AN ANALYSIS OF BUILDING ENVELOPE UPGRADES FOR RESIDENTIAL ENERGY EFFICIENCY IN HOT AND HUMID CLIMATES

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ABSTRACT

This paper presents the results of the analyses of various envelope upgrades for residential energy-efficiency in hot and humid climates. The building components considered for the upgrades include: building shape, construction type, roof and exterior walls, and windows. A DOE-2 simulation model of a 2000/2001 IECC code-compliant house in Houston, Texas, was used for the analysis. The results demonstrated the effect of incremental changes in these properties on the building's energy use, and showed that combining potential envelope upgrades can accomplish a 55% cooling energy use reduction, a 100% heating energy use reduction, and a 16% total energy use reduction for code-compliant houses in hot and humid climates.

INTRODUCTION

Residential buildings are usually skin-dominated, having smaller internal heat generation as compared to the heat gain/loss through the envelope (Givoni 1998). The building envelope can contribute up to 73% of the total heat gain/loss in a residence (DOE 2004). Thus, the envelope characteristics, such as building geometry and orientation, construction type, properties of materials, and their interaction with the outdoor conditions, impact the heat gain/loss through the envelope and the energy required for space heating and cooling. Many studies have been performed to evaluate the energy-saving potential of various strategies for the building envelope. An extensive review of the previous studies is provided in Malhotra (2005). Due to the complex interaction of the energy flows through these components, it can be inappropriate to combine results and determine the total energy-savings from a group of strategies. Therefore, this study investigated the impact of various individual envelope choices on building energy use in different scenarios, and determined the maximum energy savings that could be accomplished from combined application of these measures in a single-family residence in a hot and humid climate.

METHODOLOGY

In order to quantify the energy savings from different measures, a DOE-2 simulation model of a 2000 IECC (which includes the 2001 Supplement) (ICC 1999) code-compliant house was used as the base case, which was then modified to simulate different scenarios with changes in the properties of the building envelope components. The tasks performed for this study included: determination of the base-case house characteristics, analysis of the impact of various envelope choices in different scenarios, and determination of maximum energy savings from the combined application of potential strategies.

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

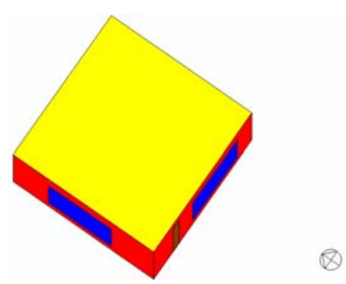


Figure 1: DOE-2 simulation model of the base-case house

Table 1: Base-case House Characteristics

Building configuration	2,500 ft.2, four bedroom, square shape, one-story, single-family detached house	
Construction type	Light-weight wood-frame	
Exterior walls	2 x 4 studs @ 16" on center, R-11 fiberglass batt insulation, and facia brick on the exterior	
Roof	2 x 10 studs @ 16" on center, R-30 ceiling insulation, and 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	10 SEER split air conditioner	
	78% AFUE natural gas furnace	
	Ducts in the conditioned space	
DHW system	40-gallon gas water heater with pilot light ignition	

Analysis of the impact of various envelope choices

The DOE-2 simulation model SNGFAM2ST.INP v1.14, developed by the Energy Systems Laboratory (ESL), Texas A&M University (Ahmed et al. 2005), was used for the analysis. This model uses parameters for various building characteristics, which can be assigned different values using an external DOE-2 include file. The simulations were performed using the Batch DOE-2 Input (BDI) program, developed by the ESL (Malhotra 2005). For this study, the house was first simulated with the base-case characteristics. The values of the parameters were then modified to simulate scenarios with different envelope characteristics to evaluate their effect on the energy use.

Four building envelope components were selected for the analysis that include: (a) building configuration (aspect ratio and number of floors), (b) roof and exterior walls (exposure, R-value, absorptance and emissivity), (c) construction type (thermal mass and air-tightness), and (d) fenestration system (window distribution on different orientations, overhang projection, U-factor, and SHGC). For each component, the effect of the incremental change in the associated properties on the building’s energy use was analyzed individually and in combination. Table 2 lists the values used for the properties of these components.

Analysis of the combined application of measures

The results of the analysis of individual envelope components were used for developing the maximum energy-efficient option. Table 3 lists the measures in the order they were applied to the base-case house. Different scenarios were simulated first using individual analysis, and then with their combined application. The results showed their individual energy saving potential, and the maximum energy savings achieved from their combined application.

Table 2: Values used for the building properties

Properties	Base case	Values used for the analysis
Building configuration	Square shape, one-story	1:3 to 3:1 east-west to north-south aspect ratio, for one and two-story configurations
Insulation[1] (hr-ft^2-°F/Btu)	Roof: R-30	R-10 to R-55
	Walls: R-11	
Absorptance[2]	Roof: 0.82	0.25 to 0.85
	Walls: 0.55	
Emissivity[3]	Roof: 0.9	0.1 to 0.9
	Walls: 0.9	
Construction type	Wood-frame 2x4 @ 16" on center	Structural insulated panels (85% reduced infiltration)
		Insulated concrete forms (50% reduced infiltration)
Window distribution	Equal window area on all sides	Equal windows on all sides to 75% windows on the south[4]
Overhang projection	No overhang	0 ft. to 6 ft. deep overhangs
Window U-factor[5] (Btu/hr-ft^2-°F)	0.47	0.2 to 1.2
Window SHGC[6]	0.4	0.25 to 0.85

Table 3: Building properties for the base-case house and maximum energy-efficient envelope option

Properties	Base-case house characteristics	Measures for maximum energy-efficiency
Construction	Wood-frame construction	SIP construction
Roofing	Gray asphalt shingles (absorptance = 0.82)	White fiber-cement shingles (absorptance = 0.23)
Exterior wall surface	Light-buff facia brick (absorptance = 0.55)	White semi-gloss paint (absorptance = 0.25)
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)
Window frames	Aluminum frames with thermal break	Vinyl frames
Exterior shading	No shading	4 ft. deep overhangs on all sides
Window distribution	Equal window area on all sides	75% on south, 15% on north, 5% on east and 5% on west

ANALYSIS AND RESULTS

The impact of various envelope choices was analyzed in Figure 2 through Figure 6, by plotting the annual energy use for space heating, space cooling, other end-

[1] For the range of values analyzed, higher R-values were achieved using thicker insulation.

[2] The lower values of absorptance are associated with light-color surfaces, whereas higher values are associated with dark-color surfaces.

[3] The lower values of emissivity are associated with metal surfaces and metallic paints, such as aluminum, copper, bronze paint, galvanized sheet, stainless steel etc. The higher values are associated with non-metallic surfaces such as plaster, paint, brick, concrete, sand, asphalt etc.

[4] This was accomplished in two steps. First, the window area on the east and west was reduced to 5% and added to the south, keeping the north window area fixed at 25% of the gross window area. Furthermore, the north window area was decreased to 15% to have 75% windows on the south.

[5] The lower values of the U-factors are associated with double-pane, low-e or triple-pane glazing. The higher values are associated with single-pane glazing.

[6] The lower values of SHGC are associated with reflected or tinted glazing. The higher values are associated with clear glazing.

uses (i.e., domestic water heating, lighting, equipment, pumps, fans and miscellaneous), and total energy use; and comparing them against the base case (shown with a black marker).

Building configuration

Simulations were performed to compare the east-west to north-south aspect ratio of the house varying from 1:3 to 3:1, for one and two-story configurations of the 2,500 ft^2 floor area of the base case. Considering that 18% window-to-floor area ratio in a 2,500 ft^2 one-story square shape house of the base case corresponds to a window area of 450 ft^2 or a window-to-wall area ratio of 28%; two sets of simulations were performed: (a) with a fixed window-to-floor area ratio (18%) that corresponds to a fixed gross window area for all configurations, and (b) with a fixed window-to-wall area ratio (28%) that corresponds to increased window area for elongated and/or two-story configurations.

To analyze the effect of building shape with and without considering the thermal mass of the construction materials, simulations were performed in "quick" (i.e., with precalculated ASHRAE weighting factors) and "delayed" (i.e., with the DOE-2's custom weighting factors) modes (DOE 1980). The evaluation using these two modes is important because most code evaluations are performed using the DOE-2 in the "quick" mode, versus the "delayed" simulation mode that tends to produce more accurate results, especially with massive wall construction (DOE 1980, Mukhopadhyay 2005). A total of 328 simulations were performed, and the annual energy use was plotted for the analysis.

Figure 2 shows that for a fixed gross window area, a 3% to 4% total energy savings resulted from an east-west elongated, two-story house. Whereas, for a fixed wall-to-window area ratio, there were heating and cooling energy penalties in elongated and/or two-story configurations because of the larger window area compared to the square shape, one-story base case. Simulations in the quick mode over-predicted the energy use by 8% to 14% compared to the delayed mode. Also, for a fixed gross window area, the most energy saving configuration was different in the quick and delayed construction modes. In the quick mode, a 2:1 two-story configuration showed the highest total energy savings (4%); whereas in the delayed mode, a 3:1 two-story configuration showed the highest total energy savings (3%).

Considering that simulation in the delayed mode produces more accurate results, it can be concluded that the east-west elongated, two-story configuration was the least energy consuming option.

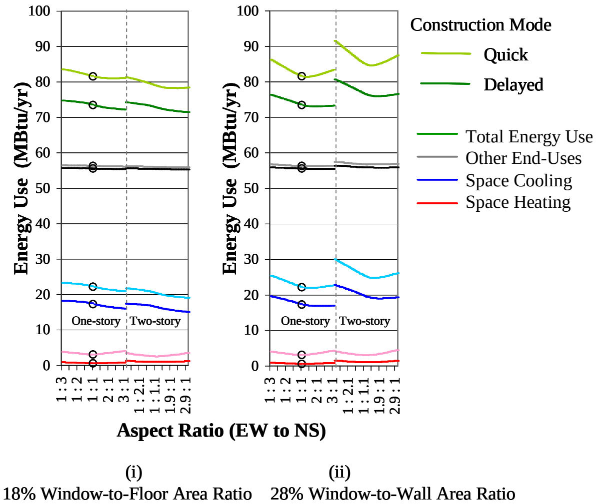


Figure 2: Effect of building configuration

Construction type

Three construction types were analyzed that included: a 2x4 wood-framed (base case), insulated concrete forms (ICFs), and structural insulated panels (SIPs). Considering that with proper installation, ICF and SIP construction allow to achieve airtightness level of up to 50% and 85% higher than the wood-frame construction, respectively (ICFA 2004, Christian 2003), three air-tightness levels were considered. For each combination, simulations were performed for the building configurations listed in Table 2, using DOE-2's delayed construction mode to incorporate the effect of thermal mass of these construction types. A total of 574 simulations were performed, and the annual energy use was plotted for the analysis.

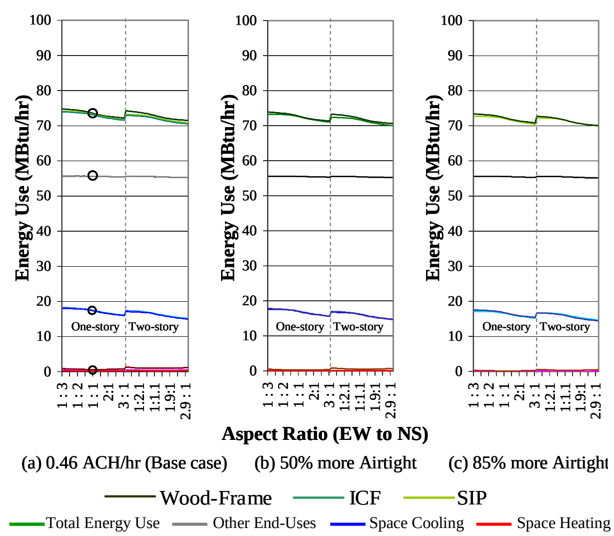


Figure 3: Effect of construction type

Figure 3(a) shows that discounting the air-tightness associated with different construction types, ICF construction was the least energy consuming due to its high thermal mass. However, Figure 3(b) and Figure 3(c) show that the highest savings were achieved from the airtight SIP construction due to the significant reduction in infiltration heat gain/ loss. For all the scenarios analyzed, a two-story, east-west elongated plan was the least energy consuming option.

Roof and exterior wall properties

The effects of exposed surface area resulted from different building configurations, R-value, absorptance and emissivity of the roof and walls were analyzed by performing simulations with the range of values of these properties listed in Table 2. Simulations were performed using the quick mode, since the actual layered construction required for the delayed analysis did not match with all the combinations analyzed. A total of 5,000 simulations were performed, and the annual energy use was plotted from the analysis.

Figure 4 and Figure 5 indicate that increasing the insulation resulted in cooling and heating energy savings. Whereas, by increasing the reflectance and emissivity, the cooling energy savings were offset by a small heating energy penalty. Changing the plan from a square shape to one elongated along the east-west axis resulted in a cooling energy savings and a heating energy penalty.

Effect of surface area

Figure 4(a) and Figure 5(a) show the effect of the exposed roof and wall area on energy savings from: (i) increasing insulation, (ii) decreasing absorptance, and (iii) increasing emissivity for the roof and walls, respectively. The following points were observed:

1. Savings from increasing the roof insulation, reflectance or emissivity were higher in a one-story house due to the increased roof area, than in a two-story house. However, impact of aspect ratio on energy savings from roof upgrades was small.
2. On the other hand, savings from the same upgrades for walls were higher in a two-story and/or east-west elongated house that has a larger exposed wall area than a square shape, one-story house.

Effect of R-value

Figure 4(b) and Figure 5(b) show the effect of insulation on energy savings from: (i) changing building configuration, (ii) decreasing absorptance, and (iii) increasing emissivity for the roof and walls, respectively. The following points were observed:

1. Savings from changing the aspect ratio were small for all roof insulation values. Savings from changing the plan from a one-story to a two-story resulted in a large savings for a less insulated roof, and a very small savings for a high insulated roof.
2. Savings from changing the building footprint from a square shape to one elongated along the east-west axis were higher for high insulated walls; whereas, equal savings were resulted from changing the building plan from one-story to two-story, irrespective of the wall insulation levels.
3. Savings from decreasing the absorptance and emissivity were small for high insulated roof and walls.

Effect of absorptance

Figure 4(c) and Figure 5(c) show the effect of absorptance on energy savings from: (i) changing building configuration, (ii) increasing insulation, and (iii) increasing emissivity for the roof and walls, respectively. The following points were observed:

1. Savings from changing the plan from a square shape to one elongated along the east-west axis were insignificant, irrespective of the roof and wall absorptance values. Savings from changing the plan from a one-story to a two-story were higher for dark roofs, and for reflective walls.
2. Savings from increasing insulation and emissivity were higher for dark roof and wall surfaces.

Effect of emissivity

Figure 4(d) and Figure 5(d) show the effect of emissivity on energy savings from: (i) changing building configuration, (ii) increasing insulation, and (ii) decreasing absorptance for the roof and walls, respectively.. The following points were observed:

1. Savings from changing the plan from a square shape to one elongated along the east-west axis were small, irrespective of the emissivity of the roof and walls. Savings from changing the plan from a one-story to a two-story were higher for a less emissive roof and for high emissive walls.
2. Savings from increasing the insulation and reflectance were higher for less emissive components.

From these observations, it can be concluded that the building configuration is critical for houses with less efficient envelopes. Improving roof properties showed a higher energy savings in a one-story building; whereas, improving walls properties showed a higher energy savings in a two-story building.

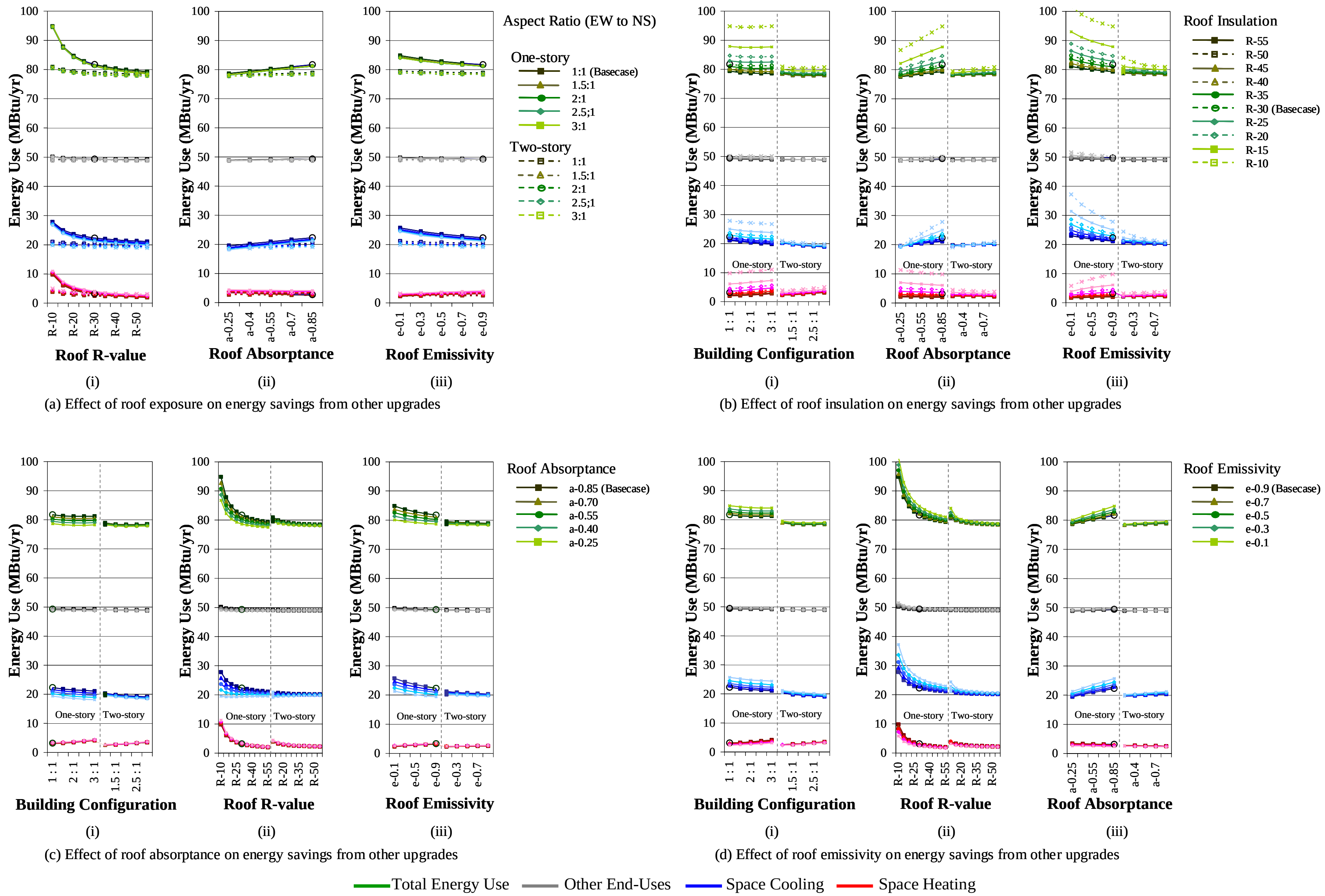


Figure 4: Effect of (a) exposure, (b) insulation, (c) absorptance, and (d) emissivity for roof

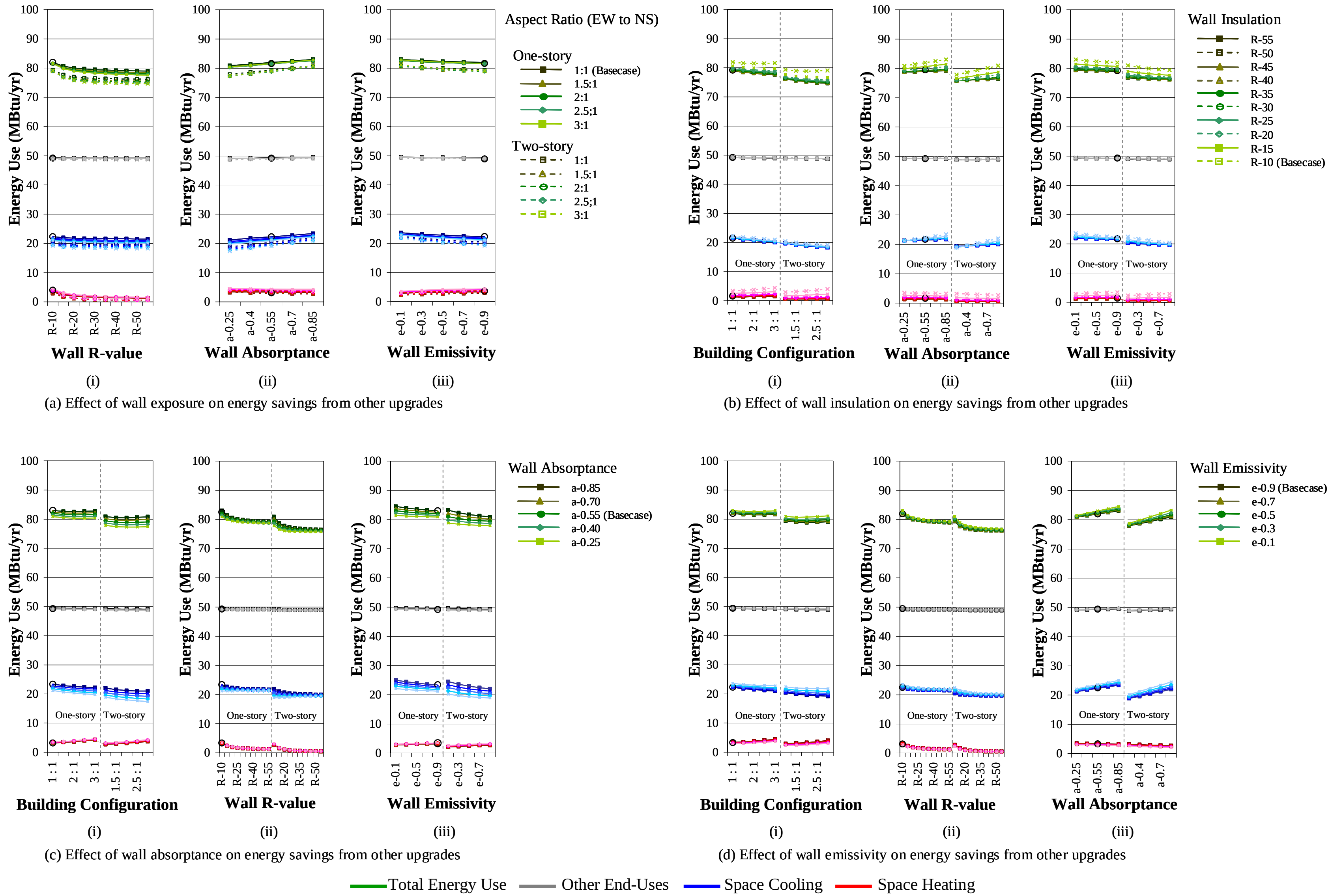


Figure 5: Effect of (a) exposure, (b) insulation, (c) absorptance, and (d) emissivity for exterior walls

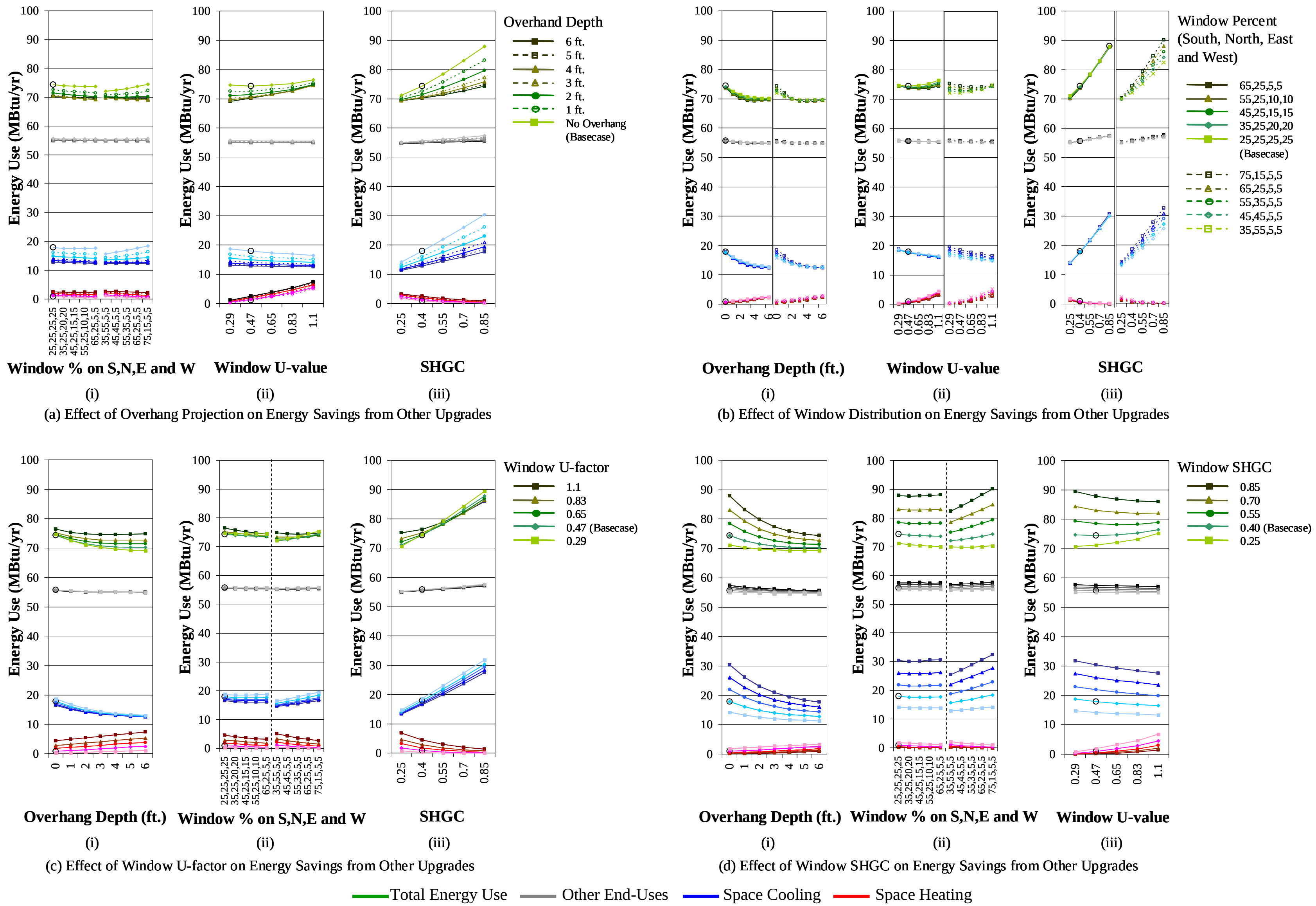


Figure 6: Effect of (a) overhang depth (b) window distribution, (c) window U-factor, and (d) SHGC

However, improvements for walls resulted in smaller savings compared to similar improvements for the roof. In all cases, diminishing energy savings were observed in the presence of other upgrades.

Fenestration properties

The combined effect of overhang projection, window distribution on different orientations, window U-factor and solar heat gain coefficient (SHGC) was analyzed by performing simulations with the range of values of these properties listed in Table 2. The impact of visible transmittance was not analyzed, since it is used only for daylighting calculations in the DOE-2. A total of 1,750 simulations were performed, and the annual energy use was plotted for the analysis.

Figure 6 indicates that increasing the overhang depth resulted in a significant cooling energy savings and a small heating energy penalty. Redistributing the east and west windows to the south resulted in small heating and cooling energy savings. Redistributing the north windows to the south resulted in a cooling energy penalty and a heating energy savings. Decreasing the window U-factor resulted in a cooling energy penalty comparable to the heating energy savings. Decreasing the SHGC resulted in a high cooling energy savings and a small heating energy penalty, thus, a significant total energy savings in all cases analyzed.

Effect of overhang depth

Figure 6(a) shows the effect of overhang projection on the energy savings from: (i) window redistribution, (ii) reducing window U-factor and (iii) reducing SHGC. The following points were observed:

1. For a house with up to 2 ft. deep overhangs, higher total energy saving resulted from redistributing east and west windows to the north than to the south. Overhangs with more than 2 ft. deep projection, provided with maximum windows on the south, resulted in the highest savings.
2. Savings from decreasing the window U-factor were higher for shaded windows. For unshaded windows, a window U-factor of 0.47 was the optimum.
3. Savings from decreasing the SHGC were higher for unshaded windows than for shaded windows.

Effect of window distribution

Figure 6(b) shows the effect of window distribution on the energy savings from: (i) increasing overhang depth, (ii) reducing window U-factor, and (iii) reducing SHGC. The following points were observed:

1. Savings/penalty from overhangs was higher for a house with more windows on the south. For most of the east and west windows redistributed on the south, an overhang depth of 4 ft. was optimum. A 7% energy savings resulted from 75% windows on the south, provided with a 4 ft. deep overhangs.
2. Savings from decreasing the window U-value was higher for less windows on the south; whereas, an energy penalty from decreasing the window U-value was higher for maximum window on the south. A window U-value between 0.47 and 0.65 resulted in maximum energy savings.
3. Savings from decreasing the window SHGC were higher for more windows on the south than on the north. However, equal savings resulted for scenarios with equal windows on the north, irrespective of the east, west and south window distribution.

Effect of window U-value

Figure 6(c) shows the effect of window U-value on the energy savings from: (i) increasing overhang depth, (ii) window redistribution, and (iii) reducing SHGC. The following points were observed:

1. Savings from increasing overhang depth were higher for less conductive windows.
2. Savings from redistributing east and west windows to the south were higher for more conductive windows. Redistributing north windows to the south resulted in small savings for more conductive windows, and in energy penalty for less conductive window.
3. Savings from decreasing SHGC were higher for less conductive windows.

Effect of SHGC

Figure 6(d) shows the effect of SHGC on energy savings from: (i) increasing overhang depth, (ii) window redistribution, and (iii) reducing window U-value. The following points were observed:

1. Savings from increasing the overhang depth were higher for windows with a high SHGC.
2. Savings from redistributing the east and west windows to the south resulted in a small savings for low SHGC windows and a small penalty for high SHGC windows. Redistributing north windows to the south resulted in an energy penalty, which was higher for high SHGC windows.
3. Decreasing the window U-value resulted in energy savings for low SHGC windows, and an energy

penalty for high SHGC windows. Thus, for low SHGC windows less U-value is desirable; and, for high SHGC windows, high U-value is desirable.

Combined application of measures

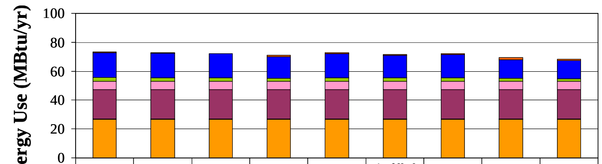
Figure 7 and Figure 8 show the annual end-use energy use for the individual and combined application of measures. Figure 7 shows that the largest cooling energy savings of 24% were achieved from overhangs, followed by 13% from reflective roof, and 10% from improved windows. However, due to the heating energy penalty from overhangs and reflective roofs, the total energy savings were small. Figure 8 shows that higher savings resulted from combining the measures, such as airtight SIP construction, maximum windows on the south, and improved windows that minimize the heating energy penalty. Figure 9 shows the impact of the combined application of the measures for different building configurations. The following observations were made:

1. As compared to the square shape, one-story, base-case house, a two-story house elongated along the east-west axis saved cooling energy. However, with a high reflectance roof, a two-story house became more energy consuming than a one-story house because of the increased wall area.
2. The impact of changing building configuration on the energy use diminished as more efficient envelope components were incorporated.
3. Among all the measures analyzed, overhangs, high reflectance roof, and efficient windows provided the maximum energy savings.

It is to be noted that for residences in Houston, space heating and cooling loads comprise less than 1% and 25% of the total energy use, respectively; whereas domestic water heating and equipment energy use comprise a significant part of the total energy use. Therefore, combined application of all the envelope upgrades resulted in a maximum annual energy savings of 55% for cooling, 100% for heating, whereas, only 16% for total energy.

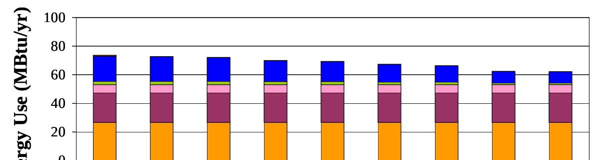
CONCLUSION

The results demonstrated that the envelope upgrades resulted in varying energy savings in different scenarios, and diminishing returns in the presence of other upgrades. The results showed that the proper selection of building envelope upgrades can accomplish a 55% cooling energy savings, a 100% heating energy savings, and a 16% total energy savings for code-compliant houses in hot and humid climates.



	Base-case	SIP Const.	SIP Const. + ERV	High-Refl. Roof	High-Refl. Walls	Ar-filled Low-e Win.	Vinyl Win. Frames	Over-hangs	+ 75% Win. on S
Heating	0.6	0.1	0	0.8	0.7	0.6	0.5	1.4	1
Cooling	17.3	17.1	16.6	15	16.6	15.6	16.3	13.1	12.5
Vent Fans	2.5	2.4	2.4	2.1	2.4	2.2	2.3	1.9	1.8
Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Equipment	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Pumps	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
Total	**73.5**	**72.7**	**72.1**	**71.1**	**72.8**	**71.6**	**72.2**	**69.5**	**68.3**

Figure 7: Energy use for individual application of measures



	Base-case	+ SIP Const.	+ ERV	+High-Refl. Roof	+High-Refl. Walls	+ Ar-filled Low-e Win.	+ Vinyl Frames	+ Over-hangs	+ 75% Win. on S
Heating	0.6	0.1	0	0	0	0	0	0	0
Cooling	17.3	17.1	16.6	14.7	14.3	12.5	11.5	8.2	7.8
Vent Fans	2.5	2.4	2.4	2.1	2.1	1.8	1.7	1.2	1.1
Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Equipment	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Pumps	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
Total	**73.5**	**72.7**	**72.1**	**70.0**	**69.5**	**67.4**	**66.3**	**62.6**	**62.0**

Figure 8: Energy use for combined application of measures

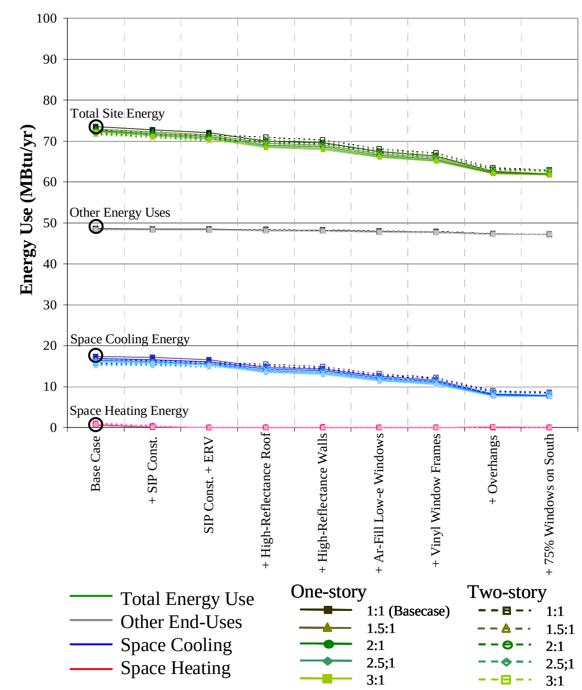


Figure 9: Effect of combined application of measure

Considering that domestic water heating and equipment energy use comprise a significant part of the total energy use, energy- effectiveness of the individual and combined application of energy-efficient measures for the building efficient measures for reducing these energy end-uses are more important. Other studies by Malhotra (2005) and Malhotra and Haberl (2006) analyze the energy saving potential and cost-effectiveness of measures for building envelope, systems and equipment. They showed 55% total energy use reduction with 5.65% increase in the first year cost and no increase in the annualized life-cycle cost.

The results of this study will facilitate better decision-making about the most effective building envelope upgrades and trade-offs for reducing residential energy use in hot and humid climates.

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