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COMPARATIVE ANALYSIS FOR ENERGY PERFORMANCE OF VARIOUS SKELETON SYSTEMS IN THE MIDWEST

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ABSTRACT

According to the Energy Information Administration (EIA), residential buildings in Indiana consumed approximately 18% of the state's total energy usage during 2017. Additionally, the Indiana Residential Code was most recently updated in 2020, after having not changed in 15 years, showing a renewed interest in improving residential building performance. Various strategies have been used in the past to reduce energy consumption or to make buildings more thermally comfortable throughout the seasons, and this is commonly seen in vernacular architecture throughout the world. In the Middle East, a typically hot and dry climate, buildings were traditionally built out of thermally massive stone and brick to help dampen the temperature swings, however this practice has moved recently to insulated concrete forms (ICFs). While the state of Indiana has a mixed-humid climate, very different from the Middle East, ICFs still provided a promise of dampening temperature swings, and providing thermal bridge free insulation. While ICFs may be more expensive than traditional wood-framed walls, energy modeling has shown that they can reduce the annual space conditioning consumption in single family detached residences, and the potential to reduce the need for larger sized mechanical equipment.

KEYWORDS: EIA, ICFs.

INTRODUCTION

Residential structures are a largely untouched area of building performance potential, especially in the Midwest. The Energy Information Administration (EIA) reported that in

2017, the residential buildings in Indiana consumed approximately 18% of the state's total energy usage (EIA, 2017). Many growing areas, such as Indianapolis, experience a suburban sprawl of developer-built homes that disregard optimal orientation and are aimed more at cost effectiveness and code compliance rather than building a durable, efficient home. While most residential structures are still built with wood frames in Indiana, concrete has a strong prevalence in commercial construction. Indianapolis is home to two large precast concrete panel plants, and many local concrete contractors have experience with insulated concrete forms (ICFs).

The Portland Cement Association performed a large modeling study into the effectiveness of various concrete assemblies in 2001. While this covered Indiana, the residential construction code has since been updated, as have the energy modeling programs used perform the study. The study revolved around a 2,450 sqft "developer style" house that varied only the wall assemblies, and all other elements remained constant. The roof in all cases was a traditionally framed, unconditioned attic. This study showed a savings on space conditioning energy as high as 52% for an ICF house compared to a wood framed house (Gajda, 2001).

It is to the advantage of the building designer that he or she has considered as many passive strategies early on in the design phase, as it has been shown that passive strategies such as superinsulation, proper orientations, and building shading can reduce the space conditioning energy consumption between sixty and eighty percent (PHIUS, 2018). A popular strategy to be considered is using thermally massive materials in appropriate locations to help reduce space conditioning loads. Thermal mass can be any material with a high thermal heat capacity, such as a phase change wax, pool of water, or concrete building assemblies.

Thermal mass works by absorbing heat energy during times where there is an excess, and then releasing it at a later time when the heat energy is needed, and can have a drastic impact on the space conditioning energy consumption, as well as the peak demand for space conditioning energy (Le Dreau and Heiselberg, 2016). Thermal mass has proven to be especially effective in warm climates with drastic diurnal temperature swings and intermittent occupancy, but can be a drawback in colder climates. Colder climates require a more tuned thermal mass to be effective (Reilly and Kinane, 2017). A study in Knoxville, Tennessee, a climate not that different from Indianapolis, has shown that thermal mass can be an effective energy saving strategy in mixed climates. Researchers at Oak Ridge National Laboratory monitored the energy consumption of identical houses, side by side, where the only difference between the houses was that one had ICF walls. Throughout one year of monitoring the houses, the ICF house used 7.5% less energy than its traditionally framed counterpart (Petrie et al, 2002).

Though a very different climate than American Midwest, the Middle East has a long tradition of building buildings out of stone, and then concrete, and most recently, ICFs. Concrete is a familiar material in the Middle East, which replaced the local materials used in vernacular architecture during the building boom in the early 1970's (Al-Abideen, 199). This familiarity makes the area a good test bed for ICF construction to take off, especially as the need for insulation in the area becomes more understood. Zein Al-Abideen noted that the part of the building most likely to fail after being built is the steel rebar rusting, and ICFs cover the rebar that would be exposed, helping prevent this failure. The ICF market in the middle east has grown, covering all building typologies from larger commercial structures to single family residences, to military installations. The flexibility of the formwork allows for traditional architectural styles to be built, but in more modern, insulated material (ICF Builder, 2012).

METHODOLOGY

This study is heavily based on the work of John Gajda at the Portland Cement Association. His work involved the predictive energy modeling of a single family house geometry using different wall assemblies, focusing on concrete constructions. These houses were modeled in 25 representative cities across North America. The energy consumption for space conditioning in the concrete walled houses were less than that of the traditionally framed counterparts (Gadja, 2001).

This study focuses on houses built in central Indiana, with Indianapolis being the representative city for this area. The base house used is the same one from the referenced study, however there is a case in which the house has been redesigned with a low-slope concrete roof, modeled after the constructions seen in the middle-east. It is important to note here that the Indiana residential energy code has been updated, so the code minimum house built in this study should already outperform the baseline home from the referenced study.

The referenced study uses DOE-2 as the energy modeling engine, however energy modeling software has made significant strides in the past two decades, not only in terms of user interface, but also accuracy. In this study, the most current version of BEopt was used. BEopt is a user interface for EnergyPlus, the current engine that the US Department of Energy has worked on building. EnergyPlus handles solar gain, ground heat transfer, and thermal mass differently than the older DOE-2, so the results of this study are considered to be more accurate. BEopt also allows for parametric runs and optimization based on cost data, and in this study, the parametric option was used. This option allowed for quick iterations of multiple assemblies on the same geometry, and easy results comparison.

The base house in this study is similar to the one in the reference study, with updated assemblies per the Indiana Residential Code (IRC), which was released in 2020. It is based on the IRC 2018, and contains Indiana specific amendments (INDHS, 2020). The geometry of the base house and the proposed house are identical, the form and apertures are identical. The base case does have a different geometry for the roof compared to the low-sloped roof, middle east inspired design, which has only a low-slope roof of concrete construction.

For Indianapolis, the baseline case wall for the house is one with 2 x 4 studs at 16” on center, filled with R-13 batt insulation, and over insulated with a 1” sheet of R-5 rigid insulation. This baseline construction can be seen on both the traditional pitched roof variants and the low-slope roof alternative. The assumption is that all these houses would have a medium darkness of aluminum siding. For shading, the pitched roof house has slight overhangs on all sides, while the low-slope has none. Both types of houses are laid out with the garage on the front of the house, and the front facing north. There are neighboring houses, identical in form to the proposed design, located to the left and right of the house at 15 ft away to emulate the actual context of a typical suburban home located in a subdivision. Figure 1 shows an isometric view of the test house with the pitched roof. Figure 2 shows an isometric view of the test house with low-slope roof.

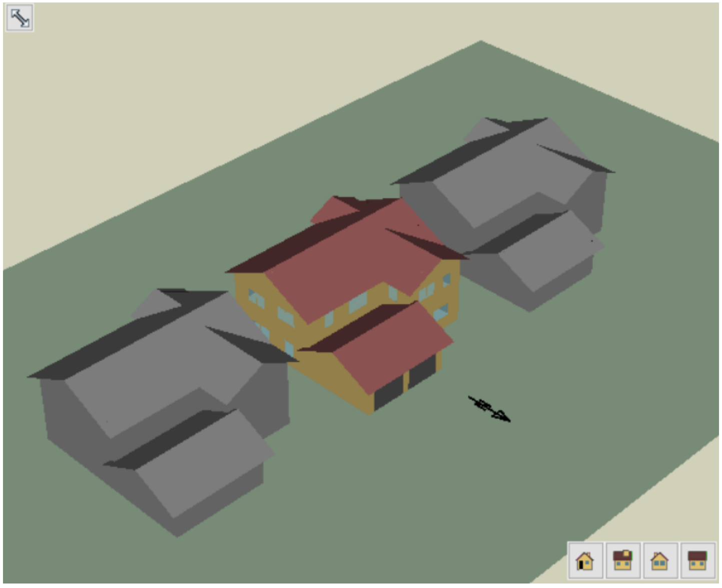

Figure 1: Isometric view detailing the pitched roof test house.

Figure 2: Isometric view detailing the low-slope roof test house.

The proposed houses vary in wall assembly only for the options with the traditional pitched roof with an unconditioned attic. The middle east inspired house has a low-slope insulated concrete roof, and the wall assemblies here are varied with framed walls and ICFs.

The parametric mode in BEopt was used to allow for quick simulations with the various enclosures. The base parameters that did not change from option to option were set first, such as the heating and cooling system, lighting fixture type, water heater, window area and type, and floor and roof assemblies and insulation values. There were two BEopt *Cases* assembled, one of the pitched roof geometry and one for the low slope roof geometry. Then the different enclosure options were selected, creating ten points per case, five of which are unnecessary for this study, and can be unselected on the results page of BEopt and will not appear on the resulting graph.

The weather file selected for the study is a TMY3 file from the Indianapolis international airport. As this study is focused on the viability of a concrete house in Indiana, and Indianapolis is the most populous area in the state, working a prototypical design for a house in Indianapolis would have the greatest impact on improving residential energy consumption.

The only thing varied about each house in either set was the exterior enclosure construction, specifically the wall assembly. The remaining inputs detailed in Table 1 were held constant throughout the run of the set. This allows for the study to focus only on the impacts of the enclosure. While building energy performance is based on a complex network of different building elements, the impact of wall type alone should have a significant impact on space conditioning energy use.

Table 1: BEopt Model Input Summary

	Climate Zone 5 Base House	Pitched Roof Framed Walls	Pitched Roof Mass Walls	Low Slope Frame Walls	Low Slope Mass Walls
Fenestration U-Factor	0.30	0.30	0.30	0.30	0.30
Fenestration SHGC	NR	0.46	0.46	0.46	0.46
Ceiling R-Value	49	R-49 Fiberglass Batt	R-49 Fiberglass Batt	R-49 above concrete deck	R-49 above concrete deck
Framed Wall R Value	20 or 13 + 5	2x6 studs @ 24” o.c. w/ R-21 Batt	NA	2x6 studs @ 24” o.c. w/ R-21 Batt	NA
		2x4 studs @16” o.c. w/ R-13 batt and R-5 XPS		2x4 studs @16” o.c. w/ R-13 batt and R-5 XPS	
Mass Wall R-Value	13/17	NA	2” EPS, 4”Concrete, 2”EPS	NA	2” EPS, 4”Concrete, 2”EPS
			2” EPS, 8”Concrete, 2”EPS		2” EPS, 8”Concrete, 2”EPS
			2” EPS, 12”Concrete, 2”EPS		2” EPS, 12”Concrete, 2”EPS
Floor R Value	30	R-30 Continuous beneath slab	R-30 Continuous beneath slab	R-30 Continuous beneath slab	R-30 Continuous beneath slab
ACH50	3	3	3	3	3

Mechanical System	NA	95% AFUE Furnace w/ 14 SEER AC	95% AFUE Furnace w/ 14 SEER AC	95% AFUE Furnace w/ 14 SEER AC	95% AFUE Furnace w/ 14 SEER AC
Water Heating System	NA	Gas EF-0.67	Gas EF-0.67	Gas EF-0.67	Gas EF-0.67
Lighting	NA	100% LED Hardwired, 34% CFL Plugin	100% LED Hardwired, 34% CFL Plugin	100% LED Hardwired, 34% CFL Plugin	100% LED Hardwired, 34% CFL Plugin

RESULTS

The results showed a decrease in energy usage in the house with ICF walls, and that the houses with the insulated concrete deck as the roof performed better than those with a pitched roof and insulated attic floor. The charts depicted below (Figures 3 through 6) detail the outputs from BEopt. Each Point on the X-axis represents an iteration of the house, and the Y-axis measures the annual site energy use of the house, broken down by end use and fuel, labeled in the legend on the right side of the chart.

Figure 3 depicts the annual site energy consumption for the pitched roof test house. The point labels can be identified using Table 2. Figure 4 the required mechanical equipment sizing for the pitched roof test house. The point labels can be identified using Table 2. Figure 5 depicts the annual site energy consumption for the low-slope roof test house. The point labels can be identified using Table 3. Figure 6 depicts the required mechanical equipment sizing for the low-slope roof test house. The point labels can be identified using Table 3.

It can be induced from Figures 3 and 5 that many of the categories, such as water heating, lighting, and plug loads are constant here, as these loads do not vary with the different wall assemblies. However space conditioning energy consumption varies between each iteration. The cooling consumption is small according to the simulations performed, however the annual heating consumption is rather large, the dominant consumption of the house. This heating consumption varies drastically between each option.

Figures 4 and 6 detail the HVAC system capacities per house. While the annual cooling consumption is small and does not vary much, the cooling capacity needs vary as well. These capacities would reflect in the sizing of the mechanical space conditioning equipment, and in the case of these prototypical Indiana houses, this is the natural gas furnace for heating and the electrically powered direct expansion system for cooling. Larger equipment is typically more expensive, and consumes more energy, so if the wall assembly changes make a significant enough impact on HVAC equipment sizing, this can also result in an upfront construction cost savings to the homeowner.

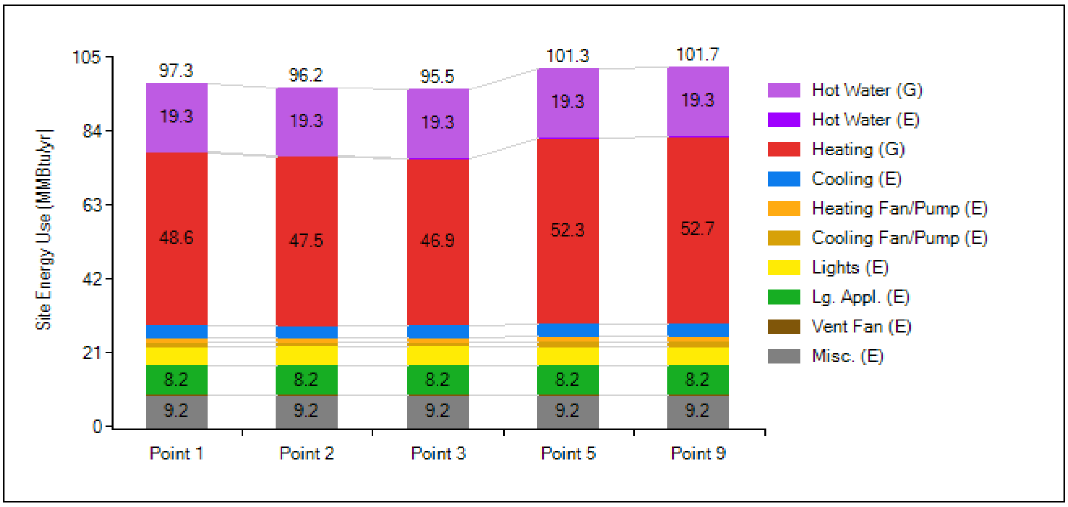

Figure 3: Annual site energy consumption for the pitched roof test house.

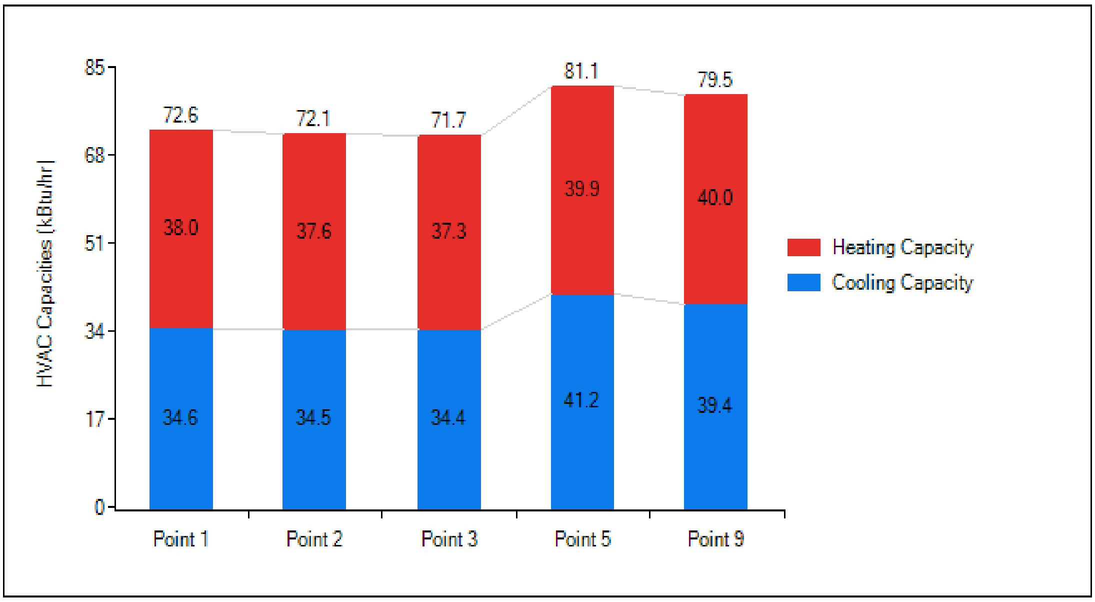

Figure 4: Required mechanical equipment sizing for the pitched roof test house.

Table 2: Pitched Roof Results Details

Point Identifier	Point 1	Point 2	Point 3	Point 5	Point 9
Wall Construction	2" EPS, 4"Concrete, 2"EPS	2" EPS, 8"Concrete, 2"EPS	2" EPS, 12"Concrete, 2"EPS	2x6 studs @ 24" o.c. w/ R-21 Batt	2x4 studs @16" o.c. w/ R-13 batt and R-5 XPS
Present Value	$84,585	$87,479	$90,623	$77,769	$79,041

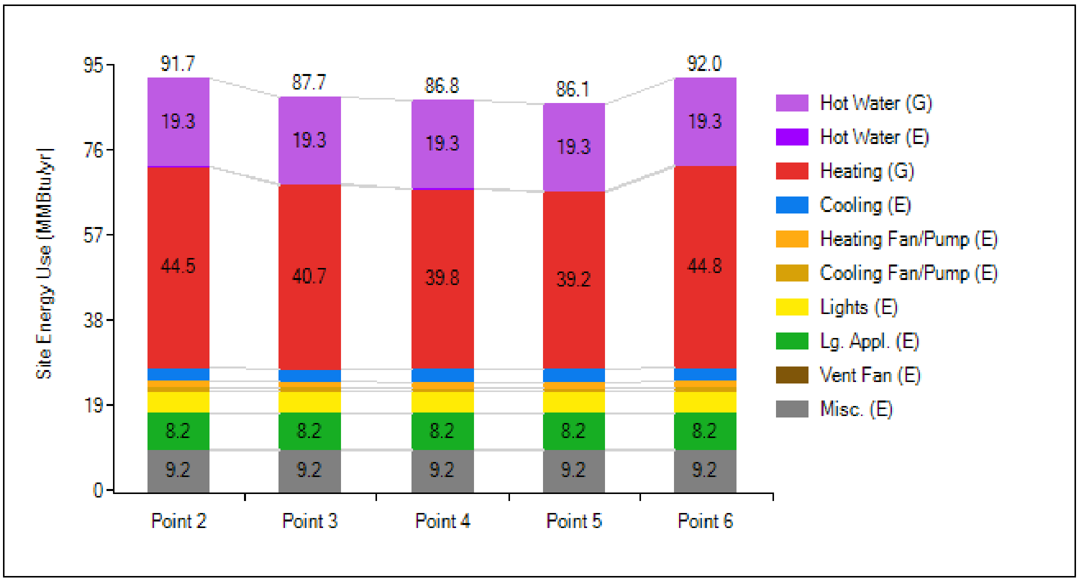

Figure 5: Annual site energy consumption for the low-slope roof test house.

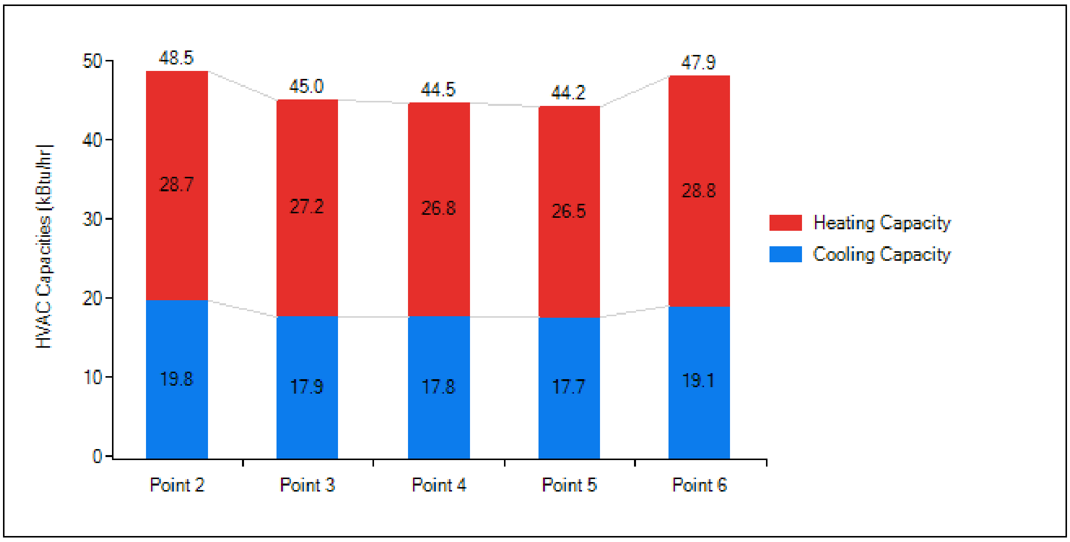

Figure 6: Required mechanical equipment sizing for the low-slope roof test house.

Table 3: Pitched Roof Results Details.

Point Identifier	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Point 6**
Wall Construction	2x6 studs @ 24” o.c. w/ R-21 Batt	2” EPS, 4”Concrete, 2”EPS	2” EPS, 8”Concrete, 2”EPS	2” EPS, 12”Concrete, 2”EPS	2x4 studs @16” o.c. w/ R-13 batt and R-5 XPS
Present Value	$66,655	$73,524	$76,475	$79,654	$67,941

DISCUSSION

The houses built with ICF walls performed well compared to their framed wall counterparts, and the houses with the low-slope roof designs performed better than their traditional pitched roof counterparts. There are two likely reasons for this. The first is the effect of the thermal mass. The only difference between the different ICF walls is the amount of concrete between the two layers of EPS insulation. The thicker the concrete became, the lower the energy consumption. This is not to say, however, that the most thermal mass possible is better, but that a well tuned and placed amount of thermal mass has shown benefits, as it has in the simulation. An excessive amount of thermal mass can create significant lag in an HVAC systems ability to respond to changing conditions, as thermal mass is good at dampening the fluctuations in space heat and cooling needs and temperature.

The other reason that these ICF walls outperformed the stud assemblies is that all of the insulation on the ICF walls is rigid, continuous insulation, while the framed counterparts relies on batt insulation. The R-20 of EPS insulation on the ICF has very little thermal bridging affecting it, as the only possibility for this could be the ties that hold the two halves of the form together. Therefore this insulation is performing closer to the nominal rating of R-20, compared to the 2 x 6 stud wall's R-21 batts. The stud wall is likely to perform closer to R-15 after taking into account the effect of the studs on thermal bridging. While both of these houses were modeled with the code minimum air tightness, a maximum ACH50 of 3.0, it is more likely that the ICF houses will perform more airtight due to their inherent continuity.

The low-slope roof houses also consumed less energy annually than their traditional counterparts. Again, the effect of the thermal mass of the concrete decking can be attributed to this as well, but it also likely has to do the effect of the thermal bridging as well. The R-49 in the unconditioned attic experienced the thermal bridging for the depth of the rafters that the insulation fills in between, and only gets the full, continuous effect of the insulation when it is placed on top of the filled in rafters. In the concrete deck assembly, the entirety of the R-49 of required insulation is placed above the deck, and is continuous, with no thermal bridging. Depending on the detailing, it is also possible to connect this deck insulation to that of the exterior on the ICF walls, eliminating the thermal bridge commonly found at the corner of the wall and roof assembly.

The HVAC capacities vary as well, and follow the same trend as the annual energy consumption noted above. The differences between the various low-slope options little, however all of the low-slope iterations have small capacity needs compared to that of the pitched roof variations. The ICF pitched roof house has slightly smaller cooling sizing, and since the equipment is usually sized in half-ton (6,000 Btu/h) increments, it is possible that the ICF house could decrease one air conditioner compressor size.

It is important to note the present value for the assemblies noted in Table 2 and Table 3. These costs are built into BEopt and have not been further refined for this study, but for comparison's sake it is clear to see that the ICF walls increase the cost of construction, and the thicker the ICF wall is, the higher the price as well. There is a strong chance that the durability of an ICF house and energy savings would pay back this higher initial cost over time, and the savings from a smaller air conditioner can offset that cost as well. If this construction style were to become more prevalent, the costs of building would likely go down, as more contractors would be competing on cost.

CONCLUSION

The benefits of thermal mass and the use of ICFs to buildings in Indianapolis are clear. In houses with pitched roofs and insulated ceilings, the annual heating consumption was reduced by 10.3% with a 16” ICF, and in the low slope roof construction, the reduction was greater, with 11.9% reduction in annual heating consumption over the similar framed wall with the same roof. The ICF house with a low slope concrete deck compared to the framed house with traditional roof reduced the annual heating consumption by 25%. Looking at the reductions in these heating demands validates ICFs as a potentially more energy efficient way to build in Indianapolis.

Further Studies

With more time, it would be worthwhile to tune a few different house forms and determine the appropriate amount of thermal mass for ASHRAE climate zone 5A, namely Indianapolis. It could also be added that with more cost data provided by local contractors, that a BEopt cost optimization study could be run to determine the optimal amount of thermal mass for cost payback, and compare this to an optimized amount of thermal mass for energy consumption alone.

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