PNNL- 22867

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Residential Wall Type Energy Impact Analysis

Prepared for:
Florida Masonry Apprentice & Educational Foundation, Inc. (FMAEF)

R. Hart, PE
V. Mendon
T. Taylor

January 2014

Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

Pacific Northwest National Laboratory (PNNL) was tasked by the Florida Masonry Apprentice & Educational Foundation, Inc. (FMAEF) to evaluate the impact of wall type selection on residential buildings including simulation of various wall assemblies in prototype one- and two-story residential buildings. The analysis was carried out using the Department of Energy's (DOE) energy simulation software, EnergyPlus™. The wall assemblies were simulated with a range of basic wall types with various parameters, including insulation level and structural infill. Basic wall structures included:

- Standard Web Concrete Masonry Unit (CMUs) – a concrete block with concrete webs connecting concrete face shells. Internal cells can be empty, filled with insulation, or filled with grout and reinforcing steel.
- Reduced-web Concrete Masonry Units (CMUr) – have less web area so heat transfer can be reduced when insulation is used in the cells.
- Insulating Concrete Forms (ICF) – poured concrete walls where rigid foam insulating layers remain in place on either side of the wall.
- Wood Frame walls – site built with insulation in the cavity between the studs as well as additional insulation sometimes added on the outside of the studs.

Analysis included 607 wall assembly combinations analyzed for one- and two-story single family residential prototypes in 15 national climate zones and three Florida climate zones. The results include 21,852 runs with end-use energy results. A companion spreadsheet is delivered with all the results and standard reporting for both the U.S. and Florida.

To further explore the benefits of mass in walls, a selected sample of walls was analyzed as described in more detail in Section 5.3 with results shown in Figure 1.

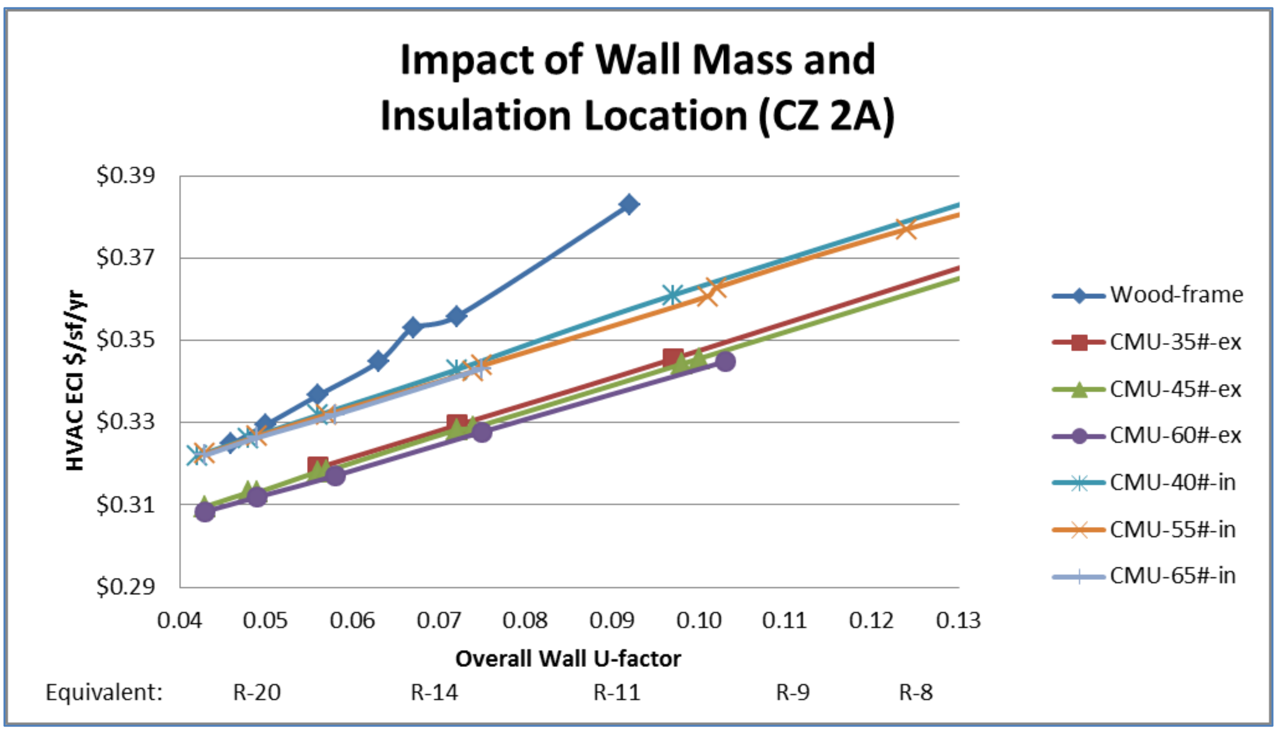

Figure 1. ECI vs. U-factor with Insulation Location and Mass, Climate Zone 2A

The impact of walls on building energy use is typically related to U-factor of the wall, or the inverse of overall wall R-value. As U-factor increases, heat loss and gain through the wall increases and energy used for heating or cooling typically increases. Higher mass walls add a heat storage element that delays the transfer of heat through walls. The benefit of this storage can be seen in Figure 1 where results for HVAC energy cost index (ECI) in annual $ per square foot of floor area for the 2-story prototypes are plotted as a function of the overall wall U-factor for climate zone 2A. While details of the wall selection and data plotted are discussed in Section 5.3, we can observe some high level results from the analysis shown in Figure 1:

- Annual home HVAC operating cost is lower for mass walls compared to wood walls, except for very low U-factors relating to high insulation levels.
- Locating insulation on the exterior (ex) of the mass walls reduces HVAC operating cost at the same insulation level compared with mass walls with interior (in) insulation.
- While higher incremental mass for a high-mass wall has some impact on HVAC operating cost, it is much less than the impact of insulation location.

While the scope of the study was to focus on generating parameters for analysis and delivering 21,852 runs with end-use energy results, in the process of creating sample reports, general observations were made. It should be emphasized that these observations are based on a selection of multiple wall assemblies for comparison and not comprehensive analysis of all the results. Heating, cooling and fan energy use and costs reported are for the whole house. The cost and energy impacts are attributed to the walls, since all other house characteristics were held constant. The general observations are discussed in more detail in the *Sample Residential Wall Result* Section and are summarized below.

- Reduced-web CMU with insulation in the cell cavities and R-4 fi-foil (a multiple layer foil product that increases the R-value of air spaces) compared to R-13 wood-frame walls, shows a reduction in energy use and cost for climate zones 1-6 even though the CMU U-factor is higher.
- The reduced-web CMU walls with insulation in the ungrouted cells have a lower U-value than standard CMU with insulation in the cells, resulting in a significant reduction in HVAC energy use and cost; however, reduced-web CMU walls with empty cells do not reduce energy use or cost compared to standard CMU walls.
- Exterior insulation on CMU walls compared to the same wall with interior insulation reduces energy use from 3% to 5%, with greater reductions in moderate climate zones. Greater reductions are also possible in all climates with some combinations of greater mass and insulation. Not all combinations were evaluated.
- The energy use of ICF walls with insulation on either side of a concrete core falls between the energy use of exterior insulated CMU walls and the energy use of interior insulated CMU walls. Exterior insulated CMU walls have the lesser energy use of the three for cases where insulation and mass are held equal.
- Mass walls generally[1] perform better than frame walls with equal amounts of insulation regardless of the placement of the insulation in the mass wall.

[1] An exception (analyzed for Climate Zones 2A and 5A) is for very heavily insulated walls, where performance is equal where the insulation is on the interior of the CMU wall. This is illustrated in Figure 1 for Climate Zone 2A.

Acknowledgments

Our thanks to the following collaborators and reviewers for their contributions to the study and this report:

- Martha VanGeem, PE; Consultant to FMAEF and technical reviewer for this project
- Don Beers, PE; MAF Staff Engineer and technical reviewer for this project
- Nick Lang; NCMA Staff Engineer and technical reviewer for this project
- Jason Thompson; NCMA Staff Engineer and technical reviewer for this project
- Pat McLaughlin; FMAEF Executive Director
- Rocky Jenkins; CEMEX Corporation and MAF President for 2013
- Robert Thomas; NCMA Executive Director

Note – Where **“FMAEF Technical Group”** is referred to as a collaborator in this project it is to acknowledge the review and input from Martha VanGeem on behalf of FMAEF, Don Beers on behalf of MAF and Nick Lang and Jason Thompson on behalf of NCMA.

Acronyms and Abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
Btu	British Thermal Units
CMUs	Standard Web Concrete Masonry Unit C90 - three web units
CMUr	Reduced-web Concrete Masonry Unit C90-11b
CF; cf	volume in cubic feet
DOE	Department of Energy
DX	Direct Expansion
ECI	Energy Cost Intensity or Energy Cost Index
EIA	Energy Information Administration
EIFS	Exterior insulation and finishing system
EUI	Energy Use Intensity or Energy Use Index
FMAEF	Florida Masonry Apprentice & Educational Foundation, Inc.
FSEC	Florida Solar Energy Center
HVAC	Heating, Ventilation, and Air-conditioning
ICF	Insulating Concrete Forms
IECC	International Energy Conservation Code
kBtu	One Thousand British Thermal Units
kBtu/ft^2	One Thousand British Thermal Units per Square Foot
kWh	kilo-watt-hour
MAF	Masonry Association of Florida
NAECA	National Appliance Energy Conservation Act
NCMA	National Concrete Manufacturer's Association
O/C; o.c.	On-center spacing
OSB	Oriented strand board
PNNL	Pacific Northwest National Laboratory
R; R-value	R-value or thermal resistance in $ft^2 \cdot h \cdot °F/Btu$
SF; sf; sq.ft.;ft^2	area in square feet
U; U-factor	U-factor or overall heat transfer coefficient in $Btu/ft^2 \cdot h \cdot °F$
pcf	Density; pounds per cubic foot
psf	Unit weight; pounds per square foot

Contents

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1.0 Introduction

This analysis is focused on generating residential energy end-uses for a set of wall types and parameters, across different climate zones. The analysis included 607 wall assembly combinations analyzed for one- and two-story single-family residential prototype building models in 15 national climate zones and three Florida climate zones. The results include 21,852 simulation runs with end-use energy results.

1.1 Research Questions

There is a long history of analysis and testing of various wall assemblies to determine heat transfer through the assemblies, with the goal of determining its impact on energy use of buildings. Heat transfer through a wall assembly under steady-state testing conditions is very different from the interactive and dynamic thermal effects that occur in the real world. Furthermore, beyond the direct heat transfer impact there are effects of:

- mass of the wall assembly that delays the impact of changing environmental conditions on the interior of the space through a thermal storage effect,
- the internal loads and solar gains that offset the need for heat and increase the need for cooling, and
- the general configuration of the house structure.

This study is targeted at modeling the interactive impacts of the total residential structure, the environment, and typical internal load conditions. The house configuration, size, orientation and load schedules are held constant so that the impact of various wall assemblies in various climate zones could be compared.

The result is a data set with heating and cooling annual end use results for single and two-story prototypes in multiple climate zones across the United States. While the scope of this work did not include comprehensive analysis of those results, the data can be used to answer questions about the impact on annual energy use of:

- added mass in walls with similar U-factors,
- location of continuous insulation on the interior vs. the exterior of the wall, or
- reduction in internal web cross section area in a concrete masonry unit.

1.2 Basis for Analysis

Energy use estimates are developed using EnergyPlus™ simulation software for various wall assemblies and residential prototype buildings.

1.2.1 Prototype Residential Buildings

Multiple residential prototype buildings are used in this analysis, with the following basis:

- National residential "Prototype Building Models"[2] based on DOE's "Residential Energy and Cost Analysis Methodology"[3] —modified as shown in Table 1—are modeled for 15 climate zones.
- Florida residential prototypes shown in Table 1 are modeled for 3 climate zones based on an EnergyPlus approximation of the existing Florida Solar Energy Center (FSEC) Residential building prototypes.
- All non-wall construction parameters, such as schedule, infiltration, glazing etc., are held constant per the National or Florida prototypes. Items that have requirements in the 2012 International Energy Conservation Code (IECC) that vary with climate zones, such as fenestration properties, have those properties vary with climate zones.

Table 1. Schedule of Residential Prototype Cases Analyzed

Stories	1	2	1	2
Conditioned Area	2000	2200	2000	2200
Basis	DOE Prototypes for IECC Analysis with parameters from 2012 IECC		Florida Solar Energy Center (FSEC) prototypes for 2010 Florida State Energy Code analysis (2009 IECC based)	
Foundation	Slab on Grade	Crawl Space	Slab on Grade	
Building Shape	Rectangular			
Window Area	15% of conditioned floor area, equally distributed to the four cardinal directions			
Heating Type	Natural Gas Furnace		Electric Heat Pump	
Cooling Type	Split system with DX cooling coil		Electric Heat Pump Cooling	
Water Heating	Natural Gas Storage Tank (40 gal)		Electric Res. Storage Tank (52 gal)	

1.2.2 Wall Heat Transfer Analysis

EnergyPlus™ simulation software[4] is used to model the annual energy end use for the residences. EnergyPlus is a whole building energy simulation program designed to model energy and water use in buildings. EnergyPlus has been compared with other simulation programs and found to have similar accuracy, especially for mass impacts on heating and cooling.[5] Modeling the performance of a building with EnergyPlus allows interactive variables such as mass, solar gain, internal loads and weather impacts to be accounted for in estimating annual heating and cooling energy use. This is achieved in part by calculating the energy use for each 15-minute interval for an entire year using typical weather data for a particular location. This sequential interval analysis allows the heat stored in the building walls to be accounted for and the impact of mass on the heating and cooling energy use to be determined. This

[2] http://www.energycodes.gov/development/residential/iecc_models
[3] http://www.energycodes.gov/sites/default/files/documents/residential_methodology.pdf
[4] http://apps1.eere.energy.gov/buildings/energyplus/
[5] Henninger and Witte. 2013. "EnergyPlus Testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASNRAE Standard 140-2011" Gard Analytics for Department of Energy, http://apps1.eere.energy.gov/buildings/energyplus/pdfs/energyplus_ashrae_140_envelope.pdf

analysis focused on the following parameters of interest:

- The analysis was based on composite layered walls where four (4) wall types were examined with multiple parameters, as discussed in the *Parameter* Section.
- Wall layer parameters include thickness, conductivity, density and specific heat and rely on published data such as ASHRAE Fundamentals as documented in the *Parameters* section.
- The focus of the analysis is annual heating, cooling, and total house site energy use.

One of the benefits of using EnergyPlus is the ability to determine the impact of heat storage capacity of high mass walls. For this analysis a 1-dimensional heat transfer, layered wall assembly model was used. Separating a wall into layers is important for a mass analysis, as compared to a simplified single composite U-factor approach for the entire wall.

Completing a 2-dimensional THERM[6] analysis of a 115 pound density CMU wall with insulation-filled cells both **without** exterior insulation (Figure 2) and **with** exterior insulation (Figure 3) will provide an illustration of the benefit of layered analysis. The THERM analysis is completed with an inside temperature of 70°F and an outside temperature of 30°F and wall and insulation mass, capacitance, and conductivity characteristics described in Appendix B.1.

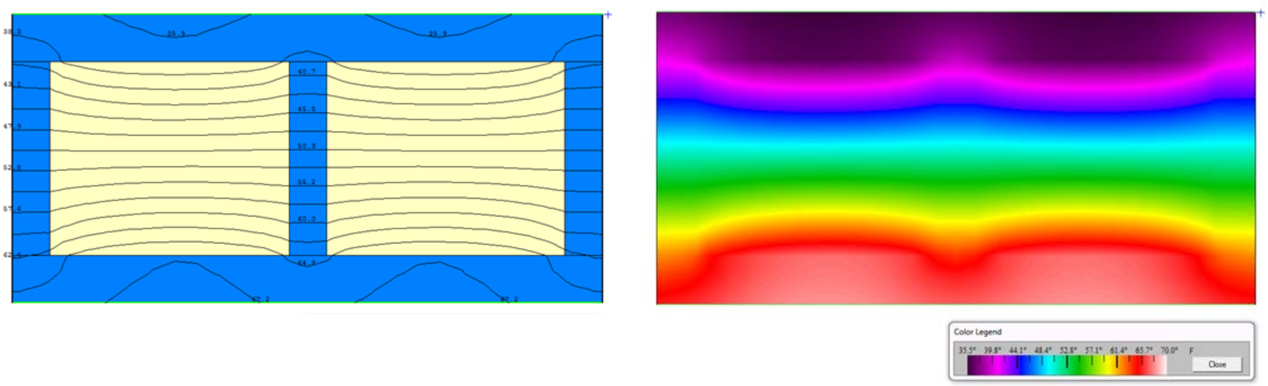

Figure 2. Heat Isotherms **without** Exterior Insulation

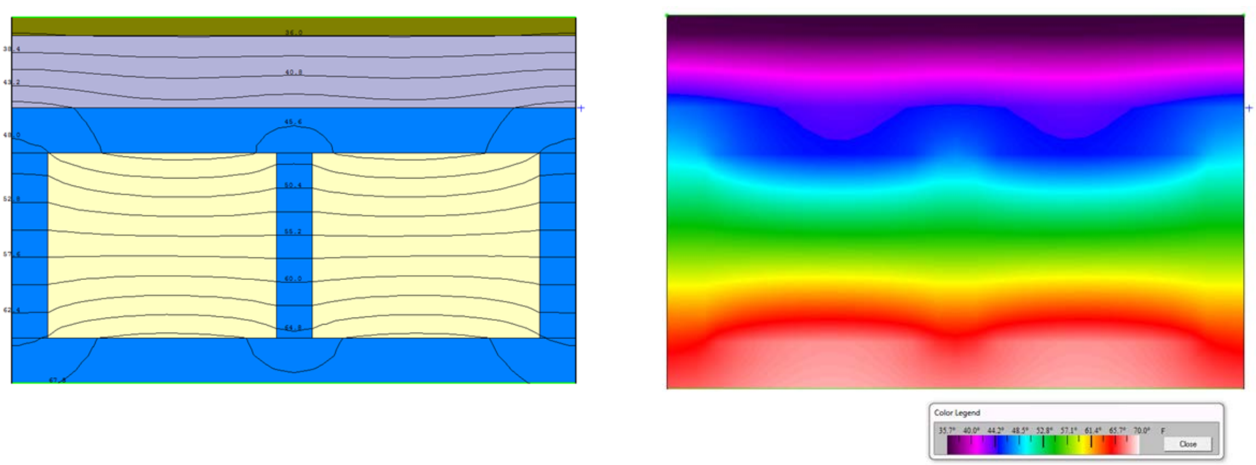

Figure 3. Heat Isotherms **with** Exterior Insulation

[6] http://windows.lbl.gov/software/therm/therm.html

In Figure 3, it can be seen that the heat conduction from the webs extends further into the face shell with the exterior insulation, resulting in a higher average temperature for that layer and more heat storage. While the 1-dimensional analysis in EnergyPlus does not exactly account for this lateral heat transfer, the layered method captures the thermal storage in each layer. The results highlighted in Section 5 show that mass walls with exterior insulation have a greater heat benefit than mass walls with the same insulation located on the interior. Note that while a 2-dimensional dynamic analysis coupled to the EnergyPlus model might have produced an improvement in accuracy of results, the conduction transfer function method calculation method used in EnergyPlus is well established as an accurate method that captures mass impacts and the use of a 2-dimensional analysis would have encumbered the project with excessive calculation time that would not have allowed the range of wall assembly combinations to be analyzed. The analysis is conducted using a composite layer approach where the stud and insulation layer in wood-framed walls and the web/insulation or web/grout layer in masonry walls are modeled as a single composite layer with averaged properties of all constituting materials.

1.3 Wall Assembly Combinations Included in Analysis

The analyzed combination simulation runs are shown in Table 2. All wall assembly combinations were run in all climate zones. The analysis was completed using EnergyPlus and the results were delivered in a spreadsheet format as described in the *Results Spreadsheet* Section. The spreadsheet includes standard reports and graphs to allow comparison of selected wall assembly energy use and energy cost. These standard reports and graphs are demonstrated in the *Sample Residential Wall Result* Section.

Table 2. Wall Type Combination Simulation Runs

Wall Type	Combinations	Number of Runs
Standard Web Concrete Masonry Unit (CMUs)	314	11304
Reduced-web Concrete Masonry Unit (CMUr)	273	9828
Insulating Concrete Forms (ICF)	12	432
Wood Frame walls	8	288
Total	607	21852

1.4 General Observations

While the scope of the study was to focus on generating parameters for analysis and delivering 21,852 runs with end-use energy results, in the process of creating sample reports, general observations were made. It should be emphasized that these observations are based on an intuitive selection of multiple wall assemblies for comparison and not comprehensive analysis of the results. The general observations are discussed in more detail in the *Sample Residential Wall Result* Section and are summarized below. Heating, cooling and fan energy use and costs reported are for the whole house. The cost and energy impacts are attributed to the walls, since all other house characteristics were held constant.

- Reduced-web CMU with insulation in the cell cavities and R-4 fi-foil compared to R-13 wood-frame walls, shows a reduction in energy use and cost for climate zones 1-6 even though the CMU U-factor is higher.

- Mass walls have a lower energy cost compared with light walls with a similar U-factor. For example, there is a decrease in HVAC energy cost for standard CMU walls with empty cells and grout at 48” on center with R-5 interior reflective board insulation (U-0.101) when compared with wood frame walls with R-13 insulation (U-0.092). This savings ranges from $46/year in climate zone 2A to $62/year in climate zone 5B for a 2400 square foot two-story home (dollar amounts are based on average energy costs and will vary depending on local energy rates).
- The CMU with R-5 interior board insulation and reflective air space results in lower heating, cooling, and total HVAC cost compared to a wood frame wall with R-13 insulation, even though the U-factor is slightly higher; attributable to the mass benefit. Mass benefit relates to the ability for a higher mass wall to store heat and release it later. This can result in reductions of both heating and cooling energy use due to the diurnal outdoor temperature cycle, depending on the climate. This occurs for all climates but is more prevalent in climate zones 1 through 4. It is more prevalent for climate zones 3C and 4C than 3B and 4B, respectively; and climate zones 3B and 4B than 3A and 4A, respectively.
- The reduced-web CMU walls with integral insulation (insulation in the cells) and interior insulation have a lower U-value on account of the reduced webbing and thus higher available area for integral insulation. This results in a significant reduction in HVAC energy use when compared with standard-web CMU walls with interior insulation.
- Reduced-web CMU walls with empty cells do not reduce energy use or cost compared to similar standard web walls with empty cells, and in fact slightly increase energy use and cost.
- Exterior insulation on CMU walls compared to interior insulation reduces energy use from 3% to 5%, with greater reductions in moderate climate zones. Greater reductions are also possible in all climates with some combinations of greater mass and insulation. Not all combinations were evaluated.
- The energy use of ICF walls, with insulation on either side of a concrete core, falls between the energy use of exterior insulated CMU walls and the energy use of interior insulated CMU walls. Exterior insulated CMU walls have the lesser energy use of the three for cases where insulation and mass are held equal. Mass walls generally perform better than frame walls with equal amounts of insulation regardless of the placement of the insulation in the mass wall.[7]

[7] An exception for some climate zones and wall assemblies is discussed in detail in Section 5.4, where the energy impact of selected walls is plotted for U-factor vs. wall unit weight.

2.0 Analysis Parameters

Analysis parameters and variables were developed and agreed to in conjunction with the FMAEF Technical Group.[8] The parameters are listed in the following sections and Appendices, and include parameters for the prototypes, wall assembly characteristics and physical properties, and the wall assembly combinations that were analyzed in the study.

Through a lengthy review process with the FMAEF Technical Group, the run selections were verified and insulation choices and assembly characteristics along with specific assembly and material parameters were finalized. The review covered prototype parameters, wall assembly and material parameters, and wall assembly runs included in the analysis.

2.1 Prototype Parameters

Two national residential prototype building models were simulated in 15 locations to represent all the climate zones defined by IECC. These models were based on PNNL's prototype building models used in the residential building codes analysis, but some characteristics were modified based on discussions with the FMAEF Technical Group. These are summarized in Appendix A.1. Two other residential prototype building models, henceforth called the Florida prototype buildings, were simulated in 3 Florida locations to represent all the Florida climate zones. The Florida prototype models were based on an EnergyPlus™ approximation of the existing Florida Solar Energy Center (FSEC) Residential building prototype building models built in EnergyGauge® which were provided to PNNL by FSEC. The development of the EnergyPlus versions was limited to the transfer of key parameters from EnergyGauge to EnergyPlus and did not include a detailed match or verification of the models.

Table 3. Schedule of Residential Prototype Cases Analyzed

Stories	1	2	1	2
Conditioned Area	2000	2200	2000	2200
Basis	DOE Prototypes for IECC Analysis with parameters from 2012 IECC		Florida Solar Energy Center (FSEC) prototypes for 2010 Florida State Energy Code analysis (2009 IECC based)	
Foundation	Slab on Grade	Crawl Space	Slab on Grade	
Building Shape	Rectangular			
Window Area	15% of conditioned floor area, equally distributed to the four cardinal directions			
Heating Type	Natural Gas Furnace		Electric Heat Pump	
Cooling Type	Split system with DX cooling coil		Electric Heat Pump	
Water Heating	Natural Gas Storage Tank (40 gal)		Electric Res. Storage Tank (52 gal)	

All prototypes have a rectangular footprint with a 15% window-to-floor ratio and a thermostat set point schedule approved by the FMAEF Technical Group. All non-wall-construction parameters, such as schedules, infiltration, fenestration area and orientation, glazing, etc., were held constant for both the

[8] Where "FMAEF Technical Group" is referred to as a collaborator in this project it is to acknowledge the review and input from Martha VanGeem on behalf of FMAEF, Don Beers on behalf of MAF and Nick Lang and Jason Thompson on behalf of NCMA.

National or Florida prototypes. All building envelope requirements are set to match the 2012 IECC and vary with climate zones, as specified by the code. The national prototypes have a base efficiency central air conditioner and gas furnace and gas water heater that each meets the minimum federal efficiency requirements in accordance with the National Appliance Energy Conservation Act (NAECA). Florida prototypes use heat pump heating and cooling, and electric water heating, all meeting minimum federal efficiencies per NAECA. The complete set of model parameters used in creating the prototype building models are detailed in Appendix A along with occupancy and equipment operation profiles. While the national prototypes are based on PNNL's analysis of the 2012 IECC, for the Florida prototypes we were unable to acquire a comprehensive technical specification document from FSEC. However, we did receive EnergyGauge input files from FSEC for prototypes they used in developing their Florida code proposals; these EnergyGauge files were used for data extraction. Recently, Florida adopted the 2012 IECC, so the 2012 IECC provisions were used with the building geometry and non-code related conditions of the FSEC prototypes.

2.2 Wall Assemblies

This analysis is based on composite layered walls of four basic wall types with multiple parameters, as shown in Table 4. The analysis excludes a discrete analysis with multi-dimensional heat flow. Each layer is modeled as a uniform composite, that is a composite mass and thermal conductivity is determined for the layer, considering the characteristics of individual studs, or CMU webs and insulated or empty cells, using methods based on available research as discussed in Section 2.3. CMU face shells and wall board were simulated as a separate layer from cavities and webs. The analysis captures the difference between putting insulation on the inside or outside of the wall.

Wall layer parameters include thickness, thermal conductivity, density and specific heat and rely on published data such as that found in the ASHRAE Fundamentals Handbook. These values were reconciled in selected cases to equivalent effective installed R-values and U-factors using methods detailed in the next section. Where published data was unavailable, such as for the reduced-web CMU, PNNL relied on data provided by the FMAEF Technical Group. The material data used in the analysis is shown in Appendix B.1. This data was reviewed extensively by the FMAEF Technical Group. The material properties are from ASHRAE Fundamentals 2009 unless another source is noted.

Table 4. Wall Type Variation Characteristics

Variable	Options Analyzed	Wall Type
Standard Web Concrete Masonry Unit (CMU) (ASTM C90 - three web units)		
Density	3	▪ Hollow CMU densities: 85 pcf, 115 pcf, 135 pcf; Face shells 1¼ in. thick and (3) webs 1 in. thick and full height
Insulation Location	2	▪ Interior and Exterior. Interior insulated walls run with ¾ in. non-reflective air space with furring strips at 24 in. on center over insulation board and ½ in. drywall with cementitious stucco on outside. Higher insulation levels with furring strips and fiberglass insulation. All exterior insulated walls with EIFS (synthetic stucco) on outside.
Insulation R	8	▪ Nominal Insulation (interior location): R0, R1, R4, R8, R13, R17, R20, R24; (exterior): R5, R9, R14, R18, R21, R25
Foam/Empty	2	▪ Cells empty and foam-insulation filled. Foam insulation in cells used with insulation combinations up to R13/R14
Grout Spacing	5	▪ Grouted cells filled at: 24 in. o/c, 48 in. o/c, 96 in.o/c, none, solid
Reduced-web Concrete Masonry Unit (CMU) (new ASTM C90-11b – reduced-web units)		
Density	3	▪ Hollow CMU densities: 85 pcf, 115 pcf, 135 pcf. Face shells 1¼ in. thick and (2) webs ¾ in. thick and full height
Insulation Location	2	▪ Interior and Exterior. Same details as CMUs ASTM C90
Insulation R	8	▪ Insulation levels: Same as CMUs ASTM C90
Foam/Empty	2	▪ Cells empty and foam-insulation filled (see comments above)
Grout Spacing	4	▪ Grouted cells at: 24 in. o/c, 48 in. o/c, 96 in. o/c, none
Insulating Concrete Forms (ICF)		
Density	2	▪ Use 120 and 145 pcf density concrete All walls with ½ in. drywall on interior (no air space as most ICF systems have plastic furring strips embedded in them.) Synthetic stucco on the exterior.
Thickness	2	▪ 4 in. thick and 6 in. thick of concrete in the core
R-Value	3	▪ Vary insulation (Insulation is split equally on both sides) with, R16 total, R20 total, R24 total.
Wood Frame walls		
		▪ All walls with 7/16 in. oriented strand board (OSB) wood sheathing on exterior and ½ in. drywall on interior.
Stud spacing	1	▪ Studs at 16 in. on center
Thickness	2	▪ 3½ in. (nominal 2 in. x 4 in.) wall with R13 batt insulation ▪ 5½ in. (nominal 2 in. x 6 in.) wall with R19 batt insulation
Insulation	4	▪ Board insulation R-Value: R0, R3, R5, R7

2.3 Methodology for Calculating Composite Wall Layer Properties

The analysis is conducted using a composite layer approach where the stud and insulation layer in wood-framed walls and the web/insulation or web/grout layer in masonry walls are modeled as a single composite layer with averaged properties of all constituting materials. Conductivity for wood-framed walls is averaged using the isothermal planes method as explained in the ASHRAE Handbook of Fundamentals.[9]

The average thermal conductivity for the web portion of the CMU walls is calculated using an area weighting method, as detailed in the NCMA Tek 6-2C[10] document. First, the R-value is calculated using the isothermal planes method for CMU walls with completely empty cells, insulation-filled cells, and grout-filled cells. The R-value for the full wall assembly in each case is calculated by adding the R-value of the face shell, face-mortar layers, and air-films to the central composite (web and cell) layer. The full wall assembly U-factor for partially grouted walls is then calculated based on area weighting the U-factors of the fully empty, fully-insulation-filled, and fully grouted walls above as detailed in the NCMA Tek 6-2C document. The R-value of the central web-and-core composite layer is back calculated by removing the R-values of the face shell and face-mortar layers and air-films. Because EnergyPlus requires conductivity and thickness as inputs, the R-values are converted to conductivity based on the thickness of each layer. Density of the composite layer is based on volume-weighting the constituent materials and specific heat is calculated based on mass-weighting all constituent materials. The composite calculations are summarized detailed in Appendix B.2.

2.4 Wall Assembly Combinations Included in Analysis

The potential combinations and estimated combination simulation runs are shown in Table 5. All wall assembly combinations were run in all climate zones. The final run list was agreed upon by the FMAEF Technical Group and PNNL during the project, although PNNL determined it was more budget effective to run all climate zones for all wall types rather than modify the climates run for each wall type.

Table 5. Wall Type Combination Simulation Runs

Wall Type	Combinations	Number of Runs
Standard Web Concrete Masonry Unit (CMU)	314	11304
Reduced-web Concrete Masonry Unit (CMU)	273	9828
Insulating Concrete Forms (ICF)	12	432
Wood Frame walls	8	288
Total	607	21852

The wall run combinations are defined in the final data spreadsheet described in Section 4.0 that has filtering capability, allowing individual wall assemblies to be selected based on characteristics analyzed.

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[9] ASHRAE. *2009 ASHRAE Handbook Fundamentals*. American Society of Heating, Refrigerating and Air Conditioning Engineers [ASHRAE], Atlanta, GA. Pg. 25.7 & pg. 27.4

[10] NCMA. 2013. *NCMA Tek 6-2C*: *R-Values and U-Factors of Single Wythe Concrete Masonry Walls*. National Concrete Masonry Association. Herndon, Virginia.

3.0 Analysis Method

The focus of the analysis is annual heating, cooling, and total house site energy use. A 15-minute time step was generally used in all simulation runs. Monthly and hourly results were not captured and delivered in this analysis.

This analysis is carried out using PNNL's one- and two-story residential building models (National models) and FSEC's one- and story building models using EnergyPlus version 7.2. The National models are simulated in 15 climate locations to represent the 15 DOE climate zones[11] and the FSEC prototypes are simulated in three Florida climate locations. The major characteristics of the prototype buildings are as discussed in the *Parameters* section with the details needed by EnergyPlus to model these buildings summarized in Appendix A. National prototypes are analyzed in DOE climate zones shown in Table 6 and Figure 4, and Florida prototypes are analyzed in Miami, Orlando, and Jacksonville. Each climate zone is modeled using TMY3 weather data from the representative city shown in Table 6. TMY3 weather data is for a Typical Meteorological Year. TMY3 data is selected from a 1976 to 2005 period of data where complete data is available and from a 1991 to 2005 period of record for other locations. In selecting the data, actual data is used for selected months from multiple years. The months selected have typical weather conditions so that the assembled TMY data is likely to predict energy use for a typical rather than an extreme year.

Table 6. Representative U.S. Cities for ASHRAE Climate Zones

Location	State	Climate Zone	Moisture Regime
Miami	FL	1A	moist
Phoenix	AZ	2B	dry
Houston	TX	2A	moist
El Paso	TX	3B	dry
San Francisco	CA	3C	marine
Memphis	TN	3A	moist
Albuquerque	NM	4B	dry
Salem	OR	4C	marine
Baltimore	MD	4A	moist
Boise	ID	5B	dry
Chicago	IL	5A	moist
Helena	MT	6B	dry
Burlington	VT	6A	moist
Duluth	MN	7	
Fairbanks	AK	8	

Note: Florida analysis listed by City: Miami, Orlando, and Jacksonville.

[11] There are eight temperature-oriented zones crossed with three moisture regimes for a potential 24 climate zones, only 15 of which occur in the U.S. Climate zones 7A and 7B are generally combined as they are in this study. Duluth is in 7A. Different results could be expected for locations in climate zone 7B.

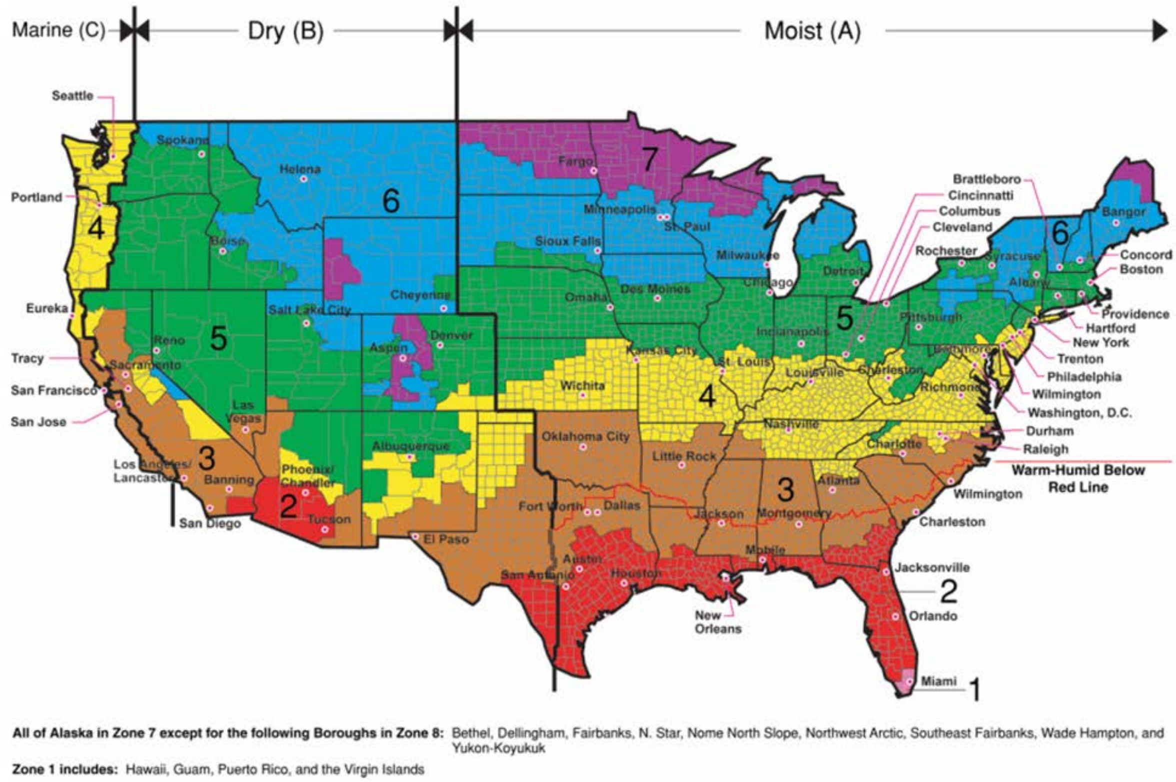


Figure 4. United States Climate Zone Map

3.1 Analysis Overview

PNNL conducted this analysis using a specially developed *gparm* template-parameter structure that allows the creation and simulation of large batches of EnergyPlus input files in one step. The U-factor calculation procedures discussed during multiple rounds of review with the FMAEF Technical Group and documented in the *Parameters* section were implemented in the template to automate the calculation and generation of the complete set of 607 wall assemblies. The results of simulation are then aggregated through automated data mining scripts into summary files. The flowchart in Figure 5 shows an overview of the analysis structure.

Once the results were generated, the files were reviewed to ensure the accuracy of inputs. The U-factor of each wall assembly as calculated by EnergyPlus was also compared against manual calculations. In all cases, the U-factor from EnergyPlus was within +/- 0.001 of manual calculations. Minor differences may be explained by conversion round-offs from the SI units used for EnergyPlus input.

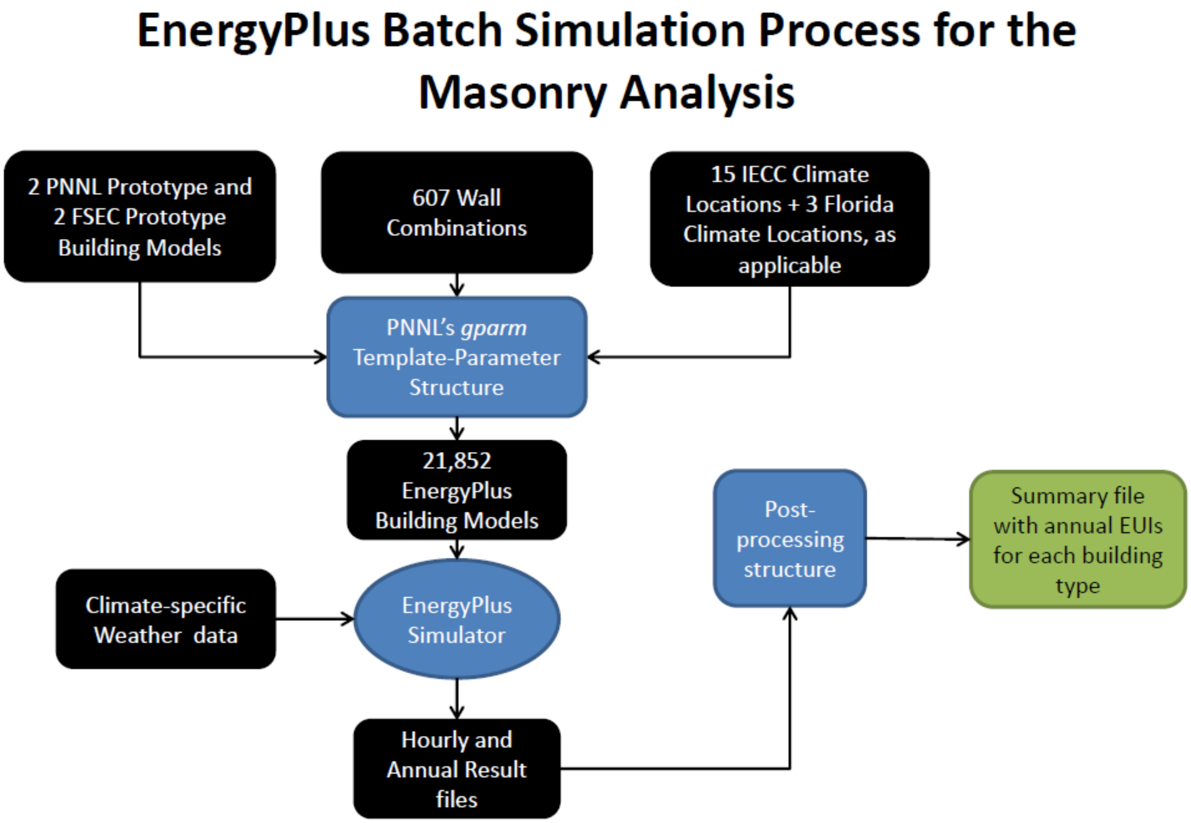


Figure 5. Overview of the Analysis Process

Two metrics are used to show results for each wall type in this report, the HVAC energy use and energy cost, including fan energy, for heating and cooling. Fan energy and cost are split between heating and cooling based on hours of operation in each mode. The metrics are on a floor area basis as an Energy Use Index (EUI) expressed in kBtu (1000 site Btu's) per square foot per year and as an Energy Cost Index (ECI) expressed in dollars per square foot per year. Metrics are shown for heating, cooling, and total HVAC. Heating is from a gas furnace for national results, and electric heat pump for Florida results. National average energy rates[12] of $0.111 per kWh and $1.048 per therm are used for the sample outputs in this report.

[12] Recent national average energy rates from Energy Information Administration

4.0 Results Spreadsheet

This study supports the analysis that produced the data results for 607 wall assemblies analyzed for two national single family residential prototypes in 15 U.S. climate zones and two Florida single family residential prototypes in three Florida climate zones. The data is incorporated in a spreadsheet organized with instructions to allow the user to select walls of interest for comparison from the 607 wall assemblies. Once selected, the wall results are displayed in three analysis sections in the spreadsheet, with energy use and cost data and graphs that can be directly printed, exported, or cut and pasted into a report. The groups of results are as follows:

- Two selected wall assemblies are compared for all 15 U.S. climate zones.
- Five selected wall assemblies are compared for a selection of three U.S. climate zones.
- Five selected wall assemblies are compared for all three Florida climate zones.

The results spreadsheet includes the following tabs:

- The **Instructions** tab includes step-by-step instructions for selecting wall assemblies and viewing results.
- **DataDictionary** includes a listing of all the results provided with both a column title and description of the data.
- **EnergyRates** includes the national or climate zone energy rates that were used to determine the cost from the simulated energy use data. The three climate zones for the five wall analysis reports are selected here, as is floor area for the whole house reporta. There is also a climate map for reference.
- **SelectCases** allows the user to filter the 607 wall assemblies by specific parameters so that wall assemblies of interest can be selected for an output report analysis.
- **StoredStudies** allows selected wall group studies with their title and notes to be stored and retrieved later for graphic reports. The tab includes a macro button to store the current study and reset the report references to the current (just selected) group of wall assemblies.
- **GraphUS-3CZ, Graph_FL, and GraphUS-ALL-CZ** are the three output reports that match the three groups of results discussed earlier. These result outputs are demonstrated in the *Sample Residential Wall Results* section. Each report tab includes several outputs for the selected wall assemblies and climate zones:
    - A table of Energy Use Index (EUI) and Energy Cost Index (ECI) results. Heating, Cooling, and total HVAC results are shown.
    - Separate bar graphs for the EUI and ECI results.
    - A table showing characteristics of the wall types included in the analysis.
    - A table showing cross-comparisons of percentage change in energy cost for all five wall assemblies selected. On the "ALL-US" tab, the percentage difference in cost is included in the main table of EUI and ECI results.
- **LandscapeTables** contains data from the graph tabs in a landscape format with more detail, including wall reference numbers.
- **WholeHouseTables** contains data from the graph tabs in a landscape format with values for the whole house HVAC energy use and cost rather than values per square foot. Values are based on a user input floor areas for one and two story houses.
- **ResultData** includes the simulation results of more than 20,000 runs of wall assembly, prototype, and climate zone combination. In this data set, each combination is run for all climate zones. This data is the main deliverable and can be used separately for other analysis.

5.0 Sample Residential Wall Results

While the focus of this study was the development of agreed-to wall assembly parameters and generation of energy use results for one and two story single family residences in multiple climate zones, a broad comparison of selected wall assemblies is shown here. Note that these analyses are selected for demonstration purposes and do not consider the full range of wall assembly results. A more systematic analysis of the results would come from future phases of work with this data. For the analyses shown here, the two-story prototypes are used. National average energy rates (EIA) of $0.111 per kWh and $1.048 per therm are used. In addition to a selected sample analysis of the benefits of mass walls, group wall comparisons include:

- U.S. Results for Similar Walls with Low Insulation Levels
- Florida Typical Wall Results
- Reduced-Web units
- Insulation Location on CMU and ICF
- National Wood-Frame vs. Insulated CMU comparison

5.1 Similar Walls with Low Insulation Levels

Walls with moderate to low insulation levels are compared in warmer climate zones. These include:

- Wood frame wall with R-13 insulation (designated Wood---,-, 16''oc,R13Co)
- CMU walls with R4 Fi-foil interior insulation, including 115 and 135 pcf density standard CMU, all with grout at 48 in. on center and empty cells (designated CMUs115,e, 48''oc,R04In and CMUs135,e, 48''oc,R04In)
- A 135 pcf density reduced-web CMU with grout at 48 in. on center and insulation-filled cells (designated CMUr135,F, 48''oc,R04In)
- A 115 pcf density standard CMU with interior R-5 board insulation and a reflective airspace (designated CMUs115,e, 48''oc,R08In)

Analysis results are shown in Table 7 for three US climate zones, with ECI and EUI graphed in Figure 6 and Figure 7 respectively. Wall assemblies are identified throughout this section with an abbreviated key corresponding to the "Wall Case" heading. Where a certain attribute is not applicable (e.g., CMU density for wood-framed walls) the attribute is replaced with dashes.

Reviewing the results, the following observations can be made. Energy use and cost represent the impact of selected walls on whole house heating, cooling, and fan energy.

- There is a slight increase in HVAC cost for the CMU walls with R-4 fi-foil (second and third rows) vs. wood frame walls with R-13 insulation in climate zones 2A and 4B even though the U factor is significantly higher for the CMU; U of 0.175 and 0.181 for CMU compared to U of 0.092 for the wood frame wall.
- Reduced-web CMU with integral insulation in the cell cavities and R-4 fi-foil (fourth row) shows a reduction in energy use and cost in climate zones 2A and 4B compared to the wood frame wall with a lower U-factor than the CMU (U of 0.125 for CMU and U of 0.092 for the wood frame). In climate zone 6B, a cold climate, energy costs and use are slightly higher for the CMU wall.

- The CMU with R-5 interior board insulation and reflective air space (fifth row) results in lower heating, cooling, and total HVAC costs compared to the wood frame wall with R-13 insulation in all climates, even though the U-factor is slightly higher; likely attributable to the mass benefit.

Table 7. Similar Low Insulation Walls

Residential Energy Use Analysis of Wall Type Impact	**Similar Low Insulation Walls**						
Wall Case	**Energy Use Index (EUI) kBtu/sf-yr**			**Energy Cost Index (ECI) $/sf-yr**			
Wall Type & CMU Density[13]; Cell Fill[14]; Grout or Stud spacing; Nominal Insulation R-Value & Location[15]; Climate Zone	**Heat EUI**	**Cool EUI**	**HVAC EUI**	**Heat ECI**	**Cool ECI**	**HVAC ECI**	**Wall Uo**
Wood---,-, 16''oc,R13Co-CZ:2A	8.24	8.82	17.06	$0.096	$0.287	$0.383	0.092
CMUs115,e, 48''oc,R04In-CZ:2A	9.12	9.37	18.49	$0.105	$0.305	$0.410	0.175
CMUs135,e, 48''oc,R04In-CZ:2A	9.20	9.42	18.62	$0.105	$0.307	$0.412	0.181
CMUr135,F, 48''oc,R04In-CZ:2A	7.36	8.66	16.02	$0.084	$0.282	$0.366	0.125
CMUs115,e, 48''oc,R08In-CZ:2A	7.08	8.62	15.69	$0.082	$0.280	$0.362	0.100
Wood---,-, 16''oc,R13Co-CZ:4B	14.89	5.51	20.40	$0.176	$0.179	$0.355	0.092
CMUs115,e, 48''oc,R04In-CZ:4B	18.16	5.22	23.38	$0.209	$0.170	$0.379	0.175
CMUs135,e, 48''oc,R04In-CZ:4B	18.46	5.22	23.69	$0.212	$0.170	$0.382	0.181
CMUr135,F, 48''oc,R04In-CZ:4B	14.21	4.85	19.06	$0.163	$0.158	$0.321	0.125
CMUs115,e, 48''oc,R08In-CZ:4B	13.02	5.00	18.02	$0.151	$0.163	$0.314	0.100
Wood---,-, 16''oc,R13Co-CZ:6B	31.82	2.78	34.60	$0.357	$0.090	$0.447	0.092
CMUs115,e, 48''oc,R04In-CZ:6B	41.88	2.42	44.30	$0.463	$0.079	$0.542	0.175
CMUs135,e, 48''oc,R04In-CZ:6B	42.60	2.41	45.01	$0.471	$0.078	$0.549	0.181
CMUr135,F, 48''oc,R04In-CZ:6B	34.52	2.25	36.77	$0.381	$0.073	$0.454	0.125
CMUs115,e, 48''oc,R08In-CZ:6B	31.13	2.41	33.54	$0.346	$0.079	$0.424	0.100

[13] r for reduced web CMU and s for standard web CMU; 115 or 135 pcf for the density of the CMU material.
[14] F for foam-insulation-filled (integral insulation) and E for empty cells.
[15] In for insulation interior to the mass and Ex for insulation exterior to the mass. This is for the insulation that is not in the wall cavity or CMU cells.

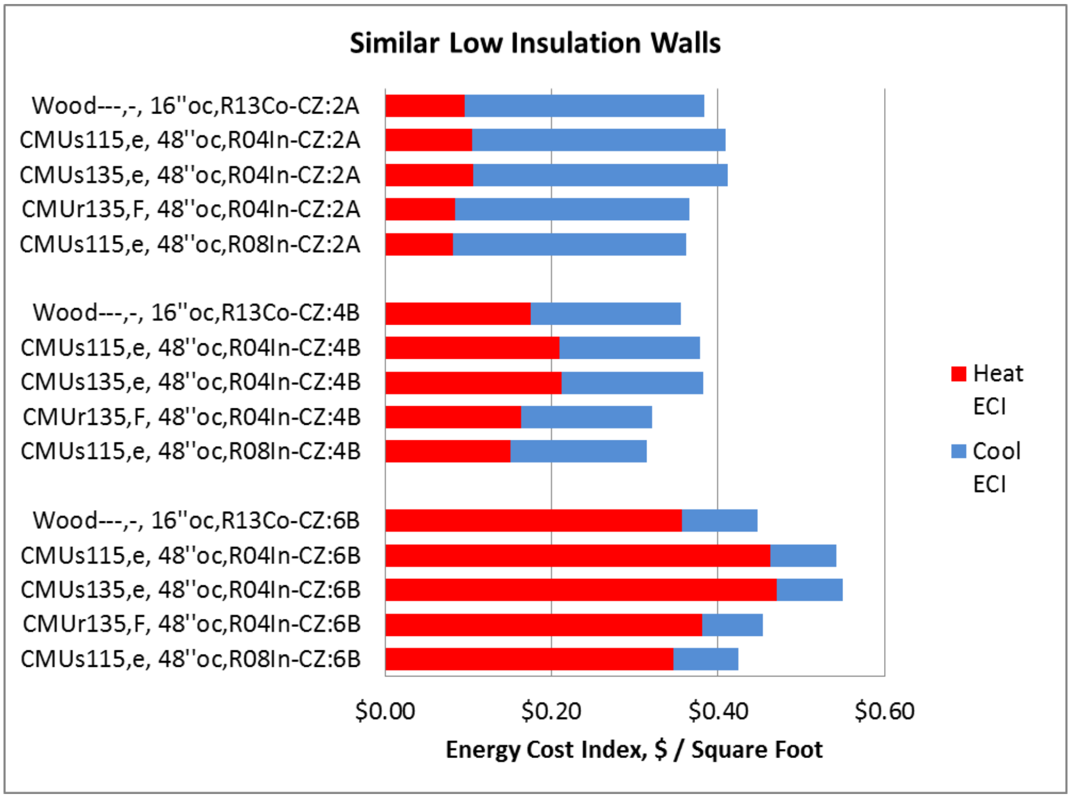


Figure 6. ECI for Similar Low Insulation Walls

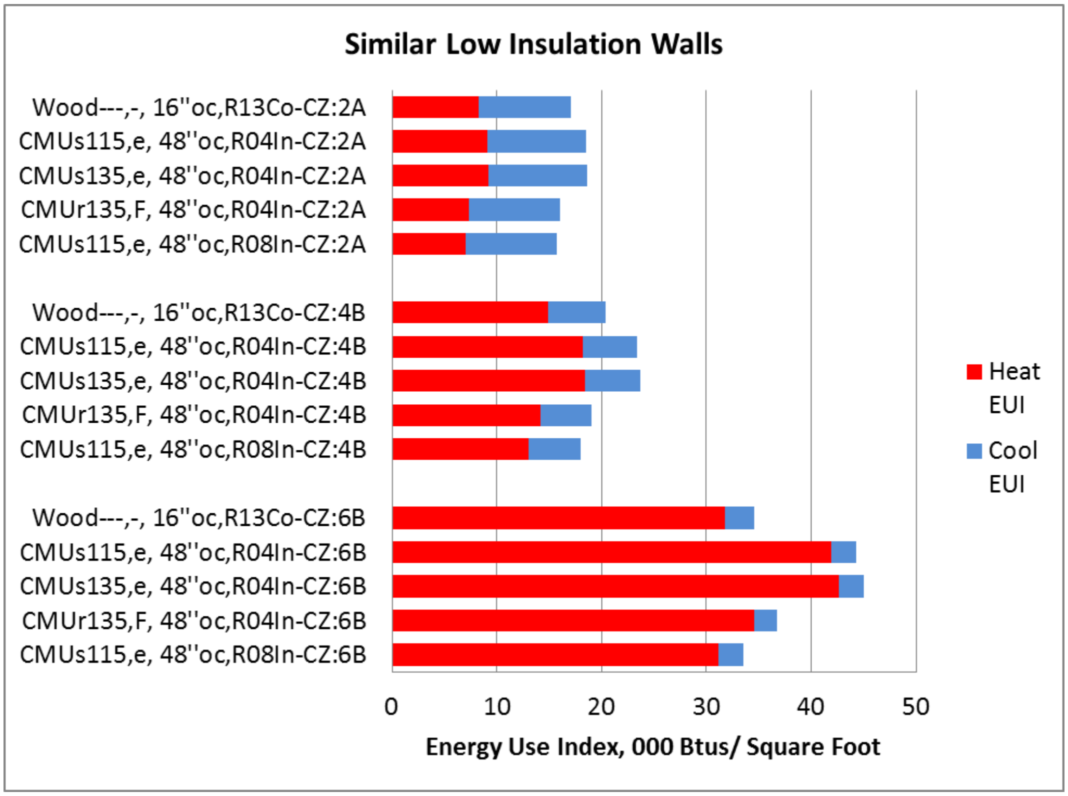


Figure 7. EUI for Similar Low Insulation Walls

5.2 Florida Typical Wall Results

Walls with moderate to low insulation levels in Florida climate zones are compared. These wall types were selected to represent common construction choices in Florida. These include:

- Standard 115 pcf density CMU walls with R4 Fi-foil interior insulation, with grout at 48 in. on center and empty cells (designated CMUs115,e, 48''oc,R04In)
- Wood frame wall with R-13 insulation (designated Wood---,-, 3.5''tk,R13Co)
- Two walls with 115 pcf density standard CMU with grout at 48 in. on center, empty ungrouted cells and board insulation located either on the exterior or interior (designated CMUs115,e, 48''oc,R08In for interior insulation and CMUs115,e, 48''oc,R09Ex for exterior insulation)
- A 145 pcf density 4-inch thick concrete wall with R-8 foam form insulation located on both the interior and exterior (designated ICF-145,-, 4.0''tk,R16Sp)

Table 8. Florida Typical Wall Results

Residential Energy Use Analysis of Wall Type and Insulation Impact	**Low Insulation Florida Walls**						
Wall Case	Energy Use Index (EUI) * kBtu/sf-yr			Energy Cost Index (ECI) * $/sf-yr			
Wall Type & Block Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	**Heat EUI**	**Cool EUI**	**HVAC EUI**	**Heat ECI**	**Cool ECI**	**HVAC ECI**	**Wall Uo**
CMUs115,e, 48''oc,R04In-CZ:Miami	0.30	9.61	9.91	$0.010	$0.313	$0.323	0.175
Wood---,-, 3.5''tk,R13Co-CZ:Miami	0.36	8.85	9.21	$0.012	$0.288	$0.300	0.092
CMUs115,e, 48''oc,R08In-CZ:Miami	0.27	8.82	9.09	$0.009	$0.287	$0.296	0.100
CMUs115,e, 48''oc,R09Ex-CZ:Miami	0.22	8.65	8.87	$0.007	$0.282	$0.289	0.100
ICF-145,-, 4.0''tk,R16Sp-CZ:Miami	0.24	8.24	8.47	$0.008	$0.268	$0.276	0.056
CMUs115,e, 48''oc,R04In-CZ:Orlando	1.24	7.02	8.26	$0.040	$0.229	$0.269	0.175
Wood---,-, 3.5''tk,R13Co-CZ:Orlando	1.31	6.75	8.07	$0.043	$0.220	$0.263	0.092
CMUs115,e, 48''oc,R08In-CZ:Orlando	1.11	6.52	7.64	$0.036	$0.212	$0.249	0.100
CMUs115,e, 48''oc,R09Ex-CZ:Orlando	1.02	6.36	7.38	$0.033	$0.207	$0.240	0.100
ICF-145,-, 4.0''tk,R16Sp-CZ:Orlando	1.01	6.16	7.17	$0.033	$0.200	$0.233	0.056
CMUs115,e, 48''oc,R04In-CZ:Jacksonville	2.91	6.15	9.06	$0.095	$0.200	$0.295	0.175
Wood---,-, 3.5''tk,R13Co-CZ:Jacksonville	2.93	5.91	8.83	$0.095	$0.192	$0.287	0.092
CMUs115,e, 48''oc,R08In-CZ:Jacksonville	2.62	5.69	8.30	$0.085	$0.185	$0.270	0.100
CMUs115,e, 48''oc,R09Ex-CZ:Jacksonville	2.52	5.45	7.96	$0.082	$0.177	$0.259	0.100
ICF-145,-, 4.0''tk,R16Sp-CZ:Jacksonville	2.42	5.30	7.72	$0.079	$0.173	$0.251	0.056

* Fan energy use and cost included in heating, cooling, and HVAC.

Analysis results are shown in Table 8, with percentage energy difference between each wall shown in Table 9. Note that heating in Florida is electric heat pump rather than a gas furnace. Reviewing the results, the following observations can be made. The energy use and costs differences are for the HVAC system and represent the impact of the wall choices.

- Compared to Miami, the Orlando and Jacksonville results show significantly more energy savings in the CMU walls with R-8 insulation compared to the wood frame wall with a lower U factor. This is probably due to more diurnal temperature swings above and below the balance point of the house in Jacksonville and Orlando than Miami.
- For all three climate zones the location of R-8 insulation on the exterior of the CMU wall (fourth listed wall) rather than interior (third listed wall) almost doubles the energy savings compared to the wood frame wall (second listed wall), as evidenced by comparing the second column of values in Table 9. Here the third and fourth walls listed have the same U-factor (U 0.10) and both save energy compared to the wood-framed wall with R-13 insulation that has a lower U-factor (U 0.092).

Table 9. Florida Typical Wall Comparison Matrix

Energy Cost Comparison	**Compare Standard Florida Walls**				
Wall Characteristics	**HVAC Energy Cost of Top Wall is __% more than Left Wall**				
Wall Type & CMU Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	CMUs115,e, 48''oc,R04In	Wood---,-, 3.5''tk,R13C	CMUs115,e, 48''oc,R08In	CMUs115,e, 48''oc,R09Ex	ICF-145,-, 4.0''tk,R16S
Miami:					
CMUs115,e, 48''oc,R04In	0.0%	-7.1%	-8.3%	-10.4%	-14.5%
Wood---,-, 3.5''tk,R13C	7.6%	0.0%	-1.3%	-3.6%	-8.0%
CMUs115,e, 48''oc,R08In	9.0%	1.3%	0.0%	-2.4%	-6.8%
CMUs115,e, 48''oc,R09Ex	11.6%	3.8%	2.4%	0.0%	-4.5%
ICF-145,-, 4.0''tk,R16S	16.9%	8.7%	7.3%	4.7%	0.0%
Orlando:					
CMUs115,e, 48''oc,R04In	0.0%	-2.3%	-7.6%	-10.6%	-13.2%
Wood---,-, 3.5''tk,R13C	2.4%	0.0%	-5.3%	-8.5%	-11.1%
CMUs115,e, 48''oc,R08In	8.2%	5.6%	0.0%	-3.3%	-6.1%
CMUs115,e, 48''oc,R09Ex	11.9%	9.3%	3.5%	0.0%	-2.9%
ICF-145,-, 4.0''tk,R16S	15.2%	12.5%	6.5%	3.0%	0.0%
Jacksonville:					
CMUs115,e, 48''oc,R04In	0.0%	-2.5%	-8.4%	-12.1%	-14.8%
Wood---,-, 3.5''tk,R13C	2.6%	0.0%	-6.0%	-9.8%	-12.6%
CMUs115,e, 48''oc,R08In	9.1%	6.4%	0.0%	-4.1%	-7.0%
CMUs115,e, 48''oc,R09Ex	13.8%	10.9%	4.3%	0.0%	-3.0%
ICF-145,-, 4.0''tk,R16S	17.3%	14.4%	7.5%	3.1%	0.0%

For the typical Florida walls, ECI and EUI are graphed in Figure 8 and Figure 9 respectively.

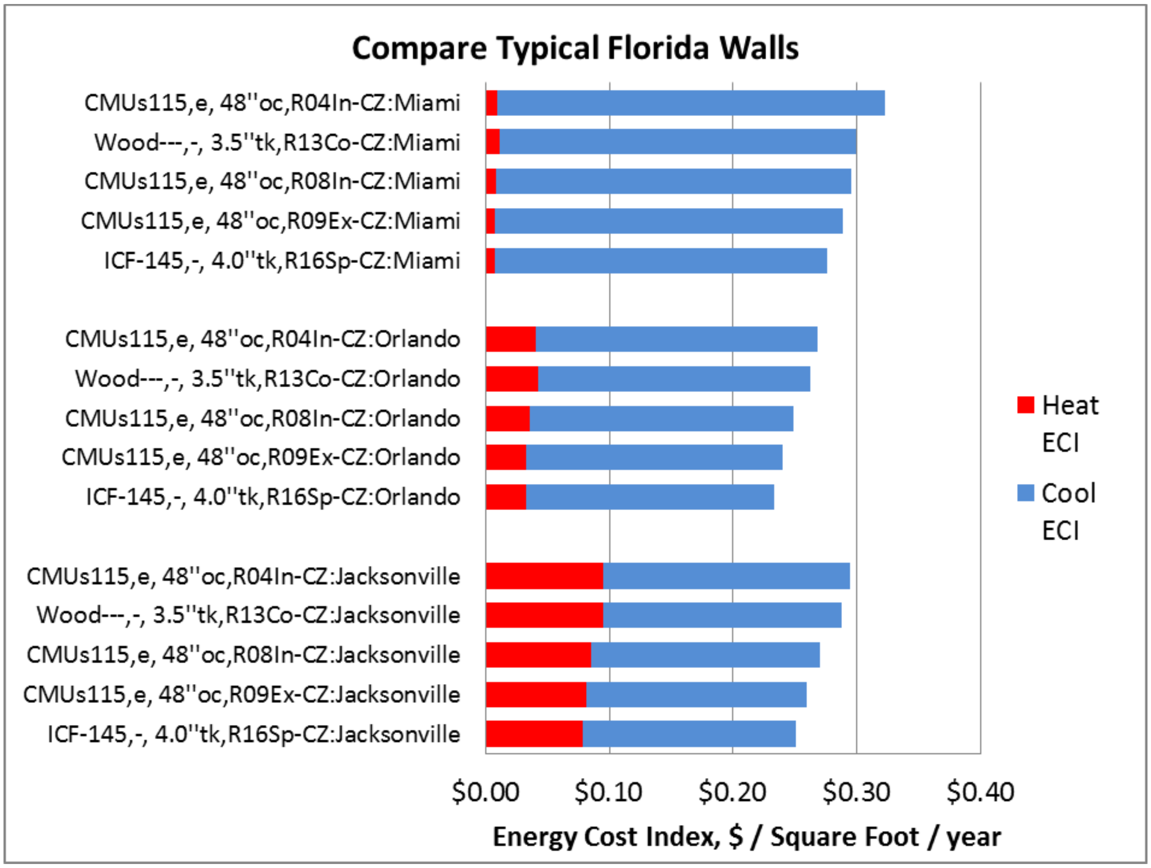


Figure 8. ECI for Florida Typical Walls

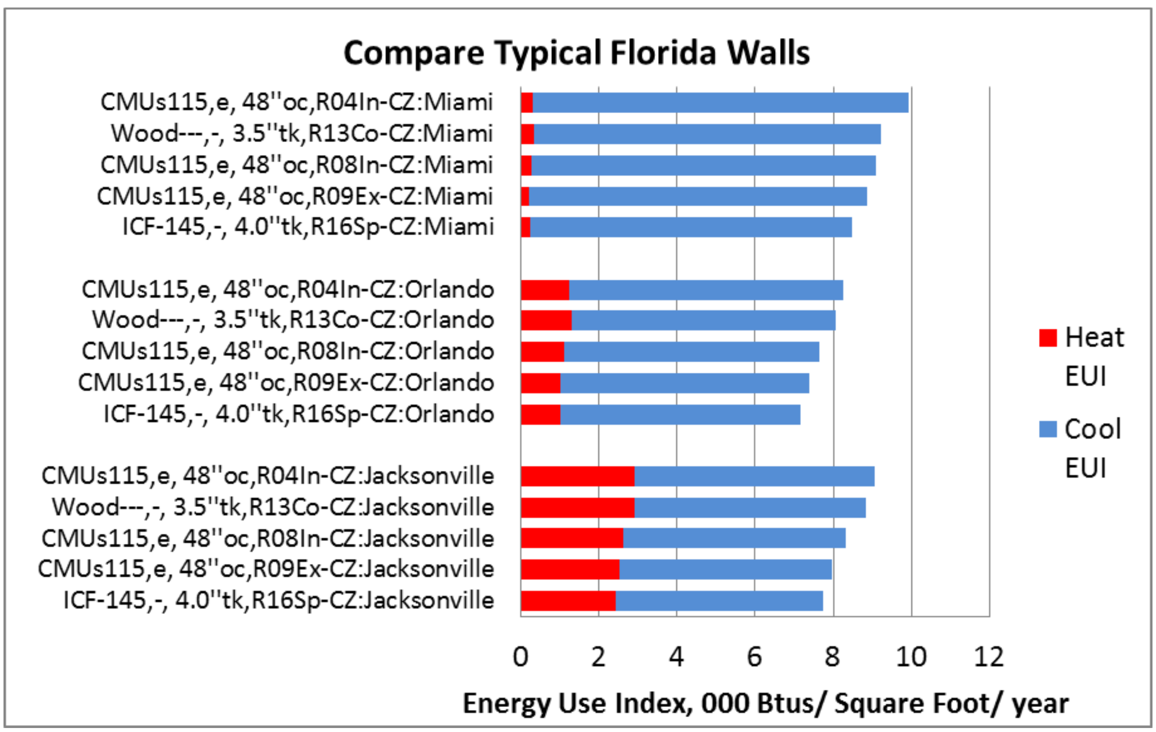


Figure 9. EUI for Florida Typical Walls

5.3 Energy Benefits of Mass Walls

To further explore the energy benefits of mass in walls, a sample of walls was selected to explore the impact of mass and insulation location. Results for HVAC energy cost index for the two-story prototypes were plotted as a function of the overall wall U-factor. Lines indicate walls with a common unit weight in pounds of the total wall assembly per square foot of wall area. Wood-frame wall assemblies have a unit weight ranging from 6 to 8 pounds per square foot of wall. CMU walls have higher unit weight, and were binned into groups with a range of five pounds per square foot of wall. A wall group with a 35# indication includes walls with unit weights from 32.5 to 37.5 pounds per square foot of wall. For the masonry walls, not all wall weights are shown to better illustrate the impact of different unit weight walls. Walls had the following characteristics:

- Wood-frame walls include both 2 x 4 and 2 x 6 framing as well as cavity insulation only and continuous exterior insulation.
- CMU walls include standard three-web CMU with empty (air-filled) ungrouted cells. CMU walls with both 24-inch and 48-inch grout spacing were included, as were all CMU densities in the data set. Insulation was either on the interior of the wall (indicated "in") or on the exterior (indicated "ex").

The steady-state impact of walls on building energy use is typically related to U-factor of the wall, or the inverse of overall wall R-value. As U-factor increases, steady-state heat loss and gain through the wall increases and energy used for heating or cooling typically increases. Higher mass walls add a heat storage element that delays the transfer of heat through walls. This storage along with dynamic or diurnal temperature conditions often gives different energy use results than would be expected under steady-state conditions. The benefit of this storage can be seen in in Figure 10 where results are shown for climate zone 2A, a cooling dominated zone, and in Figure 11 for climate zone 5A, a heating dominated zone.

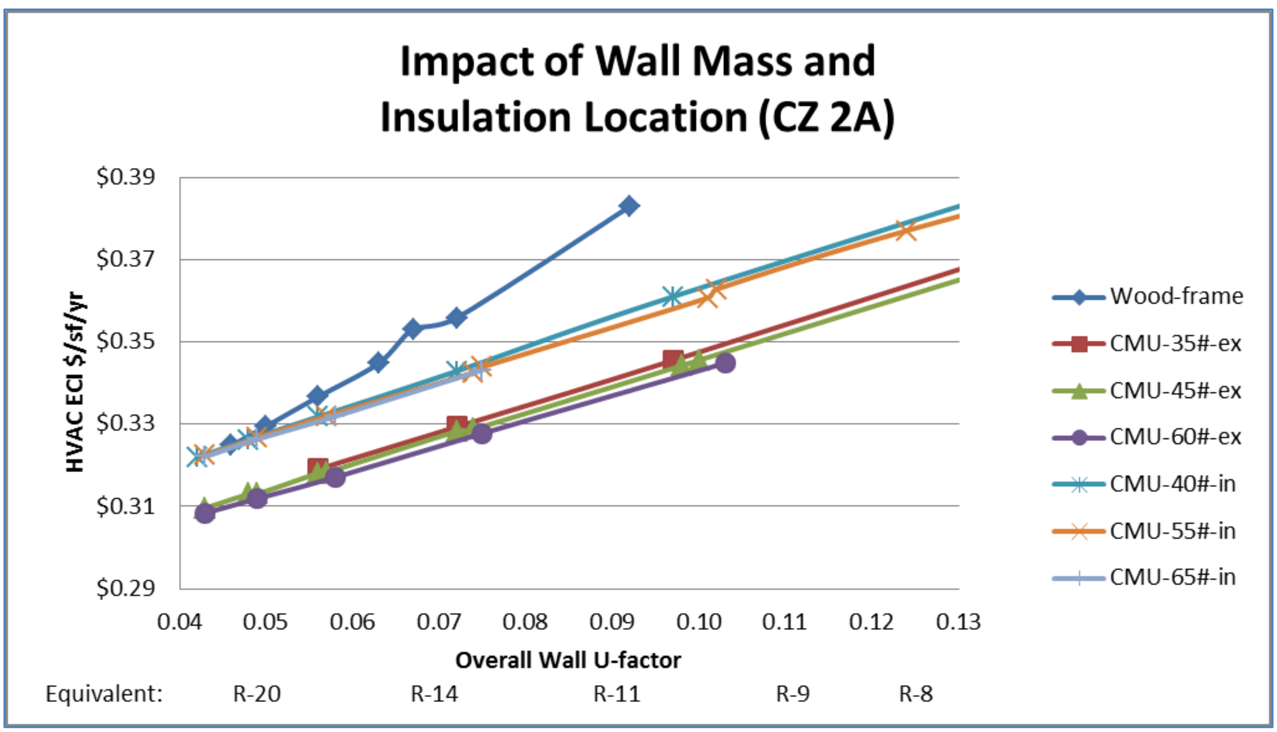


Figure 10. ECI vs. U-factor with Insulation Location and Mass, Climate Zone 2A

Observing Figure 10, the following conclusions can be drawn:

- HVAC cost is generally[16] lower for mass walls compared to wood walls.
- Locating insulation on the exterior of the mass walls reduces HVAC cost at the same insulation level.
- While higher incremental mass in high-mass walls has some impact on HVAC costs, it is much less than the impact of insulation location.

The relationships are similar in the colder climate zone shown in Figure 11, but the differences are not as great between treatments as in the warmer climate zone shown in Figure 10. While this illustration is based on a selection of the wall types rather than a comprehensive analysis of all types investigated, the sampled results indicate that for walls of similar U-factor, high-mass walls reduce HVAC energy use in homes compared to low-mass walls, and that the location of insulation is more important than the total weight of the wall, once there is a basic level of high-mass. Note also that the "A" climate zones, such as climate zones 2A and 5A used in these figures, have smaller diurnal temperature changes than the "B" climate zones. Therefore, these results may be conservative.

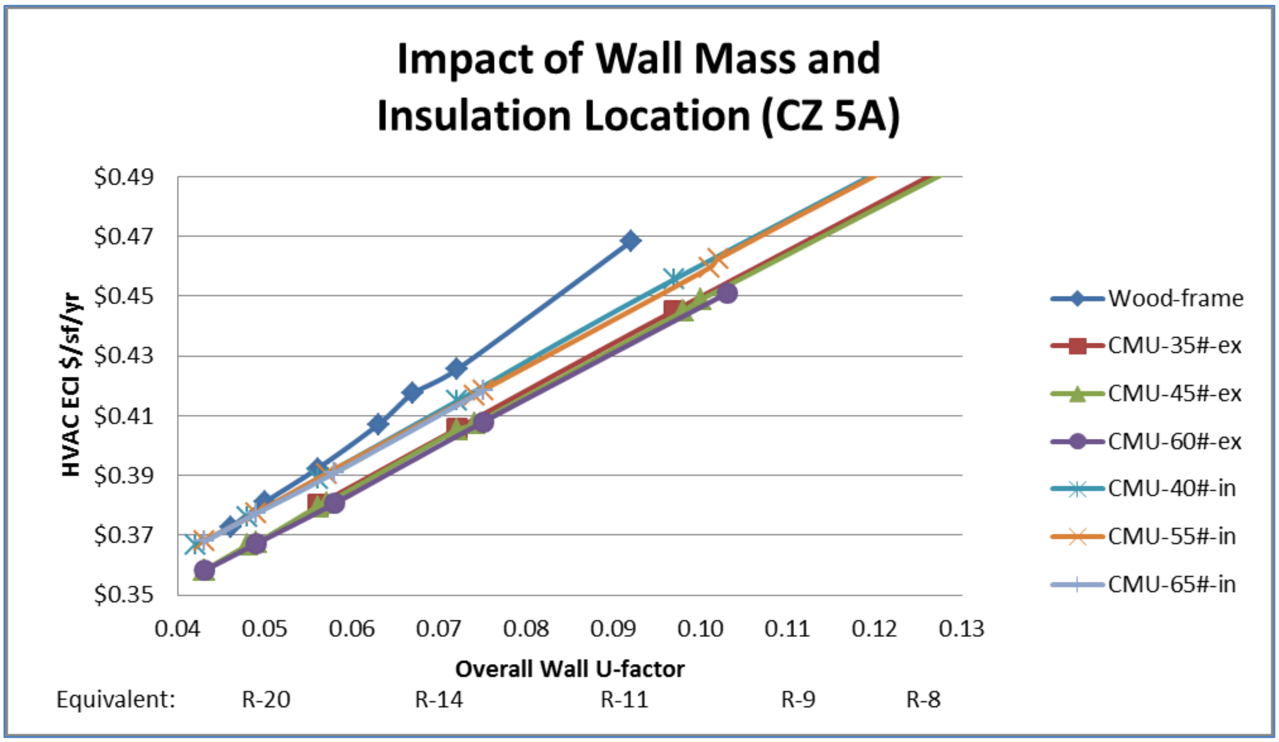


Figure 11. ECI vs. U-factor with Insulation Location and Mass, Climate Zone 5A

5.4 Reduced-Web Units

A comparison of standard-web and reduced-web units is made (note the differences in cell insulation and CMU type in each case). The wall characteristics for this analysis are detailed in Table 10. The compared walls include:

[16] An exception is for very heavily insulated walls, where performance is about equal for cases where the insulation is on the interior of the CMU wall.

- A standard 115 pcf density CMU wall with grout at 48 in. on center, no cell insulation, and Fi-foil interior insulation (designated CMUs115,e, 48''oc,R04In)
- A Reduced-web 115 pcf density CMU wall with empty cells, Fi-foil interior insulation, and 115 pcf density is also included (designated CMUr115,e, 48''oc,R04In)
- Reduced-web 115 pcf density CMU walls with insulation-filled cells and Fi-foil interior insulation (designated CMUr115,F, 48''oc,R04In)
- A standard 115 pcf density CMU wall with grout at 48 in. on center, with insulation-filled cells, and Fi-foil interior insulation (designated CMUs115,F, 48''oc,R04In)

Table 10. Wall Characteristics for Standard vs. Reduced-Web CMU

Residential Wall Types Analyzed	**Standard-web vs. Reduced-web CMU Walls**			
Characteristic	**Wall Type**			
Case: Wall Type & CMU Density; Cell Fill; Grout or Stud spacing; Nominal Insulation R-Value & Location	CMUs115,e, 48''oc,R04In	CMUr115,e, 48''oc,R04In	CMUr115,F, 48''oc,R04In	CMUs115,F, 48''oc,R04In
Prototype	singlefamily	singlefamily	singlefamily	singlefamily
Code Basis	IECC_2012	IECC_2012	IECC_2012	IECC_2012
Stories	2	2	2	2
Heating fuel	naturalgas	naturalgas	naturalgas	naturalgas
ext_wall_type	CMUs	CMUr	CMUr	CMUs
Structural thickness	7.6	7.6	7.6	7.6
Grout or stud spacing, inches	48.0	48.0	48.0	48.0
Concrete density	115.0	115.0	115.0	115.0
Assembly unit weight lbs/sf	48.8	45.2	45.8	49.4
Cell fill for CMU	empty	empty	Foam-Filled	Foam-Filled
Overall Wall U-Factor	0.175	0.175	0.113	0.130
Overall Wall R-Value equiv	5.723	5.724	8.860	7.697
Insulation Nominal R-Total	4	4	4	4
R-value of cavity insulation	4	4	4	4
R-value of continuous insul.	0	0	0	0
Continuous insul. Location	Interior	Interior	Interior	Interior
Interior airspace	none	none	none	none
Interior finish	Gypsum	Gypsum	Gypsum	Gypsum
Exterior Finish	Cementitious stucco	Cementitious stucco	Cementitious stucco	Cementitious stucco

Analysis results are shown in Table 11 for three US climate zones, with ECI and EUI graphed in Figure 12 and Figure 13 respectively.

Table 11. Energy Results for Standard vs. Reduced-Web CMU

Residential Energy Use Analysis of Wall Type Impact	**Standard-web vs. Reduced-web CMU Walls**						
Wall Case	Energy Use Index (EUI) kBtu/sf-yr			Energy Cost Index (ECI) $/sf-yr			
Wall Type & CMU Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	**Heat EUI**	**Cool EUI**	**HVAC EUI**	**Heat ECI**	**Cool ECI**	**HVAC ECI**	**Wall Uo**
CMUs115,e, 48''oc,R04In-CZ:2A	9.12	9.37	18.49	$0.105	$0.305	$0.410	0.175
CMUr115,e, 48''oc,R04In-CZ:2A	9.24	9.40	18.64	$0.106	$0.306	$0.412	0.175
CMUr115,F, 48''oc,R04In-CZ:2A	7.03	8.53	15.56	$0.081	$0.278	$0.358	0.113
CMUs115,F, 48''oc,R04In-CZ:2A	7.50	8.71	16.21	$0.086	$0.284	$0.370	0.130
CMUs115,e, 48''oc,R04In-CZ:4B	18.16	5.22	23.38	$0.209	$0.170	$0.379	0.175
CMUr115,e, 48''oc,R04In-CZ:4B	18.34	5.26	23.60	$0.212	$0.171	$0.383	0.175
CMUr115,F, 48''oc,R04In-CZ:4B	13.35	4.82	18.17	$0.154	$0.157	$0.311	0.113
CMUs115,F, 48''oc,R04In-CZ:4B	14.53	4.87	19.40	$0.167	$0.159	$0.326	0.130
CMUs115,e, 48''oc,R04In-CZ:6B	41.88	2.42	44.30	$0.463	$0.079	$0.542	0.175
CMUr115,e, 48''oc,R04In-CZ:6B	42.02	2.45	44.47	$0.465	$0.080	$0.545	0.175
CMUr115,F, 48''oc,R04In-CZ:6B	32.70	2.25	34.95	$0.361	$0.073	$0.434	0.113
CMUs115,F, 48''oc,R04In-CZ:6B	35.18	2.25	37.43	$0.388	$0.073	$0.462	0.130

* Fan energy use and cost included in heating, cooling, and HVAC.

Observations from the standard vs. reduced-web comparison are as follows (note the differences in cell insulation and wall type in each case):

- Reduced-web walls with empty cells (the second wall shown) do not reduce heat loss compared to similar standard web walls (first wall shown), and in fact slightly increase energy cost. This results from the fact that the webs actually provide more thermal resistance than the air space. Integral insulation in the cells is required to get the benefit of the reduced webbing.
- When there is insulation in the ungrouted cells (third and fourth walls with integral insulation as indicated by F) the walls have a lower U-value resulting in a significant reduction in HVAC energy when compared to walls with empty cells.
- When the reduced-web CMU (third wall) is compared to standard-web CMU (fourth wall), both with insulation in the ungrouted cells, the reduced web walls have a lower U-value due to the reduced webbing and thus higher available area for insulation. This results in a reduction in HVAC energy when compared to standard-web walls with insulated cells.

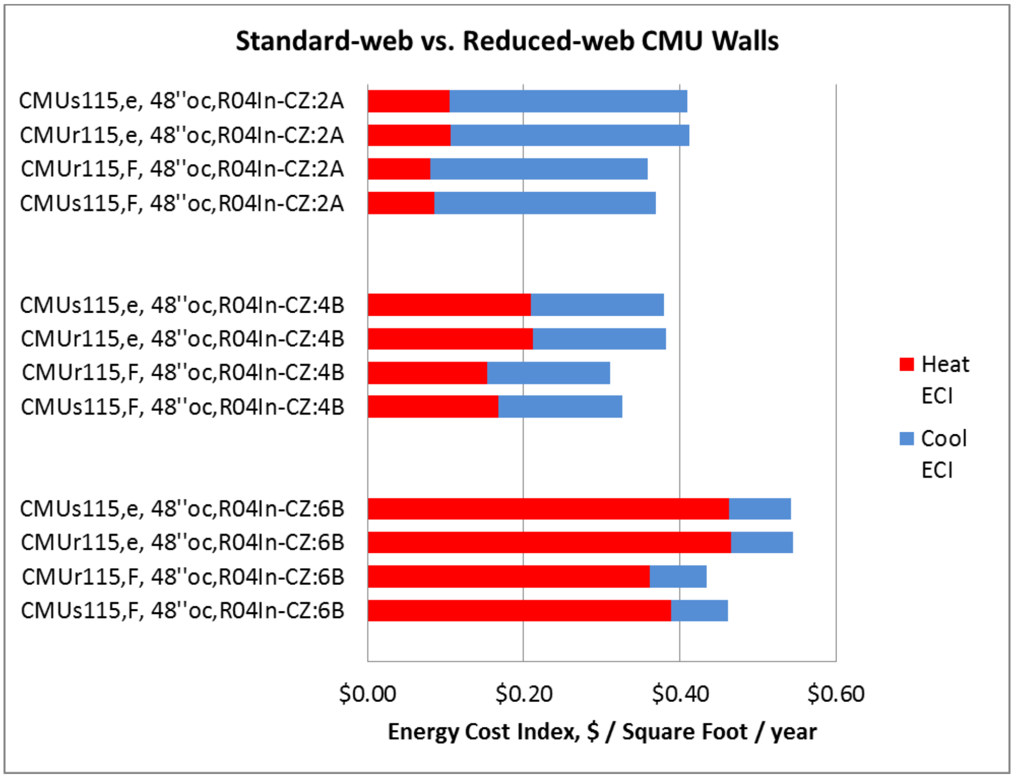


Figure 12. ECI for Standard vs. Reduced-Web CMU[17]

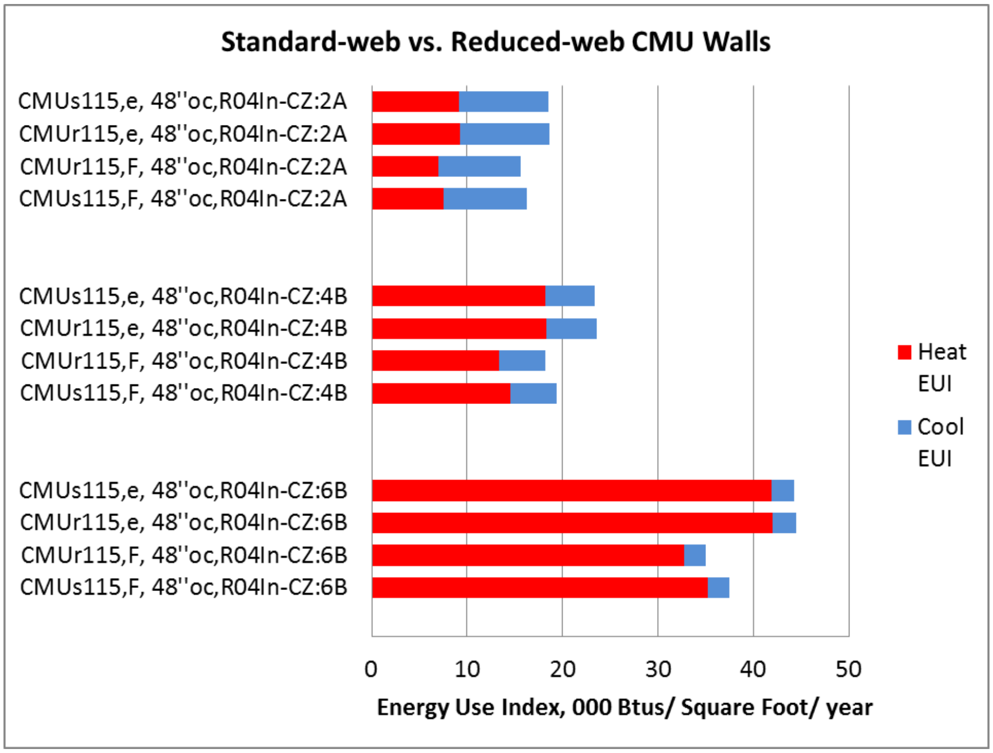


Figure 13. EUI for Standard vs. Reduced-Web CMU[17]

[17] Note the differences in cell insulation and web type in each case.

5.5 Reduced Web Unit Selected Sample Analysis

The earlier selected sample analysis of the benefits of mass in walls is extended to look at the impact of reduced-web CMU walls with integral insulation (insulation in ungrouted cells). Again, selected results for HVAC energy cost index for the 2-story prototypes were plotted as a function of the overall wall U-factor. Walls had the following characteristics:

- Wood-frame walls include both 2 x 4 and 2 x 6 framing as well as cavity insulation only and continuous exterior insulation.
- Standard CMU walls include standard three-web CMU with empty (air-filled) ungrouted cells.
- Reduced-web CMU walls include two-web CMU with integral insulation.
- For both standard and reduced web CMU walls, insulation was either on the interior of the wall (indicated "in") or on the exterior (indicated "ex"). CMU walls with both 24-inch and 48-inch grout spacing were included, as were all CMU densities in the data set.

Results are shown in Figure 14 for climate zone 2A, a cooling dominated zone, and in Figure 15 for climate zone 5A, a heating dominated zone,

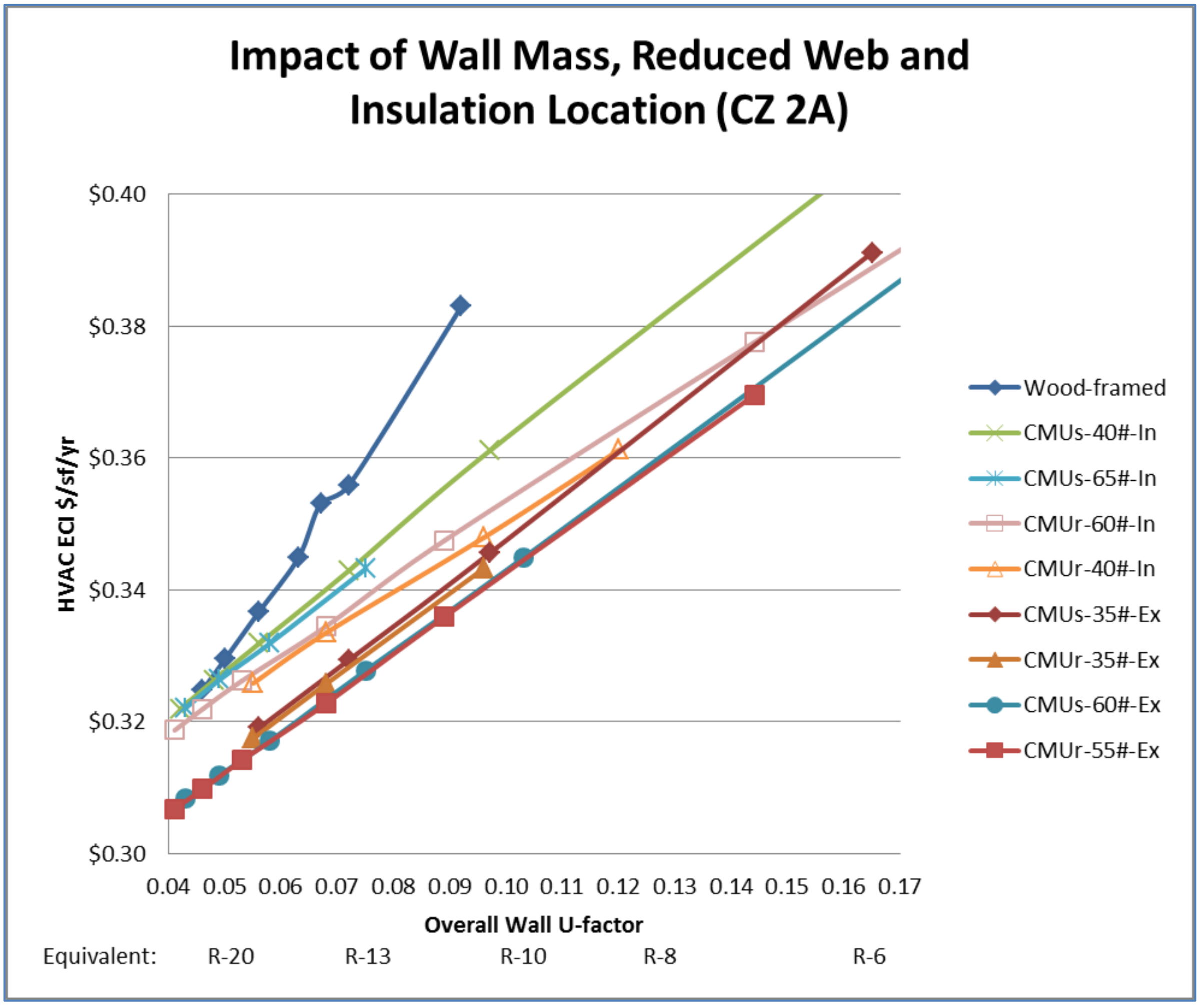


Figure 14. ECI vs. U-factor with Reduced-web CMU, Climate Zone 2A

Observing Figure 14, the following conclusions can be drawn:

- HVAC cost bears the same relationships to mass and insulation location as discussed for Figure 10.
- The reduced-web CMU with integral insulation provides reduction in HVAC costs over standard CMU with empty (air-filled) ungrouted cells when interior insulation is applied, especially at lower insulation levels.
- Interestingly, when the insulation is on the inside, the reduced-web CMU with integral insulation preforms better with a lower density, and when the insulation is exterior higher density improves performance.
- The benefit of the reduced-web CMU with integral insulation compared to standard CMU is much greater when insulation is on the inside. In fact, when the insulation is exterior, similar density standard CMU walls have almost identical energy performance.

The relationships are similar in the colder climate zone shown in Figure 15, but the differences are not as great between treatments as in the warmer climate zone shown in Figure 14.

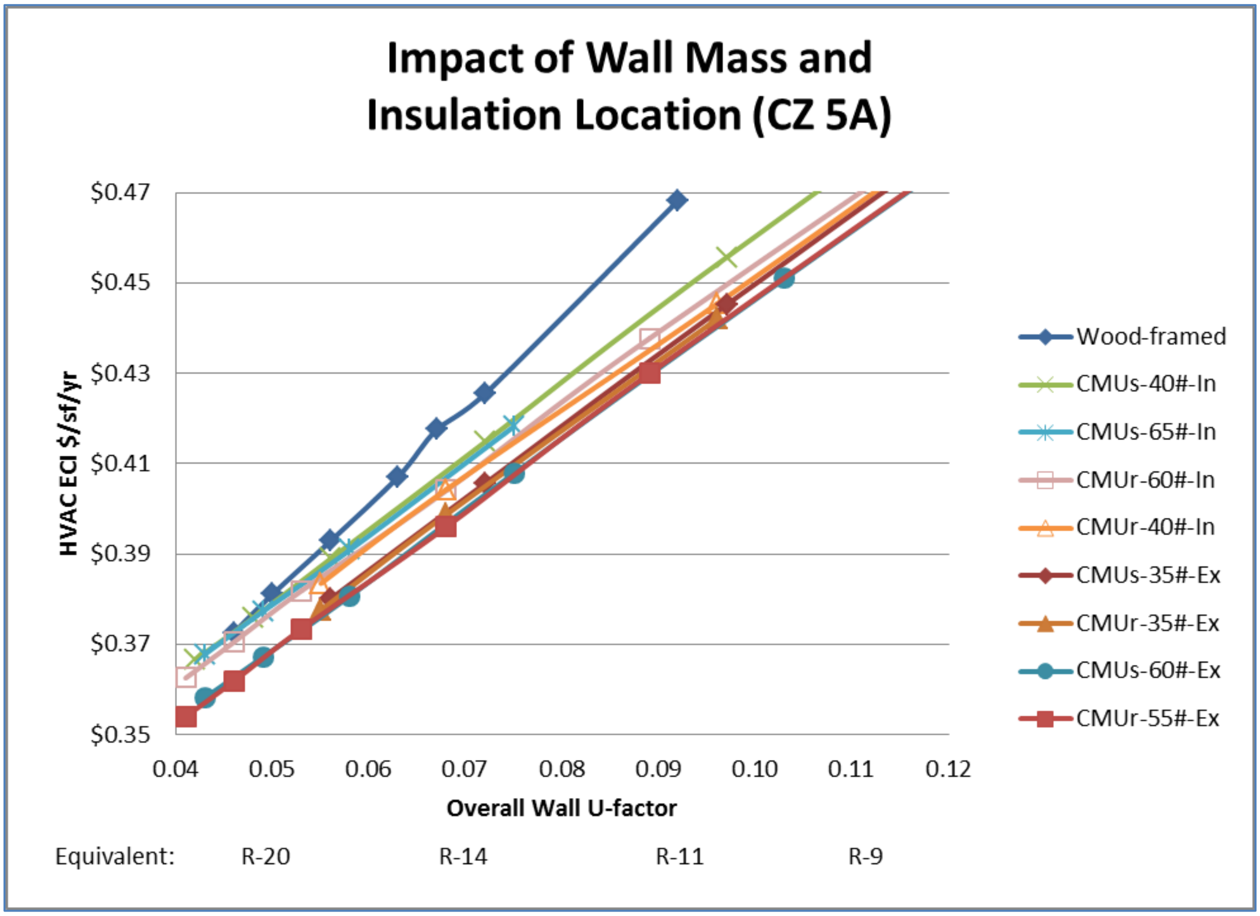


Figure 15. ECI vs. U-factor with Reduced-web CMU, Climate Zone 5A

5.6 Insulation Location on CMU and ICF

A comparison of mass and insulation location was made with heavily insulated walls. The compared walls include:

- A CMU wall with interior R-19 furred insulation and R-5 board insulation with 115 pcf density CMU with grout at 48 in. on center (designated CMUs115,e, 48''oc,R24In)
- CMU wall with the same density as the first wall with no interior insulation and with exterior board insulation selected to result in the same overall wall U-factor (designated CMUs115,e, 48''oc,R25Ex)
- ICF walls with the 120 pcf density concrete and R-24 board insulation split evenly between interior and exterior insulation with both 4 in. and 6 in. thick concrete cores (designated ICF-120,-, 4.0''tk,R24Sp and ICF-120,-, 6.0''tk,R24Sp)
- A wood frame wall with R-19 cavity insulation and R-7 board insulation is also included (designated Wood---,-, 5.5''tk,R26Ex)

Analysis results are shown in Table 12 for three US climate zones, with ECI and EUI graphed in Figure 16 and Figure 17 respectively.

Table 12. Results for Insulation Location on CMU vs. ICF & Wood Walls

Residential Energy Use Analysis of Wall Type Impact	**Insulation Location on CMU & ICF vs. Wood Frame**						
Wall Case	**Energy Use Index (EUI) kBtu/sf-yr**			**Energy Cost Index (ECI) $/sf-yr**			**Wall Uo**
Wall Type & CMU Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	**Heat EUI**	**Cool EUI**	**HVAC EUI**	**Heat ECI**	**Cool ECI**	**HVAC ECI**	
CMUs115,e, 48''oc,R24In-CZ:2A	5.37	7.98	13.36	$0.062	$0.260	$0.322	0.043
CMUs115,e, 48''oc,R25Ex-CZ:2A	4.94	7.75	12.70	$0.057	$0.252	$0.310	0.043
ICF-120,-, 4.0''tk,R24Sp-CZ:2A	5.18	7.83	13.02	$0.060	$0.255	$0.315	0.038
ICF-120,-, 6.0''tk,R24Sp-CZ:2A	5.13	7.81	12.93	$0.059	$0.254	$0.314	0.038
Wood---,-, 5.5''tk,R26Ex-CZ:2A	5.60	7.98	13.58	$0.065	$0.260	$0.325	0.046
CMUs115,e, 48''oc,R24In-CZ:4B	8.95	4.89	13.84	$0.105	$0.159	$0.265	0.043
CMUs115,e, 48''oc,R25Ex-CZ:4B	8.43	4.68	13.11	$0.099	$0.152	$0.251	0.043
ICF-120,-, 4.0''tk,R24Sp-CZ:4B	8.80	4.86	13.66	$0.104	$0.158	$0.262	0.038
ICF-120,-, 6.0''tk,R24Sp-CZ:4B	8.75	4.85	13.60	$0.103	$0.158	$0.261	0.038
Wood---,-, 5.5''tk,R26Ex-CZ:4B	9.28	4.88	14.17	$0.109	$0.159	$0.268	0.046
CMUs115,e, 48''oc,R24In-CZ:6B	22.15	2.46	24.61	$0.248	$0.080	$0.328	0.043
CMUs115,e, 48''oc,R25Ex-CZ:6B	21.87	2.29	24.16	$0.244	$0.075	$0.318	0.043
ICF-120,-, 4.0''tk,R24Sp-CZ:6B	21.53	2.42	23.96	$0.241	$0.079	$0.319	0.038
ICF-120,-, 6.0''tk,R24Sp-CZ:6B	21.43	2.41	23.85	$0.239	$0.079	$0.318	0.038
Wood---,-, 5.5''tk,R26Ex-CZ:6B	22.80	2.45	25.25	$0.255	$0.080	$0.335	0.046

Cross comparison of ECI differences between the selected wall types is shown in Table 13. Again, the percentage change in cost will differ slightly depending on which wall is considered the base. The base walls are across the top of the table. A negative increase in use is the same as an energy savings for the base wall.

Table 13. Cost Cross Comparison for Insulation Location on CMU vs. ICF & Wood Walls

Energy Cost Comparison	**Insulation Location on CMU & ICF vs. Wood Frame**				
Wall Characteristics	**HVAC Energy Cost of Top Wall is __% more than Left Wall**				
Wall Type & CMU Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	**CMUs115,e, 48''oc,R24In**	**CMUs115,e, 48''oc,R25Ex**	**ICF-120,-, 4.0''tk,R24S**	**ICF-120,-, 6.0''tk,R24S**	**Wood---,-, 5.5''tk,R26E**
CMUs115,e, 48''oc,R24In-CZ:2A	0.0%	-3.9%	-2.2%	-2.7%	0.8%
CMUs115,e, 48''oc,R25Ex-CZ:2A	4.1%	0.0%	1.8%	1.3%	4.9%
ICF-120,-, 4.0''tk,R24Sp-CZ:2A	2.3%	-1.7%	0.0%	-0.5%	3.1%
ICF-120,-, 6.0''tk,R24Sp-CZ:2A	2.8%	-1.2%	0.5%	0.0%	3.6%
Wood---,-, 5.5''tk,R26Ex-CZ:2A	-0.8%	-4.7%	-3.0%	-3.5%	0.0%
CMUs115,e, 48''oc,R24In-CZ:4B	0.0%	-5.1%	-1.0%	-1.3%	1.5%
CMUs115,e, 48''oc,R25Ex-CZ:4B	5.3%	0.0%	4.3%	3.9%	6.9%
ICF-120,-, 4.0''tk,R24Sp-CZ:4B	1.0%	-4.1%	0.0%	-0.4%	2.5%
ICF-120,-, 6.0''tk,R24Sp-CZ:4B	1.4%	-3.8%	0.4%	0.0%	2.9%
Wood---,-, 5.5''tk,R26Ex-CZ:4B	-1.5%	-6.5%	-2.4%	-2.8%	0.0%
CMUs115,e, 48''oc,R24In-CZ:6B	0.0%	-2.9%	-2.5%	-3.0%	2.2%
CMUs115,e, 48''oc,R25Ex-CZ:6B	3.0%	0.0%	0.4%	-0.1%	5.2%
ICF-120,-, 4.0''tk,R24Sp-CZ:6B	2.5%	-0.4%	0.0%	-0.5%	4.8%
ICF-120,-, 6.0''tk,R24Sp-CZ:6B	3.1%	0.1%	0.5%	0.0%	5.3%
Wood---,-, 5.5''tk,R26Ex-CZ:6B	-2.1%	-4.9%	-4.5%	-5.0%	0.0%

Observations from the insulation location comparison for these heavily insulated walls are as follows:

- Exterior insulation on CMU walls compared to interior insulation reduces energy use from 3% to 5%, with greater reductions in moderate climate zones.
- ICF walls with insulation on either side of a concrete core result in more energy use than exterior insulated CMU walls and less than interior insulated CMU walls.
- In all climate zones, wood walls with similar nominal insulation result in more energy use than any of the masonry options shown.

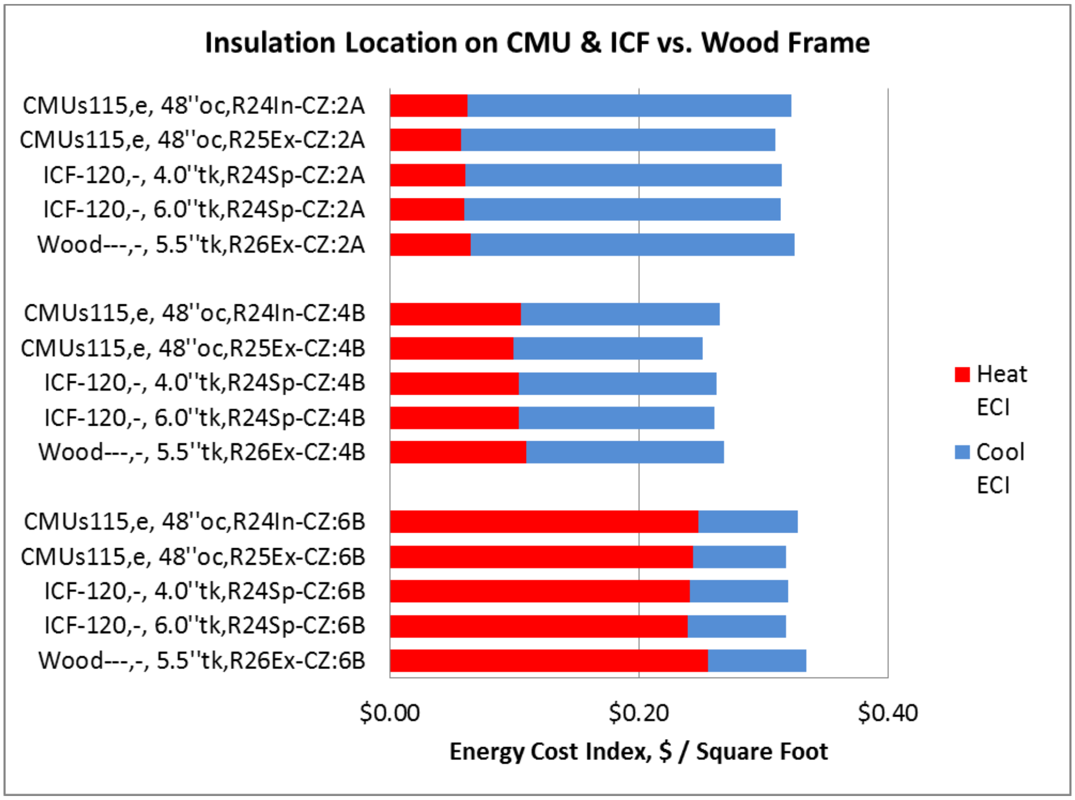


Figure 16. ECI for Insulation Location on CMU vs. ICF & Wood Walls

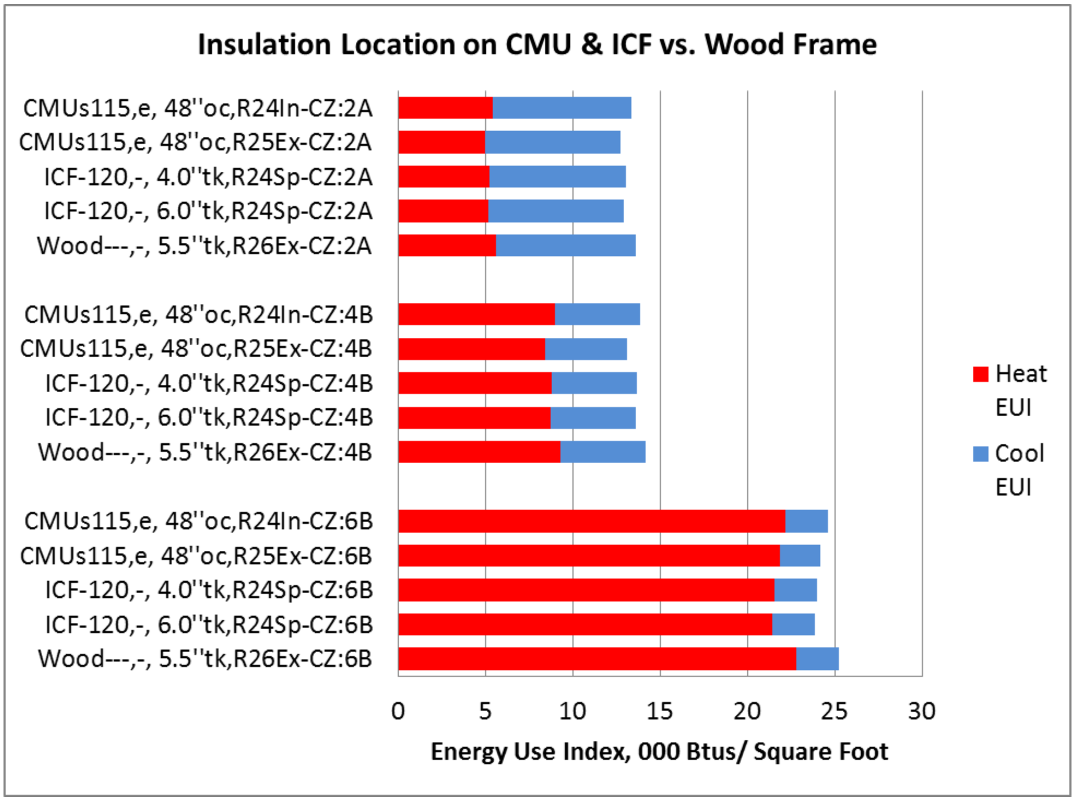


Figure 17. EUI for Insulation Location on CMU vs. ICF & Wood Walls

5.7 National Wood-Frame vs. Insulated CMU comparison

A comparison of R-13 wood -construction and standard-web with insulation is made. Analysis results are shown in Table 15 for all national climate zones, with graphic results on following pages.

Table 14. National Results for Wood vs. CMU Walls

Residential Energy Use Analysis of Wall Type Impact	**R-13 Wood vs. CMU with reflective R-5 Board**						
Wall Case	Energy Use Index (EUI) * kBtu/sf-yr			Energy Cost Index (ECI) * $/sf-yr			
Wall Type & CMU Density; Cell Fill; Grout o.c. or Wall thickness; Nominal Insulation R-Value & Location; Climate Zone	**Heat EUI**	**Cool EUI**	**HVAC EUI**	**Heat ECI**	**Cool ECI**	**HVAC ECI**	**HVAC ECI Cost Difference**
Wood---,-, 3.5''tk,R13Co-CZ:1A	1.11	12.10	13.21	$0.014	$0.394	$0.408	-$0.004
CMUs115,e, 48''oc,R08In-CZ:1A	0.65	12.14	12.80	$0.008	$0.395	$0.403	-1.1%
Wood---,-, 3.5''tk,R13Co-CZ:2A	8.24	8.82	17.06	$0.096	$0.287	$0.383	-$0.021
CMUs115,e, 48''oc,R08In-CZ:2A	7.08	8.62	15.69	$0.082	$0.280	$0.362	-5.5%
Wood---,-, 3.5''tk,R13Co-CZ:2B	5.12	12.84	17.96	$0.064	$0.418	$0.482	-$0.028
CMUs115,e, 48''oc,R08In-CZ:2B	3.60	12.59	16.19	$0.045	$0.410	$0.454	-5.8%
Wood---,-, 3.5''tk,R13Co-CZ:3A	13.84	6.74	20.58	$0.158	$0.219	$0.378	-$0.017
CMUs115,e, 48''oc,R08In-CZ:3A	13.01	6.56	19.57	$0.147	$0.213	$0.361	-4.5%
Wood---,-, 3.5''tk,R13Co-CZ:3B	8.97	7.20	16.17	$0.106	$0.235	$0.341	-$0.037
CMUs115,e, 48''oc,R08In-CZ:3B	7.12	6.77	13.89	$0.083	$0.220	$0.303	-11.0%
Wood---,-, 3.5''tk,R13Co-CZ:3C	10.05	1.80	11.85	$0.118	$0.059	$0.177	-$0.047
CMUs115,e, 48''oc,R08In-CZ:3C	7.91	1.19	9.10	$0.092	$0.039	$0.130	-26.3%
Wood---,-, 3.5''tk,R13Co-CZ:4A	20.64	4.82	25.46	$0.235	$0.157	$0.392	-$0.015
CMUs115,e, 48''oc,R08In-CZ:4A	20.06	4.61	24.67	$0.226	$0.150	$0.376	-3.9%
Wood---,-, 3.5''tk,R13Co-CZ:4B	14.89	5.51	20.40	$0.176	$0.179	$0.355	-$0.041
CMUs115,e, 48''oc,R08In-CZ:4B	13.02	5.00	18.02	$0.151	$0.163	$0.314	-11.5%
Wood---,-, 3.5''tk,R13Co-CZ:4C	19.26	3.01	22.27	$0.224	$0.098	$0.322	-$0.034
CMUs115,e, 48''oc,R08In-CZ:4C	17.92	2.55	20.47	$0.205	$0.083	$0.288	-10.4%
Wood---,-, 3.5''tk,R13Co-CZ:5A	30.67	3.88	34.55	$0.342	$0.126	$0.468	-$0.008
CMUs115,e, 48''oc,R08In-CZ:5A	30.66	3.69	34.36	$0.340	$0.120	$0.460	-1.8%
Wood---,-, 3.5''tk,R13Co-CZ:5B	21.81	4.12	25.93	$0.250	$0.134	$0.384	-$0.028
CMUs115,e, 48''oc,R08In-CZ:5B	20.72	3.71	24.43	$0.235	$0.121	$0.355	-7.4%
Wood---,-, 3.5''tk,R13Co-CZ:6A	35.37	2.71	38.08	$0.392	$0.088	$0.480	-$0.009
CMUs115,e, 48''oc,R08In-CZ:6A	35.43	2.50	37.93	$0.390	$0.081	$0.471	-1.8%
Wood---,-, 3.5''tk,R13Co-CZ:6B	31.82	2.78	34.60	$0.357	$0.090	$0.447	-$0.023
CMUs115,e, 48''oc,R08In-CZ:6B	31.13	2.41	33.54	$0.346	$0.079	$0.424	-5.1%
Wood---,-, 3.5''tk,R13Co-CZ:7	48.06	1.95	50.01	$0.528	$0.063	$0.591	-$0.006
CMUs115,e, 48''oc,R08In-CZ:7	48.34	1.69	50.03	$0.530	$0.055	$0.585	-1.0%
Wood---,-, 3.5''tk,R13Co-CZ:8	70.17	1.59	71.75	$0.769	$0.052	$0.820	$0.003
CMUs115,e, 48''oc,R08In-CZ:8	71.13	1.35	72.48	$0.779	$0.044	$0.823	0.4%

* Fan energy use and cost included in heating, cooling, and HVAC.   Wall 1 & 2 Uo: 0.092 0.101

The compared walls include:

- Wood-frame wall with R-13 insulation; U 0.092 (designated Wood---,-, 3.5”tk,R13Co)
- A standard CMU wall with 115 lb/ft^3 density CMU, grout at 48” on center, and empty cells. There is R-5 board insulation on the interior of the CMU with a reflective furred air space and gypsum wallboard. This wall is designated a nominal R-8 to distinguish it from the Fi-foil R-7 product; U 0.101 (designated CMUs115,e, 48"oc,R08In)

The CMU wall results in lower energy use and cost in climate zones 1 through 6. ECI and EUI are graphed in Figure 18 and Figure 19 respectively.

The energy use and cost savings for the CMU wall are generally greater in the B climate zones (western states with greater temperature swings) than A climate zones (eastern states) except for climate zones 2A and 2B where results are similar. The energy use and cost savings for the CMU wall are generally greater in the C climate zones (western coast with milder temperatures) than A climate zones (eastern states).

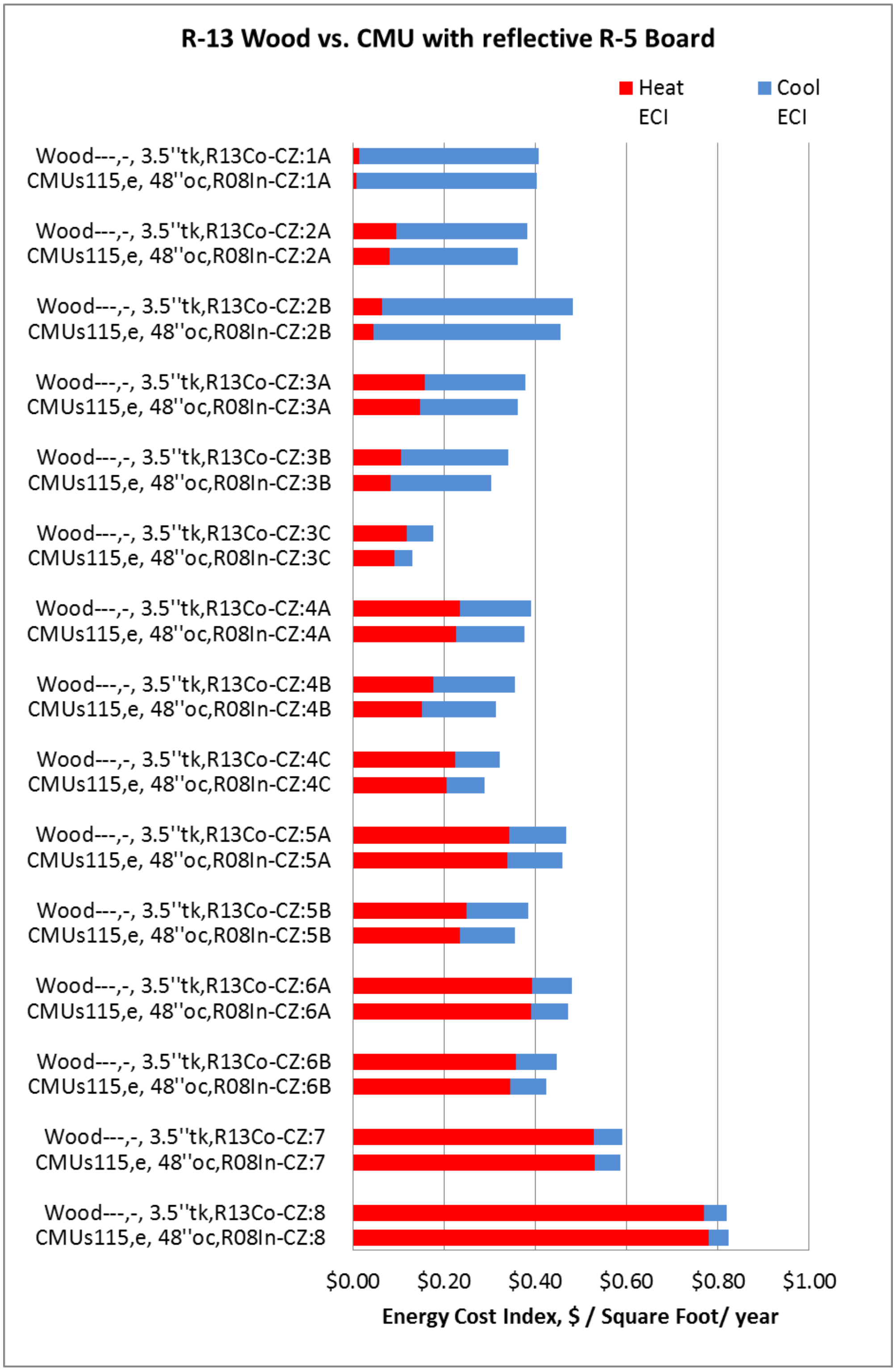


Figure 18. National ECIs for Wood vs. CMU Walls

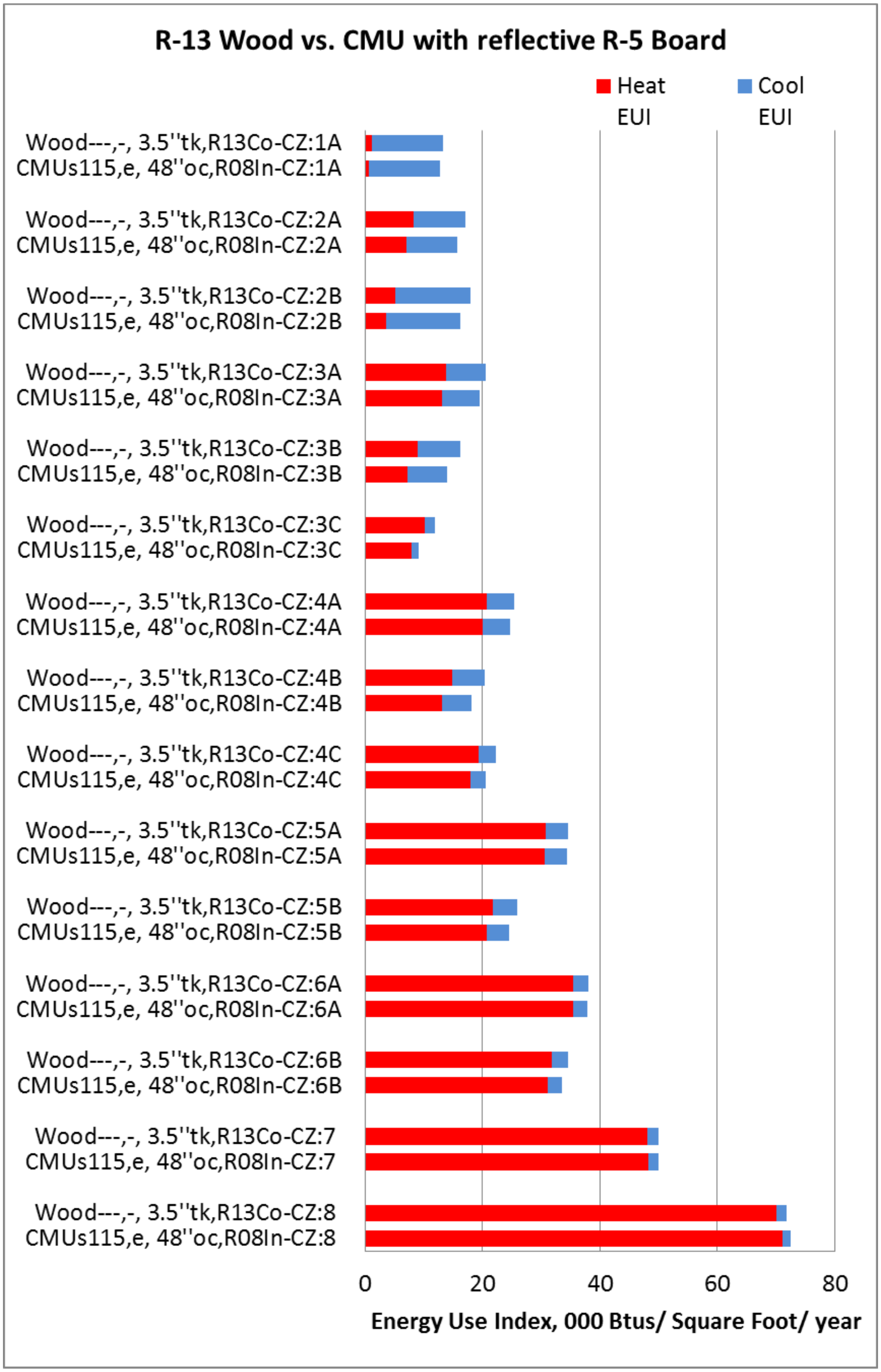


Figure 19. National EUIs for Wood vs. CMU Walls

Appendix A.1. EnergyPlus Model Parameters

	Item	Description				Data Source for PNNL Prototype	Data Source for FSEC Prototype
General							
	Prototype	**PNNL Prototypes**		**FSEC Prototypes**			
	Building Prototype	**PNNL 1**	**PNNL 2**	**FSEC 1**	**FSEC 2**		
	Climate Zones	Zone 1A: Miami (very hot, humid) Zone 2A: Houston (hot, humid) Zone 2B: Phoenix (hot, dry) Zone 3A: Memphis (warm, humid) Zone 3B: El Paso (warm, dry) Zone 3C: San Francisco (warm,marine) Zone 4A: Baltimore (mild, humid) Zone 4B: Albuquerque (mild, dry) Zone 4C: Salem (mild, marine) Zone 5A: Chicago (cold, humid) Zone 5B: Boise (cold, dry) Zone 6A: Burlington (cold, humid) Zone 6B: Helena (cold, dry) Zone 7: Duluth (very cold) Zone 8: Fairbanks (subarctic)		Miami **Orlando** Jacksonville		Masonry Analysis SOW	Masonry Analysis SOW
	Available fuel types	Natural Gas/Electricity		Electricity			
	Building Type (Principal Building Function)	**Residential**		**Residential**			
Building Shell							

	Item	Description				Data Source	Data Source
	Total Floor Area (sq feet)	2,000 (50 ft x 40 ft x 1 story)	2,200 (26.22 ft x 41.95 ft x 2 stories)	2,000 (50 ft x 40 ft x 1 story)	2,200 (26.22 ft x 41.95 ft x 2 stories)	Reference: Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes for the 2-story model and FMAEFTechnical Group input for the 1-story model	Florida EnergyGauge Model Input Summary Reports
	Building shape	**Rectangular**		**Rectangular**			
	Aspect Ratio	1.25	1.6	1.25	1.6		
	Number of Floors	1	2	1	2		
	Window Fraction (Window-to-Floor Ratio)	Average Total: 15.0% divided equally among all facades		Average Total: 15.0% divided equally among all facades		Reference: Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes	Florida EnergyGauge Model Input Summary Reports
	Window Locations	All facades		All facades			
	Shading Geometry	none		none			
	Orientation	Back of the house faces North		Back of the house faces North			
	Thermal Zoning	The house is divided into three thermal zones: 'living space', 'attic' and 'crawlspace' when applicable.		The house is divided into two thermal zones: 'living space' and 'attic'.			

	Item	Description		Data Source	Data Source
	Floor to ceiling height (ft)	8.5	FSEC1: 8.0' FSEC2: 8.0' 1st floor; 9.0' 1st floor;		Florida EnergyGauge Model Input Summary Reports
	Exterior walls				
	Construction	Depends on whether wall is wood-framed or mass-wall	Depends on whether wall is wood-framed or mass-wall		
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	IECC Requirements Residential; Walls, above grade	IECC Requirements Residential; Walls, above grade		
	Dimensions	based on floor area and aspect ratio	based on floor area and aspect ratio		
	Tilts	vertical	vertical		
	Roof				
	Construction	Composition Shingles	Composition Shingles		
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	IECC Requirements Residential; Roofs, Insulation entirely on attic floor	IECC Requirements Residential; Roofs, Insulation entirely on attic floor		
	Tilts and orientations	Gabled Roof with a Slope of 4/12	Hipped Roof with a Slope of 5/12		
	Window				
	Dimensions	based on window fraction and conditioned floor area	based on window fraction and conditioned floor area		
	Glass-Type and frame	Hypothetical window with the exact U-factor and SHGC shown below	Hypothetical window with the exact U-factor and SHGC shown below		
	U-factor (Btu / h * ft^2 * °F)	IECC Requirements Residential Glazing	IECC Requirements Residential Glazing		
	SHGC (all)				

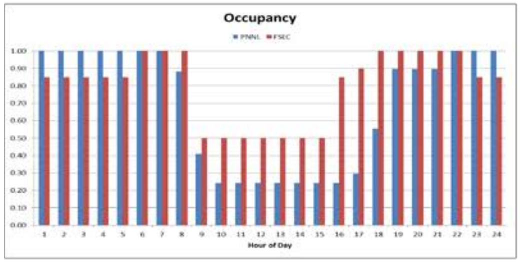
	Item	Description		Data Source	Data Source
	Operable area	100%	100%		
	Skylight				
	Dimensions	Not Modeled	Not Modeled		
	Glass-Type and frame				
	U-factor (Btu / h * ft^2 * °F)				
	SHGC (all)				
	Visible transmittance				
	Foundation				
	Foundation Type	Two Foundation Types are Modeled- PNNL1: Slab-on Grade PNNL2: Vented Crawlspace Depth 2'	One Foundation Type is Modeled- i. Slab-on Grade	Masonry Analysis SOW	Florida EnergyGauge Model Input Summary Reports
	Insulation level	IECC Requirements for floor and slab insulation, as applicable	IECC Requirements for floor and slab insulation, as applicable		IECC
	Dimensions	based on floor area and aspect ratio	based on floor area and aspect ratio		
	Internal Mass	8 lbs/ft2 of floor area	8 lbs/ft2 of floor area	IECC 2012 section 405	Florida EnergyGauge Model Input Summary Reports
	Infiltration (ACH)	2012 IECC: 5 or 3 Air Changes/Hour at 50 Pa (5 or 3 ACH50) depending on climate zone	2012 IECC: 5 Air Changes/Hour at 50 Pa (5 ACH50) in Florida climate zones	IECC 2012	Florida EnergyGauge Model Input Summary Reports
HVAC					
	System Type				
	Heating type	Natural Gas Furnace	Heat Pump cooling	Masonry Analysis SOW	Florida EnergyGauge Model Input Summary Reports
	Cooling type	Central DX Air-Conditioner	Heat Pump with supplemental electric resistance		
	HVAC Sizing				
	Air Conditioning	autosized to design day	autosized to design day		

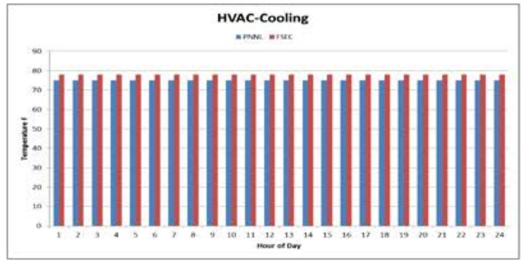
	Item	Description		Data Source	Data Source
	Heating	autosized to design day	autosized to design day		
	HVAC Efficiency				
	Air Conditioning	SEER 13	SEER 13	Federal minimum efficiency	Federal minimum efficiency
	Heating	AFUE 78%	HSPF 7.7	Federal minimum efficiency	Federal minimum efficiency
	HVAC Control				
	Thermostat Setpoint	75°F Cooling/72°F Heating	75°F Cooling/72°F Heating	IECC 2012 section 405	Florida EnergyGauge Model Input Summary Reports
	Thermostat Setback	No setback	No setback		
	Ventilation	60 CFM continuous	60 CFM continuous	IRC 2012	IRC 2012
	Supply Fan				
	Fan operation	Cycling Fan	0.5 W/cfm up to SEER 13 and 0.375 W/cfm for SEER 14 and above		Comparison of the ENERGYGAUGE USA and Beopt Building Energy Simulation Programs. DS Parker. August 2009
	Supply Fan Total Efficiency (%)	Depending on the fan motor size		Residential Centralized Air Condtioners (CAC) rule-making TSD	
	Supply Fan Pressure Drop	Depending on the fan supply air cfm			
	Domestic Hot Water				
	DHW type	Individual Residential Water Heater with Storage Tank	Individual Residential Water Heater with Storage Tank		
	Fuel type	Natural Gas/Electricity	Electricity		
	Thermal efficiency (%)	EF = 0.59 for Gas-fired Water Heaters	EF = 0.9	Federal minimum efficiency	Florida EnergyGauge Model Input Summary Reports
	Tank Volume (gal)	40 for Gas-fired Water Heaters	50	Reference: Building	Florida EnergyGauge

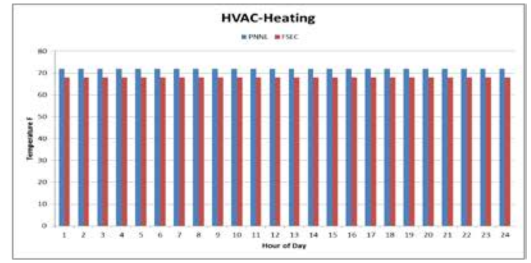
	Item	Description		Data Source	Data Source
	Hot Water Schedule	See the **Schedules** tab	Unknown	America Research Benchmark	Model Input Summary Reports
Internal Loads & Schedules					
	Lighting				
	Average power density (W/ft^2)	Living space: Interior Lighting Power Density is 0.68 W/sq.ft	See the **Internal Gains** tab for the detailed calculations	Reference: Building America Research Benchmark	Florida EnergyGauge Model Input Summary Reports
	Schedule	See the **Schedules** tab	See the **Schedules** tab		
	Internal Gains				
	Load (Btu/day)	17,900 + 23.8 x CFA + 4104 x Nbr See the **Internal Gains** tab for the detailed calculations	See the **Internal Gains** tab for the detailed calculations	Reference: IECC 2006 and Building America Research Benchmark	Florida EnergyGauge Model Input Summary Reports
	Schedule	See the **Schedules** tab	See the **Schedules** tab		
	Occupancy				
	Average people	3 3	4		
	Schedule	See the **Schedules** tab	See the **Schedules** tab		
	Exterior Lighting				
	Annual Energy (kWh)	231 kWh/yr 192 kWh/yr	Lighting energy on the **Internal Gains** tab appears to include exterior lighting as well.	Reference: Building America Research Benchmark	Florida EnergyGauge Model Input Summary Reports
	Schedule	See the **Schedules** tab	Unknown		

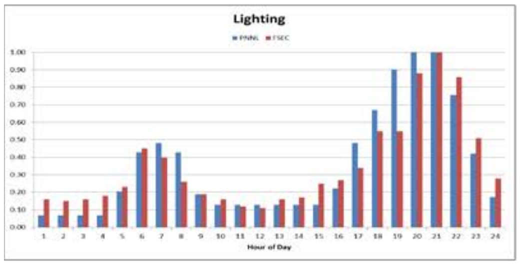
	Item	Description		Data Source	Data Source
	Garage Lighting				
	Annual Energy (kWh)	27 kWh/yr 27 kWh/yr	Lighting energy on the **Internal Gains** tab appears to include garage lighting as well.	Reference: Building America Research Benchmark	Florida EnergyGauge Model Input Summary Reports
	Schedule	See the **Schedules** tab	Unknown		

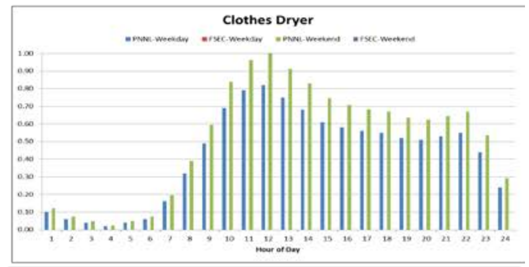
Appendix A.2. Schedule Plots

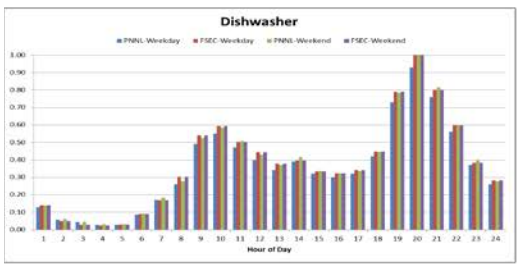


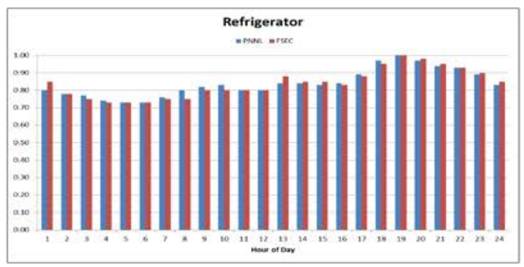


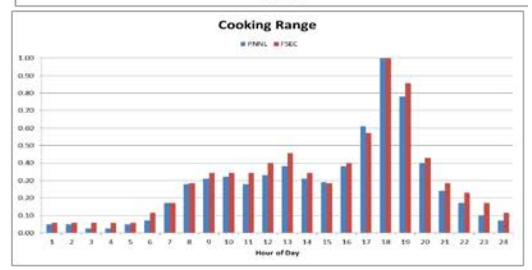


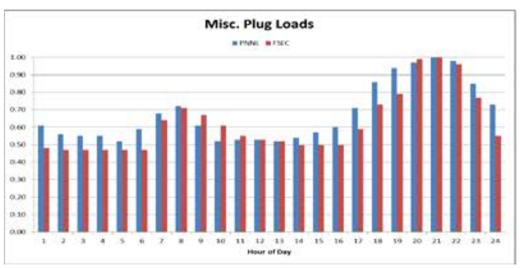












Appendix B.1. Material Parameters

Exterior Wall Layers	Conductivity {Btu-in/hr-ft2-F}	Density {lbm/ft3}	Specific Heat {Btu/lbm-F}	Typical Thickness {inches}	Typical R-value {hr-ft2-F/Btu}	Source Conductivity/ R-value	Source for Density	Source for Specific Heat
Exterior airfilm	NA	NA	NA	NA	0.170	HoF 26.1 (Table 1)	NA	NA
Gyp_board_1/2in	1.100	40.000	0.270	0.500	0.455	HoF 26.5 (gypsum board)	same	same
OSB_7/16in	0.706	41.000	0.450	0.438	0.620	HoF 26.5 (OSB 7/16")	same	same
Wood Stud (2x4)	0.800	28.000	0.390	3.500	4.375	HoF 27.3 (example 3)	HoF 26.9 for (Spruce/Pine/Fir)	HoF 26.9 for (Spruce/Pine/Fir)
Wood Stud (2x6)	0.800	28.000	0.390	5.500	6.875	HoF 27.3 (example 3)	HoF 26.9 for (Spruce/Pine/Fir)	HoF 26.9 for (Spruce/Pine/Fir)
CMU Material 085	3.300	85.000	0.220	1.250	0.379	NCMA Thermal Catalog 2	SOW	HoF 26.8 (Light wt. aggregate)
CMU Material 115	6.000	115.000	0.220	1.250	0.208	NCMA Thermal Catalog 2	SOW	HoF 26.8 (Normal wt. aggregate)
CMU Material 135	8.900	135.000	0.220	1.250	0.140	NCMA Thermal Catalog 2	SOW	HoF 26.8 (Normal wt. aggregate)
Poured Concrete 120 pcf (4") in ICF	7.750	120.000	0.220	4.000	0.516	HoF 26.8 (average for concretes 120 pcf)	SOW	HoF 26.8 (average for concretes 120 pcf)
Poured Concrete 120 pcf (6") in ICF	7.750	120.000	0.220	6.000	0.774	HoF 26.8 (average for concretes 120 pcf)	SOW	HoF 26.8 (average for concretes 120 pcf)
Poured Concrete 145 pcf (4") in ICF	16.000	145.000	0.220	4.000	0.250	Dynateck research with embedded sensors	SOW	HoF 26.8 (average for concretes 140 pcf)
Poured Concrete 145 pcf (6") in ICF	16.000	145.000	0.220	6.000	0.375	Dynateck research with embedded sensors	SOW	HoF 26.8 (average for concretes 140 pcf)
Polyurethane_foam	0.169	2.000	0.350	3.500	20.650	NCMA TEK 6	Manufacturer data	HoF 26.8 (for low-density polyurethane)
Polyisocyanurate (R5)	0.150	1.900	0.350	0.750	5.000	DOW Tuff-R	HoF 26.6 (average for unfaced, aged polyisocyanurate)	HoF 26.6 (for polyisocyanurate with facers)
EPS insulation (R5)	0.250	1.250	0.350	1.250	5.000	HoF 26.6 (Adjusted to match R5 exactly)	same	same
fiberglass_batt_insulation (R13)	0.269	0.750	0.200	3.500	13.001	90.1-2010 Table A9.4C	HoF 26.8 (average for glass-fiber batts)	HoF 26.8 (average for glass-fiber batts)
fiberglass_batt_insulation (R19)	0.306	0.750	0.200	5.500	18.003	90.1-2010 Table A9.4C	HoF 26.8 (average for glass-fiber batts)	HoF 26.8 (average for glass-fiber batts)

Exterior Wall Layers	Conductivity {Btu-in/hr-ft2-F}	Density {lbm/ft3}	Specific Heat {Btu/lbm-F}	Typical Thickness {inches}	Typical R-value {hr-ft2-F/Btu}	Source Conductivity/ R-value	Source for Density	Source for Specific Heat
FiFoil R4.1	0.183	ignore mass	hence, ignore	0.750	4.098	FiFoil	Conf. call with FMAEF on 4/5/2013	
FiFoil R7	0.212	ignore mass	hence, ignore	1.500	7.075	FiFoil	Conf. call with FMAEF on 4/5/2013	
cement_stucco	9.700	120.000	0.210	0.625	0.064	HoF 26.8	same	same
synthetic_stucco	1.560	100.000	0.210	0.313	0.200	NCMA Tek 6.2C (backed out from R0.2 and thickness 5/16")	same	same as cement_stucco
Grout	10.000	135.000	0.220	5.125	0.513	NCMA Tek 6.2C (inverse of R per inch)	HoF 26.8 (in range)	Van Geem (1985) and HoF 26.8 for Normal wt. aggregate
Reflective Air space[3]	0.268	NA	NA	0.750	2.800	DOW Tuff-R	NA	NA
Non-Reflective Airspace[3]	0.773	NA	NA	0.750	0.940	HoF 26.14 2013 (Table 3) Horiz 50/30/0.82	NA	NA
Non-Reflective Airspace (part of composite ungrouted block cell layer)	5.511	0.082	0.400	5.125	0.930	HoF 26.14 2013 (Table 3) Horiz 50/30/0.82	HoF 1.15 @52F, 60%RH	Hof 1.15; typical delta enthalpy
Interior airfilm	NA	NA	NA	NA	0.680	HoF 26.1 (Table 1)	NA	NA
Mortar	10.000	120.000	0.220	1.250	0.125	NCMA Tek 6.2C R/in = 0.10	HoF 26.11	Same as 'Grout' above

1. All material properties are taken from the 2009 ASHRAE Handbook of Fundamentals (HoF), NCMA Tek 6.2C or ASHRAE Standard 90.1-2010, unless otherwise noted.
2. EnergyPlus adds the interior and exterior air-films automatically during simulation and as a result, these are not included when specifying exterior wall construction layers in the program. These values are shown in the above table for representative purposes only.
3. Conductivity for air spaces back calculated from R-value, and is only appropriate for thickness given

Appendix B.2. Composite Parameters

Table 1a: Composite layer properties for solid grouted and non-grouted (completely empty or foam-insulation-filled) CMU ASTM C90 cases

Wall_Reference	Composite Layer	Fraction_web	Fraction_grout	Fraction_cavity	Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	R-Value of web-core layer	R-value of face-mortar layers (2)	R-value of full wall assembly
CMUs_#.###_R##_R##_no_7.6_085_e_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	5.116	5.125	15.258	0.221	1.002	0.664	2.516
CMUs_#.###_R##_R##_no_7.6_085_F_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	0.729	5.125	16.833	0.233	7.031	0.664	8.545
CMUs_#.###_R##_R##_no_7.6_085_S_So_##	masonry_wall_consol_layer	17.87%	82.13%	0.00%	8.803	5.125	126.064	0.220	0.582	0.664	2.097
CMUs_#.###_R##_R##_no_7.6_115_e_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	5.598	5.125	20.619	0.221	0.915	0.398	2.164
CMUs_#.###_R##_R##_no_7.6_115_F_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	1.211	5.125	22.194	0.230	4.230	0.398	5.479
CMUs_#.###_R##_R##_no_7.6_115_S_So_##	masonry_wall_consol_layer	17.87%	82.13%	0.00%	9.285	5.125	131.426	0.220	0.552	0.398	1.800
CMUs_#.###_R##_R##_no_7.6_135_e_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	6.116	5.125	24.193	0.221	0.838	0.279	1.966
CMUs_#.###_R##_R##_no_7.6_135_F_no_##	masonry_wall_consol_layer	17.87%	0.00%	82.13%	1.730	5.125	25.769	0.228	2.963	0.279	4.091
CMUs_#.###_R##_R##_no_7.6_135_S_So_##	masonry_wall_consol_layer	17.87%	82.13%	0.00%	9.803	5.125	135.000	0.220	0.523	0.279	1.651

Table 1b: Composite layer properties for partially grouted CMU ASTM C90 cases

Wall_Reference	Composite Layer	Fraction_grouted	Fraction_ungrouted		Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	Net Core R-value	R-value of face-mortar layers (2)	R-Value of full wall assembly
CMUs_#.###_R##_R##_no_7.6_085_e_24_##	masonry_wall_consol_layer	33.00%	67.00%		6.058	5.125	51.824	0.220	0.846	0.664	2.360
CMUs_#.###_R##_R##_no_7.6_085_e_48_##	masonry_wall_consol_layer	17.00%	83.00%		5.577	5.125	34.095	0.220	0.919	0.664	2.434
CMUs_#.###_R##_R##_no_7.6_085_e_96_##	masonry_wall_consol_layer	8.00%	92.00%		5.326	5.125	24.122	0.220	0.962	0.664	2.477
CMUs_#.###_R##_R##_no_7.6_085_F_24_##	masonry_wall_consol_layer	33.00%	67.00%		1.880	5.125	52.879	0.223	2.726	0.664	4.241
CMUs_#.###_R##_R##_no_7.6_085_F_48_##	masonry_wall_consol_layer	17.00%	83.00%		1.251	5.125	35.402	0.225	4.097	0.664	5.611
CMUs_#.###_R##_R##_no_7.6_085_F_96_##	masonry_wall_consol_layer	8.00%	92.00%		0.959	5.125	25.572	0.228	5.343	0.664	6.858
CMUs_#.###_R##_R##_no_7.6_115_e_24_##	masonry_wall_consol_layer	33.00%	67.00%		6.568	5.125	57.185	0.220	0.780	0.398	2.029
CMUs_#.###_R##_R##_no_7.6_115_e_48_##	masonry_wall_consol_layer	17.00%	83.00%		6.075	5.125	39.456	0.220	0.844	0.398	2.092
CMUs_#.###_R##_R##_no_7.6_115_e_96_##	masonry_wall_consol_layer	8.00%	92.00%		5.817	5.125	29.484	0.220	0.881	0.398	2.129
CMUs_#.###_R##_R##_no_7.6_115_F_24_##	masonry_wall_consol_layer	33.00%	67.00%		2.532	5.125	58.241	0.222	2.024	0.398	3.272
CMUs_#.###_R##_R##_no_7.6_115_F_48_##	masonry_wall_consol_layer	17.00%	83.00%		1.819	5.125	40.764	0.224	2.818	0.398	4.066
CMUs_#.###_R##_R##_no_7.6_115_F_96_##	masonry_wall_consol_layer	8.00%	92.00%		1.481	5.125	30.933	0.226	3.461	0.398	4.709
CMUs_#.###_R##_R##_no_7.6_135_e_24_##	masonry_wall_consol_layer	33.00%	67.00%		7.104	5.125	60.759	0.220	0.721	0.279	1.850
CMUs_#.###_R##_R##_no_7.6_135_e_48_##	masonry_wall_consol_layer	17.00%	83.00%		6.603	5.125	43.030	0.220	0.776	0.279	1.905
CMUs_#.###_R##_R##_no_7.6_135_e_96_##	masonry_wall_consol_layer	8.00%	92.00%		6.340	5.125	33.058	0.220	0.808	0.279	1.937
CMUs_#.###_R##_R##_no_7.6_135_F_24_##	masonry_wall_consol_layer	33.00%	67.00%		3.160	5.125	61.815	0.222	1.622	0.279	2.750
CMUs_#.###_R##_R##_no_7.6_135_F_48_##	masonry_wall_consol_layer	17.00%	83.00%		2.393	5.125	44.338	0.224	2.141	0.279	3.270
CMUs_#.###_R##_R##_no_7.6_135_F_96_##	masonry_wall_consol_layer	8.00%	92.00%		2.025	5.125	34.507	0.226	2.530	0.279	3.659

Table 2a: Composite layer properties for solid grouted and non-grouted (completely empty or foam-insulation-filled) reduced web walls

Wall_Reference	Composite Layer	Fraction_web	Fraction_grout	Fraction_cavity	Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	R-Value of web-core layer	R-value of face-mortar layers (2)	R-value of full wall assembly
CMUr_#.###_R##_R##_no_7.6_085_e_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	5.313	5.125	7.670	0.222	0.965	0.664	2.479
CMUr_#.###_R##_R##_no_7.6_085_F_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	0.449	5.125	9.417	0.245	11.409	0.664	12.923
CMUr_#.###_R##_R##_no_7.6_085_S_So_##_#_G	masonry_wall_consol_layer	8.94%	90.40%	0.66%	9.401	5.125	129.635	0.220	0.545	0.664	2.060
CMUr_#.###_R##_R##_no_7.6_115_e_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	5.554	5.125	10.350	0.221	0.923	0.398	2.171
CMUr_#.###_R##_R##_no_7.6_115_F_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	0.690	5.125	12.097	0.240	7.422	0.398	8.671
CMUr_#.###_R##_R##_no_7.6_115_S_So_##_#_G	masonry_wall_consol_layer	8.94%	90.40%	0.66%	9.643	5.125	132.316	0.220	0.531	0.398	1.780
CMUr_#.###_R##_R##_no_7.6_135_e_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	5.814	5.125	12.138	0.221	0.882	0.279	2.010
CMUr_#.###_R##_R##_no_7.6_135_F_no_##_#_G	masonry_wall_consol_layer	8.94%	0.00%	91.06%	0.950	5.125	13.884	0.237	5.397	0.279	6.525
CMUr_#.###_R##_R##_no_7.6_135_S_So_##_#_G	masonry_wall_consol_layer	8.94%	90.40%	0.66%	9.902	5.125	134.103	0.220	0.518	0.279	1.646

Table 2b: Composite layer properties for partially grouted reduced web walls

Wall_Reference	Composite Layer	Fraction_grouted	Fraction_ungrouted		Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	Net Core R-value	R-value of face-mortar layers (2)	R-Value of full wall assembly
CMUr_#.###_R##_R##_no_7.6_085_e_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		6.339	5.125	47.918	0.220	0.808	0.664	2.323
CMUr_#.###_R##_R##_no_7.6_085_e_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		5.813	5.125	28.404	0.220	0.882	0.664	2.396
CMUr_#.###_R##_R##_no_7.6_085_e_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		5.542	5.125	17.427	0.221	0.925	0.664	2.439
CMUr_#.###_R##_R##_no_7.6_085_F_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		1.601	5.125	49.089	0.223	3.201	0.664	4.715
CMUr_#.###_R##_R##_no_7.6_085_F_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		0.967	5.125	29.854	0.227	5.299	0.664	6.814
CMUr_#.###_R##_R##_no_7.6_085_F_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		0.677	5.125	19.034	0.231	7.574	0.664	9.088
CMUr_#.###_R##_R##_no_7.6_115_e_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		6.606	5.125	50.599	0.220	0.776	0.398	2.024
CMUr_#.###_R##_R##_no_7.6_115_e_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		6.069	5.125	31.085	0.220	0.844	0.398	2.093
CMUr_#.###_R##_R##_no_7.6_115_e_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		5.790	5.125	20.108	0.221	0.885	0.398	2.134
CMUr_#.###_R##_R##_no_7.6_115_F_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		2.003	5.125	51.769	0.223	2.559	0.398	3.807
CMUr_#.###_R##_R##_no_7.6_115_F_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		1.287	5.125	32.534	0.226	3.981	0.398	5.229
CMUr_#.###_R##_R##_no_7.6_115_F_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		0.954	5.125	21.715	0.230	5.372	0.398	6.620
CMUr_#.###_R##_R##_no_7.6_135_e_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		6.880	5.125	52.386	0.220	0.745	0.279	1.873
CMUr_#.###_R##_R##_no_7.6_135_e_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		6.337	5.125	32.872	0.220	0.809	0.279	1.937
CMUr_#.###_R##_R##_no_7.6_135_e_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		6.054	5.125	21.895	0.221	0.847	0.279	1.975
CMUr_#.###_R##_R##_no_7.6_135_F_24_##_#_G	masonry_wall_consol_layer	33.00%	67.00%		2.362	5.125	53.556	0.223	2.170	0.279	3.299
CMUr_#.###_R##_R##_no_7.6_135_F_48_##_#_G	masonry_wall_consol_layer	17.00%	83.00%		1.596	5.125	34.321	0.226	3.210	0.279	4.339
CMUr_#.###_R##_R##_no_7.6_135_F_96_##_#_G	masonry_wall_consol_layer	8.00%	92.00%		1.236	5.125	23.502	0.229	4.146	0.279	5.275

Table 3: Insulating Sheathing Layer properties for all cases under Insulating Concrete Form walls

Wall_Reference	Batt Insulation Composite Layer and Sheathing Layer (if applicable)	Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	R-value {hr-ft2-F/Btu}
ICF-_#.###_R16_R00_Sp_#.#_###_-_na_Sy_n_G	EPS_foam_R8_outer	0.250	2.000	1.250	0.350	8.000
	EPS_foam_R8_inner	0.250	2.000	1.250	0.350	8.000
ICF-_#.###_R20_R00_Sp_#.#_###_-_na_Sy_n_G	EPS_foam_R10_outer	0.250	2.500	1.250	0.350	10.000
	EPS_foam_R10_inner	0.250	2.500	1.250	0.350	10.000
ICF-_#.###_R24_R00_Sp_#.#_###_-_na_Sy_n_G	EPS_foam_R12_outer	0.250	3.000	1.250	0.350	12.000
	EPS_foam_R12_inner	0.250	3.000	1.250	0.350	12.000

Table 4: Composite layer properties for all cases under Wood Frame Walls

Wall_Reference	Composite Layer and Sheathing Layer (if applicable)	Fraction framing	Fraction cavity	Conductivity {Btu-in/hr-ft2-F}	Thickness {inches}	Density {lbm/ft3}	Sp. Heat {Btu/lbm-F}	R-value {hr-ft2-F/Btu}
Wood_#.###_R00_R13_no_3.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.402	3.500	7.563	0.376	8.709
Wood_#.###_R03_R13_Ex_3.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.402	3.500	7.563	0.376	8.709
	eps_R3			0.250	0.750	1.250	0.350	3.000
Wood_#.###_R05_R13_Ex_3.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.402	3.500	7.563	0.376	8.709
	eps_R5			0.250	1.250	1.250	0.350	5.000
Wood_#.###_R07_R13_Ex_3.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.402	3.500	7.563	0.376	8.709
	eps_R7			0.250	1.750	1.250	0.350	7.000
Wood_#.###_R00_R19_no_5.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.429	5.500	7.563	0.376	12.817
Wood_#.###_R03_R19_Ex_5.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.429	5.500	7.563	0.376	12.817
	eps_R3			0.250	0.750	1.250	0.350	3.000
Wood_#.###_R05_R19_Ex_5.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.429	5.500	7.563	0.376	12.817
	eps_R5			0.250	1.250	1.250	0.350	5.000
Wood_#.###_R07_R19_Ex_5.5_n-a_-_16_Sy_n_G	wood_wall_consol_layer	25.00%	75.00%	0.429	5.500	7.563	0.376	12.817
	eps_R7			0.250	1.750	1.250	0.350	7.000

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