IMPACT OF RETROFITTING ENERGY-EFFICIENT DESIGN STRATEGIES ON ENERGY USE OF EXISTING COMMERCIAL BUILDINGS: COMPARATIVE STUDY OF LOW-IMPACT AND DEEP RETROFIT STRATEGIES

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ABSTRACT

This article discusses energy-efficient retrofitting design strategies for commercial office buildings, and examines their effect on energy consumption. The objective of the research was to study how to integrate passive design strategies and energy-efficient building systems to improve building performance, and reduce the energy consumption of existing buildings in three different climate types (cold, mixed and hot climates). First, properties of existing buildings were analyzed based on national CBECS database to determine typical characteristics of office buildings located in Chicago, Baltimore and Phoenix, including size, building envelope treatment and building systems. Then, fourteen different prototypes were developed, varying the building shape and orientation to represent different building stock, and energy modeling was conducted to establish energy usage baseline. Multiple design considerations were investigated based on extensive energy simulations and modeling, where low-impact and deep retrofits were considered. Low-impact strategies included improvements to the building envelope, lighting systems and optimization of HVAC systems operation (without upgrading heating and cooling equipment). Deep energy retrofits also included improvements to building envelope and lighting, and considered changes and improvements to HVAC systems (specifically, integration of radiant systems). Energy modeling was conducted for all prototypes, and results were obtained for the baseline (current energy usage), and energy usage considering low-impact design strategies and deep retrofits. A total of 126 energy models was developed, simulated and analyzed, providing a dataset that captured energy usage for investigated scenarios. The comparative analysis of simulation results was used to determine how specific techniques lead to energy savings in different climate types, as well as for buildings of various shapes and orientations.

KEYWORDS

existing commercial buildings, retrofits, energy use, energy-efficient design, energy modeling

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1 INTRODUCTION

1.1 Background

In the U.S., commercial and residential buildings account for approximately 40% of total energy consumption. The total end-use emission of CO_2 from the commercial building sector was 897.9 $TgCO_2Eq$ in the U.S. in 2012, constituting 18% of the total emissions (EIA 2015). Reducing human dependence on fossil fuels is necessary in order to reduce CO_2 emissions and mitigate the effects of global warming. To achieve this goal, one strategy is to reuse and effectively adapt existing buildings to reduce their environmental impacts and energy consumption.

Retrofitting existing buildings by employing advanced building technologies and high performance systems offers an opportunity to significantly decrease annual energy consumption of existing commercial buildings. Retrofitted structures reduce the overall demand for new construction materials, and thus reduce the quantity of new materials required for creating inhabitable space. New building construction requires a higher quantity of new materials, while retrofitted buildings conserve the embodied energy of the original structure. Effective and reliable energy efficiency measures ensure enhanced long term energy performance and improve occupant comfort through increased natural light, optimized temperature controls, healthy building operation and maintenance systems (Tobias 2010).

Retrofitting of existing buildings has many challenges and opportunities, but is a viable approach for decreasing energy consumption associated with the building stock. The main challenge is that there are many uncertainties, such as changes to services, human behavior, policy, climate, etc. Each affects the selection of retrofit strategies and in turn the success of the retrofit project. Other challenges may include financial limitations and barriers, perceived long payback periods, and interruptions to operations (Vavaroutsos et al. 2009). However, retrofitting provides opportunities for improved energy efficiency, improved staff productivity, reduced maintenance costs, and better thermal comfort, as well as the potential to improve national energy security (Ma et al. 2012).

1.2 Literature review

A significant body of research exists on building retrofits; however, the rate at which buildings are upgraded remains low, representing only around 2.2% of existing building stock (Ma et al. 2012). More than half of commercial buildings in the U.S. (60%) were built before 1979 (CEBCS 2012). This indicates that most commercial buildings were built before energy codes were established and extensively enforced (Laustsen 2008). ASHRAE 90 was implemented without wide adoption in 1975 in response to the energy crisis of 1973. The Energy Policy Act of 1992 (EPACT 92) was enacted in an effort to improve energy efficiency. Figure 1 shows year of construction for buildings included in the Commercial Building Energy Consumption Survey (CBECS) database for the investigated climates.

A critical advantage of sustainable building refurbishment is the diversion of potential demolition materials and construction waste from landfills when buildings are demolished. Demolitions generate millions of tons of concrete, bricks, glass and other construction waste, which is associated with air pollution (Appleby 2013). Building renovation and retrofitting reduces the need for new construction, in turn reducing the negative environmental impacts of new construction and reducing the energy and materials required in the building sector.

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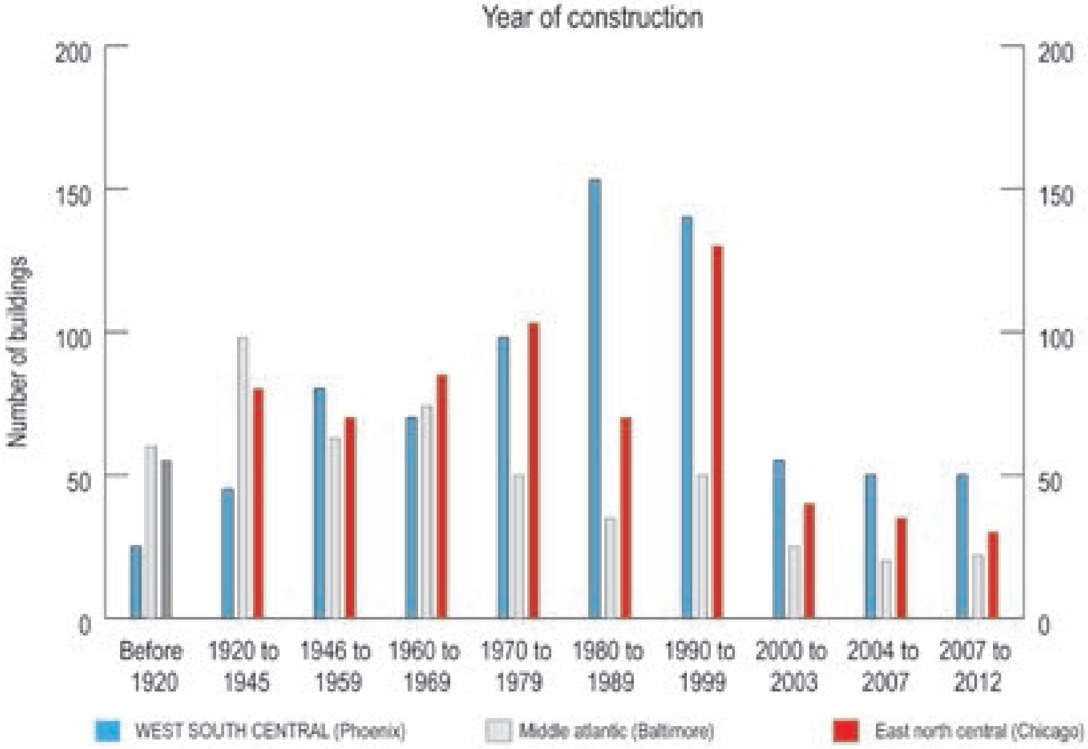
Current sustainable retrofit techniques include renovations to the building envelope, HVAC and lighting systems, building function upgrades, materials, and program (Aksamija 2015). Potential challenges and barriers to regenerative design include a building's size, build quality, and mechanical equipment (Wilkson 2012).

The overall success of a building retrofit depends on many external issues, ranging from policies and regulations, client resources and expectations, technology, building specific information, human factors, and other uncertainty factors (Ma et al. 2012). Site specific information also significantly impacts building retrofits, including geographic location, building type, size, age, occupancy, operation, maintenance, energy sources, utility costs, building materials and service systems. Building-specific information should be utilized when determining the optimal retrofit solution (Ma et al. 2012). Human factors can have significant impacts on the success of a building retrofit. These include comfort requirements, occupancy regimes, management and maintenance, activity, and access to system controls (CIBSE 2004).

Existing buildings experience performance degradation with time, change in use, as well as unexpected failures or malfunctions (Heo et al. 2012) These events can lead to significant deterioration of the overall system performance of a building, inefficiencies, and poor thermal comfort (Ma et al. 2012). A study supported by the U.S. Department of Energy identified more than 100 types of faults that may happen in commercial building services systems, and these faults can account for 2–11% of the total energy consumption of commercial buildings (Roth et al. 2005).

FIGURE 1. Year of construction for commercial buildings included in the CBECS database for investigated climates.



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Justifying the cost benefits is an important factor in renovations, especially when addressing environmental performance. Several methods have been developed to address this aspect. One of these methods is the life-cycle energy balance calculation method, which assesses the true environmental benefits and energy savings during operation and construction, with consideration for the energy embodied in building materials, structure, and technical installations (Marszal 2011). This method still has uncertainties, especially when handling the socio-economic aspects of building construction, and needs to be further explored and investigated (Hernandez 2011).

Simulation models are tools that can determine future performance, evaluate the effectiveness of retrofit strategies, and determine the most economical retrofit approaches. Simulation packages like EnergyPlus, eQUEST, DOE-2, ESP-r, BLAST, HVAC-SIM+, TRNSYS, etc., can be used to simulate whole building energy performance and thermodynamic characteristics of various retrofit measures. EnergyPlus is a simulation tool employed in our experiment and analysis, and was utilized by Chidiac et al. (Chidiac et al. 2011) and Ascione et al. (Ascione et al. 2011) to simulate the effectiveness of retrofit strategies for office buildings and historical buildings. Zmeureanu utilized DOE-2 to estimate the energy savings of building retrofits (Zmeureanu 1990). A detailed comparison of the capabilities of 20 building energy simulation tools is outlined by Crawley et al. (Crawley et al. 2008).

There are two major limitations to the use of building energy simulation for existing buildings. Standard modeling input assumptions may be inaccurate, and measured data is often required to calibrate the model (Webb 2017). Some building energy simulation software may not capture characteristics of interest in historic and traditional buildings. These may include envelope moisture buffering, and thermal stratification in large spaces. Pracchi and Heath et al. each simulated historic buildings using multiple building energy simulation software programs and found discrepancies between the results of different programs. (Pracchi 2014; Heath et al. 2010). Although software like TRNSYS and EnergyPlus are valuable tools to study the impact of alternatives on performance (Hall et al. 2013), the iteration required to find the best retrofit action is time consuming and ineffective because of the large decision space (Asadi 2012).

Dsacalaki and Santamouris performed computer simulations of five office buildings in four different European climatic zones and reported on the potential energy conservation of the retrofits (2002). Retrofit options included building envelope, HVAC, artificial lighting systems, and integration of passive components for heating and cooling. The potential of each approach was assessed utilizing energy simulations and climatic data from 10 locations in Mediterranean, Continental, Mid-Coastal, and North Coastal Europe. Results showed that deep retrofits reduced total energy consumption the most (Dsacalaki and Santamouris 2002).

Olgyay and Seruto discussed creative methods for whole building retrofits and stated the importance of whole building retrofits as a means to stabilize climate change (2010). Fluhrer et al. performed a case study to compare differences between whole building retrofits and low impact retrofit strategies (2010). When compared to a typical low-impact retrofit approach, results indicated that more energy (38%) can be saved when using a whole building retrofit (Fluhrer et al. 2010).

The energy consumption performance of single and multiple retrofit strategies was investigated by Chidiac et al. (2011). A method for determining the feasibility and cost effectiveness of varying retrofit measures was developed. The method utilized the concept of building archetype models to develop a dataset that formed the basis for mathematical equations, which could estimate energy consumption in office buildings based on key variables (Chidiac et al. 2011).

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Hestnes and Kofoed explored and evaluated retrofit strategies designed for ten existing office buildings (2002). These strategies included combinations of building envelope improvements, use of passive cooling, lighting, and HVAC improvements. The results indicate that significant reductions in building energy use can be achieved through the implementation of retrofit strategies, although the study concluded that the selection of retrofit strategies should be based on very specific building energy characteristics (Hestnes and Kofoed 2002).

Research indicating that retrofitting building envelopes is a key step towards improving the energy performance of commercial buildings was presented by Cooperman et al (2011). This study focused on current glazing retrofit technologies, which included multiple glazing, low-E coatings, noble gas fills or vacuums and electrochromic windows (Cooperman et al. 2011).

Office rating methodology was developed by Roulet et al., and uses a multi-criteria rating methodology to rank retrofit scenarios for office buildings through a list of parameters that include energy usage for heating, cooling and appliances, impact on external environment, indoor environmental quality, and cost (2002).

Flourentzou et al. determined that decision support tools are helpful in identifying and determining the best retrofit measures (2002). They created a decision aid tool based on seven modules for office building retrofits. These modules include building description and dimensions, building diagnostics, indoor environmental quality, energy use, retrofit scenarios, cost analysis, and reporting results. This strategy helps support a user to identify and establish a building state in order to determine what actions would be required to upgrade building performance (Flourentzou et al. 2002).

An integrated decision support system that recommends sustainable renovation actions for office buildings was developed by Juan et al. (2010). The system is based on trade-offs between renovation cost, improved building performance, and environmental impacts using a graph search alongside genetic algorithms (Juan et al., 2010).

Capeluto and Ochoa selected 13 urban centers to represent different climates and simulated the energy performance of buildings based on collected and observed regional data that highlighted assembly, construction, and material differences. A graphic was created to aid in the selection of retrofit strategies best suited to a given location and climate (Capeluto and Ochoa 2014).

The previous studies indicate that the energy and environmental performance of existing commercial office building can be improved significantly if retrofit approaches are selected and implemented correctly. However, studies focusing on the effect of climate variation, building form, and building orientation are limited. Therefore, this study addressed this gap in knowledge.

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2. RESEARCH OBJECTIVES AND METHODS

The goal of this research was to examine commercial retrofits located in different climate types. Research methods included multiple simulations of common commercial building prototypes in different climate zones to establish a baseline energy usage, and simulations of low-impact and deep retrofit strategies. The following research questions were addressed:

- What are the main characteristics of existing commercial buildings in the U.S.? What is the baseline energy usage for buildings located in different climates? What is the effect of shape and orientation on energy consumption?

- What are the appropriate strategies for improving energy efficiency for building retrofits located in different climate types? What are the effects of low impact and deep retrofit strategies on energy consumption? How to apply retrofit design strategies to maximize energy savings?

Research methods included data analysis, energy modeling, and energy consumption calculations. Energy simulations were employed to investigate baseline energy usage, as well as the effects of low-impact and deep retrofit design. These simulations were based on the characteristics and properties of existing commercial buildings located in three different climate zones in the U.S (cold, mixed and hot climates). The following sections describe research process and results in detail.

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3. CHARACTERIZATION OF EXISTING COMMERCIAL BUILDINGS

3.1 Building size

Chicago, Baltimore, and Phoenix were selected to represent three different climate zones (cold, mixed, and hot climates). Data from the 2012 Commercial Building Energy Consumption Survey (CBECS) database outline common features of commercial buildings within these three climate zones, and were used to develop energy models for simulations. The CBECS database provides comprehensive data pertaining to the commercial building sector in the U.S., allowing for the accurate analysis of building characteristics (Griffith et al. 2008). The database includes energy-related building characteristics, as well as energy usage data (consumption and expenditures). It focuses on buildings where at least half of the floor space is used for a purpose other than residential, industrial, or agricultural activities. This means that CBECS includes data from outside of typical commercial programs (including schools, hospitals, correctional institutions and religious buildings). CBECS data also includes more typical commercial programed spaces, such as stores, restaurants, warehouses and offices. Data is collected through a survey in which respondents supply building characteristics and energy usage data, or provide an energy provider account (CEBCS 2012). For the purposes of this study, commercial office buildings were isolated from the CEBCS data and were the main focus of the research.

The survey results show that approximately 88% of total commercial buildings are less than 25,000 ft^2 (2,300 m^2), indicating that most commercial buildings are medium to small size. The mean square area for buildings in all regions of the U.S. fluctuates between 10,000 ft^2 (930 m^2) to 25,000 ft^2 (2,300 m^2), as seen in Figure 2. The mean area per building in Chicago is 17,300 ft^2 (1,608 m^2). The mean area for buildings located in Baltimore is 22,300 ft^2 (2,100 m^2). Phoenix is located in the southwest of the U.S., and the mean area per building is about 14,500 ft^2 (1,400 m^2). Based on this data collection and analysis, 20,000 ft^2 (1,850 m^2) building prototypes and simulation models were developed to represent the general condition of existing commercial building stock in the United States.

3.2 Building envelope

To construct the energy models and set the inputs for building envelope treatment, occupancies, building systems and construction methods for existing commercial offices, CBECS data was analyzed to determine the details for each building component.

Exterior walls are mostly constructed of brick, stone, or stucco in all three climates, while concrete and shingle siding serves as the secondary exterior wall material in Chicago and Baltimore, as seen in Figure 3. In Phoenix, metal panels and concrete are also major materials used for building envelopes.

Roof construction is another critical factor that determines buildings' energy performance. Most commercial buildings located in Phoenix have metal roofing. Asphalt, fiberglass, or other shingles are the predominant roofing materials used in Chicago and Baltimore, as demonstrated in Figure 4. Shallow pitched roofs and flat roofs are the predominant roof types in West South Central, Middle Atlantic, and East North Central areas, as seen in Figure 5.

3.3 Building systems and equipment

HVAC, lighting system control and efficiency optimization plays an important role in reducing energy consumption during building operation. Packaged heating units are the most popular heating system in existing commercial buildings, based on CBECS data (Figure 6). Other types of heating equipment, such as boilers, individual heaters, and furnaces are also widely used for heating.

Packaged air conditioning units are the dominant cooling systems utilized in existing commercial buildings in Chicago and Phoenix. In Baltimore, individual air conditioners are extensively used in commercial offices. Considering that lighting accounts for a large portion of commercial office electricity consumption, the CBECS database was analyzed to determine typical lighting equipment. According to survey results, standard fluorescent fixtures are widely used, as well as incandescent and compact fluorescent fixtures.

FIGURE 2. Mean area of commercial buildings in the U.S.

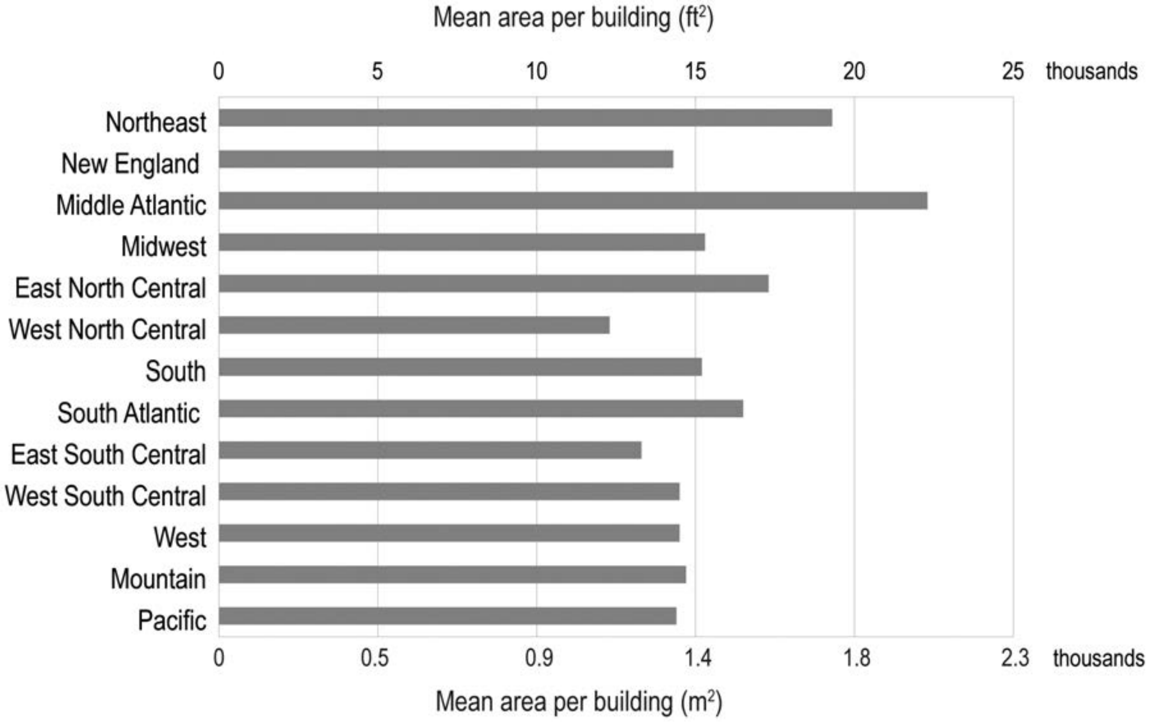

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FIGURE 3. Predominant exterior wall materials.

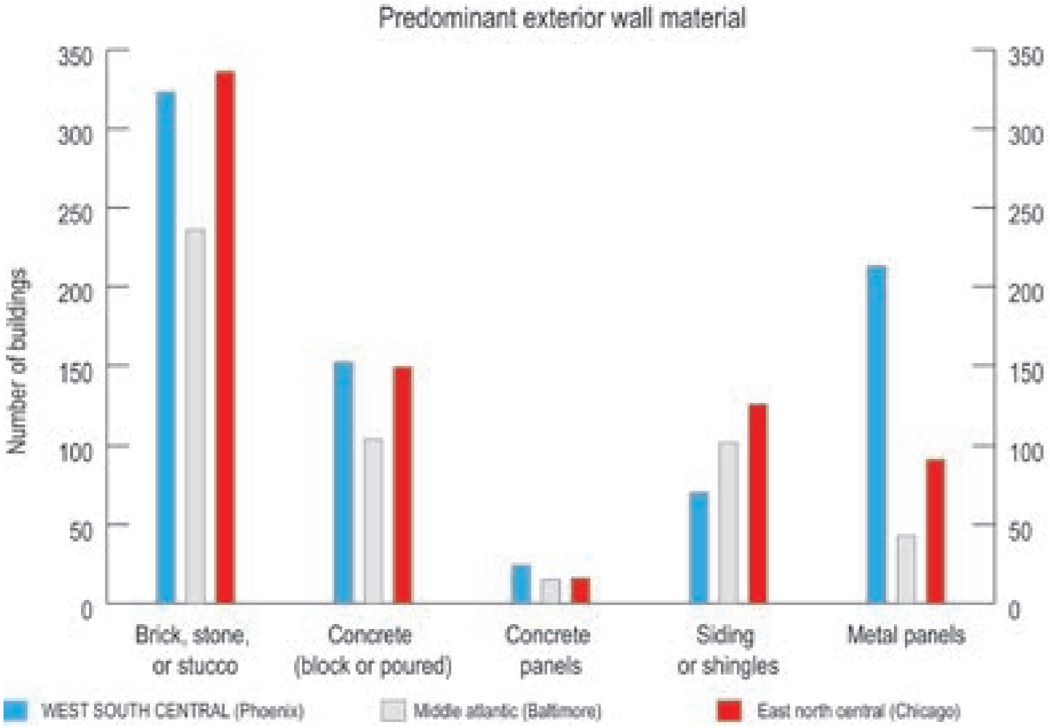

FIGURE 4. Predominant exterior roofing materials.

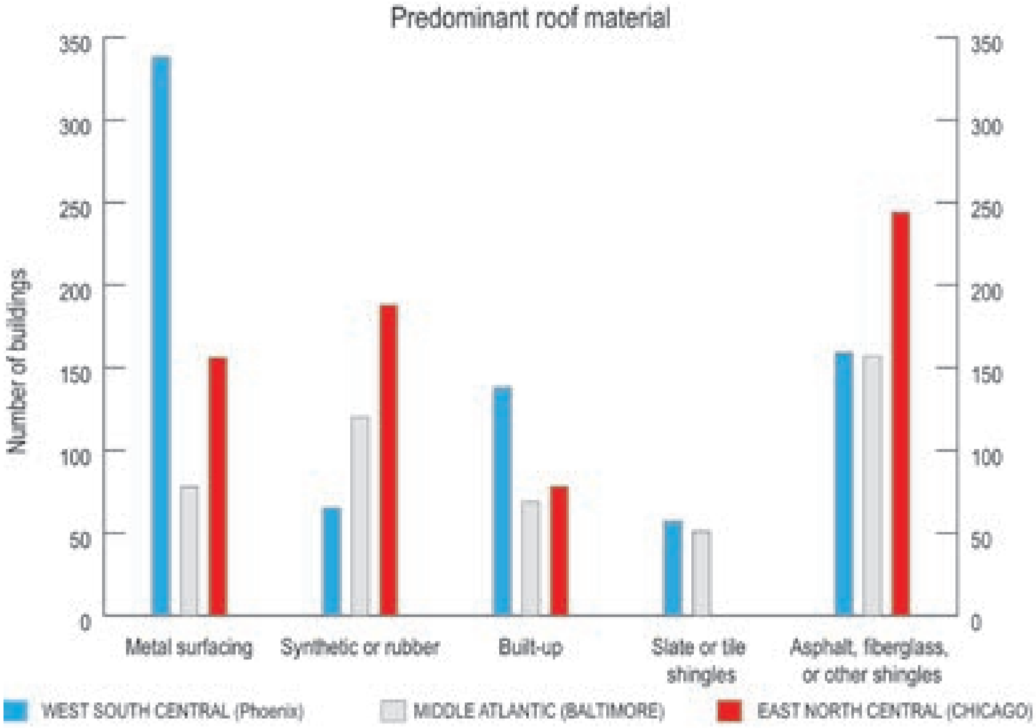

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FIGURE 5. Roofing characteristics.

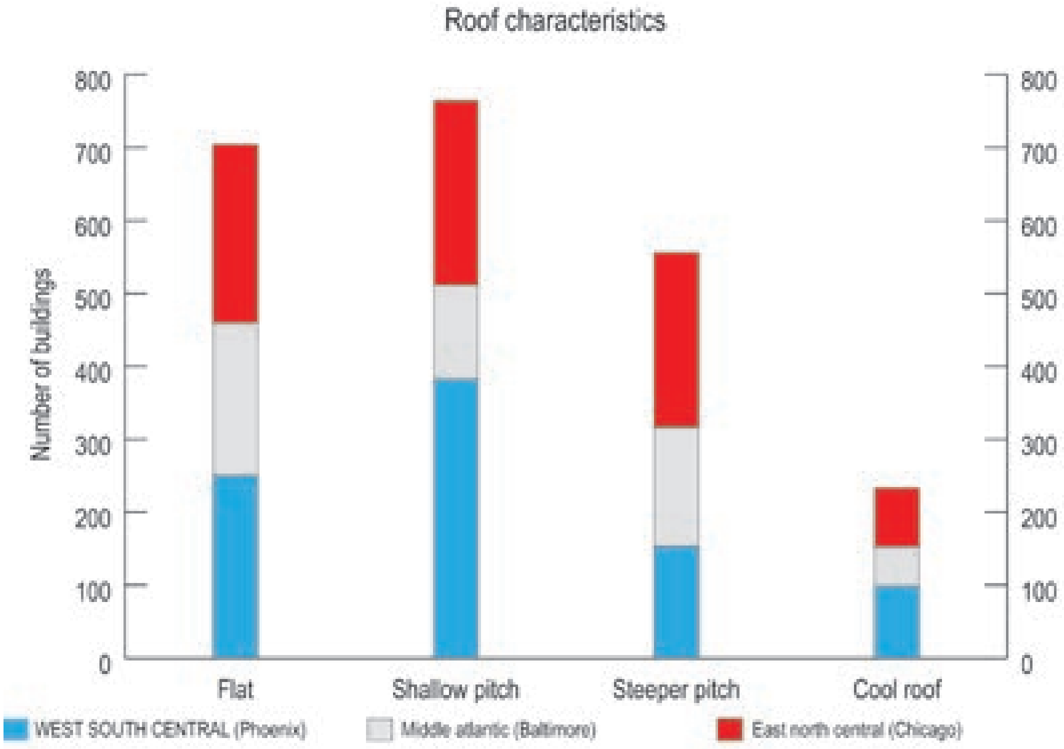
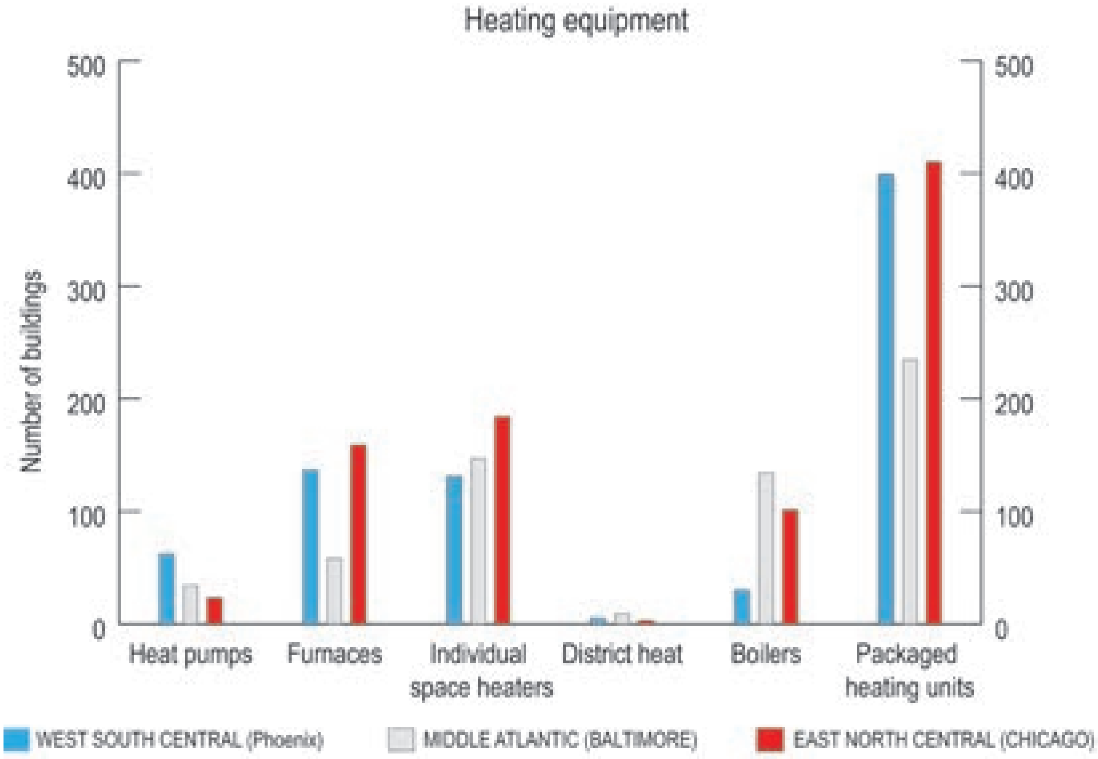


FIGURE 6. Heating equipment (more than one may apply).



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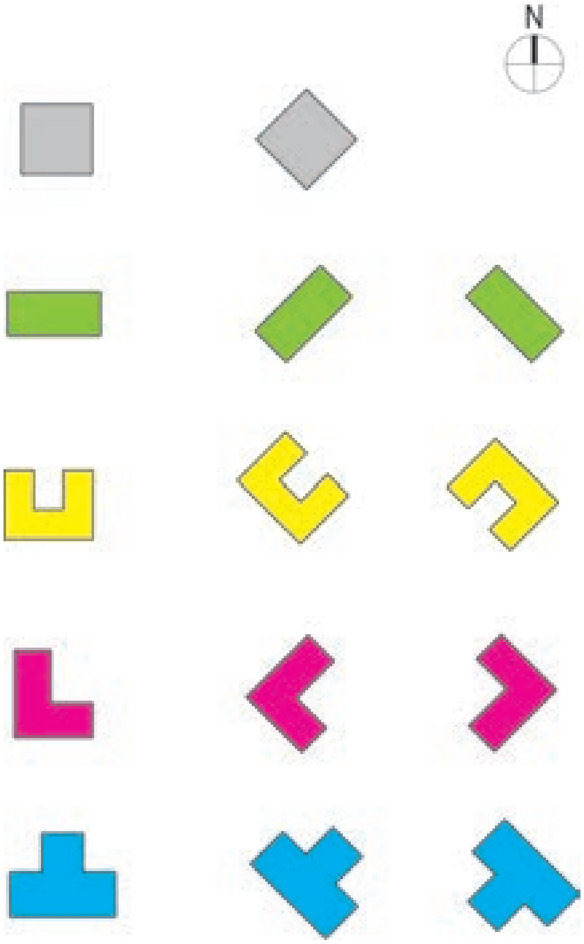
4. ENERGY MODELING

4.1 Overview of Baseline, Low Impact and Deep Retrofit Strategies

The application of energy modeling software programs helps predict the amount of energy consumption in different buildings, and tests the energy saving potential for various passive and active design strategies. The energy simulation program eQuest was used for the purposes of this research. Baseline models were created, as well as models representing retrofit design strategies. Since the building form and orientations may vary according to specific site constraints, 14 prototypes were created to represent different configurations, forms and orientations, as shown in Figure 7. For each prototype, three different models were created, representing the baseline model, and two alternative runs (low-impact and deep retrofit design options). Energy modeling was performed for all of these scenarios, and for buildings located in different climate types (Chicago, Baltimore and Phoenix). In total, 126 different energy models were developed.

The test model is described as a 20,000 ft^2 (1,850 m^2) commercial office building with four stories above ground and floor-to-floor height of 13 ft (4.0 m). The building envelope consisted of a brick facade with an R-value of 4.2, asphalt roofing with an R-value of 9.2, and 40% window-to-wall ratio. Windows consisted of double air insulated glazing with 1/2 in cavity. The inputs for baseline models located in cold climate (Chicago) were selected according to the

FIGURE 7. Building prototypes (shapes and orientations).



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2012 CBECS survey data for East North Central Region. Table 1 lists detailed inputs for the baseline model, as well as low-impact and deep retrofit strategies for Chicago.

The first alternative was based on the following retrofit strategies: thermally improved exterior walls, roofs, and windows; lower lighting power density (LPD) for functional rooms; while maintaining the same HVAC system. The results indicated that these strategies would reduce energy consumption by approximately 30% compared to the baseline models. For the building envelope, adding insulation would increase the R-value of exterior walls and the roof to better control heat transfer through building envelope. For the Chicago area, brick is the most common exterior wall material in use. A retrofit measure that added insulation would improve the R-value of existing exterior walls and would have a positive effect on the energy efficiency. Adding an air/vapor barrier, as well as insulation would increase the thermal resistance of exterior walls, control moisture transport, and eliminate possible thermal bridging at floors and partitions. Building envelope upgrades included the consideration of window replacement, exterior shading devices, and interior light shelves. These would contribute to higher energy efficiency, and would improve daylight and visual comfort. Retrofitting interior lighting fixtures to reduce lighting power density is an effective way to lower electricity consumption, and was included as one of the retrofit design strategies. The installation of occupancy sensors to control interior lighting and the addition of daylight harvesting are feasible strategies, which were incorporated into this study.

To achieve significantly lower end uses for heating, cooling, and ventilation, deep retrofit strategies can be employed. This could include the complete overhaul of HVAC systems. One such strategy is the replacement of a VAV system with radiant heating, as radiant systems are

TABLE 1. Model inputs for the baseline, low-impact and deep retrofit strategies for Chicago climate.

	Baseline	Low-Impact	Deep Retrofit
Climate Zone	5A—Cool, Humid	5A—Cool, Humid	5A—Cool, Humid
HVAC System Type	Packaged Multizone with Furnace	Packaged Multizone with Furnace	4-Pipe Fan Coils with HW Heat
Heating Equip	Furnace	Furnace	HW Boiler (forced draft)
Cooling Equip	DX Coils	DX Coils	Electric Reciprocating Hermetic (Packaged air-cooled condenser)
Daylighting Controls	No	Yes	Yes
Roof	Asphalt (R 9.2)	Asphalt (R 21.0)	Asphalt (R 21.0)
Wall	Brick (R 4.2)	Brick (R 16.0)	Brick (R 16.0)
Windows	Double Clear 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air
Window to Wall Ratio	40%	40%	40%
Window Shading	No	Yes	Yes

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much more energy efficient than typical VAV systems. Radiant systems also provide improved thermal comfort with lower energy consumption (Rhee and Kim 2015). The deep retrofit strategy considered the retrofit of HVAC equipment and the integration of radiant systems. The modeling of radiant system in eQuest was set as a 4-pipe fan coil with hot water heating. The second alternative run results were obtained simulating a radiant system. Tables 2 and 3 show modeling inputs for Baltimore and Phoenix, providing an overview for low impact and deep retrofit strategies.

4.2 Energy Usage Intensity Results

The effects of building shape and orientation on the total energy consumption is evident in the fluctuations of EUI values. The results demonstrate that for buildings with the same size and with identical systems, north-south oriented square shaped buildings have the lowest EUI. U-shape and T-shape buildings have higher EUIs. This finding indicates that compact forms and reduced surface areas benefit the energy performance of buildings. Also, the north-south orientation results in lower EUI results than other orientations when building form is constant. Retrofit alternatives provided EUI improvements that were relatively proportional across orientation and shape, however the U-shaped building appears to provide the most significant EUI improvements.

Figure 8 show results for Chicago. The average energy use intensity (EUI) for the baseline was calculated to be 126 kBtu/ft^2 (398 kWh/m^2). According to the City of Chicago Energy Benchmark report, among 248 reporting buildings, the median weather-normalized energy

TABLE 2. Model inputs for the baseline, low-impact and deep retrofit strategies for Baltimore climate.

	Baseline	Low-Impact	Deep Retrofit
Climate Zone	4A—Mixed, Humid	4A—Mixed, Humid	4A—Mixed, Humid
HVAC System Type	Packaged VAV with HW Reheat	Packaged Multizone with Furnace	4-Pipe Fan Coils with HW Heat
Heating Equip	Hot Water Coils	Furnace	HW Boiler (forced draft)
Cooling Equip	DX Coils	DX Coils	Electric Reciprocating Hermetic (Packaged air-cooled condenser)
Daylighting Controls	No	Yes	Yes
Roof	Asphalt (R 9.2)	Asphalt (R 21.0)	Asphalt (R 21.0)
Wall	Brick (R 4.2)	Brick (R 16.0)	Brick (R 16.0)
Windows	Double Clear 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air
Window to Wall Ratio	40%	17.3%	17.3%
Window Shading	No	Yes	Yes

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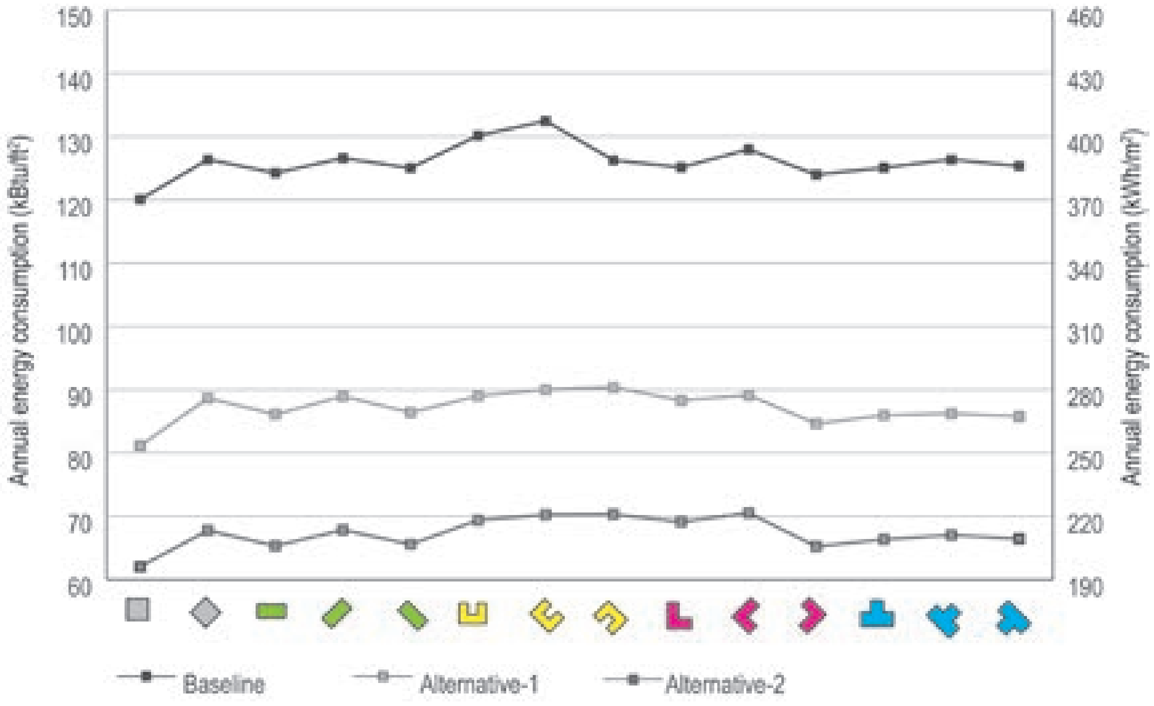
TABLE 3. Model inputs for the baseline, low-impact and deep retrofit strategies for Phoenix climate.

	Baseline	Low-Impact	Deep Retrofit
Climate Zone	2B—Hot, Dry	2B—Hot, Dry	2B—Hot, Dry
HVAC System Type	Packaged Multizone with Furnace	Packaged Multizone with Furnace	4-Pipe Fan Coils with HW Heat
Heating Equip	Furnace	Furnace	HW Boiler (forced draft)
Daylighting Controls	No	Yes	Yes
Roof	Asphalt (R 9.2)	Asphalt (R 21.0)	Asphalt (R 21.0)
Wall	Brick (R 4.2)	Brick (R 16.0)	Brick (R 16.0)
Windows	Double Clear 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air	Double Low-e 1/4in, 1/2in Air
Window to Wall Ratio	40%	17.3%	17.3%
Window Shading	No	Yes	Yes

FIGURE 8. Comparison of EUI for the baseline, low-impact and deep retrofit strategies for all scenarios (Chicago climate).



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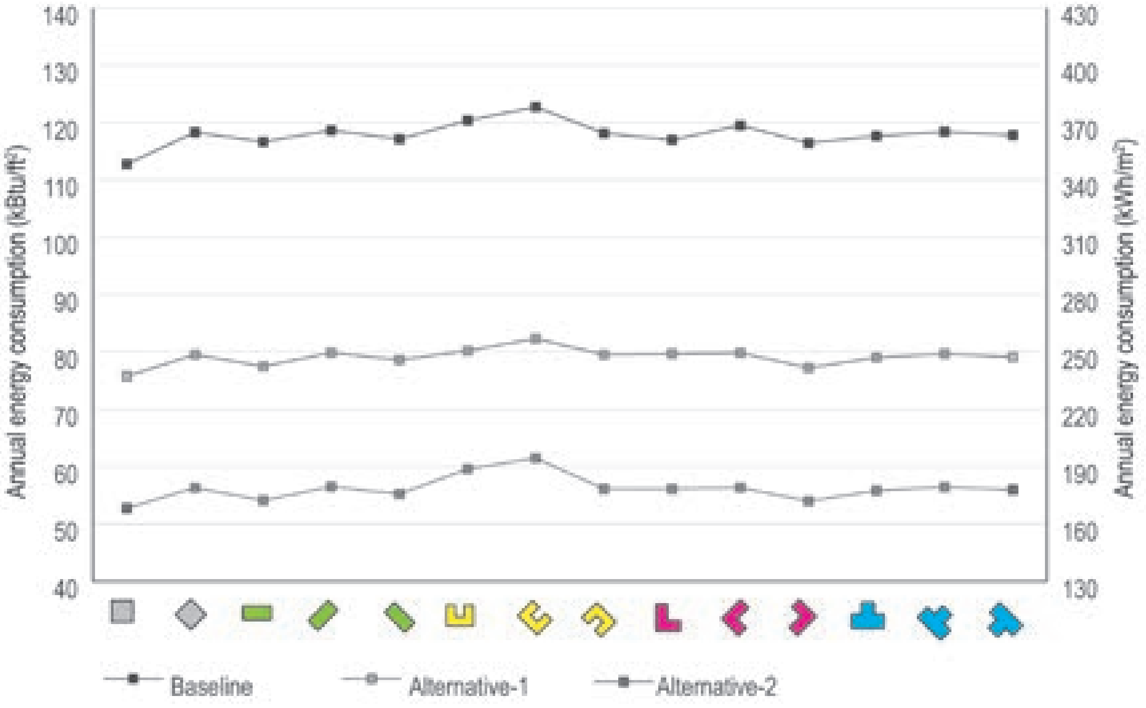
use intensity is 202 kBtu/ft²/yr (City of Chicago 2014). The EUI, according to the ASHRAE Benchmark Index based on Standard 90.1-2004 for medium offices, is 48 kBtu/ft²/yr for those located in Chicago, 40 kBtu/ft²/yr for those located in Phoenix, and 43 kBtu/ft²/yr for those located in Baltimore (ASHRAE, 2009). Therefore, the obtained result for the baseline is between the median EUI reported by the City of Chicago and energy-efficient benchmark. Low-impact retrofit strategies would save around 30% compared to the baseline models. Deep energy retrofits indicate almost 50% energy reductions compared to baseline results.

Further analysis was conducted to determine the energy consumption of commercial office buildings in Baltimore's mixed climate. The results indicate that commercial buildings in Baltimore climate generally have lower EUIs than buildings in Chicago. The estimated average EUI for the commercial building sector in Baltimore is approximately 117 kBtu/ft² (370 kWh/m²). Deep energy retrofits could lower EUIs to 56 kBtu/ft² (177 kWh/m²), as shown in Figure 9. As with Chicago, retrofit alternatives provided EUI improvements that were largely proportional across different orientations and shapes. Square, rectangle, and L-shaped buildings provided the best EUI performance, while T and U-shaped buildings offered poorer performance. Low-impact retrofits strategies provide performance improvements that are relatively consistent across building form and orientation, while deep retrofit strategies show more variation in EUI values.

The same research method was applied to study the existing commercial building stock in Phoenix. Phoenix's climate type is hot, dry and sunny, so heating demands in commercial office buildings are lower than in Chicago and Baltimore. Rather, interior cooling is critical to provide a comfortable thermal environment. The baseline run demonstrates that average EUI of a typical commercial office building in Phoenix is approximately 108 kBtu/ft² (341 kWh/m²). Without high energy demand for heating, energy usage of commercial offices' is lower compared to the

FIGURE 9. Comparison of EUI for the baseline, low-impact and deep retrofit strategies for all scenarios (Baltimore climate).



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computed values for Chicago and Baltimore, and mostly consists of cooling, equipment and lighting requirements. Alternative model runs provided EUI performance improvements that were relatively consistent across building shapes and orientations. Low-impact retrofit strategies provide less substantial EUI improvements when compared to Baltimore and Chicago. However, deep retrofits strategies provide significant EUI savings, leading to values ranging from 37 to 40 kBtu/ft^2, as seen in Figure 10.

Energy modeling of typical existing commercial office buildings in different climates uncovered how low-impact and deep retrofit design methods would reduce energy consumption. Improved building envelopes, upgraded HVAC and lighting systems, and integrated advanced building technologies would reduce the overall energy consumption of existing buildings. The next section compares impacts on heating, cooling and lighting loads for the investigated climates.

4.3 Comparison of Heating, Cooling and Lighting Loads

Figures 11 to 13 show heating, cooling and lighting loads for the first investigated scenario (square shaped building, oriented north-south). Data shows that energy consumption reduces in the heating dominated climate of Chicago with the low-impact retrofits, but significantly more with the deep retrofit strategy, as seen in Figure 11. Improved thermal insulation, as a low impact strategy, reduce heating and cooling loads. However, energy savings are maximized with improvements to HVAC system, as evident in the results for deep retrofits. Similar trends are evident for Baltimore and Phoenix. Phoenix shows the most significant energy consumption for cooling and the most significant reductions in cooling with more impactful retrofits.

FIGURE 10. Comparison of EUI for the baseline, low-impact and deep retrofit strategies for all scenarios (Phoenix climate).

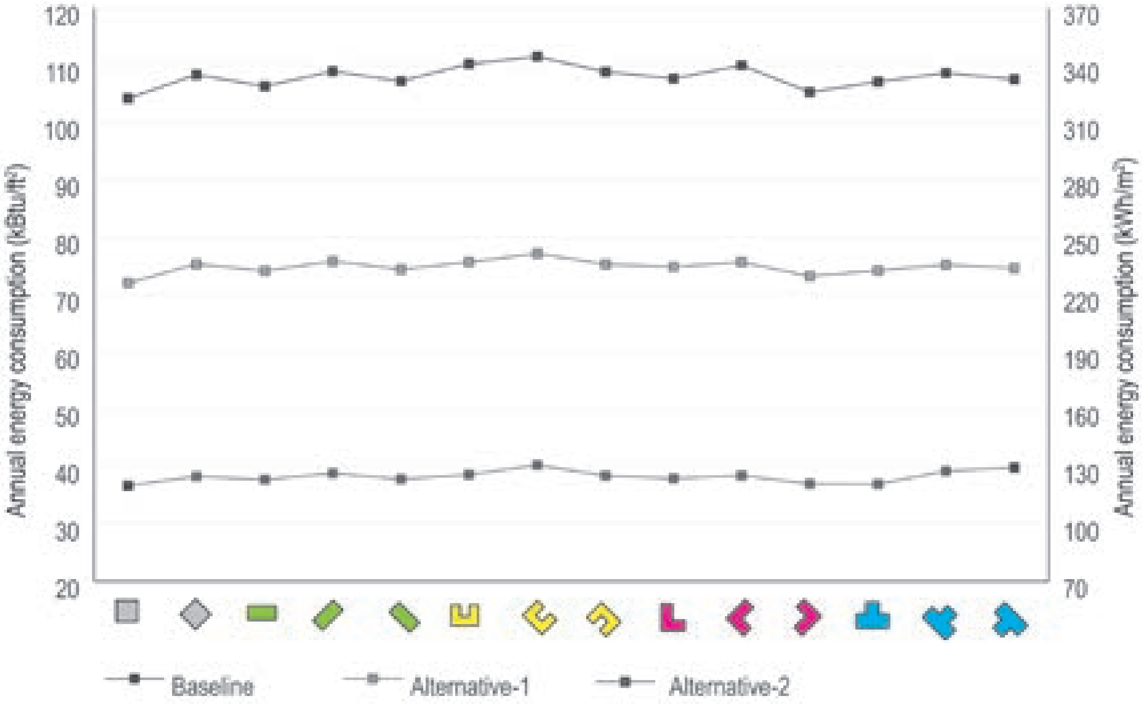

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FIGURE 11. Comparison of heating, cooling and lighting loads for the baseline, low impact and deep retrofit design strategies (Chicago climate).

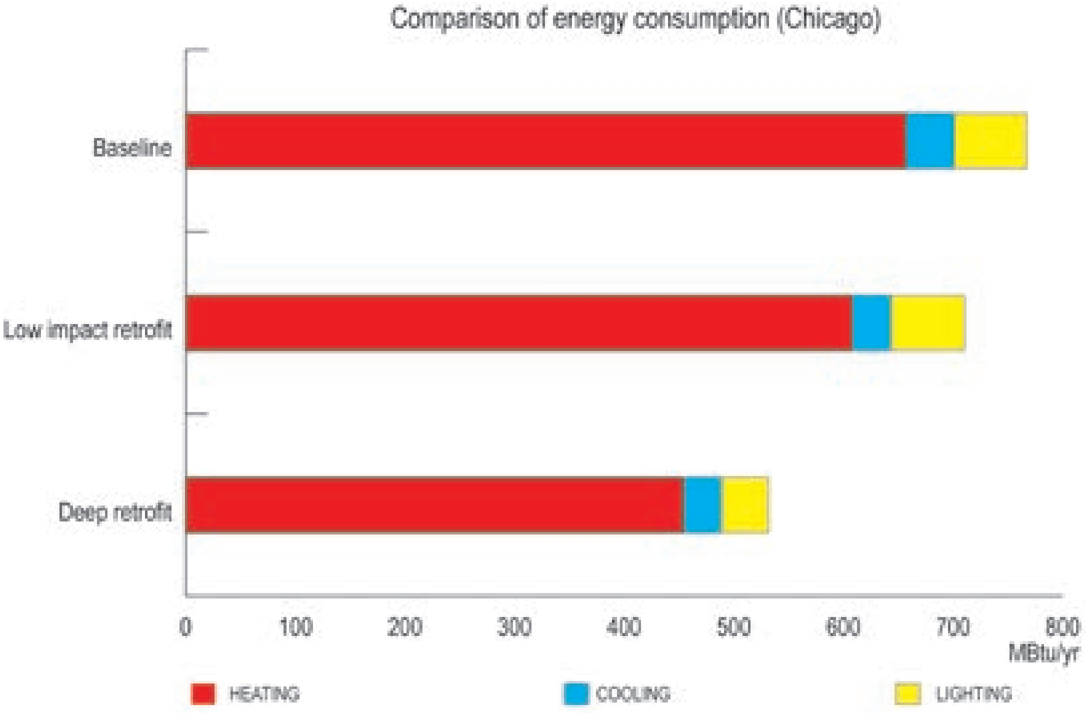

FIGURE 12. Comparison of heating, cooling and lighting loads for the baseline, low impact and deep retrofit design strategies (Baltimore climate).

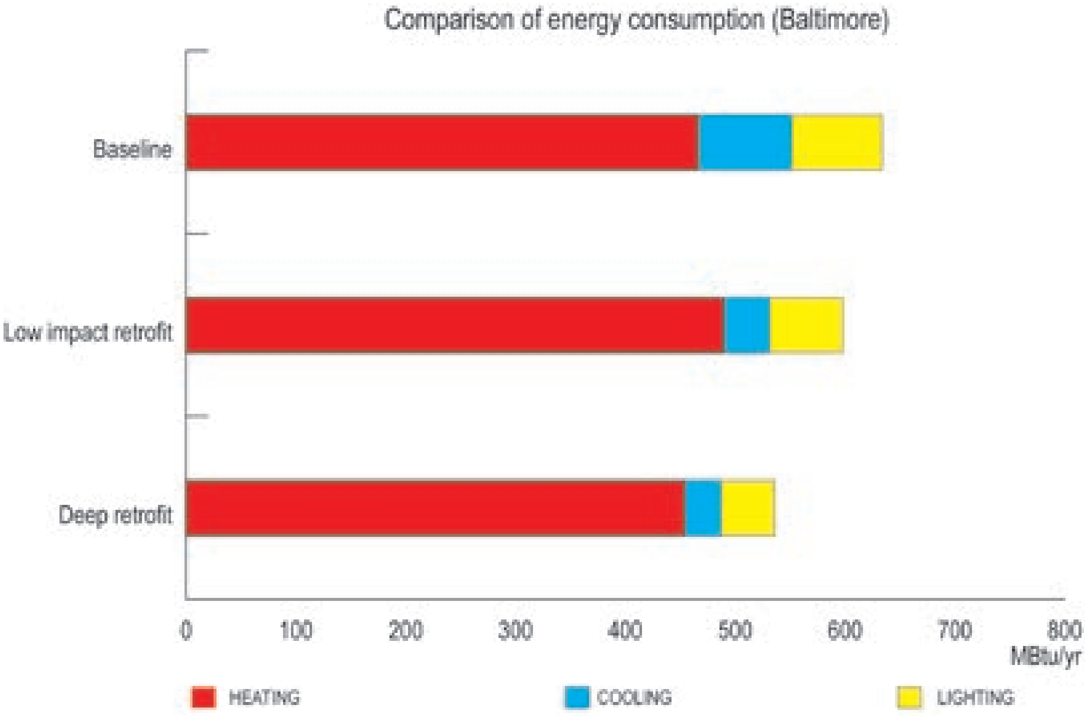

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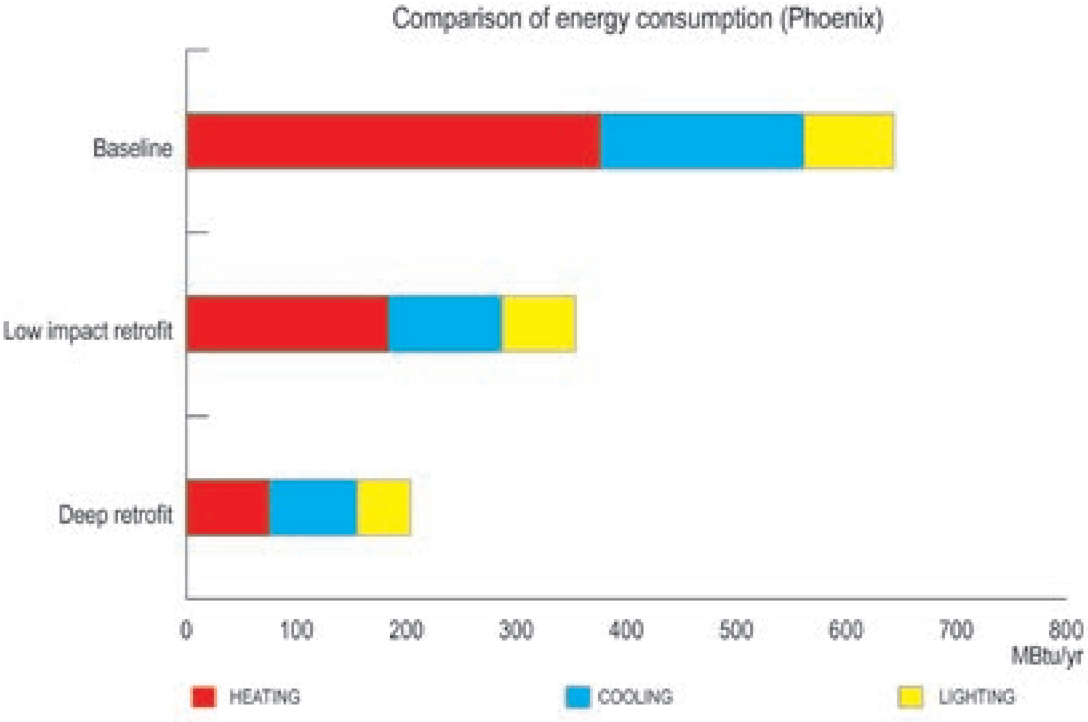
FIGURE 13. Comparison of heating, cooling and lighting loads for the baseline, low impact and deep retrofit design strategies (Phoenix climate).



5. CONCLUSION

This research explored the effects of retrofitting design strategies on energy consumption of existing commercial office buildings in three different climates. Based on comprehensive analysis of existing office buildings in the U.S., their current energy use, and the impacts of design retrofit strategies, it is evident that retrofit design can provide significant energy savings. This research analyzed both low impact and deep retrofit strategies, and quantified their effect on energy consumption of buildings with various shapes and orientations. Results show that deep retrofits would significantly reduce energy consumption of existing commercial buildings in analyzed climates.

Significant barriers still exist in the execution of deep retrofit design. Financial considerations and economic impacts are the most difficult challenges. Property owners may be reluctant to make substantial investments in retrofit analysis, design, and construction. Research and resources are limited when comparing new construction and retrofitted buildings, so it is difficult for most building owners to predict costs during the decision making process. This has led to a preference for constructing new buildings rather than retrofitting buildings in many cases. Further research should be conducted to overcome the barriers relating to economic impacts of commercial retrofits, identifying cost-effective performance-based design techniques.

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