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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.

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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

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

[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.