & $)	TIGHT STRUCTURE (MMBtu & $)	ALL STRATEGIES (MMBtu & $)
Light	2.9	2.9	2.9	2.9	2.9
Equip	8.6	8.6	8.6	8.6	8.6
Sp.Heat.	14.7	15.1	15.3	14.7	14.9
S.Cool	13.2	10.3	12.9	13.2	10.1
Ven Fans	3.5	3.6	3.7	3.5	3.5
DHW	10.2	10.2	10.2	10.2	10.2
Site.Ele	28.2	25.4	28.1	28.2	25.1
Site.N.G.	24.9	25.3	25.5	24.9	25.1
Site.Total	53.1	50.7	53.6	53.1	50.2
Light$	$68	$68	$68	$68	$68
Equip$	$202	$202	$202	$202	$202
Heat$	$138	$142	$144	$138	$140
Cool$	$309	$241	$302	$309	$237
Fans$	$82	$84	$87	$82	$82
DHW$	$96	$96	$96	$96	$96
Elec$	$661	$595	$659	$661	$588
Nat.Gas$	$234	$238	$240	$234	$236
TOT$	$895	$833	$898	$895	$824

NOTE: Electricity Costs Calculated at $23.44 $/MMBtu, or $0.08 $/kWh, Natural gas costs calculated at $9.40 $/MMBtu.

Figure 1. Front view of the two side-by-side Habitat for Humanity houses in Houston. The Standard Efficiency house is on the left and the Energy Efficient house is on the right.

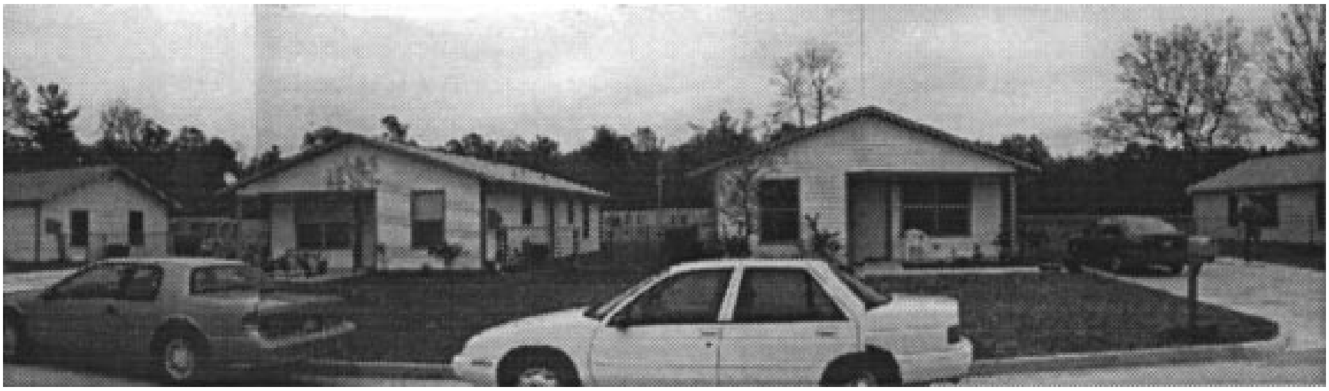


Figure 2. Back view of the two side-by-side Habitat for Humanity houses in Houston. The local weather station that was constructed can be seen between the Energy Efficient house (left) and the Standard Efficiency house (right).

Figure 3. Indoor Environmental Conditions and Fan Electricity Use for Both Houses. These graphs display comparative environmental conditions for both houses, including the temperature and relative humidity measured at the return air grill.

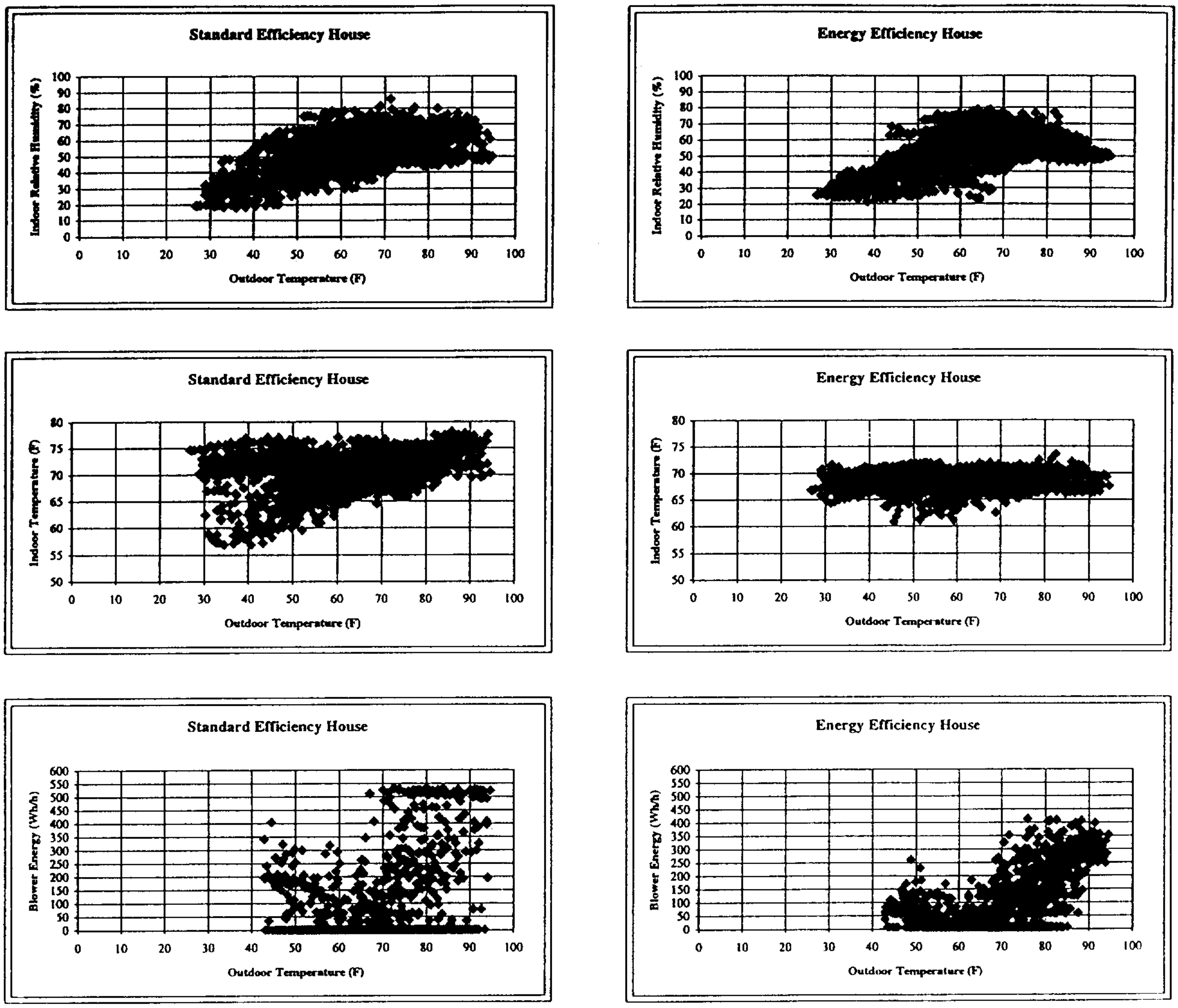
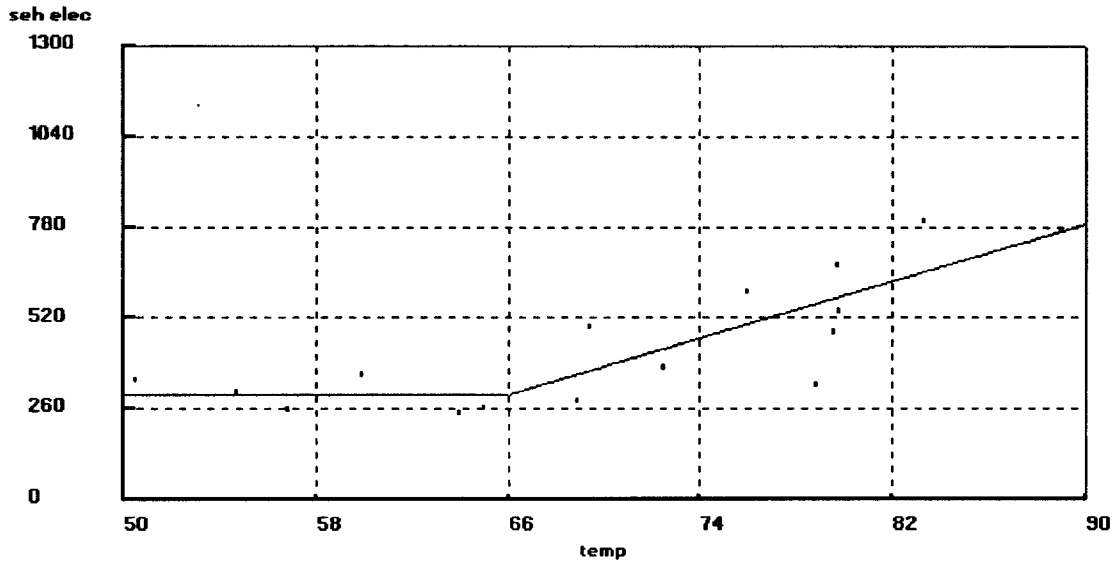


Figure 4. Monthly Electricity Utility Data for the SE house and EE houses. These figures display the results of a 3 parameter analysis of the monthly electricity use for the SE house (upper graph) and EE house (lower graph).

Standard Efficiency House (SE) Electricity Use



Energy Efficient House (EE) Electricity Use

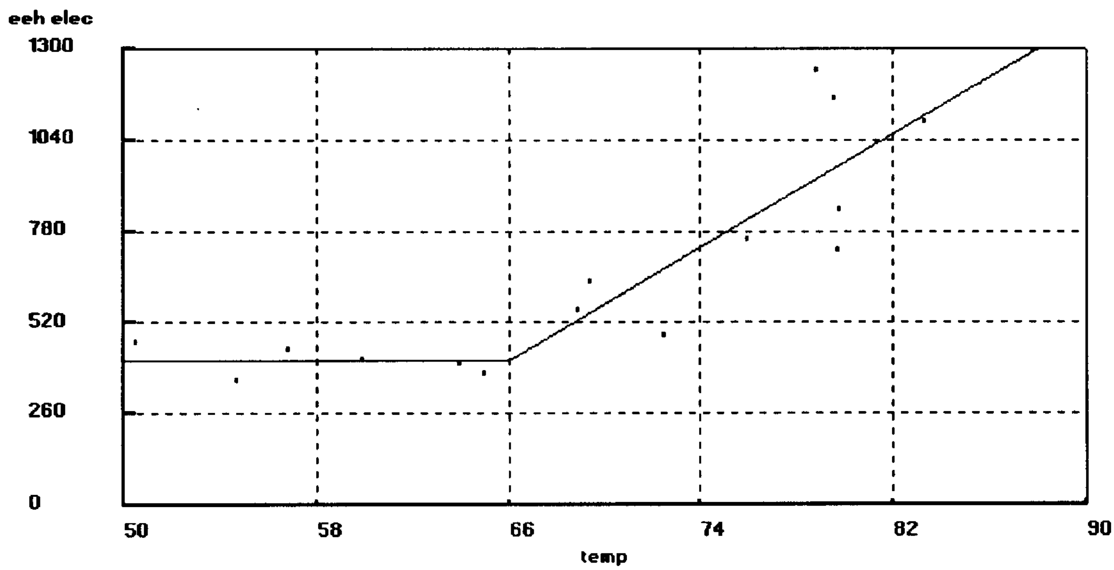
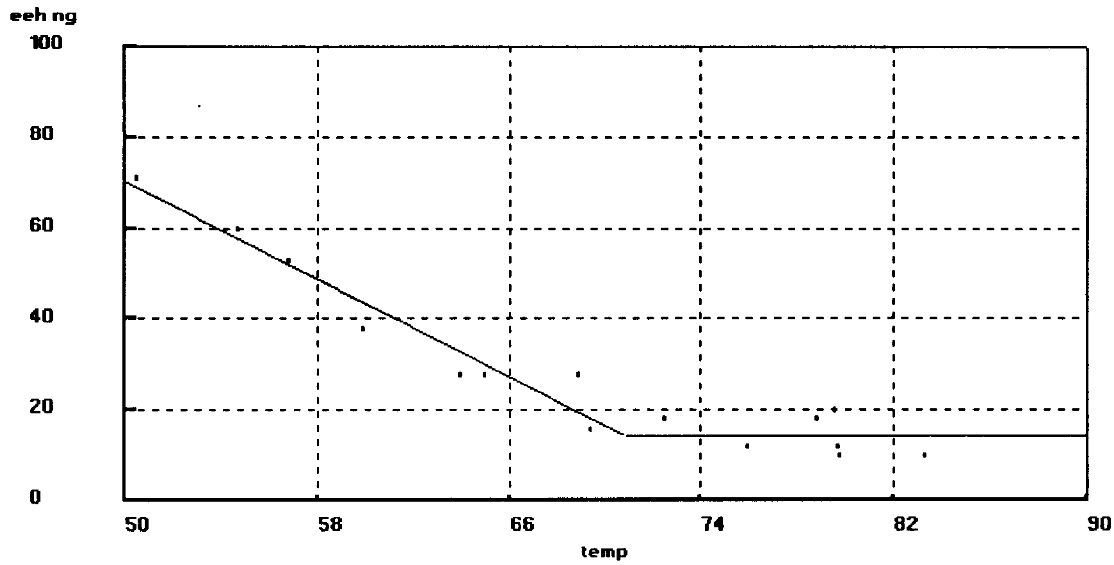


Figure 5. Monthly Natural Gas Utility Data for the SE and EE Houses. These figures display the results of a 3 parameter analysis of the monthly natural gas use for the SE house (upper graph) and EE house (lower graph).

Energy Efficient House (EE) Natural Gas Use



Standard Efficiency House (SE)Natural Gas Use

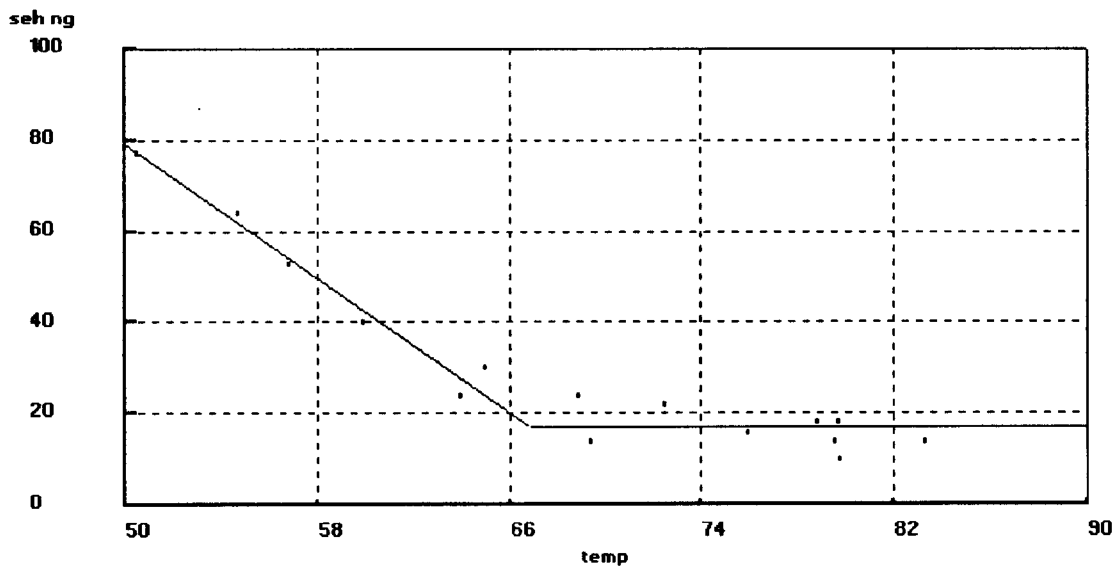


Figure 6: Adjusted simulation results. This table shows the adjusted simulation results that reflect the calibrated simulation run at average measured temperature profiles for the baseline house.