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Approved

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Dr. Lincoln Pratson

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Date

Master's Project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment, Duke University May 2012

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Andrew R. Sturges

Dr. Cary Gravatt, Adviser
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Contents

Introduction

In order to produce a model of any sort of building technology, one must have a reasonable model of the building stock. The commercial building stock of the United States consists of floor space constructed this year, last year, the year prior, and every year going back over a hundred years. Construction practices and building codes change over time, affecting the character of the buildings. Renovations are undertaken continuously, updating various pieces of the building stock to the year in which they were renovated. And of course demolitions remove still other pieces of the stock.

This cycle of construction, renovation, and demolition occurs through time, across regions, and among different building types. A model of the U.S. commercial building stock must, then, account for all of these actions (construct, renovate, demolish) across all years and in all states, keeping track of building types and associated building codes.

With this model in place, we can then examine the building codes to determine what they tell us about the stock, or explore how to adjust the codes to achieve a desired change in the stock.

Brief Background

A “building code” is a document published by an authoritative body laying out certain requirements to be followed in the construction of a building. The two most common commercial building codes are published by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and by the International Code Council (ICC). These two codes are called Standard 90.1 (ASHRAE) and the International Energy Conservation Code (ICC).

When a local governing body (usually a state or a county) “adopts” a certain building code, it obliges all new construction to follow the rules and principles laid out by the adopted code. Existing buildings are unaffected, except to the extent that they are renovated, in which case the renovations must follow the building code.

Building codes are not static documents; both the ICC and ASHRAE update their building codes continuously, and publish a new edition every three years. These generally become more stringent in terms of building energy usage, safety, and environmental concerns.

A particular state may adopt one building code, such as the 2004 edition of ASHRAE standard 90.1, and then several years later choose to adopt a newer edition, such as 2010. After the newer edition of the building code is adopted, all newly constructed buildings must then follow the regulations of that newer code. From this it becomes clear that to know what building code a certain structure is following, one must know both the year the structure was built, and the building code in effect in that state during that year. For more detail on the building codes, see Part III, Building Codes.

In this paper, we are concerned with advanced lighting controls. By carefully reading a particular building code’s chapter on lighting requirements, we can determine approximately what percentage of a certain type of building’s total floor space is covered by the lighting requirements under consideration. For example, ASHRAE standard 90.1-2004 requires all buildings greater than 5,000 square feet to be outfitted with a full-building automatic lighting shut-off device. This implies that 100% of the building’s floor space is “covered” by this requirement. However, a more careful reading reveals that certain areas, such as 24-hour lobbies and space where patient care is rendered, are exempt from the lighting shut-off requirement. A large school, with no patient care and no 24-hour lobbies would be 100% covered. But a large hospital, with several 24-hour facilities and a large portion of space dedicated to patient care, might be only 60% covered.

For this reason, we see that not only must we know the date of construction of a particular structure along with knowing the building code in effect on that date, but we also must know what kind of building activity takes place in that structure. If we know the construction date, the effective building code, and the building type, we can read the effective code and determine what percentage of that structure’s total floor space is covered by a particular part of the building code.

Furthermore, if a particular building undergoes a serious renovation after a state has adopted a newer edition of a building code, then the renovated portion is subject not to the original building code, but to the newly adopted code.

With this background in mind, we see that modeling the complete commercial building stock will require keeping track of construction dates, construction location, building types, effective building code on the construction date, renovation dates, and effective building codes on the renovation dates.

Such an accounting system proved too complicated for the author to implement in Excel, so we construct the system as a small computer program in the Python programming language. The remainder of this paper will discuss how this model was built and the results it generated, along with a deeper discussion of building codes and how we developed the input data for the model.

Part I: The Model

Model Construction

The model itself is written in the Python programming language to facilitate execution speed, error handling, modularity, and debugging. Inputs come from standard comma separated value (CSV) files, and the CSV output can be loaded into Excel for graphing and analysis.

The Building Stock Model Class

We construct a building stock using object-oriented programming paradigms to track individual building years. Each year of commercial floor space construction is represented as one distinct Python “object”, representing a construction year in a certain state. This stock object keeps track of its own year of construction, renovation and demolition functions, region, as well as floor space by building type and construction or renovation year.

This object can then be moved through time, representing aging, and can control its own demolition and renovation rate functions. These can be defined to any precision by the user. If a portion of a particular year’s floor space is renovated some number of years after that floor space was originally constructed, then the renovated floor space is “moved” to an internal bin-year representing the renovation year.

However, it remains in the same stock object, since its year of construction remains unchanged. In this way, one building stock object (constructed in a particular year) will have floor space assigned internally to multiple bin-years.

Example: Washington State, 2004

For example, take the 2004 construction year in Washington State. According to the Annual Energy Outlook (AEO) and the Commercial Buildings Energy Consumption Survey (CBECS), 32,276,203 square feet of commercial floor space was constructed in Washington in that year, so we instantiate a 2004 building object with 32.276 million square feet, representing the state of Washington. We also know that in 2004 Washington State had adopted ASHRAE standard 90.1-1999 as its commercial building code, so we know that the entire stock of 32.276 million square feet in this object are subject to this building code.

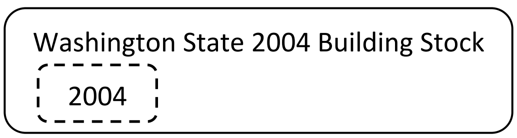

Figure 1. Stock object before aging

Next, we can “age” this object by one year. When it’s aged to 2005, some fraction of the floor space constructed in 2004 will be demolished, and some fraction of what remains will be renovated. (In reality it would be unlikely to demolish or renovate a building one year after construction; we discuss more realistic functions in the next section.) We subtract the demolished portion from the 2004 bin, and move the renovated portion from the 2004 bin to a new 20005 bin. Note that no new floor space is added once we have left 2004 because this object represents only floor space constructed in 2004.

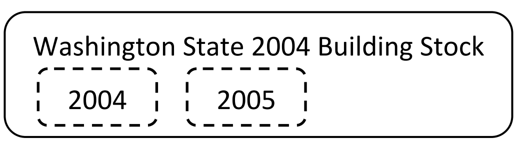

Figure 2. Stock object with two internal year-bins

Next we age the 2004 object (which now has renovation bins for 2004 and 2005) one more year; now in 2006, some portion of the floor space in both the 2004 and 2005 bins will be demolished, and some portion of what remains will be renovated. The demolished portion will be subtracted from each bin, and the renovated portion will be moved out of the 2004 and 2005 bins and into the 2006 bin.

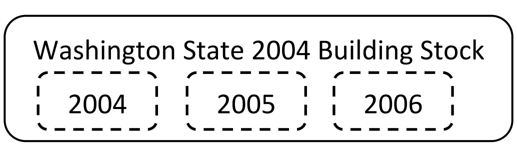

Figure 3. Stock object with three internal year-bins

However, in 2006, the state of Washington updated its commercial building code from the 1999 edition to the 2001 edition of ASHRAE standard 90.1, illustrating the need to keep track of internal year-bins within the 2004 stock object. Now we have bins for 2004, 2005, and 2006, but the 2006 bin holds commercial space renovated under a more recent building code than the 2004 and 2005 bins.

This process can be repeated an arbitrary number of times, and the object aged to any year.

Renovation or Demolition Rate Function

As a building stock object ages, some of the floor space is demolished, and some of what remains is renovated. Any floor space renovated in a given year must be renovated according to the building code in effect that year (the internal year-bin), regardless of when the original building was constructed (the year of the stock object).

Because each stock object keeps track of its own age, region, building types, and renovation bin-years, the demolition and renovation functions can be made functions of these same parameters.

Most building won't undergo major renovations immediately after construction or immediately after a prior renovation. The following code shows just one example of the kind of function we could define for either renovation or demolition rates. Here, we form a step-wise renovation function based on the number of years since the last renovation.

```
if years_since_last_renovation < 7:
    rate = 0
elif years_since_last_renovation < 15:
    rate = 0.01
elif years_since_last_renovation < 25:
    rate = 0.05
elif years_since_last_renovation < 50:
    rate = 0.07
else:
    rate = 0.1
```

A similar function can be defined for demolition rates. Accurate data on renovation and demolition rates are not available through the same sources as commercial floor space and population, and may not be available at all. New construction is reported by the Energy Information Administration in the Annual Energy Outlook (AEO), as well as from private commercial sources such as the McGraw-Hill Corporation. The difference between years of new construction and existing floor space leads to an estimate of demolition. Renovation rates are more difficult to estimate. For this model, we leave the renovation function as a variable input.

Running the Stock Model

With state-level building stock objects able to track the age and quantity of their own commercial floor space internally, modeling the national stock is simply a matter of instantiating a building stock object for every state and for every construction year desired. For example, we could instantiate stock objects for each state (51 including DC) for the years 1975 to 2010 (36 years), for a total of 1,836 objects. Aging each of these objects to the 2010 would then provide a complete picture of the US building stock in

2010, by state, year of construction, building type, and building code. (Note that this particular example would not include that portion of the building stock constructed prior to 1975.)

The model includes interface functions to simplify instantiating, aging, compiling, and printing the results. A typical run only requires that a user indicate a start year, end year, and an array of construction data.

Model Output

The model outputs a single table, with each row indicating a unique element of the national commercial floor space stock. The sample below was taken from a model run exploring a single statute from ASHRAE 90.1 requiring a full-building automatic lighting shut-off. "Covered" refers to the amount of floor space falling under this requirement.

state	year	building_type	code_title	subspace	floor_space
WA	2013	Assembly	ASHRAE 2007	covered:	1887405.743
WA	2013	Assembly	ASHRAE 2007	uncovered:	186666.502
WA	2013	Assembly	ASHRAE 2007	total:	2074072.245
WA	2013	Education	ASHRAE 2007	covered:	2527412.925
WA	2013	Education	ASHRAE 2007	uncovered:	105308.8719
WA	2013	Education	ASHRAE 2007	total:	2632721.797
WA	2013	Food Sales	ASHRAE 2007	covered:	265885.7193
WA	2013	Food Sales	ASHRAE 2007	uncovered:	108601.2093
WA	2013	Food Sales	ASHRAE 2007	total:	374486.9286
WA	2013	Food Service	ASHRAE 2007	covered:	416971.9516
WA	2013	Food Service	ASHRAE 2007	uncovered:	178702.265
WA	2013	Food Service	ASHRAE 2007	total:	595674.2165

Table 1. Sample model output (excerpt)

User Inputs to the Model

The model takes inputs in the form of comma separated value (CSV) files.

Construction History

Commercial construction history and commercial construction projections comprise a fundamental input to the model. Because the Commercial Buildings Energy Consumption Survey (CBECS) provides data only at the division level, it is necessary to disaggregate this data to the state level. The discussion of how we chose to undertake this is left to Part II, Developing the Inputs. Below is a sample of the raw data. The model includes functions to parse data in this form. Each cell represents the total square footage constructed in a given state and in a given year, across all building types.

state	1975	1976	1977	1978	1979	1980
AK	1322807	2543045	2895773	1941883	2341884	1547089
AL	22367166	27584039	18184047	22240008	29568988	66232122
AR	13129904	16026661	10625519	13019128	17371110	38890549

AZ	8034697	14879909	17407522	12067341	15325027	10464875
CA	75738150	1.39E+08	1.6E+08	1.1E+08	1.35E+08	91119223
CO	9094381	16694737	19352291	13273597	16567411	11126093
CT	20466074	7419517	2886021	7217229	9071875	5178692
DC	4297771	5112606	3257522	3859967	4971309	10857567

Table 2. Sample user-provided construction history by state (data in square feet). Sources : CBECS, 1979—2003 (historical data); AEO 2012 (projections).

Building Type Breakdowns

The mode includes an input file describing the breakdown of building types in each Census division. Users are unlikely to need to edit this file. The building types are those described by the AEO's National Energy Modeling System:

- Assembly,
- Education,
- Food Sales,
- Food Service,
- Health Care,
- Lodging,
- Large Office (>50,000 ft2),
- Small Office (≤50,000 ft2),
- Mercantile & Service,
- Warehouse,
- Other.

We take this breakdown as constant over time, and peg it to the 2003 year as reported by CBECS 2003. See below for a more lengthy discussion of building types.

Cendiv	Building Type	Percentage
1	1	0.124836
1	2	0.08658
1	3	0.021612
1	4	0.012906
1	5	0.013786
1	6	0.108274
1	9	0.237097
1	10	0.118974
1	11	0.10168
1	78	0.174255

Table 3. Excerpt from cendivs_NEMS_percentages.csv

Building Code Adoption by States

A third input file is where the user defines scenarios related to state energy code adoption over time. Historical data from 2002 to 2012 is included, and any projections are left to the user.

State	2005	2006	2007	2008	2009	2010	2011	2012
CT	12	12	12	12	12	14	14	16
DC	9	9	9	9	14	15	15	15
DE	8	8	8	8	8	16	16	16
FL	11	11	11	13	13	15	15	15
GA	9	9	9	14	14	14	14	16
HI	0	0	0	0	0	14	14	14
ID	9	12	12	14	14	14	14	16
IL	9	10	10	14	14	16	16	16
IN	0	6	6	2	2	15	15	15
IA	5	13	14	14	14	16	16	16
KS	12	12	0	14	14	14	14	14

Table 4. Excerpt from state_energy_code_compliance.csv Source: Department of Energy (www.energycodes.gov)

The sample provided here shows actual historical adoption. See below for a complete discussion of building codes and state adoption. The code key follows:

Index	Building Code
8	ASHRAE 1999
9	IECC 2000
10	IECC 2001
11	ASHRAE 2001
12	IECC 2003
13	ASHRAE 2004
14	IECC 2006
15	ASHRAE 2007
16	IECC 2009

Table 5. Excerpt from state_energy_code_key.csv

Building Code Coverage by Building Type

The table below, given as an example, provides information about full-building automatic lighting shutoff, from section 9.4.1.1 of ASHRAE standard 90.1. More generally though, this is the place where the user can describe how a particular piece of the building codes (such as the full-building automatic lighting shut-off discussed here) affect various building types.

Building Type	13	14	15	16	17	18
1	0.91	0.91	0.91	0.91	1	1
2	0.96	0.96	0.96	0.96	1	1
3	0.71	0.71	0.71	0.71	1	1

4	0.7	0.7	0.7	0.7	1	1
5	0.76	0.76	0.76	0.76	0.76	0.76
6	0.98	0.98	0.98	0.98	1	1
9	0.89	0.89	0.89	0.89	1	1
10	0.92	0.92	0.92	0.92	1	1
11	0.92	0.92	0.92	0.92	1	1
78	0.88	0.88	0.88	0.88	0.98	0.98

Table 6. Excerpt associating code coverage from six codes with various building types

In the excerpt above, building types are listed in the first column (see "Building Types" below), and code vintages are listed across the top row (see Table 5). In this example, under building code 15 (ASHRAE 2007), building type 1 (Assembly), 91% of the total floor space would be covered under the full-building automatic lighting shut-off requirement. (The remaining 9% are comprised of buildings less than 5,000 square feet, which are exempted from the requirement.) In this way, the user can select a part of a building code and inform the model how coverage of that requirement changes by building type and across code editions. For a full discussion of how this table is formed, see below.

With all of these inputs in place, the model undertakes the vast accounting scheme necessary to keep track of building types, states, building codes, construction dates, renovation dates, demolition dates. Then it associates the floor space with the proper codes and determines what percentage of that code is "covered" under the user-defined assumptions laid out above.

Results

Running the model under various input scenarios—adjusting state code adoption or commercial construction growth—leads to results which can be compared against a baseline. For these scenarios, we model the effect on full-building automatic lighting shut-off, from ASHRAE standard 90.1 section 9.4.1.1.

Full-Building Automatic Lighting Shut-off

AHSRAE standard 90.1-2004 includes, for the first time, a section 9.4.1.1 called "Automatic Lighting Shut-off":

> Interior lighting in buildings larger than 5,000 ft^2 shall be controlled with an automatic control device to shut off building lighting in all spaces. This automatic control device shall function on either a) a scheduled basis using a timer, b) an occupant sensor, or c) a signal from another control system that indicates the area is unoccupied. The following shall not require an automatic control device: (a) Lighting intended for 24-hour operation; (b) Lighting in spaces where patient care is rendered; (c) Spaces where an automatic shutoff would endanger the safety or security of the room or building occupants (American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2004).

Section 9.4.1.1 presents an unambiguous requirement for an advanced lighting control, and it is this requirement that we model in the following scenarios.

In general, we assume that any space in a commercial building larger than 5,000 ft2, not used for patient care and built under the requirements of ASHRAE 2004, will be "covered" by an automatic control device. Any space not under this building code or where patient care is rendered is considered "uncovered."

Other Codes

Section 9.4.1.1 first appeared in the 2004 edition of ASHRAE standard 90.1, but has remained largely unchanged in the 2007 and 2010 edition. However, two minor changes do appear: in the 2007 edition the 5000 ft^2 qualifier was removed and in 2010 the stipulation that building lights be turned on to only 50% power was added. The area of coverage therefore changes little (only about 10% of the commercial building stock is comprised of buildings less than 5,000 ft^2). Furthermore, building codes published by the International Energy Conservation Code (IECC) wholly adopt the ASHRAE chapters on lighting. As such, we can assume that all states that have adopted either ASHRAE or IECC from 2004 to 2012 are subject to this requirement.

Establishing Model Scenarios

Because the model is capable of projecting the national building stock breakdown into the future, historical data only account for part of the model's input. Projected data must account for two major inputs:

1. Commercial construction starts
2. State building code adoption

Commercial construction starts are only necessary if the user wishes to instantiate building stock objects past 2002, the last year for which CBECS 2003 provides reliable historical data. Similarly, state building code adoption is known from 2002 to the present via the Department of Energy's energycodes.gov site. Any projection of building stock must make assumptions about whether and how states will adopt newer building codes.

Baseline Scenario: Freeze at 2012

To establish a baseline candidate, we use two data projections:

1. Commercial construction starts from the Annual Energy Outlook (AEO) 2011 Standard Scenario;
2. State building code adoption based on no changes after 2012.

AEO 2011 provides reasonable projections based on practical assumptions about economic and population growth. The assumption that building code adoption will freeze after 2012 is based largely on necessity; the latest codes have already been adopted by some states, so further progress would require making assumptions about building codes that have not yet been written. The following figure illustrates the results of this base case scenario.

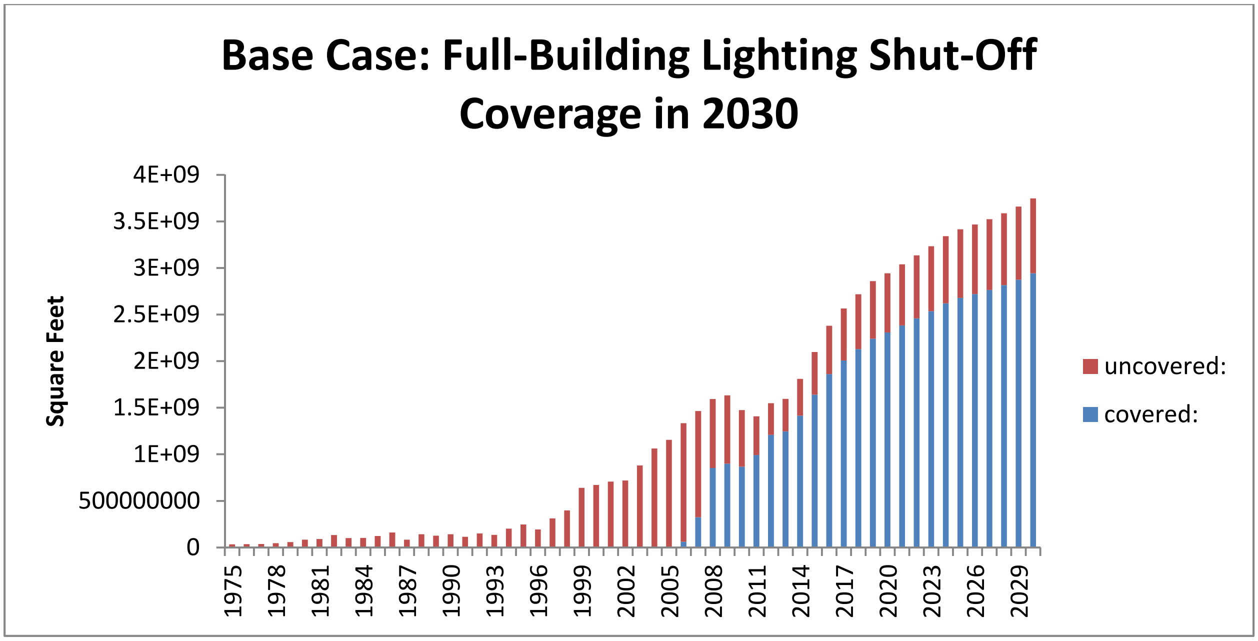

Figure 4. Results from base case scenario

The base case chart shows the dramatic effect of the 2007 and 2010 editions of ASHRAE standard 90.1, which states began adopting in 2006. These codes introduce the full-building automatic lighting shut-off requirement. Coverage will never reach 100% of commercial floor space due to explicit exemptions for certain spaces with safety and patient care purposes.

Scenario: Full Compliance with the Federal Building Code

This scenario models the effect of a more stringent federal building code. While today's federal building code is nominally the 2007 edition of ASHRAE standard 90.1, compliance is low, and 14 states have no commercial building code at all. In this full-compliance scenario we assume all states adopt ASHRAE standard 90.1-2007 in 2015, unless they have already adopted a more stringent code. The following chart shows the results, a snapshot of the national building stock taken in 2030.

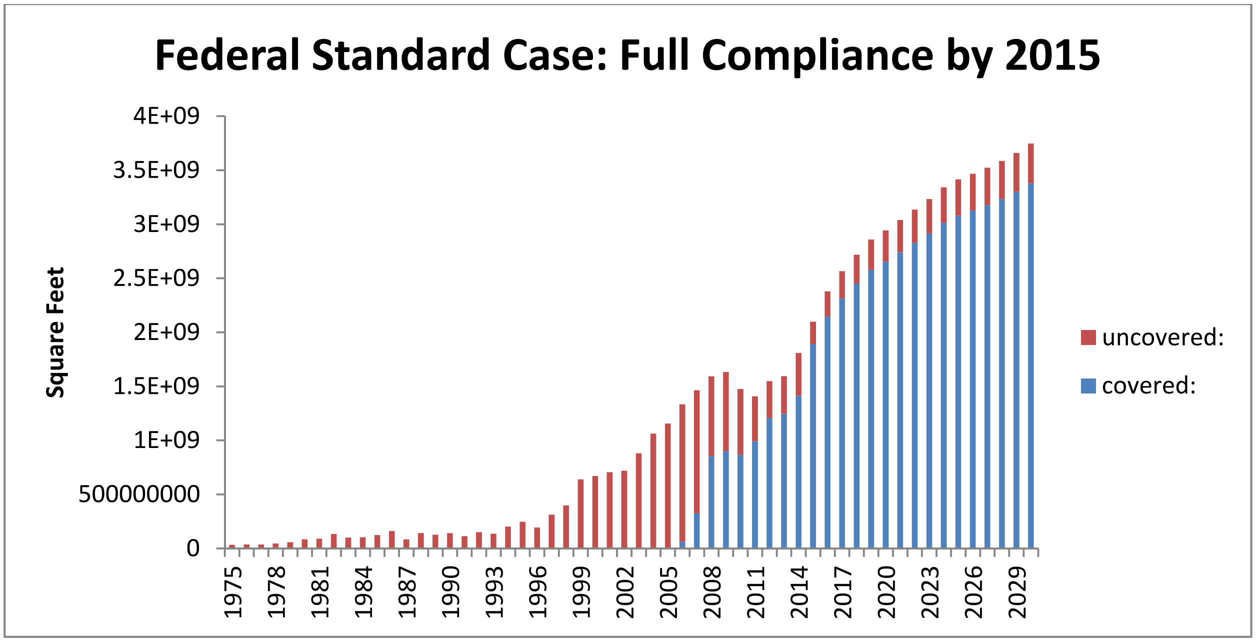

Figure 5. Results from full compliance scenario

Uncovered floor space has dropped somewhat, but comparison with the base case is difficult. Instead, we provide a comparison based on percentage of covered floor space as a percentage of total floor space.

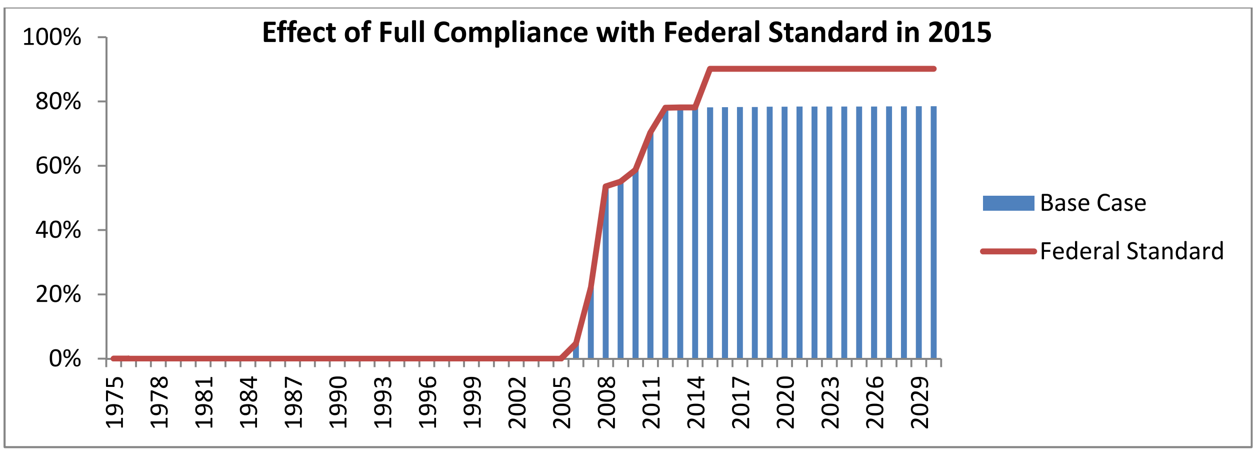

Figure 6. Comparison of two scenarios

The results show a 12% jump in covered floor space starting in 2015. The base case shows coverage without full compliance to be already at 78%, with full compliance bringing it up to 90%. Note that this chart represents not a historical trend but a snapshot of the total building stock in 2030.

Scenario: AEO High- and Low-Growth

While adjusting various building code adoption scenarios, it is also possible to change the projected commercial construction starts. In addition to the base case, AEO also provides a low-growth and a highgrowth scenario. Lower construction starts would reduce the impact of future building codes, necessitating, for example, higher energy efficiency to achieve the same energy savings.

Source Code

The best means of sharing source code is through its online repository. The complete source for this project can be found at https://github.com/arsturges/lighting_floor_space_stock_model, where it can be forked and modified on a user's local machine, or simply downloaded as a tar or zip package and run locally. It requires Python 3, available at http://www.python.org. The repository includes all inputs discussed in this paper.

Part II: Developing the Inputs

Disaggregating from the Census division level to the state level

CBECS reports quadrennial data on the Census regional and divisional level, but due to privacy concerns, does not identify buildings' states.

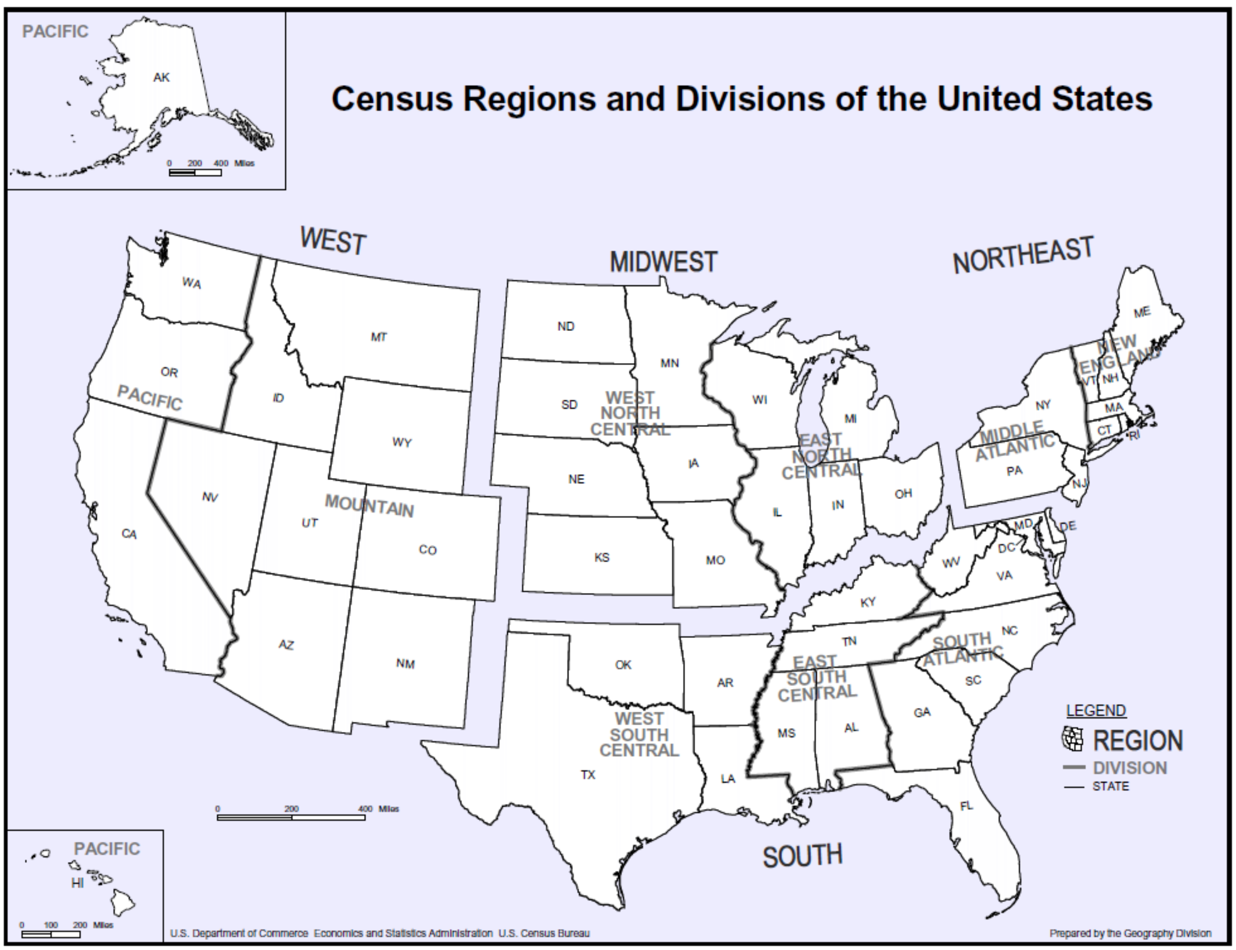

Figure 7. CBECS reports at the Census division level only (U.S. Census Bureau)

Because building codes are defined only at the state level, it is necessary to disaggregate a Census division's reported commercial floor space into its constituent states. To do this, we note a correlation (R^2=0.89) between each division's total floor space and its total population. See Figure 8. We assume that some correlation exists at the state level as well, and we use this to assign a Census division's floor space to its individual states for each CBECS year. State population data comes from the decennial Census as well as annual intercensal estimates.

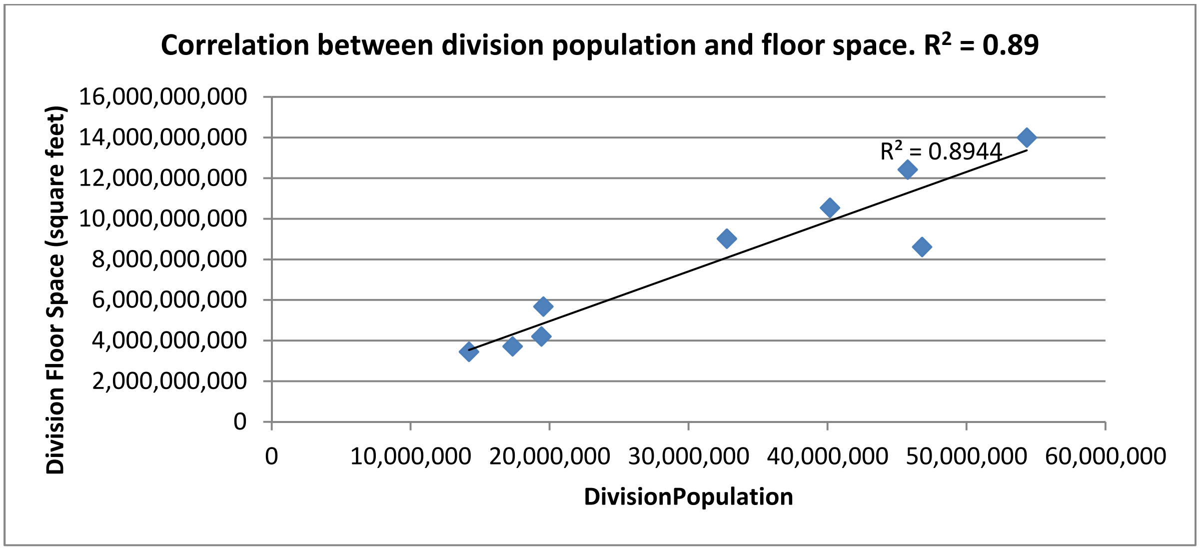

Figure 8. In 2003, floor space correlated to population with an R^2 value of 0.89. (Commercial Buildings Energy Consumption Survey, 2003)

State population projections were taken from the last available US Census Projections data, available by age and sex from the 2000 Census and released in 2005. This data includes projections out to 2030. The US Census Bureau notes that it "does not have a current set of state population projections and currently has no plans to produce them" (U.S. Census Bureau). Further refinement of this model could replace these Census Bureau estimates with data provided by individual states.

Dividing a state's population by the total population of that state's Census division provides a multiplier which can be used to disaggregate quantities from the census division down to the state level. Using this method, we assign new construction data to individual states by year.

Table 7. Division floor space from CBECS 2003

Census Division	2003 Commercial Floor Space
New England	3,452,402,461
Middle Atlantic	10,542,816,652
East North Central	12,423,689,980
West North Central	5,679,628,435
South Atlantic	13,998,562,648
East South Central	3,718,860,777
West South Central	9,021,862,511

Mountain	4,206,606,021
Pacific	8,613,471,038

Building Code Adoption by States

In order to relate a particular vintage of commercial floor space to a specific building code, we must know the state and the building code adopted by the state during that vintage year. To compile a table of historical code adoption by state, we used data from the Department of Energy's Energy Efficiency and Renewable Energy (EERE) Building Energy Codes Program (www.energycodes.gov).

Since 2002, this site has hosted an updated status of state energy code adoption. By searching through archived versions of this site, we compiled a timeline for each state's code adoption. It should be noted that this represents a conservative picture of actual building code adoption. As explained by EERE, some states with no official building code have effectively adopted a state-wide code: "Arizona is a 'home rule' state with no mandatory state-wide commercial energy code. However, many counties and cities have adopted an energy efficiency code, most often the 2006 International Energy Conservation Code (IECC), therefore the 2006 IECC was used as the base code in the analysis" (Pacific Northwest National Laboratory, 2009).

The complete data appears in Table 8, found in the appendix. The indices refer to the individual building codes (as outlined in Table 9), with higher numbers indicating later editions with presumably more stringent standards.

Some Remarks on Building Code Adoption

This table leads to several noteworthy conclusions.

First, in the decade since 2002, building code adoption has not increased dramatically. Three states—Idaho, Illinois, and Massachusetts—have adopted a building code for the first time, while one state—Maine—dropped the program entirely. In 2012, eleven states have adopted no building code.

Second, among states with a building code, states are choosing more recent editions. In 2002, the most popular building code, as adopted by 21 states, was ASHRAE 1989, representing a 13-year lag between the code year and the calendar year. In 2012 the most popular building code, as adopted by 22 states, was IECC 2009, representing a 3-year lag between code year and calendar year.

Third, states adopting a building code for the first time (or having failed to update building codes for multiple decades) tend to adopt relatively late editions. For example, Kentucky adopted its first building code in 2006, and by 2008 had adopted IECC 2006, representing a two-year lag. In 2010 Indiana adopted a modern code for the first time, choosing ASHRAE 2007, and Vermont in 2007 adopted ASHRAE 2004, having previously had no building code. States choosing to adopt late editions for their first building codes may suggest that commercial building practices did not lag far behind what modern building codes were otherwise dictating. In fact, this was conclusion drawn by EERE in a 2007 assessment of commercial building codes:

Standard 90.1-1999 was chosen as the baseline construction for states with older codes because it has been around long enough (about 10 years) to allow many of the concepts and requirements embodied in it to become common practice in the construction industry. Standard 90.1-1999 also represents a major change in ASHRAE standards, coming ten years after the previous version of Standard 90.1. Standard 90.1-1999 is old enough that states considering adoption of Standard 90.1-2007 will still see significant savings, but not so old that states will be misled by the savings shown in this report. Keeping with the concept of Standard 90.1-1999 as "common practice" in the construction industry, Standard 90.1-1999 was also used as the base code for states with no state-wide commercial energy code. Some home rule states requested a specific code be used in the analysis; for all other home rule states Standard 90.1-1999 was used as the base code (Pacific Northwest National Laboratory, 2009).

Fourth, among states adopting any building code in 2012, all but two (Arkansas and West Virginia) met or exceeded the federal standard. Eight states had no building code at all. This suggests a general willingness to comply with the spirit of the Energy Policy Act of 2005, which requires states to adopt or exceed the federal code, or explain to the Department of Energy why compliance is not appropriate. See Part III for more legislative detail. Furthermore, at the time of the 2011 determination that selected ASHRAE 2007 as the federal building code, 16 states had already adopted or exceeded it despite having a two year window to comply.

Fifth, actual compliance with a state-adopted building code depends on the state and jurisdiction. Code enforcement varies by region.

Building Code Adoption as an Input

With this timeline of code adoption in place, it then becomes possible to associate floor space constructed or renovated in a certain year and in a particular state with that state's adopted building code in that year. In this way, we have constructed a building stock model in each year by state, with that state's total commercial floor space separated by the building codes under which it was constructed. In other words, we can have a function that accepts state and year as arguments, and returns an array of floor space and code years.

Building Types

Each edition of the CBECS defines principal building activities (PBA), which are defined as "the primary business, commerce, or function carried on within each building."[1] PBAs are not consistent across survey editions.

The Energy Information Administration's National Energy Modeling System (NEMS), from which we get commercial floor space projections, defines a slightly different set of PBAs, but offers a correspondence table, reproduced below (National Energy Modeling System, 2011).

NEMS	2003 CBECS PBAs

[1] http://www.eia.gov/emeu/cbecs/building_types.html

Assembly	Public Assembly, Religious Worship
Education	Education
Food Sales	Food Sales
Food Service	Food Services
Health Care	Health Care – Inpatient
Lodging	Lodging, Skilled Nursing, Other Residential Care
Large Office (>50,000 ft2)	Office (> 50,000 square feet), Health Care - Outpatient (> 50,000 square feet)
Small Office (≤50,000 ft2)	Office (≤50,000 square feet), Health Care - Outpatient (≤50,000 square feet)
Mercantile & Service	Mercantile Service
Warehouse	Refrigerated Warehouse, Non-refrigerated Warehouse
Other	Laboratory, Public Order and Safety, Vacant, Other

We get historical construction data from CBECS, and construction projections from NEMS. In the final output, we chose to use the NEMS building type definitions.

Part III: Building Codes

Policy Background

The Energy Conservation and Production Act of 1976 (ECPA), as amended by the Energy Policy Act of 2005 (EPACT), requires that the U.S. Department of Energy determine whether changes to two specific building codes would improve energy efficiency of U.S. buildings. If the DOE finds that changes to these codes would improve energy efficiency in buildings, then states are directed to revise their building standards to meet or exceed these model codes. These codes are the International Energy Conservation Code (IECC) for the residential sector, and ANSI/ASHRAE/IESNA Standard 90.1 for the commercial sector.

It is important to note, however, that these codes are not true federal energy standards. No law requires states to adopt these building codes. Instead, each is required to demonstrate to the Energy Secretary that its own building codes are at least as stringent as these "model" codes, or explain why compliance would not be appropriate. In reality, most states choose to adopt these model codes as the state building codes.

Federal Residential Building Code

U.S. Code section 6833 outlines the steps by which individual states must comply with a national code. First, §6833(a)(5) mandates that whenever the federal model building code for residential buildings (IECC) is modified, the Energy Secretary must determine within one year whether the modification would improve energy efficiency in residential buildings.

Then, §6833(a)(5)(B) dictates that each state review its own residential building code and determine, within two years of the Secretary's determination, whether it is appropriate to revise this code to meet or exceed the federal residential building code.

Finally, states must either revise its building code accordingly (§6833(a)(3)), or explain to the Energy Secretary why revising the code would not be appropriate (§6833(a)(4)).

Federal Commercial Building Code

The process for revising state commercial building codes is similar, and covered in §6833(b).

First, the Energy Secretary must determine, within 12 months of any change to ASHRAE standard 90.1, whether such change would improve the energy efficiency of commercial buildings (§6833(b)(2)(A)).

Then, states have two years to update their own commercial building code to meet or exceed the revised ASHRAE 90.1 standard (§6833(b)(2)(B)(i)).

As of October 11, 2011, the federal commercial building code baseline standard is ANSI/ASHRAE/IESNA Standard 90.1-2007. (Department of Energy, 2011)

"Energy Conservation Standards for New Buildings"

This legislation appears in U.S. Code Title 42 (The Public Health and Welfare), Chapter 81 (Energy Conservation and Resource Renewal), Subchapter II (Energy Conservation Standards for New Buildings), sections 6831—6840. The Code lays out the goals of the subchapter as follows:

> (b) The purposes of this subchapter, therefore, are to -
>
> > (1) redirect Federal policies and practices to assure that reasonable energy conservation features will be incorporated into new commercial and residential buildings receiving Federal financial assistance;
> >
> > (2) provide for the development and implementation, as soon as practicable, of voluntary performance standards for new residential and commercial buildings which are designed to achieve the maximum practicable improvements in energy efficiency and increases in the use of nondepletable sources of energy; and
> >
> > (3) encourage States and local governments to adopt and enforce such standards through their existing building codes and other construction control mechanisms, or to apply them through a special approval process.

Challenges to Adoption, Implementation, and Enforcement

DOE's Building Energy Codes group provides an introduction to the challenges faced by the regulating agency:

> Though the savings of more stringent building energy codes is clear, there are challenges involved in their adoption, implementation, compliance, and enforcement. For example, adoption is not automatic in most states. Without statewide adoption, jurisdictions are left without state guidance or resources, and builders can face a patchwork of codes across their region. Adding complication, the challenges of implementation, compliance, and enforcement vary depending on the jurisdiction; lack of training as well as lack of manpower are often cited

> as roadblocks to proper enforcement. As with any aspect of building codes, plan review and inspections take time, and this must be accounted for in department staffing. Training is critical to the design, building, and enforcement communities. Not only is there a need for understanding new code language, but new construction techniques and new materials and technologies must be considered and understood (Department of Energy, Building Energy Codes, 2010).

While DOE helps publish and promulgate a national energy code for both residential and commercial buildings, the states are not required to adopt those codes per se. Instead, they are merely required to adopt some code equally as stringent as or more stringent than the two federal codes.

> The policy of the U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE) Office of Building Technologies is to recommend that states, if so inclined, make "good amendments properly." It is recognized that states are required to update their energy codes to meet or exceed the latest model code**.** States may develop their own codes, or adopt the model codes with or without amendments. DOE does not officially direct the states which codes to adopt or how to adopt these codes (Department of Energy).

ASHRAE 90.1

U.S. Code sections 6831—6840 ("Energy Conservation Standards for New Buildings") chooses ANSI/ASHRAE/IESNA Standard 90.1 as the model commercial building energy efficiency code. At the time of implementation, the standard had recently been updated to the 1989 edition. Since then, ASHRAE 90.1 has undergone numerous major revisions, most recently in 2004, 2007, and 2010. Today, the document is under "continuous maintenance," meaning it can adopt revisions during the year between official approved publications, which now happens in the fall of every third year.

Differences between approved publications may be substantial.

> The Committee's unanimously approved Workplan goal of the 2010 edition was to reduce energy cost by 30% compared to the 2004 version of the standard. Toward that goal, 109 addenda were processed by the committee and approved by the ASHRAE and IES Boards of Directors and are included in this edition…The most significant changes included are … [m]ost interior lighting power densities have been lowered, additional occupant sensing controls and mandatory daylighting requirements are added for specific spaces, and a new five-zone exterior lighting power density table has been added (American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2004).

Lighting and Lighting Controls in Building Codes

This building stock model was designed with the intent to explore the effect of building code adoption on advanced lighting control coverage. However, it could be used for any part of a building code that can be said to "cover" a part of a building's floor space. Below we discuss in detail the elements of the building codes that could be used in running this model. Note that for the base cases presented in Part I, we used only section 9.4.1.1 to illustrate.

ASHRAE 90.1-2010

ASHRAE 90.1-2010 covers lighting in chapter 9, and lighting controls in section 9.4. Section 9.4 requires that all building lights under automatic controls be turned on to 50% power only, and only through manual switching can 100% power be applied.

The document defines an automatic control device as a device capable of automatically turning loads off and on without manual user intervention (section 3.2). It defines an occupant sensor as a device that detects the presence or absence of people within an area and causes lighting, equipment, or appliances to be regulated accordingly.

Section 9.4.1.1 requires all interior lighting to be installed with an automatic control device. This device must use a timer, an occupancy sensor, or a signal from a third system, such as an alarm system.

Furthermore, every room in a building must have its own control device, and that control device must have at least one dimmer setting between 30—70% of full power. Certain rooms, such as classrooms, conference rooms, storage closets, copy rooms, small offices, restrooms, and dressing rooms, must additionally have an occupancy sensor. Any building rooms not falling into one of these categories must have either a manual shut-off or an occupancy sensor (9.4.1.2)

Section 9.4.1.3 covers parking garages, which are excluded from this analysis due to a decision by CBECS not to include parking garages in certain survey years. Parking garage lighting must be controlled by a timer, an occupancy sensor, or a signal from a third system. Each lighting zone of no more than 3,600 ft^2 shall have an activity sensor that will turn down the lighting system by at least 30% when no activity is detected for at most 30 minutes. The power of all lights near windows or wall openings must be reduced in response to daylight.

Section 9.4.1.4—5 describes lighting controls for areas with significant natural light. This includes areas of at least 250 ft^2 next to windows, and at least 900 ft^2 under skylights. These lights must be controlled by photosensors which can be easily and properly calibrated, and which have at least four steps (0—35, 35—50, 50—75, 75—100). Notably, retail spaces are excepted from this rule.

ASHRAE Standard 90.1-2007

ASHRAE Standard 90.1-2007 is more widely adopted than the 2010 edition. It serves as the official Federal commercial building code today. Major differences between the 2007 and 2010 edition of the standard are:

- No requirements for photosensors in areas with side- or top-lighting
- No requirement that building lighting be turned on to no more than 50% power; all lights may be automatically turned on to full power.

ASHRAE Standard 90.1-2004

The 2004 edition of the code is the first code that addresses advanced lighting controls. Section 9.4.1.1 requires automatic control of full-building lighting, to be controlled by photosensors, timers, or an alarm system. The intent is to allow a building’s lighting to be shut off after business hours. Notably, this requirement is exempt for buildings of less than 5,000 square feet, representing about 10% of the US commercial building stock.

International Energy Conservation Code

The International Code Council's International Energy Conservation Code is an alternative to ASHRAE standard 90.1. Many states adopt the IECC instead of ASHRAE, possibly because it includes prescriptions for both commercial and residential building in one code. Like ASHRAE it is released every three years.

Lighting in the International Energy Conservation Code

The commercial portions of IECC borrow heavily from ASHRAE standard 90.1. In fact, a building is considered in compliance with IECC lighting requirements if it complies with the lighting requirements of the preceding ASHRAE standard. For example, IECC 2009 specifies that compliance may be achieved by following the lighting requirements from ASHRAE 2007.

In a state which has adopted an IECC code, a building may comply by following IECC or by following ASHRAE, which is less stringent. Because it is impossible to know whether a certain building followed IECC or the slightly older and less stringent ASHRAE, we conservatively assume that all lighting compliance in IECC states was done by following ASHRAE standards.

Conclusion

This paper described one method for estimating the effect of building codes on the adoption of advanced lighting controls. We used Python to create a building stock model, and associated individual building stock objects with construction, renovation, demolition, building type, state, and building code data. We outlined several potential analysis scenarios, and established a base case and a 'full compliance with a federal standard.' This scenario showed that mandating full compliance with ASHRAE standard 90.1-2007 would increase the total commercial floor space covered by a full-building lighting shut-off requirement would increase from 78% to 90% by 2030.

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Appendix – Historical Code Adoption by State

Table 8. State timeline of building code adoption.

State	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012

Alabama	0	0	0	0	0	0	0	0	0	0	0
Alaska	0	0	0	0	0	0	0	0	0	0	0
Arizona	0	0	0	0	0	0	0	0	0	0	0
Arkansas	5	5	5	12	12	12	12	12	12	12	12
California	8	8	8	8	11	13	13	13	15	15	15
Colorado	0	0	0	0	0	0	0	12	0	0	0
Connecticut	5	5	5	12	12	12	12	12	14	14	16
Delaware	5	5	5	8	8	8	8	8	16	16	16
DC	5	5	9	9	9	9	9	14	15	15	15
Florida	5	5	5	11	11	11	13	13	15	15	15
Georgia	5	9	9	9	9	9	14	14	14	14	16
Hawaii	5	0	0	0	0	0	0	0	14	14	14
Idaho	0	9	9	9	12	12	14	14	14	14	16
Illinois	0	0	0	9	10	10	14	14	16	16	16
Indiana	1	1	1	0	6	6	2	2	15	15	15
Iowa	5	5	5	5	13	14	14	14	16	16	16
Kansas	5	5	12	12	12	0	14	14	14	14	14
Kentucky	6	0	0	0	12	12	14	14	14	14	16
Louisiana	5	5	5	5	11	11	13	13	13	13	15
Maine	8	11	11	11	11	11	11	11	16	0	0
Maryland	9	9	9	9	12	12	14	14	16	16	16
Massachusetts	0	8	10	10	10	10	13	13	16	16	16
Michigan	2	2	8	8	8	8	8	8	8	15	15
Minnesota	5	5	5	5	5	5	5	13	13	13	13
Mississippi	0	0	0	0	0	0	0	0	0	0	0
Missouri	0	0	0	0	0	0	0	0	0	0	0
Montana	5	5	5	12	12	12	12	12	16	16	16
Nebraska	3	3	3	3	12	12	12	12	12	12	16
Nevada	4	0	0	0	12	12	12	13	14	14	14
New Hampshire	5	5	8	8	9	9	14	14	14	14	16
New Jersey	5	8	8	8	8	13	13	13	13	13	15
New Mexico	2	2	2	12	12	12	12	14	14	14	14
New York	5	10	10	10	10	10	12	12	12	12	16
North Carolina	8	9	9	9	9	13	13	13	14	14	14
North Dakota	0	0	0	0	0	0	0	0	0	0	0
Ohio	5	8	8	8	13	13	13	14	14	14	16
Oklahoma	5	5	5	5	5	12	14	0	0	0	0
Oregon	5	5	8	8	8	8	13	13	16	16	16
Pennsylvania	2	2	12	12	12	14	14	14	16	16	16
Rhode Island	5	9	8	12	12	12	14	14	16	16	16
South Carolina	5	5	5	12	12	12	14	14	14	14	14

South Dakota	0	0	0	0	0	0	0	0	0	0	0
Tennessee	2	2	2	2	2	2	2	2	2	2	14
Texas	9	9	10	10	10	10	10	10	10	16	16
Utah	8	8	12	12	12	14	14	14	16	16	16
Vermont	0	0	0	9	0	13	13	13	13	13	16
Virginia	5	5	9	9	12	12	13	13	14	14	16
Washington	8	8	8	8	11	11	13	13	13	13	15
West Virginia	2	0	9	9	9	12	12	12	12	12	12
Wisconsin	5	9	9	9	9	9	14	14	14	14	16
Wyoming	0	0	0	0	0	0	0	0	0	0	0

Index	Building Code
0	None
1	ASHRAE 1975
2	ASHRAE 90A-1980
3	MEC 1983
4	MEC 1986
5	ASHRAE 1989
6	MEC 1992
7	ASHRAE 1992
8	ASHRAE 1999
9	IECC 2000
10	IECC 2001
11	ASHRAE 2001
12	IECC 2003
13	ASHRAE 2004
14	IECC 2006
15	ASHRAE 2007
16	IECC 2009
17	ASHRAE 2010
18	IECC 2012

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