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Barriers to Greater Penetration of Energy Efficient Wall Assemblies in the United States Housing Market

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EXECUTIVE SUMMARY

Figure 1 The ENJOY! House
Source: Momenta Creative

In 2010, Rutgers, The State University of New Jersey and the New Jersey Institute of Technology (NJIT) partnered to compete as *Team New Jersey* in the U.S. Department of Energy Solar Decathlon 2011 (SD2011) competition. *Team New Jersey* was one of 20 collegiate teams, selected from an international pool of 45 applicants, challenged to design, build, and operate solar-powered houses that are affordable, energy-efficient, and attractive. A PSE&G Technology Demonstration Grant helped support the construction of *Team New Jersey's* ENJOY! demonstration house. The ENJOY! House was constructed with precast concrete insulated panels and featured many other innovative design strategies such as evacuated solar thermal tubes, an inverted hip roof for rainwater collection and an innovative home automation system that integrated a Siemens Apogee controller (typically used in commercial buildings) with a Control4 user interface (user-friendly app on a tablet or smartphone) that controlled HVAC, lighting, and home entertainment equipment. In the period following the competition, team members, including the Rutgers Center for Green Building (RCGB) continue to assess the commercial potential of specific innovations inspired by the competition experience, including barriers to greater penetration of energy efficient wall assemblies in the U.S. residential market, the focus of this White Paper.

Although wood frame construction continues to be the predominant wall assembly system used in the U.S. residential housing market, there are several alternative wall assembly systems including precast concrete panels, insulated concrete forms (ICFs), structural insulated panels (SIPs) and autoclaved aerated concrete (AAC) that perform equally or better in terms of energy performance, resistance to hazards such as fire, winds and earthquakes, and improved indoor environmental quality, although not always in terms of their cost (see Table 1) When paired with spray foam insulation, wood frame construction achieves some of these benefits as well, but at increased cost.

◉	◓	○	◒	●
Excellent	Very Good	Good	Fair	Poor

	WOOD FRAME WALL	PRECAST CONCRETE SANDWICH PANEL	INSULATED CONCRETE FORMS (ICFS)	STRUCTURAL INSULATED PANELS (SIPS)	AUTOCLAVED AERATED CONCRETE (AAC)
MATERIAL COST	◓	◒	◒	○	○
LABOR COST	◓	○	◒	○	○
EQUIPMENT COST	◉	○	○	○	○
TIME ON SITE	◒	◓	○	◉	◓
ENERGY EFFICIENCY	◓	◓	◓	◉	○
WIND RESISTANCE	◒	◓	◉	◓	○
FIRE RESISTANCE	◒	◉	◓	○	◉
SEISMIC RESISTANCE	○	◓	◓	◉	○
INSECT/MOLD	◒	◓	○	○	◉
INDOOR AIR QUALITY	◒	◓	◓	◓	◓
ACOUSTIC PERFORMANCE	◒	◓	◉	◒	◉
MAINTENANCE COST	◒	◓	◓	◓	◓

Table 1 Wall Assembly Comparison, Rutgers Center for Green Building 2013

This White Paper identifies several barriers to market penetration of alternative wall assemblies such as increased cost and lack of financing, limited workforce training and institutional factors including codes, environmental regulations and industry structure. Another significant barrier to market penetration, lack of information about the relative benefits of wall assembly types, is addressed head-on in this research, resulting in the Consumer Reports style of comparison displayed in Table 1.

This research also identifies a number of other potential strategies to address market barriers including continued research into materials benefits, dissemination of construction methods best practices for various material/assembly types, the promotion of life cycle cost protocols and financing mechanisms, research into consumer and building occupant behavior across different housing types, policy and regulation amendments, and workforce training and education.

The Rutgers Center for Green Building has been implementing these and related strategies and has identified the need for further action in several areas including research, training, policy/regulation, and the dissemination of information. This work is consistent with the Center's objective to work with industry partners to promote better performing buildings and satisfied occupants, regardless of the type of materials or assembly.

INTRODUCTION: CHARACTERIZATION OF RESIDENTIAL WALL ASSEMBLIES AND MARKET POSITIONS

This report investigates how different wall assemblies compare in terms of energy performance and cost as well as other attributes – wind and hazard resistance, construction methods, indoor environmental quality, and design flexibility and aesthetic appeal. Residential wall assemblies selected for this report include the traditional and predominate stick-built framing and the following, relatively more recent introductions to the U.S. market: pre-cast concrete panels, insulated concrete forms (ICFs), structural insulated panels (SIPs) and autoclaved aerated concrete (AAC). This Introduction provides a brief description on each of these material assemblies and presents its market position.

Wood Frame Construction

Wood frame construction is currently the most commonly used residential wall assembly in the United States. This construction method dates back to Neolithic times and has been used in many parts of the world for thousands of years, particularly in areas with an abundance of lumber. While wood frame construction allows builders to enclose a large area with minimal cost and achieve a wide variety of architectural styles, it is material intensive. Building a typical 2,000 square foot wood frame home with 2x4s requires an acre of forest or 44 individual trees (Freed, 2008). Although the U.S. is home to only 5 percent of the global population, it is responsible for over 15 percent of the world's consumption of wood (Nebraska Energy Office).

Pre-cast Concrete Panels

Concrete has also been an important building material for thousands of years, from early forms of concrete used to build the Egyptian pyramids to use in the construction of the ancient Roman aqueducts to today's many varieties of concrete products (The Concrete

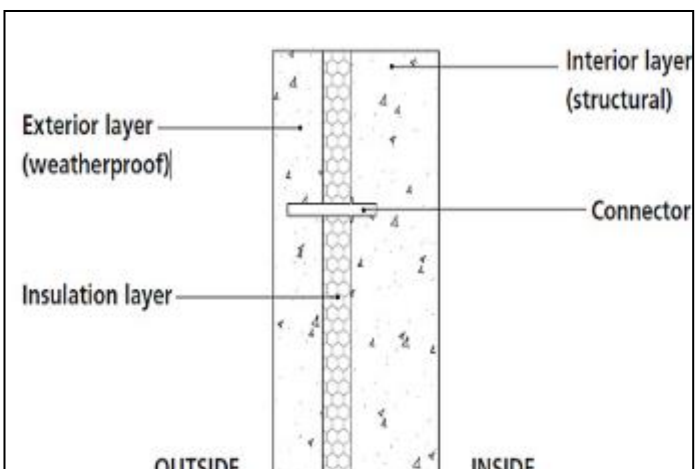

Figure 2 Precast Concrete Panel
Source: http://selector.com/au/suppliers/national-precast-concrete-association-npcaa/products/concrete-sandwich-panels

Network, Timeline of Concrete and Cement History). Precast concrete is made of natural raw materials such as stone, gravel, and sand, which are readily available. Pre-cast concrete panels are produced by casting concrete in a reusable mold which is cured in a controlled environment, then transported to the construction site and lifted into place (Allen and Iano). This is in contrast to the standard concrete that is poured into site-specific forms and cured on site. In the early 20th century, pre-cast concrete paneled buildings were pioneered in Liverpool and then adopted all over the world. The modern uses for pre-cast concrete technology involve a variety of architectural and structural applications, as well as transportation related products (Jersey barriers) and waste products (grease interceptors). The sandwich panels were invented by using a layer of continuous insulation separating the inner and outer layers (See Figure 2). The NJ Solar Decathlon team used double wall precast concrete panels to construct the NJ ENJOY! House.

Insulated Concrete Forms (ICFs)

Insulating concrete forms (ICFs) are wall assemblies composed of rigid plastic foam forms that hold concrete in place during curing. The forms remain in place afterwards and serve as thermal insulation for concrete walls (See Figure 3) (NAHB).

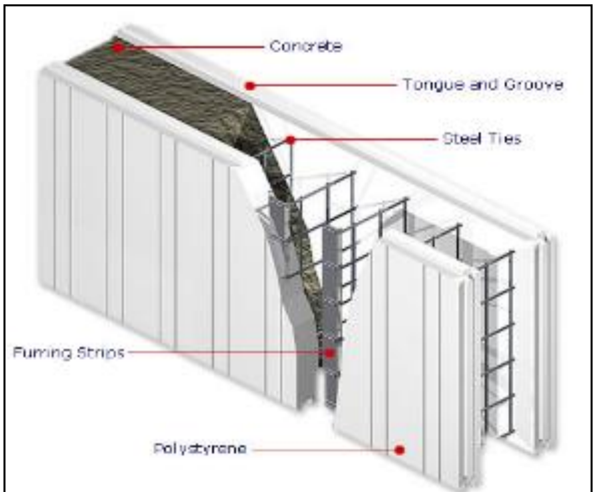

Figure 3 Insulated Concrete Form
Source: http://homerenovation.onsugar.com/Little-Something -About-Insulated-Concrete-Forms-20203938

The first ICF in North America was patented in 1967 (ICF Builder Magazine, 2010). In 1972, a Swiss company developed one of the current best-known ICF products by using recycled cement and polystyrene. Today, most ICFs are manufactured with pure polystyrene or polyurethane. ICFs are most commonly used for the construction of low-rise buildings, ranging from residential to commercial and industrial (Freed, 2012).

Structural Insulated Panels (SIPs)

Figure 4 SIP installation
Source: Andersen

Structural insulated panels (SIPs) are thick, rigid foam insulation sandwiched wall assemblies. This assembly is typically made of an inner core of expanded polystyrene insulation between two structural skins that could be oriented strand board (OSB) or expanded polystyrene foam (EPS). Those components are connected together by splines or connector pieces (Green Building Advisor). The U.S. Forest Service first developed SIPs in the 1930s. The University of Wisconsin then built the first SIPs house in 1937, which was dedicated by First Lady Eleanor Roosevelt, bringing attention to this new technology (The Timber Frame Company). This structure withstood the harsh climate of Wisconsin, serving as a daycare center at the University of Wisconsin-Madison until it was removed in 1998 to make room for a new pharmacy school (Home Front Homes).

Autoclaved Aerated Concrete (AAC)

Figure 5 ACC
Source:© 2012 Hanley Wood, LLC.

The commercial use of Autoclaved Aerated Concrete (AAC) began in Sweden in the early 1920s. Modern use began in the U.S. in the 1990s and was promoted by the foundation of a nationwide group of AAC manufacturers (Mason Contractors Association of America, 2008). AAC is suitable for bearing walls and shear walls of low to medium-rise buildings, both unreinforced and reinforced masonry-type unit (Mason Contractors Association of America, 2008). ACC is a lightweight precast structural product made with all-natural raw materials and laid with thin- bed mortar. It usually weighs one -sixth to one-third the weight of conventional concrete (Mason Contractors Association of America, 2008). AAC starts as a concrete paste, typically made up of Portland cement, sand, and lime. In some cases, leftover fly ash from coal-burning blast furnaces can be substituted for the sand, although this may affect the quality of the resultant AAC block (Kurama *et al*, 2009). This paste is mixed with a small amount of water and aluminum powder and set in a mold for three to four hours. The aluminum chemically reacts with the silicate and forms hydrogen gas, which both greatly expands the material and forms the characteristic porous structure of AAC. This soft version is cut with a wire into the desired form (block, lintel panels or wall panels) and then placed into an autoclave chamber to be steam pressure treated for 12 hours. During this process, the air bubbles are kept in place as the material hardens, resulting in a material that is one sixth to one third the density of conventional concrete, about the same proportion for compressive strength, and a sixth or less thermally conducive when compared to conventional concrete.

MARKET SHARE OF RESIDENTIAL WALL ASSEMBLIES

The home construction industry is made up of almost 100,000 builders who construct approximately 2 million new homes and retrofit nearly 27 million more each year (U.S. DOE, 2008). Figure 6 represents U.S. housing starts between January 2010 and January 2012.

Figure 6 U.S. Housing Starts January 2010 – January 2012
Source: SIPA

Stick-built framing (or wood frame construction) is the predominant wall assembly method in the U.S. residential market. In 2006, new residential construction accounted for about 39 percent of all solid wood products consumed in the United States and new residential construction continues to be the leading market for solid softwood products in the United States (Adair 2008, McKeever 2009). While stick-built framing has provided an accessible and familiar method for building homes, there are several alternative wall assembly technologies that have been introduced into the U.S. market over the last several decades. These other residential wall assemblies enjoy smaller market share, although in many cases that market share is growing.

In 1999, concrete accounted for 12% of the above-grade, single-family residential market broken down as 10.5% concrete masonry, 1.3% ICFs, 0.017% autoclaved aerated concrete (AAC) and 0.017% other concrete building methods. By 2003, concrete's share of the above-grade, single-family residential market had increased to 25% broken down as 13% masonry, 9.5% ICFs, 1% AAC, and 1.5% other concrete building systems (The Concrete Network). A 2008 market share analysis prepared for the Precast/Prestressed Concrete Institute, projected the market share for precast/prestressed concrete to hover around .8% of the total construction market through 2010 (PCI).

Within the concrete grouping, the use of ICFs in particular has increased as homebuilders have become more familiar with the technology.

Between 1996 and 2006, ICF market share in the building construction industry increased almost six fold, with almost all gains in the residential market for use in both below-and above-grade applications (Lyman, Joseph, 2007).

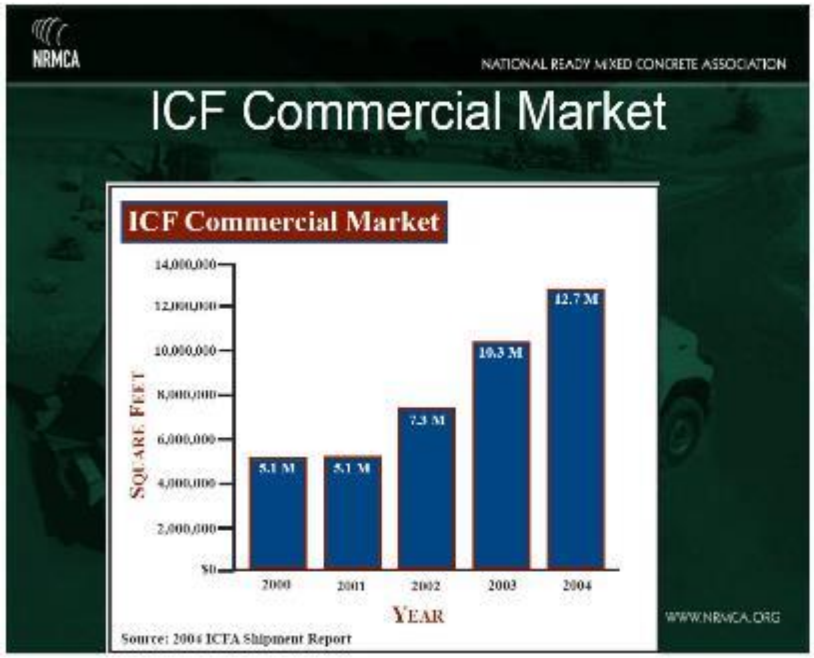

Figure 7 Year over year gains for shipped ICF product
Source: National Ready Mixed Concrete Association

The SIP industry also has experienced growth in its single-family residential market share over the last five years and now hovers around 1% of the market (SIPA, 2012). Of the total 42 million square feet of SIPs produced in North America in 2009, 43% went to residential buildings. The SIP industry experienced a 12% decrease in residential production volume in 2009, compared to a 28% drop in U.S. single-family housing starts (Quacent New Building Materials Co., LTD, 2010). A survey conducted by the Structural Insulated Panel Association (SIPA) showed a drop in total SIP production of 4% in 2011, compared to an 8.5% drop in single-family housing starts. Single-family housing is the industry's primary market segment.

Both ICFs and SIPS use foam insulation in their construction and, as such, the market for foam insulation is growing. Insulated Concrete Form (ICF) and Structural Insulated Panel (SIP) manufacturer PFB Corporation has seen continuous sales growth over the past few years, despite an overall housing downturn. PFB is currently expanding manufacturing in the U.S. and has seen strong positive pricing trends beginning to emerge (Konrad, 2012). Forecasts from BASF, a leading U.S. manufacturer, indicate that demand for foam insulation products has increased from 1,646 MM lbs. in 2009 to 1,878 MM lbs. in 2012; this upward trend also holds specifically for expanded polystyrene (EPS) and urethane foams that are used in integrated materials like ICFs and SIPs (Sievers, M.).

AAC is a major residential construction product in Europe and many parts of the world; however, the material has had difficulty maintaining a strong manufacturing presence in the United States. According to Stefan Schnitzler's Applied Research Paper: Autoclaved Aerated Concrete as a Green Building Material, the late adoption of the use of AAC in the U.S. can likely be attributed to the high initial capital cost needed to set up AAC manufacturing facilities and unlike many parts of the world where AAC use is well-established, the majority of the U.S. residential market is composed of wood frame construction (2006). Although it can be shipped anywhere, AAC is not as widely available in the U.S. as most concrete products (Portland Cement Association, Concrete Homes). There are currently a handful of manufacturing facilities in North America. The material has generated discussion in the industry and has been featured in public sector demonstration projects such as U.S. DOE's Challenge Home Case Study homes in Winter Park, Florida (U.S. DOE, Building Technologies Office).

WALL ASSEMBLY ATTRIBUTES

Energy Performance

The performance of residential wall assemblies can have a significant impact on the comfort inside a home as well as the energy needed to heat and cool the structure. Appropriate insulation of the wall assemblies can decrease heat flow by providing effective resistance, thus lower the utility cost. The insulation level is specified by using R-value, which is a measure of the ability of the insulation layer to resist heat traveling through that depends on its material, thickness and density. In general, the higher the R-value of the insulation, the better the energy efficiency. Table 2 summarizes the relative performance of alternative residential wall assemblies during their operating life (installed in a building). The detailed breakdown on how these R values are calculated and what sources of information are used can be found in Appendix B.

Wall Assembly Type	**Model**	**Resistance R (h.sq ft.F/Btu)**
Stick Frame Walls	4" Wall- with Batt Insulation	15
	4" Wall- with Polyurethane Foam Insulation	26
	6" Wall- with Batt Insulation	21
	6" Wall- with Polyurethane Foam Insulation	38
Structural Insulated Panels	4" SIP Wall	20
	12" SIP Wall	67
Autoclaved Aerated Concrete (AAC)	8” AAC	10
Insulated Concrete Forms (ICF)	8” Insulated Concrete Forms	10
	12" Insulated Concrete Forms	11
Precast Concrete Sandwich Panels	typical 8-inch precast sandwich panel	12

Table 2 R Value

Typical wood frame wall assemblies of 2x4 and 2x6 have R-values between R-5 and R-7. This does not include any insulation. Air infiltration is responsible for up to 40% of energy losses of wood frame structure. The cracks, openings and joints among all wall pieces contribute to air leaks. A new conventional wood frame house has about 2 to 3 air changes per hour, and over time, the wood will shrink and deteriorate, leading to 10 to 20 air changes per hour (QuadLock, 2012). Wood frame construction is typically paired with batt insulation; however, when combined with spray foam insulation, it is more energy efficient. Some spray foam installations can have twice the R-value (per inch) than that of traditional batt insulation. Spray foam can also create an effective air barrier by filling small cavities (U.S. DOE, Types of Insulation).

Concrete can capture a large amount of heat with little temperature swing. With two layers of precast concrete and an insulation layer in between with high thermal performance, typical 8-inch precast sandwich panel has an R-value of approximately 12, reducing 25% amount of baseline energy use (PCI, 2009). The ENJOY! Solar Decathlon house had precast concrete walls with an overall R-value of 33.

Figure 8 Home constructed with precast concrete panels in Jersey City, NJ
Source: Kevin R. Wexler *
http://www.nj.com/homegarden/index.ssf/2010/08/building_an_asymmetrically_sha.html

ICF wall assemblies have effective thermal resistance because the insulation materials provide two uninterrupted insulation layers, reducing energy losses by about 25%. The concrete is poured in the form of a semi-liquid that can force air out and fill voids. A chemical reaction can turn the concrete into a solid without air leaks, resulting in only 0.5 to 2 air changes per hour (Quadlock, 2012).

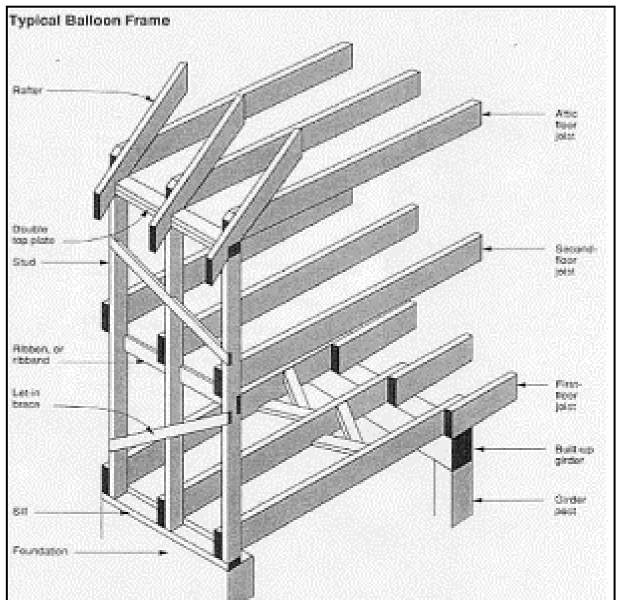

Figure 9 Balloon frame construction
Source:
http://activerain.com/blogsview/160660/balloon-framing-not-mortgages-

SIPs provide uniform insulation with an R-value varying from approximately R-20 to R-67, depending on the SIP thickness that can vary from 4- to 12- inches. According to the U.S. DOE, SIPs can provide energy savings of 12-14% compared to conventional wood frame construction (2012) and some SIPs organizations such as SIPs of America suggest that much higher energy savings can be achieved. ICFs are typically made from EPS, while SIPs can be made from EPS or urethane, both of which offer high per-inch insulation. Closed-cell spray foam like EPS, for example, has a high insulation value of approximately R-6.2 per inch of thickness compared to standard fiberglass blankets and batts that have R-values R-2.9 and R-3.8 per inch of thickness (U.S. DOE, Energy Savers).

From a performance perspective, AAC creates an energy efficient envelope and protects against unwanted air losses. Physical testing demonstrates heating and cooling savings of roughly 10% to 20% compared to conventional frame construction (Portland Cement Association, Concrete Homes). With no traditional foam or fiberglass as insulation layer, the mass concrete and the air of AAC provides great insulation by preventing air filtration and eliminating thermal movement (Staub Design, LLC, 2004-2011). Typically, AAC products have an R- value of about 1.25 per inch, but the exact benefits change by thickness and location of construction (Create Green Home, 2008). A standard 8" AAC block wall should have an R-value of 10, but in reality, because it can store and release energy to adjust indoor environments, reaching an R-value equivalent to 20 (International Masonry Institute, 2010).

To compare the energy performance of these different wall assembly systems, a detailed energy simulation study on an average New Jersey house was conducted. The house has a detached garage and a basement, a common choice in New Jersey (Figure 10). The area of the model house was obtained from previous DOE studies on average New Jersey homes. More specifically, the variable to be investigated is the type of the wall assembly system used in the house. DesignBuilder, an energy simulation program built on top of EnergyPlus energy simulation engine, was chosen as the energy simulation and analysis program. Although there are a variety of energy simulation programs on the market, several studies have shown that EnergyPlus produces most reliable and accurate results. We chose the Newark weather profile as the weather input in the analysis, and a detailed occupancy schedule is specified to reflect a reasonable heating and cooling requirement. In each run of the simulation, we choose a different type of wall assembly system while keeping the rest of parameters constant. This ensures a fair comparison among different wall assembly systems can be made.

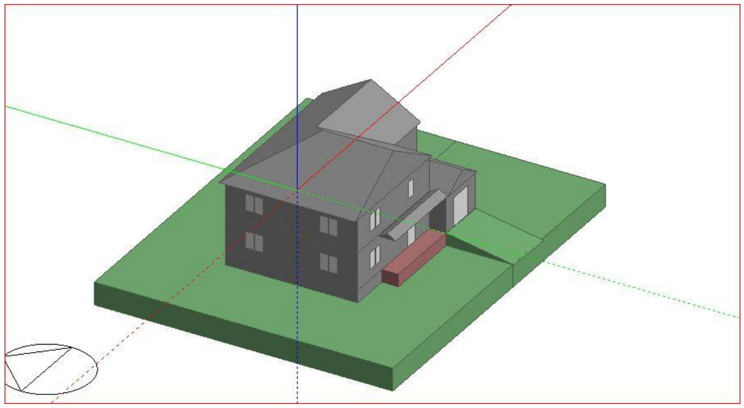

Figure 10. The House Model used in Energy Simulation

Table 3 provides a global view of the energy performance of the ten different wall assembly systems according to the simulation results. The wall assembly systems are listed in a decreasing order in terms of energy performance. Figure 11 shows a graphical comparison of the performance of these wall assembly systems. It can be noted that the 12" SIP shows the best performance while 8" AAC ranked at the last. However, it should also be noted that the differences among these wall assembly systems are minor (<12%).

	Total Cooling (kBtu)	Zone Heating (kBtu)	External Infiltration (kBtu)	Heating (Gas) (kBtu)	Cooling (Electricity) (kBtu)
12" SIP	9420	40978	34325	49371	5641
6x2 with Polyurethane Foam Insulation	9595	42908	34174	51697	5745
4x2 with Polyurethane Foam Insulation	9774	44866	34029	54055	5853
6x2 with BATT Insulation	9898	46221	33933	55688	5927
4" SIP	9972	47026	33877	56658	5971
4x2 with BATT Insulation	10177	49237	33732	59322	6094
8" PRECAST	10364	51230	33610	61723	6206
12" ICF	10494	52607	33532	63382	6284
8"ICF	10560	53333	33493	64256	6324
8" AAC	10615	53956	33460	65007	6356

Table 3. Comparison of Yearly Performance across Different Wall Assembly Systems

Overall, the results suggest that there are several types of alternative wall assembly systems, including 12" SIP, 2x6 with Polyurethane Foam Insulation, 2x4 with Polyurethane Foam Insulation, performing better than 2x6 with BATT Insulation-based wood frame construction in terms of energy performance. Also, the 4" SIP appears to be superior than 2x4 with BATT Insulation in term of energy performance. Nevertheless, in spite of the fact that equivalent superior energy performance can be reaped from all of these types of wall assembly systems, the market share of these systems has grown very slowly. The factors contributing to this situation are not clear, but likely are comprised by some combination of the factors noted starting on Page 24 of this document.

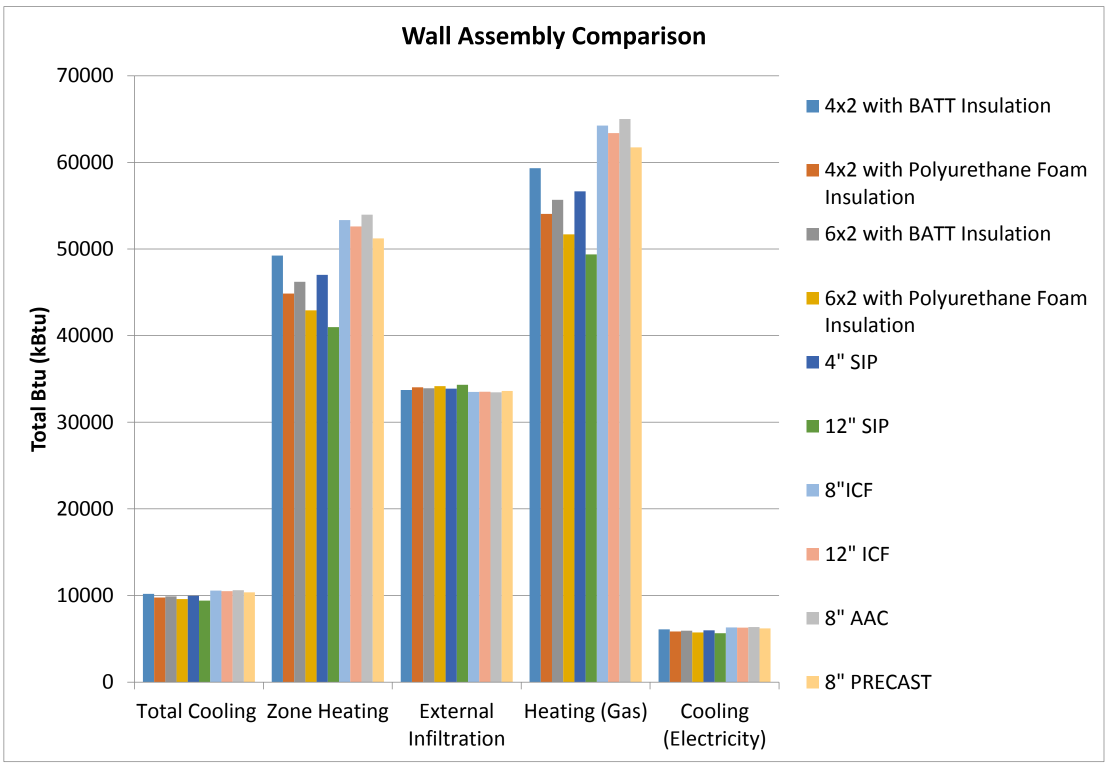

Figure 11. A Graphical Comparison of the Yearly Energy Performance among Different Wall Assembly Systems

Demolition/Reuse/Recycle Potential

While a full life cycle analysis is not undertaken here, another aspect of energy use, environmental impact and economic value relates to the reuse potential of the material assembly.

Wood forms can generally be reused 40 to 50 times without major maintenance. Separating wood during demolition is relatively simple and ideally structural wood elements are reused. Typical removal of non-structural wood frame wall costs $1.25 per square feet of labor while removal of structural wood frame wall costs $2.50 per square feet of labor (socialREMODEL, 2012). However, because of the limited options available to reuse wood directly as building materials, structural wood are often down-cycled into feedstock for biomass fuel, mulch, and compost (Calrecycle, 2011).

The waste produced by demolition of concrete structure includes dust, powder, and fragments that are commonly sent to a landfill. This waste can be major source of air pollution, posing health concerns. If separated from the steel, concrete can be reused over and over while the insulation layer is usually destroyed. In recent years, an increase in environmental awareness and regulations, has led to more concrete recycling (The Concrete Network). Precast concrete panel demolition costs around $3-$3.50 per square feet of labor.

Unlike traditional concrete buildings, where temporary formwork is set up and removed once the concrete is cured, with ICF, the formwork is built using large, hollow polystyrene forms which are filled with concrete and reinforcing bar, with the polystyrene remaining as insulating layer (Building Research Establishment Ltd, 2012). This contributes to a more complex demolition process. While concrete is relatively easy to divert from the landfill and can be reused after separation from steel, disposal of polystyrene presents a major challenge. It does not biodegrade for centuries (Environmental News Network, 2008). SIPs often also contain polystyrene and have waste management issues similar to those of ICFs. The growing presence of integrated, energy efficient building materials in the waste stream is an area of concern. While these material assemblies have enabled increased operational efficiencies for buildings, the risk is that they create negative net values for waste prevention as documented by the Oregon Department of Environmental Quality (Quantis, 2009). Concurrently, the labor cost for demolition of ICF and SIP walls is about five times higher than demolition of wood frame construction.

In AAC demolition, some waste can be reused or recycled through voluntary commitment by manufacturers. AAC does not contain toxic substances and does not off gas (European Autoclaved Aerated Concrete Association, 2012). Also, AAC waste can be ground up and blend back into new concrete (Staub Design, LLC, 2004-2011).

Wind Resistance

Of the wall assemblies investigated in this study, wood frame walls are the least structurally resistant to wind damage. Wood frame walls can withstand the weight and speed of debris generated during wind travelling up to 115 mph (Powell, 2011). The strength of precast concrete gradually increases over time and this is an advantage over some materials that deteriorate in strength over time, such as wood. Precast concrete panels can withstand wind up to 200 mph, which is equivalent to about a category 5 hurricane (First National Panel Company, Inc., 2004-2005). Solid concrete walls formed with ICFs have proven to be the best protection against flying debris created by winds as high as 250 mph (UplandTeam, 2007). SIPs are also highly wind resistant, having been tested with 200 miles an hour winds without sustaining damage (UBuildIt Holdings, LLC, 2011 University of Florida Extension, 2013). The wind load capacity for AAC varies but AAC is designed to withstand wind up to 150 mph (International Masonry Institute, 2010). It should be noted, however, that typically this parameter only applies in hurricane regions, and in those regions, generally the windows and doors are most vulnerable, not the walls.

	Maximum Wind
Wood frame wall	115 mph
Precast Concrete sandwich panel	200 mph
Insulated Concrete Forms(ICFs)	250 mph
Structural Insulated Panels(SIPs)	200 mph
Autoclaved Aerated Concrete(AAC)	150 mph

Table 4 Wind Resistance

Hazard Resistance (fire, earthquakes)

Wood is a combustible material that can burn easily and wood frame construction usually collapses in less than an hour in a fire (see Table 5). By comparison, precast concrete is non-combustible and provides fire endurance. Concrete layers protect the sandwich insulation without contributing to fire load and concrete panels can achieve up to a 4-hour fire rating (Designer's Notebook, 2011). Walls constructed with ICFs can typically achieve a 2-hour fire rating while SIPs walls earn a one-hour fire rating (UBuildIt Holdings, LLC, 2011). The 4-hour fire rating for a typical 8" AAC wall is better than that of a traditional concrete wall with same thickness. Also, AAC does not give off toxic fumes because it is not combustible (PCA).

Homes constructed from wood as well as those constructed from precast concrete panels have high resistance to seismic activity if the structure is properly connected to its foundation. ICFs and SIPs have both demonstrated capacity to withstand earthquakes. In 1995 in Kobe, Japan, there was a devastating earthquake and one of the only buildings left standing with minimal damage was a building constructed with SIPs (UBuildIt Holdings, LLC, 2011). AAC has strong resistance to earthquakes and is approved for use in the Seismic Design Categories A, B and C (Mason Contractors Association of America, 2008).

	Fire	Earthquake	Insect/Mold
Wood frame wall	Combustible Collapses in an hour or less	Moderate material for anti-seismic	Porous and susceptible to water and bugs
Precast Concrete sandwich panel	Can achieve up to 4- hour fire rating	Better material for anti-seismic	Fewer moisture penetration Inedible for insects
Insulated Concrete Forms(ICFs)	Achieve 2-hour fire rating	Better stand up to earthquake	Food source for mold is eliminated EPS provides nesting place for insects/rodents
Structural Insulated Panels(SIPs)	Achieves a 1-hour fire rating	Tested at 7 grade earthquake with no damage	Free of moisture EPS provides nesting place for insects/rodents
Autoclaved Aerated Concrete(AAC)	Achieve a 4-hr fire rating	Approved for use in the Seismic Design Categories A, B and C	Resistance to water and mold inorganic, insect resistant

Table 5 Hazard Resistance

Indoor Environmental Quality

Indoor environmental quality includes many factors that impact a structure's interior including indoor air quality, insect and mold susceptibility and acoustics.

Indoor Air Quality/Insect/Mold Susceptibility

Indoor air quality focuses on airborne contaminants (Whole Building Design Guide, Enhance Indoor Environmental Quality). Indoor air can be more polluted than the air outside and poor indoor air quality can cause health problems including sore eyes, nose, headaches, asthma and other respiratory issues (U.S. EPA). Long-term exposure to mold can exacerbate allergies and asthma and endanger individuals with suppressed immune systems (U.S. EPA, The Inside Story: A Guide to Indoor Air Quality). Mold and insects can also cause property damage through feeding on organic material, like wood and paper, causing decomposition (Polysteel, 2003).

Wood frame construction can harbor unseen mold and mildew, which can lead to poor air quality and health problems for occupants. Water can be absorbed into the wood, causing it to rot and mold, making it susceptible to insects, and compromising the material's strength. This is of particular concern in humid regions (Michael, 2010).

The limited number of joints in precast concrete panels means minimal moisture penetration, which helps minimize mold. Precast concrete panels do not produce dust or airborne contaminants (UBuildIt Holdings, LLC, 2011). Precast concrete is not organic and is not a food source for insects (Designer's Notebook, 2011).

Since buildings constructed with SIPs are airtight, mechanical ventilation is required. These systems bring fresh air into the building in controlled amounts and exhaust indoor air to the outside. This allows air in SIPs homes to be filtered for allergens and dehumidified. With humidity controlled, buildings constructed with SIPs are less susceptible to mold growth and dust mites (SIPA).

ICF wall assemblies do not facilitate mold growth and have zero air infiltration rates (UBuildIt Holdings, LLC, 2011). Composed of two inorganic materials, EPS and concrete, the food source for mold is eliminated and EPS does not provide any nutrition for insects. However, some kinds of insects and rodents may use the thermal insulation provided by EPS as a nesting shelter. Any foam insulation products can provide such a desirable environment for insects and rodents (SIPA).

The closed cells and inorganic materials of AAC make AAC wall assemblies resistant to water, rot, mold, mildew, and insects (Autoclaved Aerated Concrete Construction, 2012).

Acoustical performance

Sound can travel through solid materials and air in the form of vibrations. Dampening of vibration and conversion of sound energy into heat of friction occurs by using special soundproof materials, thereby helping to reduce sound transmission. The sound transmission classification (STC) is the standard used for walls (Goulet, 2002). It should be noted here that typically, the windows of a building are the weak link when it comes to acoustical performance. The solid walls can usually all be designed for good resistance to acoustic penetration.

	Sound Transmission Classification	**Perception**
Wood frame wall	STC rating 36	Able to hear outside noise, individual words and phrases
Precast Concrete Sandwich panel	STC rating 49 +	Loud speech can be audible, and music be easily heard
Insulated Concrete Forms (ICFs)	STC rating 55-60	Unwanted noise would be inaudible
Structural Insulated Panels (SIPs)	STC rating 20 - 50	Effective at blocking high frequency noise, but not low
Autoclaved Aerated Concrete (AAC)	STC rating 44-60	Unwanted noise would be inaudible

Table 6 STC Rating

The STC rating of wood frame walls is approximately 36 (see Table 6). With this rating, building occupants will be able to hear the outside noise of construction or traffic on the street as well as individual words and some phrases spoken outside. Precast concrete panels have a high sound resistance with an STC rating of 49 and above. With this rating, loud speech is audible, and music can be easily heard (Designer's Notebook, 2011). ICFs have an STC rating of between 55 and 60 and can keep the inside of a house quieter than traditional wood frame construction. SIPs provide effective blockage of high frequency noise. However, low frequency sounds are not as effectively blocked by SIP building envelopes. SIPs STC ratings vary from high 20s to about 50, depending on the thickness of the insulation layer (SIPA, 2012).

The porous nature of AAC helps it to absorb sound (Neithalath, N. *et al*, 2005). ACC has a higher surface mass which dampens the sound vibration and transmission (Autoclaved Aerated Products Association, 2006). In fact, the original applications of AAC construction in the United States were freeway sound walls. STC ratings of AAC are from 44 to 60 depending on thickness and the final product (Schnitzler, 2006).

ADDITIONAL FACTORS – BARRIERS TO MARKET PENETRATION

Relative benefits notwithstanding, there are a number of factors that may affect the market penetration of various wall assemblies including cost, lack of information and training and institutional factors such as codes, other regulations and industry structure. In the literature on the diffusion of innovations, several factors are cited as possible determinants in the adoption of innovative practices in home building. One study that drew on a NAHB Profile Survey, found that firm size, type of construction and locational characteristics are additional factors that affect innovation diffusion in the housing industry (Blackley and Shepard).

	Labor	**Equipment**	**Time on Site**		**PSF Cost (2012)**
Wood frame wall	No specialized expertise required	Basic tools	Complete in 3 to 4 months (erected 2 to 3 days	2x4 stud 2x6 stud	R-5 $4.24 R-7 $5.01
Precast Concrete sandwich panel	Repeated use of materials can reduce cost	Tools Cranes Lifts	Complete in 2 to 3 months (erected in a few days)	Typ. 8" precast concrete sandwich panel	R-19 $41.11
Insulated Concrete Forms (ICFs)	Expertise needed	Tools + Cranes	Complete in approx. 2 months (erected in a few days)	8" thickness 12" thickness	R-17 $27.47 R-26 $30.78
SIPs	Expertise needed	Tools + Cranes	Complete in 2-4 weeks	4" thickness 12"thickness	R-16 $17.01 R-40 $22.04
AAC	Trained labor needed	Tools + Cranes	4 minutes a block / Less than a month	Typ. 8"	R-10 $10.10

Table 7 Overall Construction Cost

Cost

Although most of the alternative wall assemblies investigated here have higher initial costs than wood frame construction, the lifecycle cost, which takes into account all expenses incurred over the useful life of each system including initial costs, operating costs and disposal costs, should also be taken into consideration. The dollar figures included in Table 7 are for Commercial Construction, Standard Union, 2012, New Brunswick, NJ, per Cost Works, RS Means. Although these costs are for commercial construction, they are intended to provide a general estimate of wall assembly costs. In order to get the insulation cost, the cost of non-insulated material was added to the cost for rigid type insulations with the R-values needed. In some cases it is a combination of insulations. Although RS Means has a Sustainable category, some of the wall assemblies are still considered cutting edge and are not included in RS Means.

Construction Cost

There are many factors to consider regarding the construction cost of wall assemblies. These include material cost, labor, equipment and time on site. In addition, factors such as project location, local economy, and transportation of materials, can impact the overall construction cost.

Material Cost

Raw materials for wall assemblies come from diverse sources, and obtaining each one of them involves a different series of inputs. The material for wood frame walls is primarily wood, partly used for framing and the rest as structural panels. The price of lumber is typically volatile and very difficult to predict. Currently, lumber prices are under $350 per 1,000 board feet (National Association of Home Builders, 2012).

Ready-mix concrete is usually sold in bags, but the price varies depending on time and location. In 2010, an 80-pound concrete bag cost between $3.50 and $4 (King, 2011). The cost of concrete mixed bag is about $500 per 1,000 board feet.

The materials included for manufacturing of ICFs are very similar to precast concrete, mostly concrete and the insulation layer. The most common insulation layer used in wall assemblies are expanded polystyrene (EPS), which is currently derived from the combustion of fossil fuels (EPS Molders Association). The price of EPS ranges from around $200 to $500 per ton but is very much dependent on location, cleanliness, level of compaction and current market situation (Hasswell, 2012).

EPS and oriented strand board (OSB) are two key materials used in SIPs. OSB is an engineered wood product shaped by layering wood in specific orientations. The price of OSB varies accordingly to the price of lumber. However, one typical 7/16 inch OSB Sheathing Board costs $7.47 at The Home Depot (Wallender, 2012).

ACC walls that are installed as block units (8” x 8” x 24”) cost approximately $3 per unit (NAHB Toolbase - Autoclaved Aerated Concrete). Currently the number of AAC manufacturing facilities is limited in United States, resulting in higher initial costs.

A potential barrier for greater use of advanced wall assemblies is the supply chain for residential construction. Typically, manufacturers of the various energy efficient materials have sold directly to contractors working on homes or the end users themselves. Addressing the need for a clearing house or wholesale distributer of the innovative assemblies may provide for a higher utilization of these products.

Labor Cost

Labor cost is closely related to construction method. Conventional wood frame construction is accomplished by connecting wood pieces with nails and screws and then attaching to studs that are usually 2 X 4 or 2 X 6 pieces of lumber. Two common ways of framing includes balloon framing (See Figure 9**)** and platform framing.

Framing walls with lumber is a straightforward process, consisting of plates at top and bottom, headers and wall studs, with trimmers and king studs needed for openings of windows and doors. As noted above, 2x4 and 2x6 lumber are the most common sizes used for wall construction, while the former can be used for exterior walls; the latter is used for most interior walls. The process starts from marking top and bottom plates, with studs generally spaced 16" on center, then cutting the studs, assembling walls and corner posts while laying out window and door openings, and finally nailing on sheathing and raising bracing onto place (Hometime, 2012).

The labor cost to frame a house is approximately $5 to $10 per square foot. Wood framing is currently the most common method of construction and there is familiarity with this method throughout the industry (CostOwl, 2012).

Precast concrete wall assemblies are manufactured in the factory to get precise dimensions and maintain high quality. They are heated and cured, and then insulation foam is applied. The final product is delivered to the jobsite and set into place (NorthPoint Construction Services, 2005). SIPs are also manufactured in a factory and shipped to the construction site. CAD drawings of the structure to be built are converted to shop drawings, which are then plugged directly into computer numerical control fabrication machines. Special channels (chases) are cut into the foam to allow for the electrical wiring, and the insulation core is recessed around the edges to accept the connection splines or dimensional lumber used during construction (BASF, 2006).

The average labor cost for precast concrete panel installation is approximately $10 per square foot (Reed Construction Data, 2012). Precast concrete panel wall assemblies require more specialized expertise on site than wood framing.

Since ICF is a relatively new method of construction, builders have less experience estimating ICF construction costs. Costs vary depending on ICF thickness with a typical cost range of $27-$32 per square foot. Although SIPs can require more specialized expertise than wood framing (GreenBuilding Talk, 2010), a study commissioned by BASF and conducted by RS Means Business Solutions quantified the insulation performance differences between using SIPs and conventional framing and found that using SIPs instead of wood framing can reduce framing labor costs by 55% (RS Means, 2006).

For the manufacturing of AAC, the raw materials mentioned above are first mixed into slurry and an expansion agent is added in, making the mixture expand. Then the mixture is wire cut into specific sizes and later autoclaved by baking, which causes the material to cure faster (Portland Cement Association, 2012). The AAC block are larger and lighter than conventional concrete, and in a variety of sizes, with a standard 8 "x 8 "x 24" unit that weighs about 33 lbs. (Schnitzler, 2006). AAC precast blocks are stacked like conventional concrete masonry units and panels are generally installed with a crane (NAHB Toolbase - Autoclaved Aerated Concrete).

The labor costs of building with AAC range from $5 to $10 per square foot (Staub Design, LLC). Since AAC is a kind of masonry, worker skill required is similar to that of using typical concrete masonry units (CMU). AAC is also lightweight compared to conventional concrete (Hess *et al*, 2010), which enables workers to handle the block easier and set them up faster than typical concrete blocks. However, there are few contractors that are familiar with AAC and trained labor is needed. The thin-set mortar used for AAC requires a higher precision level than the traditional cement-based mortar (Schnitzler, 2006).

<u>Equipment Cost</u>

Equipment is typically rented on daily, weekly, and monthly rates. Some companies use established rental rates to charge small tools to the project based upon the duration of use. Other companies may include a 3% to 5% mark-up on labor costs to cover small tools (Nocus, 2009).

Wood framing does not require expensive equipment and can be completed with basic tools such as framing hammer, tape measure, ladder, trimmer, etc. The construction of precast concrete panel walls requires basic tools and cranes to lift the panelized wall in place. The cost of the equipment varies depending on its loading limit and size, and hourly rent of a crane can cost as much as $350 and up to $1000. A crane is also needed for construction with ICFs and SIPs. Although AAC can be cut with basic tools, heavy equipment such as a crane is sometimes required for installation.

Chart for Overall Cost Analysis (Dollars)

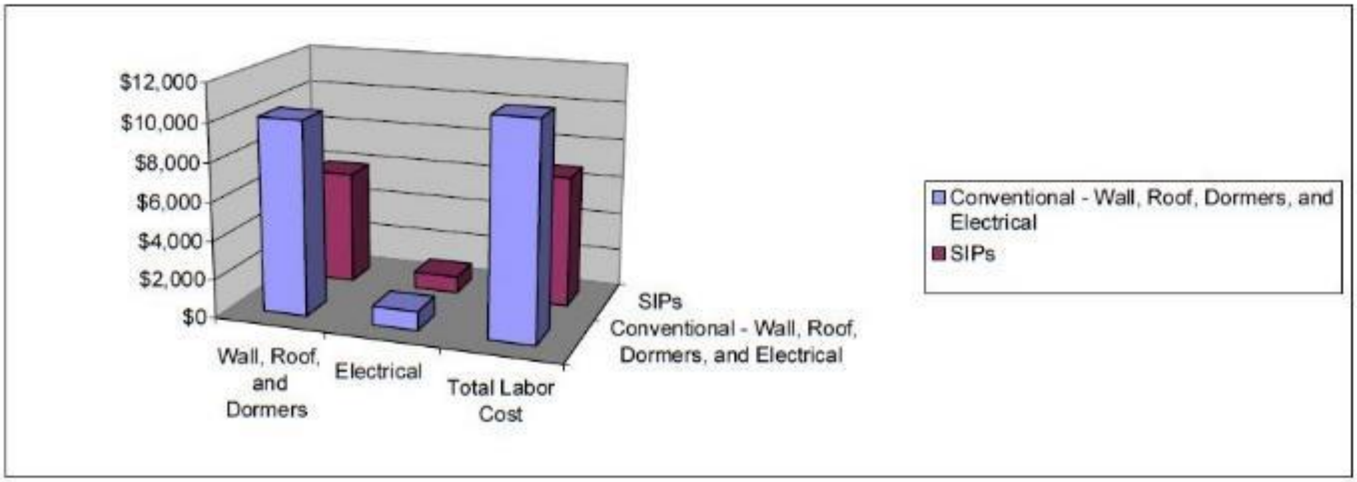

Figure 12 Overall Cost Analysis Comparing SIPs and Conventional Framing
Source: BASF Corporation, Time & Motion Study, 2006

<u>Time on site</u>

There are various factors in addition to materials that affect the construction time on site such as size and complexity of the project, location and weather. Generally, a wood frame house can be constructed in around 3 to 4 months, and erected within 2 to 3 days, while precast concrete panel houses can be built in around 2 to 3 months and the building shell erected in just a couple of days (Partnership for Advancing Technology in Housing, 2006).

A small team can put up the basic structure of an ICF house in a few days. Typically, the exterior wall, insulation and structure are completed in just one process, leading to about 2 months of total construction time. The speed of construction is one of the main benefits of SIPs. SIPs projects can typically be fully erected and ready for windows and doors in 2-4 weeks, providing an average of 60% savings in time (Technical Quality Service Ltd, 2006). Time on site for constructing an AAC home can be 30% less than the time spent on site constructing a wood frame house because the components are easy to erect and walls can be installed quickly (Global Modular Concepts, 2006). An ACC project can generally be constructed within a month.

Per Square Foot Cost

According to RS Means CostWorks, the per square foot cost for constructing wood frame walls in the New Brunswick area in 2012 was about $4.24 (with 2x4 studs) (see Table 7) and about $41.11 per square foot for precast concrete panel walls (CostWorks, 2012). However, by reusing the same dimensions for components, the same molds can be used for construction of precast concrete panels, minimizing the total number needed and the changes between casting (Martin and Perry, 2004). The construction cost for SIPs, was lower, about $17-22 per square foot of wall area, while cost for ICFs were more expensive coming in at approximately $27-30 per square foot of wall area. The cost of AAC was roughly $10.00 per square foot (CostWorks, 2012).

Maintenance Cost

	Maintenance	**Insurance/ Mortgage**
Wood frame wall	More Frequently	Higher/ No
Precast Concrete sandwich panel	Less, long term durability	Lower/ Yes
ICFs	Less repair and maintenance	Lower/ Yes
SIPs	Less repair and maintenance	Lower/ Yes
Autoclaved Aerated Concrete(AAC)	Less repair and maintenance	Lower/ Yes

Table 8 Maintenance & Insurance/Mortgage Comparison

Under favorable conditions, wood walls can provide lasting performance. However, wood frame construction also faces potential threats such as mold, insect damage and other hazards. Wood frame walls need to be maintained more frequently than the other wall assemblies presented here, raising the maintenance cost. Precast concrete panels have robustness, longevity, and durability. Precast concrete wall assemblies have facades that are resistant to impact, corrosion, weather, abrasion, and other damage, (Designer’s Notebook, 2011). The most important aspect of maintenance for precast concrete panels is the sealant in the joints. If a sealer has been used, it will require reapplication. The timeframe for reapplication varies but typically needs to occur from every 7 to 20 years (Whole Building Design Guide, Building Envelope Design Guide). ICF, SIP and AAC systems require minimal maintenance due to rot and rust resistance (State of Georgia-DOT, 2001).

Insurance & Mortgage Costs

The building materials and systems used for home construction can impact financial aspects of homeownership including insurance and mortgage costs. Stick frame houses have 15% to 25% higher insurance rates compared to concrete homes, which are stronger and fire resistant (Solution Pro). In 2008, the first green homeowner’s insurance was introduced into the market by the Fireman’s Fund. This insurance offers coverage for policyholders with “green” homes or those who want to upgrade their homes with “green” improvements after a loss (Fireman’s Fund). Several other home insurers now offer green insurance, such as Liberty Mutual Insurance, Farmers Insurance and Lexington Insurance. On the other hand, there are anecdotal cases in which developers or builders have reported being quoted higher insurance rates than market due to the inclusion of green technology in their buildings. They have been told that the technologies are newer and therefore more risky and more difficult to replace, although this may not be the case (Communications between builder groups and the Center for Green Building, misc. dates).

Energy Efficient Mortgages (EEMs) are special mortgages that allow debt to income ratios to be stretched when purchasing an energy efficient home. EEMs credit a home’s energy efficiency in the mortgage (Energy Star). However, there has not been a robust demand for EEMs. Even Fannie Mae’s EEMs did not take off, in part because they offered extra money for energy savings at a time when the mortgage industry was basically giving away money on stated income, without the additional effort of going through an EEM (SEEC LLC).

Since then, other financing programs that offer incentives for energy efficiency or renewable energy projects have emerged such as the Wells Fargo Solar Home Equity program, which offers a cash incentive when Wells Fargo home equity financing is used to purchase a solar energy system. In regards to mortgage, insurance and real estate costs and valuation, there appears to be a lag between understanding the value of energy efficient materials and systems and the availability of financial tools to promote and support them. The new National Green Building Investment Underwriting Standards for Residential Buildings, which focuses on the value of energy efficiency and renewable energy investments in homes, may help, as it gains market acceptance (Capital Markets Partnership, 2008).

Design Flexibility and Aesthetic Appeal

Wood frame construction allows for extensive design flexibility and can provide the aesthetic of a natural material. Wood framing is easily modified during the construction process. There is a perception in the industry that precast concrete wall assemblies offer somewhat limited design flexibility. However, as the construction technology has developed, both aesthetic and functional options for wall systems have increased (PCI – Central Region). ICFs also allow for design flexibility and provide design options similar to that of wood frame construction, including angles, curves as well as arches. However, changes during construction to homes built with ICF are difficult to make.

Similar to precast concrete, some architects share the misconception, along with the general public, that the use of SIPs is limited to simple shapes and that they are not flexible enough to be used with innovative or unusual designs. Design details may need to be modified to work with SIPs, but complex shapes and angles can be produced and SIPs can be tailored to suit specific requirements (SIPs Design, 2012). AAC products can be manufactured in a range of sizes depending on the application. This allows for design flexibility. ACC also offers a variety of aesthetic choices such as textures, colors and patterns (State of Georgia DOT, 2001).

The use of wall assemblies other than wood framing may also hamper the ability of hanging pictures and other objects on the walls. These advanced assemblies may also limit the flexibility of moving the locations of electrical outlets, light switches and other traditional wall inserts.

Education & Training

Lack of training and knowledge about alternative wall assemblies can act as a barrier to the use of newer wall assembly technology. Training and education is needed for both the design and construction teams about new materials and methods of installation. A lack of awareness and technical knowledge across the industry has slowed the growth of alternative wall assemblies in the market. Contractors have well-established methods of construction for framing and it takes time to transition to new practices (U.S. DOE, 2010). In addition, there may be a lack of easily accessible information regarding the alternative wall assembly systems.

Institutional Framework

Building Codes & Regulations

Codes and regulations establish uniform guidelines for safety but can act as barriers too. Codes and regulations interfere with innovation if they increase costs and uncertainty (Koebel and Cavell, 2006). Hassell *et al* (2003) note that regulation and code enforcement personnel tend to choose conventional materials that they are familiar with over innovative ones, thereby lessening the incentive for builders to innovate. Engineers typically have relied on “rules-of-thumb” and other design practices passed down through the profession as “acceptable” to meet the standards. This would be especially true if, being disposed to choosing innovation, the regulator had to familiarize themselves with the innovation to determine if the innovation meets local requirements. This takes time and may remove any time/cost benefits associated with the innovation.

The two primary building codes in use in the United States are the International Building Code (IBC) and International Residential Code (IRC). These codes are developed in a process defined by the International Code Council (ICC). New innovative materials must be approved and incorporated into the code before they can be used in residential buildings. The building official can approve any material that meets the intent of the code. Guidance is provided by the ICC Evaluation Service, which is further discussed in an upcoming section of this paper.

The process by which an innovative new material is added to the code can be a lengthy process. Anyone can submit a code change request, but typically a product manufacturer or consortium of manufacturers or trade association will bring forward a new material to be incorporated into the building code. There is a staff review for compliance with code development procedures, and then the change request is presented at a committee action hearing. This public meeting has a code committee presiding and the change proponent will typically present material testing from a third-party lab as well as any standards that may have been developed, such as ASTM sheets. The code committee will then approve or disapprove of the change by majority and subsequently, the entire voting membership of the ICC can then vote on the committee action. Assuming approval of the change, public comment is then opened for 60 days following approval. At the end of the public comment period, a public comment hearing is held to present all public comments as well as the results of the committee votes. A final vote is cast on whether or not to change the code by the ICC Governmental Member Representatives – those who administer, formulate or enforce the regulations (ICC 2014).

Energy Subcodes

The two primary building energy codes in use in the United States are the ANSI/ASHRAE/IESNA Standard 90.1 Energy Standard for Buildings except Low-Rise Residential Buildings (more commonly referred to as ASHRAE Standard 90.1) and the International Energy Conservation Code (IECC). Commercial buildings and multi-family residential buildings more than three stories above grade are covered by ASHRAE Standard 90.1. The IECC addresses all commercial and residential buildings, and compliance with ASHRAE 90.1 qualifies as compliance with the IECC. The development of these energy codes can impose barriers for greater penetration of energy-efficient wall assemblies in that the codes specify which materials may or may not be utilized in a building. Both of the primary energy codes are only updated about every three years, adding significant lead time for the approval of an innovative building material (U.S. DOE, Building Energy Codes 101). The building official can approve any material that meets the intent of the code. Since the intent of the IECC is energy efficiency, R-values and U-values are sufficient to meet the intent of the IECC. However, the IRC and IBC are referenced, so a building official can reject a material that in his/her opinion does not meet the intent of those codes.

ASHRAE Standard 90.1 and the IECC are both developed using a collaborative process. This presents great advantages to the end product, but it also means that a significant amount of time passes between proposal for inclusion of a new material and adoption of the revised code. The process for revising the IECC and ASHRAE 90.1 ensures that the design, code enforcement and engineering communities, as well as building owners and operators and academic and government entities, are included in the update of the code. Since the IECC is written with enforceable language, local and state governments are able to make adjustments based on regional goals and adopt and implement the code easily. However, with all of the stakeholders involved in the revision process, individual parties or interests could potentially limit the inclusion of innovative buildings materials, whether that be key product manufacturers or elected officials (U.S. DOE, Building Energy Codes 101). The revision process for each of the primary energy codes are shown below in Figures 13 and 14.

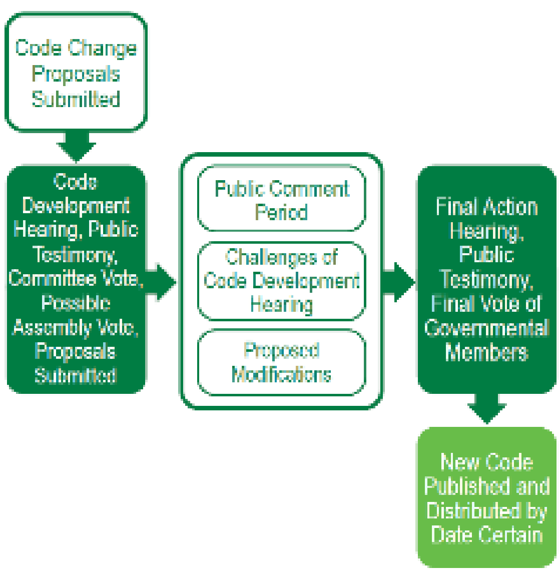

Figure 13 IECC Revision Process
Source: U.S. DOE, Building Energy Codes 101, 2010

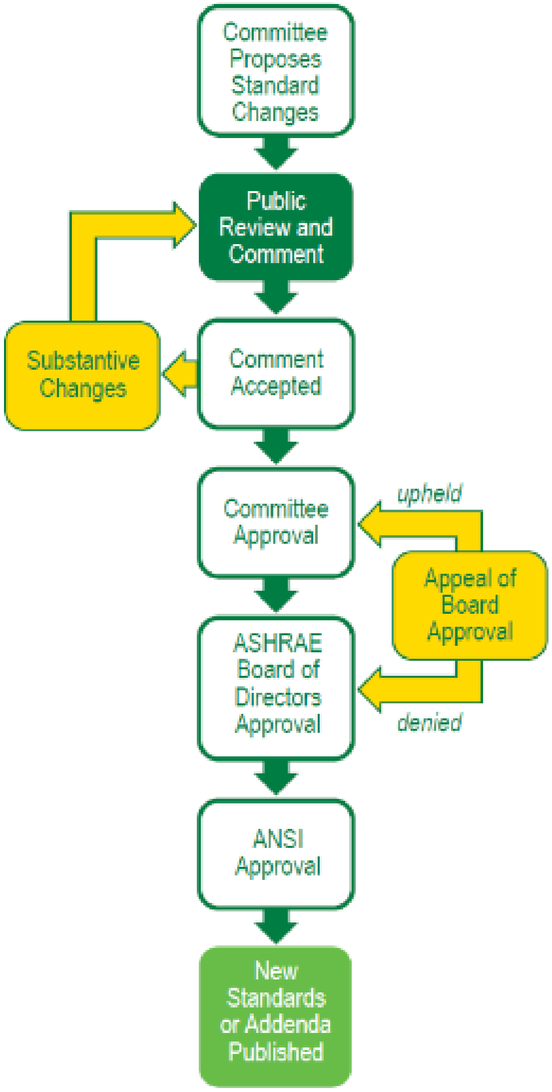

Figure 14 ASHRAE Standard 90.1 Revision Process
Source: U.S. DOE, Building Energy Codes 101, 2010

Once the codes are updated and adopted, another regulatory process that may reduce the incentives for a builder to innovate are planning and zoning departments enforcing them, as well as elected officials (Hassell *et al*, 2003). An innovation may require a change to a building or land use code, requiring extensive and public zoning hearings, which can add costs and delay the development process. Once the building or land use codes are decided upon at the local level, the next challenge is enforcing the code in the field. Educating the code enforcement officials and the construction community in the latest adopted energy code is key to greater penetration of energy efficient homes, particularly in an environment where the most updated energy code may not be the adopted standard in a specific jurisdiction. Building officials often do not have time to perform a compliance check on energy performance with other matters taking higher precedence, such as building safety (Lynch, 2010).

Beyond energy subcodes, a probably greater regulatory barrier to greater penetration of energy-efficient wall assemblies is found in the International Building Code (IBC), the standard by which most government entities adopt a building code. When materials and systems that are not specifically addressed in the code are proposed for a building permit, the building official can accept them under the "Alternative Materials, Designs and Methods..." of Chapter 1 of the IBC, if it is determined that the material meets the intent of the code. This process is often a barrier to innovation because the judgment of meeting the intent will vary with the number of building officials. To provide guidance to building officials on new products, the ICC Evaluation Service (ICC-ES) issues Evaluation Reports, which have to be applied for and paid for. These reports take time to produce and are expensive to commission. Building officials are not obliged to follow these reports, but they can use them to support their judgments. The ICC-ES website currently lists 16 reports on SIPs, 26 reports on ICFs, and 7 reports on AAC (ICC Evaluation Service, 2013). So, again, it may not be the codes per se that are the barrier but rather their use.

Performance-based Codes

According to Werner Gregori, who patented the first ICF in North America, “The U.S. and Canada need a performance-based building code . . . Until that happens, though, the industry needs to consolidate and standardize the product . . . Manufacturers should not see each other as competition, but should bring out a generic product and work to get the price down. The distribution chain is too long, and it makes the price too high. Shorten the distribution chain, standardize the product, and the consumer will create enough demand . . . ” (Gregori, 2010 interview).

As energy codes become more and more stringent, focusing on greater levels of energy reduction, the prescriptive path for compliance will become that much more difficult to meet. (Lynch, 2010). Beginning with IECC 2009 and continuing with IECC 2012, the use of performance-based compliance provides an alternative to the traditional prescriptive-based path. A complete list of various energy codes with performance path options for compliance can be found in Table 9 below. With each update of the energy code, the performance path will continue to become the more likely method of achieving compliance for new buildings. The challenge for builders (and code officials) is that this method adds an additional required skill set in the building process - the creation (review) of an energy model for the building. The execution of this compliance path typically entails a comparative analysis of the predicted performance of the proposed design with that of a minimum prescriptive compliant building and involves the development of a vast array of assumptions and input variables. In order to achieve consistent and meaningful results, performance-based option in the various codes sets forth a number of requirements for the execution of the analysis.

Commercial Code	Latest Version	Compliance Criteria
ASHRAE 90.1	2010	Section 11 – Energy Cost Budget Appendix G – Performance Rating System
International Energy Conservation Code (IECC), International Existing Building Code (IEBC) & International Green Construction Code (IGCC)	2012	IECC Section C407 – Total Building Performance
Title 24 California Energy Commission – Building Energy Efficiency Standards & CA Green Building Code (CALGreen)	2013	Title 24, Part 11, Appendix A4
Florida Building Code, Energy Conservation (Chapter 5 – Commercial Energy Efficiency)	2010	Section 506 – Total Building Performance
GSA P100 - Facilities Standards for the Public Building Services*	2010	LEED Energy & Atmosphere – Optimize Energy Performance (ASHRAE 90.1-2007 Appendix G)
ASHRAE 189.1	2011	Section 7.5.2 – Performance Option/Annual Energy Cost Appendix D – Performance Option for Energy Efficiency

Table 9 Energy Performance Options for Code Compliance, Source: Hogan, July 2013

Generally, smaller building design firms have a stronger appeal for the simplest of compliance options. Larger design and construction firms typically retain internal energy-efficiency specialists to perform the sophisticated analyses required for making the kinds of design decisions needed to meet the performance compliance options in energy codes. These more sizeable firms prefer to employ the ability to make more complex substitutions of building systems and features to allow for design flexibility and potential savings in life-cycle costs. Simple compliance options offer predictability and avoid delays in getting permit applications approved. As the simpler prescriptive compliance path becomes less common and more stringent, the smaller developers may be forced to spend limited project resources on energy analysis for compliance rather than investing in a greater amount of energy-efficient components, such as high-performing wall assemblies. The end result may not mean more energy-efficient buildings, but instead buildings with more confident performance outcomes. Buildings that incorporate the highest of energy-efficient designs are able to use the simplest compliance options because those designs will typically comply with energy codes unquestionably, eliminating the need for a complex energy analysis (Hogan, July 2013).

While energy code compliance generally can be broken into prescriptive vs. performance, in actuality, there is a broader spectrum of options. The simplest is the “true prescriptive”, specifying exactly which materials can or cannot be used. A component performance option considers the energy rating of an assembly of materials, such as an AFUE rating on a furnace, which is composed of various materials (piece parts). This is the most common performance option, allowing the developer to piece together the various components in an energy model using the product manufacturers’ performance rating. The next step up is the partial system performance addressing more than one component, but less than a total building system. A full system performance compliance option includes a whole building system, such as the building’s service water heating system. The multiple system performance option considers the efficiency of multiple systems, but not inclusive of all of the building’s systems. The most complex compliance option is the total building performance option evaluating the total energy consumption for an entire building (Hogan, July 2013). Table 10 below outlines the six major building system categories comparing how they comply with the applicable energy codes from a prescriptive or performance path perspective.

Table 10 Building System Compliance Options, Source: Hogan, July 2013

Building System	Compliance Option	Compliance Parameter	Applicable National Energy Code
Building Envelope	Prescriptive	Opaque Assemblies: R-value for Insulation for Roofs, Walls, Floors	Standard 90.1-2010, IECC 2012
		Fenestration: Frame Material, Number of Glazing Layers, Gap Width, Low-Emissivity Coatings, Gas Fill, Spacer Type	Standard 90.1-2010, IECC 2012, 2012 Washington State Energy Code
		Air Leakage: Caulking and Sealing	Standard 90.1-2010, IECC 2012
	Component Performance	U-factors for Opaque Assemblies: Roofs, Walls, Floors	Standard 90.1-2010, IECC 2012
		U-factors, Solar Heat Gain Coefficient, Minimum Visible Transmittance and Air Leakage for Fenestration Windows, Skylights, Doors	Standard 90.1-2010, IECC 2012
Mechanical System	Prescriptive	R-value for Insulation for Pipes and Ducts, or Minimum Thickness and Material Conductivity	Standard 90.1-2010, IECC 2012
	Component Performance	Minimum Efficiency for Equipment for Space Heating and Space Cooling: AFUE for Furnaces, SEER for Air Conditioners	Standard 90.1-2010, IECC 2012
		Minimum Capabilities for Thermostats: Temperature Range, Deadband, Setting Options for Occupied and Unoccupied Hrs	Standard 90.1-2010, IECC 2012
Service Water Heating System	Prescriptive	R-value for Insulation for Pipes, or Minimum Thickness and Material Conductivity	Standard 90.1-2010, IECC 2012
	Component Performance	Minimum Efficiency for Equipment for Service Water Heaters	Standard 90.1-2010, IECC 2012
Power	Prescriptive	No common examples	
	Component Performance	Minimum Efficiency for Transformers	Standard 90.1-2010
Lighting System	Prescriptive	Maximum Lamp Wattage & Lamp Diameter, Maximum Number of Lamps Per Fixture & Type of Ballast	2009 Washington State Energy Code

	Component Performance	High-Efficacy: Minimum Lumens Per Watt That Varies Based on the Lamp Wattage	Standard 90.1-2010, IECC 2012
Other Equipment	Prescriptive	No common examples	
	Component Performance	Minimum Efficiency for Motors	Standard 90.1-2010

Industry and organizational structure

Further to the discussion of organizational structure begun in the codes section above, characteristics of firms within the industry can serve as barriers or opportunities for the use of new systems such as alternative wall assembly systems, although the causality is not always clear. For instance, there is large variation in the literature on whether the size of a firm is relevant or not when it comes to adopting innovative practices. Koebel *et al* (2004) found large national builders operating in a single market area tended to be more innovative, but otherwise size was not statistically significant. Small builders were also noted as possibly being more sensitive to their customers, making them more likely to use innovative materials at their request (demand-pull). Large firms have been argued to be more likely to follow current building practice (Koebel and Cavell, 2006), while small firms are typically controlled by one owner who is more likely to be a technology champion, leading the small firm to adopting innovations.

As well, organizational culture plays a role as it " . . . reflects the firm's business strategy, approach to innovation, support for innovation champions and R&D, and emphasis on internal and external cooperation or competition" (Koebel and Cavell, 2006). Technology champions within small housing firms have been noted to usually be the owner, thereby allowing them to charge forward with an innovation easier (Koebel, 2008), whereas the owners of large firms have to convince their investors and others about the rewards of an innovation outweighing the risks. Small firms also tend to have little to no budget in testing out innovative building materials, but large firms do have such resources. Large firms, as noted above, though, tend to be path-dependent and not likely to move towards innovation on their own. For more on this topic, see Appendix A: Case Study - Discussion about AAC with a NJ Developer.

New Building Design and Construction Process

Building Information Modeling

Building information models are intelligent digital representations of building facilities. They provide integrated data repositories for information related to building systems. Creation of building information models and the use of structured data stored in building information models to support lifecycle management of building facilities are broadly referred to Building Information Modeling (BIM), a process-oriented concept (Eastman et al. 2010). BIM promises better organization and sharing of information, which leads to better quality and more efficient design and construction. In the past ten years, the applications of BIM in the Architecture, Engineering, and Construction (AEC) industry have grown exponentially. On many large-scale projects, great cost savings have been reported as the result of implementing BIM.
Whether BIM can benefit small scale projects such as residential construction as well as it does to large scale projects is the focus of many ongoing research studies. Despite of this, BIM applications in the residential construction sector are rapidly growing, in particular in the design stage. This is due to a number of driving forces: (1) architects can design quicker and better with BIM software tools; (2) BIM-based design facilitates prefabrication of residential building structure components; and (3) BIM models provide great 3D visualizations which allow construction professionals to quickly grasp design intent.

A question of interest to this study is whether BIM, as a new paradigm of design and construction process, can influence the penetration of energy efficient wall assemblies in the United States housing market. Close examination of the role of BIM in design and construction suggests several pathways that BIM can influence this matter. First, home owners are always concerned with the aesthetic appeal of homes that are built with alternative wall assembly systems other than wood assembly walls. BIM provides genuine 3D visualization that can dispel any myth about the aesthetic appeal of homes. So home owners can make more informed decisions rather than relying on tribal knowledge. Second, BIM provides convenient tools for conducting energy simulations. The outcome of these simulations can make energy savings from adopting certain wall assembly systems more apparent to future home owners, thus influencing their decision making on choices of wall assembly systems. Third, BIM results in more accurate design information, which promotes the use of prefabricated structures for improving construction efficiency. In other words, fewer design errors encourage the adoption of some wall assembly systems, such as precast concrete panels, which are traditionally regarded as difficult to use on residential projects due to the fact that they are difficult to be modified in the field and leave little room for mistakes.

Certainly, in order to encourage prefabrication, a precondition is that BIM software tools need to provide necessary mechanisms to model complex construction details for different types of wall assembly systems. Stick frame construction has dominated the residential market for decades; therefore, construction workers are very familiar with its construction methods. However, this is not true with other alternative wall assembly systems. To compensate the lack of understanding of construction details and methods used in alternative wall assembly systems, BIM tools must provide mechanisms for designing construction details related to the construction of these alternative systems. Perhaps the infrequent use of precast concrete panels in the current residential housing market is partially due to the limitations of existing BIM programs in modeling precast concrete structures. Before 2009, there were no BIM standards for modeling precast concrete to the level of construction details. Autodesk Revit, a leading BIM design program used by architects, did not provide adequate functionalities for modeling precast concrete panels before it introduced the option of breaking walls into panels in 2010. Currently, modeling of construction details associated with prefabricated concrete panels is still a very difficult task in Revit. In responding to this, an effort on developing BIM standards for precast concrete has been seen in the precast concrete industry (Jeong and Eastman 2010). After more than 5 years of research development at the national level, a standard for modeling concrete precast products and exchanging such information between BIM programs has been developed. But it will take several years for this standard to be diffused into software implementations.

Disaster Resilience

Hurricane Sandy was a classic late-season hurricane that originated in the southwestern Caribbean Sea, and slowly moved north parallel to the coastline of the United States. By the time Sandy made landfall in the US, it had weakened to a post-tropical cyclone. Nevertheless, Sandy drove a catastrophic storm surge into the New Jersey and New York coastlines. The surge and 70-knot maximum sustained winds damaged or destroyed at least 650,000 homes and left nearly 8.5 million people without power for durations lasting days to months. In addition to these immediate damages, hurricane Sandy also posed long term threats, such as mold, to residential communities. Considering the overwhelming damages sustained by many residential homes, a question arises: had these homes been built with wall assemblies that have stronger wind resistance and hazard resistance, would the damage be minimized?
Most of the residential homes damaged by hurricane Sandy were built with the classical stick frame construction. They used wood assembly walls, which perform poorly in against wind and flooding as demonstrated during hurricane Sandy (Figures 15). Now many homes are facing the threat of mold as the secondary impact of flooding.

Figure 15. Hurricane Destruction to Wood Assembly Walls

Alternative wall assembly systems such as precast sandwich concrete panel, SIP, and ICF have much better performance than wood assembly systems in terms of withstanding wind, flood, fire, mold, and insects. It seems the need to build a more resilient community could drive the wider adoption of alternative energy efficient wall assembly systems. This will be particularly true as data from many global climate change studies suggest that natural disasters such as hurricanes will occur with greater frequency and ferocity under the influence of global warming and as changes to the planet's climate become more pronounced. The capability to withstand natural disasters will become a critical factor in choosing building materials. The demand to build stronger and more resilient buildings will continue to grow. Within this global context, alternative wall assembly systems that have similar energy performance but better disaster resilience than the traditional wood frame assembly will almost certainly gain more ground in the U.S. housing market.

CONCLUSION

Table 11 below illustrates the relative benefits of select wall assembly systems. AAC, for example, provides a high level of protection against fire as well as strong resistance to insect and mold and superior acoustic performance, contributing to a comfortable and healthy indoor environment. SIPs provide particular advantage in the areas of saving time on the construction site and superior energy performance and resistance to seismic activity. Although ICFs can have higher material and labor costs, they offer excellent wind resistance and superior acoustic performance as well as very good energy performance and strong protection against hazards such as fire and seismic activity. Precast panels can also present high material and equipment costs, but offer a high level of protection against fire and very good energy performance. All of the alternative wall assemblies offer very good savings in the area of maintenance. Wood frame construction scores well in the areas of material, labor and equipment costs, and adequately in terms of energy efficiency given proper insulation, but there is a tradeoff when it comes to, resistance to hazards, indoor environmental quality and maintenance costs.

Excellent	Very Good	Good	Fair	Poor

	WOOD FRAME WALL	PRECAST CONCRETE SANDWICH PANEL	INSULATED CONCRETE FORMS (ICFS)	STRUCTURAL INSULATED PANELS (SIPS)	AUTOCLAVED AERATED CONCRETE (AAC)
MATERIAL COST	Very Good	Fair	Fair	Good	Good
LABOR COST	Very Good	Good	Fair	Good	Good
EQUIPMENT COST	Excellent	Good	Good	Good	Good
TIME ON SITE	Fair	Very Good	Good	Excellent	Very Good
ENERGY EFFICIENCY	Very Good	Very Good	Very Good	Excellent	Good
WIND RESISTANCE	Fair	Very Good	Excellent	Very Good	Good
FIRE RESISTANCE	Fair	Excellent	Very Good	Good	Excellent
SEISMIC RESISTANCE	Good	Very Good	Very Good	Excellent	Good
INSECT/MOLD	Fair	Very Good	Good	Good	Excellent
INDOOR AIR QUALITY	Fair	Very Good	Very Good	Very Good	Very Good
ACOUSTIC PERFORMANCE	Fair	Very Good	Excellent	Fair	Excellent
MAINTENANCE COST	Fair	Very Good	Very Good	Very Good	Very Good

Table 11 Wall Assembly Comparison, Rutgers Center for Green Building 2012

There are also areas in which these wall assemblies perform less well – for many initial cost is an inhibiting factor as is unfamiliarity of the construction trades. The following recommendations can help to overcome these and other barriers to greater market acceptance.

Recommendations

1. Provide education and information about alternative wall assembly systems to familiarize the design and construction industry with the technology, mainstream the construction methods, thus reducing the learning curve and cost of professional expertise.

2. Disseminate information, educate and work with stakeholders to advance regulations, codes and policies to support wall assemblies that provide high levels of energy performance and safety.

3. Develop tools and resources that contribute to a stronger understanding about energy efficient technologies in the mortgage, finance and insurance industries.

4. Increase accessibility to information and resources about wall assembly alternatives including demonstration projects, research, case studies and cost data.

5. Conduct research and evaluation of wall assembly materials, construction methods, occupant responses and comfort, life cycle costs, and post occupancy evaluation, using industry accepted material testing, building simulation models and cost-benefit models, and use this knowledge to develop industry standards for manufacturing and quality assurance.

These efforts will help contribute to the body of knowledge about wall assembly systems, compare advantages and disadvantages, and advance the industry towards supporting building systems and materials and that offer energy efficiency, safety, comfort and cost savings, adopting them for use as conventional materials within the standards of building design.

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APPENDIX A: CASE STUDY - Discussion about AAC with a NJ Developer

In order to better understand how organizational structure and related factors affect the decision-making behavior of the firm, two members of a NJ development company (referred to as Developer 1 and Developer 2 below) were interviewed about their experiences. The company is a small developer formed in 1980 that focuses on re-development projects within the New Jersey area, although the company has also completed projects outside of the state. The company is unusual in that it has a lot of experience with AAC. Interview questions were formulated based on the work of Koebel and Cavell (op.cit.) and Hassel *et al* (op.cit) within the framework of innovation diffusion and barriers research. The interview was conducted in 2011 by Bill Haslag as part of a school-based project.

Pursuant to this interview, in the case of this company, the size of the firm does matter in deciding on whether or not to use an innovative material as this smaller firm reports being able to be more innovative and flexible. As would be expected, client desires matter as well and the company relies on outside resources to learn about new products, although it is perhaps more of a "pull" than a market "push" situation, as the firm reports hearing about an innovation and then finding someone to consult with about it.

On the topic of contractors, the developer reports that prior work experience is key for general contractors. It doesn't appear that finding AECs with AAC experience is as difficult as might have been imagined. This is perhaps due to a couple of factors pertaining to AAC, one being that AAC is not "innovative" in the strictest sense. It has been used in Europe for decades, so there is educational material available for use, which lowers that particular barrier. Another factor could be the cited ease-of-use of the material itself. The developer cited that it is a very easy material to work with and takes very little time to show a worker how to use (personal correspondence, 2011).

Another interesting interview finding is that building code perhaps does not offer as many restrictions for the use of AAC as initially thought. However, the developer said building codes are still an obstacle in the use AAC as there have not been enough studies for the use of AAC.

Excerpts from 2011 Interview:

As I understand it, your company is very much for the use of AAC. Did the size of the firm have anything to do with this decision?

Developer 1 - **Yes we are a smaller company that has fewer decision-makers and therefore more apt to use an innovative product**.

Developer 2- **When marketing, smaller companies are typically more innovative and can pull the trigger on this type of decision.**

Have codes and regulations ever restricted or flat out discouraged the use of AAC in any of your projects so far?

Developer 1 - **Yes, certain codes have restricted the use of AAC because it has not been recognized for its qualities and the studies have not been done. This is one of the factors and affects the overall use of AAC in a significant way.**

Developer 2 - **The AAC industry sought to answer the codes and standards issues early on in their introduction into the USA and looked at the structural issues primarily and the performance issues concurrently. There are some issues that today's building environment have actually helped in accepting AAC, however we are still finding that there is more data needed and this [is] in the works.**

How do client's wants and wishes affect the use of AAC, or the remodeling plan in general?

Remodeling where moisture had affected drywall fire partitions AAC really met the clients' demands. Also AAC fire rating, lightweight and single trade construction has moved client remodelers to use it.

Small firms not having the budget to test new materials, they'll sometimes have a "technology champion" as the owner. Large firms have a larger budget to experiment, but they also have investors to convince. As a small developer, has this been your experience?
Developer 1 - **Yes as per above we are a small firm with owners who are “champions” for the product.**

Your company works with a large number of subcontractors, correct? What about general contractors? Are certain contractors chosen more frequently than others? Why? How are some contractors chosen over others?
Developer 1- **Contractors are chosen for their ability to perform the work requested and stay in budget. Work history is of key importance when choosing a subcontractor.**

What resources does your company have, either internally or externally, to learn about new products?
Developer 1 - **We are a smaller firm and we rely upon professionals that we hire to analyze products.**
Developer 2 – **Our company appears to be more in tune with what the market needs and is flexible enough to react to the market needs much more quickly than larger firms that [are] less flexible.**

Does your company’s use of AAC require special considerations during [the early steps of the building process]?
Developer 1 - **Yes, innovative design is important in land development and getting support for a development plan.**

For the pre-construction phase does AAC restrict who among the general contractors or subcontractors you can choose from?

Developer 1 - **Some engineers and architects have more experience with AAC and this can drive at least part of the team on the job. All the companies we would hire to build the project both GC or sub would have the ability to understand and perform the work.**

For the design phase, is there ever any anticipation of meeting difficulties from building inspectors by choosing to use AAC?

Developer 1 - **Yes though each year stumbling blocks are removed as more and more codes include the material for different use.**

Does a developer ever look at how their material use will affect the post-construction phase or a homebuyer's ability to buy the home or is that process outside the developer's field?

Developer 1 - **Absolutely a developer looks at how a buyer will be affected by every decision made regarding everything from site selection down to each material and how it will affect the buyer’s ability and desire to make the purchase. If it is a property they will own or sell this is very important as it must meet the performance that they have said the building would achieve.**

APPENDIX B: An Energy Simulation Study

Background

The purpose of this simulation study is to study the energy performance of various wall assembly systems through energy simulation. Wood frame construction has been a traditional and dominant choice of wall assembly systems in the U.S. residential housing market. Alternatively, wall assembly systems including precast concrete panels, insulated concrete forms (ICFs), structural insulated panels (SIPs) and autoclaved aerated concrete (AAC) have been used in residential construction because it is believed that these systems perform equally or better in terms of energy performance, resistance to hazards such as fire, winds and earthquakes, and improved indoor environmental quality, although not always in terms of their cost. While there are many industry case studies on the energy performance of these various wall assembly systems, a comprehensive assessment across all these wall assembly systems do not exist. In this research, we conducted a detailed energy simulation study on an average New Jersey house to compare the energy performance of these different wall assembly systems. The research results will provide quantitative understanding on the energy performance of these wall assembly systems in New Jersey.

Research Methods

In this research, we developed a CAD model for an average New Jersey house that can be used in energy simulation programs. The variable to be investigated is the type of the wall assembly system used in the house. DesignBuilder, an energy simulation program built on top of the EnergyPlus energy simulation engine, was chosen as the energy simulation and analysis problem. Although there are a variety of energy simulation programs on the market, several studies have shown that EnergyPlus produces most reliable and accurate results. We chose the Newark weather profile as the weather input in the analysis, and a detailed occupancy schedule is designed to reflect a reasonable heating and cooling requirement. In each run of simulation, we choose a different type of wall assembly system while keeping the rest of parameters constant. This ensures a fair comparison among different wall assembly systems can be made. The following provides detailed information about the model home and explains the calculation of R-values for different building components.

Model Home

A two-story residential house model was developed in this study (Figure B1). The house has a detached garage and a basement, a common choice in New Jersey. The area of the model house was obtained from previous DOE studies on average New Jersey homes. The comparison for the model house and average New Jersey house is shown below in table B1. Figures B2 through B6 show the floor plans and elevation views for the designed model house.

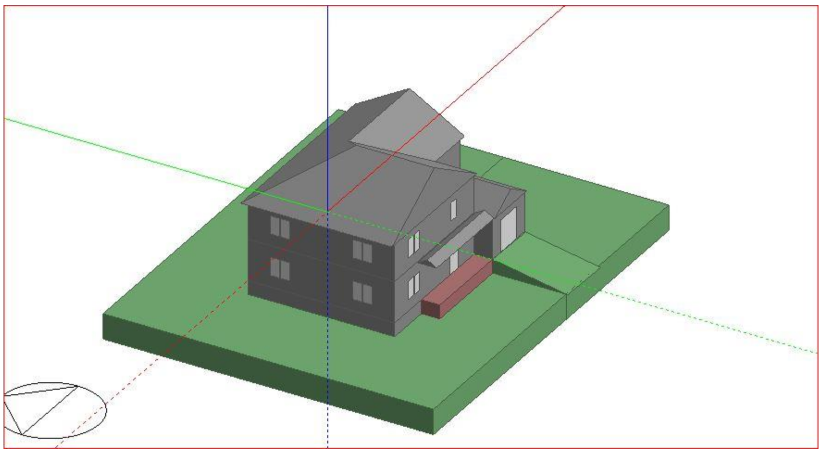

Figure B1. The 3D Model House

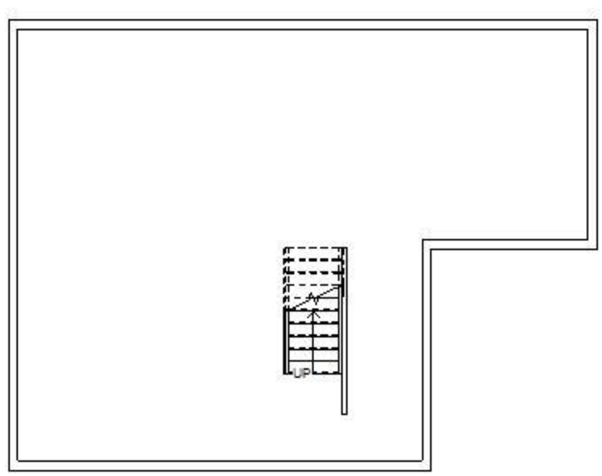

Figure B2. Basement Floor Plan

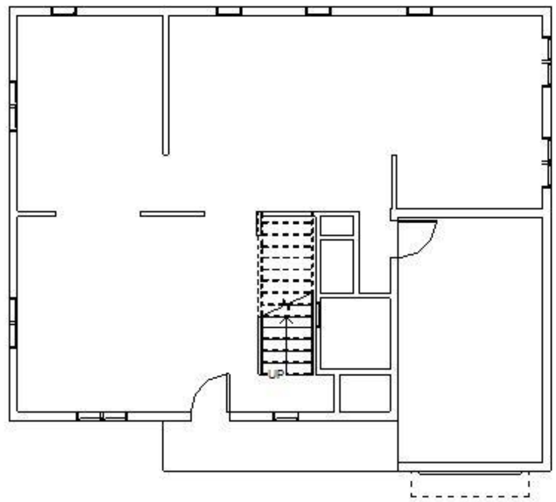

Figure B3. First Floor Plan

	Typical Single Family House in New Jersey	Model House	
			Difference from baseline model
Area of Conditioned space (sq. ft.)	2180	2209	+29
Area of Unconditioned space (sq. ft.)	Data Not available	1243	
Area of Conditioned volume (cu ft.)	37060	37553	+493
Floors Above Grade	2	2	
Number of bedrooms	4	4	
Foundation wall			
• foundation wall height (ft.)	8.5	8.5	
• Above Grade (ft.)	3	3	
• Below Grade (ft.)	5.5	5.5	
Wall Area (sq. ft.)	3366	3961	+595
Windows Area (sq. ft.)			
• East	72	72	0
• South	72	72	0
• North	60	64	4
• West	60	64	4
Door Area (sq. ft.)			
• Front	21	21	0
• Side	21	21	0
Ceiling Area (sq. ft.)	2180	2162	-18

Table B1. Comparison between Typical New Jersey House and the Model House

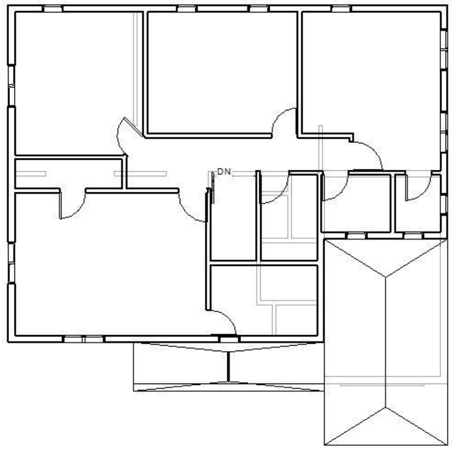

Figure B4. Second Floor Plan

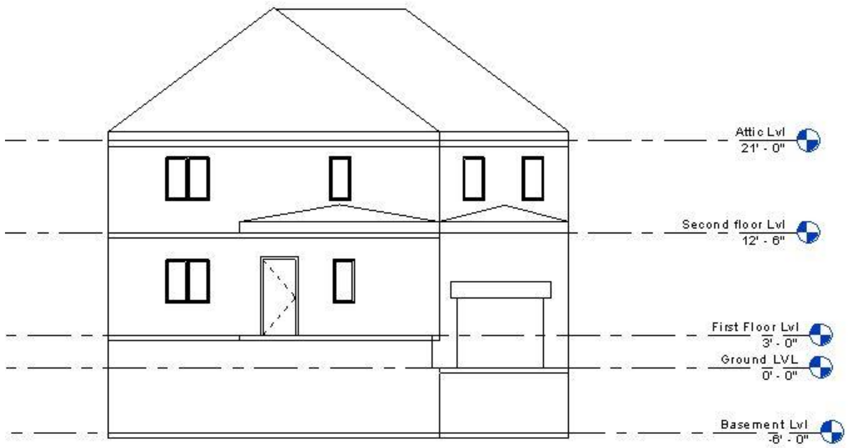

Figure B5. South Elevation View

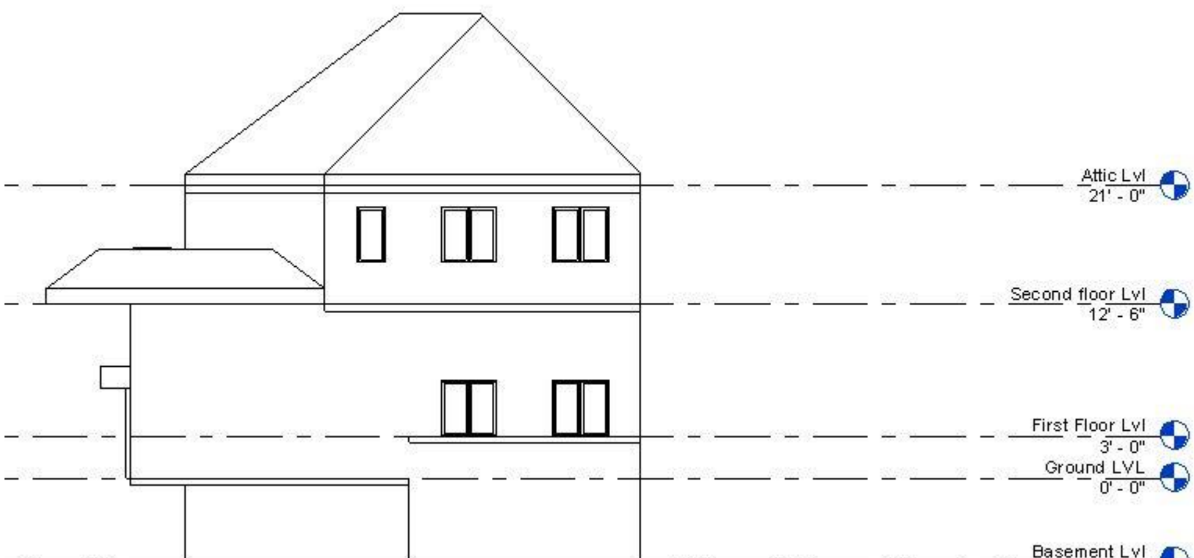

Figure B6. North Elevation View

R-Value for Building Components

To ensure consistency in choosing R-values for different building components, we use the 2012 International Energy Conservation Code for New Jersey as the guide for choosing R-values. Accordingly, Table B2 shows the R-Values for different building components materials used in the energy model.

Building Components	R-Value
Ceiling	0.4
Wood Frame Wall	49
Mass Wall	20
Floor	19
Basement Wall	10
Floor Slab	10
Crawl Space Wall	10

Table B2. R-Value for Building Components

In some cases, the choice of roofing system is correlated with the choice of wall assembly system. For example, stick frame construction is usually built with a stick frame roofing system while the other more advance wall assembly systems may use a roofing system made of structurally insulated panels. To accommodate this condition, two different roof systems were used in the analysis. The following table shows the R-value calculation for the two roofing systems used in the analysis.

Material	Thickness (inches)	Conductivity K (Btu.in/h.sq ft.F)	Resistance R (h.sq ft.F/Btu)	Reference	Material Specification
Roof for Stick Frame Construction					
• Vinyl Sliding	0.38		0.62	ASHRAE 2013	
• Vapor seal 2 layer of mopped 15lb felt		0.12	0.12	ASHRAE 2013	
• Fiberboard	0.50		0.68	ASHRAE 2013	
• Air Gap					
• Batt Insulation	6.00	0.32	18.75	ASHRAE 2013	R-19
• Gypsum Board	0.50	1.1	0.909	ASHRAE 2013	
Total Thickness	7.38	Total R- value	21.079		
Roof for other Wall Assembly					
• Vinyl Sliding	0.38		0.62	ASHRAE 2013	
• Vapor seal 2 layer of mopped 15lb felt		0.12	0.12	ASHRAE 2013	
• Fiberboard	0.50		0.68	ASHRAE 2013	
• Air Gap					
• Oriented Strand Board	0.50		0.68	ASHRAE 2013	
• Polyurethane Foam Insulation	3.00	0.17	17.6	ASHRAE 2013	Medium Density, Closed Cell
• Oriented Strand Board	0.50		0.68	ASHRAE 2013	
Total Thickness	4.88	Total R- value	20.38		

Table B3. R-Value calculation for roofing system

A wall assembly system is often composed of several layers of materials. To calculate the R-value for a wall assembly system, it involves the calculation and summation of R-values for each individual layer of material. To determine the R-value for each individual layer of material, we used several common standards as the guideline. These standards include ASHRAE 2013, NCMA TEK6-2B, and ASTM C518. It is also important to use standard layer compositions for a given wall assembly system. The R-Value calculations for each of the wall assembly systems are shown in Table B4.

Material	Thickness (inches)	Conductivity K (Btu.in/h.sq ft.F)	Resistance R (h.sq ft.F/Btu)	Reference	Material Specification
Stick Frame Walls					
4" Wall- Variation 1					
• Vinyl Sliding	0.4		0.62	ASHRAE 2013	
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Batt Insulation	4.0	0.32	12.42	ASHRAE 2013	Glass Fiber BATT
• Vapor seal 2 layer of mopped 15lb felt		0.12	0.12	ASHRAE 2013	
• Gypsum Board	0.5	1.1	0.909	ASHRAE 2013	
Total Thickness	5.4	Total R- value	14.749		
4" Wall- Variation 2					
• Vinyl Sliding	0.4		0.62	ASHRAE 2013	
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Polyurethane Foam Insulation	4.0	0.17	23.52	ASHRAE 2013	Medium Density, Closed Cell
• Vapor seal 2 layer of mopped 15lb felt			0.12	ASHRAE 2013	
• Gypsum Board	0.5	1.1	0.909	ASHRAE 2013	
Total Thickness	5.4	Total R- value	25.849		
6" Wall- Variation 1					
• Vinyl Sliding	0.4		0.62	ASHRAE 2013	
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Batt Insulation	6.0	0.32	18.75	ASHRAE 2013	Glass Fiber BATT
• Vapor seal 2 layer of mopped 15lb felt			0.12	ASHRAE 2013	
• Gypsum Board	0.5	1.1	0.909	ASHRAE 2013	
Total Thickness	7.4	Total R- value	21.079		
6" Wall- Variation 2					
• Vinyl Sliding	0.4		0.62	ASHRAE 2013	
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Polyurethane Foam Insulation	6.0	0.17	35.29	ASHRAE 2013	Medium Density, Closed Cell
• Vapor seal 2 layer of mopped 15lb felt			0.12	ASHRAE 2013	
• Gypsum Board	0.5	1.1	0.909	ASHRAE 2013	
Total Thickness	7.4	Total R- value	37.619		
Structural Insulated Panels					

4" SIP Wall					
Vinyl Sliding	0.4		0.62	ASHRAE 2013	
Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Polyurethane Foam Insulation	3.0	0.17	17.6	ASHRAE 2013	Medium Density, Closed Cell
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Total Thickness	4.4	Total R- value	19.58		
•					
12" SIP Wall					
Vinyl Sliding	0.4		0.62	ASHRAE 2013	
Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Polyurethane Foam Insulation	11.0	0.17	64.7	ASHRAE 2013	Medium Density, Closed Cell
• Oriented Strand Board	0.5		0.68	ASHRAE 2013	
• Total Thickness	12.4	Total R- value	66.68		
Autoclaved Aerated Concrete					
8"					
Interior Stucco			0.72	Based on NCMA TEK6-2B	
Autoclaved Aerated Concrete	8.0	0.96	8.33[1]	Based on NCMA TEK6-2B	115 pcf Concrete
• Exterior Plaster			0.72	Based on NCMA TEK6-2B	
• Total Thickness	8.0	Total R- value	9.77		
Insulated Concrete Forms					
8" Wall					
Vinyl Sliding	0.4		0.62	ASHRAE 2013	
Expanded Polystyrene Panels	1.0	0.25	4	ASHRAE 2013	
Reinforced Concrete	6.0		0.9	NCMA TEK 6-2B	115 pcf Concrete
• Expanded Polystyrene Panels	1.0	0.25	4	ASHRAE 2013	
• Interior Stucco			0.72	Based on ASTM C518	
• Total Thickness	8.4	Total R- value	10.24		
•					
• 12" Wall					
Vinyl Sliding	0.4		0.62	ASHRAE 2013	
Expanded Polystyrene Panels	1.0	0.25	4	ASHRAE 2013	
Reinforced Concrete	10.0		1.5	NCMA TEK 6-2B	115 pcf Concrete
• Expanded Polystyrene Panels	1.0	0.25	4	ASHRAE 2013	
• Interior Stucco			0.72	Based on ASTM C518	

• Total Thickness	12.4	Total R- value	10.84		
•					
• Precast Concrete Panels					
8" Wall					
Gypsum Plaster Board	1.0	1.1	0.909	ASHRAE 2013	
Precast Concrete (waterproof)	2.0		0.3	NCMA TEK 6-2B	115 pcf Concrete
Polyurethane Foam Insulation	1.5	0.17	8.82	ASHRAE 2013	
• Air Gap	0.5		1		
• Precast Concrete (Structural)	3.0		0.45	NCMA TEK 6-2B	115 pcf Concrete
• Exterior Plaster			0.72	Based on ASTM C518	
• Total Thickness	8.0	Total R- value	12.199		

Table B4. R-Value Calculations for Different Wall Assembly Systems

[1] The steady state R-value (per NCMA TEK6-2B) was found to be 8.33, and this was the value utilized in this study. Other studies have shown that the effective R-value of AAC can be set at 1.43 to 2.53 times higher than the steady state R-value when the thermal mass and dynamic benefit for massive systems is considered. This additional factor for Dynamic Benefit for Massive Systems (DBMS) varies depending on geographic region. In the Northeast area climate (Washington D.C.), the DBMS value for AAC is 1.67 (see Table 4.0 below), yielding an effective R-value of 13.93. For 2x4 stud wall construction, the DBMS is 1.0, yielding an effective R-value of 12.5. Additionally, air infiltration is lower for AAC than wood frame construction. Thus, the performance of AAC is closer to that of a 2x6 stud wall (R-19) than a 2x4 stud wall (R-11). The selection of R-value for AAC is a controversial choice, since effective value is the most accurate parameter, but in order to use it, effective R-values would need to be used for all types of wall assemblies. Effective R-values are not well documented for all assemblies, thus the steady state value was selected for AAC in this energy study (Hebel).

City	AAC wall			Two-core CMU wall			2x4 Wood Stud Wall		
	steady-state R-value	DBMS	Effective R-value	steady-state R-value	DBMS	Effective R-value	Steady-state R-value	DBMS	Effective R-value
Atlanta	8.34	1.91	15.93	2.29	0.89	2.04	12.5	1.0	12.5
Denver		1.84	15.34		0.91	2.08			
Miami		1.62	13.51		0.62	1.42			
Minneapolis		1.43	11.93		0.57	1.31			
Phoenix		2.53	21.10		1.46	3.34			
Washington		1.67	13.93		0.78	1.78			

Table 4.0 - Dynamic thermal performance characteristics for AAC units, two-core CMU and wood frame walls.

Results and Discussion

For each type of wall assembly systems, thermal analysis was conducted to determine cooling and heat loads. The following summarizes the energy simulation results in terms of a number of key metrics including Total Cooling, Zone Heating, External Infiltration, Heating (Gas), and Cooling (Electricity). The definitions of these metrics are provided as the following.

- Total Cooling:
- Zone Heating:
- External Infiltration:
- Heating (Gas):
- Cooling (Electricity):

Table B5 provides a global view of the energy performance of the ten different wall assembly systems studied in this research. The wall assembly systems are listed in a decreasing order in terms of energy performance. Figure B7 shows a graphical comparison of the performance of these wall assembly systems. It can be noted that 12” SIP shows the best performance while 8” AAC ranked at the last. However, it should also be noted that the difference among these wall assembly systems are minor (<12%). Therefore, the energy performance gain can be easily offset if other factors are considered such as construction productivity.

	Total Cooling (kBtu)	Zone Heating (kBtu)	External Infiltration (kBtu)	Heating (Gas) (kBtu)	Cooling (Electricity) (kBtu)
12" SIP	9419.756923	40978.24961	34324.7118	49371.3907	5640.573448
6x2 with Polyurethane Foam Insulation	9594.599208	42908.37866	34174.1266	51696.83798	5745.268429
4x2 with Polyurethane Foam Insulation	9773.962294	44865.96514	34028.9152	54055.37051	5852.671281
6x2 with BATT Insulation	9898.291882	46221.40254	33932.63	55688.43289	5927.121111
4" SIP	9972.154973	47026.39429	33877.4676	56658.30207	5971.349584
4x2 with BATT Insulation	10177.11121	49237.41799	33732.3232	59322.19516	6094.078097
8" PRECAST	10363.61222	51230.33767	33610.4618	61723.30061	6205.75602
12" ICF	10493.76349	52607.23544	33531.9726	63382.20952	6283.690824
8"ICF	10560.46604	53332.54146	33492.5849	64256.07177	6323.632852
8" AAC	10614.6089	53955.89625	33459.5768	65007.11428	6356.053565

Table B5. Yearly Performance Comparison across Various Wall Assembly Systems

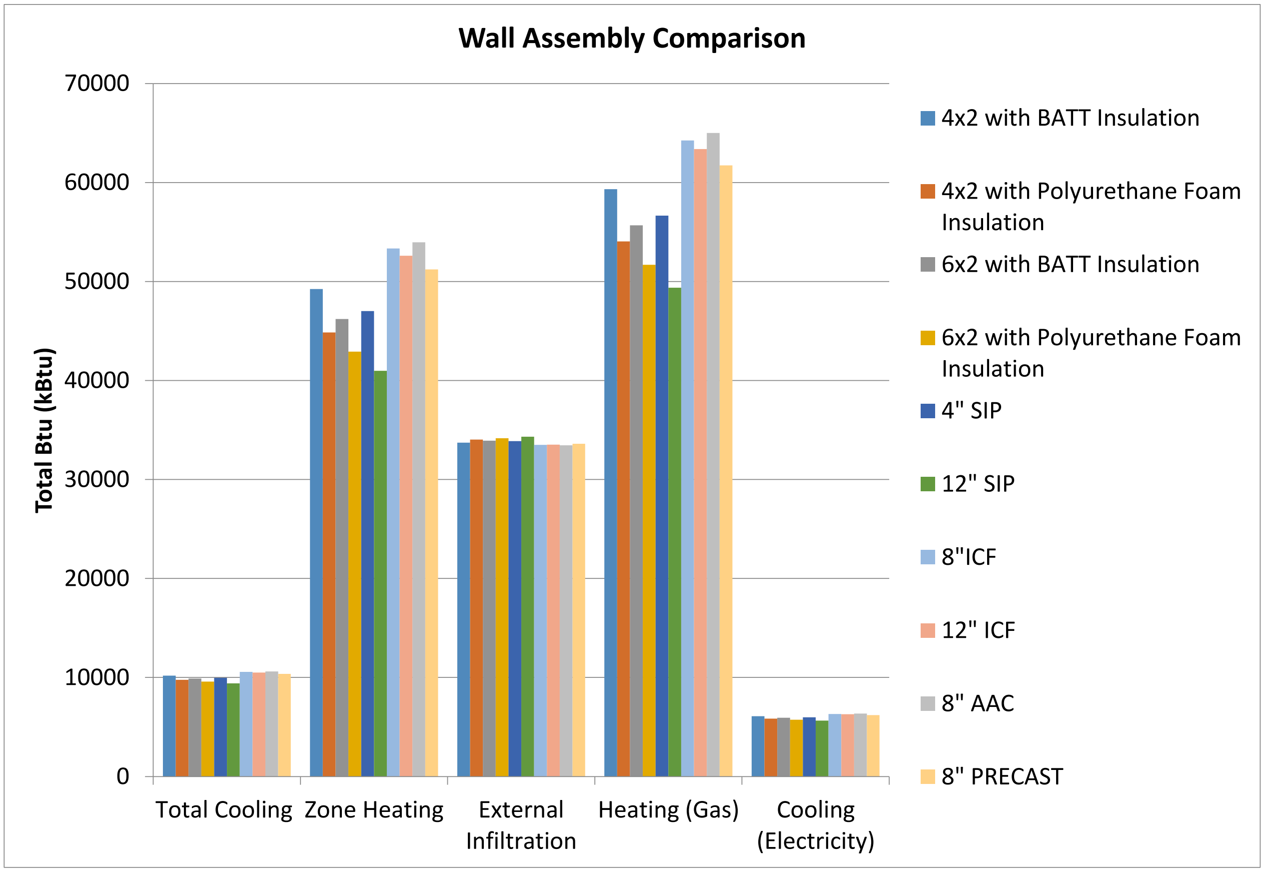

Figure B7. A Graphical Comparison of the Yearly Energy Performance among Different Wall Assembly Systems

To gain more insights on the energy performance on a monthly basis, the detailed breakdowns of energy performance for each type of assembly wall system are shown in Figures B8 – B12. It can be noted that the results are consistent with the above finding. Overall, the results suggested that there are several types of alternative wall assembly systems, including 12” SIP, 6x2 with Polyurethane Foam Insulation, 4x2 with Polyurethane Foam Insulation, performing better than 6x2 with BATT Insulation-based wood frame construction in terms of energy performance. Also, 4” SIP appears to be superior than 4x2 with BATT Insulation in term of energy performance. Nevertheless, given the superior energy performance that can be reaped from these types of wall assembly systems, the market share of these systems has grown very slowly. The factors contributing to this situation is not clear. But likely, lack of detailed data to support the claims made by manufacturers could be one reason. In this study, we validated the performance of several wall assembly systems, highlighting the opportunities to use these alternative wall assembly systems to improve energy efficiency.

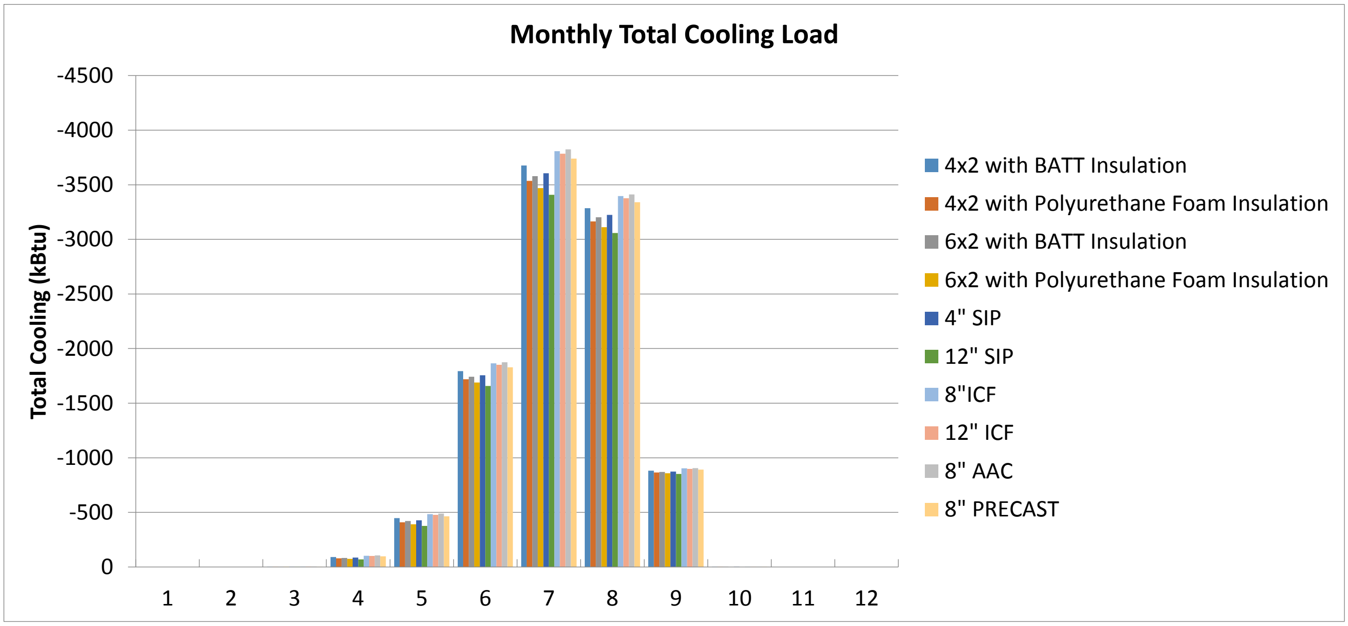

Figure B8. Monthly Total Cooling Load Comparison

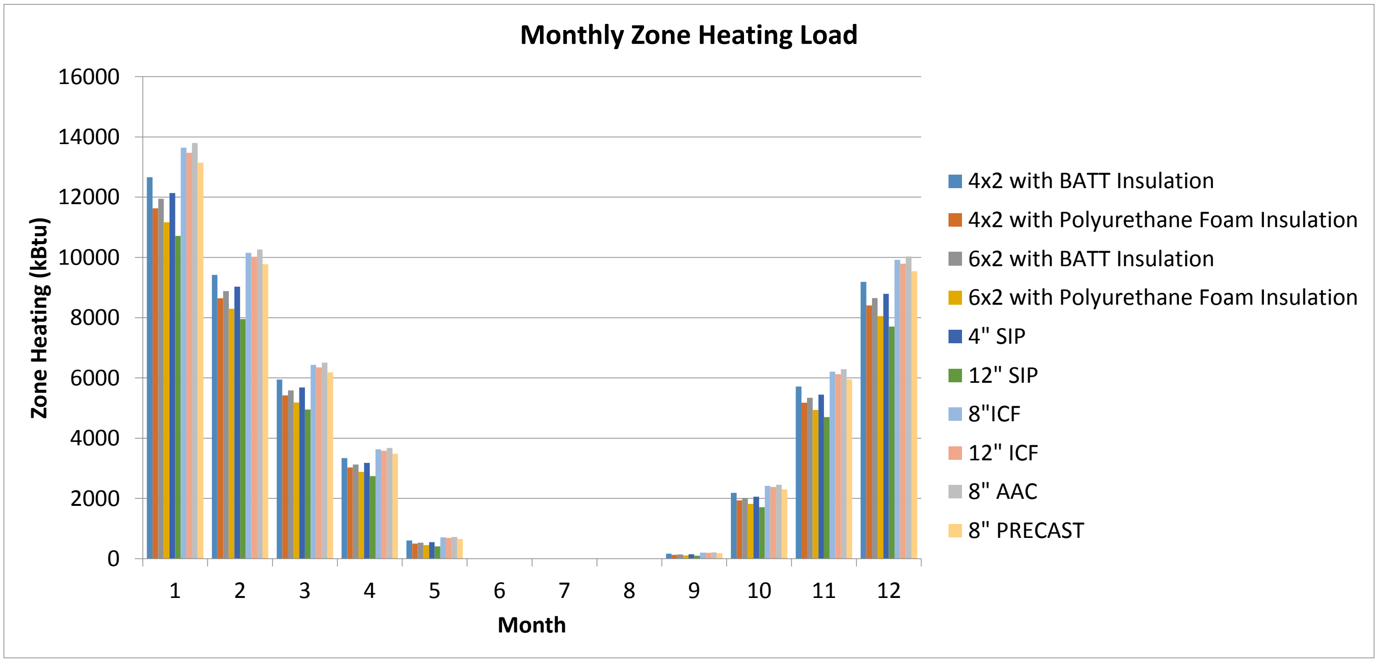

Figure B9. Monthly Zone Heating Load Comparison

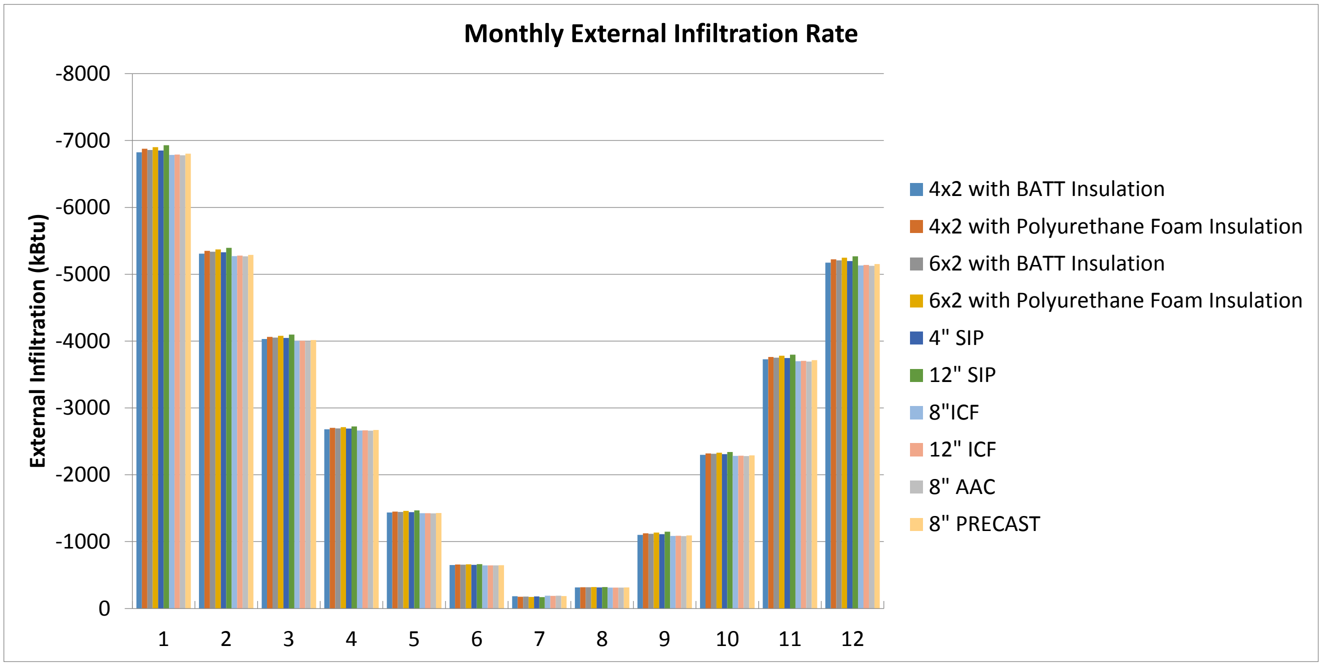

Figure B10. Monthly External Infiltration Rate Comparison

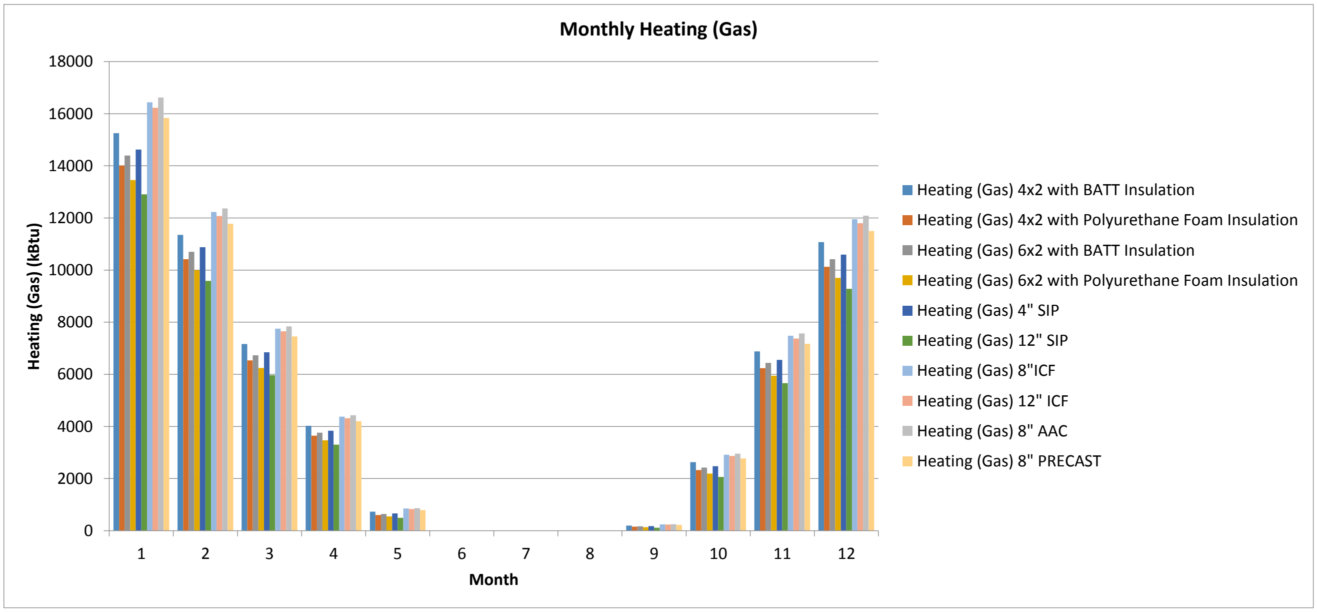

Figure B11. Monthly Heating (Gas) Comparison

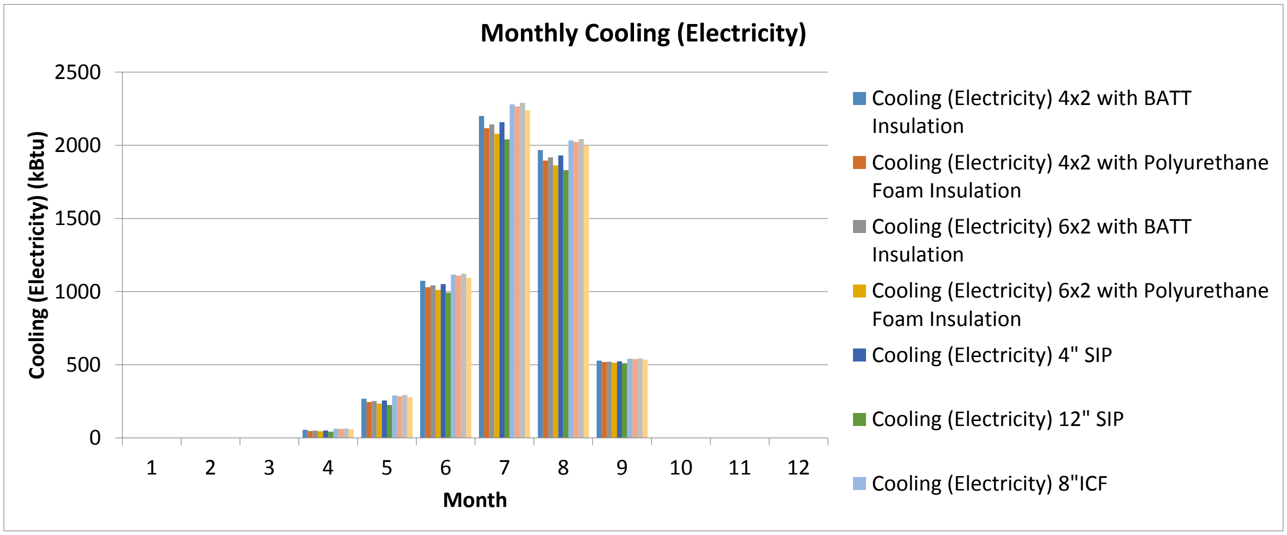

Figure B12. Monthly Cooling (Electricity) Comparison