IEREK PRESS
Academic Research Community

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ARChive

ISSN (Print: 2537-0154, online: 2537-0162)

International Journal on:

The Academic Research Community Publication

DOI: 10.21625/archive.v3i1.427

The Effects of Exterior Thermal Mass (eTM) on Energy Consumption in Residential Buildings

Amir Ghoreishi[1]

[1] *PhD LEED*

Abstract

Exterior Thermal Mass (eTM) is known to improve building energy and thermal comfort performance. Despite its known benefits, studies to date have not thoroughly addressed the effects of eTM on building environmental performance by considering a wide range of influential factors and various climatic conditions. This paper addresses such a gap in the body of knowledge by conducting a comprehensive and detailed analysis of eTM impacts on residential buildings' energy performance. Using quantitative research and simulation analyses, this study has found various trends of energy reductions and, in a few cases, energy increases depending upon the location of projects.

In fact, the cooling energies are shown to increase of up to 4% for the scenario of 20 cm thickness wall in several locations. Aiming for better energy and design load scenarios, this research has also established the optimal eTM depth to help architects and engineers make informed design decisions with regard to building envelopes, which is particularly important for developing countries with similar climates studied in this paper, where the use of masonry materials is widely common. As for future steps, further exploration of cooling energy increase phenomenon, which was observed for several climates is recommended. Also, coupling eTM with code-required thermal insulation based upon specific climatic locations and evaluate their integrated performance can be considered

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Keywords

Thermal Mass; Thermal Insulation; Heating and Cooling Energy; Energy Efficiency; Sustainability

1. Introduction

Given the increasing awareness toward global warming and climate change, the concept of energy efficiency in the built environment is gaining utmost attention worldwide (Reilly & Kinnane, 2016). As a major energy-consuming sector, the building industry has attempted to incorporate energy-saving measures into building codes and regulations with the primary focus on building thermal resistance and insulation, to the exclusion of thermal mass (Bellamy & Mackenzie, 2001). Thermal mass helps store heating energy in building materials, which can impact energy demands and indoor thermal comfort. Thermal mass can reduce energy consumption especially in residential buildings where there are no significant internal gains (Ghoreishi & Murray, 2017) while maintaining a comfortable internal temperature with no heating or cooling (Gregory et al., 2008). To minimize building energy usage and create a more sustainable energy prospect, thermal mass needs to be fully utilized.

It is known that thermal mass functions as a transient heat transfer medium as opposed to steady-state conditions, and is primarily occurring within the building structure. This is consistent with dominant thermal mode for the vast majority of buildings around the world (Reilly & Kinnane, 2016). Thermal conductivity and thermal resistance, which are material depth/thickness independent and dependent respectively, do not account for the transient and dynamic nature of heat transfer.

However, as a transient heat exchange substance, thermal mass can affect a building's energy and thermal comfort performance through its envelope and structural elements, indoor air volume and, last but not least, interior walls, slabs, partitions, furniture and so forth. In fact, the thermal effects of furniture on indoor environments have gained more attention from scholars; however, due to its variability, its effects are usually discounted (Raftery et al., 2014; Hichman & Heiselberg, 2017). Unlike thermal resistance/transmittance, which has been studied extensively, thermal mass and its effects on building energy and thermal performance is yet to be researched comprehensively. Moreover, building codes often lack appropriate acknowledgment of and provisions for thermal mass effects (Berg-Hallberg, 1985). Furthermore, they mainly restrict its use for cooling demand purposes (not heating), and do not consider interactions between ambient conditions, occupants and thermal mass (Department of Communities and Local Government, 2016; Department of Energy and Climate Change, 2012; Kinnane, et al., 2016).

As for simulation and modeling, many studies focus on a detailed analysis of a specific building type/design located in a specific location, which makes it difficult to extrapolate from their analyses an overall conclusion (Cetin et al., 2016, Gregory et al., 2008). For instance, Hoes et al. (2011 & 2016) studied the effects of high thermal mass on the reduction of overheating in a mid-European climate such as in the Netherlands, where heating may not be the governing design factor. However, in many parts of the world the amount of energy used for heating greatly surpasses that used for cooling (Ghoreishi & Ali, 2011), but the research for heating dominant locations remains undeveloped (Reilly & Kinnane, 2016). Parametric studies of thermal mass have proven to cover a broader range of building mass-related parameters (Ghoreishi & Ali, 2011) although they have had rather limited scopes. Aste et al. (2009) studied different thermal mass wall assemblies but the scope of research was limited to Milan, Italy. Other studies have researched the effects of various arrangements of wall assembly layers with respect to different thermal mass and insulation combinations. They have primarily focused on varying wall thickness to discover the effects of different arrangements (Kossecka & Kosney, 2002, Bojic & Loveday, 1997, Ghoreishi & Ali, 2012). While informative , many of these studies have failed to develop a reasonable framework to assess the effects of thermal mass with respect to its transient nature. This is particularly important when modeling multi-layer thermal behaviors, which is a common practice in most modern constructions, unless each layer is treated separately (Gori et al., 217; Ma & Wang, 2012; Kircher & Max, 2015; Underwood, 2014). Additionally, existing literature does not either adequately address the impact of thermal mass in cold and temperate climates, or only focuses on detailed analyses, which are hardly generalizable (Cetin et al, 2016; van et al., 2016).

According to a study that focused on the effects of thermal mass and insulation on intermittent versus continuous heating and cooling, intermittent cooling scenarios resulted in the most energy reductions (Bojic & Loveday, 1997). However, in the case of continuous cooling, no energy reductions were observed, although cooling loads appeared to have reduced. Interestingly, heating demands seemed to have increased because of high thermal mass in the intermittent heating scenarios.

Despite the importance and benefit of thermal mass, few studies deeply evaluate its effects in a generalizable and quantifiable manner. Moreover, many previous studies or published guidelines by the government and industry can be misleading with respect to the benefits of thermal mass (Wang & Ma, 2016; Portland Cement Association, 2016; American National Standards Institute, 2009).

This paper aims to comprehensively the impact of thermal mass on the energy performance in residential buildings by using modified building envelope parameters, considering both heating and cooling requirements, and more importantly contextualizing the results in eight main US climates. This will help produce outcomes, which are more quantifiable and generalizable. In fact, the results of this study are applicable to similar climates around the world. For instance, in many developing countries from South East Asia to Middle East and Africa, masonry materials with significant thermal mass are widely used. Moreover, there are considerable similarities between various U.S. climate zones with those in developing countries. As an example, the tropical regions of South and South East Asia have similar climactic conditions with those of Miami, Florida. The countries in the Middle East and Africa mostly have similar climates to those in Phoenix, Arizona. Therefore, the conclusions of this study concerning thermal mass effects in various U.S. climate zones are applicable to similar locations in most developing countries.

2. Energy simulation and analysis

To evaluate the effects of thermal mass on building energy performance, the author conducted an investigation on a rectangular-shaped open-spaced building model using quantities research method and simulation analysis. A 10-story building, similar to the U.S. Department of Energy's (DOE) benchmark commercial building model, was selected as the base case model for the study (DOE, 2008). It should be noted that the main focus of this research has been to address the impact of eTM on building energy consumptions in various climates, not necessarily the building's practical design.

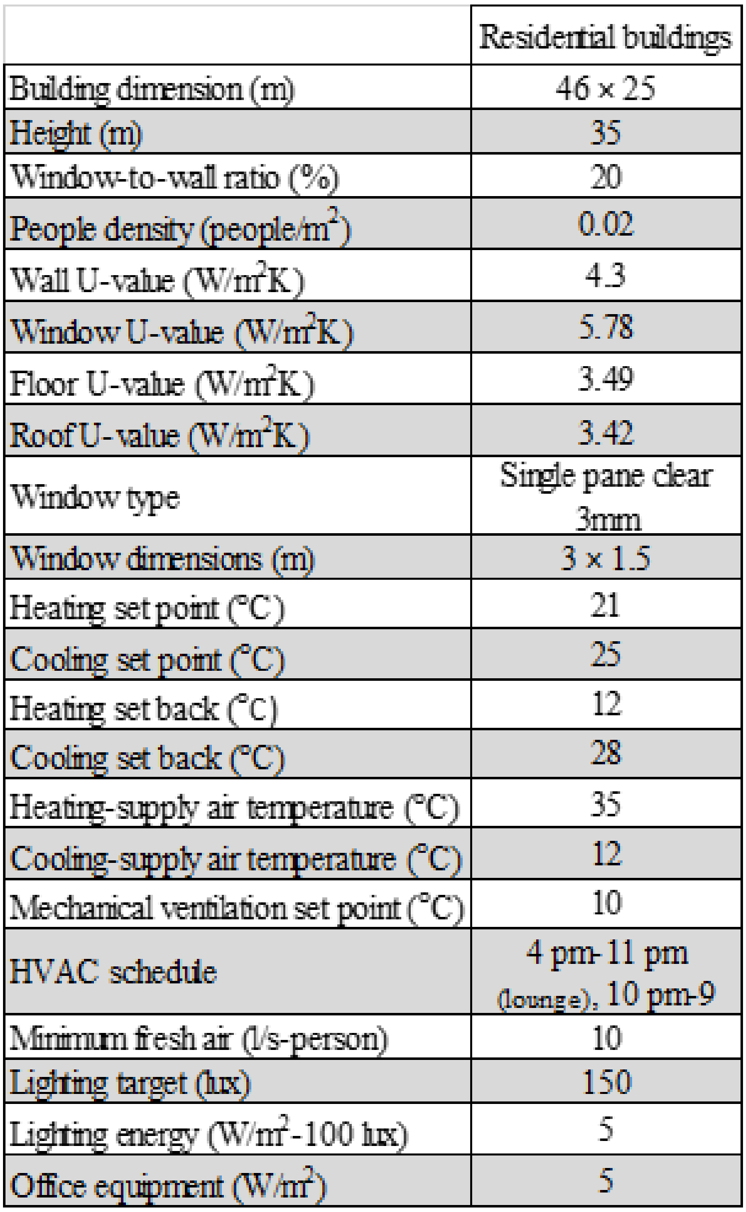
The wall thickness was chosen to evaluate the impact of eTM on energy performance. The annual heating and cooling energy use and the combination of these two parameters were selected as the measurement parameters of the building's energy consumption. The heating and cooling loads were also measured to determine the extent of eTM effects on the size of HVAC systems. Heating and cooling requirements were represented by the amount of gas and electricity consumption per Kilo British Thermal Unit (kBtu), respectively. Also, the unit of kBtu/hour was used to measure the heating and cooling loads. The energy simulation was conducted through the Energy Plus computer program using Design Builder as the interface software. In addition, eight different locations in the U.S. representing eight different climate zones were chosen, as follows:

- Miami, FL: 1A, very hot and humid
- Phoenix, AZ: 2B, hot and dry
- San Francisco, CA: 3C, warm and marine
- Albuquerque, NM: 4B, mixed-dry
- Chicago, IL: 5A, cool-humid
- Minneapolis, MN: 6A, cool-marine
- Duluth, MN: 7, cold-dry
- Fairbanks, AK: 8, very cold

2.1. Base case model

Table 1 describes the architectural, structural, and mechanical characteristics of the base case model for the residential building, including U-values, set-point temperatures, occupancy and activity schedules, and internal loads. These specifications were determined on the basis of the DOE benchmark model and the International Energy Conservation Code as implemented by the Design Builder and Energy Plus programs.

Table 1. The specifications of the base case model

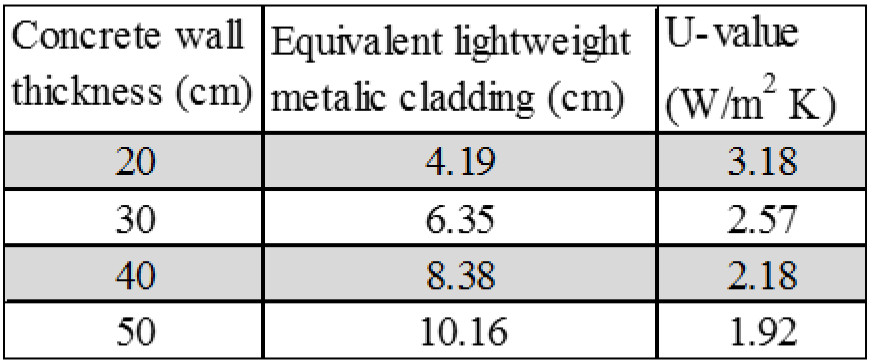


	Residential buildings
Building dimension (m)	46 × 25
Height (m)	35
Window-to-wall ratio (%)	20
People density (people/m^2)	0.02
Wall U-value (W/m^{2}K)	4.3
Window U-value (W/m^{2}K)	5.78
Floor U-value (W/m^{2}K)	3.49
Roof U-value (W/m^{2}K)	3.42
Window type	Single pane clear 3mm
Window dimensions (m)	3 × 1.5
Heating set point (°C)	21
Cooling set point (°C)	25
Heating set back (°C)	12
Cooling set back (°C)	28
Heating-supply air temperature (°C)	35
Cooling-supply air temperature (°C)	12
Mechanical ventilation set point (°C)	10
HVAC schedule	4 pm- 11 pm (lounge), 10 pm-9
Minimum fresh air (l/s-person)	10
Lighting target (lux)	150
Lighting energy (W/m^2-100 lux)	5
Office equipment (W/m^2)	5

Each floor of the building consists of two main thermal zones: (1) the core circulation area, and (2) the open space around the core area. To assess the impact of eTM within variable wall constructions, four different wall thicknesses were chosen: 20 cm, 30 cm, 30 cm and 50 cm. However, the concrete slab thickness of 15 cm and the window-to-wall ratio of 30% remain constant for all cases. To ensure that the principal element of the building façade that delays heat transfer is the concrete wall and not the windows, single-pane glass was selected for the windows instead of double-pane. To study the operation of HVAC systems (VAV with terminal re-heat), an open office space was chosen to represent the primary usage of this building type for HVAC operation. To strictly focus on the role of eTM in improving building energy performance without any interference from thermal insulation, the code-required thermal insulation was excluded from the wall assembly.

It is known that extra layers of materials can lead to greater heat resistance (lesser heat transmittance), which can affect the building's energy use. To minimize (neutralize) such effects and solely assess the impact of thermal mass property of concrete material while increasing the thermal mass wall thickness, a parallel study was conducted using identical case studies as the control group. The only difference was the type of material used, which is changed from concrete to lightweight metallic cladding. presumably, with little to zero thermal mass properties as compared with the concrete material. To ensure similar heat resistance/transmittance between the thermal mass and “non-thermal mass” (control) cases, the thickness of metallic cladding was modified to obtain the similar U-value as the corresponding concrete wall scenarios. For instance, an 20 cm concrete wall has the U-value of 3.18 (W/m^2 K). The thickness of 4.19 cm is chosen for the control wall to achieve the similar U-value. Table 2 shows all equivalent wall thicknesses for the lightweight metallic cladding.

Table 2. Thermal and non-thermal mass wall U-value equivalency



Concrete wall thickness (cm)	Equivalent lightweight metalic cladding (cm)	U-value (W/m^2 K)
20	4.19	3.18
30	6.35	2.57
40	8.38	2.18
50	10.16	1.92

Eventually, by comparing the heating and cooling requirements of cases studies, which are expected to vary, the effects of thermal mass and non-thermal mass walls on building energy use will be determined. In addition, the decrease and/or possible increase of energy use in various climates as the result of modifying wall thicknesses can be explained which, in turn, could lead to discovering the optimal wall thickness for each climate zone.

Although this building model is based upon the U.S. DOE benchmark commercial building, the specifications of the model are applicable to many large scale buildings in most developing countries. In fact, the use of concrete as structure and even curtain wall may be even more common in developing countries that it is in the U.S. Ghoreishi and Ali (2011) showed that in most developing countries, concrete is the most commonly used structural material, which, in turn, would make its thermal mass characteristics widely available to utilize. Therefore, the results of this research can be used by designers and engineers in most developing countries who would like to see the benefits of concrete thermal mass being utilized for energy conservation purposes.

2.2. Heating energy demands

Figure 1 demonstrates the heating energy demands in a residential building given four different wall thicknesses and in eight different climate zones as previously discussed.

Table 3 demonstrates the percentage reduction of heating energies for four wall thickness scenarios in various locations, comparing each case against the scenario where, presumably, there is no thermal mass.

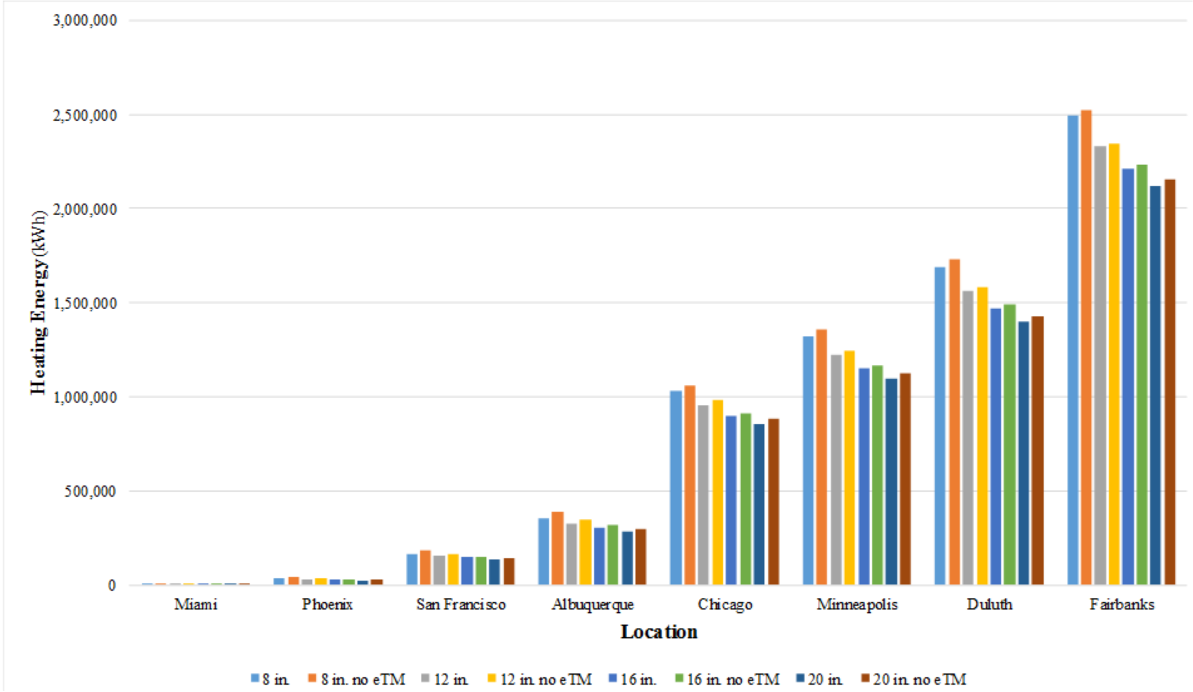
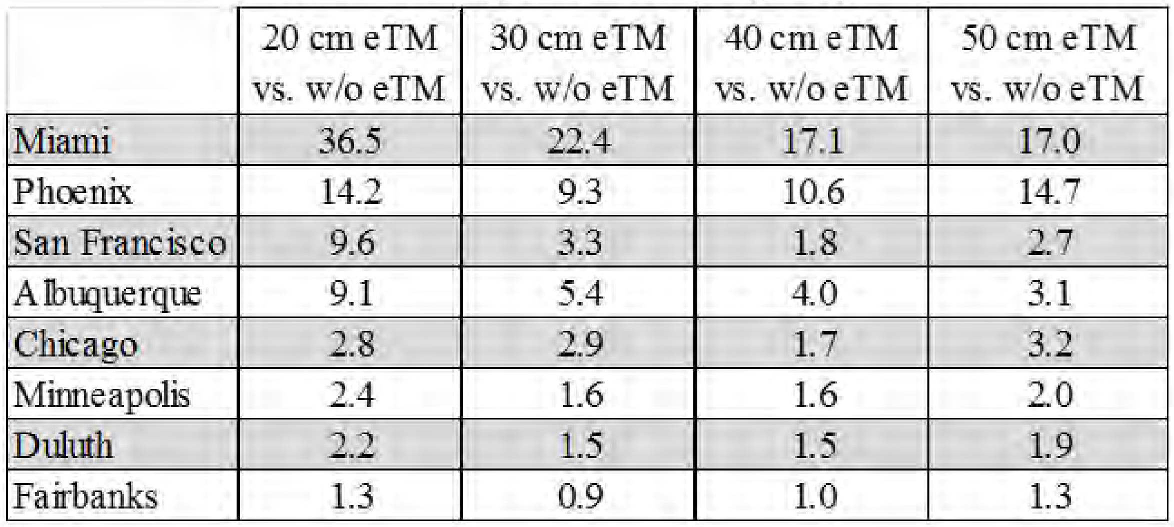


Figure 1. Heating energy use

Table 3. Percentage reduction of heating energy



	20 cm eTM vs. w/o eTM	30 cm eTM vs. w/o eTM	40 cm eTM vs. w/o eTM	50 cm eTM vs. w/o eTM
Miami	36.5	22.4	17.1	17.0
Phoenix	14.2	9.3	10.6	14.7
San Francisco	9.6	3.3	1.8	2.7
Albuquerque	9.1	5.4	4.0	3.1
Chicago	2.8	2.9	1.7	3.2
Minneapolis	2.4	1.6	1.6	2.0
Duluth	2.2	1.5	1.5	1.9
Fairbanks	1.3	0.9	1.0	1.3

As shown in Table 3, there is a direct positive correlation between the presence of eTM and the reduction of the building's heating requirements for all locations. The reductions resulting from eTM ranges from 1% to 37% depending upon the climatic conditions. In comparison, the 20 cm thick wall appears to have, on average, the biggest reductions across the board. Moreover, hot climates such as Miami and Phoenix are shown to have the most heating energy reductions. It should be noted that, given the small impact of heating demands on building energy use in these climates, the overall energy savings may not be very tangible. However, San Francisco and Albuquerque, with significant heating degree days, show a heating energy reduction of up to 15%.

2.3. Cooling energy demands

As shown in Figure 2, the cooling energies of residential building scenarios were evaluated in the same U.S. climates given their different eTM wall thicknesses and non-thermal mass arrangements representing different degrees of thermal mass in building envelope.

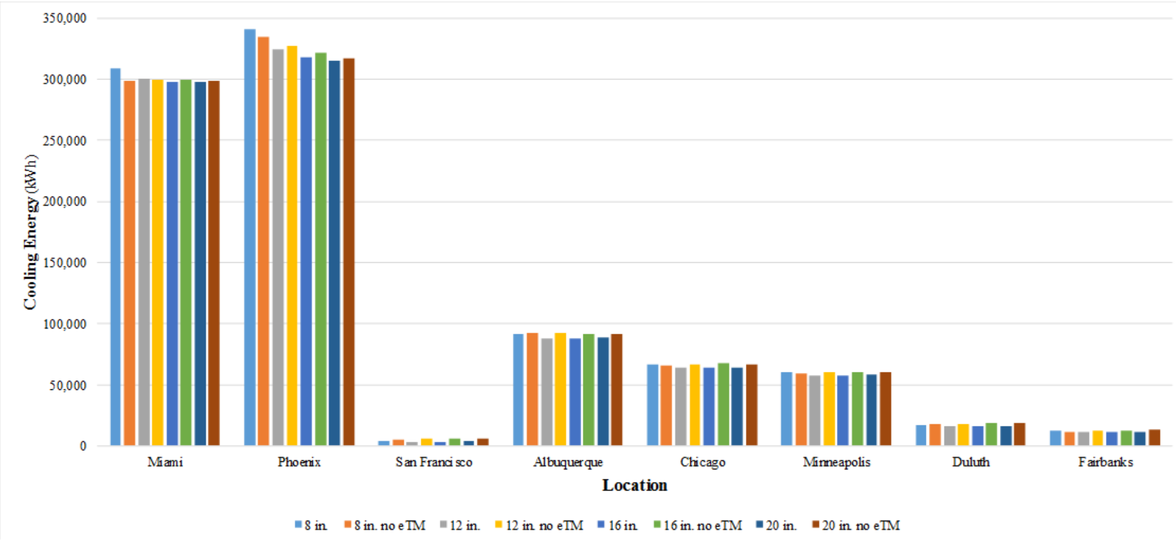


Figure 2. Cooling energy use

Table 4 demonstrates percentage reduction and/or increase of cooling energy use for all four wall thickness scenarios comparing different thermal and non-thermal mass cases.

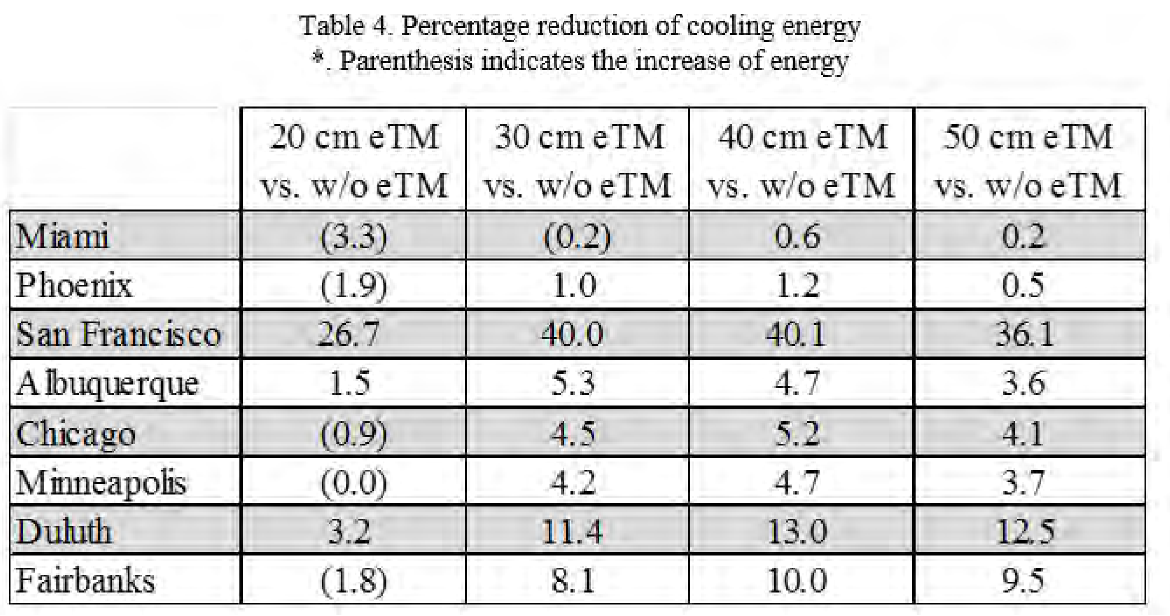


Table 4. Percentage reduction of cooling energy
*. Parenthesis indicates the increase of energy

	20 cm eTM vs. w/o eTM	30 cm eTM vs. w/o eTM	40 cm eTM vs. w/o eTM	50 cm eTM vs. w/o eTM
Miami	(3.3)	(0.2)	0.6	0.2
Phoenix	(1.9)	1.0	1.2	0.5
San Francisco	26.7	40.0	40.1	36.1
Albuquerque	1.5	5.3	4.7	3.6
Chicago	(0.9)	4.5	5.2	4.1
Minneapolis	(0.0)	4.2	4.7	3.7
Duluth	3.2	11.4	13.0	12.5
Fairbanks	(1.8)	8.1	10.0	9.5

As shown in Table 4, despite a few cases where the presence of the eTM is shown to have led to a cooling energy increase, thermal mass has been able to reduce cooling demands ranging from 2% to 40 %. The 30 cm wall thickness shows the best energy reduction performance in almost all locations across the board. In fact, the increase of eTM beyond 30 cm shows an energy reduction, which can be attributed to the phenomenon of "diminishing returns," where added thermal mass may not translate into greater reductions of energy consumption. San Francisco and Duluth demonstrate the largest energy reduction by up to 40%.

2.4. Total heating and cooling demands

To evaluate the overall energy performance of buildings, total heating and cooling requirements of the different scenarios were studied. Figure 3 shows the results of building energy consumption for different climate zones based on wall thickness and eTM cases.

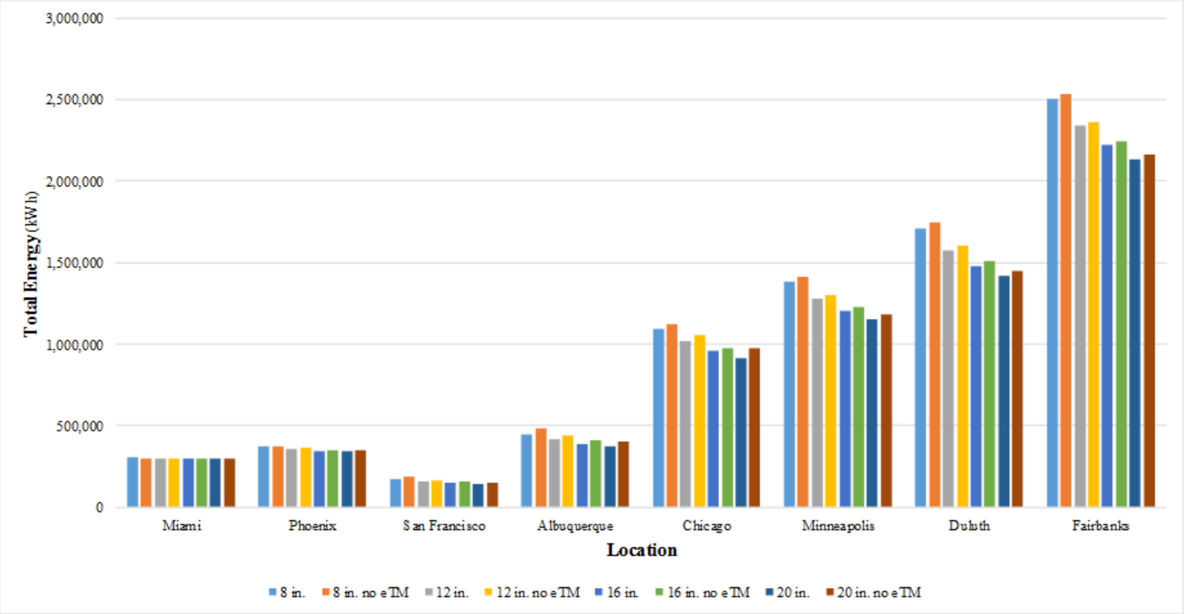
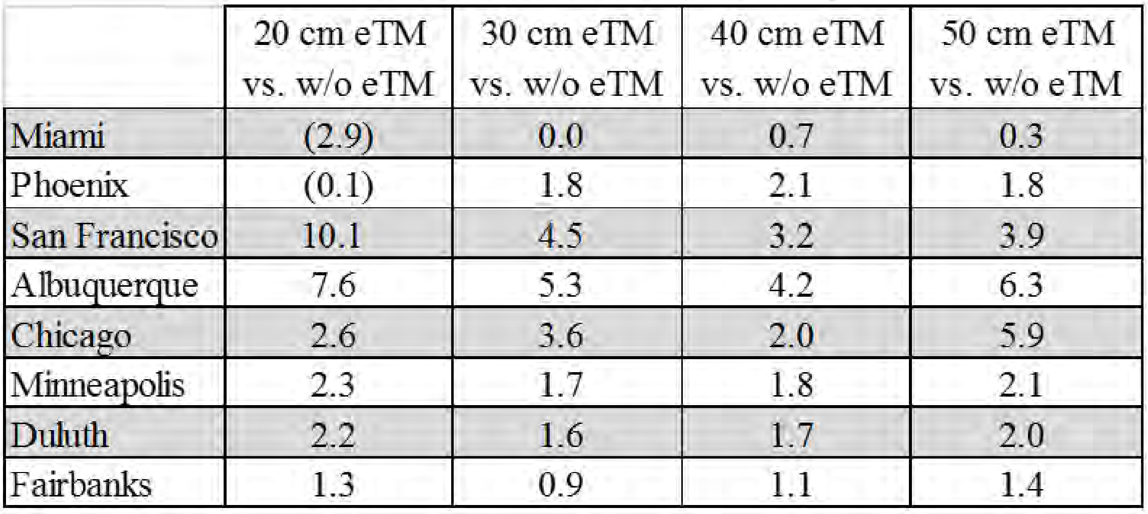


Figure 3. Total energy use

Table 5 indicates the percentage reduction and/or increase of total energy use for all wall thickness scenarios comparing different eTM cases.

Table 5. Percentage reduction of total energy
*. Parenthesis indicates the increase of energy



	20 cm eTM vs. w/o eTM	30 cm eTM vs. w/o eTM	40 cm eTM vs. w/o eTM	50 cm eTM vs. w/o eTM
Miami	(2.9)	0.0	0.7	0.3
Phoenix	(0.1)	1.8	2.1	1.8
San Francisco	10.1	4.5	3.2	3.9
Albuquerque	7.6	5.3	4.2	6.3
Chicago	2.6	3.6	2.0	5.9
Minneapolis	2.3	1.7	1.8	2.1
Duluth	2.2	1.6	1.7	2.0
Fairbanks	1.3	0.9	1.1	1.4

As demonstrated in Table 5, the building's total energy performance significantly improved for most cases in the presence of eTM as compared to that of non-eTM walls. San Francisco and Albuquerque show the largest overall energy reductions ranging from 4 to 11%. Except for San Francisco, the increase of wall thickness from 20 cm to 50 cm does not appear to have considerably changed the trend of energy reductions.

2.5. Heating and cooling loads

Heating and cooling loads are used to size and design a building's primary mechanical systems such as chillers and boilers. In addition to heating and cooling energy demands, this study evaluated the effect of eTM and non-eTM walls on heating loads as shown in Figure 4.

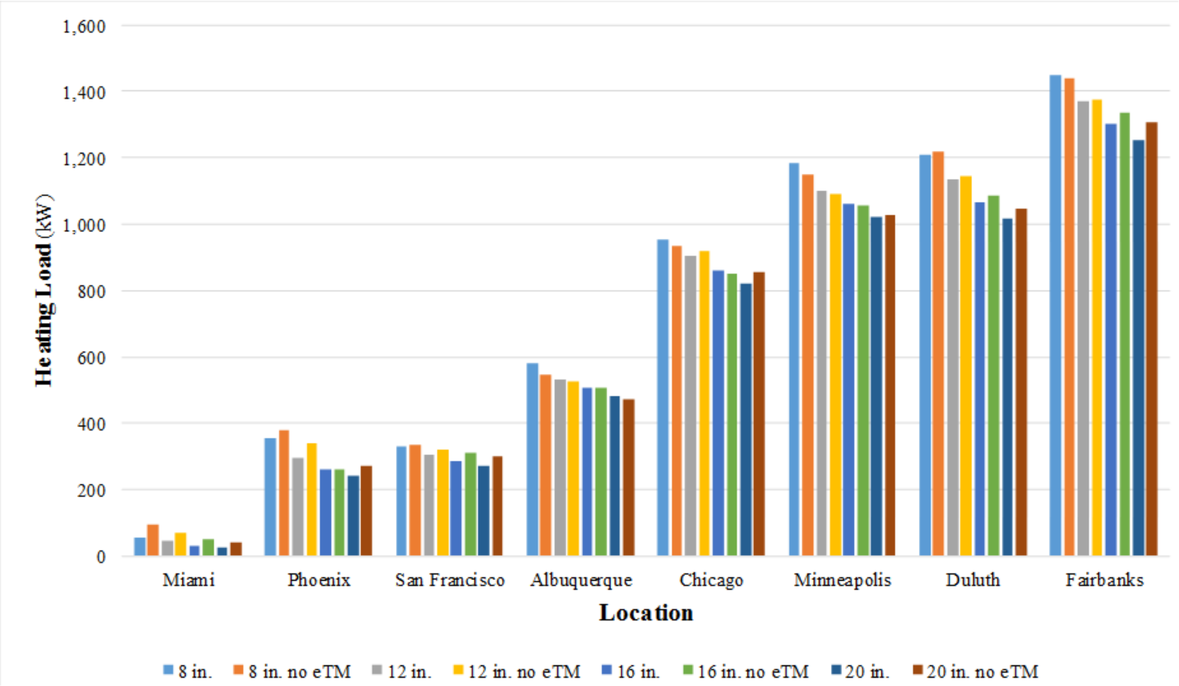


Figure 4. Heating load

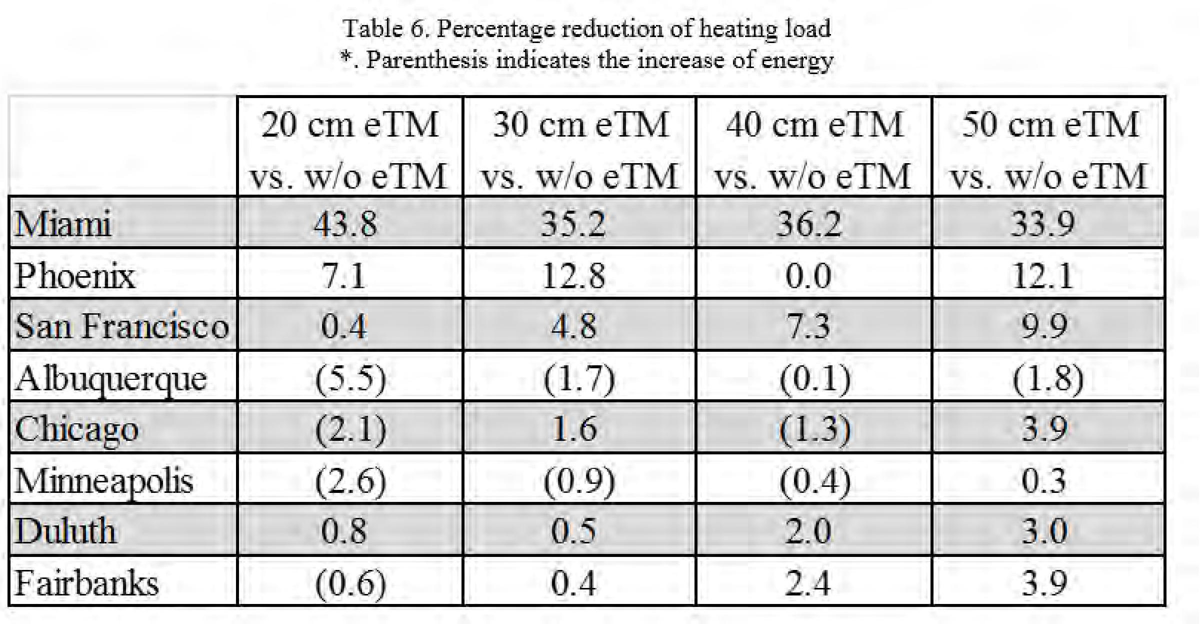


Table 6. Percentage reduction of heating load
*. Parenthesis indicates the increase of energy

	20 cm eTM vs. w/o eTM	30 cm eTM vs. w/o eTM	40 cm eTM vs. w/o eTM	50 cm eTM vs. w/o eTM
Miami	43.8	35.2	36.2	33.9
Phoenix	7.1	12.8	0.0	12.1
San Francisco	0.4	4.8	7.3	9.9
Albuquerque	(5.5)	(1.7)	(0.1)	(1.8)
Chicago	(2.1)	1.6	(1.3)	3.9
Minneapolis	(2.6)	(0.9)	(0.4)	0.3
Duluth	0.8	0.5	2.0	3.0
Fairbanks	(0.6)	0.4	2.4	3.9

Table 6 demonstrates the effect of thermal mass cases on the heating loads. Except for a few cases, heating loads are reduced, ranging from 1% to 44% lower in various locations. On average, hot climates show a larger reduction of heating loads in the presence of eTM. The 30 cm wall once again is demonstrating the larger reductions of heating loads in almost all climates as compared to other wall thicknesses. Albuquerque and Minneapolis show a rather consistent increase of heating loads because of eTM increase.

Figure 5 shows the effects on cooling loads in various climate zones with and without eTM wall assemblies.

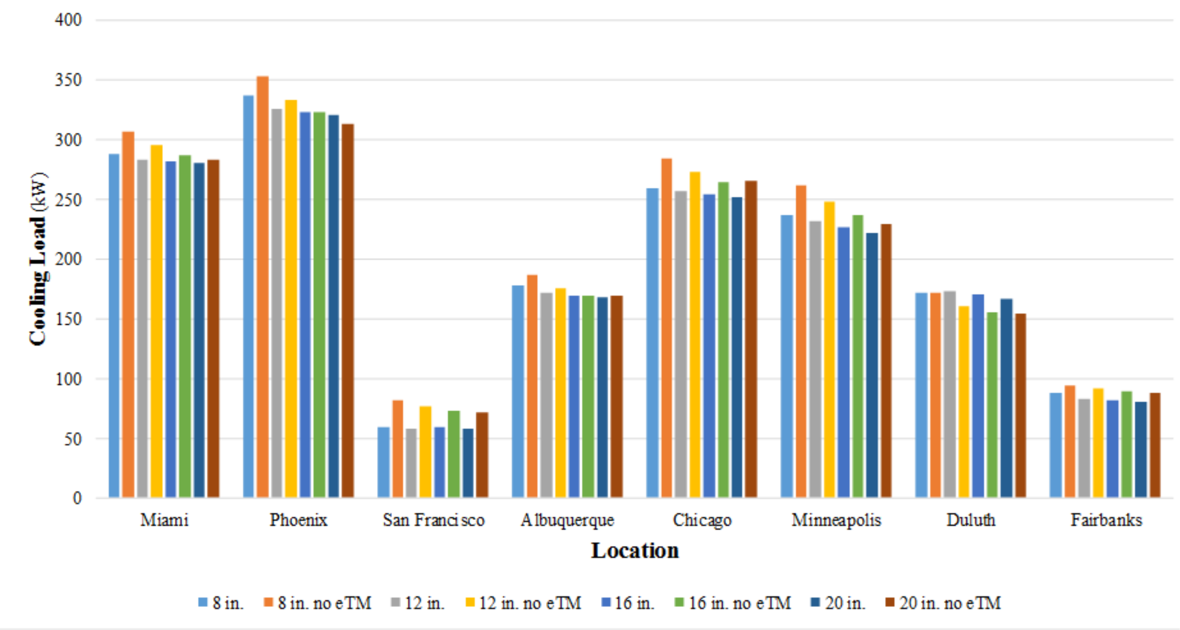
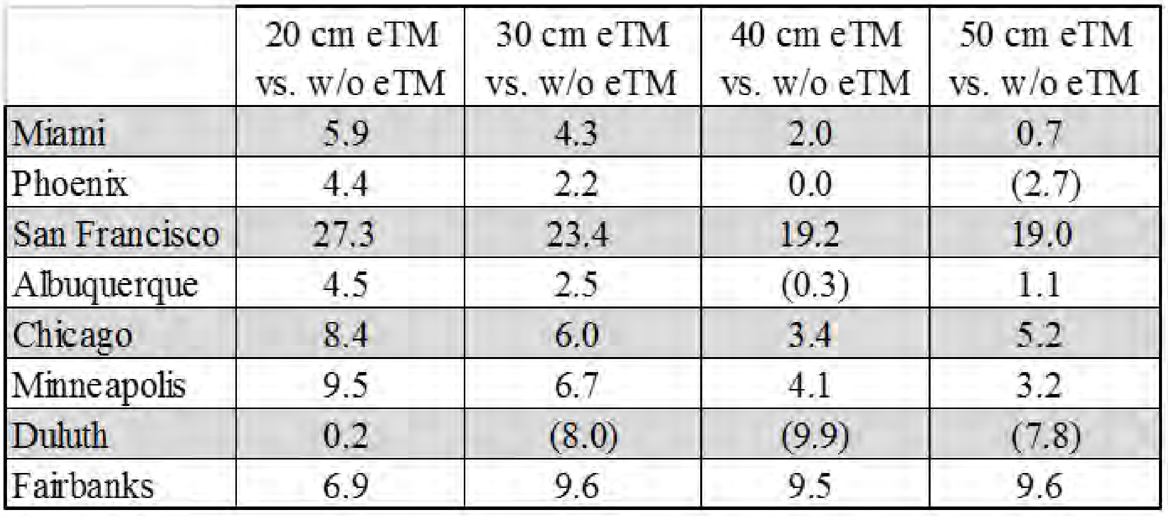


Figure 5. Heating load

Table 7 indicates the extent of cooling load changes due to eTM effects. Except for Duluth, other locations show considerable cooling load reductions. As a matter of fact, San Francisco and Fairbanks show a reduction of cooling loads of up to 28%, which is significant especially for large scale projects. The 20 cm wall seems to have the best performance in terms of reducing cooling loads in comparison with other case studies, with the exception of in Fairbanks.

Table 7. Percentage reduction of cooling load
*. Parenthesis indicates the increase of energy



	20 cm eTM vs. w/o eTM	30 cm eTM vs. w/o eTM	40 cm eTM vs. w/o eTM	50 cm eTM vs. w/o eTM
Miami	5.9	4.3	2.0	0.7
Phoenix	4.4	2.2	0.0	(2.7)
San Francisco	27.3	23.4	19.2	19.0
Albuquerque	4.5	2.5	(0.3)	1.1
Chicago	8.4	6.0	3.4	5.2
Minneapolis	9.5	6.7	4.1	3.2
Duluth	0.2	(8.0)	(9.9)	(7.8)
Fairbanks	6.9	9.6	9.5	9.6

3. Conclusion

This paper has studied the influence of eTM and non-eTM walls with identical heat resistance on residential building energy performance in main U.S. climate zones. Findings indicate that the presence of eTM, in most cases, will result in a considerable reduction of energy consumption.

In terms of heating energies, the eTM wall reduces energy consumption across the board. However, this reduction is as high as 37% in hot locations such as Miami and as modest as 2% in cold climates such as Fairbanks. Generally speaking, the increase of wall thickness from 20 cm to 50 cm may not necessarily translate into greater energy reduction. As a matter of fact, on average, the 20 cm wall thickness seems to be an optimal thickness as far as heating energy is concerned. Heating loads, on the other hand, do not closely follow the same pattern of energy reductions in all climates, and show signs of increase in locations such as Albuquerque. The 30 cm wall thickness appears to be the optimal case to achieve the heating load reductions.

As for cooling demands, except for a few cases of energy increase, eTM has led to considerable energy reductions of up to 40% in locations such as San Francisco. The 30 cm wall thickness can be considered the best energy performing scenario compared to other wall thicknesses. Beyond this depth, the increase of eTM does not necessarily appear to help further energy reduction. In contrast, it seems to have lessened its effectiveness. Cooling loads also are shown to have considerably decreased as a result of eTM, and 20 cm appears to be the optimal wall thickness. Given the obtained contrary results regarding wall thickness and maximum heating or cooling load reductions, one may want to consider other factors such as the reduced initial cost of smaller HVAC systems when making design decisions.

Total energy consumption is probably the main factor in evaluating the effectiveness of concrete eTM in improving building energy performance. Overall, eTM has had a strong role in reducing building energy use, which can be particularly beneficial for large scale buildings. The optimum wall thickness in terms of energy reduction appears to be strongly dependent upon the location of the project, and it differs from one location to another. However, it is worth noting that the increase of wall thickness does not appear to necessarily translate into greater energy reductions. In fact, the benefits from added thermal mass may be very well outweighed by the extra material and construction costs.

4. Future research

Unlike heating energy use, cooling energy is shown to have increased in the presence of eTM for a few cases. Further studies are needed to determine other possible causes. To have a better understanding of eTM benefits, one may want to evaluate the energy cost savings resulting from wall thickness increases with the additional material, labor and construction costs. In addition to eTM, studying the internal thermal mass and its possible effects on building energy performance in conjunction with eTM is recommended. Given the code-required thermal insulation, coupling of thermal mass with insulation (Ghoreishi, A. & Murray, S., 2017) needs to be further investigated. Additionally, the effects of thermal mass on thermal comfort parameters such as surface and/or air temperature in residential buildings needs to be further studied as it is crucial to the health and well-being of building occupants.

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