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Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings

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ABSTRACT

Energy efficiency in new building construction has become a key target to lower nation-wide energy use. 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, and estimate the implications from a cost on energy-based carbon emissions. A total of 576 energy simulations are run for 12 prototypical buildings in 16 cities, with 3 building designs for each building-location combination. Simulated energy consumption and 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 20–30% on average and up to over 40% for some building types and locations. These reductions can often be done at negative life-cycle costs because the improved efficiencies allow the installation of smaller, cheaper HVAC equipment. These improvements not only save money and energy, but reduce a building's carbon footprint by 16% on average. A cost on carbon emissions from energy use increases the return on energy efficiency investments because energy is more expensive, making some cost-ineffective projects economically feasible.

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 easiest and 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, whole building energy simulations, state level emissions rates, and statewide average utility rates to determine the energy savings and cost-effectiveness of energy efficiency improvements, the resulting carbon emissions reduction, and the impact a cost on carbon would have on energy efficiency investment decisions.

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 20–30% on average and up to over 40% for some building types and locations. Although increasing energy efficiency usually increases 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 be lower for the more efficient building design because, through integrated design, the improved efficiency reduces the size of the heating and/or cooling system required to meet the peak heating and/or cooling loads.

The building type, local climate, and study period impact the financial benefits from energy efficiency improvements. The longer the study period, the greater the energy savings from energy efficiencies and the lower the life-cycle costs for more energy efficient building designs. The local climate impacts the appropriate integration of said improvements and the resulting savings from energy efficient designs. Energy efficiency varies by building type because of inherent design differences (e.g., number of stories, amount of glazing, and process loads).

The cost-effective energy efficiency improvements not only save money, but also reduce a building's carbon footprint. Carbon footprints are reduced by an average of 16% across all building types and sizes for a 10-year study period. These reductions are greater in buildings located in states that use large amounts of coal-fired electricity because of the large amounts of carbon

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Abbreviations: AIRR, adjusted internal rate of return; ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; BEES, building for environmental and economic sustainability; CBECS, commercial buildings energy consumption survey; EIA, U.S. Department of Energy's Energy Information Administration; eGRID, U.S. Environmental Protection Agency's *2007 Emissions and Generation Integrated Database*; EPA, Environmental Protection Agency; HVAC, heating, ventilation, and air conditioning; LCC, life-cycle costing; LEC, low energy case; LEED, leadership in energy and environmental design; M, R, and R, maintenance, repair, and replacement; MARR, minimum average rate of return; NIST, National Institute of Standards and Technology; NREL, National Renewable Energy Laboratory; tCO_2e, ton of carbon dioxide equivalent.

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dioxide emitted through coal combustion. A cost of carbon emissions is added to the building owner/operators energy costs based on the amount of energy use and type of fuel source. An additional cost on carbon increases the relative cost-effectiveness of energy efficiency improvements and potential carbon emissions reduction in new commercial buildings. Many energy efficiency measures are cost-effective without climate change policy, and should be implemented regardless of carbon restrictions. However, a cost on carbon results in a greater adjusted internal rate of return on energy efficiency investments, and makes energy efficiency projects more attractive relative to alternative investments. The change in cost-effectiveness is most prevalent in regions of the country that rely heavily on coal-fired power generation.

2. Literature review

Researchers at the NREL have written several papers based on whole building energy simulations of energy efficient building designs. Torcellini et al. [1] analyzes existing "high-performance" commercial buildings, and finds that current technology can "substantially change how buildings perform" by decreasing energy use by 25–70% below code, which can be realized through a "whole-building design approach." Griffith et al. [3] develops a methodology for modeling commercial building energy performance by simulating the U.S. building stock, and determines that a set of building types and locations are required to effectively represent the building stock. Weather, building design, and energy loads lead to a large variation in total site energy use (less than 50 kBtu/ft^2 yr to almost 250 kBtu/ft^2 yr). Griffith et al. [4] simulates the potential for net zero energy commercial buildings in the U.S., and determines that with current technologies and design practices, 62% of buildings and 47% of floor space could reach net-zero energy use. Improving the building envelope, lighting controls, plug and process loads, and HVAC system to the best currently available technologies would decrease energy use 43% below an ASHRAE 90.1-2004 compliant design. These studies are focused on energy use and energy consumption costs while ignoring life-cycle environmental and economic performance of the entire building.

ASHRAE has recently introduced *ASHRAE Advanced Energy Design Guides* [2] for several building types, which give recommendations on how to build a minimum of 30% better than *ASHRAE 90.1-1999*. The recommendations are based on the use of conventional technologies and design approaches, and vary by climate zone. There is no analysis regarding the cost-effectiveness of these recommendations or the resulting environmental flows.

The literature studies the costs of decreasing energy use in buildings, but focuses primarily on individual components instead of the entire building system. Cetiner and Ozkan [5] simulates different glass facade designs, and finds that the most efficient double facades are more energy efficient but are not cost-competitive with the most efficient single facade. Sekhar and Toon [6] finds double pane, low-e, reflective windows to be life-cycle cost-effective for a 20-story building. Carter and Keeler [7] determines that green roofs increase total net present value costs by 10–14%, and construction costs need to decrease by about 20% before green roofs will become cost-effective with conventional roof designs. In the Praditsmanont and Chungpaibulpatana [8] case study, increased insulation thickness has a payback period of only three to five years. Levinson and Akbari [9] simulates four buildings types for 236 cities across the U.S., and determines that cool roofs save on average \$0.356/m^2 of roof area annually across the U.S. The results vary by location, from \$0.126/m^2 to \$1.14/m^2. Consol [10] determines that designing commercial buildings to meet 30% above current energy efficiency standards is not cost-effective. This study is of limited value because it only considers one prototypical building design. The results from the literature are mixed regarding the cost-effectiveness of increased energy efficiency in commercial building design. A possible reason for this may be that none of the literature incorporates an integrated design approach.

The literature makes indirect links between energy use, environmental performance, and life-cycle cost through the analysis of LEED certified buildings. Newsham et al. [11] determines that, on average, LEED certified buildings save energy (18–39%) but with a large variation across individual buildings. Between 28% and 35% of LEED buildings actually use more energy per square foot than a comparable non-LEED building. The level of certification is not an indicator of increased energy efficiency, which implies a disconnect between environmental performance and energy use. Paumgartten [12] finds that the first costs of constructing a building to obtain LEED certification can easily be offset by the energy savings over a 40-year study period, and lead to savings as high as 250% of the up front costs.

While the topics of energy use, environmental performance, life-cycle costs, and integrated design have each been studied, no study combines all aspects together to determine the simultaneous impacts of energy efficient design on life-cycle costs, life-cycle carbon emissions, and energy use in an integrated building design context for commercial buildings across different climate zones.

3. Study design

Twelve building types are evaluated to consider a range of building sizes and energy intensities. For a prototypical building of each type, Table 1 shows the number of floors, size, and *CBECS* occupancy type, and includes the percentage of the U.S. commercial building stock floor space accounted for by the building type [13]. Table 1 shows the building types evaluated in this paper represent 46% of the U.S. commercial building stock floor space. A three-story and six-story dormitory, three-story and six-story apartment building, and 15-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 because office buildings represent the largest building category, 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 (5000–450 000 ft^2).

Life-cycle costing and life-cycle assessment are conducted over four different study period (i.e., analysis period) lengths: one 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 more 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 because of the assumptions made about costs and occupant behavior decades into the future, such as future energy costs and energy consumption.

For each building type, energy simulations are run for sixteen U.S. cities located in different *ASHRAE 90.1-2004* sub-climate zones [14].[1] These cities are chosen as representative cities based on geographical location, population, and data availability.[2]Fig. 1 is a map of the *ASHRAE 90.1-2004* climate zones. At least one city from

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[1] Climate zones range from hot (1) to cold (8), and some have sub-zones: moist (A), dry (B), and marine (C).

[2] Chosen cities are Amarillo, Texas, Anchorage, AK, Birmingham, AL, Honolulu, HI, Kansas City, MO, Los Angeles, CA, Miami, FL, Minneapolis Minnesota, New Orleans, LA, New York, NY, Phoenix, AZ, Pittsburgh, PA, Portland, ME, Salt Lake City, UT, San Francisco, CA, and Seattle, WA.

Table 1
Building characteristics of simulated building types.

Building type	Number of floors	Floor height m (ft)	Building size m^2 (ft^2)	Occupancy type	U.S. floor space (%)
Dormitory	3	3.66 (12.0)	2 323 (25 000)	Lodging	7.1
Dormitory	6	3.66 (12.0)	7 432 (80 000)		
Hotel	15	3.05 (10.0)	41 806 (450 000)		
Apartment	3	3.05 (10.0)	2 090 (22 500)		
Apartment	6	3.15 (10.3)	5 574 (60 000)		
School, Elementary	1	4.57 (15.0)	4 181 (45 000)	Education	13.8
School, High	2	4.57 (15.0)	12 077 (130 000)		
Office	3	3.66 (12.0)	1 858 (20 000)	Office	17.0
Office	8	3.66 (12.0)	7 432 (80 000)		
Office	16	3.05 (10.0)	24 155 (260 000)		
Retail store	1	4.27 (14.0)	743 (8 000)	Mercantile [a]	6.0
Restaurant	1	3.66 (12.0)	465 (5 000)	Food service	2.3

[a] Only includes non-mall floor area.

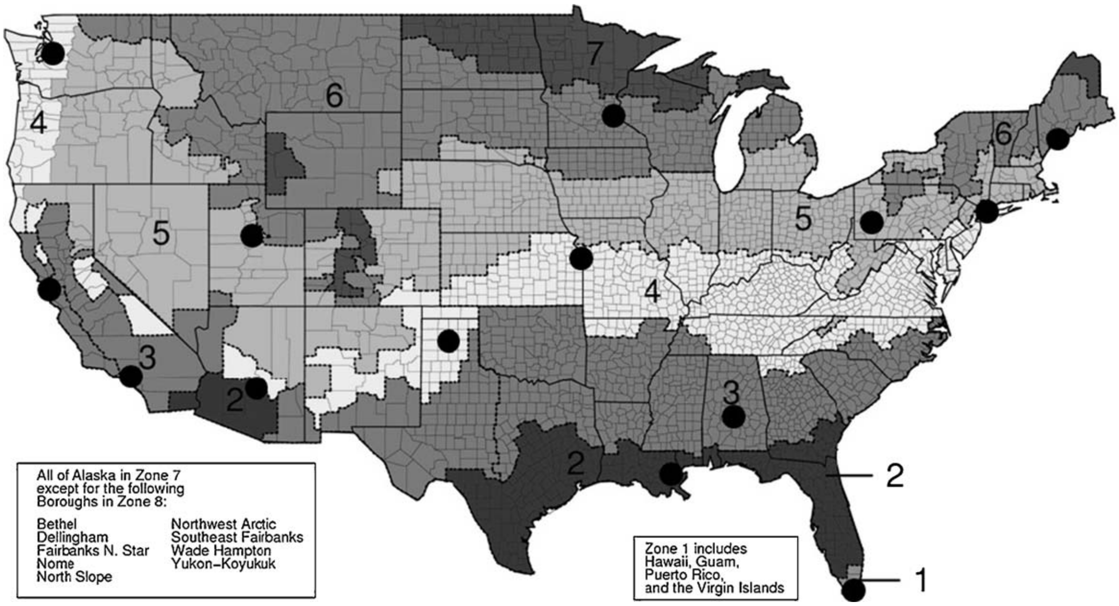

Fig. 1. *ASHRAE 90.1-2004* climate zones with cities from the analysis (not shown: Honolulu, HI in Zone 1; Anchorage, AK in Zone 7).

each of the sub-climate zones, excluding Zone 6B and Zone 8, is included in the analysis.[3]

4. Cost data

4.1. Building construction costs

Prototypical building and component assembly costs originate from the RS Means *CostWorks* online database [15]. The RS Means *CostWorks Square Foot Estimator* "default costs" for each building type, by component, are used to estimate the costs of a "prototypical building."[4] This prototypical building is used as a baseline to create a compliant building for each of the three energy efficiency design alternatives being considered in this analysis: designs to the *ASHRAE 90.1-2004* and *ASHRAE 90.1-2007* [16] energy efficiency standards, 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 three building designs. The components that are changed to meet *ASHRAE 90.1-2004* and *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 the energy standards. The 7.6 cm (3 in.) expanded polystyrene/perlite composite rigid insulation used as roof deck insulation in the prototypical buildings for offices, dormitories, and hotels is replaced with 7.6–10.2 cm (3–4 in.) of extruded polystyrene (EPS) rigid insulation depending on the *ASHRAE* standard and location. The polyisocyanurate roof deck insulation in the prototypical school buildings is increased from 5.1 cm (2 in.) to 6.4 cm to 7.6 cm (2.5–3 in.) depending on the standard and location. Fiberglass blanket insulation (38.1 cm (15 in.) wide) is used in the wall cavities, with an *R*-value varying by location from 11.0 to 18.9.[5] If the blanket insulation cannot meet the required

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[3] Climate Zone 6B and Zone 8 have a small portion of the total building stock due to the relatively sparse population distribution. The mountain west census division accounts for 6.5% of U.S. commercial buildings and 6% of U.S. commercial floor space. The only Zone 8 area in the United States is located in northeastern Alaska.

[4] 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.

[5] The smallest insulation value is R-11 because it is the lowest *R*-value available for blanket insulation.

R-value, then 1.3 cm (0.50 in.) or 1.9 cm (0.75 in.) polyisocyanurate rigid insulation is placed on the wall exterior.

Windows are altered in three ways: number of panes, low-emissivity (low-e) coatings, and solar heat gain control films. There are five different combinations of these three characteristics used in the cost estimates: (1) single pane, (2) single pane with solar heat gain control, (3) double pane, (4) double pane with solar heat gain control, and (5) double pane with solar heat gain control and a low-e coating. Some prototypical buildings have single pane windows that must be replaced by double pane windows. Double pane windows' cost data are available from the RS Means database. Low-e coatings are assumed to add an extra 15% to the window material costs while solar heat gain control films add an extra 10% to window material costs.[6]

The LEC design increases the thermal efficiency of insulation and windows while introducing daylighting and window overhangs. The new insulation requirements go beyond *ASHRAE 90.1-2007* by adding at least 1.3 cm (0.5 in.) of polyisocyanurate rigid insulation to the wall exterior for all climate zones. Rigid insulation is added because the blanket insulation already fills the 8.9 cm (3.5 in.) wall cavity. Roof deck insulation is increased for all climate zones by at least an R-5 continuous insulation (ci) value, for a total of R-20 ci to R-35 ci. The LEC requires schools to use 7.6–12.7 cm (3–5 in.) of polyisocyanurate rigid insulation and all other building types to use 7.6–17.8 cm (3–7 in.) of EPS rigid insulation. The LEC also adds daylighting controls and overhangs for window shading based on the *EnergyPlus* "Example File Generator" recommendations [17]. Daylighting is included for all building types at a cost of \$28.17/m^2 (\$2.62/ft^2).[7] Overhangs are priced at \$133.01/m^2 (\$12.37/ft^2), and are used in all but the coldest climate zones.[8]

The three designs alter the heating and cooling loads of the building, which leads to a change in the appropriate size of the HVAC system. Whole building energy simulations, which will be discussed in the next section, "autosize" the HVAC system to determine the smallest system that will still meet the ventilation load requirements. Smaller HVAC systems cost less to purchase and install, which can offset some or all of the additional costs from other measures to increase the building's energy efficiency. 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 costs.

Construction costs for each building in each location are determined by summing the baseline costs for the prototypical building and the changes in costs required to meet the alternative designs. National average construction costs are adjusted with the 2008 RS Means *CostWorks City Indexes* to control for local price variations. The "weighted average" city construction cost index is used to adjust the costs for the baseline prototypical building while "component" city indexes are used to adjust the costs for the design changes.[9]

The city-indexed construction costs do not account for contractor and architect fees. Once the indexed construction costs of the building have been calculated, it is multiplied by the contractor "mark-up" rate. The result is then multiplied by the architectural fees rate.[10] The result is the "first costs."

4.2. Maintenance, repair, and replacement costs

Component and building lifetimes and component repair requirements are collected from Towers et al. [19]. Building service lifetimes are assumed constant across climate zones: apartments last for 65 years; dormitories for 44 years; hotels, schools and office buildings for 41 years; retail stores for 38 years; and restaurants for 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 (13 years for replacement and 9 years for repairs in Miami) and long ones in cold climates (50 years for replacement and 33 years for repairs in Anchorage). The opposite is true of heating units with a lifespan of 18 years and repairs every 4 years in Anchorage and 50 years for replacement and 19 years for repairs in Miami.

Future costs are collected from two sources. The 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 et al. [19]. RS Means *CostWorks* is the source of M, R, and R costs for the components that change across building designs. In this analysis, only HVAC system components are replaced over the maximum 40-year study period. Windows have an assumed annual repair cost equal to replacing 1% of all window panes.

4.3. Energy costs

Utility rates for electricity and natural gas are obtained from the 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* [20] is used to obtain the average retail natural gas prices by state for 2007. Whole building energy simulations for the 192 building type-location combinations are run in *EnergyPlus 3.0* through its "Example File Generator" to obtain each buildings annual energy use for electricity and natural gas. 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.[11]

4.4. Building residual value

The 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 (minus any components replaced over the time period) multiplied by the ratio of the remaining life of the building to the service life of the building. The remaining residual value stems from the only component replaced over the study period, the HVAC equipment. The HVAC system components have different remaining lives – and thus residual values – than the building as a whole. 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 service life of the equipment.

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[6] The low-e and solar heat gain control film cost estimates are from the RS Means database.

[7] Cost of 10 fixtures per 92.9 m^2 (1000 ft^2) [15].

[8] Cost data obtained from Winiarski et al. [18].

[9] Component indexes used in the analysis are "thermal and moisture protection," "openings," "fire suppression, plumbing, and HVAC," and "electrical, communications, and utilities."

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

[11] The assumption of constant efficiency performance is made because it is unclear how building energy efficiency will deteriorate over time. Controlling for building temporal energy efficiency deterioration is beyond the scope of this paper, but is an excellent topic for future research.

5. Life-cycle cost analysis

Life-cycle costing (LCC) estimates the net present value of all relevant costs throughout the study period, including construction costs, maintenance, repair, and replacement costs, energy costs, and residual values.[12] LCC of buildings compares the costs from a "base case" building design costs from alternative building designs.

LCC is generally used to determine if future operational savings justify higher initial investments. Since the *ASHRAE 90.1-2004* design is compliant with the oldest energy standard studied, it is expected to lead to the lowest first costs and least energy efficient building. Both the *ASHRAE 90.1-2007* design and the LEC design are compared to the *ASHRAE 90.1-2004* design – the "base case" – to determine the LCC, carbon emissions, and carbon cost savings for each 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 and alternative design's LCCs. The adjusted internal rate of return (AIRR) is the annualized return on the energy efficiency investment costs.[13] 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, including M, R, and R costs, energy costs, and residual values, are discounted to their equivalent present values based on the relevant discount factors [22]. All costs and values are discounted based on the 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 costs over the study period. NIST's *BEES* software [23] is used to compute the life-cycle costs for the building design alternatives in compliance with ASTM Standards of Building Economics [24].

6. Environmental life-cycle assessment

The environmental flows from operational energy use are derived from two sources. The state-level average emissions per 3.414 MBtu/h (1 MW) of electricity for carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) are obtained from *eGRID 2007* [25]. *eGRID* integrates data from three sources: emissions data from the EPA, generation data and fuel mixes from the EIA, and electric generating company data from the Federal Energy Regulatory Commission. Electricity emissions data (excluding CO_2, SO_2, and NO_x) and 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 [26] that have been adapted to the NIST *BEES* life-cycle assessment framework. The adapted Environmental Input–Output Tables quantify resource inputs and pollutant flows for 172 substances based on national average flows per dollar spent in the U.S. construction industry's commercial and institutional building sector.

The *BEES* software is used to assess the life-cycle energy and material flow from construction and operation of the building and estimate its carbon footprint. Life-cycle carbon emissions (including all greenhouse gas emissions) are highlighted in this paper to allow for a direct comparison across building types, designs, and locations. Carbon emissions from operational energy use are reported separately to study how a cost on carbon impacts a building's life-cycle costs.

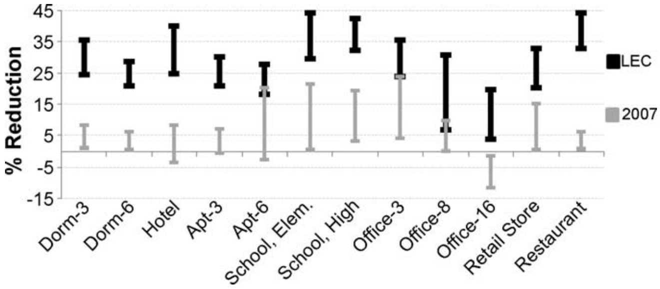

Fig. 2. Annual energy use savings relative to *ASHRAE 90.1-2004* compliant design, by building type.

7. Results

Twelve building types, representing a range of building sizes and energy intensities, are evaluated over four study period lengths for three alternative building designs. For each building type, energy simulations are run for sixteen U.S. cities located across different sub-climate zones. The resulting energy use and energy costs, life-cycle costs, carbon emissions, and carbon cost implications are discussed below.

7.1. Energy use and costs

ASHRAE 90.1-2004 compliance is expected to lead to the least efficient design because newer standards are expected to lead to higher energy efficiency. However, the change in total operational energy use for the *ASHRAE 90.1-2007* design relative to the base case *ASHRAE 90.1-2004* design for all building types range from an increase of 11.5% to a decrease of 23.8% with a mean decrease of only 3.2% for a one-year study period. Fig. 2 shows that not only are most reductions relatively small, the use of *ASHRAE 90.1-2007* over *ASHRAE 90.1-2004* does not necessarily lead to energy use reductions due to minor relaxation of glazing performance requirements for some climate zones.[14]

As is expected, increasing the energy efficiency of a building beyond the *ASHRAE* standard requirements decreases annual energy use. Fig. 2 shows the LEC leads to reductions of 3.2–44.2% relative to the base case *ASHRAE 90.1-2004* design for a one-year study period.[15] Nine of the twelve building types have an energy savings greater than 20% for all locations while eight of the twelve have at least one location that has a 30% or greater energy reduction. Five building types have average energy reductions over 30%. A 30% reduction in energy use for most building types relative to *ASHRAE 90.1-2004* appears to be achievable and reasonably straightforward to reach through 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 price projections, and building process loads. The smallest savings in energy and energy costs occurs in colder cities, Anchorage and Minneapolis, while the greatest savings occurs in cities located in more

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[12] Fuller and Petersen [21].

[13] The AIRR is preferred over the IRR because it adjusts the rate of return for reinvestment of interim receipts.

[14] Each figure plot the range between the maximum and minimum values by building type.

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

temperate climates. There is a slight variation in annual energy cost savings across study period lengths because fuel price escalation rates vary over time. However, these differences do not alter the interpretations from the results.

7.2. Life-cycle costs

The study period length is important in determining which design alternative is the most cost-effective. The *ASHRAE 90.1-2004* design is the most cost-effective choice for only 31 of the 192 building type-location combinations for a one-year study period while *ASHRAE 90.1-2007* is the preferred choice for 65 combinations. However, as already discussed *ASHRAE 90.1-2007* is sometimes not as energy efficient as *ASHRAE 90.1-2004* depending on the location and building type. Overall, the *ASHRAE 90.1-2004* or *ASHRAE 90.1-2007* designs are the most cost-effective choice, relative to the LEC, for only 96 of the 192 building type-location combinations (50%) 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 10-year study period, the LEC is most cost-effective for 69%, or 37 additional building type-location combinations. This number increases to 88% for a 25-year study period and 93% for a 40-year study period. The LEC design simultaneously decreases building energy use and life-cycle costs for these building type-location combinations. These results support the use of stricter standards for building energy efficiency because social gains from reduction in fossil fuel use and carbon emissions will occur at a negative cost to the building owner/operator.

Different building types will realize different levels of savings. As seen in Fig. 3, the LEC is cost-effective over a 10-year study period in all locations for dormitories, high schools, hotels, six-story apartments, restaurants, and eight-story office buildings. The LEC is cost-ineffective for two building types.[16] Sixteen-story office buildings have relatively high electrical plug loads, which decrease the portion of total energy use that can be reduced with energy efficiency improvements. Retail stores realize a relatively small reduction in HVAC size requirements. Savings in HVAC capital costs are not significant enough to offset the initial investments costs from additional insulation.

7.3. 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 other investment options. For this reason, the AIRR of these investments is estimated for comparison with rates of return for alternative investments. As already discussed, the AIRR is a measure of economic worth that is used to compare investment options on an annual percentage yield basis. 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 are greater than the costs for more insulation, daylighting controls, and overhangs added to the *ASHRAE 90.1-2004* design. For these buildings, there is a compelling economic case for improved energy efficiency even over a one-year study period. Nearly all locations in the following building types have infinite returns in the LEC relative to *ASHRAE 90.1-2004* over a one-year study period: both dormitory buildings and eight-story office buildings (100%), high schools (88%), and both apartment buildings (81%). Restaurants (56%), elementary schools (56%), and hotels (19%) have some infinite returns as well. Of the 192 building type-location combinations, 54% have infinite returns over a one-year study period; this figure remains relatively unchanged over other study period lengths.

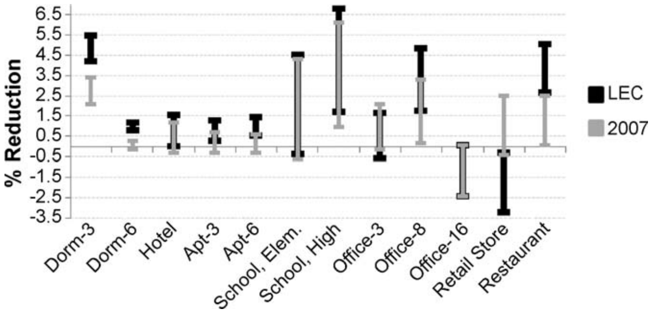

Fig. 3. Life-cycle cost savings relative to *ASHRAE 90.1-2004* compliant design over a 10-year study period, by building type.

Negative AIRRs indicate a negative return on investment. As the study period length increases, the number of building type-location combinations with negative AIRRs decreases. For a one-year study period, 41% of AIRRs are negative. This value drops quickly to 20% at 10 years, 8% at 25 years, and 4% at 40 years. 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 192 building type-location combinations analyzed for a 1-year study period, 111 have an AIRR above 3.0%.[17] This increases to 153 with a 10-year, 177 with a 25-year, and 184 with a 40-year study period. This is an increase from 58% to 96% of building type-location combinations. Over 56% for all study periods have an AIRR greater than 10%, which is higher than the inflation-adjusted annual return from U.S. stocks of around 7% [27].

7.4. Life-cycle carbon emissions

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 cases for both the *ASHRAE 90.1-2007* and LEC designs. Fig. 4 shows the range of CO_2e emissions reduction for each design alternative over a 10-year study period. For the *ASHRAE 90.1-2007* design, only one building type averages an increase in CO_2e emissions (16-story office building) over a 10-year study period. For the LEC over this period, the change in CO_2e emissions ranges from a 0.5% increase to a 32.6% decrease depending on building type and location, with a mean of -16%. Life-cycle CO_2e reductions are lower, in percentage terms, than operational energy CO_2e reductions because more material is required to make some energy efficiency improvements.[18]

Emissions reduction is highest for cities that have a combination of (1) reductions in energy use of at least 25% and (2) consumption of electricity based on at least 35% coal-fired generation. Cities such as Salt Lake City, Amarillo, Kansas City, Minneapolis, and Pittsburgh have the most significant CO_2e

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[16] The interpretations across building types is the same for other study period lengths.

[17] In 2008, the MARR for energy-related investments in federal buildings was 3.0% in real terms.

[18] Changes in materials-related CO_2e emissions average a decrease of 6% for a 10-year study period versus a decrease of 29% for energy-related CO_2e emissions.

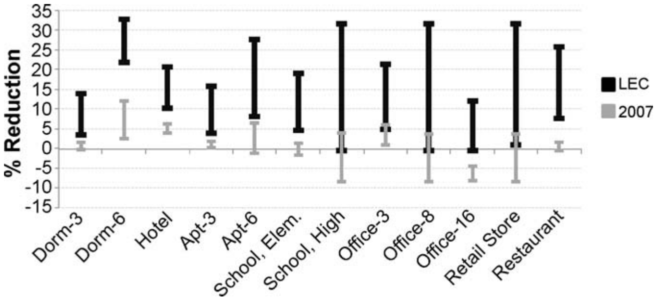

Fig. 4. Life-cycle CO_2e emissions reduction relative to *ASHRAE 90.1-2004* compliant design over a 10-year study period, by building type.

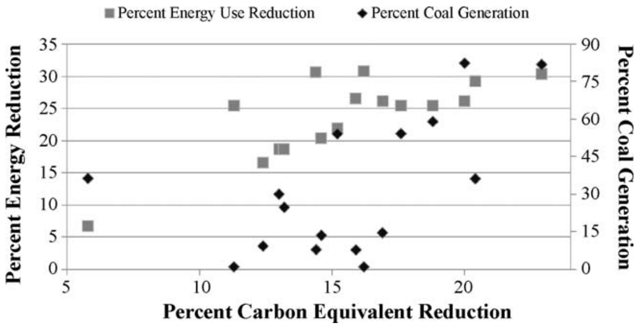

Fig. 5. Life-cycle CO_2e emissions reduction relative to energy use reduction and coal-fired generation levels.

reductions. Each has a middle-to-high ranking in both categories relative to the other locations. The opposite can be said about states with middle-to-low rankings in both categories, which are the cities with the lowest carbon emissions reductions. To further support the point, a regression was run with percent energy savings and percent of generation originating from coal explaining the percent of carbon emissions reduction. Both are statistically significant at the 1% level and the R^2 is 0.859, implying that 86% of the variation in the percent of carbon reduction can be explained by these two factors. This correlation between emissions reduction, energy use reduction, and coal-based generation levels can be seen visually in Fig. 5.

The cost of reducing carbon emissions is negative for all locations with a reduction in life-cycle costs, which accounts for 80% of building type-location combinations over a 10-year study period. The mean cost under the LEC for a 10-year study period is $-\$108/tCO_2e$ with a wide range of $-\$5134/tCO_2e$ to $\$5167/tCO_2e$. Only 28 building type-location combinations have a positive cost per metric ton of carbon reduction under the LEC for a 10-year study period (14 each for 16-story office buildings and retail stores). The highest costs per ton of CO_2e reduction for the LEC occurs in the cold climate zones because of the lower energy savings and on the West Coast (marine climate zones) because of the low carbon emissions rates from electricity use in those states.

Study period length is an important determinant of the cost per ton of CO_2e reduction. For a one-year study period, 27% of building type-location combinations have positive costs per reduced ton of emissions. This value decreases to 20% for a 10-year, 8% for a 25-year, and 4% for a 40-year study period. The mean cost per ton drops from over $\$1000/tCO_2e$ for a one-year study period to $-\$108/tCO_2e$ for a 10-year study period. This shift from a high positive cost to a negative cost in just 10 years highlights the importance of life-cycle costing in establishing the business case for carbon-reducing technologies in building design.

7.5. Carbon costs

Introducing a cost on carbon emissions changes the cost-effectiveness of energy efficiency measures.[19] A range of carbon costs is considered: $\$10/tCO_2e$, $\$20/tCO_2e$, $\$30/tCO_2e$, $\$40/tCO_2e$, and $\$50/tCO_2e$ emissions – but only the results from $\$50/tCO_2e$ are reported here to show the maximum estimated impacts in the analysis.[20] It is assumed that electricity producers and natural gas distributors pass 100% of the carbon costs through to the consumer for each unit of electricity or gas consumed. The cost attributable to electricity production that is lost in transmission of electricity is assumed not to be passed on to the consumer.

A cost on carbon emissions increases the life-cycle costs for all three design alternatives, with less efficient designs realizing the largest increase. Increasing energy efficiency decreases life-cycle costs associated with energy use by a larger amount than if there is no cost on carbon. For each unit of energy saved, there is a reduction of both the marginal cost of purchasing the energy and a reduction of the cost associated with the carbon in that unit of energy.

Under the LEC, the change in life-cycle costs from adding a $\$50/tCO_2e$ emissions cost can be large relative to the total life-cycle costs of a building: a mean of -3.1% and a range of 5.7% to -13.0% over a 10-year study period. The carbon costs impact the return on energy efficiency investments regardless of the chosen MARR, especially for the longer study period lengths. The number of building type-location combinations that have an AIRR greater than the federal MARR for energy-related investments (3%) increases from 129 to 143, a 7% point increase, for a 10-year study period. The increase for a 25-year study period is even greater, a 9% point increase. No matter what the expected return (MARR), carbon costs will make a difference. The number of combinations with an AIRR greater than 10% over a 10-year study period increases by about the same amount, an 8% point increase.

The energy efficiency measures studied are often cost-effective without carbon restrictions. However, a cost on carbon emissions increases the return on investment for all measures, and could make otherwise cost-ineffective measures cost-effective. Locations with significant coal-based electricity, such as the central United States, see the greatest carbon cost savings through improved energy efficiency. A carbon cost has minimal cost impacts on locations with large amounts of alternative energy, such as West Coast cities, because the marginal CO_2e reduction from energy efficiency improvements is small.

8. Conclusions

There are five conclusions from this analysis that are relevant to the current debate over energy efficiency investments in buildings. First, conventional energy efficiency measures can be used to reduce energy use by 20–30% 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's* recommendations.

Second, the group of energy efficiency measures recommended in the LEC for the building types studied are life-cycle cost-effective for some building types and locations regardless of study period length. This result contradicts recent research using the flawed simple payback method that found it cost-ineffective to improve energy efficiency by 30%.[21] The key difference is that the integrated

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[19] Higher material costs as a result of higher energy costs in production from the cost on carbon emissions are excluded from this analysis.

[20] The impacts from $\$10/tCO_2e$ to $\$40/tCO_2e$ are a linear fraction of the $\$50/tCO_2e$ impacts (e.g., a \$40 carbon cost has 80% of the impact of a \$50 cost).

[21] Consol [10].

design approach taken in this analysis allows the HVAC system to be appropriately sized based on the heating and cooling loads of the design.

Third, the investor's time horizon determines the cost-effective building design for many building type-location combinations. Much of the realized costs of a building are overlooked when the future costs of operating and maintaining the building are not taken into account. As the study period length increases, more building type-location combinations find it cost-effective to adopt the most energy efficient building design alternative, with the greatest change occurring between the 1–10-year and 10–25-year study periods.

Fourth, these energy efficiency investments reduce the carbon footprint of the building by as much as 32% 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.

Finally, the introduction of a cost on carbon increases the rate of return on energy efficiency investments across all locations and building types, often turning the LEC into the most cost-effective choice. The greatest incentives to reduce energy use occur in the same states that use the most electricity from coal-fired generation.

The results lead to several implications of interest to government decision-makers. 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. A cost on carbon emissions further increases the return on investment for energy efficiency improvements, improving the business case by increasing the likelihood that the energy efficiency investments will be the best investment alternative. These increases in return on investment are greatest in states that have the largest carbon emission rates.

9. Limitations and future directions

There are a number of limitations in the scope and precision of this analysis that will be addressed in future work. This is a first application of a new framework to analyze the cost-effectiveness and carbon cost implications of integrated building energy efficiency designs. The approach can be expanded or improved in the near term by expanding the scale and scope of the building types, locations, and design alternatives studied and by developing more detailed, precise, and relevant data. NIST is currently incorporating these enhancements into its databases and BEES analysis framework. Once these improvements are made, NIST hopes to expand the framework by introducing the following: more precise environmental flow estimates, alternative electricity pricing schemes, project financing, government financial incentives, building temporal efficiency deterioration, and enacted climate change legislation impacts.

While there are currently limitations to this analysis, the framework it establishes provides a solid starting point for future research into the cost-effectiveness of integrated, energy efficient building designs, their carbon footprints, and the cost-effectiveness impacts of carbon costs.

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