A Methodology to Quantify the Impact of Building Energy Code Upgrades on Building Energy Savings: A Case Study on Small Offices

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Abstract

In the United States, building energy codes, which set minimum efficiency requirements for new buildings, are commonly used and periodically updated to improve energy efficiency of new buildings and reduce their energy consumption over their service life. Knowing the savings impacts of the energy efficiency measures (EEMs) in the codes is very helpful for jurisdictions considering adoption of newer codes. This paper proposes a novel methodology to analyse and rank the impacts of individual EEMs on commercial buildings while accounting for the interactions of the EEMs. A case study is performed on a prototypical small office building in three climate zones. The impacts of multiple EEMs, representing changes in requirements through five editions of ASHRAE 90.1, were evaluated. The results indicate that the lighting-related EEMs have the most significant impacts on energy savings across all three climate zones; the night setback control requirement for cooling generates high savings in hot climates; and the improved envelope insulation and outdoor air control requirements can bring important savings for buildings in cold climates. These findings can help policymakers understand the importance of the EEMs and make informed decisions on their code adoption.

Introduction

The Annual Energy Outlook 2018 showed that the commercial building sector consumed approximately 18% of U.S. primary energy in 2017 (EIA 2018). The annual energy consumption of U.S. commercial buildings is projected to increase by 12.3% by 2050 based on historical building energy data. Recent studies on the analysis of high-efficiency building technologies demonstrated their significant potential to reduce energy consumption (Glazer 2016; Griffith et al. 2007; Kneifel 2010, 2011).

In the United States, building energy codes set minimum efficiency requirements for new and retrofit buildings, assuring reductions in energy use and emissions over the life of the building. As a national model energy code for commercial and multifamily high-rise residential buildings, ANSI/ASHRAE/IES Standard 90.1 is periodically updated to require new and cost-effective technologies to improve building energy efficiency (ASHRAE 2004, 2007, 2010, 2013, 2016).

To evaluate the energy savings of Standard 90.1, the U.S. Department of Energy (U.S. DOE) created a set of prototypical building energy models by using building energy simulation programs. The model set contains 16 commercial and multifamily prototypes in 15 climate zones in EnergyPlus to support development and energy savings evaluation of the standards and advise future development. The published models include code-compliant prototypes to meet requirements in ASHRAE Standard 90.1 (ASHRAE 2004, 2007, 2010, 2013, and 2016) and the International Energy Conservation Code (IECC 2006, 2009, 2012, and 2015).

To support the adoption of new code editions by state building departments or local jurisdictions, the U.S. DOE is required by law (under the Energy Conservation and Production Act, or ECPA) to issue a determination as to whether the latest edition of ASHRAE Standard 90.1 will improve energy efficiency compared to the previous edition. The U.S. DOE’s determination reports identified 44 changes from 90.1-2004 to 90.1-2007, 109 changes from 90.1-2007 to 90.1-2010, 110 changes from 90.1-2010 to 90.1-2013, and 121 changes from 90.1-2013 to 90.1-2016, for a total of 384 changes from 2004 through 2016 (Thornton et al. 2011; Halverson et al. 2014; DOE 2016). However, these determination reports only provide information on overall savings, not the impacts of individual changes. Hart and Xie (2014) published an analysis report that broke down building energy uses by end use to show the impacts of the combined code changes in the last few editions. The analysis shows the reductions by end use from 90.1-2004 to 90.1-2013, but it does not distinguish the contributions from the individual energy efficiency measures (EEMs). Such information is particularly important for jurisdictions when they consider partially adopting a code or making their state-specific code changes.

Building energy models are effective for evaluating the impact of energy code EEMs on energy consumption in commercial buildings because they allow one or more EEMs to be changed while other parts of the building remain the same. Some researchers have used building energy models in building energy analyses to identify impactful EEMs for energy consumption. Tian (2013) reviewed the existing work to identify sensitive EEMs for building energy consumption by using sensitivity analysis methods. Eisenhower et al. (2012) did sensitivity decomposition of building energy models to identify how the EEMs impact energy consumption. These sensitivity analysis approaches usually require building samples to evaluate the sensitivity of EEMs within their uncertainty ranges. However, current methods are not suitable for evaluating the impact of EEMs during energy code edition upgrades, for two primary reasons. First, the building energy code EEMs are discrete, and it is unsuitable to select samples in the ranges of uncertainty. Second, the sets of EEMs that have different values between two adjacent codes are not consistent. Thus, it is not suitable to use sensitivity analysis methods where the EEMs need to have the same number of levels. To address these limitations, we propose a new methodology to analyse the individual and interactive impacts of the EEMs based on the values presented in building energy codes.

As mentioned earlier, there were 384 code changes from 90.1-2004 to 90.1-2016. In this study, the changes are embodied in the different editions of the DOE Commercial Prototype Building Models (DOE 2018). This paper proposes a novel methodology to analyse how energy code EEMs impact site energy use intensity (EUI) and applies this methodology to small office buildings across five ASHRAE 90.1 editions. The methodology consists of forward and backward analyses to evaluate the individual and interactive impacts of energy code EEMs. As a case study, 15 small office building models are selected from the DOE Commercial Prototype Building Energy Models. The models are in ASHRAE climate zones 1A, 5A, and 8, and meet the requirements of ASHRAE Standard 90.1-2004, 90.1-2007, 90.1-2010, 90.1-2013, and 90.1-2016. All the EEMs with different values in consecutive editions of ASHRAE Standard 90.1 are identified. By using the proposed methodology and the small office models, we compare EUIs to determine the EEMs that have the greatest impact through ASHRAE 90.1 upgrades.

Methodology

The proposed methodology consists of four steps (Figure 1). The first step is to identify which EEMs are revised in consecutive energy code editions. These EEM changes are encompassed in representative building models for each energy code edition, such as the DOE Commercial Prototype Building Models. The second step is to conduct the forward-process simulation. In this step, we can identify changes in site EUI when one EEM is updated to meet the requirements of the newer building energy code. The third step is to conduct the backward-process simulation. In this step, we can identify changes in site EUI when one EEM is degenerated to meet the requirements of the older building energy code. Based on the site EUI changes identified in steps 2 and 3, the fourth step is to analyse the impacts that these EEMs have on the building site EUI.

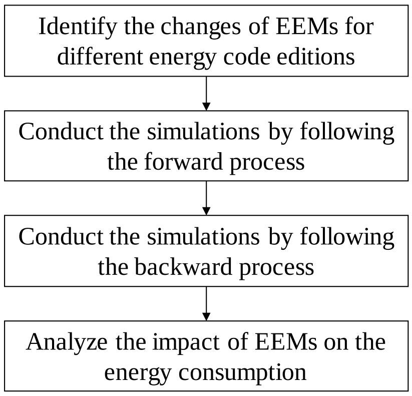


Figure 1: Methodology.

Changes of the EEMs

To evaluate the degree of impact that individual EEMs have on site EUI, the first task is to identify which EEMs have changed between consecutive editions of building energy codes. A building energy model consists of a large set of EEMs, and the uncertainties of the EEMs have an aggregated impact on the uncertainty of energy data. The impact of EEMs on building energy consumption is also compounded when various energy code editions are considered, since different values are provided for some EEMs. To identify the changes to EEMs, we compared the DOE Commercial Prototype Building Models, which mirror the different editions of ASHRAE 90.1. The EEM changes are summarized in Table 2.

Forward and Backward Processes

We propose two processes, forward and backward, which rank EEMs by their relative impact on site EUI and together fully define the area of potential site EUI values between two adjacent energy code editions. There are two main advantages to this methodology. First, both the individual and the interactive impacts of EEMs on building site EUI are considered. If we use the one-at-a-time method to adjust only one EEM's value at a time, we can only identify the individual impact of EEMs on building site EUI. Second, this methodology has a relatively low computational time compared with performing exhaustive simulations. For instance, 10 EEMs are changed between two models. We would need to run 2^{10} simulations (1,024 simulations) to exhaust all possibilities. By using this methodology, we only need to run $[2 \times \sum_{i=1}^{10} i]$ simulations (110 simulations).

To demonstrate the forward and backward processes, we assume that there are three EEMs with indices of 1, 2, and 3 that have different values in two energy code editions (old code and new code). The baseline is the building energy model that meets the requirements of the old code and is naturally assigned a site EUI reduction of 0 MJ/m^2. The same baseline is used in both the forward and backward processes.

In the forward process, we improve the EEMs from following the old code to the new code (Figure 2). First, we calculate the site EUI of the baseline model. Then, we conduct three simulations to improve indices 1, 2, and 3 and update the model with index 1 since it reduces the site

EUI the most. In the next step, we improve indices 2 and 3 and update the model with index 2 since it causes more site EUI reduction than index 3. Finally, we update index 3. This ranking process allows us to easily identify which EEMs had the greatest impact on site EUI, which will be discussed further in the *Impact Analysis*. In this case, the baseline and three EEMs result in a total of seven simulations. The calculations in the forward process are expressed in equation (1) below.

$$\begin{cases} Y(X_1) = f_1(X_1) - 0, where\ Y(X_1) = \max_{i=1,2,\ldots,n}\big(Y(X_i)\big) \\ Y(X_2) = Y(X_1) + f_2(X_2) + f_{1,2}(X_1, X_2), where\ Y(X_2) - Y(X_1) = \max_{i=2,3,,\ldots,n}\big(Y(X_i) - Y(X_1)\big) \\ \vdots \\ Y(X_n) = Y(X_{n-1}) + f_n(X_n) + \sum_{i=1}^{n-1} f_{i,n}(X_i, X_n) + \cdots + f_{1,2,\ldots,n}(X_1, X_2, \ldots, X_n) \end{cases} \quad (1)$$

$$\begin{cases} Y(\overline{X_1'}) = Y(X_n) - \left(f_1'(X_1') + \sum_{i=2}^{n} f_{1,i}'(X_1', X_i') + \cdots + f_{1,2,\ldots,n}'(X_1', X_2', \ldots, X_n')\right), where\ Y(X_n) - Y(\overline{X_1'}) = \max_{i=1,2,\ldots,n}\big(Y(X_n) - Y(\overline{X_i'})\big) \\ Y(\overline{X_2'}) = Y(\overline{X_1'}) - \left(f_2'(X_2') + \sum_{i=3}^{n} f_{2,i}'(X_2', X_i') + \cdots + f_{2,3,\ldots,n}'(X_2', X_3', \ldots, X_n')\right), where\ Y(\overline{X_1'}) - Y(\overline{X_2'}) = \max_{i=2,3,,\ldots,n}\big(Y(\overline{X_1'}) - Y(\overline{X_i'})\big) \\ \vdots \\ Y(\overline{X_n'}) = Y(\overline{X_{n-1}'}) - f_n'(X_n') \end{cases} \quad (2)$$

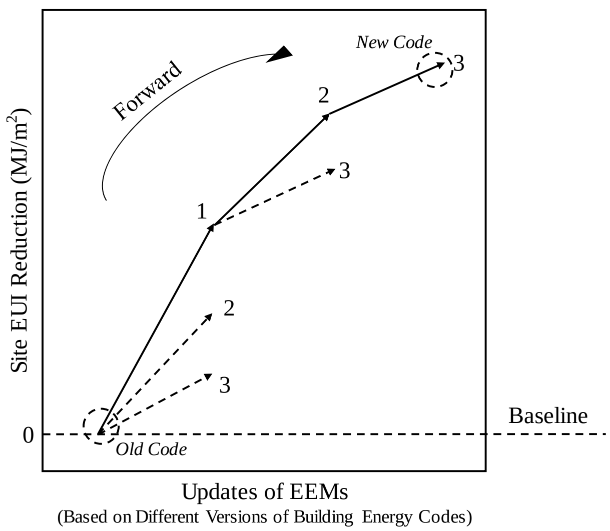


Figure 2: Order of EEM selection (forward process).

In equation (1), n is the total number of EEMs. X_i is the improvement of EEM $i = 1,2, \ldots, n$. We assume that X_1 changes the site EUI the most, then X_2, then the others. $Y(X_i)$ is site EUI reduction compared with the baseline after improving EEM *i*; $f_i(X_i)$ is the individual contribution of EEM *i* to the site EUI reduction when improving EEM *i*, while $f_{i,\ldots,j}(X_i, \ldots, X_j)$ is the interactive impact of EEMs *i* through *j* on site EUI reduction when improving EEMs *i* through *j*. In other words, the combined impact of several EEMs is the sum of these EEMs' individual impacts and interactive impacts.

In the backward process, we degenerate the EEMs from following the new code to the old code (Figure 3). In the first step, we start with the new code model from the forward process and conduct three simulations to degenerate indices 1, 2, and 3. Similar to the forward process, only the EEM that obtains the greatest site EUI reduction is degenerated in the first step (index 1). This is followed by the EEM with the second greatest site EUI reduction in the next step (index 2). Finally, index 3 is degenerated, completing the loop back to the baseline model. In this case, the three EEMs result in six simulations. The calculations in the backward process are expressed in equation (2) above.

In equation (2), n is the total number of EEMs. X_i' is the degeneration of EEMs. X_i' is the degeneration of EEM $i = 1,2, \ldots, n$. We assume that X_1' changes the site EUI the most, then X_2', then the others. $Y(\overline{X_i'})$ is site EUI reduction compared with the baseline after degenerating EEM *i*; $f_i'(X_i')$ is the individual contribution of EEM *i* to site EUI reduction when degenerating EEM *i*; $f_{i,\ldots,j}'(X_i', \ldots, X_j')$ is the interactive impact of EEMs *i* through *j* on site EUI reduction when degenerating EEMs *i* through *j*. Again, the combined impact of several EEMs is the sum of these EEMs' individual impacts and interactive impacts.

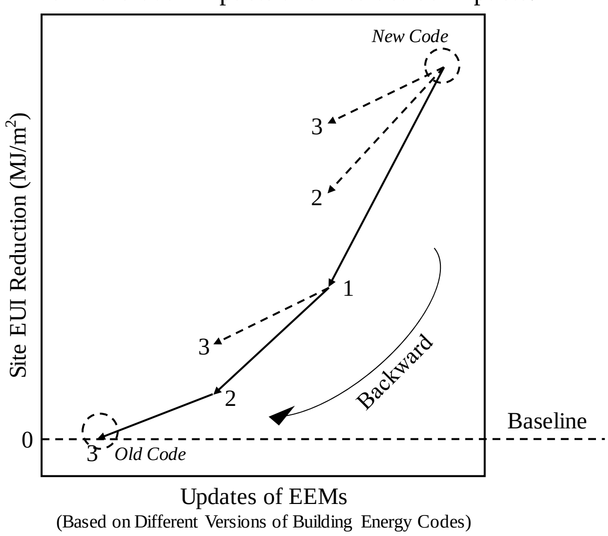


Figure 3: Order of EEM selection (backward process).

Impact Analysis

The results of both the forward and backward processes are used to evaluate the impact of each EEM on site EUI

(Figure 4). During both forward and backward processes, the prior EEM has greater impact than later ones. It is worth noting that the orders of the EEMs are possibly different in the forward and backward processes. In equation (1), the decrease of site EUI has only one term, $f_1(X_1)$, when improving EEM 1. In equation (2), the increase of site EUI has $f_1'(X_1') + \sum_{i=2}^{n} f_{1,i}'(X_1', X_i') + \cdots + f_{1,2,\ldots,n}'(X_1', X_2', \ldots, X_n')$ when degenerating EEM 1, which includes interactive impact of EEM 1 and other EEMs. Thus, based on the two processes, we can evaluate both the individual and interactive impacts of EEMs on building site EUI.

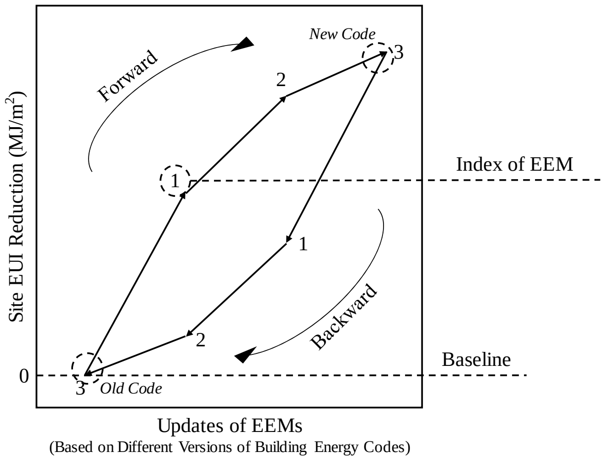


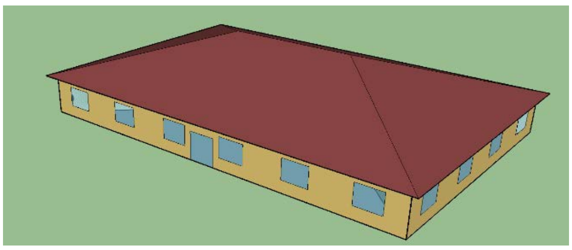
Figure 4: Combined forward and backward processes for impact analysis.

Model Description

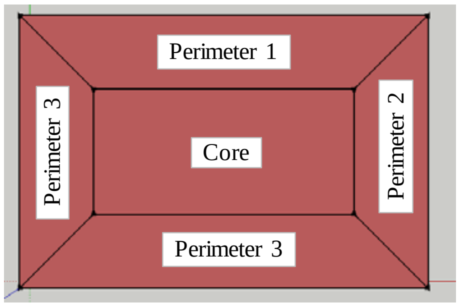
To evaluate the proposed methodology, we apply it to prototypical small office building models in three climate zones (1A, 5A, and 8) to analyze the impact of the EEMs on site EUI. The baseline building models are collected from the DOE Commercial Prototype Building Models and meet the requirements of ASHRAE Standard 90.1-2004, 90.1-2007, 90.1-2010, 90.1-2013, and 90.1-2016.

General Description

Figure 5 displays the geometry of the prototypical small office building models. While the models represent different climate zones and editions of ASHRAE 90.1, they have the same geometry. The building model is rectangular in shape, has one story, and contains five conditioned thermal zones. The windows are evenly distributed along the four exterior walls, and the door faces south.



(a) Building Shape



(b) Thermal Zoning

Figure 5: Geometry (a) and thermal zones (b) of small office building model.

Table 1 lists information about the location, geometry, envelopes, and systems. Honolulu, Buffalo, and Fairbanks are selected as typical cities for climate zones 1A, 5A, and 8, respectively. The total floor area is 510.97 m^2 for each model. The window-to-wall ratio is 24.4% for the south façade and 19.8% for the other three orientations. The exterior wall type is wood frame, and the roof construction is an attic with wood joists. Further, the building models use an air-source heat pump for heating and cooling and an electric water heater for domestic hot water.

Table 1: Description of small office building models.

Item	Description
Location	Climate zone 1A: Honolulu, HI (very hot, humid) Climate zone 5A: Buffalo, NY (cool, humid) Climate zone 8: Fairbanks, AK (subarctic)
Total Floor Area	510.97 m^2 (27.68 m × 18.44 m)
Aspect Ratio	1.5
Number of Floors	1
Window-to-Wall Ratio	24.4% (south) 19.8% (north, west, east)
Window Locations	Evenly distributed along four façades
Shading	None
Thermal Zoning	Perimeter zone depth: 5 m Four perimeter zones, one core zone, and an attic zone Percentages of floor area: perimeter 70%, core 30%
Floor to ceiling height	3.05 m
Exterior Wall Type	Wood-frame walls
Roof Type	Attic roof with wood joists
Window Type	Hypothetical window with weighted U-factor and solar heat gain coefficient
Foundation	Slab-on-grade floors (unheated)
HVAC Heating Type	Air-source heat pump with gas furnace as backup
HVAC Cooling Type	Air-source heat pump
Domestic Hot Water Type	Tank-type electric water heater

Fifteen building models are used in this case study, representing three climate zones and five editions of ASHRAE Standard 90.1. Figure 6 below shows the site EUIs and end-use EUIs for each of these models. The site EUIs range from 300 to 700 MJ/m^2. Within the same code edition, the models in climate zone 8 have the highest site EUIs, and the models in climate zone 5A have the lowest site EUIs. In each climate zone, the building models consume progressively less energy with newer building energy code editions, as expected. Further, due to the upgrades to ASHRAE Standard 90.1, the end-use EUIs for internal lighting in the three climate zones, cooling in the climate zone 1A, and heating in climate zone 8 are notably decreased.

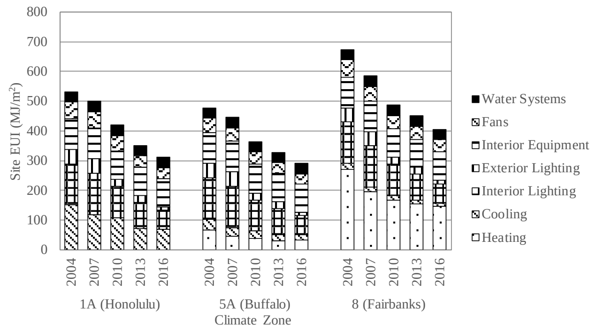


Figure 6: Annual site EUIs of the models for small office buildings with the five editions of ASHRAE Standard 90.1.

Results

By using the methodology introduced in this paper, we identify EEM changes, conduct the simulations, and generate the results. The first step is to identify how EEMs changed between different editions of ASHRAE Standard 90.1. Since the models meet the requirements of the different editions of ASHRAE Standard 90.1, we assume the changes between models embody the EEM changes between the respective ASHRAE Standard 90.1 editions. After identifying the differences between the models, we then correlate the reasons for these changes with specific EEM changes that occurred in the standards. For example, the lighting schedule on/off fractions change between the models in climate zones 1A, 5A, and 8 for ASHRAE Standard 90.1-2007, 90.1-2010, and 90.1-2013. These fraction changes are caused by changes in occupancy sensor requirements in the lighting controls. Table 2 summarizes these EEM changes.

For the forward and backward processes, Figures 7-9 show these results for climate zones 1A, 5A, and 8, respectively. Approximately 200-300 simulations are required for each climate zone. For example, in climate zone 1A, 12 simulations need to be conducted to analyse the impact of EEMs on site EUIs when the building energy code is updated from 90.1-2004 to 90.1-2007; 90 simulations are needed when the building energy code is updated both from 90.1-2007 to 90.1-2010 and from 90.1-2010 to 90.1-2013; 20 simulations are needed when the building energy code is updated from 90.1-2013 to 90.1-2016. In total, climate zone 1A requires 212 simulations. Similarly, in climate zones 5A and 8, we conduct 276 and 276 simulations, respectively.

The EEM indices in Figures 7-9 correspond to those listed in Table 2. For each loop, the baseline is the building model with the older edition of ASHRAE Standard 90.1. For example, in the left subfigure of Figure 7, the baseline is the building model with ASHRAE 90.1-2004. Since the lower left point of the loop represents the baseline, the site EUI reduction with respect to the baseline at this point equals 0, as expected. Because some EEMs are not changed between adjacent editions of ASHRAE Standard 90.1, the loops in Figure 7-9 do not include all EEMs.

Table 2: Changes to EEMs during the building energy code upgrades (where dashes indicate no changes).

Index	EEM	2004 -> 2007	2007 -> 2010	2010 -> 2013	2013 -> 2016
1	Occupancy sensor for lighting control	–	1A, 5A, 8	1A, 5A, 8	–
2	Plug receptacle control	–	1A, 5A, 8	1A, 5A, 8	–
3	Vestibule	5A, 8	–	–	–
4	Lighting power density	–	1A, 5A, 8	1A, 5A, 8	1A, 5A, 8
5	Exterior lighting power and exterior lighting control	–	1A, 5A, 8	–	1A, 5A, 8
6	Roof insulation	5A, 8	–	1A, 5A, 8	–
7	Exterior wall insulation	5A, 8	–	5A, 8	–
8	Fenestration performance	5A, 8	–	1A, 5A, 8	1A, 5A, 8
9	Door insulation	–	–	–	1A, 5A, 8
10	Continuous air barrier	–	1A, 5A, 8	–	–
11	Design ventilation rate	1A, 5A, 8	–	–	–
12	Cooling rated coefficient of performance (COP)	1A, 5A, 8	–	1A, 5A, 8	–
13	Heating rated COP	1A, 5A, 8	–	1A, 5A, 8	–
14	Fan power limit and fan motor efficiency	–	1A, 5A, 8	–	–
15	Night setback	–	–	1A, 5A, 8	–
16	Service water heater tank insulation	–	1A, 5A, 8	–	–
17	Daylighting control	–	1A, 5A, 8	1A, 5A, 8	–
18	Motorized outdoor air damper control	–	1A, 5A, 8	–	–

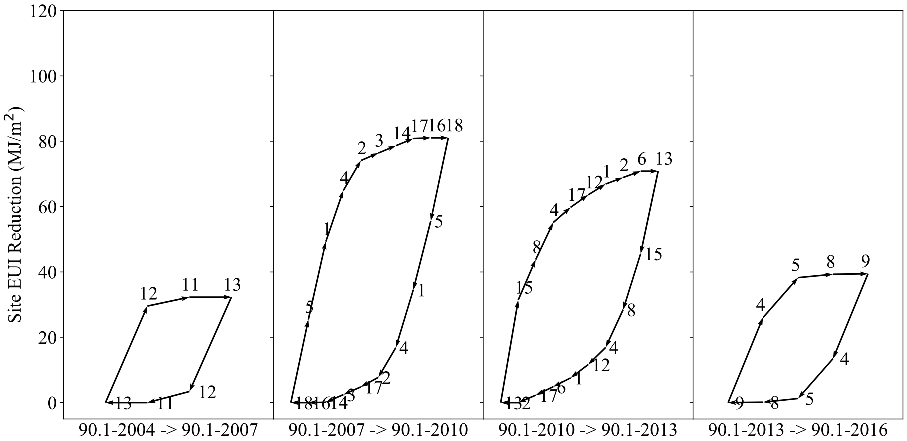


Figure 7: Impact of EEMs on site EUIs (climate zone 1A).

From each subfigure, we can identify the sensitive EEMs that are important contributors for saving energy during the building energy code upgrades. This is indicated by the largest upward jump between EEMs.

The first subfigure shows the results during the update of ASHRAE Standard 90.1 from 2004 to 2007. Only three EEMs are changed during this upgrade. The most sensitive EEM is cooling rated COP (index 12) (approximately 90.5% of total energy savings), and the other two EEMs (indices 11 and 13) do not significantly change the site EUI.

The second subfigure shows that nine EEMs are updated during the code edition revisions from 2007 to 2010. The three most sensitive EEMs are exterior light power (index 5), occupancy sensor for lighting control (index 1), and lighting power density (index 4). These represent approximately 31.4%, 27.7%, and 20.6% of the total energy savings, respectively. Thus, during the upgrade of ASHRAE Standard 90.1 from 2007 to 2010, the most significant contributors to energy savings in climate zone 1A, which is very hot and humid, involve lighting fixtures and controls. The third subfigure also contains nine changed EEMs. The three most sensitive EEMs are night setback (index 15), fenestration performance (index 8), and lighting power density (index 4). These represent approximately 40.0%, 20.8%, and 16.2% of the total energy savings, respectively.

The last subfigure shows the improvement of the EEMs from ASHRAE Standard 90.1-2013 to 90.1-2016. Four EEMs are improved. The two most significant sensitive EEMs are lighting power density (index 4) and exterior lighting control (index 5). These represent approximately 66.0% and 30.9% of the total energy savings, respectively.

Based on this analysis, the lighting-related improvements significantly contribute to the energy savings during edition upgrades of ASHRAE Standard 90.1 in climate zone 1A.

Comparing these four subfigures in Figure 7, we see that the highest energy savings for the building models in climate zone 1A appear during the update of ASHRAE Standard 90.1 from 2007 to 2010; the site EUI decreases by approximately 80 MJ/m^2 through this upgrade.

Similarly, Figure 8 illustrates that the highest energy savings for the building models in climate zone 5A also appear during the update of ASHRAE Standard 90.1 from 2007 to 2010; the site EUI decreases by approximately 85 MJ/m^2 through this upgrade. By analysing each subfigure in Figure 8, we can identify the sensitive EEMs that significantly affect the changes in site EUI.

The first subfigure shows the results during the update of ASHRAE Standard 90.1 from 2004 to 2007. Seven EEMs are changed during this upgrade. The three most important sensitive EEMs are cooling rated COP (index 12), exterior wall insulation (index 7), and design ventilation rate (index 11). These represent approximately 21.6%, 19.2%, and 17.7% of the total energy savings, respectively.

The second subfigure shows that nine EEMs are updated during the code edition update from 2007 to 2010. The three most important sensitive EEMs are exterior lighting power and exterior lighting control (index 5), occupancy sensor for lighting control (index 1), and lighting power density (index 4), which echo the results found in climate zone 1A. These represent approximately 30.3%, 21.8%, and 15.7% of the total energy savings, respectively.

The third subfigure contains 10 changed EEMs. The three most important sensitive EEMs are lighting power density (index 4), night setback (index 15), and daylighting control (index 17). These represent approximately 26.3%, 18.2%, and 10.5% of the total energy savings, respectively. By comparing with Figure 7, the site EUI reduction from ASHRAE Standard 90.1-2010 to 90.1-2013 is much lower in climate zone 5A than in climate zone 1A. This is because night setback for cooling usually has a large impact on site EUI in hot areas, but a small impact in cold areas.

The last subfigure shows the improvement of the EEMs from ASHRAE Standard 90.1-2013 to 90.1-2016. Four EEMs are improved. The two most significant sensitive EEMs are lighting power density (index 4) and exterior lighting power and exterior lighting control (index 5), which also parallels the conclusions found for climate zone 1A. These represent approximately 59.9% and 32.3% of the total energy savings, respectively.

Based on this analysis, the lighting-related improvements in climate zone 5A significantly contribute to the energy savings during edition upgrades of ASHRAE Standard 90.1, just as with climate zone 1A. However, the changes in the night setback do not have a significant impact on energy savings in climate zone 5A since the changes are related to the cooling setpoint temperature during the night.

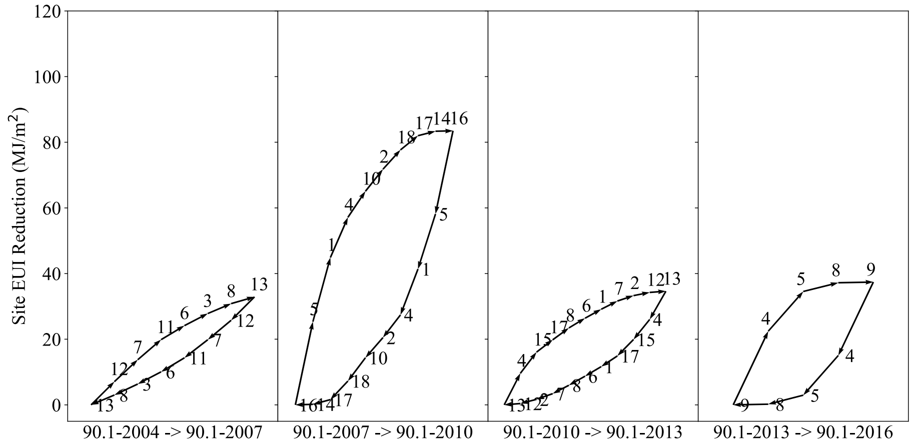


Figure 8: Impact of EEMs on site EUIs (climate zone 5A).

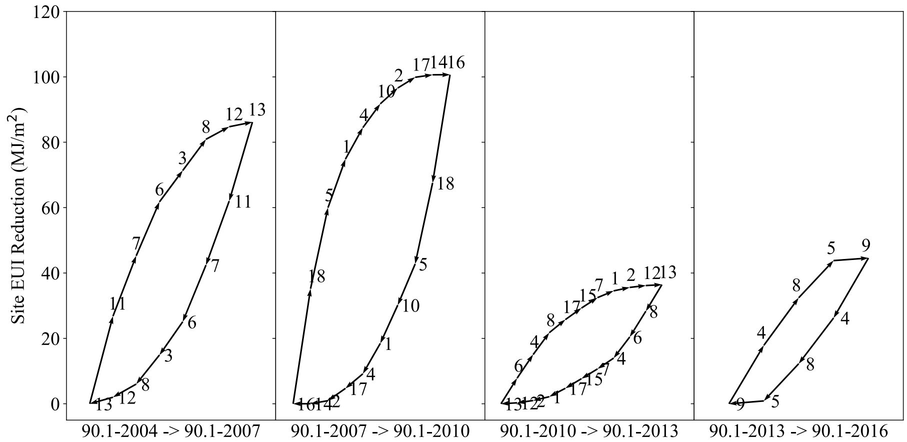


Figure 9: Impact of EEMs on site EUIs (climate zone 8).

Figure 9 illustrates that the highest energy savings for the building models in climate zone 8 appear during the update of ASHRAE Standard 90.1 from 2007 to 2010; the site EUI decreases by approximately 100 MJ/m^2 through this upgrade. By analysing the four subfigures, we obtain much information about how the individual EEMs affect the site EUIs during the energy code upgrades.

The first subfigure shows the results during the update of ASHRAE Standard 90.1 from 2004 to 2007. Seven EEMs are changed during this upgrade. The top three sensitive EEMs are design ventilation rate (index 11), exterior wall insulation (index 7), and roof insulation (index 6). These represent approximately 29.6%, 22.1%, and 19.6% of the total energy savings, respectively. In extremely cold areas, improving the envelope insulation and ventilation rate is important for saving energy.

The second subfigure shows that nine EEMs are updated during the code edition update from 2007 to 2010. The three most important sensitive EEMs are motorized outdoor air damper control (index 18), exterior light settings (index 5), and occupancy sensor for lighting control (index 1). These represent approximately 33.9%, 24.6%, and 13.6% of the total energy savings, respectively.

The third subfigure contains nine changed EEMs. The three most important sensitive EEMs are roof insulation (index 6), lighting power density (index 4), and fenestration performance (index 8). These represent approximately 21.9%, 20.8%, and 13.3% of the total energy savings, respectively. Similar to the other cases, the lighting power density again represents a key update. The envelope improvements are also significant for extremely cold areas.

The last subfigure shows the improvement of the EEMs between ASHRAE Standard 90.1-2013 and 90.1-2016. Four EEMs are improved. The three most significant sensitive EEMs are lighting power density (index 4), fenestration performance (index 8), and exterior lighting power and exterior lighting control (index 5). These represent approximately 40.6%, 32.0%, and 25.5% of the total energy savings, respectively.

Based on this analysis, the lighting-related and fenestration improvements significantly contribute to the energy savings during edition upgrades of ASHRAE Standard 90.1 in climate zone 8.

Based on the analysis of Figures 7-9, we can conclude the following: (1) the edition upgrade from ASHRAE Standard 90.1-2007 to 90.1-2010 reduces the site EUI the most for small office buildings in all three climate zones; (2) lighting-related improvements are important for energy savings in all three climate zones and are the main contributors to energy savings during the edition upgrades from ASHRAE Standard 90.1-2007 to 90.1-2010 and from 90.1-2013 to 90.1-2016; (3) improvements to envelope insulation and outdoor air settings significantly contribute to energy savings in cold areas; (4) improving the night setback for cooling is useful for saving energy in hot areas, but not in cold areas.

Conclusion

This paper proposes a new methodology to analyse how energy code EEMs impact energy consumption. The methodology is implemented to analyse the sensitivity of EEMs for small office building models with five editions of ASHRAE Standard 90.1 in three climate zones, for a total of 15 models. The methodology is suitable for any building type and consists of four steps: (1) identify the EEM changes for different editions of models; (2) conduct the simulations by following the forward process; (3) conduct the simulations by following the backward process; and (4) analyse the impact of the EEMs on energy consumption. By using the proposed methodology, we analysed the impacts of energy code EEMs on site EUI. The results show that lighting improvements significantly impact energy savings in all three climate zones; the night setback control requirement for cooling generates high savings in hot climates; and the improved envelope insulation and outdoor air control requirements can bring important savings for buildings in cold climates. The results indicate where notable energy savings can be achieved through energy code upgrades for small office buildings. Future analyses will expand on this work to delve deeper into why EEM decisions impact site EUI differently across various climate zones and how the individual and interactive EEMs impact site EUI for other building types, such as large offices or hospitals.

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