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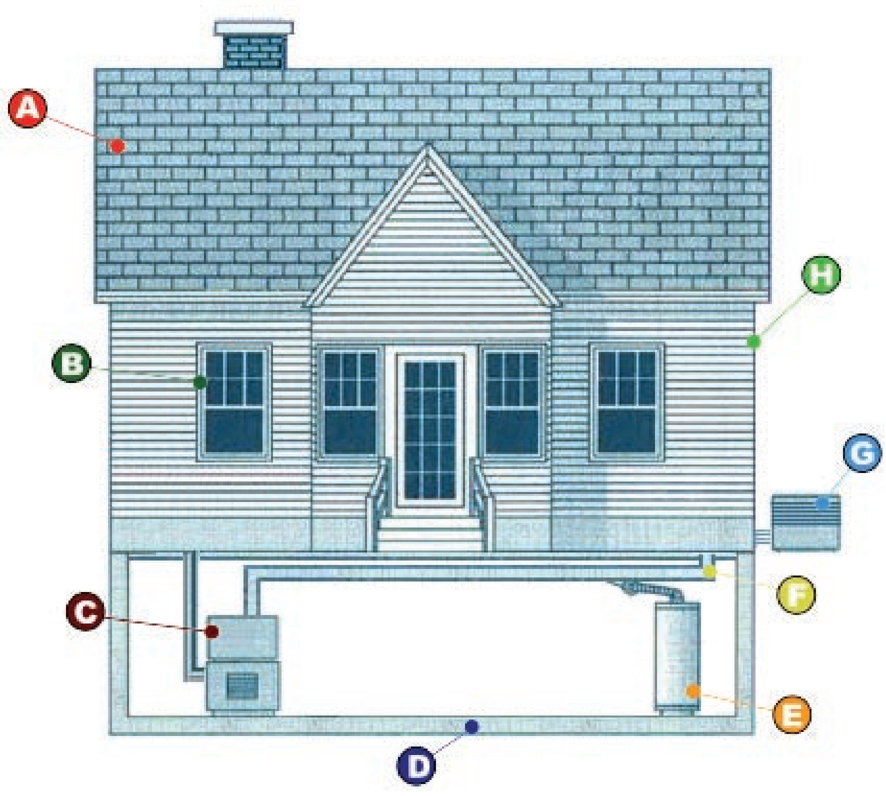
Building America Research Benchmark Definition, Updated December 29, 2004



Robert Hendron
National Renewable Energy Laboratory

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Building Technologies Program

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Building America Research Benchmark Definition

National Renewable Energy Laboratory

Updated December 29, 2004

To track progress toward aggressive multi-year whole-house energy savings goals of 40-70% and onsite power production of up to 30%, the U.S. Department of Energy (DOE) Residential Buildings Program and the National Renewable Energy Laboratory (NREL) developed the Building America Research Benchmark in consultation with the Building America industry teams. The Benchmark is generally consistent with mid-1990s standard practice, as reflected in the Home Energy Rating System (HERS) Technical Guidelines (RESNET 2002), with additional definitions that allow the analyst to evaluate all residential end-uses, an extension of the traditional HERS rating approach that focuses on space conditioning and hot water. A series of user profiles, intended to represent the behavior of a "standard" set of occupants, was created for use in conjunction with the Benchmark.

Benchmark House Specifications

The following sections summarize the definition of the Benchmark, updated for the FY05 Building America subcontracts. A comprehensive description of other important Building America reference houses (Builder Standard Practice and Regional Standard Practice), along with guidance for using hourly simulation tools to compare an energy efficient prototype house to the various base case houses, can be found in the NREL technical report addressing systems-based performance analysis of residential buildings (Hendron et al. 2004). NREL and other Building America partners have also developed a series of tools, including spreadsheets with detailed hourly energy usage and load profiles, to help analysts apply the Benchmark quickly and in a consistent manner. These tools can be found on the Building America web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

Any element of the Benchmark definition that is not specifically addressed in the following sections is assumed to be the same as the Prototype house. Because the definition is intended to be software-neutral, certain elements of the Benchmark cannot be modeled directly using every common simulation tool. The full Building America Performance Analysis Procedures (Hendron et al. 2004) includes application notes addressing some practical implementation issues that may be encountered when simulating the Benchmark using DOE-2.2 or EnergyGauge.

Building Envelope

All building envelope components (including walls, windows, foundation, roof, and floors) for the Benchmark shall be consistent with the HERS Reference Home as defined by NASEO/RESNET in the "National Home Energy Rating Technical Guidelines," dated September 19, 1999 (RESNET 2002). These requirements are summarized below, along with a few minor clarifications and additional requirements. References to U-values in the 1993 Model Energy Code (MEC) have been updated to 2003 International Energy Conservation Code (IECC), because the corresponding U-values are identical and the IECC is more readily available (ICC 2003).

The Benchmark envelope specifications are as follows:

- The same shape and size as the Prototype
- The same area of surfaces bounding conditioned space as the Prototype with the exception of the attic, which shall be insulated at the attic floor and have a ventilation area of 1 ft^2 per 300 ft^2 ceiling area, regardless of the Prototype attic design
- The same foundation type (slab, crawl space, or basement) as the Prototype
- The same basement wall construction type as the Prototype (e.g., masonry, wood frame, other)
- No sunrooms
- No horizontal fenestration, defined as skylights, or light pipes oriented less than 45 degrees from a horizontal plane
- Window area (A_F) determined by Equation 1 for detached homes and by Equation 2 for attached homes:

Equation 1: $$A_F = 0.18 \times A_{FL} \times F_A$$

Equation 2: $$A_F = 0.18 \times A_{FL} \times F_A \times F$$

where

A_F = total window area (ft^2)

A_{FL} = total floor area, including basement (ft^2)

F_A = (exposed thermal boundary wall area)/(total thermal boundary wall area)

F = (total thermal boundary wall area)/(total thermal boundary wall area + common wall area), or 0.56, whichever is greater

and where

total thermal boundary wall is any wall that separates directly or indirectly conditioned space from unconditioned space or ambient conditions, including all insulated basement walls but not including unvented crawl space walls;

exposed thermal boundary wall is any thermal boundary wall not in contact with soil; and

common wall area is the total area of walls adjacent to another conditioned living unit, including basement and directly or indirectly conditioned crawl space walls.

- The window area calculated above is distributed with the same proportion on each wall and on each floor as the Prototype house. The energy use is calculated with the Benchmark house in each of four orientations rotated in 90º increments relative to the Prototype orientation (+0º, +90º, +180º, +270º), and the average of these four cases is used to represent the energy use of the Benchmark.
- Thermal conductance of all thermal boundary elements equal to the requirements, expressed as U values, of Paragraph 502.2 of the 2003 IECC (ICC 2003), as summarized below. Unless otherwise specified, these U-values are for entire assemblies, including sheathing, framing, finishes, and so on.

- U-value (U_w) for the opaque fraction of exterior walls from Table 1 or 2, as appropriate.
- The U-value and solar heat gain coefficient for vertical fenestration, including windows and sliding glass doors, shall be determined using Table 3. The values in Table 3 were calculated based on the HERS methodology for determining maximum window U-value, assuming a floor area to wall area ratio of 1.0. If the simulation tool uses a window library, a window that approximately matches the U_F and SHGC shall be selected, and the frame R-value shall be increased or decreased until the overall window U_F matches the value in Table 3.

Table 1. Opaque Wall U-Values (U_w) for Detached Homes (Excerpted from ICC 2003)

Annual Heating Degree Days Base 65 (HDD65) from Nearest Location Listed in Chapter 9 of ASHRAE Standard 90.2 or NREL's *Solar Radiation Data Manual*[1]	U_w Air to Air, Includes Framing (Btu/hr-ft^2-ºF)
> 13000	0.038
9000-12999	0.046
6500-8999	0.052
4500-6499	0.058
3500-4499	0.064
2600-3499	0.076
<2600	0.085

[1] See *Solar Radiation Data Manual for Buildings* (or the "Blue Book") published by the National Renewable Energy Laboratory (NREL 1995) (http://rredc.nrel.gov/solar/old_data/nsrdb/bluebook/).

Table 2. Opaque Wall U-values (U_w) for Attached homes (Excerpted from ICC 2003)

Heating Degree Days Base 65 (HDD65) from Nearest Location Listed in Chapter 9 of ASHRAE Standard 90.2, or NREL's *Solar Radiation Data Manual*	U_w Air to Air, Includes Framing ($Btu/hr\text{-}ft^2\text{-}^oF$)
>9000	0.064
7100-8999	0.076
3000-7099	0.085
2800-2999	0.100
2600-2799	0.120
<2600	0.140

Table 3. Vertical Fenestration U-values (U_F) and Solar Heat Gain Coefficients (SHGC)

HDD65 from Nearest Location Listed in Chapter 9 of ASHRAE Standard 90.2, or NREL's *Solar Radiation Data Manual*	U_F Air to Air, Includes Framing and Sash ($Btu/hr\text{-}ft^2\text{-}^oF$)	SHGC, Includes Framing and Sash
≥7000	0.36	0.32
6000-6999	0.39	0.32
5000-5999	0.46	0.58
4000-4999	0.53	0.58
3000-3999	0.58	0.58
2000-2999	0.62	0.65
1000-1999	0.79	0.65
≤999	1.00	0.79

- U-value of an insulated floor above a vented crawl space or other unconditioned space shall be as specified in Figure 1 (excerpted from ICC 2003).
- U-value of insulated walls in an unvented crawl space shall be as specified in Figure 2 (excerpted from ICC 2003). This U-value represents the combined effect of wall components and the surface air film, but it does not include adjacent soil.
- U-value of insulated basement walls shall be as specified in Figure 3 (excerpted from ICC 2003), and the insulation shall be located on the interior surface of the walls. This U-value represents the basement wall assembly, including the surface air film, but it does not include ground effects.
- R-value and depth of slab edge insulation for slab-on-grade construction shall be as specified in Figure 4 (excerpted from ICC 2003). This R-value is for rigid foam insulation and does not include the slab itself or ground effects.
- U-value of insulated roof/ceiling shall be as specified in Figure 5 (excerpted from ICC 2003). If the Prototype includes an attic, the Benchmark shall have an unconditioned attic with insulation at the attic floor.

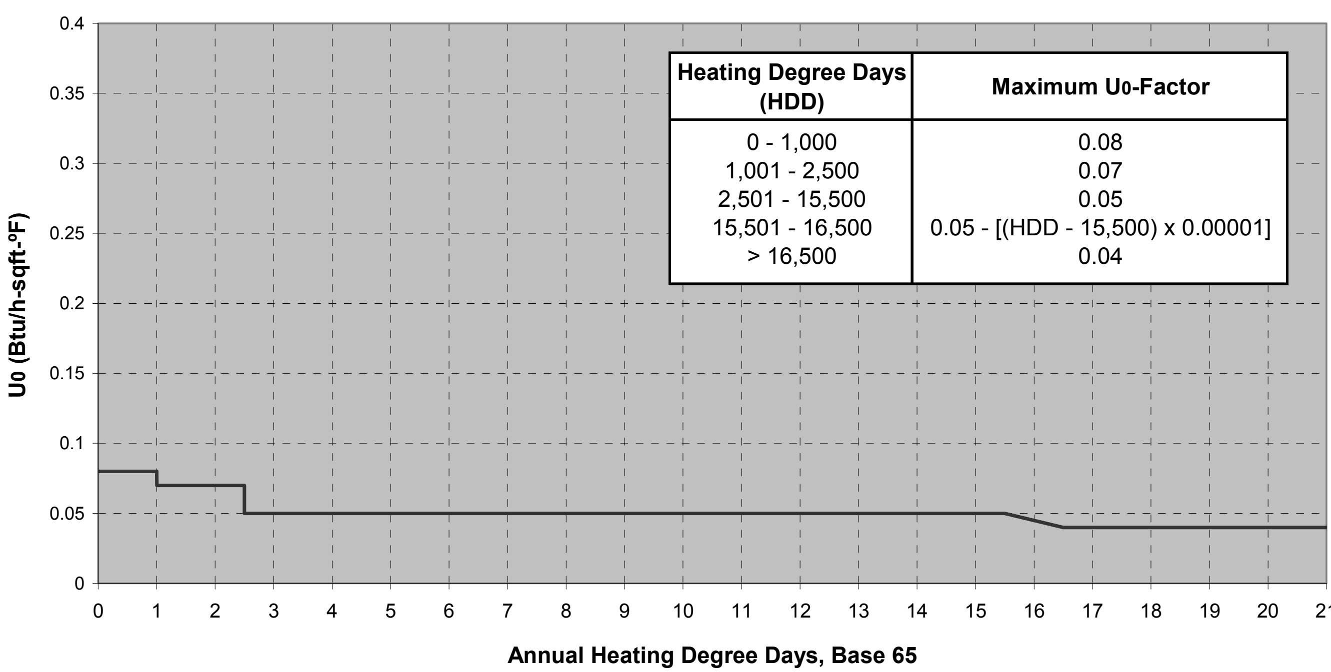
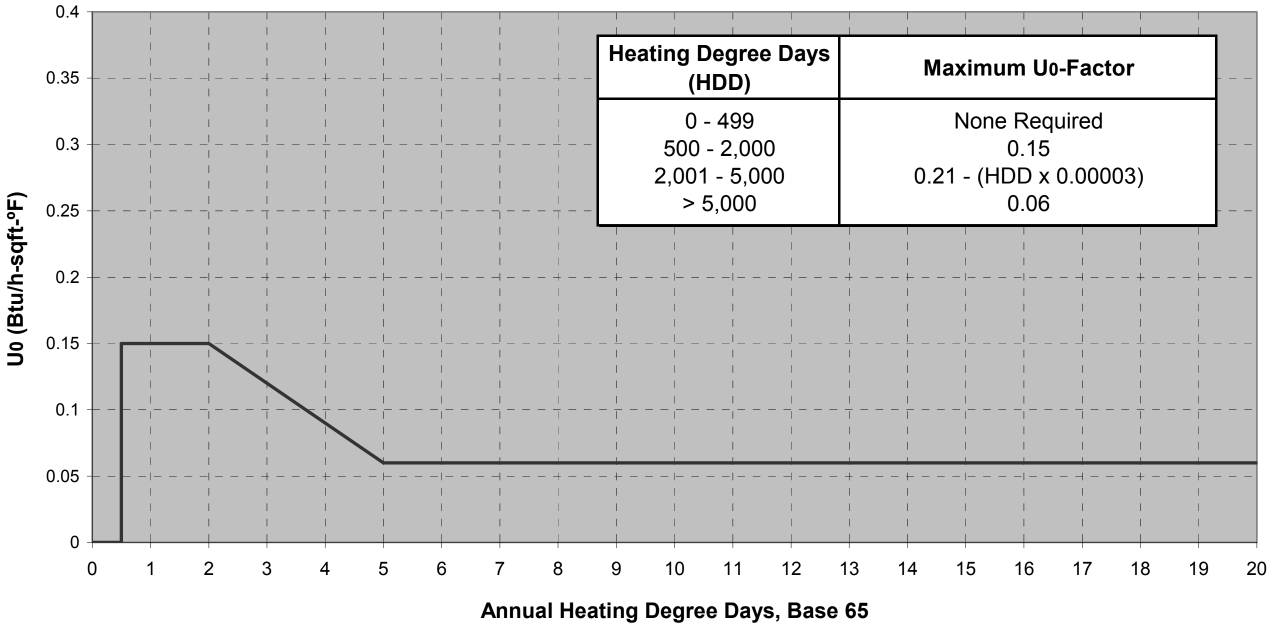
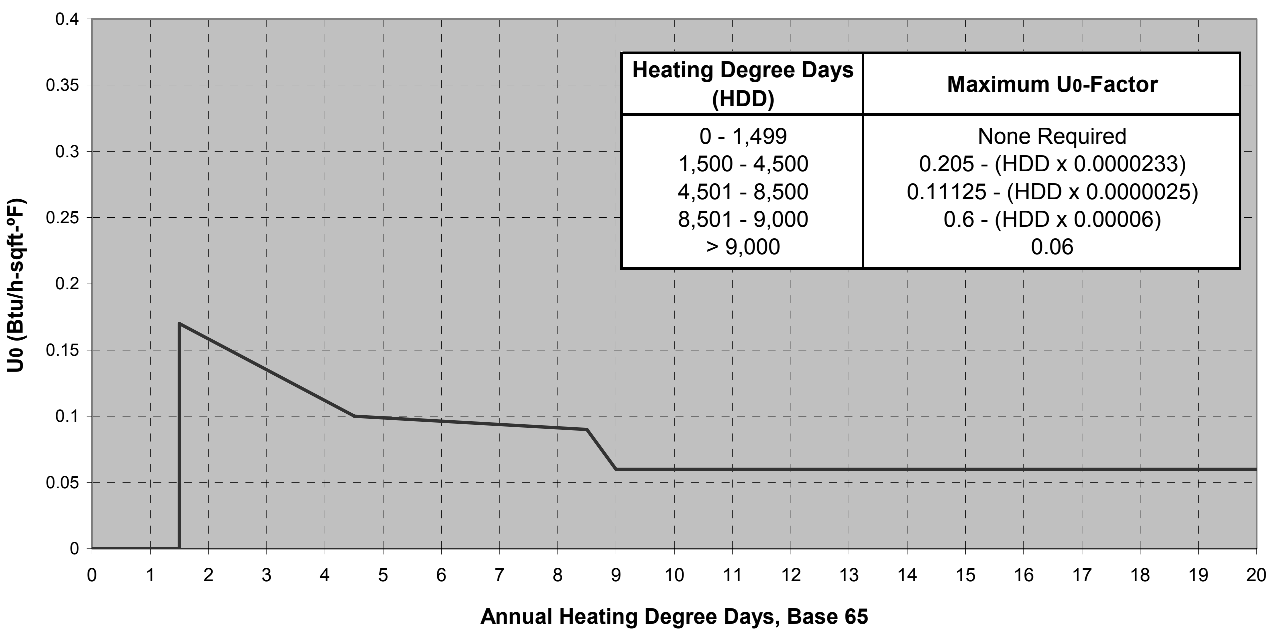


Figure 1. U-value of floor over unconditioned space (excerpted from ICC 2003)



Heating Degree Days (HDD)	Maximum U_0-Factor
0 - 499	None Required
500 - 2,000	0.15
2,001 - 5,000	0.21 - (HDD x 0.00003)
> 5,000	0.06

Figure 2. Unvented crawl space wall U-value (excerpted from ICC 2003)



Heating Degree Days (HDD)	Maximum U_0-Factor
0 - 1,499	None Required
1,500 - 4,500	0.205 - (HDD x 0.0000233)
4,501 - 8,500	0.11125 - (HDD x 0.0000025)
8,501 - 9,000	0.6 - (HDD x 0.00006)
> 9,000	0.06

Figure 3. Basement wall U-value (excerpted from ICC 2003)

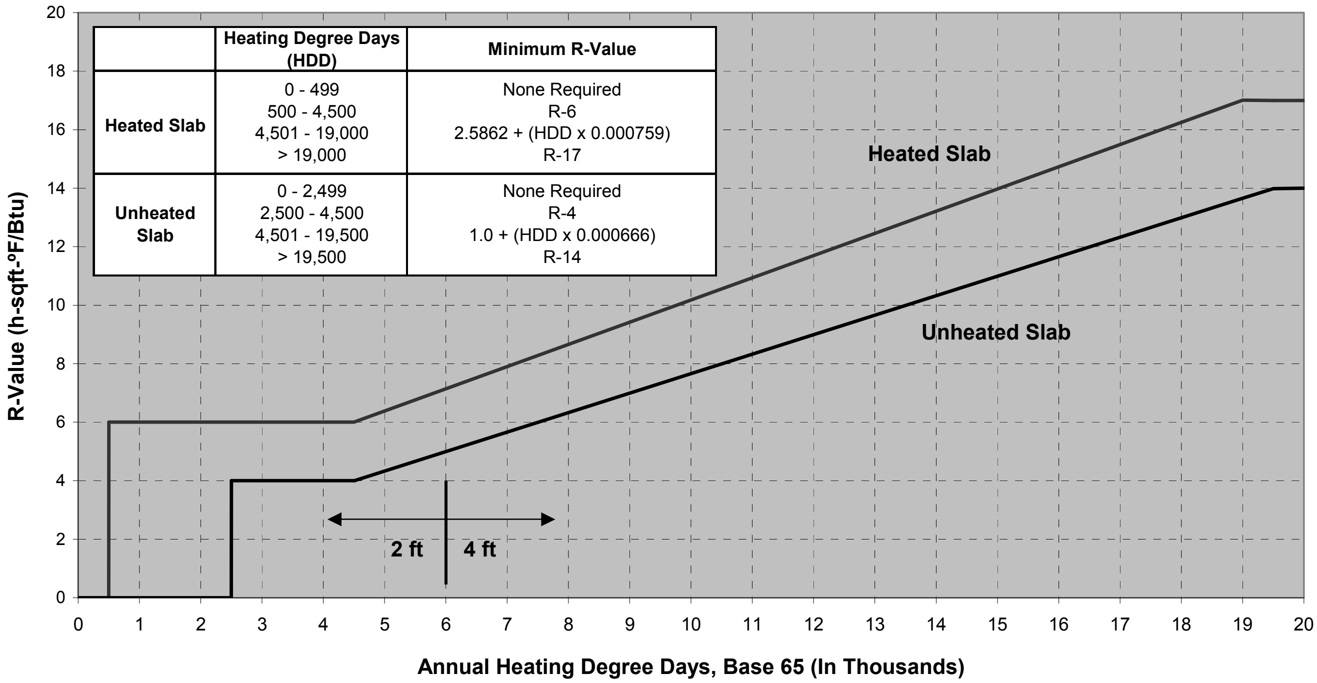


Figure 4. Slab insulation R-value and depth (excerpted from ICC 2003)

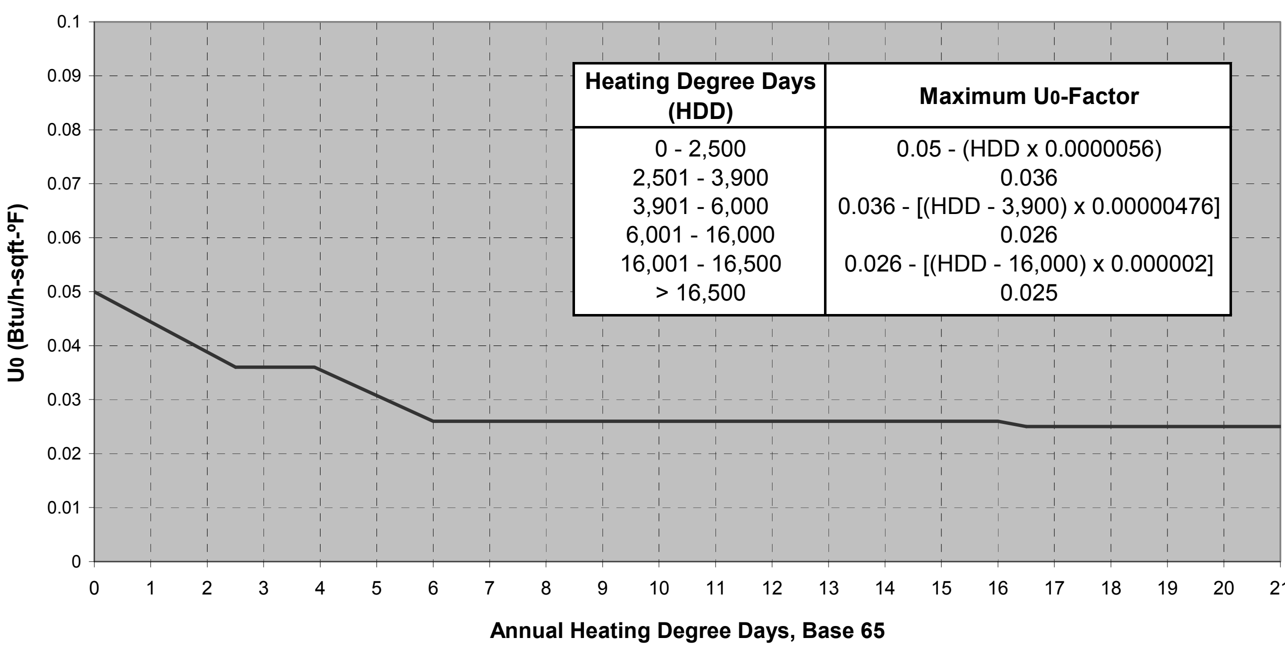


Figure 5. Roof/ceiling assembly U-value (excerpted from ICC 2003)

- No external shading at any time from roof projections, awnings, adjacent buildings, trees, etc. Basic architectural features such as attached garages and enclosed porches shall be included in the Benchmark model, but the model shall not include window shading effects from these features.
- No self-shading shall be modeled for the Benchmark.
- Total area of opaque exterior doors is equal to 40 ft^2, facing north, with door U-value equal to 0.20 Btu/hr·ft^2·°F (air to air).
- Solar absorptivity is equal to 0.50 for opaque areas of exterior walls and 0.75 for opaque areas of roofs.
- Total emittance of exterior walls and roofs is equal to 0.90.
- The above-grade exterior walls shall be light-frame 2x4 or 2x6 wood construction with sufficient insulation to achieve the correct overall U-value. The framing factors in Table 4 are representative of typical construction practices, and shall be used as inputs for the Benchmark model.
- Interior partition walls shall be light-frame (2x4) wood construction.
- Masonry floor slabs shall have 80% of floor area covered by R-2 carpet and pad and 20% of floor area directly exposed to room air.

Table 4. Benchmark Framing Factors

Enclosure Element	Frame Spacing (inches o.c.)	Framing Fraction (% area)
Walls	16	23%
Floors	16	13%
Ceilings Below Unconditioned Space	24	11%

Space Conditioning/Air Distribution Equipment

Space-conditioning equipment type and efficiency for the BA Benchmark shall meet the following requirements:

- The minimum National Appliance Energy Conservation Act (NAECA) efficiency in effect on January 1, 1992, for the same type of heating, ventilating, and air-conditioning (HVAC) equipment found in the Rated Home, except that the efficiencies given in Table 5 are assumed when
  - (a) A type of device not covered by NAECA is used in the Prototype.
  - (b) The Prototype is heated by electricity using a device other than an air-source heat pump.
  - (c) The Prototype does not have a heating system, and there is at least one month in which heating is required (see the section on Operating Conditions).
- If the Prototype does not have a cooling system, both the Benchmark and Prototype shall be modeled assuming a standard 10 SEER air conditioner.
- If the simulation tool requires the use of EER instead of SEER for a heat pump or air conditioner, then the EER for the Benchmark shall be calculated using Equation 3. If the actual EER for the Prototype is not readily available, Equation 3 may also be used to make an approximate conversion from SEER to EER (Wassmer 2003):

Equation 3: $$EER = -0.02 \times SEER^2 + 1.12 \times SEER$$

- Heating and cooling equipment (including the air handler) shall be sized using the procedures published by the Air Conditioning Contractors of America (ACCA). (See www.accaconference.com/Merchant2/merchant.mv?Screen=CTGY&Store_Code=ACCOA&Category_Code=M)
- The Benchmark shall not have a whole-house fan.
- The Benchmark shall have no supplemental dehumidification beyond that provided by a standard air conditioner.
- The Benchmark air handler shall have power consumption equal to 0.00055 kW/cfm.

The air distribution system in the Benchmark shall have the properties listed in Table 6. The location of the ductwork in the Benchmark is based on the type of foundation used for the Prototype. If the simulation tool does not permit the input of duct specifications to this level of detail, then two values (one for heating, one for cooling) of seasonal distribution system efficiency (DSE) shall be estimated and applied to the heating and cooling system efficiencies to represent typical losses from ducts. The DSE values shall be determined using Table 6 and the procedures in the Draft ASHRAE Standard 152P (ASHRAE 2001b). A spreadsheet developed by Lawrence Berkeley National Laboratory (LBNL) and modified by NREL is posted on the Building America Web site to assist with this calculation.

Table 5. Benchmark Space-Conditioning Equipment Efficiencies

Prototype Equipment	Function	Benchmark Space-Conditioning Device
Electric or No System	Heating	6.8 HSPF Air Source Heat Pump
Non-Electric Boiler	Heating	80% AFUE Gas Boiler
Non-Electric Warm Air Furnace or Other Non-Electric Heating	Heating	78% AFUE Gas Furnace
Any Type or No System	Cooling	10 SEER Electric Air Conditioner

Table 6. Duct Locations and Specifications for the Benchmark

	Prototype Foundation Type	Benchmark Duct Specification	
		One-Story	***Two-Story or Higher***
Supply Duct Surface Area (ft^2)	All	0.27 x FFA[a]	0.20 x FFA
Return Duct Surface Area (ft^2)	All	0.05 x $N_{returns}$ x FFA (Maximum of 0.25 x FFA)	0.04 x $N_{returns}$ x FFA (Maximum of 0.19 x FFA)
Supply Duct Insulation (Conditioned Space)	All	R-3.3	
Return Duct Insulation (Conditioned Space)	All	None	
Supply/Return Duct Insulation (Unconditioned Space)	All	R-5.0	
Duct Material	All	Sheet Metal	
Duct Leakage (Inside + Outside)	All	15% of Air Handler Flow (10% Supply, 5% Return) (Percentage lost to each space equal to percentage of duct area in that space, as specified below)	
Air Handler Location	All	Conditioned Space	Conditioned Space
Supply Duct Location	Slab-on-grade or Raised floor	100% Attic[b]	65% Attic[b], 35% Conditioned Space
	Crawl space	100% Crawl space	65% Crawl space, 35% Conditioned Space
	Basement	100% Basement	65% Basement, 35% Conditioned Space
Return Duct Location	Slab-on-grade or Raised floor	100% Attic[b]	100% Attic[b]
	Crawl space	100% Crawl space	100% Crawl space
	Basement	100% Basement	100% Basement

[a] Finished floor area (ft^2)

[b] If the Prototype does not have an attic, then this percentage of duct leakage in the Benchmark is assumed to be in an attached garage. If the Prototype does not have an attached garage, then the leakage is assumed to be in conditioned space.

Domestic Hot Water

The assumptions in Table 7 shall be made for the domestic hot water system in the Benchmark. Both storage and burner capacity are determined using the guidelines recommended by ASHRAE in the *HVAC Applications Handbook* (ASHRAE 1999); these are based on the minimum capacity permitted by the Department of Housing and Urban Development (HUD) and the Federal Housing Administrations (FHA) (HUD 1982). Energy factor is the NAECA minimum for the corresponding fuel type and storage capacity (DOE 2002a). An example set of Domestic Hot Water (DHW) specifications based on a typical three-bedroom, two-bathroom Prototype is shown in Table 8. The "Appliance and DHW" spreadsheet developed by NREL automates many of the equations discussed in the following paragraphs and can be downloaded from the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

NREL has also developed a spreadsheet that calculates the correct DHW inputs for the TRNSYS computer program, including standby heat loss coefficient (UA). The spreadsheet also has a comprehensive set of inputs and outputs that can be used to help calculate DHW properties for the Prototype house (Burch and Erickson 2004). It can be found on the Building America Web site in the section for building scientists (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

Table 7. Characteristics of Benchmark Domestic Hot Water System

	Water Heater Fuel Type in Prototype	
	Electric	*Gas*
Storage Capacity (V) (Gallons)	See *ASHRAE HVAC Applications 1999*	See *ASHRAE HVAC Applications 1999*
Energy Factor (EF)	0.93 – (0.00132 x V)	0.62 – (0.0019 x V)
Recovery Efficiency (RE)	0.98	0.76
Burner Capacity	See *ASHRAE HVAC Applications 1999*	See *ASHRAE HVAC Applications 1999*
Hot Water Set-Point	120°F	
Fuel Type	Same as Prototype[a]	
Tank Location	Same as Prototype	

[a] *If the Prototype does not have a DHW system, or the hot water system uses solar energy or a fuel other than gas or electricity, the Benchmark shall use the same fuel for water heating as that used for space heating.*

Table 8. Example Characteristics of Benchmark Domestic Hot Water System Based on a Prototype with Three Bedrooms and Two Bathrooms

	Water Heater Fuel Type in Prototype	
	Electric	*Gas*
Storage Capacity (V) (Gallons)	50	40
Energy Factor (EF)	0.86	0.54
Recovery Efficiency (RE)	0.98	0.76
Burner Capacity	5.5 kW	36,000 Btu/hr
Supply Temperature	120°F	
Fuel Type	Same as Prototype	
Tank Location	Same as Prototype	

Four major end uses are identified for domestic hot water: showers, sinks, dishwasher, and clothes washer. The average daily water consumption by end use is shown in Table 9. For showers and sinks, the specified volume is the combined hot and cold water. This allows hot water use to fluctuate depending on the cold water (mains) temperature.[2] Hot water usage for the clothes washer and dishwasher were estimated based on several scientific references studied by NREL. For showers and sinks, the water usage is based on the average of three domestic hot water studies (Christensen 2000 et al., Burch and Salasovich 2002, CEC 2002). The relationship between the number of bedrooms and hot water usage was derived from the 1997 Residential Energy Consumption Study (RECS) (DOE 1999). This relationship also applies to machine energy for certain appliances, which will be discussed later in this report.

Hourly hot water use profiles for individual hot water end uses are shown in Figures 6 through 8. For software tools that do not accept this level of detail, the combined hourly hot water profile may be used, as shown in Figure 9.

This combined hourly profile is based on a 1990 study conducted by Becker and Stogsdill (1990), which included hot water data from several earlier studies. The profiles for the clothes washer and dishwasher are based on the electrical end-use measurements in the ELCAP study conducted in the Pacific Northwest by the Bonneville Power Administration in the 1980s (Pratt et al. 1989). It is assumed that the normalized hourly profiles for electricity and hot water are the same for these two appliances. The shower and sink profile was derived by subtracting the hourly clothes washer and dishwasher hot water consumption from the combined hourly hot water usage for a three-bedroom house in Memphis, Tennessee.

[2] The clothes washer in the Prototype may also consume a variable amount of hot water depending on mains temperature if it uses a thermostatic control valve to adjust the proportion of hot and cold water necessary to maintain a certain wash temperature. However, the Benchmark clothes washer does not have this feature.

Table 9. Domestic Hot Water Consumption by End Use

End Use	End-Use Water Temperature	Water Usage
Clothes Washer	N/A	7.5 + 2.5 x N_{br} gal/day (Hot Only)
Dishwasher	N/A	2.5 + 0.833 x N_{br} gal/day (Hot Only)
Shower and Bath	105°F	17.5 + 5.83 x N_{br} gal/day (Hot + Cold)
Sinks	105°F	12.5 + 4.16 x N_{br} gal/day (Hot + Cold)

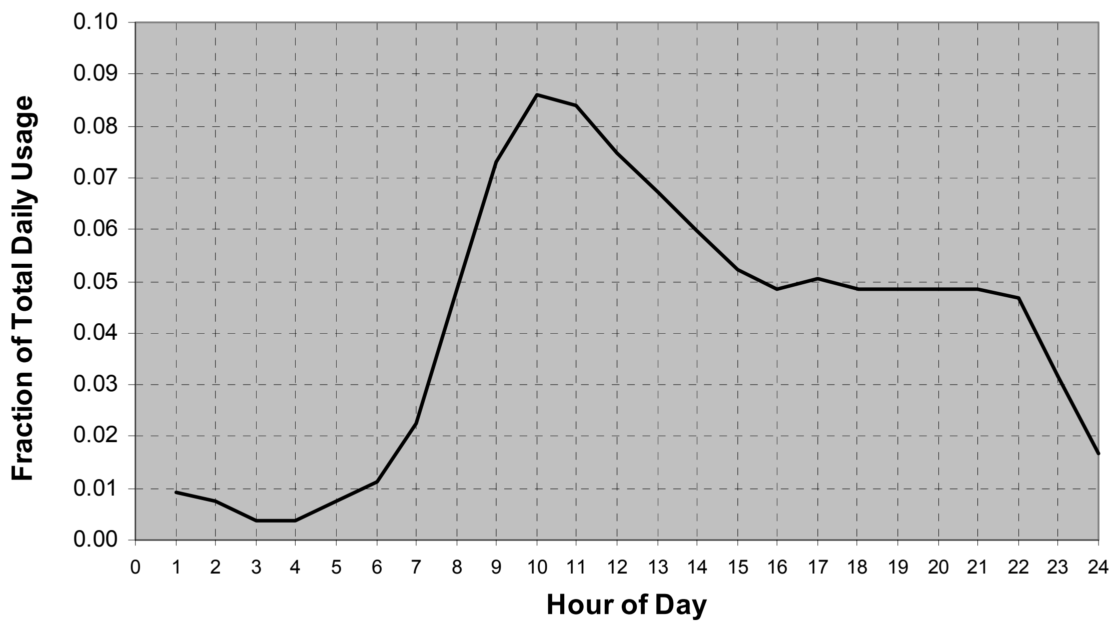


Figure 6. Clothes washer hot water use profile

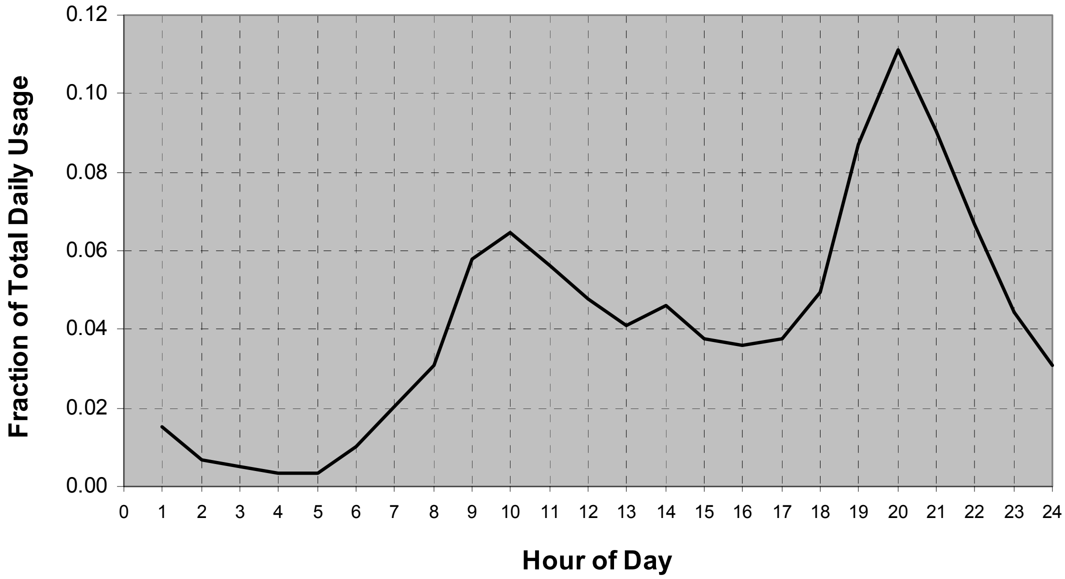


Figure 7. Dishwasher hot water use profile

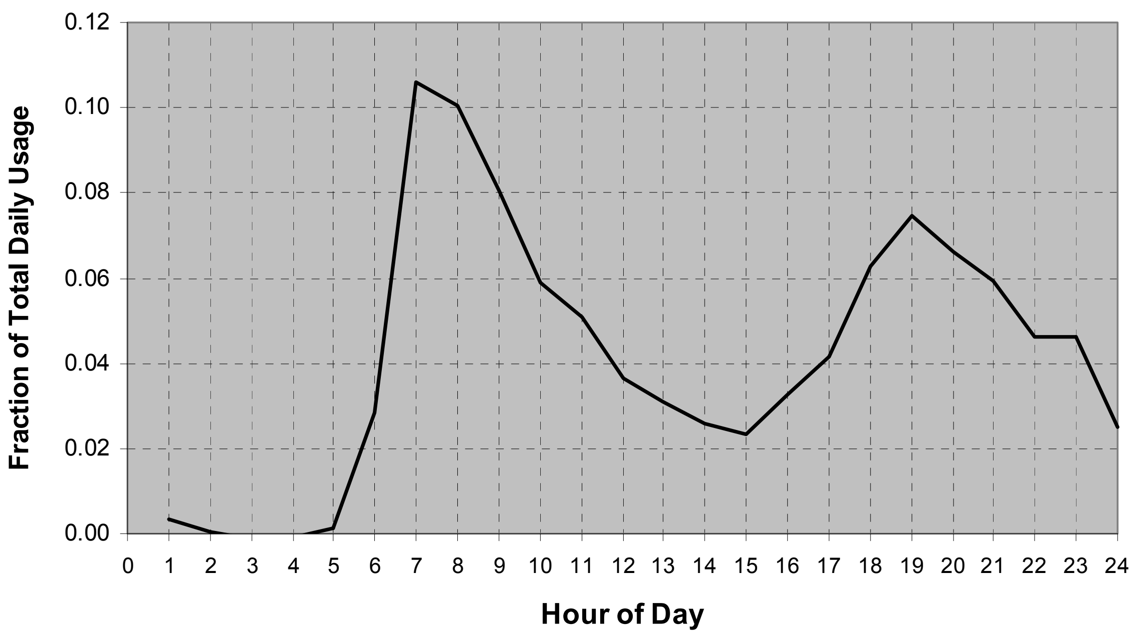


Figure 8. Shower, bath, and sink hot water use profile

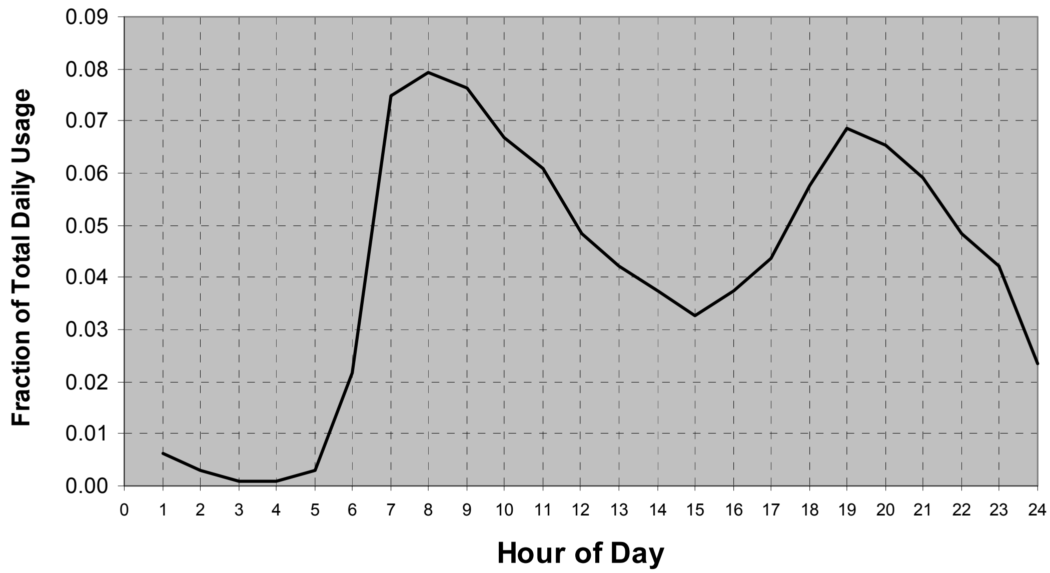


Figure 9. Combined domestic hot water use profile

The mains water temperature for a typical house varies significantly depending on the location and time of year. The following equation, based on TMY2 data for the location of the Prototype, shall be used to determine the daily mains water temperature for both the Benchmark and the Prototype:

Equation 4: $\mathbf{T_{mains} = (T_{amb,avg} + \textit{offset}) + \textit{ratio} * (\Delta T_{amb,max} / 2) * \sin(0.986 * (day\# - 15 - \textit{lag}) - 90)}$

where

T_{mains} = mains (supply) temperature to domestic hot water tank (ºF)

$T_{amb,avg}$ = annual average ambient air temperature (ºF)

$\Delta T_{amb,max}$ = maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,avg,january}$) (ºF)

0.986 = degrees/day (360/365)

day# = Julian day of the year (1-365)

offset = 6°F

ratio = $0.4 + 0.01 (T_{amb,avg} - 44)$

lag = $35 - 1.0 (T_{amb,avg} - 44)$.

This equation is based on analysis by Christensen and Burch of NREL using data for multiple locations, as compiled by Abrams and Shedd (1996), Florida Solar Energy Center (Parker 2002), and Sandia National Laboratories (Kolb 2003). The *offset, ratio,* and *lag* factors were determined by fitting the available data. The climate-specific *ratio* and *lag* factors are consistent with water pipes being buried deeper in colder climates.

In order for the constant terms in the *ratio* and *lag* factors to be representative of an average climate, the data fitting was done relative to a nominal $T_{amb,avg}$ = 44ºF. The *lag* is relative to ambient air temperature, and $T_{amb,minimum}$ is assumed to occur in mid-January (day# = 15). The choices for these nominal values are not critical, because although different assumptions would change the constant terms in the *ratio* and *lag* factors, the coefficients would also change, so the prediction of T_{mains} values would be unchanged. For models that use average monthly mains temperature, day# in Equation 4 shall be calculated using Equation 5.

Equation 5: day# = 30 * month# - 15

where month# = month of the year (1–12).

An example using Equations 4 and 5 to determine the monthly mains temperature profile for Chicago, Illinois, is shown in Figure 10.

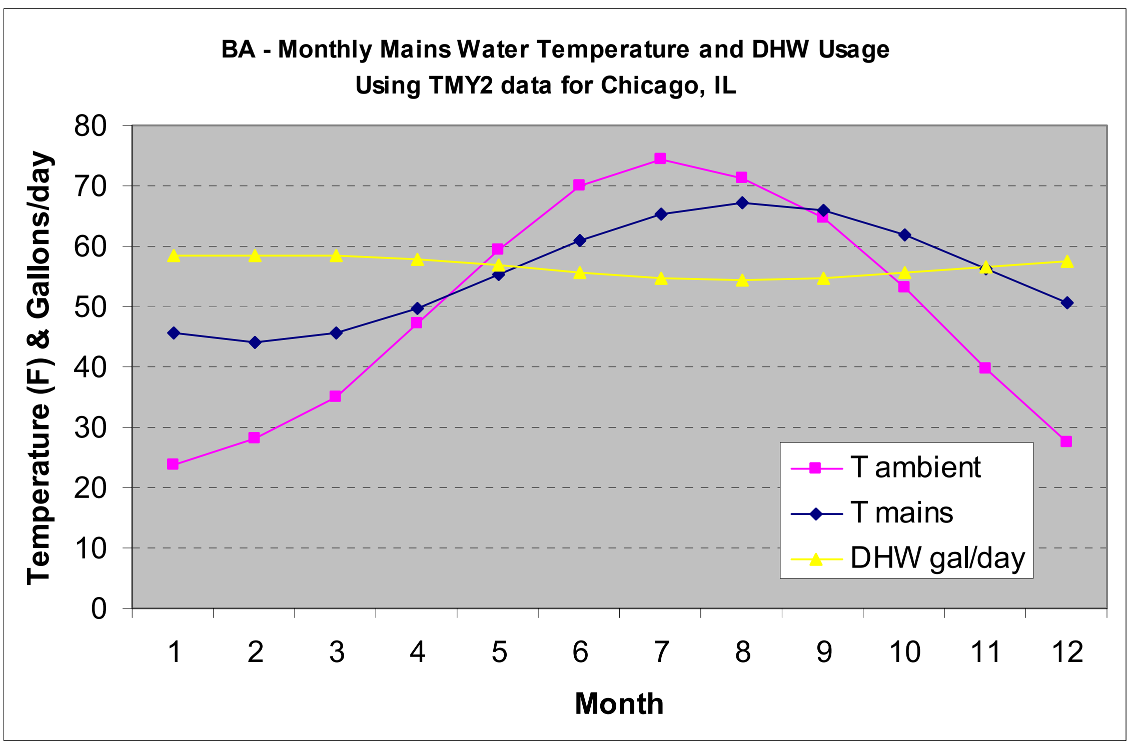


Figure 10. Mains temperature profile for Chicago

Air Infiltration and Ventilation

The hourly natural air change rate for the Benchmark shall be calculated based on the Specific Leakage Area (SLA) determined using Equation 6:

Equation 6: $\mathbf{SLA = ELA/CFA = 0.00057}$

where ELA = effective leakage area (ft^2), defined as the amount of open area that would result in the same total air exchange as the actual leakage area of the house at a pressure of 4 Pa

CFA = conditioned floor area (ft^2).

When specifying natural infiltration for a Benchmark with either a directly or indirectly conditioned basement, the SLA shall be adjusted to account for the in-ground portions of the walls of the conditioned basement. Equation 7 shall be used to make this adjustment:

Equation 7: $\mathbf{SLA_{overall} = [(CFA_{bsmt} * SLA_{bsmt}) + (CFA_{a\text{-}g} * SLA_{a\text{-}g})] / [CFA_{total}]}$

where

SLA = ELA (ft^2) / CFA (ft^2)

$SLA_{a\text{-}g}$ = SLA_{std} (where subscript "a-g" indicates above-grade or exposed)

SLA_{bsmt} = SLA_{std}*(above-grade basement wall area)/(total basement wall area)

SLA_{std} = 0.00057.

This can be calculated by zone, applying SLA_{bsmt} to the basement zone and SLA_{std} to the above-grade zone of the Benchmark and treating the energy balances separately for each zone. It can also be done by applying $SLA_{overall}$ to the combined spaces if the Benchmark is modeled as a single zone.

Additional air exchange as a result of mechanical ventilation shall be calculated using Equation 8, based on a simple continuous exhaust fan designed in accordance with ASHRAE Standard 62.2, and added to the natural infiltration assuming negligible interactive effects. The fan energy use for the Benchmark shall be calculated using Equation 9.

Equation 8: **Ventilation air exchange (cfm) = 0.01 x FFA + 7.5 x ($\mathbf{N_{br}}$ +1)**

where FFA = finished floor area (ft^2)

N_{br} = number of bedrooms.

Equation 9: **Ventilation fan energy (kWh/yr) = 0.03942 x FFA + 29.565 x ($\mathbf{N_{br}}$ +1) ,**

Note that finished floor area is used in these equations instead of conditioned floor area. We believe that finished floor area more accurately represents the area that occupants use in their daily activities (see also the treatment of lighting and plug loads).

It is assumed that cross-ventilation is available to provide natural ventilation in the Benchmark under favorable weather conditions.

Lighting Equipment and Usage

The total annual hard-wired lighting use for the Benchmark is determined using Equations 10 through 12. These equations are derived from data for both single-family and multi-family housing documented in a lighting study conducted by Navigant for DOE (Navigant 2002).

Equation 10: Interior lighting = 0.8*(FFA * 0.8 + 455) kWh/yr.

Equation 11: Garage lighting = 100 kWh/yr.

Equation 12: Exterior lighting = 250 kWh/yr.

Annual hard-wired indoor lighting, in kilowatt-hours, represents approximately 80% of all indoor lighting and is expressed as a linear function of finished house area relative to a constant base value. Garage and exterior lighting are treated as constants. When combined with plug-in lighting (discussed in the next section), the total interior lighting calculated using this equation is in the middle range of residential lighting energy use found in other lighting references, as shown in Figure 11, including Huang and Gu (2002), the 1993 Residential Energy Consumption Survey (RECS) (DOE 1996), a Florida Solar Energy Center study (Parker et al. 2000), default lighting for Visual DOE software (Eley 2002), a lighting study conducted by Navigant for DOE (Navigant 2002), and two other studies in Grays Harbor, Washington (Manclark and Nelson 1992), and Southern California (SCE 1993).

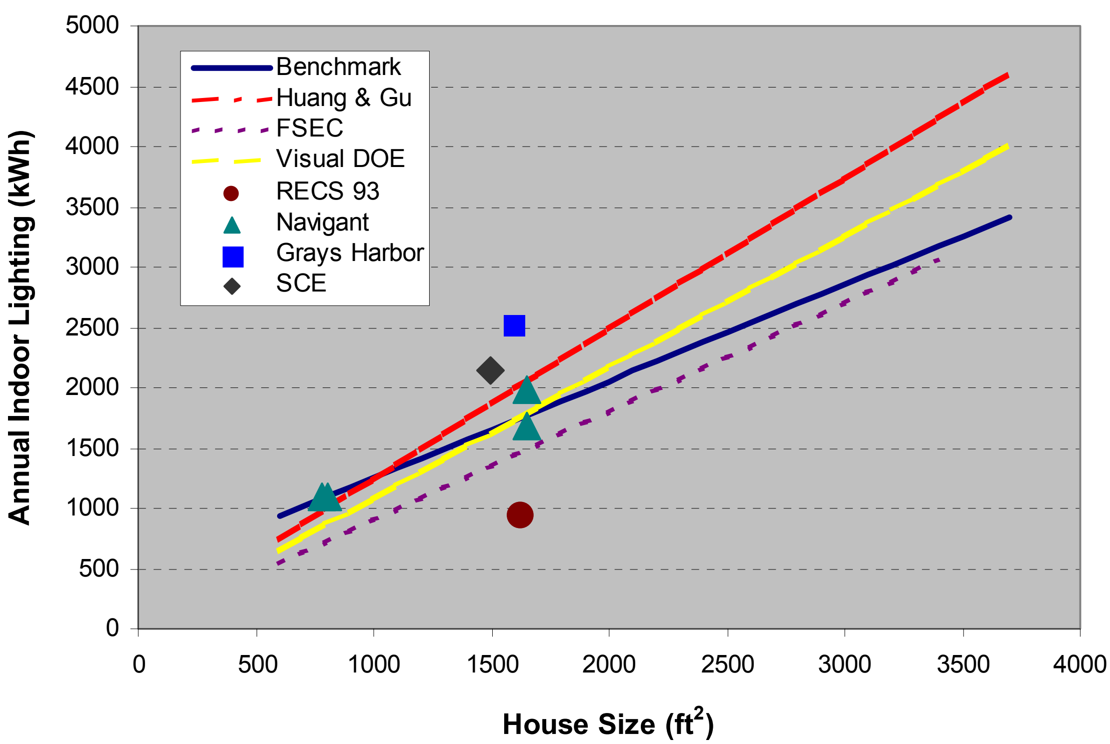


Figure 11. Comparison of Benchmark lighting equation to other references

The Benchmark lighting budget is based on an assumption that 86% of the interior lighting comes from fixtures that contain incandescent lamps, and the remaining 14% is assumed to come from fixtures containing fluorescent lamps. This is consistent with the source data set from 161 homes monitored by Tacoma Public Utilities (TPU) for the Bonneville Power Administration, which was the basis for the Navigant study. Although the core data set used in this study is the most complete and comprehensive residential lighting data set that we have identified, it is nevertheless limited in terms of geographic location, number of homes, length of study, percent of fixtures monitored, and type of homes studied. The Navigant report includes an appendix providing information about the characteristics of the homes monitored in the TPU study.

If a comprehensive lighting plan has not been developed for the Prototype house, and only fluorescent and incandescent lamps are installed, then a simplified approach may be used to estimate energy savings compared to the Benchmark using Equation 13. This equation is based on an assumption that the efficacies of incandescent and fluorescent light fixtures are the same in the Prototype as they were in the TPU study and that fluorescent lighting is distributed equally among hard-wired fixtures in all rooms.

Equation 13: **Prototype hard-wired indoor lighting (kWh/yr) =** $\mathbf{L_B*(1.12*F_I + 0.279*F_F)}$

where L_B = indoor lighting for the Benchmark from Equation 10 (kWh/yr)

F_I = fraction of hard-wired lamps that are incandescent

F_F = fraction of hard-wired lamps that are fluorescent.

The annual average normalized daily load shape for interior lighting use is shown in Figure 12, based on a draft LBNL report by Huang and Gu (2002). This load shape is also used for exterior and garage lighting. Monthly variations in load shape and lighting energy use as a result of changes in the length of days can be accounted for, as long as the variation is applied to all the simulation models and total annual energy use remains the same.

Energy savings may be calculated on the basis of a number of usage variations, depending on the capability of the modeling tool. Variations include day types (weekday vs. weekend), occupancy types (day-use vs. non-day-use or "nuclear" vs. "yuppie"), season (summer vs. winter), and room types (living area vs. bedroom area).

Individual normalized profiles can be "rolled up" to various levels of detail appropriate to the simulation model. An example of one detailed set of profiles developed by NREL is shown in Figure 13. Other profiles are included in spreadsheets available on the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

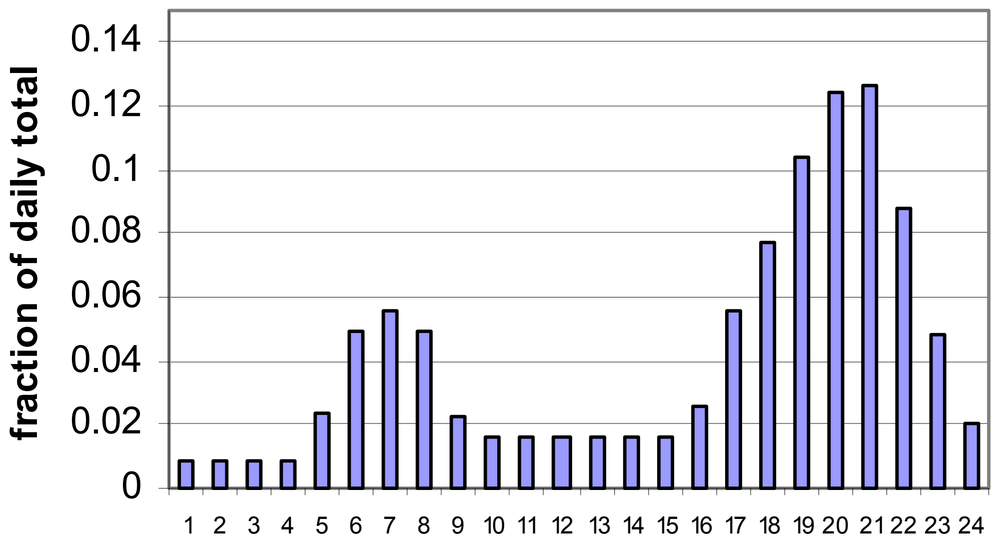


Figure 12. Interior lighting profile (built up from detailed profiles)

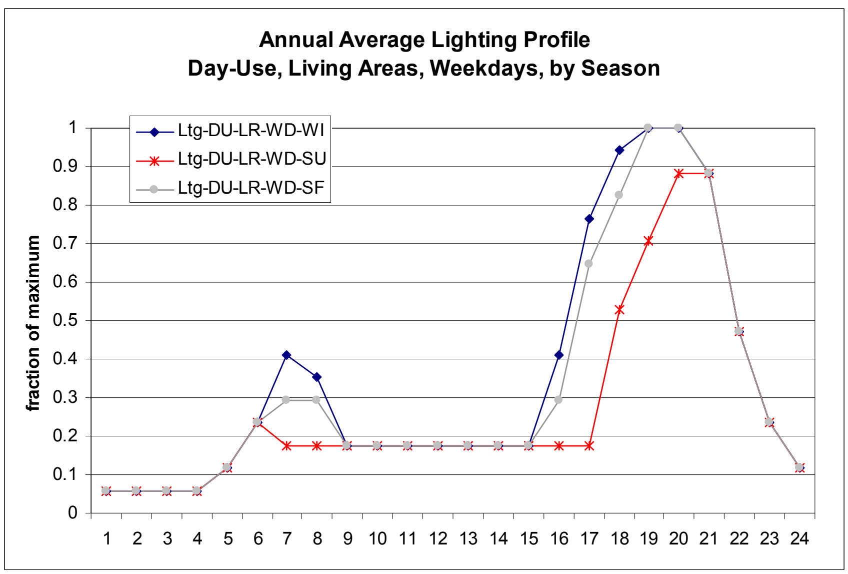


Figure 13. Example of a detailed lighting profile (expressed as fraction of peak daily lighting energy)

The lighting plans for the Prototype and Benchmark should be based on the same hours of operation unless the Prototype includes specific design measures that alter the operating time of the lighting system, such as occupancy sensors, dimming switches, or a building automation system. Average operating hours estimated in the Navigant study are generally a good starting point (Table 10), but there may be substantial differences between typical lighting designs found in the TPU sample and the lighting design developed in conjunction with the architecture of the Prototype. The analyst must ultimately apply good engineering judgment when specifying operating hours for the lighting system.

Table 10. Average Lighting Operating Hours for Common Room Types in a Sample of 161 Homes in the Pacific Northwest (Source: Navigant 2002)

Room Type	Operation (Hours/day/room)	Room Type	Operation (Hours/day/room)
Bathroom	1.8	Kitchen	3.0
Bedroom	1.1	Living Room	2.5
Closet	1.1	Office	1.7
Dining Room	2.5	Outdoor	2.1
Family Room	1.8	Utility Room	2.0
Garage	1.5	Other	0.8
Hall	1.5		

Appliances and Other Plug Loads

As with lighting, several characteristics must be defined for appliances and other plug loads: the amount of the load, the schedule of the load, the location of the load, the fraction of the load that becomes a sensible load, and the fraction of the load that becomes a latent load. Though the internal load may be treated as an aggregate, the energy consumption for each end use must be considered separately. A breakdown of annual energy consumption and associated internal loads for major appliances and other equipment is shown in Table 11. Not all of the energy consumed by appliances is converted into internal load; much of the waste heat is exhausted to the outside or released down the drain in the form of hot water. The appliance loads were derived by NREL from EnergyGuide labels, a Navigant analysis of typical models available on the market that meet current NAECA appliance standards, and several other studies. The daily loads rolled up at the whole-house level for a typical 1800-ft^2, three-bedroom house in Chicago are shown in Table 12.

For a house of typical size (1000-3000 ft^2), the loads from the occupants and most appliances are assumed to be a function of the number of bedrooms. The exceptions are the refrigerator and cooking loads, which are assumed to be constant regardless of the number of bedrooms. The "Other Appliance & Plug Loads" end use is assumed to be primarily a function of finished floor area. A multiplier is applied if the prototype is located in one of the four most populated states as determined in the EIA Residential Energy Consumption Survey (RECS) (DOE 2001). Multipliers for these four states were estimated based on the final electric end-use regression equations developed for the 2001 RECS, substituting national average values for known housing characteristics and physical traits of the occupants (such as number of bedrooms, number of ceiling fans, and age of homeowner) and removing end-uses that are disaggregated in the Benchmark (such as lighting and clothes dryer). The resulting multipliers are listed in Table 13. The multiplier is 1.0 for all states not listed because insufficient information is available about the magnitude of plug loads in those states.

The plug load equation brings the total internal sensible load (including heat gain from occupants) approximately in line with the equation used to calculate internal loads in the IECC (ICC 2003) and with the total energy consumption for single-family homes in the 2001 RECS. However, the internal load from appliances and lighting in the IECC equation is not a function of the number of bedrooms. Therefore, it is impossible to fully reconcile the Benchmark internal heat gain with that of the IECC for all combinations of floor area and number of bedrooms. However, the internal loads for the Benchmark and IECC are consistent for a typical 1800-ft^2, three-bedroom house. The constant internal sensible load value of 72,000 Btu/day specified in the HERS guidelines (RESNET 2002) is even less flexible than the equation in the IECC. Still, the HERS internal load is approximately the same as the sensible load calculated based on Table 11 (73,052 Btu/day) for a typical 1800-ft^2, three-bedroom house. Table 11 also results in a total latent load equal to approximately 20% of the total sensible load for a house of typical size, which is consistent with the HERS Guidelines. The IECC does not address latent load.

Table 11. Annual Appliance and Equipment Loads for the Benchmark[3]

Appliance	Electricity (kWh/yr)	Natural Gas (therms/yr)	Sensible Load Fraction	Latent Load Fraction
Refrigerator	669		1.00	0.00
Clothes Washer (3 ft^3 drum)	52.5 + 17.5 x N_{br}		0.80	0.00
Clothes Dryer (Electric)	418 + 139 x N_{br}		0.15	0.05
Clothes Dryer (Gas)	38 + 12.7 x N_{br}	26.5 + 8.8 x N_{br}	1.00 (Electric) 0.10 (Gas)	0.00 (Electic) 0.05 (Gas)
Dishwasher (8 place settings)	103 + 34.3 x N_{br}		0.60	0.15
Range (Electric)	604		0.40	0.30
Range (Gas)		45	0.30	0.20
Plug-In Lighting	0.2*(FFA * 0.8 + 455)]		1.00	0.00
Other Appliance & Plug Loads	1.67 x FFA x F_S		0.90	0.10

[3] End-use loads in this table include only energy used within the machine. Associated domestic hot water use is treated separately (see "Domestic Hot Water"). The Appliance spreadsheet on the Building America Web site (www.eere.energy.gov/buildings/building_america/benchmark_def.html) can assist with the calculation of this split for an energy-efficient clothes washer or dishwasher based on the EnergyGuide label.

Table 12. Total Rolled-Up Appliance and Equipment Loads for the Benchmark (1800-ft^2, Three-bedroom Prototype, Chicago)

House Type	Electric kWh/yr	*Sensible Fraction*	*Latent Fraction*	Gas therms/yr	*Sensible Fraction*	*Latent Fraction*
All Electric	5804	0.75	0.10			
Electric with gas dryer	5045	0.78	0.10	53	0.10	0.05
Electric with gas cooking	5200	0.72	0.07	45	0.30	0.20
Gas dryer/cooking	4441	0.92	0.07	98	0.19	0.12

Table 13. Plug Load Multipliers for Four Most Populated States (F_S).

State	Multiplier (F_S)
New York	0.82
California	0.77
Florida	0.94
Texas	1.11
All other States and territories	1.00

The hourly, normalized load shape for combined residential equipment use is shown in Figure 14 and is based on the ELCAP study of household electricity use in the Pacific Northwest (Pratt et al. 1989). In most situations this profile is adequate for simulating all electric and gas end-uses except space conditioning and hot water. However, because some individual end-use profiles are nearly constant (such as refrigerator and transformer loads) and some are highly dependent on time of day (such as the range and dishwasher), we have also developed a series of normalized hourly profiles for major appliances and plug loads, shown in Figures 15 through 20. Numerical values associated with these profiles can be found in the "Appliances and Domestic Hot Water" spreadsheet posted on the Building America web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html). The hourly profiles for machine energy usage in the clothes washer and dishwasher are identical to those provided earlier in the section on DHW (see Figures 6 and 7). The profile for plug-in lighting is the same as the profile for hard-wired lighting presented in Figure 12.

All hourly end-use profiles were taken from the ELCAP study, except the profile for "Other Appliance and Plug Loads," which was derived by subtracting the energy consumption profiles for the major appliances from the combined profile for all equipment, assuming an all-electric, 1800-ft^2, three-bedroom house in Memphis, Tennessee. Internal sensible and latent loads from appliances and plug loads shall be modeled using the same profile used for end-use consumption. Appliance loads may be modeled in either the living spaces or bedroom spaces, depending on their location in the Prototype.

Large end uses in the Prototype that are not part of typical houses (such as swimming pools, Jacuzzis, and workshops) are not included in the models for either the Prototype or the Benchmark. The efficiency of these end uses should be addressed in a separate analysis.

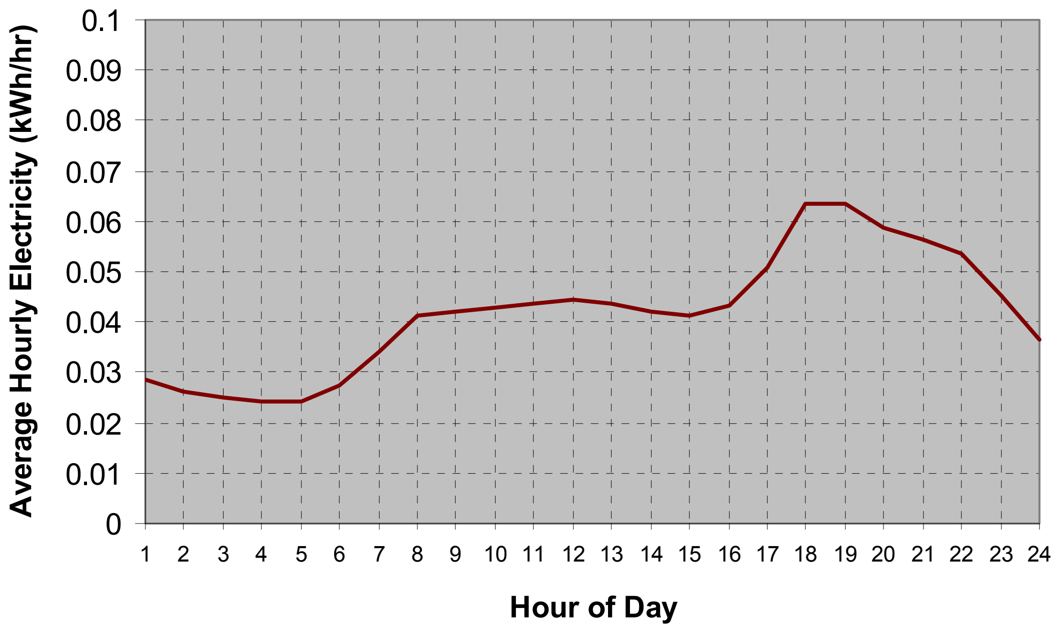


Figure 14. Total combined residential equipment profile (Pratt 1989)

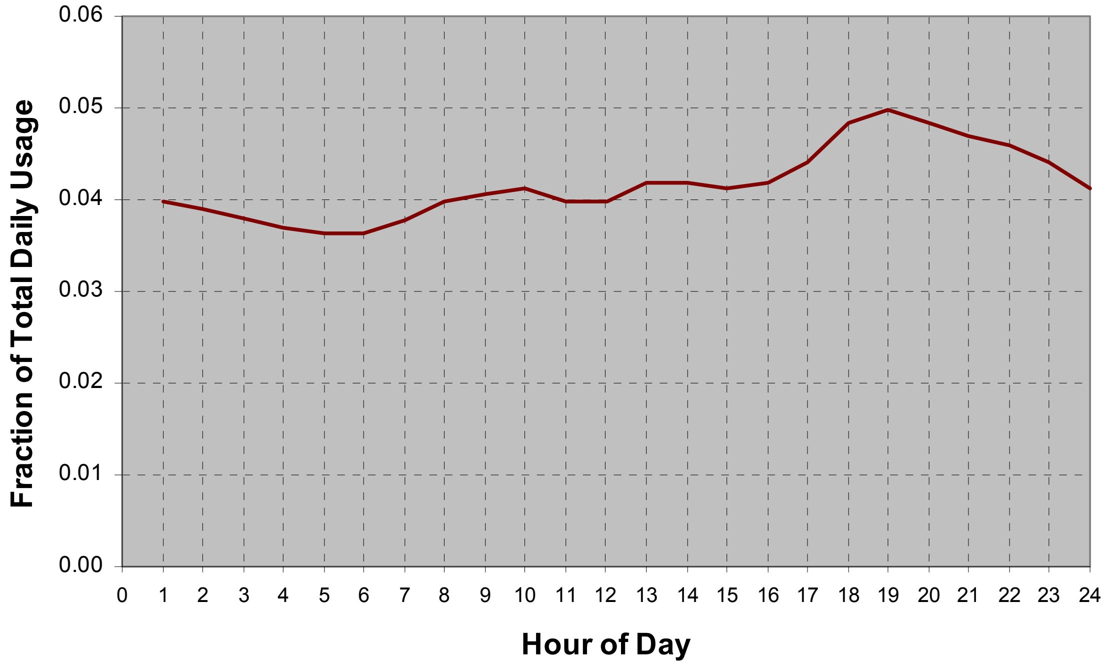


Figure 15. Refrigerator normalized energy use profile (Pratt 1989)

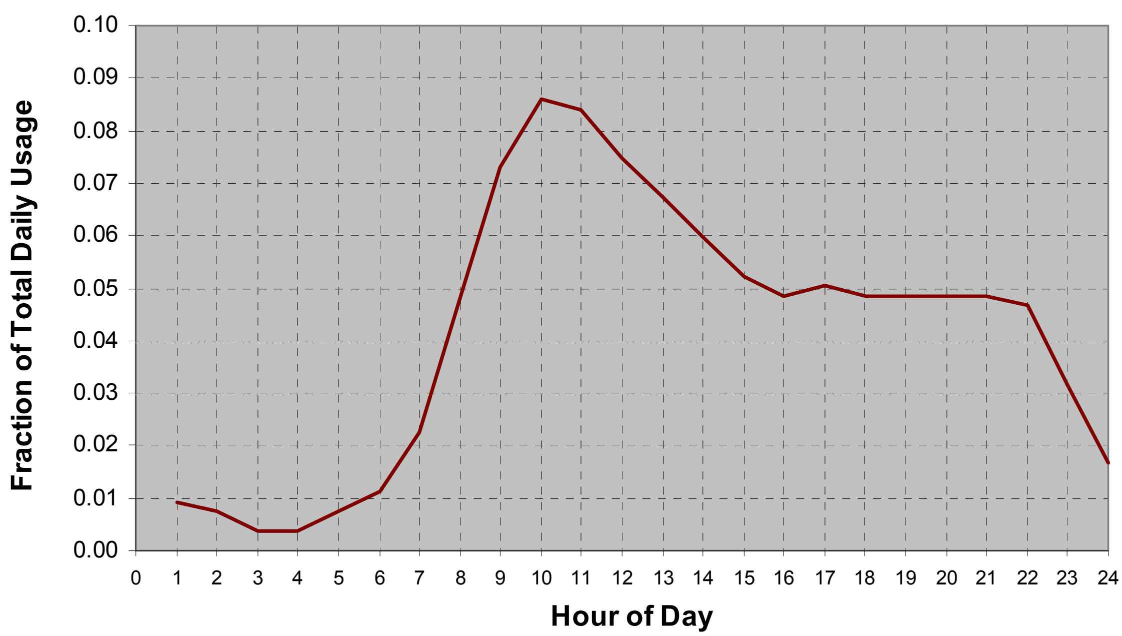


Figure 16. Clothes washer normalized machine energy use profile (Pratt 1989)

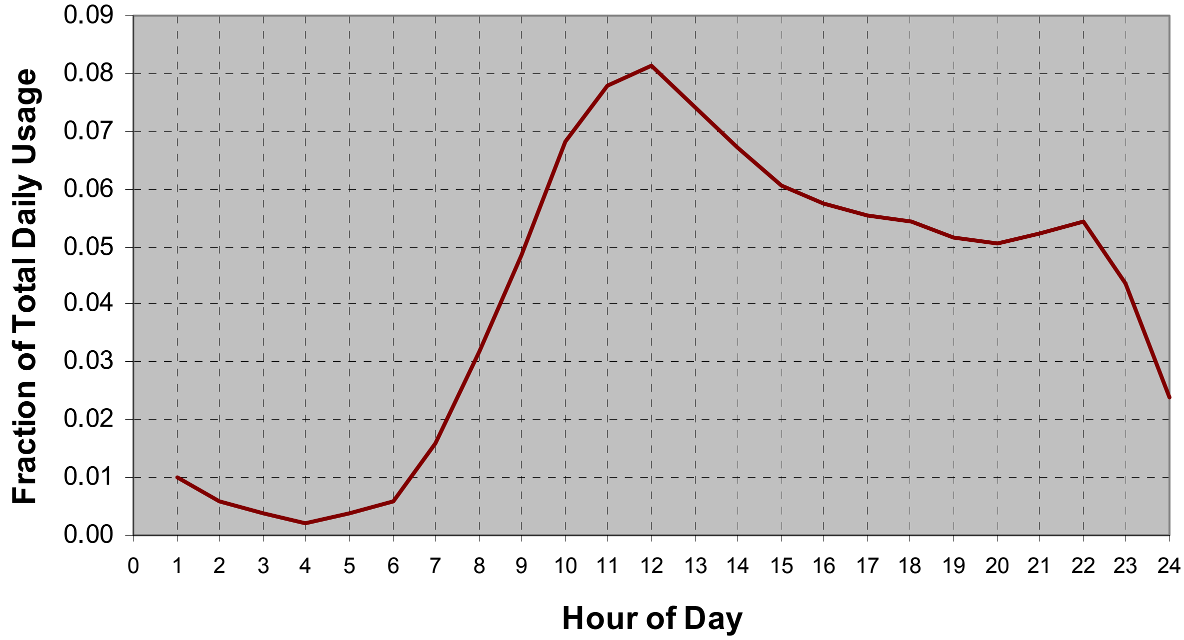


Figure 17. Clothes dryer normalized energy use profile (Pratt 1989)

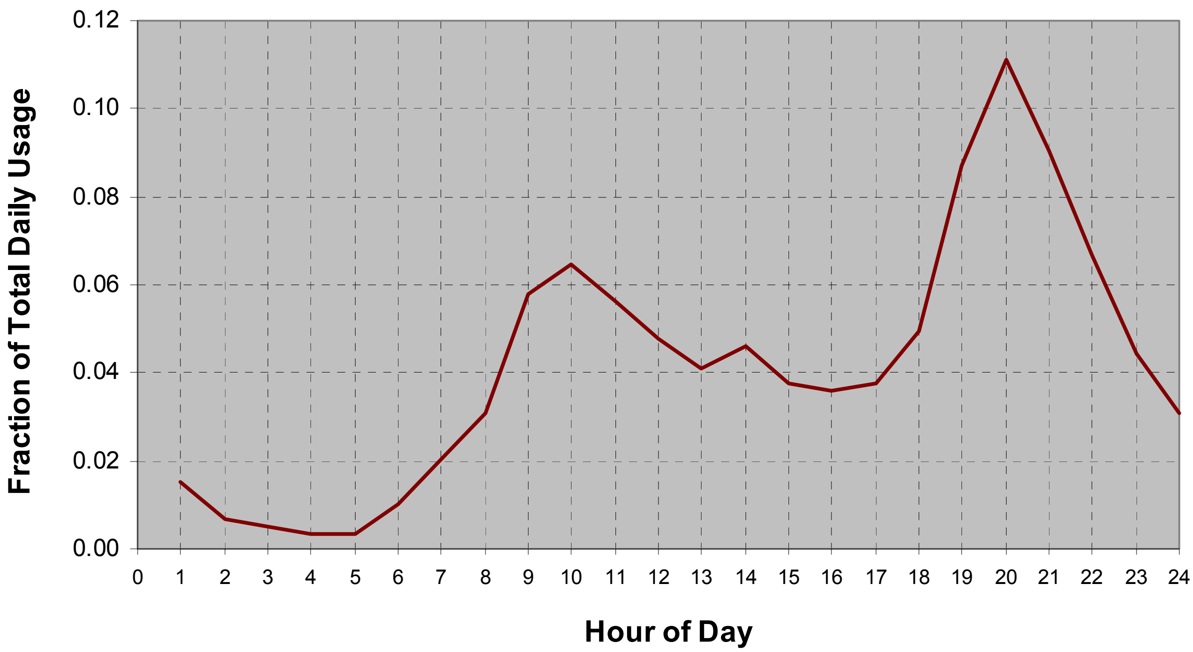


Figure 18. Dishwasher normalized energy use profile (Pratt 1989)

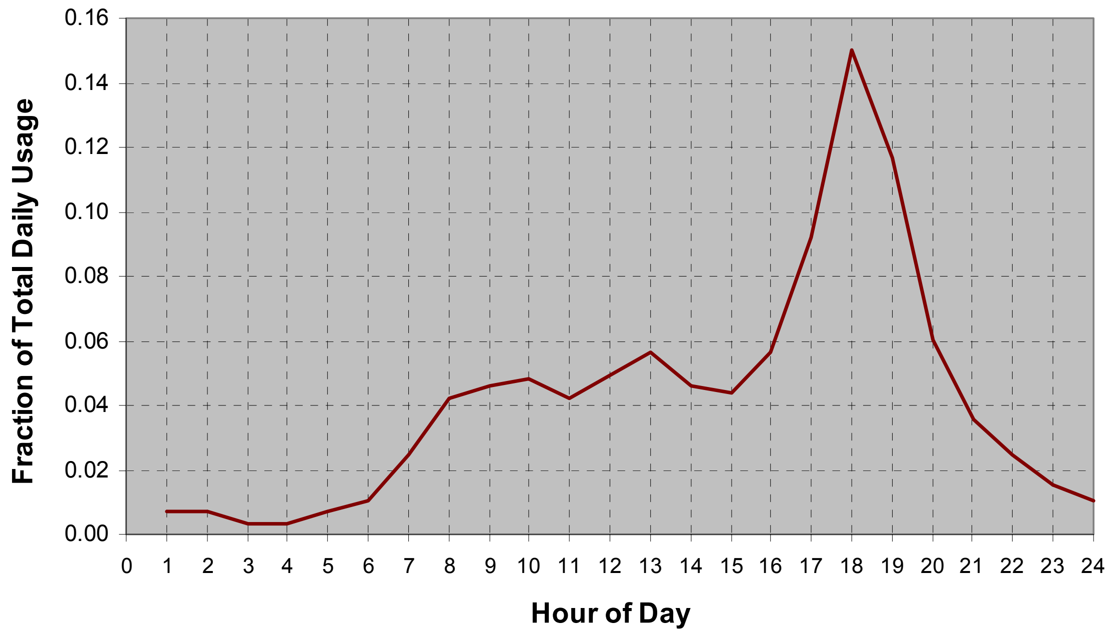


Figure 19. Range/oven normalized energy use profile (Pratt 1989)

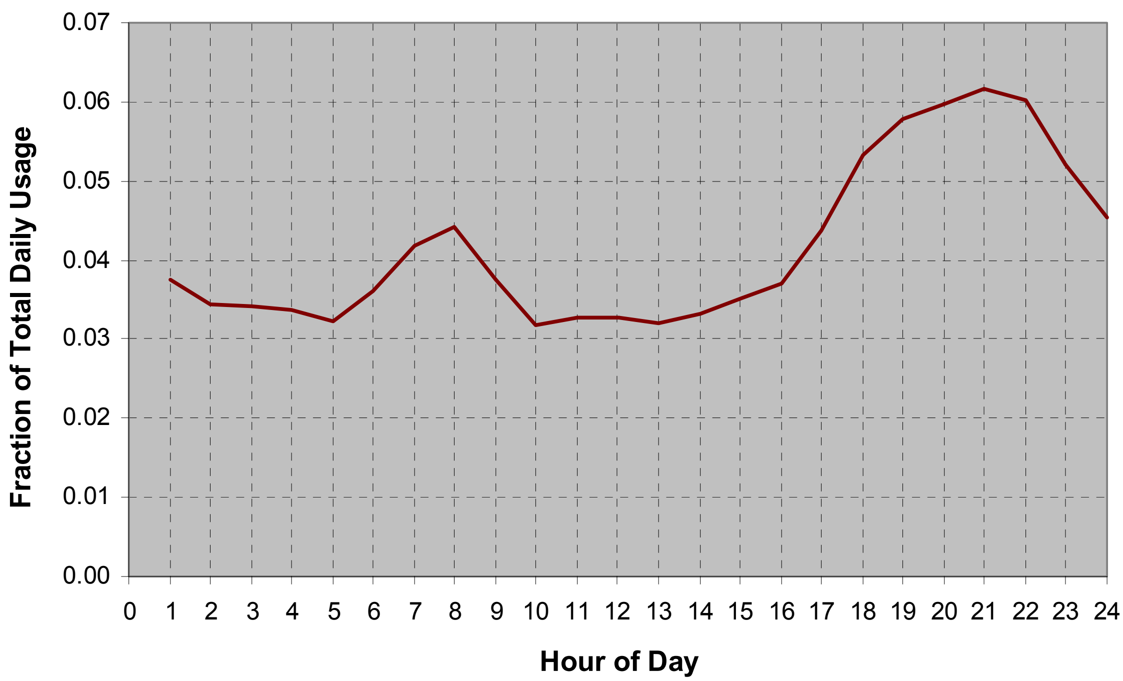


Figure 20. Other appliance and plug load normalized energy use profile

Site Generation

A review of data from the Energy Information Administration (DOE 2001) shows that there is rarely any site electricity generation in a 1990s vintage house. This is a reflection of the low market penetration of site electricity systems. Therefore, all electricity is purchased from the local utility in the Benchmark. As costs for photovoltaic systems and other site electricity systems continue to decline, they are expected to begin to make a significant contribution toward meeting residential energy needs by the year 2020. Therefore, site electricity generation must be included in the whole-house energy performance analysis of the Prototype.

Operating Conditions

The following operating conditions and other assumptions shall apply to both the Prototype house and the Benchmark. The operating conditions are based on the cumulative experience of the authors through their work on Building America, HERS, Codes and Standards, and other residential energy efficiency programs.

- Thermostat set points based on the optimum seasonal temperature for human comfort as defined in ASHRAE Standard 55-1992 (ASHRAE 1992).

  Set point for cooling: 76°F with no setup period
  Set point for heating: 71°F with no setback period

- The natural ventilation schedule shall be set to reflect windows being opened occasionally. In situations in which there is a cooling load, the outdoor temperature is below the indoor temperature, and the windows are not already open, then the probability of the windows being opened shall be set at a constant 50%. The natural ventilation rate shall be 5 ACH unless each living area and bedroom provides at least two openings on different orientations and the net area of openings exceeds 12% of the floor area of the house (cross-ventilation), in which case a natural ventilation rate of 7 ACH shall be used. If there are local circumstances that would tend to discourage window operation (pollution, security, community standards, etc), then it is acceptable to use a lower probability than 50%, as long as the same natural ventilation schedule is applied to both the Benchmark and Prototype.

- Interior shading multiplier = 0.7 during the cooling season and 0.85 during the heating season and during swing seasons when both cooling and heating occur. Specific guidelines for defining seasons are presented later in this section.

- Internal loads from lighting, appliances, and other equipment were discussed in previous sections. These loads are not necessarily the same for the Prototype and the Benchmark; therefore, they are not considered operating conditions for the purposes of the Building America performance analysis.

- Annual cycles for clothes washers, dryers, and dishwashers calculated using the NREL Appliance and DHW spreadsheet posted on the Building America website.

- The occupancy schedule is defined with the same level of detail as other internal load profiles. For typical Building America houses, the number of occupants shall be assumed to be equal to the number of bedrooms. Sensible and latent gains shall be accounted for separately, and different loads shall be applied in different space types, as described in Table 14. The occupant heat gains are based on ASHRAE recommendations (ASHRAE 2001a). The average hourly occupancy profile is shown in Figure 21, and an example set of detailed hourly occupancy curves is shown in Figure 22. Detailed occupancy profiles based on different day and room types are available in spreadsheet format on the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html). These profiles, which were developed by NREL, were based on the basic ASHRAE occupancy schedule combined with engineering judgment.

Table 14. Peak Sensible and Latent Heat Gain from Occupants (ASHRAE 2001a)

Living Area Sensible Gain:	230	BTU/person/hr
Bedroom Area Sensible Gain:	210	BTU/person/hr
Living Area Latent Gain:	190	BTU/person/hr
Bedroom Area Latent Gain:	140	BTU/person/hr

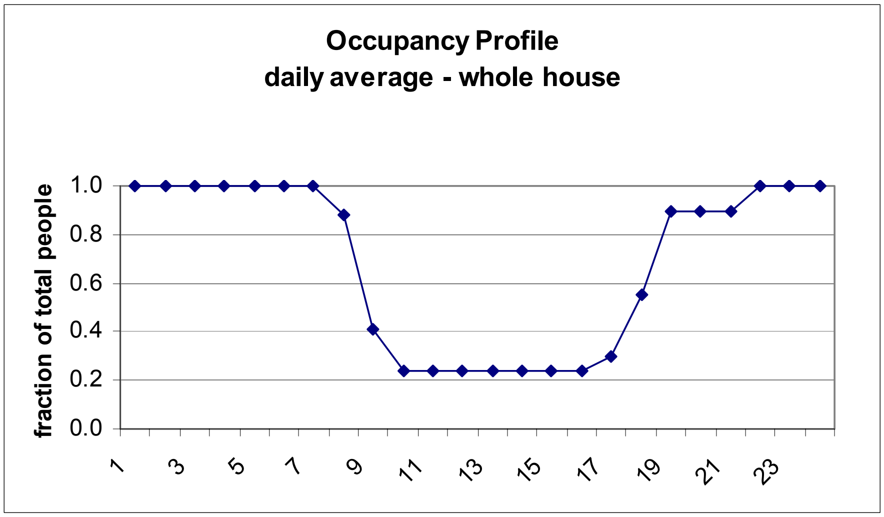


Figure 21. Average hourly load profile from occupants for all day-types and family types (16.5 hours/day/person total)

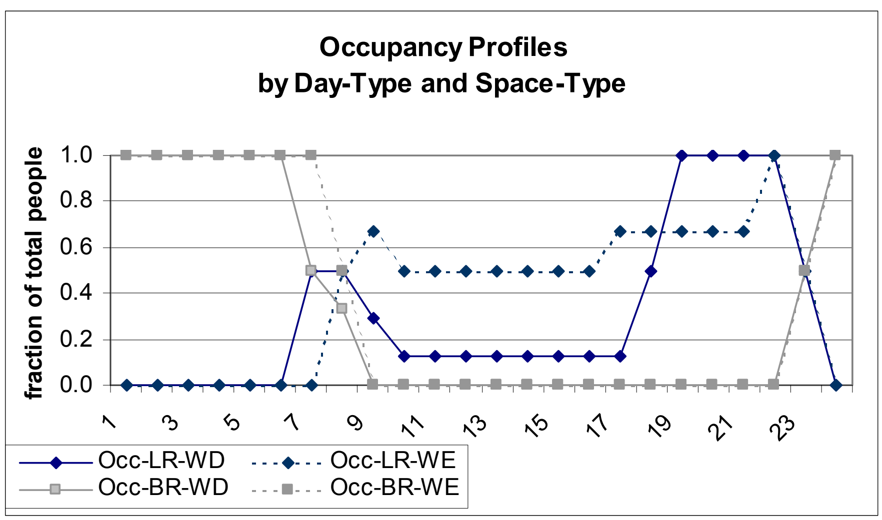


Figure 22. Detailed hourly load profiles resulting from occupants being in different parts of the house on weekdays (WD) and weekends (WE)

- The internal mass of furniture and contents shall be equal to 8 lbs/ft^2 of conditioned floor space. For solar distribution purposes, lightweight furniture covering 40% of the floor area shall be assumed.

- Weather data shall be based on typical meteorological year (TMY2) data from 1961 to 1990[4] or equivalent data for the nearest weather station.

- Heating and cooling shall only occur during certain months of the year in accordance with the guidelines presented below. Alternate operating profiles may be acceptable with sufficient justification. The heating and cooling seasons shall be determined on the basis of the monthly average temperatures (MAT) and the 99% (annual, not seasonal) winter and summer design temperatures (WDT and SDT, respectively) based on TMY2 data or ASHRAE Fundamentals 2001 for the nearest location, in accordance with the following procedures:

Step 1. MAT Basis

(I) The heating system shall be enabled for a month in which the MAT is less than 71.5°F.

(II) The cooling system shall be enabled for a month in which the MAT is greater than 66°F.

Step 2. WDT and SDT

(I) The heating system shall be enabled in December and January if the WDT is less than or equal to 59°F, regardless of the outcome in Step 1 above.

(II) The cooling system shall be enabled in July and August regardless of the outcome in Step 1 above.

Step 3. Swing Season Adjustment

(I) If, based on Steps 1 and 2 above, there are two consecutive months in which the heating system is enabled the first month and the cooling system is enabled the following month, or vice versa, then both the heating system and the cooling system shall be enabled for both of these months.

Reporting Energy Use and Energy Savings

Reporting energy use and energy savings in a consistent format is an important component of Building America analysis. The following tables shall be supplied with the analysis report for every Building America Prototype.

Table 15 shows an example of a site energy consumption report for a hypothetical Prototype in Virginia, along with all relevant base cases. Similar information based on source energy is presented in Table 16, along with percent energy savings for each end use. End uses are described in more detail in Table 17.

[4] Analytic Studies Division, National Renewable Energy Laboratory (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/).

The "Percent of End Use" columns in Table 16 show the Prototype energy use for each end use as a fraction of the appropriate base case. The "Percent of Total" columns show the contribution of each end use toward an overall energy reduction goal. Note that site generation for the Benchmark is always zero.

Source energy is determined using Equation 14.

$$\textbf{Equation 14:}\quad \text{Source MBtu} = \text{kWh} \bullet 3.412 \bullet M_e / 1000 + \text{therms} \bullet M_g / 10$$

where $M_e = 3.16$ = site-to-source multiplier for electricity (DOE 2002b)

$M_g = 1.02$ = site-to-source multiplier for natural gas (DOE 1995).

Table 15. Example Summary of Site Energy Consumption by End Use Using Building America Research Benchmark

	Annual Site Energy							
	BA Benchmark		Region Standard		Builder Standard		BA Prototype	
End Use	(kWh)	(therms)	(kWh)	(therms)	(kWh)	(therms)	(kWh)	(therms)
Space Heating	11225	0	11286	0	11286	0	4397	0
Space Cooling	2732	0	2432	0	2432	0	902	0
DHW	4837	0	4838	0	4838	0	1351	0
Lighting	3110		3110		3110		1204	
Appliances + Plug	7646	0	7646	0	7646	0	7436	0
OA Ventilation	400		400		400		400	
Total Usage	29950	0	29712	0	29712	0	15690	0
Site Generation	0	0	0	0	0	0	7402	0
Net Energy Use	29950	0	29712	0	29712	0	8289	0

Table 16. Example Summary of Source Energy Consumption by End Use Using Building America Research Benchmark

					Source Energy Savings					
	Estimated Annual Source Energy				Percent of End-Use			Percent of Total		
	Benchmark	Region	Builder	Proto	BA	Reg	Bldr	BA	Reg	Bldr
End Use	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	Base	Base	Base	Base	Base	Base
Space Heating	115	116	116	45	61%	61%	61%	23%	23%	23%
Space Cooling	28	25	25	9	67%	63%	63%	6%	5%	5%
DHW	50	50	50	14	72%	72%	72%	12%	12%	12%
Lighting	32	32	32	12	61%	61%	61%	6%	6%	6%
Appliances + Plug	78	78	78	76	3%	3%	3%	1%	1%	1%
OA Ventilation	4	4	4	4	0%	0%	0%	0%	0%	0%
Total Usage	307	304	304	161	48%	47%	47%	48%	47%	47%
Site Generation	0	0	0	-76				25%	25%	25%
Net Energy Use	307	304	304	85	72%	72%	72%	72%	72%	72%

Table 17. End-Use Categories

End Use	Potential Electric Usage	Potential Gas Usage
Space Heating	Supply fan during space heating, HP, HP supplemental heat, water boiler heating elements, water boiler circulation pump, electric resistance heating, HP crankcase heat, heating system auxiliary	Gas furnace, gas boiler, gas back-up HP supplemental heat, gas ignition stand-by
Space Cooling	Central split-system A/C, packaged A/C (window or through-the-wall), supply fan energy during space cooling, A/C crankcase heat, cooling system auxiliary	Gas absorption chiller (rare)
DHW	Electric hot water heater, HP water heater, hot water circulation pumps	Gas hot water heater
Lighting	Indoor lighting, outdoor lighting	None
Equipment	Refrigerator, electric clothes dryer, gas clothes dryer (motor), cooking, miscellaneous	Cooking, gas clothes dryer
OA Ventilation	Ventilation fans, supply air fan during ventilation mode	None
Site Generation	Photovoltaic electric generation	None

Table 18 reports energy savings for individual energy efficiency measures applied to the Prototype, in terms of source energy and energy cost. "Source Energy Savings %" is determined by comparing the source energy for each measure increment to the source energy for the Benchmark (i.e., the first row). In this column, the incremental savings for each measure are added to the savings for all the previous measures. The final row of the column is the overall energy savings achieved for the Prototype house.

When available, actual energy tariffs for the Prototype house shall be used to determine whole-building energy costs. Energy cost and measure savings are compared with the Builder Standard Practice (representing a real design or set of practices that is currently being used by the builder) rather than with the Benchmark. This provides an evaluation of the improvements in the performance of the Prototype compared with that of homes currently being sold by the builder partner.

Reporting of peak hourly energy consumption is also encouraged for every Prototype. Peak energy is based on the hour with the greatest gas or electric energy consumption during the course of one year, as determined by the hourly simulation.

Table 18. Example Measure Savings Report[5] Using Building America Research Benchmark

					National Average		Builder Standard (Local Costs)			
	Site Energy		Est. Source Energy		Energy Cost		Energy Cost		Measure	Package
Increment	(kWh)	(therms)	(MBtu)	Savings (%)	($/yr)	Savings (%)	($/yr)	Savings (%)	Value ($/yr)	Savings ($/yr)
Bldg America Benchmark	29950	0	306.9		$ 2,995		$ 2,950			
Regional Std Practice	29712	0	304.4	1%	$ 2,971	1%	$ 2,927			
Builder Std Practice (BSP)	29712	0	304.4	1%	$ 2,971	1%	$ 2,927			
BSP + improved walls	27779	0	284.6	7%	$ 2,778	7%	$ 2,736	7%	$ 190.4	$ 190
BSP ++ Low-E Windows	25810	0	264.5	14%	$ 2,581	14%	$ 2,542	13%	$ 193.9	$ 384
BSP ++ Smaller A/C (5 -> 4 tons)	25420	0	260.5	15%	$ 2,542	15%	$ 2,504	14%	$ 38.4	$ 423
BSP ++ Inc. Bsmt Wall Insulation	25170	0	257.9	16%	$ 2,517	16%	$ 2,479	15%	$ 24.6	$ 447
BSP ++ Ground Source HP (+DHW)	19331	0	198.1	35%	$ 1,933	35%	$ 1,904	35%	$ 575.1	$ 1,023
BSP ++ Solar DHW	17718	0	181.5	41%	$ 1,772	41%	$ 1,745	40%	$ 158.9	$ 1,181
BSP ++ Lighting, Appl. & Plug	15690	0	160.8	48%	$ 1,569	48%	$ 1,545	47%	$ 199.8	$ 1,381
Site Generation										
BSP ++ PV	8288	0	84.9	72%	$ 829		$ 816	72%	$ 729.0	$ 2,110

[5] Calculated using national average electric cost = $0.10/kWh and national average gas cost = $0.50/therm.

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14. ABSTRACT *(Maximum 200 Words)*
To track progress toward aggressive multi-year whole-house energy savings goals of 40-70% and onsite power production of up to 30%, the U.S. Department of Energy (DOE) Residential Buildings Program and the National Renewable Energy Laboratory (NREL) developed the Building America Research Benchmark in consultation with the Building America industry teams. The Benchmark is generally consistent with mid-1990s standard practice, as reflected in the Home Energy Rating System (HERS) Technical Guidelines (RESNET 2002), with additional definitions that allow the analyst to evaluate all residential end-uses, an extension of the traditional HERS rating approach that focuses on space conditioning and hot water. A series of user profiles, intended to represent the behavior of a "standard" set of occupants, was created for use in conjunction with the Benchmark.

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