Cost-Effectiveness of Energy Efficiency Measures Exceeding Current Standards in New Commercial Buildings

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Abstract

Building energy efficiency has become a top priority for governments across the globe due to the recent energy price volatility and increasing concern regarding climate change. New buildings are considered the easiest and least costly way in which to increase energy efficiency, making new construction an excellent target for efficiency improvements. The goals of this paper are to estimate life-cycle energy savings, carbon emission reduction, and cost-effectiveness of energy efficiency measures in new commercial buildings using an integrated design approach. A total of 1416 energy simulations are run for 12 prototypical buildings in 59 cities, with two building designs, ASHRAE 90.1-2007 compliant and a "Low Energy Case," for each building-location combination. Whole building energy consumption simulations and extensive building cost databases are used to determine the life-cycle cost-effectiveness and carbon emissions of each design. The results show conventional energy efficiency technologies can be used to decrease energy use in new commercial buildings by 10 % to 20 % on average and up to over 25 % for some building types and locations. These reductions can often be done at negative life-cycle costs over a short study period because the improved efficiencies allow the installation of smaller, less expensive HVAC equipment. These improvements not only save money and energy, but reduce a building's carbon footprint by 14 % on average.

Keywords: carbon footprint, energy efficiency, integrated design, life-cycle assessment, life-cycle costing

1. Introduction

Building energy efficiency has come to the forefront of political debates due to high energy prices and climate change concerns. Improving energy efficiency in new commercial buildings is one of the lowest cost options to decrease a building's energy use, owner operating costs, and carbon footprint. This paper uses life-cycle costing and life-cycle assessment with extensive building cost databases and whole building energy simulations to determine the energy savings and cost-effectiveness of energy efficiency improvements and the resulting carbon emissions reduction.

The results of this analysis show that conventional energy efficiency technologies such as thermal insulation, low-emissivity windows, window overhangs, and daylighting controls can be used to decrease energy use in new commercial buildings by 10 % to 20 % on average and up to over 25 % for some building types and locations. Although improving energy efficiency may increase the first costs of a building, the energy savings over the service life of the building often offset these initial higher costs. The first costs can often be lower for the more efficient building designs because, through integrated design, the improved efficiency reduces the size of the heating, ventilation, and air conditioning (HVAC) system required to meet the peak heating and cooling loads.

The energy efficiency improvements not only save money, but also reduce a building's carbon footprint. Carbon footprints are reduced by an average of 14 % across all building types and sizes for a ten-year study period with the greatest reductions occurring in areas relying heavily on coal-based electricity.

2. Study design

Twelve building types are evaluated to consider a range of building sizes and energy intensities. The building types evaluated in this paper represent 46 % of the U.S. commercial building stock floor space (CBECS, 2003). A three-story and six-story dormitory, three-story and six-story apartment building, and fifteen-story hotel represent the lodging category. An elementary school and high school represent education buildings. Three sizes of office buildings (three-story, eight-story, and 16-story) are used to represent the largest building category; offices accounting for 17 % of U.S. building stock floor space. A one-story retail store represents non-mall mercantile buildings while a one-story restaurant represents the food service industry. Building size ranges from 465 m^2 to 41 806 m^2 (5000 ft^2 to 450 000 ft^2).

Life-cycle costing and life-cycle assessment are conducted over four different study period lengths: 1 year, 10 years, 25 years, and 40 years. A one-year study period length represents the time horizon of an investor who intends to turn over the property soon after it is built, such as a developer. The 10-year, 25-year, and 40-year study periods represent long-term owners at different ownership lengths. Longer study periods are effective at capturing all relevant costs of owning and operating a building. However, longer study periods increase uncertainty in the precision of the life-cycle cost estimates due to the assumptions made about costs and occupant behavior in future decades, such as energy costs and energy consumption.

For each building type, energy simulations are run for sixteen U.S. cities located in different *ASHRAE 90.1-2007* sub-climate zones (ASHRAE, 2007). These cities are chosen as representative cities based on geographical location, and population. At least one city from each of the sub-climate zones, excluding Zone 6B and Zone 8, is included in the analysis.

3. Cost data

3.1 Building construction costs

Prototypical building and component assembly costs originate from the RS Means *CostWorks* online database. The RS Means *CostWorks Square Foot Estimator* "default costs" for each building type are used to estimate the costs of a "prototypical building."[1] This prototypical building is used as a baseline to create a compliant building for the two energy efficiency design alternatives being considered in this analysis: the *ASHRAE 90.1-2007* energy efficiency standard design and a higher efficiency "Low Energy Case" (LEC) design.

The RS Means *CostWorks Cost Books* are used to adapt the RS Means prototypical buildings to the two building designs. The only components that must be changed to meet *ASHRAE 90.1-2007* are insulation and windows. Insulation material and/or thickness in both the walls and roof decks are changed in order to meet *ASHRAE 90.1-2007*. Windows are altered in three ways: increasing the number of panes, adding low-emissivity (low-e) coatings, and adding solar heat gain control films depending on the *ASHRAE 90.1-2007* requirements.

The LEC design increases the thermal efficiency of insulation and windows, and introduces daylighting and window overhangs. The new insulation requirements go beyond *ASHRAE 90.1-2007* by adding up to R-15 to the roof deck and R-16.1 to the wall exterior. The U-factor, solar heat gain coefficient, and visual transmittance are improved by up to 0.10, 0.05, and 0.07, respectively. The LEC also adds daylighting controls and overhangs for window shading where optimal, based on the *EnergyPlus* "Example File Generator" recommendations. Daylighting is included for all building types and locations while overhangs are used in all building types and locations except for the coldest climate zones.[2]

The two building designs have different heating and cooling loads, which leads to differences in the appropriate size of the HVAC system. Whole building energy simulations automatically size ("autosize") the HVAC system to the smallest system that will still meet the ventilation load requirements. Smaller HVAC systems have lower assembly costs, which can offset some or all

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[1] Disclaimer: Certain trade names and company products are mentioned throughout the text. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.

[2] Cost data obtained from Winiarski et al. (2003).

of the additional first costs from other energy efficiency measures (i.e. insulation). Based on the costs of the system used in the prototypical building, the HVAC costs are increased or decreased to the appropriate size specified in the energy simulations based on a linear interpolation of assembly costs.

Construction costs for each building are determined by summing the baseline costs for the prototypical building and the changes in costs required to meet the building design. National average construction costs are adjusted with the 2008 RS Means *CostWorks City Indexes* to control for local price variations. Once the indexed construction cost of a building has been calculated, it is multiplied by the contractor "mark-up" rate. This value is then multiplied by the architectural fees rate, resulting in the building's "first costs."[3]

3.2 Maintenance, repair, and replacement costs

Component and building lifetimes and component repair rates are collected from Towers, Dotz, and Romani (2008). Building service lifetimes are assumed constant across climate zones: apartments - 65 years; dormitories - 44 years; hotels, schools and office buildings - 41 years; retail stores - 38 years; and restaurants - 27 years. Insulation and windows are assumed to have a 50-year lifespan. Insulation is assumed to have no maintenance and repair requirements while windows have an annual repair rate of 1 % of window panes. The heating and cooling units have different lifespans and repair rates based on climate. Cooling units have short lifespans and repair frequencies in hot climates and long ones in cold climates. The opposite holds true for heating units, with longer lives and less maintenance in warmer climates.

Future costs are collected from two sources. Baseline average maintenance, repair, and replacement (M, R, and R) costs (excluding HVAC) per square foot for each building type, by year of service life, are from Towers, Dotz, and Romani (2008). RS Means *CostWorks* is the source of M, R, and R costs for the components that change across building designs. In this analysis, HVAC system components are the only components replaced over the study period. Based on the repair rate, windows have an assumed annual repair cost equal to replacing 1 % of all window panes.

3.3 Energy costs

Utility rates for electricity and natural gas are obtained from the U.S. Energy Information Administration (EIA). The state-wide average retail price per 3.6 MJ (1 kWh) of electricity is used as the building owner's/operator's cost of electricity consumption. The EIA *December 2008 Natural Gas Monthly* is used to obtain the average retail natural gas prices by state for 2007. Whole building energy simulations for the 708 building type-location combinations are run in the *EnergyPlus 3.0* "Example File Generator" web interface to obtain each building's annual

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[3] Contractor fee and architectural fee rates are the default rates provided by RS Means at 25 % and 7 %, respectively.

energy use for electricity and natural gas. For simplicity, the annual energy use for each fuel type is multiplied by the average fuel cost for the building location to obtain a building's annual energy costs. It is assumed that the building maintains its energy efficiency performance throughout the study period.

3.4 Building residual value

Building residual value -- its value at the end of the study period -- is estimated based on first costs and remaining component and building lifetimes. The baseline residual value is the first cost (excluding any components replaced over the time period) multiplied by the ratio of the remaining life of the building to the study period of the building. The lone additional residual value comes from the HVAC equipment, which is the only component replaced over the study period. Any remaining years in the lifetime of the HVAC equipment is used to estimate a residual value by taking the initial cost of the HVAC system and multiplying it by the ratio of remaining life to estimated lifetime of the equipment.

4. Life-cycle cost analysis

Life-cycle costing (LCC) estimates the net present value of all relevant costs throughout the study period, including construction costs, M, R, and R costs, energy costs, and residual values.[4] LCC of buildings compares the costs from a "base case" building design to costs from alternative building designs.

The "base case" in this paper is assumed to be the *ASHRAE 90.1-2007* design because it is the most recent building energy efficiency standard written into current U.S. state building code requirements.[5] The LEC design is compared to the *ASHRAE 90.1-2007* design to determine the LCC and carbon emissions for this more efficient alternative. This study analyzes LCC results via two measures: net savings as a percentage of base case LCC and the adjusted internal rate of return. Net savings is the difference between the base case (*ASHRAE 90.1-2007*) and alternative (LEC) design's LCCs. The adjusted internal rate of return (AIRR) is the annualized return on the energy efficiency investment costs. The AIRR of building energy efficiency investments can be compared to an investor's minimum acceptable rate of return (MARR), such as gains from competing investments in the stock or bond market over the same study period or, in the case of the federal government, the savings in interest payments from decreasing the national debt. If the AIRR is greater than the investor's MARR, the energy efficiency investment is preferred.

All future costs are discounted to their equivalent present values based on the appropriate discount factors (Rushing, 2008). All costs and values are discounted based on the U.S. Department of Energy (DOE) real discount rate for energy conservation projects (3.0 % in 2008). EIA energy price forecasts are embodied in the discounting of electricity and natural gas

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[4] Source: Fuller et al. (1996).

[5] ASHRAE 90.1-2004 has been implemented by 24 states and Washington, D.C. while 90.1-2007 has been implemented by 3 states, 90.1-2001 by 8 states, and 90.1-1999 or earlier by 15 states.

costs over the study period. National Institute of Standards and Technology's (NIST) *Building for Environmental and Economic Sustainability* (*BEES)* software (Lippiatt, 2007) is used to compute the life-cycle costs for the building design alternatives in compliance with ASTM Standards of Building Economics (ASTM, 2007).

5. Environmental life-cycle assessment

The environmental flows from operational energy use are derived from two sources. The state-level average emissions per 1 MW (3.412 MBtu / h) of electricity for carbon dioxide (CO_2) are obtained from *eGRID* 2007 (EPA, 2007). Natural gas emissions data are collected from *BEES 4.0*. Life-cycle environmental flows from building construction, repair, and replacement are derived from U.S. Environmental Input-Output Tables included in the *SimaPro 7* software. The *BEES* software is used to assess the life-cycle energy and material flows from construction and operation of the building and estimate its carbon footprint.

6. Results

Twelve building types, representing different building sizes and energy intensities, are evaluated over four study period lengths for two alternative building designs. For each building type, energy simulations are run for 59 U.S. cities located across the United States. The resulting energy use and energy costs, life-cycle costs, and life-cycle carbon emissions are discussed below.

6.1 Energy use and costs

As is to be expected, increasing the energy efficiency of a building beyond the *ASHRAE 90.1-2007* standard requirements decreases energy use. Figure 1 shows the LEC leads to reductions across the 50 cities of 6.5 % to 31.2 % relative to the *ASHRAE 90.1-2007* design for a one-year study period.[6] Seven of the twelve building types have an energy savings greater than 10 % for all locations. Eleven of the twelve have at least one location that has a 20 % or greater energy reduction. Seven building types have average energy reductions over 15 %. A 15 % reduction in energy use for most building types relative to *ASHRAE 90.1-2007* appears to be achievable with conventional building technologies.

Energy cost savings are not perfectly correlated with energy use reductions due to differences in the marginal costs of electricity and natural gas across states, region-specific EIA future price projections, and building process loads. The smallest savings in energy and energy costs occurs in colder cities while the greatest savings occurs in cities located in more temperate climates. A

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[6] These magnitudes are less than the HVAC energy savings because energy from user demands such as process loads is assumed to be constant across the alternatives.

slight variation in annual energy cost savings across study period lengths occurs because fuel price escalation rates vary over time, but these variations do not alter the interpretations.

6.2 Life-cycle costs

The study period length is important in determining which design alternative is the most cost-effective. The *ASHRAE 90.1-2007* design is the cost-effective choice for only 186 of the 708 (36 %) building type-location combinations relative to the LEC over a one-year study period. This shows how quickly energy efficiency measures -- when applied in an integrated design context -- can pay for themselves.

An increase in the study period length increases the number of building type-location combinations for which the LEC is the optimal design alternative. For a ten-year study period, the LEC is cost-effective for 97 %, or 167 additional building type-location combinations. This number increases to 99 % for a 25-year and 40-year study periods. The LEC design simultaneously decreases building energy use and life-cycle costs for these building type-location combinations. These results support stricter building energy efficiency standards because social gains from reduction in fossil fuel use and carbon emissions will occur at negative costs to the building owner/operator.

Different building types realize different levels of savings. As seen in Figure 2, the LEC is cost-effective over a 10-year study period in all locations for high schools, elementary schools, hotels, six-story apartments, retail stores, restaurants, and all office buildings. The LEC is cost-ineffective in some locations for dormitories and 3-story apartments due to lower overall energy savings.[7]

6.3 Adjusted internal rate of return

An investment in building energy efficiency may lead to lower life-cycle costs but still be a poor investment relative to an owner's/operator's other investment options. For this reason, the AIRR of energy efficiency investments are estimated for comparison with rates of return for alternative investments. Some building types and locations analyzed have an infinite AIRR for the LEC design because first costs decrease. The cost savings from HVAC capacity reduction overcome the costs for additional insulation, daylighting controls, and overhangs. For these buildings, there is a compelling economic case for the energy efficiency improvements even over a one-year study period. Nearly all locations in the following building types have infinite returns in the LEC relative to *ASHRAE 90.1-2007* over a one-year study period: hotels (100%), 8-story office buildings (100 %), 16-story office buildings (100 %), restaurants (100 %), elementary schools (97 %), high schools (97 %), 3-story dormitories (83 %), 3-story offices (68 %), and retail stores (64 %). Apartment buildings and 6-story dormitories have infinite returns in less than 10 % of locations. Of the 708 building type-location combinations, 69 %

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[7] The interpretations across building types are the same for all other study period lengths.

have infinite returns over a one-year study period; this figure remains relatively unchanged over other study period lengths.

The longer the study period, the more cost-effective energy efficiency designs become because the energy savings occurs year after year while the first costs are constant and the additional cost of maintaining the building is relatively small. The AIRR on energy efficiency investments varies widely both within and across study period lengths. Of the 708 building type-location combinations analyzed for a 1-year study period, 499 have an AIRR above 3.0 %, the MARR for U.S. federal projects. This increases to 599 with a 10-year and 638 with a 25-year study period. This is an increase from 70 % to 90 % of building type-location combinations. Over 55 % for all study periods have an AIRR greater than 10 %, which is higher than the inflation-adjusted long-term annual return from U.S. stocks of around 7 % (Hammond, 2006).

6.4 Life-cycle carbon emissions

For the LEC design, life-cycle carbon dioxide equivalent (CO_2e) emissions from building materials production (for construction and component replacements) and operational energy use are reduced in nearly all building type-location combinations. Figure 3 shows the range of CO_2e emissions reduction for each building type under the LEC over a 10-year study period. The reduction in CO_2e emissions ranges from 0.3 % to 25.0 %, with a mean of 14 %. Life-cycle CO_2e reductions are slightly lower, in percentage terms, than operational energy CO_2e reductions because material-based emissions often increase with energy efficiency improvements (i.e. more embodied emissions).[8]

Emissions reduction, in percentage terms, is highest for cities that either have reductions in energy use of at least 15 % and/or at least 60 % coal-fired electricity generation. Cities in the central United States have the most significant CO_2e reductions. Cities in this area of the country have middle-to-high ranking in both categories relative to the other locations. The opposite can be said about states with low rankings in both categories, which are the West Coast cities with the lowest carbon emissions reductions. Further support is indicated by an Ordinary Least Squares regression with percentage energy savings and percentage of generation originating from coal as independent variables explaining the percentage of carbon emissions reduction (dependent variable). Both variables are statistically significant at the 1 % level and the R^2 ranges from 0.505 to 0.804 depending on the building type, implying that these two factors explain 51 % to 80 % of the variation in the carbon reduction percentage.

The cost of reducing carbon emissions in the LEC alternative design is negative for all locations with a reduction in life-cycle costs relative to the *ASHRAE 90.1-2007* design, which account for 97 % of building type-location combinations over a ten-year study period. The mean cost under the LEC for a ten-year study period is -\$181/tCO_2e with a range of -\$733/tCO_2e to \$133/tCO_2e.

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[8] Energy-related CO_2e emissions reduction is equivalent to energy reduction in percentage terms due to the constant emissions rate assumed for electricity generation.

Only 21 (3 %) building type-location combinations have a positive cost per metric ton of carbon reduction under the LEC for a ten-year study period (twelve for 3-story apartment buildings, six for 6-story dormitories, two for retail stores, and one for 3-story dormitories). The highest cost per ton of CO_2e reduction for the LEC occurs in cold climate zones due to lower energy savings.

On the contrary, 26 % of building type-location combinations for a one-year study period have positive costs per ton of CO_2e emissions. The shift of 71 % of building type-location combinations from positive costs for carbon reduction for a one-year study period to negative costs for a 10-year study period emphasizes the importance of using life-cycle costing in establishing the business case for energy efficient, carbon-reducing building technologies.

7. Conclusions

There are four conclusions from this analysis that contribute to the current debate over energy efficiency investments in buildings. First, conventional energy efficiency measures can be used to reduce energy use by 10 % to 20 % below *ASHRAE 90.1-2007* requirements on average without any significant alterations to the building design. These results give credence to the cost-effectiveness of building to meet *ASHRAE Advanced Energy Design Guide* recommendations, which advise how to construct buildings 30 % below *ASHRAE 90.1-1999* requirements.

Second, the LEC energy efficiency measures are life-cycle cost-effective relative to *ASHRAE 90.1-2007* requirements for some building types and locations for all study period lengths. This result contradicts recent research by Consol (2008) that found it cost-ineffective to improve energy efficiency by 30 % relative to *ASHRAE 90.1-2004*. The key difference is that this analysis uses an integrated design approach, which allows the HVAC system to be appropriately sized based on the HVAC loads of the building design.

Third, the investor's time horizon determines the cost-effective building design for many building type-location combinations. A short time horizon overlooks many of the realized costs of a building by ignoring the future costs of operating and maintaining the building. As the study period length increases, more building type-location combinations find it cost-effective to adopt a more energy efficient building design, with the greatest change occurring between the one-year to ten-year study periods.

Finally, these energy efficiency investments reduce the carbon footprint of the building by up to 25 % over a 10-year study period. The largest carbon reductions occur in states with the greatest energy reductions and states that rely heavily on coal-fired electricity generation, while states with large amounts of alternative energy use realize much smaller reductions.

In summary, investments in building energy efficiency measures recommended by whole building energy simulations are often cost-effective and have competitive annual investment returns in many areas of the United States, while improving efficiency and lowering a building's impact on climate change.

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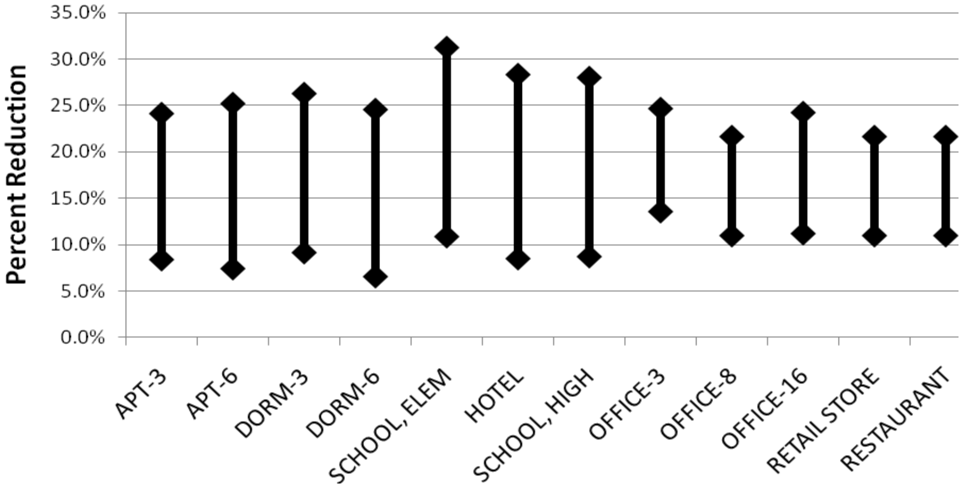

Figure 1: Annual energy use reduction relative to ASHRAE 90.1-2007

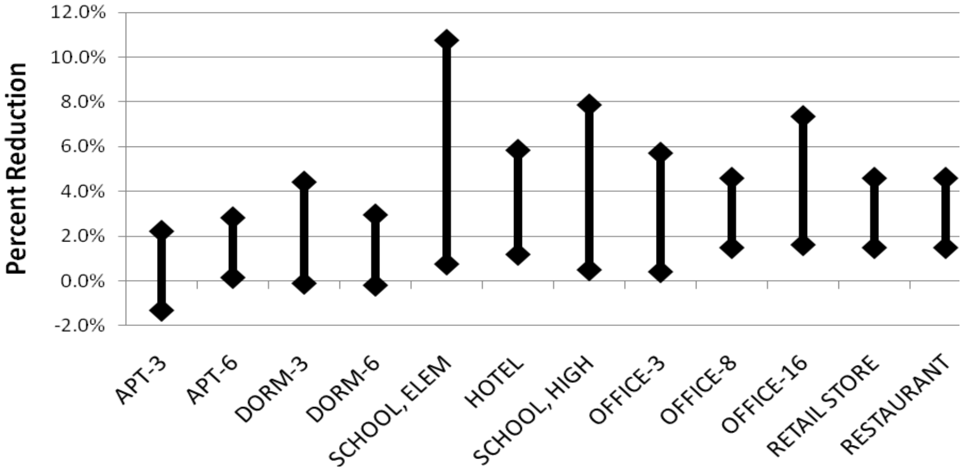

Figure 2: Life-cycle cost reduction relative to ASHRAE 90.1-2007

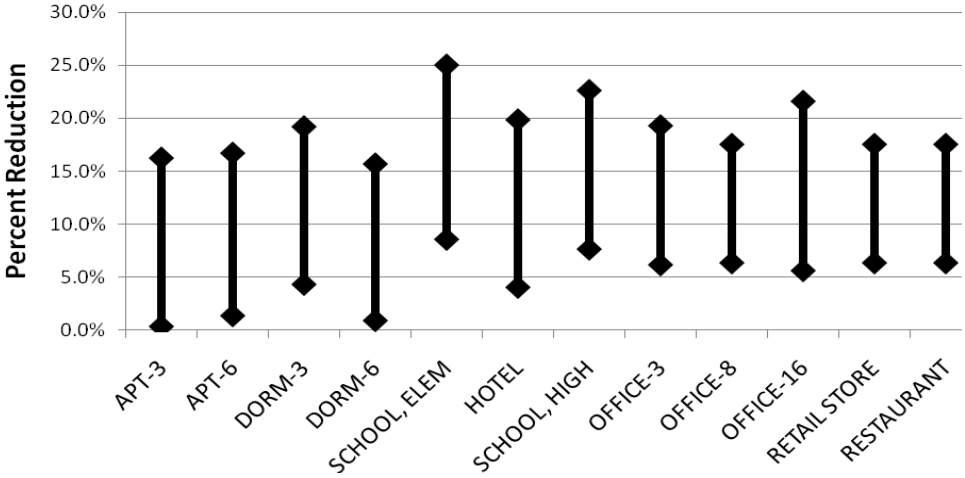

Figure 3: Life-cycle CO2e emissions reduction relative to ASHRAE 90.1-2007