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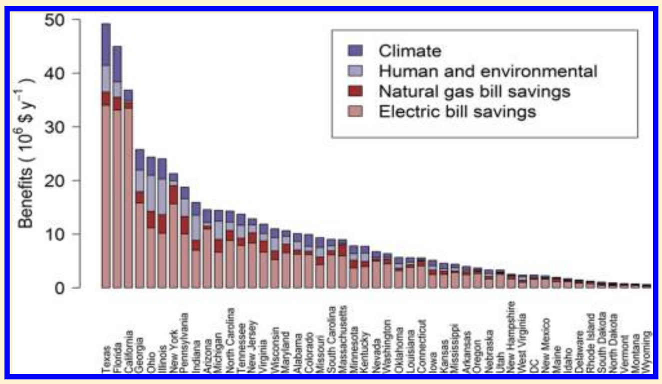
Evaluating the Benefits of Commercial Building Energy Codes and Improving Federal Incentives for Code Adoption

Nathaniel Gilbraith, Inês L. Azevedo,* and Paulina Jaramillo

Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

ABSTRACT: The federal government has the goal of decreasing commercial building energy consumption and pollutant emissions by incentivizing the adoption of commercial building energy codes. Quantitative estimates of code benefits at the state level that can inform the size and allocation of these incentives are not available. We estimate the state-level climate, environmental, and health benefits (i.e., social benefits) and reductions in energy bills (private benefits) of a more stringent code (ASHRAE 90.1−2010) relative to a baseline code (ASHRAE 90.1−2007). We find that reductions in site energy use intensity range from 93 MJ/m^2 of new construction per year (California) to 270 MJ/m^2 of new construction per year (North Dakota). Total annual benefits from more stringent codes total \$506 million for all states, where \$372 million are from reductions in energy bills, and \$134 million are from social benefits. These total benefits range from \$0.6 million in Wyoming to \$49 million in Texas. Private benefits range from \$0.38 per square meter in Washington State to \$1.06 per square meter in New Hampshire. Social benefits range from \$0.2 per square meter annually in California to \$2.5 per square meter in Ohio. Reductions in human/environmental damages and future climate damages account for nearly equal shares of social benefits.



INTRODUCTION

Commercial buildings account for approximately 19% of total U.S. energy consumption and are consistently shown to hold technically and economically feasible efficiency options.[1−4] The federal government has set aggressive goals for capturing this potential.[5,6] For example, the goal of the Building Energy Codes Program (BECP) within the U.S. Department of Energy is to reduce annual energy consumption by 1.5 EJ (1 exajoule = 10^{18} joules) by 2030 through the use of energy codes.[5] One such code is the *Energy Standard for Buildings Except Low Rise Residential Buildings* (hereinafter ASHRAE 90.1−2010), which was developed in collaboration with the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). Like its predecessors, ASHRAE 90.1−2007 and 90.1−2004, ASHRAE 90.1−2010 is a commercial building energy code that localities and states can easily adopt and integrate into existing building codes. This code "packages" many of the diverse energy efficiency options available in the commercial building sector into a single policy.[7] All new commercial buildings in locations where the code is adopted must then meet these standards.

ASHRAE 90.1−2010 is expected to reduce the annual energy consumption of an average new commercial building by 19% relative to ASHRAE 90.1−2007.[7] ASHRAE and the Pacific Northwest National Laboratory (PNNL) estimated these savings using the building energy simulation model EnergyPlus and commercial building prototypes designed to minimally comply with the 90.1−2007 and 90.1−2010 code levels.[8] Forty-one individual code amendments are responsible for these predicted savings. These amendments update code requirements for HVAC (17 amendments), lighting (14 amendments), building envelope (6 amendments), and other components/systems (4 amendments).[7] Table S1 in the Supporting Information (SI), SI1, shows the key differences between the code 2007 and 2010 code levels.

The federal government acts to increase the implementation of building energy efficiency options by providing technical and monetary assistance as code adoption incentives for states. Each year, the Department of Energy allocates \$26 million in monetary incentives to states according to a formula where one-third of this funding is distributed evenly across states, and two-thirds are distributed proportionately based on state energy consumption and state population.[9] States qualify for this funding when they meet certain criteria, including the adoption of the most recent commercial building energy code. The revenue available to states through this program is relatively small and so it is unclear how many states adopt codes as a

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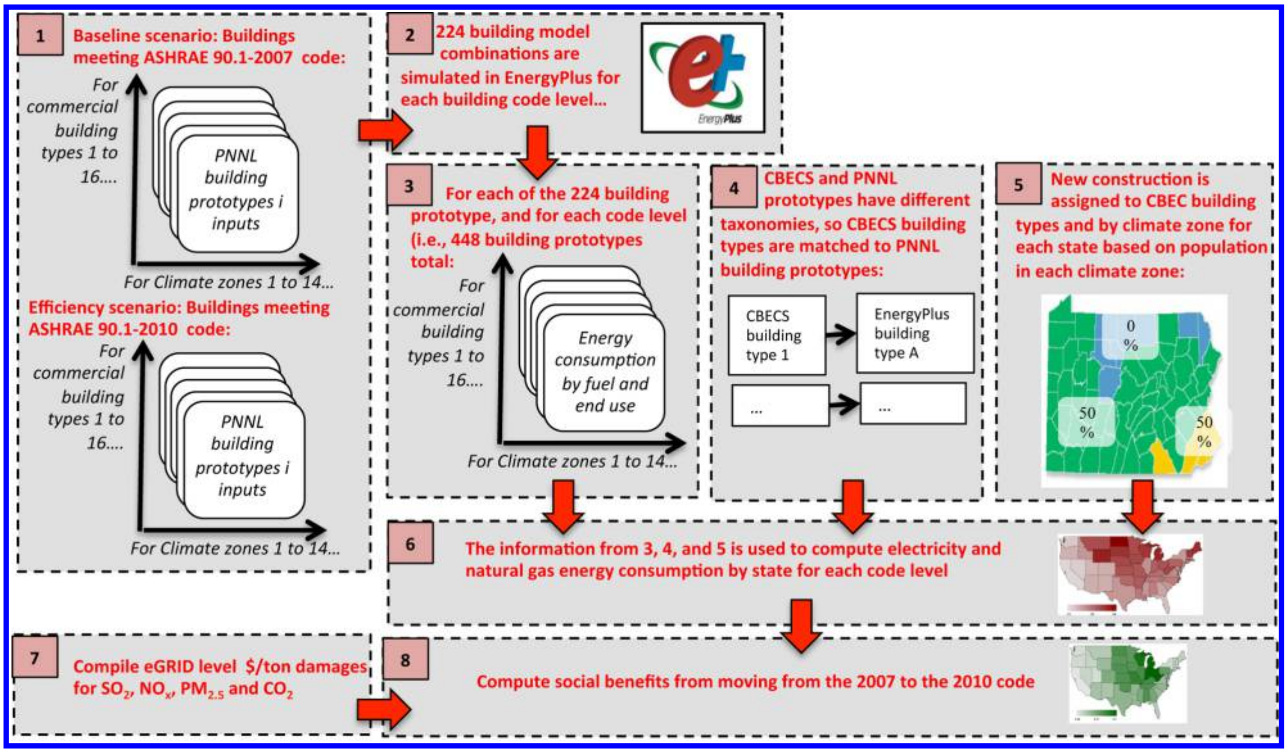

Figure 1. Model schematic describing the methods. Boxes 1, 2, and 3 are described in detailed in the methods section called "Simulating Commercial Building Energy Use Intensity under Different Code Levels by Building Type and Climate Zone". Boxes 4 and 5 are described in the methods section called "Estimating New Commercial Building Construction by State, Climate Zone, and Building Type". Finally, Boxes 6, 7, and 8 correspond to the description provided under "Estimating Private and Social Benefits of Building Energy Codes.

result of the incentives. However, the widespread adoption of ASHRAE 90.1−2007 following a one-time incentive budget increase, from $26 million to $3 billion through the American Reinvestment and Recovery Act, indicates that states are aware of the program. Figure S1 in SI2 shows the current code level of each U.S. state.

Previous research suggests that building energy consumption, and the effect of commercial building energy codes on energy consumption, vary greatly across building types and climate zones.[7,10−13] Further, states are diverse in their climates, types of buildings constructed, and total amount of commercial floor space constructed.[14] This heterogeneity suggests that the benefits of energy codes could vary substantially between states. However, quantitative estimates of code benefits at the state-level, which could help policymakers set total incentives appropriately and understand how incentive funding compares with potential benefits, are not available. The guidance provided by existing studies is constrained by their limited scope that focuses on an individual or small number of states and/or on a small subset of commercial building types and climate zones.[15,16] Other available studies do not consider differences between states in the types of buildings constructed and the magnitude of construction.[13,17] Finally, the benefits of energy codes, beyond energy, and carbon dioxide emissions savings, are an emerging issue of interest.[18] This paper aims to fill these knowledge gaps by developing and applying a method to estimate state-level social benefits of energy codes for commercial buildings. We focus our discussion on social benefits (i.e., reductions in external costs, such as health and environmental effects, and damages associated with climate change) because the federal government can reasonably spend social resources to capture social benefits.

In this work, we estimate the benefits of a more stringent commercial building energy code (90.1−2010) for new commercial buildings constructed in each individual state in the continental United States. To use a consistent baseline code, we select to use the 90.1−2007 code level for all states (despite the fact that a few states have already adopted more stringent building codes). Our objectives are to assess how the potential energy, climate, environmental, and human health benefits of ASHRAE 90.1−2010 are distributed across states and to compare how well potential benefits align with the magnitude and allocation of the federal incentives designed to capture those benefits. For those states that have already adopted the 90.1−2010 code, our estimates correspond to the benefits that are currently being captured.

■ MATERIALS AND METHODS

Methods Overview. We estimate state-level energy consumption and emissions for new commercial buildings when new commercial buildings meet either the ASHRAE 90.1−2007 or the 90.1−2010 code. We estimate the monetary value of the benefits of states switching to the more stringent (2010) code level. Our model relies on the key assumptions that new commercial building energy consumption can be modeled using building energy simulation and that monetary estimates of the marginal damages of pollutant emissions reflect the social cost of pollution. In Figure 1, we show the framework used in this analysis, and here we briefly describe the method used.

We use building prototypes by building type and climate zone that were developed by the Pacific Northwest National Laboratory (PNNL) (see (1) in Figure 1). These building prototypes meet either the 2007 or the 2010 code level. We use these building prototypes to estimate energy consumption by fuel and by end use in new commercial buildings. To do so, we use a building energy simulation model—EnergyPlus (see (2 and 3) in Figure 1). We also use historical construction from a PNNL data set on commercial building construction from 2003 to 2007 and on the Commercial Building Energy Consumption Survey (CBECS) in order to get total energy consumption by commercial buildings in each state (see (5) in Figure 1). The PNNL building prototypes and the building types in CBECS have different building taxonomies. Before getting a total state value, we thus match the PNNL prototype building with the closest CBECS type building (see (4) in Figure 1). Through this process we match approximately 80% of new commercial building construction with an EnergyPlus prototype.

We compute the energy consumption by state for each code level (see (6) in Figure 1), and the respective difference in energy consumption between building code levels. We estimate the upstream reductions in emissions of pollutants that affect human health, environmental health (SO_2, NO_x, $PM_{2.5}$), and climate (CO_2) (see 7 and 8 in Figure 1). Finally, we convert changes in energy consumption and emissions into monetary values using state specific energy prices as well as location and pollutant specific marginal damage estimates.

We report energy, emissions, and monetary results for a single year (i.e., the first year of a building's life). In addition to single year results, we also report the results for a scenario where more stringent energy codes have an assumed effective lifetime of 10 years and future benefits are discounted at 3% annually. Monetary values from other research are scaled to 2010$ using the Consumer Price Index (CPI). For example, the damages caused by pollution from the AP2 integrated assessment model are scaled from 2000$ to 2010$ using the CPI. In the sections that follow, we provide more details on methods and data.

Simulating Commercial Building Energy Use Intensity under Different Code Levels by Building Type and Climate Zone. We use building prototype models from PNNL as inputs to the EnergyPlus software to simulate new commercial building energy consumption for different building types and climate zones.[7] For our baseline, we simulate building energy consumption at the ASHRAE 90.1−2007 code level, the most common energy code level across states in the U.S. We then compare baseline energy consumption with energy consumption at the ASHRAE 90.1−2010 code level. The difference between building models at the 90.1−2007 and 90.1−2010 code levels is the result of the 41 code changes, as described in SI1. Prototypes exist for 16 building types, including office buildings, retail stores, and schools across 14 U.S. climate and subclimate zones, resulting in 224 building models for each of the commercial building energy code levels. These prototypes meet the minimum standards of each code level.[7]

EnergyPlus is a freely available building energy simulation model created by the Department of Energy (DoE).[19] EnergyPlus simulates the energy consumption of a building over a chosen time period (e.g., 1 year) using input files that specify building characteristics and weather data. EnergyPlus performs heat balance calculations at each time step to determine energy losses (e.g., loss through walls, windows, and floors) and gains (e.g., solar insolation through windows, heat gain from lighting/equipment/occupants).[19,20] The characteristics of building systems, such as furnace or air conditioner technology types and efficiencies, determine the amount of electricity or natural gas needed to maintain the desired indoor conditions. Indoor conditions are specified in building operating schedules. Operating schedules also define building characteristics such as thermostat set points, occupancy, equipment operation, and lighting schedules.

We convert the EnergyPlus simulation results into building energy use intensities (annual energy use per square meter) for delivered electricity and natural gas for all building models. In the SI, section SI3, we show the baseline energy savings by building type.

A National Research Council report on energy efficiency standards and green building certification suggests that using building simulation models often results in energy consumption estimates that differ substantially from the actual building energy consumption.[21] In order to address this issue, in the SI, section SI4, we compare the simulated energy consumption of the building prototypes at the 90.1−2004 code level with the actual energy consumption of the U.S. commercial buildings constructed from 1990−2003.[22,23] We use simulated energy consumption at the 90.1−2004 code level for this validation exercise because it most closely matches the CBECS data; CBECS has not published more recent building energy consumption data since 2003. Across all building prototypes, the simulated electricity and natural gas consumption of buildings at the 90.1−2004 code level are similar to the actual electricity and natural gas consumption of equivalent buildings in 2003 (for more details see Figures S3 and S4 in SI4). Given the lack of more recent data, we are unable to validate the modeled energy consumption for building prototypes that meet the 90.1−2007 and 90.1−2010 code levels.

Estimating New Commercial Building Construction by State, Climate Zone, and Building Type. The goal of this step is to allocate state level estimates of new commercial building construction by climate zone and by EnergyPlus building prototype. A complicating factor is that there are estimates of state-level construction data by CBECS building type, but not by EnergyPlus building prototype.[14] Most CBECS building types aggregate similar building types (for example "offices") whereas EnergyPlus prototypes have a subset of categories (i.e., small, medium, and large offices). In the SI, Section SI5, Table S2, we show how CBECS building types map to EnergyPlus prototypes. For example, based on PNNL data, CBECS office buildings are divided among small office (38%), medium office (40%), and large office (22%) EnergyPlus prototypes; we assume this ratio is constant across states.[14] With this method, we match approximately 80% of commercial building floor space constructed from 2003 through 2007 (the date range of the PNNL construction data set) to EnergyPlus prototypes.

We then further allocate state-level construction data for each EnergyPlus prototype across the climate zones within each state. A map of the climate zones of each U.S. county as defined by the Department of Energy is shown in the SI, section SI6.[24] As suggested in Deru (2011), we allocate new construction to each climate zone in proportion to the fraction of state population change within that climate zone.[25] Population changes for each climate zone in a state are calculated using county level population changes between 2000 and 2010 from the U.S. Census.[24,26] The final output is a data set for each state that specifies new commercial building floor space by EnergyPlus prototype and climate zone. Population change is well correlated with commercial building construction, as we show in the SI, section SI7.

Estimating State Level Commercial Building Energy Consumption. Finally, we calculate the total change in energy consumption of newly constructed commercial buildings in each state by multiplying building and climate specific energy use intensities by building and climate specific estimates of commercial building construction. The result is site electricity and natural gas savings, for a single year, due to increasing the stringency of the building energy code.

Estimating Private and Social Benefits of Building Energy Codes. In order to evaluate the effects of adopting the more stringent code, we estimate both the private benefits and social benefits that occur due to reductions in energy consumption. For this analysis, we define private benefits as the monetary value of energy bills savings to consumers and calculate private benefits by multiplying changes in energy consumption by state-specific average commercial electricity and natural gas prices from the Energy Information Administration.[27,28]

In order to quantify the social benefits of energy savings we follow the method used by the National Research Council (NRC).[29] The NRC calculates the total social cost of pollutant emissions as the product of multiplying county specific pollutant emissions by the county and pollutant specific damages caused by those emissions.

County Specific Social Cost of Pollutant Emissions. The Air Pollution Emission Experiments and Policy analysis (APEEP) integrated assessment model forms the basis of the social cost per unit of pollution for both NRC (2010) and our research.[30] The AP2 integrated assessment model (the most recent version of the APEEP model) quantifies the damages related to human morbidity and mortality, changes in agriculture and timber yields, reductions in visibility, damage to human structures, and lost recreational opportunities.[31] In practice, however, human mortality and morbidity account for the vast majority of the dollar value of reducing pollutant emissions.[30] While there are several integrated assessment models that could be used to estimate the social cost of pollution (e.g., ref 32), we rely on the AP2 integrated assessment model given that it has been extensively used in the literature.[29,33−35] Further, while we note that there is a large uncertainty associated with any exercise that monetizes health and environmental effects associated with air pollution, the output damages from the AP2 integrated assessment model broadly replicate the larger integrated assessment literature. For example, per kilogram of pollution $PM_{2.5}$ emissions are the most harmful, followed by SO_2, and NO_x and geography plays an important role in determining the damages caused by pollution.[36] In this paper we use the AP2 integrated assessment model damage values for SO_2, NO_x, and $PM_{2.5}$ for each U.S. County for 2008; these are the most recent damages values that are publicly available.[33,34] Finally, since the AP2 model does not include CO_2, we use a social cost of carbon emissions of $33 per metric ton of CO_2 in our baseline scenario.[37]

Social Benefit of Electricity Savings. We value changes in emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) that result from decreases in consumption of electricity as a result of the adoption of building energy codes. The social benefit of the more stringent code ($) equals the electricity saved in the state (e.g., MWh), scaled by a transmission loss factor, and multiplied by the reduction in external damages for each unit of source electricity savings (e.g., $/MWh).

To estimate the state average reduction in external damages for each megawatt hour of electricity savings, we first calculate reductions in external damages per megawatt hour for each eGRID subregion. The electricity grid is highly interconnected and contains generators in discrete locations. Therefore, we cannot assume that reducing electricity consumption by one megawatt hour in a given county will correspond to one less megawatt hour of electricity production in that county. Instead, we estimate how a change in consumption affects production, emissions, and social costs for eGRID subregions, as described in the next paragraph. We break the U.S. electricity grid into eGRID subregions because they "uniformly attribute electric generation in a specific region of the country".[38] A map of the eGRID subregions used is shown in the SI, Section SI8. Equation 1 shows how we calculate the average social benefit for each eGRID subregion:

$$\Delta S = \sum_{cty=1}^{\mathrm{CTY}} \Delta D_{\mathrm{cty}} \times \mathrm{ef}_{\mathrm{cty}} \times \mathrm{gen.\ fraction}_{\mathrm{cty}} \quad (1)$$

Where ΔS is the social benefit per MWh ($/MWh) between using each of the code levels, ΔD is the avoided damage from reducing pollutants in each county ($/ton), ef is the emission factor of electricity generators in each county (tons/MWh) and gen·fraction is fraction of total subregion generation that occurs in each county (unitless).

We use generation and emissions data from 2011, the latest year with generation and emissions data for all pollutants. Generation data is from EIA-923 form. Emissions data is from the EPA Clean Air Markets Program (CO_2, SO_2, and NO_x emissions data) and the 2011 National Emissions Inventory (NEI; $PM_{2.5}$ emissions data).[39−41] We then value pollutant emissions using the AP2 integrated assessment model values and the social cost of carbon previously described.

Finally, we estimate state averaged social benefits based on the source of electricity generation in the state (i.e., eGRID subregion). For example, the electricity generation from power plants that are located in Pennsylvania and that belong to the Reliability First Council East (RFCE) account for 70% of total generation in Pennsylvania, so we assume that 70% of damages from RFCE, and 30% of the damages are at the levels from Reliability First Council West subregion (RFCW). Finally, the state average social benefit rate is multiplied by a regional estimate of average line losses from eGRID to convert from social benefits due to source energy savings to social benefits due to site energy savings.[42]

Social Benefit of Natural Gas Savings. The social benefit of reducing natural gas consumption in buildings ($) is estimated by the site natural gas savings (e.g., GJ) multiplied by social benefit per unit of site natural gas avoided (e.g., $/GJ). Given that reductions in site natural gas will reduce emissions at the building site, we estimate the state average social benefit rate by weighting the avoided external damages in each county by the fraction of construction that occurs in each county. As described above, new construction in each county is based on population change in each county.

We calculate the social benefit rate for CO_2 and NO_x and estimate that other natural gas related pollutant emissions will be negligible.[43,44] Emissions factors are from the AP-42 emissions factors database: 50.6 $\mathrm{kg_{CO2}/GJ_{natural\ gas}}$ and 0.042 $\mathrm{kg_{NOx}/GJ_{natrual\ gas}}$.[44] A more recent analysis of natural gas combustion in residential furnaces confirms that AP-42 emission factors reasonably approximate actual NO_x emis-

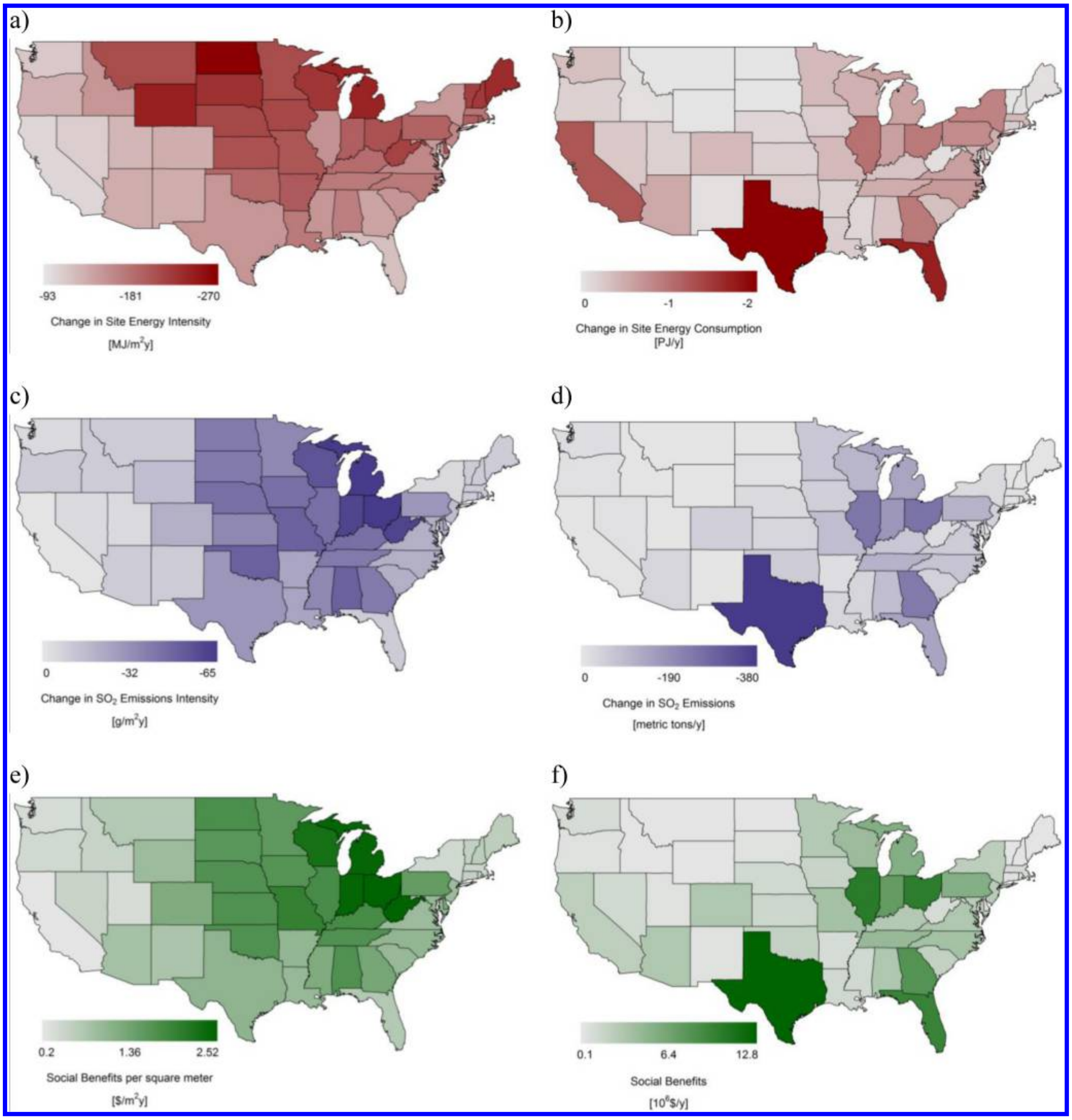

Figure 2. Effect of each state switching from ASHRAE 90.1−2007 to 90.1−2010 in terms of reductions in intensity and total savings. Figures show (a) site energy use intensity reductions, (b) state annual site energy consumption reductions, (c) new building SO_2 emissions intensity reductions, (d) state annual SO_2 emissions reductions, (e) building code annual social benefits per unit of floor space constructed, and (f) annual social benefits from adopting the more stringent code.

sions.[43] We value CO_2 emissions using the same social cost of carbon as for electricity, $33 per metric ton, and NO_x emissions using the AP2 integrated assessment model NO_x valuation for ground level emissions.[33,34,37]

RESULTS

For all results in this section, we denote "social savings" as the reductions in health, environmental, and climate change related damages, and "private savings" for the reductions in electricity and natural gas energy bills.

State-Level Effects of ASHRAE 90.1−2010. Figure 2a shows the potential reductions in site energy use intensity for states in the continental U.S., which range from 93 MJ/m^2 of new construction per year (California) to 270 MJ/m^2 of new construction per year (North Dakota). States have different changes in building energy use intensity due to differences in climate, variations in building energy savings across climate zones, and also differences in the mix of buildings constructed in each state. However, total potential energy savings (Figure 2b) correlate strongly with total area of new commercial

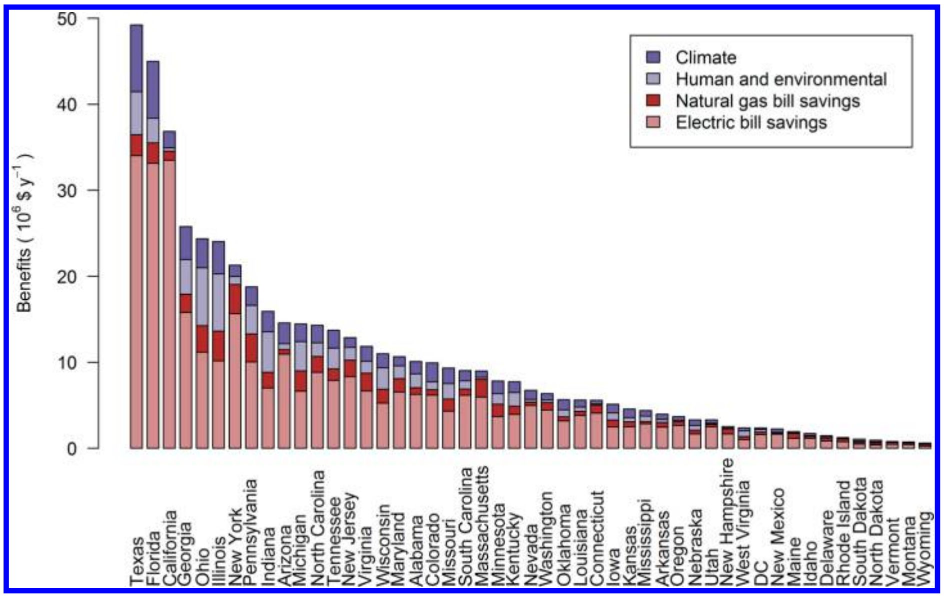

Figure 3. Total annual potential benefits of commercial building energy codes by state for one year worth of new building construction. Private benefits correspond to reductions in electricity and natural gas expenditures. Social benefits correspond to the reductions in human and environmental damages and avoided climate damages.

construction and are highest in states with the largest amounts of new construction.

Figure 2c and d show the changes in SO_2 emissions. We highlight SO_2 because it accounts for 78% of total human and environmental damages and 38% of total social benefits when including the climate benefits of avoided CO_2 emissions. This finding is in agreement with existing integrated assessment literature: SO_2 pollution causes the greatest human and environmental damages (accounts for the greatest share of benefits) despite the fact that SO_2 causes less damage per ton than $PM_{2.5}$ because of the large number of tons emitted (saved).[34,45,46] Potential savings of other pollutant emissions are shown in the SI, Section SI9. Potential emissions savings depend on both state level building construction rates and the emissions intensity of electricity production in individual states. States with large amounts of construction only have large emission reductions (relative to other states) if the grid emission rate is non-negligible; states with small amounts of construction do not have large emission reductions.

Figure 2e and f show the annual social (i.e., health, environmental and climate change) benefits of adopting the 90.1−2010 building energy code. Annual social benefits range from \$0.2 per square meter in California to \$2.5 per square meter in Ohio. As with changes in emissions, we find a strong correlation between social benefits and the amount of new commercial construction but only when social benefits per unit of energy savings are non-negligible. Figure 2 also highlights that federal policy makers should differentiate between states with high energy, emissions, and social benefits intensity and states with large total energy, emissions, and social benefits. Incentivizing states based on the intensity of benefits will not necessarily incentivize the states with the largest total benefits.

To date, 13 states (California, Delaware, the District of Columbia, Illinois, Iowa, Massachusetts, Maryland, Mississippi, Oregon, Rhode Island, Utah, Virginia, and Washington) have adopted ASHRAE 90.1−2010. According to our model these states account for 18% of national social benefits, 25% of national private benefits, and 23% of total benefits.[47] Given that these states have adopted ASHRAE 90.1−2010, our results provide a first order estimate of the benefits that these states are already capturing.

Ten other states (Arizona, Colorado, Kansas, Maine, Minnesota, Missouri, Oklahoma, South Dakota, Tennessee, Wyoming) continue to have building codes that are below the 90.1−2007 level. Those 10 states represent 16%, 13%, and 14% of our computed nationwide social benefits, private benefits, and total benefits. When we rerun our analysis assuming that these 10 states have adopted the ASHRAE 90.1−2004 as a baseline code level, we estimate the benefits of adopting the 90.1−2010 code, in these states, is approximately 38% larger that when the 90.1−2007 code is used as the baseline (see SI, section SI10).

State-level effects vary by orders of magnitude between the states with the highest and lowest potential benefits. Additionally, the potential benefits of commercial building energy codes are relatively concentrated, with about 20% of states holding about 50% of benefits across most of the metrics evaluated. The same group of states consistently provides large fractions of potential benefits.

Figure 3 shows state-level private and social benefits associated with the reductions in energy consumption for one year of operating all new commercial building at the 90.1−2010 code level instead of the 2007 level. Of the \$506 million first-year benefits estimated by our model, private benefits account for 74% (\$372 million) of total benefits and social benefits account for the remaining 26% (\$134 million). Reductions in electricity expenditures account for the majority of private benefits. For the social benefits, reductions in human/environmental damages and future climate damages account for nearly equal shares of social benefits. The fraction of total benefits that accrue privately versus socially varies substantially across states. In all states, the reductions in energy bills are larger than the reductions in environmental, health, and climate change damages. For example, private benefits account for half of total potential benefits in Ohio; while private benefits account for the majority of total potential benefits in California. Social benefits will scale linearly with the value of human and environmental impacts. For example, if the social cost of carbon is assumed to be \$65 per ton of CO_2 instead of \$33, then social benefits increase to 35% of total benefits from 26% of total benefits.[46]

Figure 3 shows the *annual* private and social benefits of adopting the more stringent energy code. Lifetime benefits will be much larger. To account for this, we review electric and natural gas utility energy efficiency program documentation and find that most efficiency measures are expected to last at least 10 years.[48,49] Using 10 years as a first order estimate of the effective lifetime of building codes, we estimate the present value social benefits for the amount of new floor space constructed in a year. For example assuming the new floor space was constructed in 2011 (and using emissions factor projections from 2011 to 2021), the present value benefits over a 10-year period would be \$990 million. If instead we perform the same calculation but exclude the 13 states that have already adopted the 90.1−2010 code, this value amounts to \$800 million in present social benefits nationwide.

Comparing Social Benefits and Current Federal Incentive Adoption Incentives. When states adopt building energy codes, society has the potential to realize social benefits from reductions in fossil energy consumption and emissions of air pollutants. Policies to improve building codes and incentivize the adoption of building codes are an important mechanism for capturing these potential benefits.

We evaluate the effectiveness of the current incentive policies by asking whether the magnitude of building code benefits are similar to the incentive funding provided to capture those benefits. Nationally, for the 38 states that have not adopted the 90.1−2010 code, approximately \$800 million dollars (present value) in social benefits are foregone the first year codes are delayed. If code adoption is delayed five years then cumulative foregone social benefits reach \$3.5 billion. These benefits are substantially larger than the \$26 million in annual incentive funding provided to states. The large magnitude of the social benefits suggests that federal policy makers should re-evaluate the resources being allocated to building code related efforts.

Policymakers should consider increasing the incentives dedicated to increasing code adoption if two conditions are met. First, policymaker should believe that increasing incentives will increase code adoption; this hypothesis is supported by the broad adoption of more stringent codes after the American Recovery and Reinvestment Act funds temporarily increased incentives substantially.[47,50] Second, the total federal and state resources being devoted to codes (including current incentives, administrative costs, technical assistance, and implementation and enforcement costs) should not exceed the social benefits of the codes or increasing funding will not increase net social benefits. If these conditions are met, we recommend that federal policymakers consider increasing the resources devoted to the adoption of more stringent building energy codes.

Next, we compare the percentage of social benefits provided by each state with the percentage of total incentive funding provided to each state, that is, the equitability of the allocation mechanism used by the federal government (Figure 4), under the assumption that the goal is to reduce health, environmental, and climate change related damages. If the goal of the incentive funding formula is to allocate incentive dollars at an equal rate per unit of benefits across states, then the points in Figure 4 should lie along a 1:1 line. We find that the current funding scheme misallocates approximately 25% of annual incentive funds, or \$6.4 million annually. The current allocation formula would more equitably distribute incentives based on potential

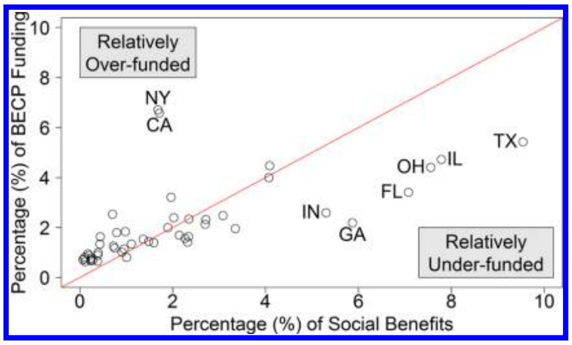

Figure 4. Percentage of annual Building Energy Codes Program (BECP) funding each state receives (y-axis) versus the percentage of social potential benefits, excluding private benefits (x-axis). The solid line indicates a 1:1 ratio between percentage of national benefits and percentage of national incentive funding. The distance on the y-axis between each point and the solid line shows the discrepancy between potential benefits and actual funding; points above the line show relatively overfunded states and points below the line show relatively under-funded states. The states with the largest discrepancies between funding and potential benefits are labeled.

social benefits if Florida, Georgia, Illinois, Indiana, Ohio, and Texas received larger incentives and California and New York received smaller incentives. The underlying cause for this funding misallocation is that the incentive allocation formula does not take into account average grid emissions rates; funds are allocated based on population and energy consumption only. Our results indicate that energy and population are an important start to equitably allocating incentives, but an improved model would consider state average grid emission rates as well. To be clear, according to our analysis, all states seem to be underfunded, but some are relatively more underfunded than others. We do highlight the caveat that we have not considered the costs for program implementation.

Sensitivity Analysis. We vary model parameters to assess the sensitivity of model results to data uncertainty. Specifically we vary the allocation of buildings across (1) climate zones, (2) building types, and (3) the energy savings of buildings meeting 90.1−2010 relative to meeting 90.1−2007. Additionally, we vary (4) the emission rates of pollutants emitted during electricity production. We test the sensitivity of (1) and (2) because population change is an imperfect proxy for construction and because allocating commercial construction data to a set of prototypes involves judgment and is likely to be imperfect.[14] We test (3) because building energy simulations often overestimate actual energy savings.[21,51] Finally, we test parameter (4) because existing emissions regulations are projected to change grid emission rates substantially in the future.

We perform a Monte Carlo simulation that randomly varies the fraction of building floor space allocated to each climate zone and building type, parameters (1) and (2). We provide additional details on the method and findings of this analysis in the SI, Section SI11. Model results are largely insensitive to changes in the allocation of buildings across climate zones: reallocating "x" percent of buildings to different building types or climate zones results in a less than "x" percent change in results for nearly all simulations. The low sensitivities indicate that uncertainty in the building construction mix and distribution will not change our qualitative conclusions.

To quantify the effect of decreased building energy savings on total potential energy savings, parameter (3), we reduce both the electricity and natural gas energy savings of a single building type by 25% and rerun the model. We repeat the process for all 16 building types. When energy savings is reduced by 25% total energy savings are reduced by up to 5% in in retail buildings, the building type that accounts for the largest shares of total construction. Total state energy savings are reduced by less than 1% for most other building types. Total energy savings are most sensitive to changes in the energy savings of retail stores, secondary schools, hospitals, and large hotels. Above average increases in efficiency for hospitals and large hotels drive the large reductions in total energy savings when building energy savings was reduced. Above average annual construction for retail and secondary schools drove the large reductions in total energy savings when building energy savings was reduced. We provide further discussion on the energy savings of individual building types in the SI, Sections SI3 and SI11. Misestimating the energy savings of more than one building type has an additive effect on our results (e.g., misestimating two building types that each individually reduces state savings by 1% and 2% yield a total reduction in savings of 3%).

Social benefits will also change due to changes in electricity grid emission rates, parameter (4), but future emission rates are uncertain. We use EIA projections of electricity grid emission rates to provide a first order estimate of future code benefits, with the understanding that such projections are inherently uncertain and often very different from actual emissions. EIA provides electricity grid emissions rate projections by eGRID subregion for CO_2, SO_2, and NO_x.[52] We assume $PM_{2.5}$ emission factors change proportionately the SO_2 emission factor, but that the marginal damage of pollutant emissions remains constant. Then, we rerun the model using emissions projections through 2040 (see SI, Section SI11, Figure S12). We find that the social benefits of 90.1−2010 are likely to decrease over the next ten years and then to remain near $100 million annually through 2040 (nominal dollars). We provide additional discussion of the changes in benefits at the state level in the SI, Section SI11.

Table 1. Benefits of the 90.1−2010 Energy Code, Relative to the 90.1−2007 Building Energy Code[a]

social benefits (10^6 \$/y)	(a) Single year worth of construction benefits (nominal dollars)			(b) ten year PV; buildings constructed in
	2011 (baseline)	2020	2040	2011
human/ environmental	65	27	28	380
climate	69	70	68	610
total	**134**	**97**	**96**	**990**

[a]In all cases, the benefits refer to the amount of floor space constructed in one year. In (a) we show the annual savings, in nominal dollars, for one year worth of construction in 2011, 2020, or 2040. The difference across years is due to different pollution emissions rates for those years, using historical emissions rates in 2011, and projected emission rates from the EIA, for 2020, and 2040.[52] Health and environmental benefits assume that marginal damages of NO_x, SO_2, and $PM_{2.5}$ pollution ($ per ton of pollutant) remain constant over time.[34] We value climate benefits using the EPA social cost of carbon ($33/metric ton of CO_2).[37] In (b) we show the 10-year present value benefits of one year worth of new construction for year 2011. Future benefits are discounted at 3% annually.

In general, our findings and conclusions are not sensitive to uncertainties in the distribution of construction across building types and climate zones, the energy savings of an individual building type, and projections of electricity grid emissions rates. If the emissions intensity of the electricity grid decreases as projected, then the potential annual benefits of adopting 90.1−2010 are likely to decrease slightly over the next ten years, but remain substantially larger than the incentive funding provided to states through 2040. Climate benefits will also shift to accounting for two-thirds of social benefits, an increase from the one-half of social benefits they provide today. Decarbonization of the electricity grid would virtually eliminate the emission benefits of building energy codes. However, there are no signs that such a decarbonization will take place in the coming decades.

Future Work. We estimate the health, environmental and climate change benefits, and the savings from reduced energy bills that may occur when states adopt more stringent building energy codes. We find that the benefits vary substantially across states and building types. Given that individual building efficiency programs are also implemented, such as utility energy efficiency programs targeted at individual appliances or building types, it is important to develop estimates of the social benefits provided by individual efficiency measures. Additionally, we use a conservative estimate of effective code lifetime to estimate net cost of deferring code adoption; other researchers have assumed longer building lifetimes when estimating benefits. Further research should be conducted to clarify the effective lifetime of building codes and therefore the benefits that a state forgoes when choosing to not adopt a more stringent code. We anticipate factors such as building renovation rates, the lifetime of efficiency measures, and energy efficiency "learning curves" should be incorporated into such a decision analysis model.

Finally, we calculate social benefits using annual average emissions factors at the eGRID subregion level. Recent research has suggested that grid emission rates vary by time of day and season. Future work should quantify the differences in emissions savings estimates between average emission factors and "marginal emissions factors" for common efficiency measures and how these differences may affect decision making.[53]

■ CONCLUSION

Quantitative estimates of the social benefits of more stringent building codes at the state level, which could help set incentives levels and make allocation decisions, have not been available. We assess how the potential energy, climate, environmental, and health benefits of a more stringent code (ASHRAE 90.1−2010) are distributed across states relative to the baseline code (ASHRAE 90.1−2007). We find that total potential energy savings, emissions savings, and monetary benefits correlate strongly with total area of new commercial construction. The amount of floor space constructed each year in the U.S. provides an annual benefit of $134 million in human, environmental, and climate benefits. Assuming the code has an effective lifetime of 10 years, the present social benefits of one year worth of new construction are $990 million. These benefits are substantially larger than the $26 million in annual federal incentives provided to states to spur code adoption. Further, we find that social benefits will remain substantially larger than the federal incentive funding levels when considering projected reductions in grid electricity emissions intensity. Finally, the current incentive allocation formula does not fund states based on potential social benefits and misallocates 25% of the funds. We recommend that federal policy-makers increase the incentives for adopting more stringent energy codes, if policy-makers (1) believe that larger incentives will increase the adoption of more stringent building energy codes; (2) find that total current spending across federal and state programs directed at building energy codes is smaller than the social benefits reported here; and (3) the marginal social benefit of increasing incentives is larger than the marginal social cost of increasing incentives.

■ ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: iazevedo@cmu.edu.

Notes

The authors declare no competing financial interest.

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