AN ANALYSIS OF MAXIMUM RESIDENTIAL ENERGY EFFICIENCY IN HOT AND HUMID CLIMATES

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ABSTRACT

This paper presents the results of an analysis to determine practical, energy-efficient strategies for reducing residential energy use in hot and humid climates. Strategies considered include: efficient building envelope, improved fenestration, efficient lighting, appliances, and HVAC and DHW systems. These strategies were analyzed with a DOE-2 simulation model of a 2000/2001 International Energy Conservation Code (IECC) compliant single-family, detached house in Houston, Texas. The results show that the proper selection of measures can accomplish a 55% total annual energy reduction for a code-compliant house in a hot and humid climate, which consists of energy use reduction of 78% for space cooling, 53% for domestic water heating, 17% for space heating, and 44% for other end-uses (i.e., lighting, equipment, heating/cooling fans, and pump and miscellaneous).

INTRODUCTION

Energy-efficient building design can be accomplished by minimizing the energy use and optimizing the performance of individual systems and components of the building by analyzing them in a combined simulation. The benefits of energy-efficient design, in the residential sector, are direct and tangible, provided that all strategies with the most combined energy and cost-saving potential are adopted. Many studies have been performed to evaluate strategies for residential energy-efficiency. An extensive review of those studies is provided in Malhotra (2005). While most of the studies are specific to certain building components and systems, some have addressed optimal building design by evaluating combined effect of various energy-efficient measures for building components and systems, sometimes supplemented with integrated photovoltaic (PV) systems. Among the studies performed in hot and humid climates, Parker et al. (2000) used simulation and monitoring of test houses in Florida, and showed more than 75% cooling energy use reduction with energy efficient building envelope systems and integrated PV. Chulsukon (2002) showed 30% annual energy savings from building envelope upgrades in residences in Thailand, Bangkok. Another study by Rasisuttha and Haberl (2004) showed 20% savings from building envelope and system upgrades, and 73% savings from further addition of solar thermal and PV systems in Thailand.

These studies have used a base case with different building characteristics, and a combination of measures that differ between the studies. Therefore, the results from these studies may not always be generalized, and require different criteria for comparing the results between studies. In addition, due to the complex interaction of the energy flows through various building components, it can be inappropriate to combine savings from individual strategies, directly, to determine the energy-saving potential of a group of strategies for making design decisions.

Christensen et al. (2005) has also performed similar work. He developed the BEopt – software for identifying the most cost-effective combination of strategies from the user-selected options; however, the energy efficient options are limited to predefined measures. Also, certain issues were not fully explained, such as inputting the building geometry, layering of materials for different construction types, frames and shading. Also, the report did not explain the base-case cost by component, against which the additional cost could be compared. Therefore, the current study investigates the individual and combined energy-saving potential of various strategies to determine an optimum combination that could minimize energy use of a single-family, detached house in the hot and humid climate of Houston, TX.

METHODOLOGY

In order to quantify the energy savings from different measures, a simulation model was used for a 2000/2001 IECC (ICC 1999) code-compliant base-case house, which was then modified to simulate the

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different scenarios with energy-efficient measures applied individually and in combination. The cost-effectiveness of these measures was then assessed using the annualized life-cycle cost analysis. The tasks performed for this study included: determination of the base-case house characteristics, development of the DOE-2 simulation model, analysis of energy saving measures for individual building components, and analysis of the individual and combined application of measures for maximum energy-efficiency.

Determination of the Base-case House Characteristics

For this study, a DOE-2 simulation model of a 2000/2001 IECC compliant single-family, detached house in Houston, Texas was selected as the base-case (Figure 1).

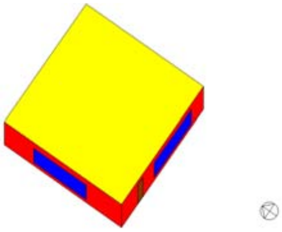

Figure 1. DOE-2 Simulation Model of the Base-case House.

Table 1 lists the main characteristics of the base-case house. The general characteristics of the house such as, the size of the house, occupancy, type of construction and building systems were determined from the housing survey data by the National Association of Home Builders (NAHB 2003) and the U.S. Census Bureau (USCB 2002), supplemented by assumptions based on the typical characteristics of a similar house. The characteristics of the building envelope and windows, efficiency of HVAC and DHW systems, and internal loads were chosen to conform to the 2000/2001 IECC standard design (Chapter 4).

Table 1. Base-case House Characteristics.

Building configuration	2,500 sq. ft., four bedroom, square shape, one-story, single-family detached house
Construction type	Light-weight wood-frame
Exterior walls	2 x 4 studs @ 16" o.c., R-11 fiber-batt cavity insulation, brick fascia on the exterior
Roof	2 x 10 studs @ 16" o.c., R-30 ceiling insulation, aspen gray asphalt shingle roofing
Windows	Gross window area: 18% of conditioned floor area, distributed equally on all four sides
	Double pane low-e air-filled windows; aluminum window frames with thermal break
	No exterior shading
Underground floor	Slab-on-grade floor with 4” heavy weight concrete, no perimeter insulation
HVAC Systems	SEER-10 electric split air conditioner, 78% AFUE natural gas furnace, ducts in the conditioned space
DHW system	40 -gallon gas water heater with a standing pilot light

Development of the DOE-2 Simulation Model

The DOE-2 simulation model of the house was adopted from the input file, SNGFAM2ST.INP version 1.14, developed by the Energy Systems Laboratory, Texas A&M University (Ahmed et al. 2005). This input file uses parameters for various building characteristics, which can be assigned different values using an external file. For this study, the house was first simulated with the base-case characteristics as listed in Table 1. The values of the parameters were then modified to simulate scenarios with different building characteristics, to evaluate their effect on the energy use.

Analysis of Energy-saving Measures for Individual Building Components

Five building components were selected for the analysis that include: (a) building configuration (aspect ratio and number of floors), (b) roof and wall properties (exposure, R-value, absorptance and emissivity), (c) construction type (layering of materials and air tightness), (d) fenestration properties (e.g. window distribution on different orientations, overhang projection, U-factor, and SHGC), and (e) air-conditioner and DHW system efficiencies. For each component, the effect of incremental change in the associated properties on the building energy use was analyzed in combination by assigning different values to the corresponding parameters of the input file. The results of the simulations demonstrated the combination of properties with the highest energy-saving potential for each of the five building components analyzed (Malhotra 2005, Malhotra and Haberl 2006).

Analysis of the Individual and Combined Application of Measures

The results of the analysis of energy-saving measures for individual building components were used to determine strategies for developing the maximum energy-efficient house, which include: airtight construction with structural insulated panels (SIPs), reflective roof and exterior walls, improved windows, and efficient air-conditioner and DHW system. Also, energy efficient lighting (IESNA 2000) and appliances (ACEEE 2004) were considered for simulating the maximum energy-efficient house. Table 2 lists these strategies in the order they were applied to the base-case house.

The cost-effectiveness of the analyzed strategies was compared for their individual and combined application, using the annualized life-cycle cost analysis method (ASHRAE 2003, Haberl 1993). Table 3 lists the various costs associated with the

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Table 2. List of Building Properties for the Base-case House and Energy-efficient Option.

Steps	Properties	Base-case Characteristics	Energy-efficient Design Measures
1		Base-case house	-
2a	Construction	Wood-frame construction	SIP construction
2b	Ventilation	No mechanical ventilation	Energy recovery ventilator
3	Roofing	Gray asphalt shingle roofing (absorptance = 0.82)	White fiber-cement shingles (absorptance = 0.23)
4	Exterior wall surface	Light buff fascia brick (absorptance = 0.55)	White semi-gloss paint (absorptance = 0.25)
5	Glazing	Double pane air-filled low-e (U = 0.47, SHGC = 0.4)	Double pane argon-filled low-e (U = 0.29, SHGC = 0.28)
6	Window frames	Aluminum window frames with thermal break	Vinyl window frames
7a	Exterior shading	No shading	4 ft. deep overhangs on all sides
7b	Window distribution	Equal window area on all sides	75% on south, 15% on north, 5% on east and 5% on west
8	Lighting	Incandescent lamps	Compact fluorescent lamps
9	Refrigerator	Conventional model (660 kWh/yr)	Energy star model (392 kWh/yr)
10	Freezer	Conventional model (900 kWh/yr)	Energy star model (353 kWh/yr)
11	Dishwasher	Conventional model (696 kWh/yr)	Energy star model (181 kWh/yr)
12	Clothes washer	Conventional model (816 kWh/yr)	Energy star model (186 kWh/yr)
13	Domestic water heater	Tanktype, with a standing pilot light (EF = 0.54)	Instantaneous, with electronic ignition (EF = 0.85)
14	Air-conditioner	SEER-10 air-conditioner	SEER-15 air-conditioner

applied measures. The first year costs were obtained from product information data (Malhotra 2005). The energy costs were calculated using the DOE-2 simulation results, assuming the utility rates to be 0.09 $/kWh for the electricity and 0.8 $/therm for the natural gas. The maintenance and replacement costs were determined from the average life of the measures, assuming 25 year life of the building. Also, economic factors such as, the inflation rate (Inflationdata 2005), mortgage rate (Bankrate 2005), and insurance and property tax were defined to calculate the annualized costs.

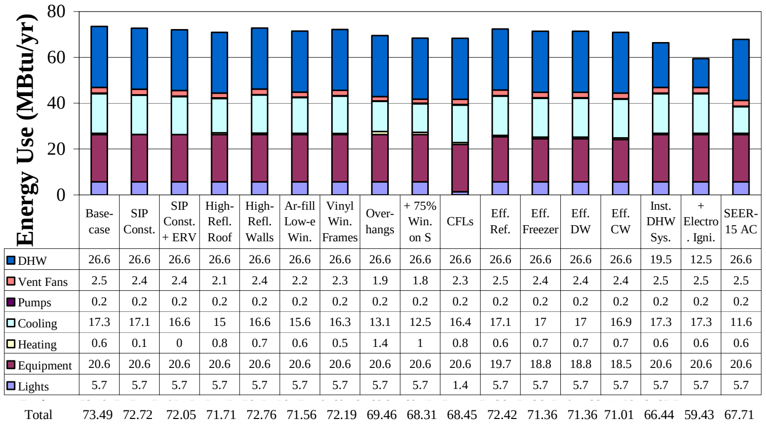
RESULTS

Energy Analysis of Individual and Combined Application of Energy-efficient Measures

Figure 2 and Figure 3 show the annual end-use energy use for the individual and combined application of measures to the base-case house. Figure 2 shows that the largest space cooling savings (33%) were achieved from the SEER-15 air-conditioner, followed by 28% savings from overhangs with 75% of the windows on the south. A 53% domestic water heating energy savings was achieved from the high efficiency instantaneous water heater with electronic ignition. The largest equipment energy savings (20%) was achieved from the horizontal-axis clothes washer. Compact fluorescent lamps (CFLs) saved 75% lighting energy use. Among all the measures applied individually, the instantaneous water heater with electronic ignition had the highest total annual energy-saving potential (19% savings), followed by 7% each from overhangs with window redistribution favoring the south side, and from the CFLs. Figure 3 shows that the space cooling, domestic water heating and equipment energy use comprised a significant part of the total energy use (24%, 36% and 28%, respectively of the base-case house), and that the space heating and lighting energy use were only 1% and 8% of the total energy use of the base-case house. Whereas, after the combined application of all the measures, the space cooling and domestic water heating energy use could be significantly reduced, with the equipment energy contributed the most (42%) to the total energy use of the efficient house.

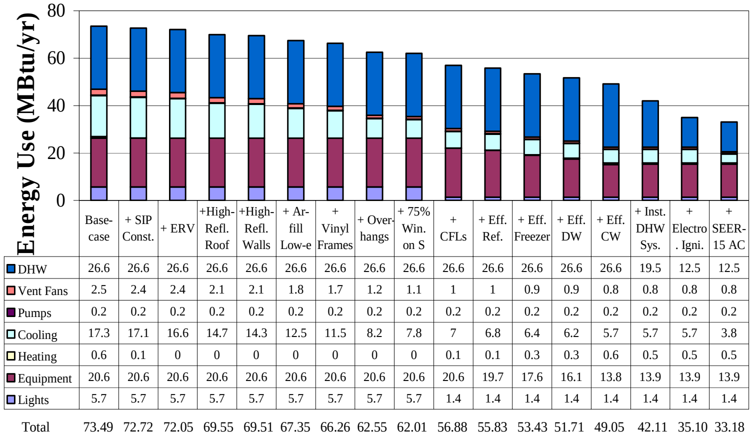
Table 3. Various Costs Associated with the Base-case House and the Maximum Energy-efficient Option.

Item No.	Energy-Efficient Measures	First Year Costs				Annual Energy Costs			Maintenance and Replacement Cost		
		Base-case Cost ($)	Increased Cost ($)	Difference ($)	Cumulative Increase (%)	Individual Application ($)	Incremental Application ($)	Cumulative Decrease (%)	Maintenance Cost ($)	Replacement Cost ($)	Year
1	Base-case House	$224,598	-	-	-	$1,438	$1,438	-	$100 (Annual)	$26	Annually (for Lighting)
										$550	10 (for DHW System)
										$2,548	15 (for AC, Clothes Washer and Dishwasher)
										$850	20 (for Refrigerator and Freezer)
2a	SIP Construction	$220,650	$222,857	$2,207	0.98%	$1,426	$1,426	-0.85%	$100	As Above (for the Base-case)	
2b	+ Energy Recovery Ventilator	$0	$1,099	$1,099	0.49%	$1,411	$1,411	-1.89%	$100	As Above (for the Base-case)	
3	High-Albedo Roofing	$2,500	$5,000	$2,500	1.11%	$1,371	$1,356	-5.75%	$100	As Above (for the Base-case)	
4	High-Albedo Exterior Walls	$7,475	$6,325	($1,150)	-0.51%	$1,417	$1,344	-6.57%	$100	$1,500	10 (for Repainting the Walls)
5	Argon-Filled Low-e Windows	$5,300	$6,096	$796	0.35%	$1,386	$1,287	-10.53%	$100	As Above (for the Base-case)	
6	Vinyl Window Frames	$6,096	$7,500	$1,405	0.63%	$1,406	$1,259	-12.50%	$100	As Above (for the Base-case)	
7a	Overhangs	$0	$2,520	$2,520	1.12%	$1,317	$1,160	-19.37%	$100	As Above (for the Base-case)	
7b	+ 75% Windows on the South	$0	$0	$0	0.00%	$1,295	$1,146	-20.33%	$100	As Above (for the Base-case)	
8	Efficient Lighting	$26	$279	$252	0.11%	$1,301	$1,010	-29.79%	$100	As Above (for the Base-case)	
9	Efficient Refrigerator	$550	$800	$250	0.11%	$1,409	$981	-31.78%	$100	$250	Added to the 20th Year Replacement Cost
10	Efficient Freezer	$300	$530	$230	0.10%	$1,380	$915	-36.36%	$100	$230	Added to the 20th Year Replacement Cost
11	Efficient Dishwasher	$500	$1,149	$649	0.29%	$1,380	$869	-39.62%	$100	$649	Added to the 15th Year Replacement Cost
12	Efficient Clothes Washer	$600	$950	$350	0.16%	$1,371	$794	-44.78%	$100	$350	Added to the15th Year Replacement Cost
13	Tankless Water Heater	$550	$950	$400	0.18%	$1,326	$686	-52.32%	$100	$400	Added to the10th Year Replacement Cost
14	SEER-15 AC	$1,448	$2,637	$1,189	0.53%	$1,286	$635	-55.84%	$100	$1,189	Added to the15th Year Replacement Cost
			Total	$12,696	5.65%		Total	-55.84%			



	Base-case	SIP Const.	SIP Const. + ERV	High-Refl. Roof	High-Refl. Walls	Ar-fill Low-e Win.	Vinyl Win. Frames	Over-hangs	+ 75% Win. on S	CFLs	Eff. Ref.	Eff. Freezer	Eff. DW	Eff. CW	Inst. DHW Sys.	+ Electro. Igni.	SEER-15 AC
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	19.5	12.5	26.6
Vent Fans	2.5	2.4	2.4	2.1	2.4	2.2	2.3	1.9	1.8	2.3	2.5	2.4	2.4	2.4	2.5	2.5	2.5
Pumps	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Cooling	17.3	17.1	16.6	15	16.6	15.6	16.3	13.1	12.5	16.4	17.1	17	17	16.9	17.3	17.3	11.6
Heating	0.6	0.1	0	0.8	0.7	0.6	0.5	1.4	1	0.8	0.6	0.7	0.7	0.7	0.6	0.6	0.6
Equipment	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	19.7	18.8	18.8	18.5	20.6	20.6	20.6
Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	1.4	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Total	73.49	72.72	72.05	71.71	72.76	71.56	72.19	69.46	68.31	68.45	72.42	71.36	71.36	71.01	66.44	59.43	67.71

Figure 2. Annual Energy Use for Individual Application of Measures.



	Base-case	+ SIP Const.	+ ERV	+High-Refl. Roof	+High-Refl. Walls	+ Ar-fill Low-e	+ Vinyl Frames	+ Over-hangs	+ 75% Win. on S	+ CFLs	+ Eff. Ref.	+ Eff. Freezer	+ Eff. DW	+ Eff. CW	+ Inst. DHW Sys.	+ Electro. Igni.	+ SEER-15 AC
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	19.5	12.5	12.5
Vent Fans	2.5	2.4	2.4	2.1	2.1	1.8	1.7	1.2	1.1	1	1	0.9	0.9	0.8	0.8	0.8	0.8
Pumps	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Cooling	17.3	17.1	16.6	14.7	14.3	12.5	11.5	8.2	7.8	7	6.8	6.4	6.2	5.7	5.7	5.7	3.8
Heating	0.6	0.1	0	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.6	0.5	0.5	0.5
Equipment	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	19.7	17.6	16.1	13.8	13.9	13.9	13.9
Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Total	73.49	72.72	72.05	69.55	69.51	67.35	66.26	62.55	62.01	56.88	55.83	53.43	51.71	49.05	42.11	35.10	33.18

Figure 3. Annual Energy Use for Combined Application of Measures.

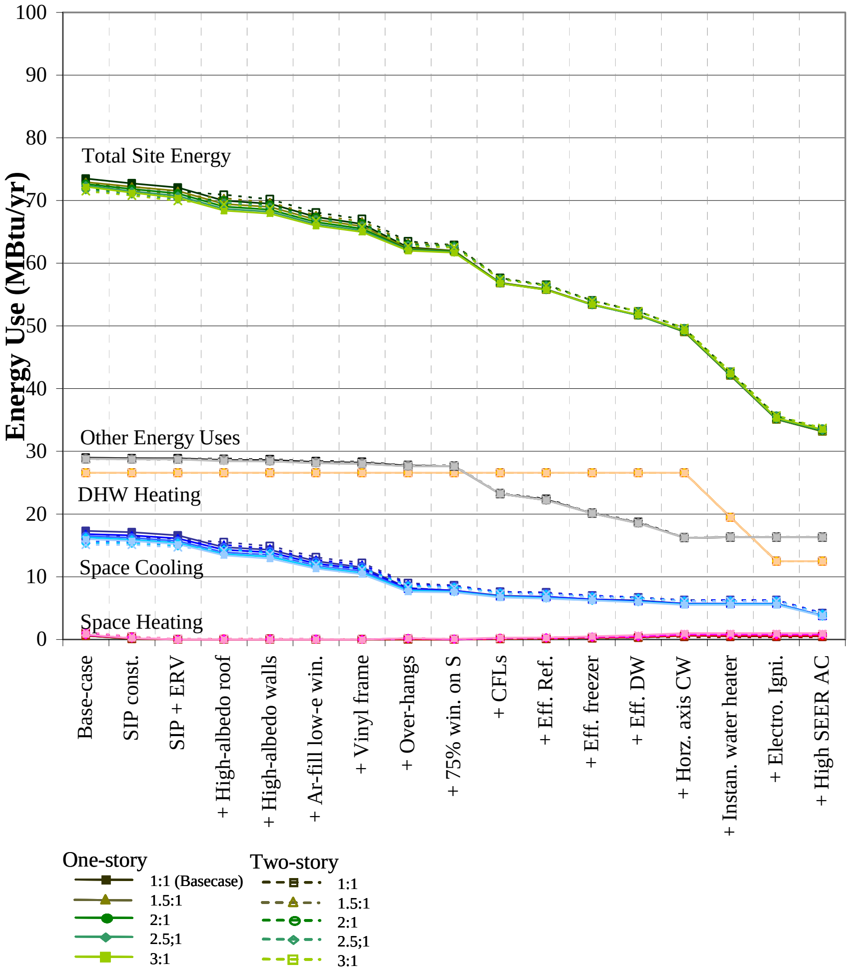


Figure 4. Effect of Combined Application of Measures on Annual Energy Use.

Figure 4 shows the impact of the combined application of the measures on the space heating, space cooling, domestic water heating, other end-uses, and total energy use. This graph includes the results of the simulation for different building configurations that includes east-west to north-south aspect ratio of 1:3 to 3:1 for one and two-story configurations. In this figure, measures with the highest incremental savings have the steepest slope. The following observations were made:

1. As compared to a square-shaped, one-story, base-case house, a two-story house elongated along the east-west axis saved cooling energy. However, with a high reflectance roof, the two-story house became more energy consuming than a one-story house because of the increased wall area (window areas remained equal).

2. The impact of changing the building configuration on the energy use diminished as more efficient building systems and components were incorporated in the house.

3. The instantaneous water heater without a pilot light was the most effective strategy, followed by CFLs. Other measures providing significant energy savings included the addition of overhangs, high reflectance roof, efficient windows, and efficient appliances.

By applying energy-efficient measures to the base-case house, the maximum reduction of 78% was achieved in space cooling energy use, followed by 53% reduction in domestic water heating energy use, 44% for other end-uses that include lighting, equipment, heating/cooling fans, and pump and miscellaneous, and a 17% reduction in space heating energy use. The space heating energy savings were less because some of the measures resulted in small heating energy penalty. A maximum of 55% total energy savings could be achieved from combining all the measures.

<u>Economic Analysis of Individual and Combined Application of Energy-efficient Measures</u>

Figure 5 through Figure 7 show the input and results of the economic analysis. The first year costs for the individual and combined application of measures are shown in Figure 5. Figure 6 and Figure 7 show the annual energy costs and the annualized life-cycle cost for the two approaches. The first year cost of the base-case house was $224,598 that includes $220,650 for the construction (Building Journal 2005) and $3,948 for the installation of the

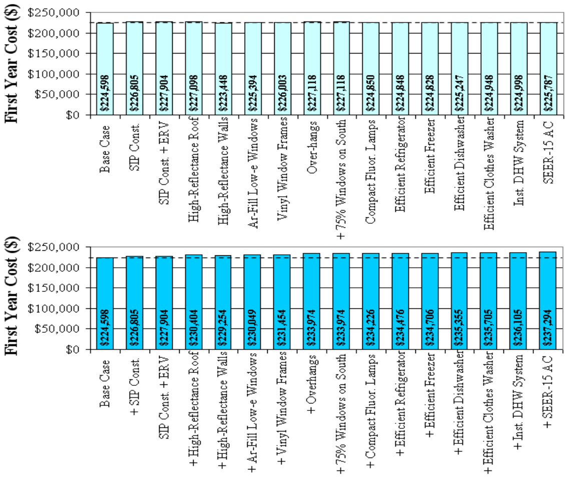


Figure 5. First Year Costs for Individual and Combined Application of Measures.

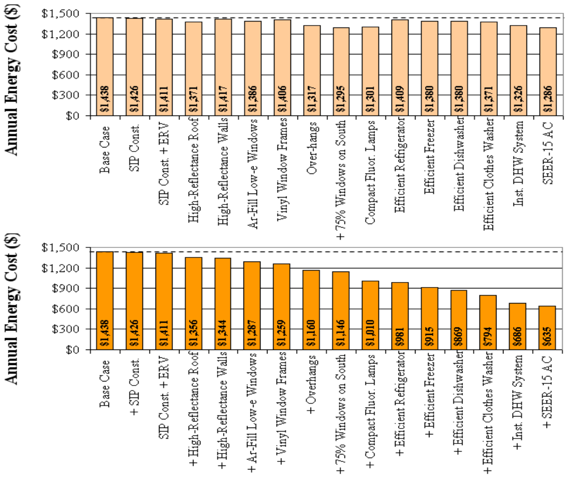


Figure 6. Annual Energy Costs for Individual and Combined Application of Measures.

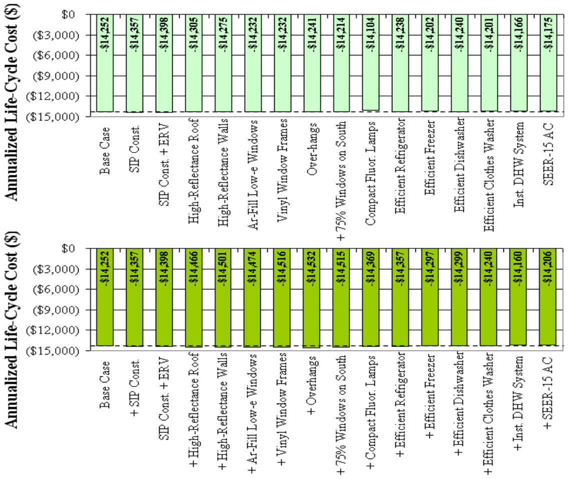


Figure 7. Annualized Life-cycle Costs for Individual and Combined Application of Measures.

HVAC and DHW systems and appliances. The annual energy cost for the house was $1,438. Taking into account all the costs and economic factors, the annualized life-cycle cost of the base-case house was $14,252.

A comparison of the annualized life-cycle costs of the house with individual and combined application of energy-efficient measures shows that the combined application of these measures had different impact on annualized life-cycle costs. The individual application of each measure decreased the annual energy cost by a significant amount. However, some of the measures increased the annualized life-cycle cost of the house, due to high first year cost and maintenance and replacement costs. The combined application of measures significantly decreased the annual energy cost to $635 and decreased the annualized life-cycle cost of the house to $14,206. Quite unexpectedly, measures that were found to be cost-effective on individual applications had diminishing returns for the house with improved characteristics. From the energy saving and life-cycle cost analyses, the following conclusions were made:

1. High reflectance roofing has significant energy saving potential; however, less expensive reflective roofing options should be considered for increased cost-effectiveness.

2. The high SEER air-conditioner was a cost-effective energy-saving measure. However, for a house with high-performance envelope and reduced cooling requirement, such installation is cost-effective only when system downsizing is considered to reduce the first cost.

3. The CFLs and tankless water heater with electronic ignition were cost-effective energy-saving measures irrespective of the other building characteristics, since their performances were not affected by space heating or cooling loads.

4. Among home appliances, the efficient refrigerator, freezer and clothes washer were cost-effective measures. Considering only the equipment energy use, the efficient dishwasher was not a cost-effective measure due to its high initial cost. Selecting less expensive models and considering water savings from efficient models could demonstrate a cost-effective installation of such models (i.e., water savings were not considered in this study).

5. The addition of overhangs was a cost-effective measure. However, this measure was less cost-effective in a house with other energy-efficient upgrades. Considering this measure at the design stage could be very cost-effective where the cost of constructing overhangs would be included in the overall construction cost, and would not increase the first year cost, significantly.

6. Installation of argon-filled, low-e windows with aluminum frames was a cost-effective energy-saving measure; whereas, the same measure with a vinyl frame reduced the cost-effectiveness of this measure.

CONCLUSIONS

The results of the energy analysis demonstrated that the proper selection of measures can accomplish 55% total annual energy reduction for a code-compliant house in a hot and humid climate, which consists of energy use reduction of 78% for space cooling, 53% for domestic water heating, 17% for space heating, and 44% for other end-uses. The savings correspond to those reported by Parker et al. (2000) in a test house of characteristics similar to those used in this study. Considering the annualized life-cycle cost, CFLs, instantaneous DHW system with electric ignition, high SEER air-conditioner, efficient appliances, argon-filled low-e windows, and maximum windows on south with overhangs were found to be cost-effective. For the measures that increased the life-cycle cost less expensive alternatives should be considered for cost-effectiveness.

This study analyzed the energy-saving measures that can be simulated with the DOE-2 program. This excluded the analysis of many other energy-saving measures such as, daylighting, natural ventilation, solar thermal and photovoltaic, heat pumps, radiant heating systems, combined space and water heating systems etc. These measures can be analyzed using other simulation programs in conjunction with the DOE-2 to maximize energy savings.

ACKNOWLEDGEMENTS

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