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Comparative Performance Analysis: HERS Index Score Dependencies Related To Home Geometries And Operating Assumptions

Florida Solar Energy Center

Philip Fairey
Florida Solar Energy Center, pfairey@fsec.ucf.edu

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Author

Philip Fairey

1679 Clearlake Road
Cocoa, Florida 32922, USA
(321) 638-1000

www.floridaenergycenter.org

A Research Institute of the University of Central Florida

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Abstract

EnergyGauge USA v.3.1.02 is used examine the impact of geometry and operating conditions on comparative simulation analysis techniques that are used to evaluate home energy performance with respect to a standardized reference case. A cohort of homes is simulated using the HERS Index scoring system in 15 U.S. cities that are representative of the 8 International Energy Conservation Code (IECC) climate zones. All of the homes are configured to have the thermal envelope characteristics specified by Table R402.1.1 of the 2012 IECC. All homes are also configured to meet all other mandatory requirements of the 2012 IECC, including 75% high efficiency lighting, insulated hot water piping, programmable thermostats and sealed air handlers. In addition, all homes have envelope leakage as specified by Section R402.4.1.2 of the 2012 IECC and are mechanically ventilated in accordance with the requirements of ASHRAE 62.2-2013.

The cohort of homes is configured as 2-story homes with 1200, 1800, 2400, 3600, 4800 and 7200 square feet of conditioned floor area. The 2400 ft^2 home is also configured as a 1-story and a 3-story prototype. The 2-story, 2400 ft^2 home is also configured to have from 1 to 6 bedrooms. Thus, a total of 13 different home geometry and operating condition configurations are simulated in 15 different cities. Results of the simulations are analyzed to determine the geometry and operating condition dependencies of the comparative simulation analysis procedures specified by the RESNET Standards.[1]

Background

During the past decade, experience using the HERS Index score as a measure of home performance has indicated that home geometry plays a significant role in the reported home performance score, with larger homes being advantaged and smaller home being disadvantaged by the comparative analysis methodology used to determine the HERS Index score. This experience is well founded by the science, whereby the geometry of the HERS Reference Home mimics the geometry of the Rated Home. As home size increases, the energy consumption of the HERS Reference Home also increases. However, at the same time, the impact of envelope improvements in larger homes causes a greater difference in performance between the HERS Reference and the Rated Homes than it does in smaller homes.

In addition to home size, the HERS methodology employs the number of bedrooms of a home (as a surrogate for occupants) to determine the appliance energy use and internal gains of a home. As a result, identical homes of the same size but with a different number of bedrooms will

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[1] RESNET, 2013, "National Mortgage Industry Home Energy Rating System Standards." Residential Energy Services Network, Oceanside, CA.
(http://www.resnet.us/standards/RESNET_Mortgage_Industry_National_HERS_Standards.pdf)

experience score differences. If, as in most new codes, homes are required to be mechanically ventilated, the required quantity of outdoor ventilation air will also be impacted by the number of bedrooms, also resulting in score differences.

Finally, the height of a home will generate differences. As home height increases, the ratio between ceiling area and wall area changes substantially. For example, for square homes, a single-story home will have three times the ceiling area of a three-story home of the same conditioned floor area. Similarly, the gross wall area of the three-story home will be more than five times the wall area of the single-story home. For two-story homes (probably the most common cohort), the gross wall area difference for a square home is 2.8 times the wall area of an equally sized one-story home. The reason these differences matter is because the thermal integrity of ceilings is generally much greater than the thermal integrity of walls. As an example, the 2012 IECC calls for ceiling insulation of R-49 in climate zone 4. The wall insulation requirement in this climate zone is less than half this quantity at R-20.

Methodology

EnergyGauge USA v.3.1.02 is used to compute HERS Index scores for a cohort of homes in 15 U.S. cities that are representative of the 8 IECC climate zones. All of the homes are configured with an aspect ratio of 1:1 (i.e. square) on a crawlspace foundation and all are configured with thermal envelope characteristics as specified by Table R402.1.1 of the 2012 IECC. All homes are equipped with NAECA minimum efficiency heating, cooling and hot water equipment and all are configured to meet all other mandatory requirements of the 2012 IECC, including 75% high efficiency lighting, insulated hot water piping, programmable thermostats and sealed air handlers. In addition, all homes have envelope leakage as specified by Section R402.4.1.2 of the 2012 IECC and are mechanically ventilated in accordance with the requirements of ASHRAE 62.2-2013. All homes have tested air distribution systems inside the conditioned space with no duct leakage.

Table 1 provides the geometric configurations of the cohort of homes evaluated by the study. All home geometries are square with their window areas equally distributed to the four cardinal wall orientations so as to be “solar neutral.”

Table 1: Home geometries evaluated

Conditioned Area	1,200	1,800	2,400	2,400	2,400	3,600	4,800	7,200
No. Bedrooms	3	3	3	3	3	3	3	3
No. Stories	2	2	1	2	3	2	2	2
WFA %	15%	15%	15%	15%	15%	15%	15%	15%
Window Area	180	270	360	360	360	540	720	1,080
Door Area (N)	40	40	40	40	40	40	40	40
Wall Perimeter	98	120	196	139	113	170	196	240
Floor Height	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Wall Height	17	17	8.5	17	25.5	17	17	17
Wall Width	24.49	30.00	48.99	34.64	28.28	42.43	48.99	60.00
Wall Area	1,666	2,040	1,666	2,356	2,885	2,885	3,331	4,080
Ceiling Area	600	900	2,400	1,200	800	1,800	2,400	3,600
Volume	10,200	15,300	20,400	20,400	20,400	30,600	40,800	61,200

The highlighted 2400 ft^2, 3-bedroom, 2-story home is the most typical of these configurations and served as the baseline for the analysis in determining how the other homes varied from this basis. In addition to 3 bedrooms, the 2400 ft^2, 2-story home was also configured with 1, 2, 4, 5 and 6 bedrooms to study the impact of the number of bedrooms, which significantly impacts appliance loads and internal gains in evaluated homes. Thus, the 8 configurations represented by Table 1 were augmented by 5 additional configurations to examine the impact of operating assumptions.

The values given in Table 1 were selected in part because they are representative of the standards employed by the IECC codes. For example, the window-to-floor area percentage (WFA%) is held constant for all homes because that is what the codes do. This is likely the correct approach because the utilitarian functions of windows are to provide daylighting and ventilation, both of which are likely more closely correlated to the floor area of the home than some other component of the home (e.g. the exterior wall area). Also note that the door area, which by code has the same fenestration U-Factor as the windows, does not vary by floor area but is held constant for all configurations. This causes the overall fenestration-to-floor area percentage to vary across floor areas. Table 2 provides the variation in each of these home configuration characteristics.

Table 2: Variation in configuration characteristics impacting the analysis

Conditioned Area	1,200	1,800	2,400	2,400	2,400	3,600	4,800	7,200
No. Stories	2	2	1	2	3	2	2	2
Win/floor area	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
Fen/floor area	18.3%	17.2%	16.7%	16.7%	16.7%	16.1%	15.8%	15.6%
Win/wall area	10.8%	13.2%	21.6%	15.3%	12.5%	18.7%	21.6%	26.5%
Fen/wall area	13.2%	15.2%	24.0%	17.0%	13.9%	20.1%	22.8%	27.5%
ceil/wall area	36.0%	44.1%	144.1%	50.9%	27.7%	62.4%	72.0%	88.2%

While not addressed by IECC codes, the ceiling-to-wall area percentage has the largest variance in this study, being as small as 27.7% for the 3-story, 2400 ft^2 home and as large as 144.1% for the 1-story, 2400 ft^2 home. However, even for the 2-story cohort, this factor varies from 36% to 88% with the larger homes having the larger percentages. Likewise, there is significant variance in the window-to-wall area percentage in this cohort of homes, varying from 10.8% in the smallest home to 26.5% in the largest home. Finally, while the window-to-floor area percentage does not vary across these homes, the fenestration-to-floor area percentage does, being larger in the smaller homes than in the larger homes.

The foundation for these homes was also held constant across the cohort of homes. A vented crawlspace was assumed for all homes. There are multiple foundation types used for homes – slab-on-grade, crawlspace and basement – and a given home may have a combination of all three. Ground temperatures vary by climate and will differentially impact the energy performance of homes. Of these foundation types, the vented crawlspace impacts these climatic performance differences the least and was selected for this study for that reason.

The 13 home configurations were simulated using TMY3 weather files from 15 U.S. cities, representing the 8 climate zones given by the IECC. Table 3 provides the cities used in the study.

Table 3: U.S. TMY3 weather file cities

City, State	IECC Zone	HDD	Avg. Temp (F)	Home ACH50	62.2 wsf
Miami, FL	1A	150	76.1	5	0.41
Phoenix, AZ	2B	997	74.8	5	0.43
Houston, TX	2A	1,439	68.6	5	0.41
El Paso, TX	3B	2,499	64.4	3	0.48
San Francisco, CA	3C	2,736	56.8	3	0.60
Memphis, TN	3A	2,999	62.7	3	0.46
Albuquerque, NM	4B	4,157	56.6	3	0.54
Salem, OR	4C	4,583	53.1	3	0.55
Baltimore, MD	4A	4,631	55.8	3	0.50
Boise, ID	5B	5,395	52.2	3	0.56
Chicago, IL	5A	6,399	50.0	3	0.60
Burlington, VT	6A	7,491	46.2	3	0.61
Helena, MT	6B	7,587	44.9	3	0.63
Duluth, MN	7A	9,620	39.2	3	0.70
Fairbanks, AK	8	13,072	29.4	3	0.70

Each of the homes is mechanically ventilated in accordance with the requirements of ASHRAE Standard 62.2-2013. The columns labeled ‘Home ACH50’ and ’62.2 wsf’ give the home envelope air tightness and weather and shielding factors used to determine the normalized leakage and natural infiltration rate for each of the homes in accordance with the ASHRAE Standard 62.2. A flow exponent of 0.65 was used for the calculations. Mechanical ventilation fan flow rates were calculated in accordance with the ASHRAE standard as $Q_{fan} = Q_{tot} – Q_{inf}$. Exhaust ventilation systems were assumed for all homes with ventilation fan power equal to 0.30 watts/cfm. The result is that each configuration required a slightly different mechanical ventilation rate and fan power in every climate save the three climate sets with the same 62.2 wsf values.

A version of EnergyGauge USA v.3.1.02, configured to provide results of the HERS Index score calculation to three decimal places was used for the analysis so that HERS Index score rounding would not be problematic for the analysis of results. The HERS Index scores were stored for each simulation for use in the analysis of results.

Findings

Simulation Results and Analysis

Home size was found to make a significant difference in HERS Index scores. Table 4 presents a synopsis of the results showing the HERS Index scores for each 2-story, 3-bedroom home size.

Table 4: HERS Index scores for all 2-story, 3-bedroom home configurations

Cond. Area:	1,200	1,800	2,400	3,600	4,800	7,200	Range
Miami, FL	75.2	71.4	68.7	65.5	63.8	61.8	13.4
Phoenix, AZ	71.1	67.5	64.8	61.7	60.0	57.9	13.2
Houston, TX	74.4	70.4	67.5	64.0	62.0	60.0	14.4
El Paso, TX	70.2	66.2	63.7	60.7	59.1	57.1	13.1
San Francisco, CA	75.4	71.2	68.2	64.4	62.1	59.8	15.6
Memphis, TN	71.0	67.1	64.4	61.3	59.6	57.2	13.8
Albuquerque, NM	71.6	67.5	64.9	61.8	60.1	57.9	13.7
Salem, OR	78.5	74.1	71.2	67.6	65.5	62.9	15.6
Baltimore, MD	73.6	69.5	66.9	64.0	62.3	60.3	13.3
Boise, ID	77.8	73.2	70.2	66.6	64.4	61.8	16.0
Chicago, IL	76.6	72.3	69.4	65.9	63.8	61.2	15.5
Burlington, VT	74.8	70.5	67.8	64.3	62.3	60.2	14.7
Helena, MT	75.5	71.0	68.3	64.9	62.9	60.8	14.7
Duluth, MN	72.9	68.4	65.5	62.0	60.0	57.8	15.1
Fairbanks, AK	70.7	66.2	63.5	60.3	58.6	56.5	14.2

For all cities in all climates the range of HERS Index scores was large, ranging from a low of 13.1 points in El Paso, TX to a high of 16 points in Boise, ID. To facilitate further analysis, the data given in Table 3 was normalized using the HERS Index scores for the 1200 ft^2 home as the basis of the normalization yielding the values shown in Table 5.

Table 5: Normalized HERS Index scores all 2-story, 3-bedroom home configurations

Cond. Area:	1,200	1,800	2,400	3,600	4,800	7,200	Range
Miami, FL	1.000	0.950	0.914	0.872	0.849	0.822	0.178
Phoenix, AZ	1.000	0.949	0.912	0.868	0.845	0.815	0.185
Houston, TX	1.000	0.946	0.908	0.861	0.834	0.806	0.194
El Paso, TX	1.000	0.943	0.908	0.866	0.842	0.814	0.186
San Francisco, CA	1.000	0.943	0.904	0.854	0.824	0.793	0.207
Memphis, TN	1.000	0.944	0.906	0.863	0.839	0.806	0.194
Albuquerque, NM	1.000	0.943	0.906	0.863	0.839	0.809	0.191
Salem, OR	1.000	0.944	0.907	0.862	0.834	0.801	0.199
Baltimore, MD	1.000	0.944	0.909	0.870	0.847	0.820	0.180
Boise, ID	1.000	0.941	0.902	0.856	0.828	0.794	0.206
Chicago, IL	1.000	0.944	0.906	0.860	0.832	0.798	0.202
Burlington, VT	1.000	0.942	0.906	0.860	0.833	0.804	0.196
Helena, MT	1.000	0.941	0.905	0.860	0.834	0.805	0.195
Duluth, MN	1.000	0.937	0.897	0.850	0.823	0.793	0.207
Fairbanks, AK	1.000	0.936	0.897	0.853	0.828	0.799	0.201

These normalized HERS Index score data are then used to conduct regression analysis of the results from all climates simultaneously. Figure 1 presents the results of this analysis.

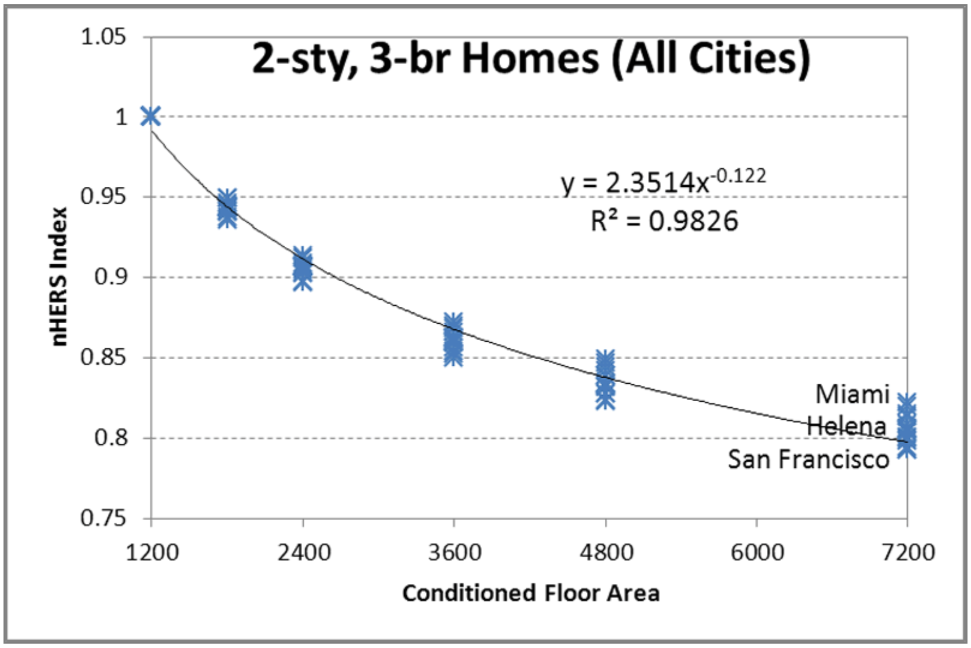

Figure 1: Normalized HERS Index scores for all home sizes in all climates

As shown in Figure 1, the most appropriate fit to the data is the square footage of the home raised to an exponent. In the case of these data, the exponent is -0.122 with a regression coefficient (R^2) of 0.9826 so less than 2% of the variance remains unexplained.

A similar analysis was conducted for the number of bedrooms in the home. Table 6 presents the HERS Index score data from the simulations and Table 7 presents the normalization of the Table 6 values.

Table 6: HERS Index scores for 2400 ft2, 2-story homes

No. Bedrooms:	1	2	3	4	5	6	Range
Miami, FL	65.8	67.3	68.7	70.3	71.6	72.8	7.0
Phoenix, AZ	62.7	63.8	64.8	65.8	66.8	67.8	5.1
Houston, TX	64.2	65.9	67.5	68.9	70.3	71.5	7.3
El Paso, TX	60.5	62.2	63.7	65.1	66.4	67.7	7.2
San Francisco, CA	63.9	66.1	68.2	70.1	71.9	73.6	9.7
Memphis, TN	61.1	62.7	64.4	66.0	67.4	68.7	7.7
Albuquerque, NM	61.6	63.2	64.9	66.5	67.9	69.3	7.7
Salem, OR	67.6	69.5	71.2	72.8	74.3	75.8	8.1
Baltimore, MD	63.5	65.3	66.9	68.6	70.2	71.6	8.1
Boise, ID	66.8	68.5	70.2	71.8	73.4	74.9	8.1
Chicago, IL	66.3	67.8	69.4	70.9	72.4	73.8	7.6
Burlington, VT	64.3	66.1	67.8	69.6	71.2	72.8	8.5
Helena, MT	64.6	66.5	68.3	70.1	71.8	73.5	8.9
Duluth, MN	62.1	63.8	65.5	67.2	68.8	70.4	8.3
Fairbanks, AK	60.3	61.9	63.5	65.1	66.6	68.2	7.9

Table 7: Normalized HERS Index scores for 2400 ft2, 2-story homes

No. Bedrooms:	1	2	3	4	5	6	Range
Miami, FL	1.000	1.023	1.043	1.068	1.088	1.106	0.106
Phoenix, AZ	1.000	1.017	1.034	1.049	1.065	1.081	0.081
Houston, TX	1.000	1.026	1.051	1.072	1.094	1.113	0.113
El Paso, TX	1.000	1.027	1.052	1.076	1.098	1.118	0.118
San Francisco, CA	1.000	1.035	1.067	1.097	1.125	1.152	0.152
Memphis, TN	1.000	1.028	1.054	1.080	1.104	1.126	0.126
Albuquerque, NM	1.000	1.027	1.054	1.080	1.103	1.125	0.125
Salem, OR	1.000	1.028	1.053	1.077	1.098	1.120	0.120
Baltimore, MD	1.000	1.028	1.053	1.079	1.105	1.127	0.127
Boise, ID	1.000	1.027	1.052	1.076	1.100	1.122	0.122
Chicago, IL	1.000	1.024	1.048	1.070	1.093	1.114	0.114
Burlington, VT	1.000	1.028	1.055	1.082	1.108	1.132	0.132
Helena, MT	1.000	1.029	1.057	1.084	1.112	1.137	0.137
Duluth, MN	1.000	1.027	1.054	1.082	1.108	1.134	0.134
Fairbanks, AK	1.000	1.026	1.052	1.079	1.105	1.131	0.131

Regression analysis of the data given in Table 7 results in the equation shown in Figure 2.

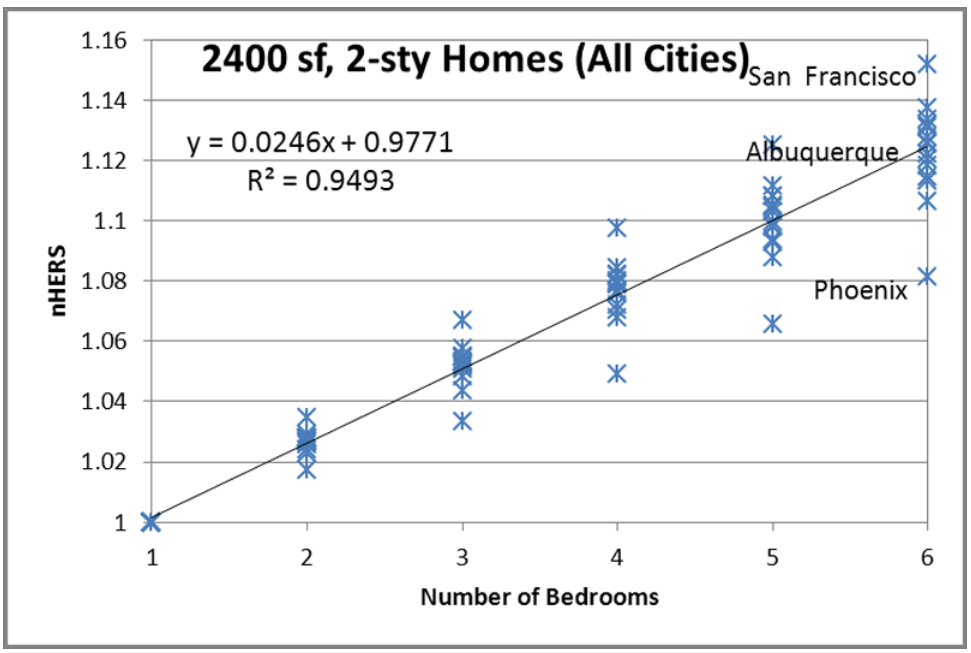

Figure 2: Normalized HERS Index for number of bedrooms in all climates

For the number of bedrooms, the best fit is linear rather than exponential and the correlation coefficient is greatly improved as compared with the R^2 for the data on number of stories with only about 5% of the variance remaining unexplained by the regression equation. San Francisco and Phoenix are the outlying climates for number of bedrooms.

The final analysis is conducted for the HERS Index score data for the number of stories. Table 8 gives the raw HERS Index score values for this analysis.

Table 8: HERS Index scores for 2400 ft2, 3-bedroom homes

No. Stories:	1	2	3	Range
Miami, FL	69.1	68.7	68.2	0.9
Phoenix, AZ	65.1	64.8	64.8	0.3
Houston, TX	68.3	67.5	67.0	1.2
El Paso, TX	65.5	63.7	62.3	3.2
San Francisco, CA	72.3	68.2	65.8	6.5
Memphis, TN	66.3	64.4	63.2	3.2
Albuquerque, NM	68.5	64.9	64.0	4.5
Salem, OR	73.0	71.2	70.1	2.9
Baltimore, MD	69.0	66.9	65.5	3.5
Boise, ID	71.6	70.2	69.2	2.5
Chicago, IL	70.8	69.4	68.7	2.1
Burlington, VT	71.1	67.8	65.8	5.3
Helena, MT	72.3	68.3	66.0	6.3
Duluth, MN	68.5	65.5	63.8	4.7
Fairbanks, AK	66.4	63.5	62.1	4.3

Normalization of the Table 8 data results in Table 9.

Table 9: Normalized HERS Index scores for 2400 ft2, 3-bedroom homes

No. Stories:	1	2	3	Range
Miami, FL	1.000	0.994	0.988	0.012
Phoenix, AZ	1.000	0.996	0.996	0.004
Houston, TX	1.000	0.989	0.982	0.018
El Paso, TX	1.000	0.972	0.951	0.049
San Francisco, CA	1.000	0.943	0.910	0.090
Memphis, TN	1.000	0.970	0.952	0.048
Albuquerque, NM	1.000	0.947	0.935	0.065
Salem, OR	1.000	0.975	0.961	0.039
Baltimore, MD	1.000	0.969	0.949	0.051
Boise, ID	1.000	0.980	0.966	0.034
Chicago, IL	1.000	0.981	0.971	0.029
Burlington, VT	1.000	0.953	0.925	0.075
Helena, MT	1.000	0.945	0.913	0.087
Duluth, MN	1.000	0.955	0.931	0.069
Fairbanks, AK	1.000	0.956	0.935	0.065

Regression of the data in Table 9 results in the equation shown in Figure 3.

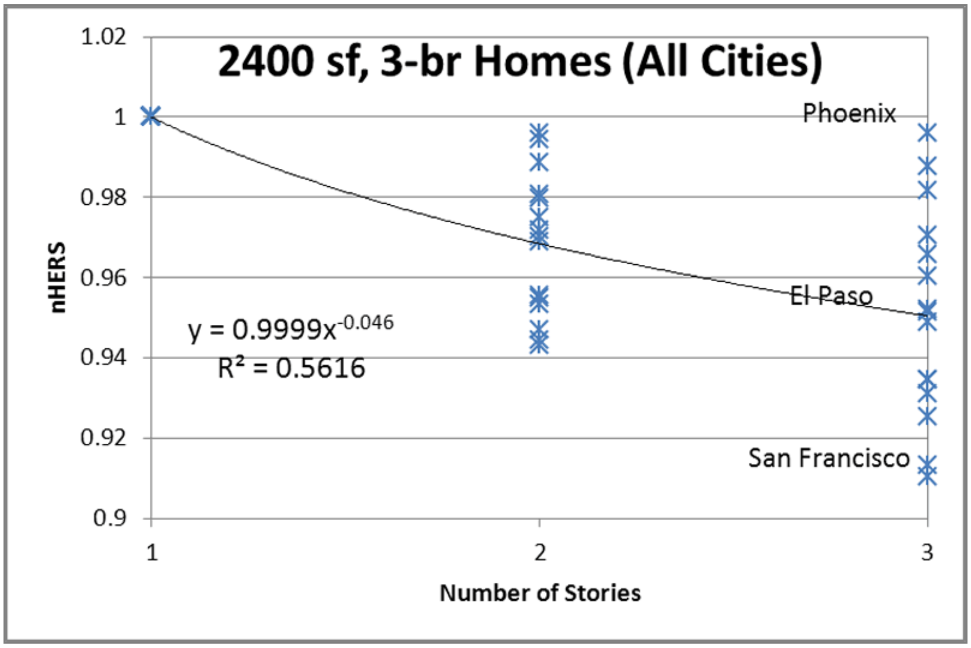

Figure 3: Normalized HERS Index for number of stories in all climates

It is evident from Figure 3 that the local climate dependence of building height is very strong with a large variance for 3-story homes. As in Figure 1, the best fit to the data is exponential. However, unlike in Figure 1, the correlation coefficient is quite weak, with 44% the data unexplained by the best fit regression. As for the number of bedrooms, San Francisco and Phoenix represent the extremes of the climate dependence with El Paso being the median.

The variance in these data is large enough to examine the climate dependence more closely. Table 10 provides the rank ordering of normalized HERS score results for the 3-story homes showing the city and climate zone associated with each.

Table 10: Rank ordering of results by city

City	Zone	nHERS	%ΔUA
Phoenix	2B	0.996127	-7.9%
Miami	1A	0.987577	-0.9%
Houston	2A	0.981841	-7.9%
Chicago	5A	0.9706	-22.7%
Boise	5B	0.965703	-22.7%
Salem	4C	0.960512	-22.7%
Memphis	3A	0.952009	13.6%
El Paso	3B	0.951397	13.6%
Baltimore	4A	0.949015	32.8%
Fairbanks	8	0.934679	19.4%
Albuquerque	4B	0.934522	32.8%
Duluth	7A	0.93104	19.4%
Burlington	6A	0.925362	60.5%
Helena	6B	0.913128	60.5%
San Francisco	3C	0.910314	13.6%
	Median	0.951397	13.6%

Table 10 shows some general grouping of results by climate zone with warmer climates generally nearer the top and colder climates generally nearer the bottom. However, Baltimore and Albuquerque are separated and San Francisco is quite removed from El Paso and Memphis. Nonetheless, the cities in climate zone 5 (including Salem in 4C) and in climate zone 6 are closely grouped.

However, it is also clear from Table 10 that climate severity is not the only factor causing the variance because there is a significant difference between the rankings of the cities in climate zones 5 (which includes Salem) and the cities in climate zone 6. Thus, one can hypothesize that at least part of the variance in this factor may be due to the difference between the changes in wall, ceiling and floor U-factors between the HERS Reference cases and the improved cases (2012 IECC), where these values may have greater differences in some climate zones than in others.

This is of course magnified by the fact that ceiling insulation values are significantly greater than wall insulation values and that the ceiling-to-wall area percentage in the 1-story homes is approximately 5 times greater than in the 3-story homes. Thus, if envelope insulation values have differentially changed is some climates more than in others, the impact would be most prevalent in the 3-story homes.

To examine this factor, the sum of the U-factors times component areas (UA) for the 1-story and 3-story 2400 ft^2 configurations is examined and the percent change (%ΔUA) is calculated for each climate. In general, the %ΔUA value is negative for the cities at the top of the ranking list shown in Table 10, meaning that the difference in UA between the HERS Reference case and the improved case is less for the 3-story home than for the 1-story home. Regression of these %ΔUA values against the nHERS values reveals that %ΔUA explains about 54% of the variance, indicating that the change in envelope efficiency characteristics between the HERS Reference cases and the improved cases (IECC 2012) does indeed explain more than 50% of the variance seen in Figure 3. Figure 4 provides results of this regression analysis.

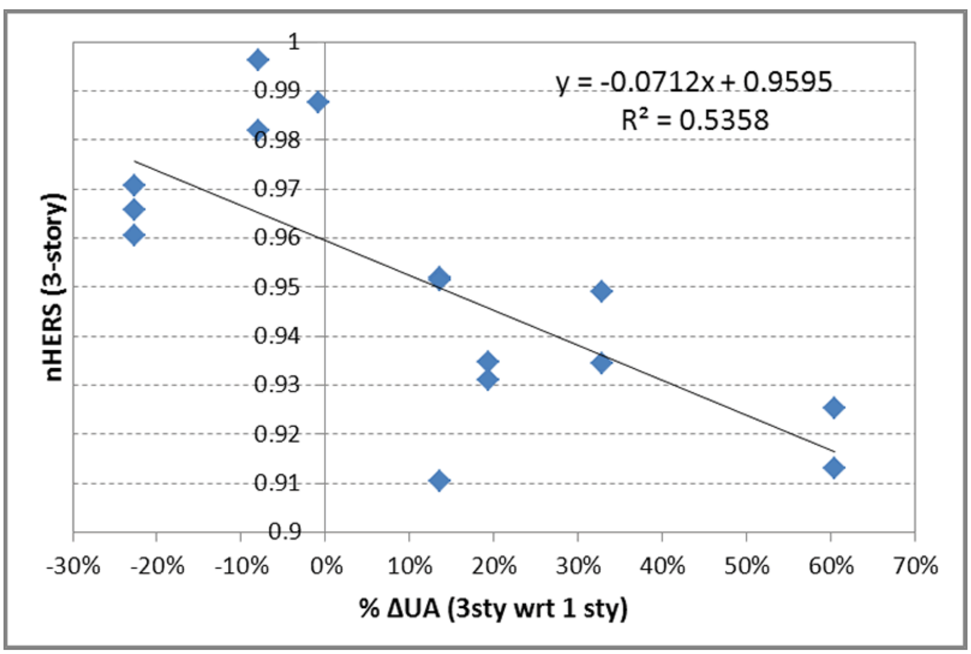

Figure 4. Regression of %ΔUA against nHERS for 3-story homes

Another way of looking at these data is to say that 54% of the unexplained 44% variance in the number of stories regression shown in Figure 3 is explained by this %ΔUA factor, leaving only about 24% of the variance unexplained. Thus, if %ΔUA is consistent across climate zones, the correlation coefficient (R^2) shown in Figure 3 would be substantially improved and the median nHERS value shown in Table 10, which corresponds to the regression line in Figure 3, is likely to be representative of the impact of the number of stories on the HERS Index Score.

Based on these regression results, it is possible to construct an equation that will characterize the HERS Index score differences caused by all three of the dependencies. We will call this the HERS adjustment factor or AF. We construct this equation using the 2,400 ft^2, 2-story, 3-bedroom home as the basis. The resulting equation is as follows:

$$AF = ((2400/CFA)^{0.122}) * (1+ (0.0246*(Nbr-3))) * ((2/NS)^{0.046}) \qquad \text{Eq. 1}$$

As an example of how this factor may be used, we construct another variable called $HERS_{adj}$ or the adjusted HERS Index score, where

$$HERS_{adj} = HERS/AF \qquad \text{Eq. 2}$$

Table 11 presents the $HERS_{adj}$ values for the HERS Index scores presented in Table 4.

Table 11: Adjusted HERS Index Scores for all 2-story, 3-bedroom home configurations

Cond. Area:	1,200	1,800	2,400	3,600	4,800	7,200	Range
Miami, FL	69.1	68.9	68.7	68.9	69.5	70.7	2.0
Phoenix, AZ	65.3	65.1	64.8	64.8	65.3	66.2	1.4
Houston, TX	68.3	68.0	67.5	67.3	67.5	68.6	1.3
El Paso, TX	64.5	63.9	63.7	63.8	64.3	65.3	1.6
San Francisco, CA	69.3	68.7	68.2	67.7	67.6	68.4	1.7
Memphis, TN	65.3	64.7	64.4	64.4	64.8	65.5	1.1
Albuquerque, NM	65.8	65.2	64.9	64.9	65.4	66.2	1.3
Salem, OR	72.1	71.6	71.2	71.1	71.3	71.9	1.1
Baltimore, MD	67.6	67.1	66.9	67.2	67.8	69.0	2.1
Boise, ID	71.5	70.7	70.2	70.0	70.1	70.6	1.5
Chicago, IL	70.4	69.8	69.4	69.3	69.4	69.9	1.1
Burlington, VT	68.8	68.1	67.8	67.6	67.8	68.8	1.2
Helena, MT	69.4	68.6	68.3	68.2	68.5	69.5	1.3
Duluth, MN	67.0	66.0	65.5	65.1	65.3	66.1	1.9
Fairbanks, AK	65.0	63.9	63.5	63.4	63.7	64.7	1.6

Two things are apparent from Table 11. First, the values in the highlighted column are identical to the values for the same column in Table 4 (i.e. the adjustment factor equals 1.0). Second, the range of scores has been substantially reduced compared with Table 4. Where the largest range in Table 4 was 16 points, the largest range in Table 11 is 2.0 points – almost an order of magnitude reduction in the range of scores.

Potential Error

Tables 4-9 evaluate each of the HERS Index score dependencies independently of one another. Equation 1 combines these independent dependencies into a single equation that accounts for all three dependencies together. One can examine the potential error of Equation 1 by applying Equation 2 to all of the home configurations and then calculating the percent difference between the calculated values for each configuration with respect to the 2400 ft^2, 3-bedroom, 2-story home that is used as the basis in Equation 1. Table 12 presents the adjusted HERS Index scores ($HERS_{adj}$) calculated using Equation 2 for each of the 13 configurations in each of the 15 cities evaluated.

Note in Table 12 that the range of values has increased compared with Table 11. Since all three of the major dependencies (CFA, NS and Nbr) are combined in Equation 1, this is not unexpected. Nonetheless, the maximum adjusted HERS Index score range of 3.8 is still about 4 times smaller than the maximum HERS Index score range for the raw HERS Index scores of 16.

However, this score range does not represent the potential error of Equation 1. The potential error for Equation 1 is actually relative to the HERS Index score for the 2,400 ft^2, 3-bedroom, 2-story baseline home rather than the absolute range of all adjusted HERS Index scores. Table 13 examines this error by comparing the adjusted HERS Index score for each configuration to the HERS Index score of the baseline 2,400 ft^2, 2-story, 3-bedroom home. For these calculations, the maximum error band for Equation 1 for the evaluated configurations in the evaluated climates is +2.8% and -3.1% of the baseline home HERS Index.

Table 12: All Homes; Adjusted HERS Index

Cond. Area:	1,200	1,800	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	3,600	4,800	7,200	Range
No. Stories:	**2**	**2**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**2**	**2**	**2**	
No. Bedrooms:	**3**	**3**	**3**	**1**	**2**	**3**	**4**	**5**	**6**	**3**	**3**	**3**	**3**	
Miami, FL	69.1	68.9	66.9	69.2	69.0	68.7	68.6	68.3	67.8	69.5	68.9	69.5	70.7	3.8
Phoenix, AZ	65.3	65.1	63.0	65.9	65.4	64.8	64.2	63.7	63.1	66.0	64.8	65.3	66.2	3.2
Houston, TX	68.3	68.0	66.1	67.6	67.6	67.5	67.2	67.0	66.6	68.3	67.3	67.5	68.6	2.4
El Paso, TX	64.5	63.9	63.5	63.6	63.7	63.7	63.5	63.3	63.0	63.5	63.8	64.3	65.3	2.3
San Francisco, CA	69.3	68.7	70.0	67.2	67.8	68.2	68.4	68.5	68.6	67.0	67.7	67.6	68.4	3.0
Memphis, TN	65.3	64.7	64.3	64.2	64.3	64.4	64.4	64.3	64.0	64.4	64.4	64.8	65.5	1.4
Albuquerque, NM	65.8	65.2	66.4	64.8	64.8	64.9	64.9	64.8	64.6	65.2	64.9	65.4	66.2	1.8
Salem, OR	72.1	71.6	70.7	71.1	71.2	71.2	71.1	70.8	70.6	71.4	71.1	71.3	71.9	1.6
Baltimore, MD	67.6	67.1	66.9	66.8	67.0	66.9	66.9	66.9	66.7	66.8	67.2	67.8	69.0	2.3
Boise, ID	71.5	70.7	69.4	70.2	70.3	70.2	70.1	70.0	69.7	70.5	70.0	70.1	70.6	2.1
Chicago, IL	70.4	69.8	68.6	69.7	69.6	69.4	69.2	69.0	68.8	70.0	69.3	69.4	69.9	1.8
Burlington, VT	68.8	68.1	68.9	67.6	67.7	67.8	67.9	67.9	67.8	67.1	67.6	67.8	68.8	1.8
Helena, MT	69.4	68.6	70.1	67.9	68.2	68.3	68.4	68.4	68.4	67.3	68.2	68.5	69.5	2.8
Duluth, MN	67.0	66.0	66.4	65.3	65.4	65.5	65.5	65.6	65.5	65.0	65.1	65.3	66.1	2.0
Fairbanks, AK	65.0	63.9	64.3	63.4	63.4	63.5	63.5	63.5	63.5	63.2	63.4	63.7	64.7	1.8

Table 13: All Homes; Adjusted HERS Index % Error w.r.t. 2,400ft^2, 3-bedroom, 2-story Baseline Home

Cond. Area:	1,200	1,800	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	3,600	4,800	7,200	% Error	
No. Stories:	**2**	**2**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**2**	**2**	**2**		
No. Bedrooms:	**3**	**3**	**3**	**1**	**2**	**3**	**4**	**5**	**6**	**3**	**3**	**3**	**3**	**Max**	**Min**
Miami, FL	-0.6%	-0.3%	2.6%	-0.8%	-0.5%	0.0%	0.1%	0.6%	1.3%	-1.2%	-0.2%	-1.1%	-2.9%	2.6%	-2.9%
Phoenix, AZ	-0.8%	-0.5%	2.8%	-1.8%	-0.9%	0.0%	0.9%	1.7%	2.6%	-1.9%	0.0%	-0.8%	-2.2%	2.8%	-2.2%
Houston, TX	-1.2%	-0.7%	2.0%	-0.1%	-0.2%	0.0%	0.4%	0.8%	1.3%	-1.2%	0.3%	0.0%	-1.6%	2.0%	-1.6%
El Paso, TX	-1.2%	-0.3%	0.3%	0.1%	-0.1%	0.0%	0.2%	0.6%	1.1%	0.2%	-0.2%	-0.9%	-2.5%	1.1%	-2.5%
San Francisco, CA	-1.7%	-0.8%	-2.7%	1.4%	0.6%	0.0%	-0.4%	-0.5%	-0.6%	1.7%	0.7%	0.8%	-0.3%	1.7%	-2.7%
Memphis, TN	-1.4%	-0.6%	0.2%	0.3%	0.1%	0.0%	0.0%	0.2%	0.6%	0.0%	-0.1%	-0.7%	-1.7%	0.6%	-1.7%
Albuquerque, NM	-1.4%	-0.5%	-2.3%	0.2%	0.1%	0.0%	0.0%	0.2%	0.5%	-0.5%	0.0%	-0.7%	-2.0%	0.5%	-2.3%
Salem, OR	-1.3%	-0.5%	0.7%	0.1%	-0.1%	0.0%	0.2%	0.6%	0.9%	-0.4%	0.2%	-0.1%	-1.0%	0.9%	-1.3%
Baltimore, MD	-1.1%	-0.3%	0.0%	0.1%	-0.1%	0.0%	0.0%	0.0%	0.3%	0.2%	-0.5%	-1.3%	-3.1%	0.3%	-3.1%
Boise, ID	-1.8%	-0.7%	1.1%	0.0%	-0.1%	0.0%	0.1%	0.3%	0.6%	-0.4%	0.3%	0.2%	-0.6%	1.1%	-1.8%
Chicago, IL	-1.4%	-0.5%	1.2%	-0.3%	-0.2%	0.0%	0.3%	0.6%	1.0%	-0.8%	0.3%	0.1%	-0.7%	1.2%	-1.4%
Burlington, VT	-1.4%	-0.4%	-1.6%	0.3%	0.1%	0.0%	-0.1%	-0.1%	0.1%	1.1%	0.3%	0.0%	-1.5%	1.1%	-1.6%
Helena, MT	-1.5%	-0.4%	-2.5%	0.5%	0.2%	0.0%	-0.1%	-0.2%	-0.2%	1.5%	0.2%	-0.2%	-1.8%	1.5%	-2.5%
Duluth, MN	-2.4%	-0.9%	-1.4%	0.3%	0.1%	0.0%	-0.1%	-0.2%	-0.1%	0.7%	0.5%	0.3%	-1.0%	0.7%	-2.4%
Fairbanks, AK	-2.4%	-0.7%	-1.3%	0.0%	0.0%	0.0%	-0.1%	-0.1%	-0.1%	0.4%	0.1%	-0.4%	-1.9%	0.4%	-2.4%
Maximum Error (all homes, all cities)														2.8%	-3.1%

Previous Adjustment Efforts

Both the U.S. Environmental Protection Agency's (EPA) ENERGY STAR homes program and the U.S. Department of Energy's (DOE) Building America program have developed geometry adjustments for use in their new homes programs. Both of these federal programs also use a form of HERS ratings to qualify new homes for their programs.

For the ENERGY STAR new homes program, EPA has prescribed a Size Adjustment Factor (SAF), defined as follows:

$$SAF = (CFA_{bench}/CFA_{actual})^{0.25} <= 1.0$$

where

$$CFA_{bench} = 400 + 600*Nbr \text{ with } Nbr=>1$$

thus

$$SAF = ((400 + 600*Nbr) / CFA_{actual})^{0.25} <= 1.0 \qquad \text{Eq. 3}$$

This SAF, when multiplied by the HERS Index of the ENERGY STAR reference home, provides the target HERS Index that a new home must meet to qualify for the ENERGY STAR new home program. Since EPA limits SAF to values equal to or less than unity, it does not provide any credit for smaller homes – only consequences for larger homes.[2] The SAF values for a number of home configurations is given in Figure 5.

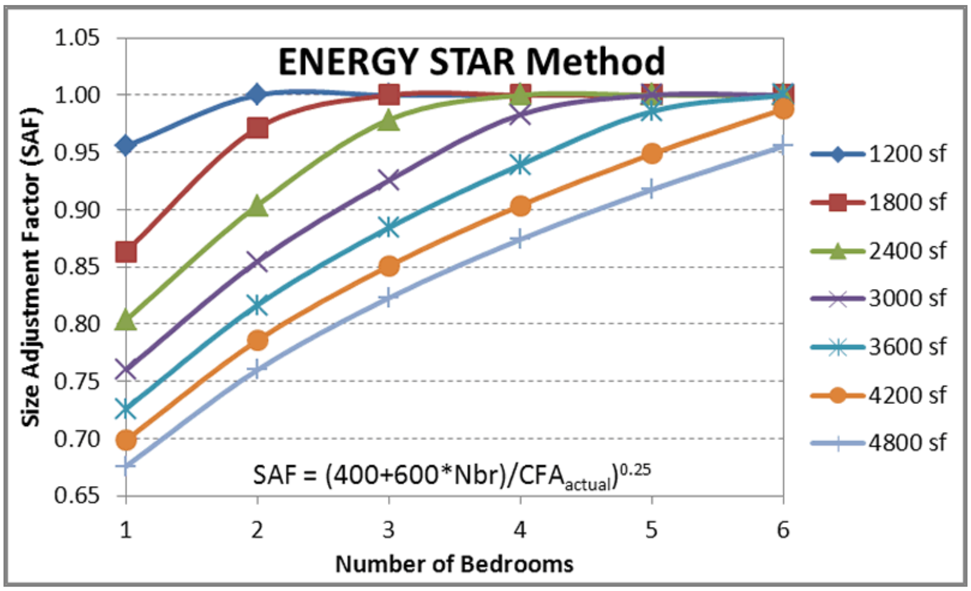

Figure 5: EPA's ENERGY STAR new homes program Size Adjustment Factor

DOE's Building America program has also specified a comparative modeling adjustment – also based on conditioned floor area and number of bedrooms. However, the Building America modeling adjustment method differs from the EPA approach in two respects. First, it is based on Building America prototype simulation results rather than intuition and second, rather than limiting the adjustment to values less than unity, it allows values greater than one, providing a credit for small homes.

[2] http://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/V3HERS_IndexTargetProcedure.pdf

The BA method results in a home size multiplier (M_{SIZE}) that is applied to the BA Benchmark Home's projected energy use to yield an Adjusted Benchmark Home energy use. The BA Prototype home's energy use is then compared against this Adjusted Benchmark Home energy use to determine the Prototype Home's energy saving percentage. The BA multiplier equation is as follows:

$$M_{SIZE} = (Nbr/3)^{0.034} * (2400/CFA_{actual})^{0.167} \quad \text{Eq. 4}$$

Note that the exponential form of the equation for the conditioned floor area is the same as the form in Equation 1 but the value of the exponent is different, with Equation 4 providing more weight to CFA than Equation 1. Equation 4 also has a different form for number of bedrooms with an exponential rather than a linear fit. The relationship between conditioned floor area and number of bedrooms for the BA size multiplier is shown in Figure 6.

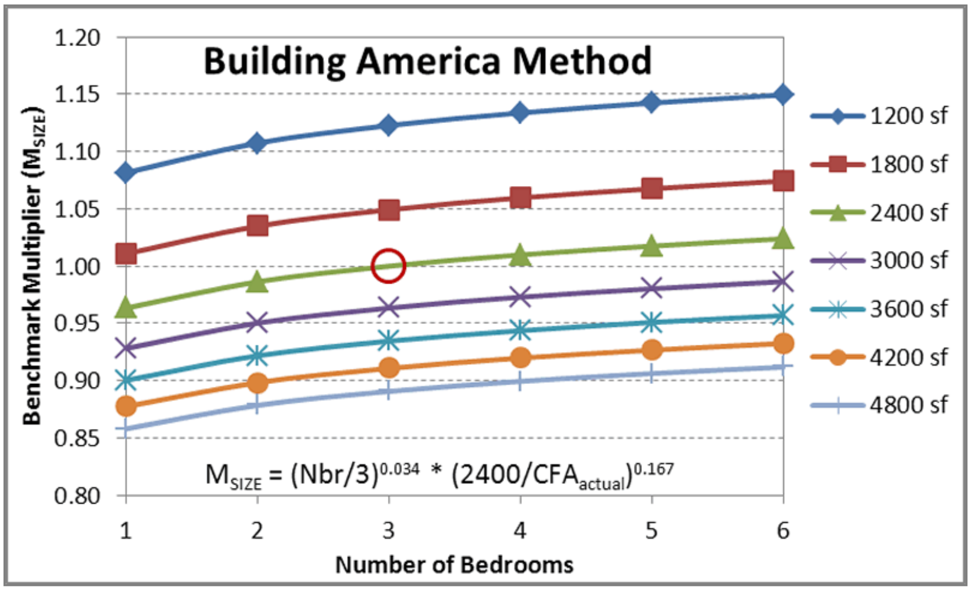

Figure 6: Building America's Benchmark Home Size Multiplier

The BA Benchmark 'M_{SIZE}' value serves the same purpose as the EPA 'SAF.' However, M_{SIZE} is applied in a slightly different manner than SAF, albeit with the exact same effect, by multiplying the BA Benchmark Home's projected energy use by M_{SIZE} prior to comparing it with the BA Prototype Home's energy use. [3]

Comparison of Methods

Since all three of these adjustment methods are constructed to function in the same manner, it is possible to compare them one with the other. For this purpose, we assume that the 2,400 ft^2, 3-bedroom, 2-story home is the basis of comparison. By this we mean that the goal is for all other home geometries and number of bedrooms to provide the same HERS Index score as this home in a given climate. Using this basis and the score adjustment method given by Equation 2, the three methods can be compared in terms of their percent error with respect to the basis used for this study (i.e. the HERS Index score for the 2,400 ft^2, 3-bedroom, 2-story home).

[3] Hendron, R and C. Engebrecht, October 2010, "Building America House Simulation Protocols." National Renewable Energy Laboratory, Golden, CO. (http://www.nrel.gov/docs/fy11osti/49246.pdf)

For the EPA ENERGY STAR SAF, the error can be substantial with percentage errors in adjusted HERS Index scores in the 20% range for large homes. Figure 7 compares the projected HERS Index score error for the EPA SAF and the HERS AF method developed in this study.

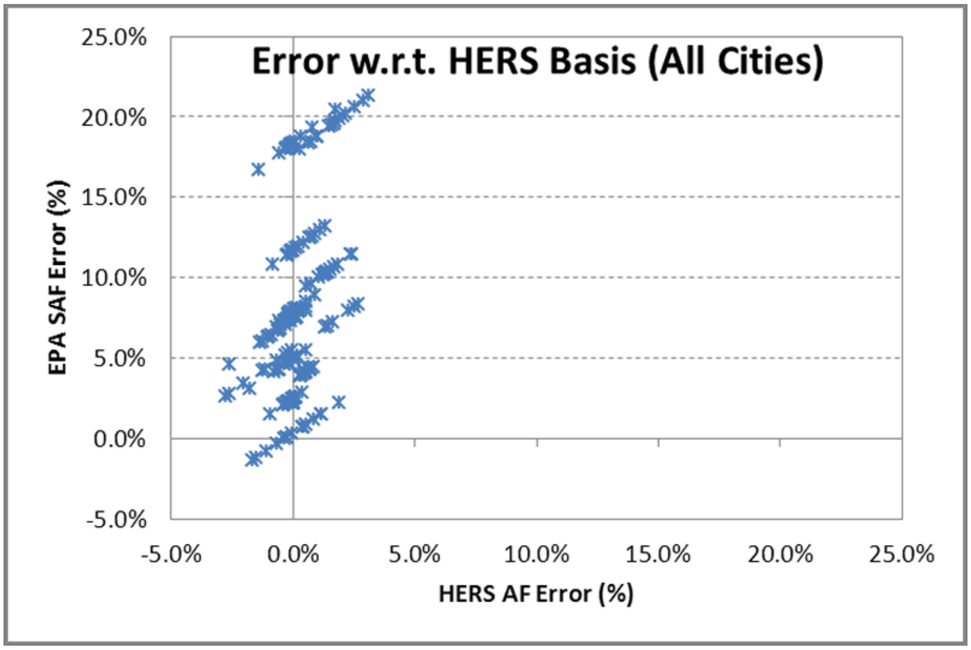

Figure 7: ENERGY STAR 'SAF' error versus HERS 'AF' error

While the error shown for the AF developed by this study shows a potential error for the 15 cities studied of about ± 3% (+2.8% to -3.1%), the error for the ENERGY STAR SAF is +21.3% to -1.4%. Thus, compared to the HERS AF, the SAF yields a significantly greater consequence for larger homes.

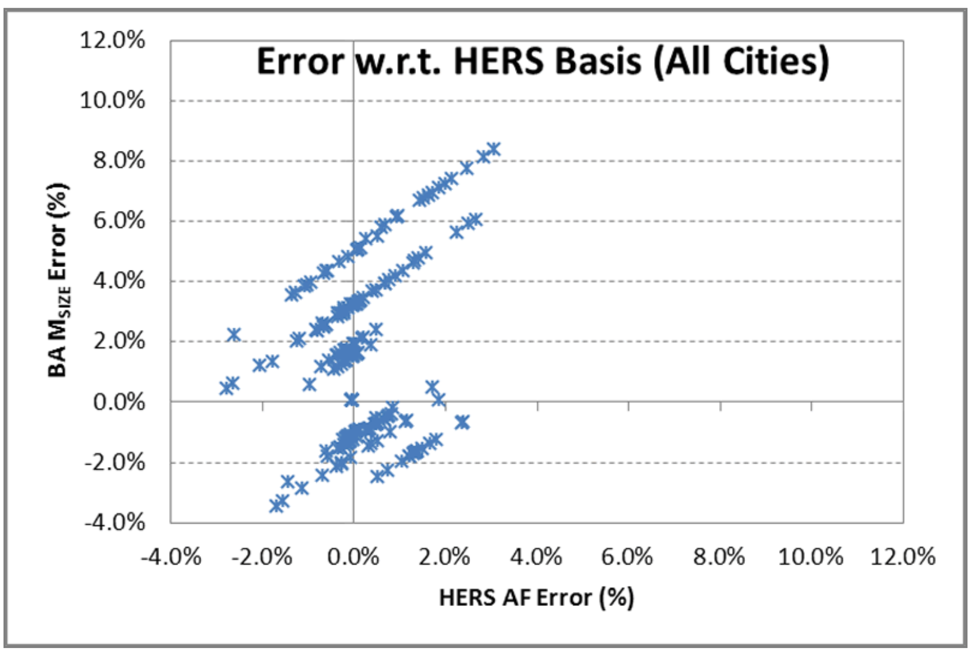

Figure 8: Building America 'M_{SIZE}' error versus HERS 'AF' error

Figure 8 provides similar error data for the BA method compared against the same HERS AF data. Here there is less difference between the BA method and the HERS AF methods, with the

BA method error ranging from -3.5% to +8.3%. However, again there is greater consequence for large homes using the BA method.

Conclusions

Typical comparative performance simulation analysis is subject to geometry and operation dependencies that result in homes with identical thermal envelope and equipment efficiencies producing apparent performance differences. These apparent performance differences exist for valid technical and mathematical reasons, however, their impact is such that larger homes are advantaged and smaller homes are disadvantaged by comparative performance simulation analysis where the baseline home has the same geometric and operation characteristics as the evaluated home.

HERS ratings are one of the comparative performance simulation analysis methods that exhibit these geometry and operation dependencies. As the use of the HERS Index score has grown during the past decade, these geometric and operation dependencies have been recognized by the EPA ENERGY STAR and DOE Challenge Home programs that use the HERS Index score as the qualifying metric for their high-efficiency home programs. Both of these federal high-performance home programs employ adjustments designed to compensate for home size and operating dependencies.

However, these adjustments do not necessarily correspond directly with the dependencies that are inherent within the HERS rating system. This study shows that HERS Index scores for improved homes can vary by more than 15 points (or 18% of the HERS Index score) as a result of geometry and operation dependencies. This study also shows that HERS Index scores can be adjusted for these dependencies such that this range is reduced by a factor of four. The study also shows that the potential error in adjusted performance differences can limited to approximately ±3%, even with large variations in climatic impacts.

Performance adjustments specified for the two federal high-performance home programs show a much larger variance, with the adjustment for conditioned floor area standing out as the largest difference. This difference might be justified from a policy perspective if one of the objectives of federal high-performance home programs is to reduce overall home size. However, based on the findings of this study, these much larger conditioned floor area adjustments cannot be justified based purely on the technical geometry and operating dependencies of the comparative performance analysis method specified for HERS Index scoring.