



Energy Impacts of Envelope Tightening and Mechanical Ventilation for the U.S. Residential Sector

J.M. Logue¹, M. H. Sherman, I.S. Walker, B.C. Singer

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¹ Corresponding author: jmlogue@lbl.gov

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ABSTRACT

Effective residential envelope air sealing reduces infiltration and associated energy costs for thermal conditioning, yet often creates a need for mechanical ventilation to protect indoor air quality. This study estimated the potential energy savings of implementing airtightness improvements or absolute standards along with mechanical ventilation throughout the U.S. housing stock. We used a physics-based modeling framework to simulate the impact of envelope tightening, providing mechanical ventilation as needed. There are 113 million homes in the US. We calculated the change in energy demand for each home in a nationally representative sample of 50,000 virtual homes developed from the 2009 Residential Energy Consumption Survey. Ventilation was provided as required by 2010 and proposed 2013 versions of ASHRAE Standard 62.2. Ensuring that all current homes comply with 62.2-2010 would increase residential site energy demand by 0.07 quads (0.07 exajoules (EJ)) annually. Improving airtightness of all homes at current average retrofit performance levels would decrease demand by 0.7 quads (0.74 EJ) annually and upgrading all homes to be as airtight as the top 10% of similar homes would double the savings, leading to roughly \$22 billion in annual savings in energy bills. We also analyzed the potential benefits of bringing the entire stock to airtightness specifications of IECC 2012, Canada's R2000, and Passive House standards.

HIGHLIGHTS: ► Housing stock compliance with ASHRAE 62.2 would increase annual site energy demand by less than 1% ► WAPs and non-WAP retrofit programs could reduce stock site energy demand by 0.7 quads (0.74 EJ) annually ► Improving tightening methods could double the tightening related energy impact of retrofits ► IECC 2012 standard seems to capture most of the energy savings of the tightness standards explored

KEYWORDS: HVAC, weatherization, ASHRAE 62.2, retrofit, WAP, energy bills

INTRODUCTION

The residential sector is estimated to use 10.2 quads (10.8 EJ) of site energy and 23% of the source energy annually in the U.S. [1]. Heating and cooling accounts for an estimated 5 quads of site energy (5.3 EJ), about half of the site energy used in residences [2]. Effective envelope air sealing reduces weather driven infiltration and annual energy costs for thermal conditioning. The impact of air sealing is a function of the initial condition of the home, the improvement in air tightness, and the local climate. Effective air sealing often leads to a requirement for mechanical ventilation to ensure acceptable indoor air quality. In recent years there has been a proliferation of federal, state and local residential retrofit programs that incorporate air sealing as a central measure to reduce energy use and associated carbon emissions. Estimates of the energy savings of air sealing and energy costs of mechanical ventilation are often based on extrapolations from simulations [3-5] or comparisons of pre- and post- retrofit energy bills of homes [6-7]. Matson and Sherman conducted the only previous nationwide United States modeling effort to estimate the total energy impact of infiltration and the variability in the impact [8]. We could find no study that estimates the US population benefits of current levels of home tightening seen in retrofits or applying proposed building standards. An understanding of how the benefits of air tightness improvements vary by region, home type, starting air tightness, and other factors could improve program efficacy by focusing on homes that will provide the largest energy savings. Program value could be improved by comparing incremental benefits of increasing air sealing effectiveness (or reaching more stringent air tightness targets) against the costs of achieving these higher levels of home performance.

We developed and applied a physics based-modeling framework to address four main questions: 1) What would be the energy impact of altering the US housing stock to comply with ventilation standards? 2) What would be the energy benefit of tightening all existing homes by the average improvements seen in the low-income Weatherization Assistance Program (WAP) and non-WAP retrofit programs? 3) What would be the benefit of improving air sealing effectiveness to bring all homes to the air tightness levels currently seen in the top 10% of similar homes? and 4) What would be the energy impact of achieving various standards for absolute air tightness in all US residences?

METHODS

We analyzed a virtual, representative cohort of U.S. homes to estimate the energy impact of tightening building envelopes and adding mechanical ventilation for a typical meteorological year. We applied an incremental ventilation energy model (IVE) to estimate the change in energy demand due to a change in ventilation in each home in the analyzed cohort. We used a simplified airflow model along with location based weather data to determine the impact of changes in envelope and duct tightening on airflow through the home. The methods of the analysis and details of the virtual cohort are described below.

Incremental Ventilation Energy (IVE) Modeling Approach

The IVE model was described in detail and compared to a comprehensive physics-based energy, moisture and airflow model by Logue et al. [9] and will be described briefly here. The IVE model uses the change in hourly airflow between two conditions for one home to calculate the overall change in HVAC energy use. The change in total HVAC energy used, ΔE_{HVAC} , is calculated as the sum of four contributions: changes to (1) heating (ΔE_{heat}) and (2) cooling (ΔE_{cool}), (3) changes to the energy used by the air distribution fan for a ducted, forced air system (ΔE_{blower}), and (4) changes to energy used by ventilation fans (ΔE_{fans}), as shown in Equation 1.

$$\Delta E_{HVAC} = \Delta E_{Heat} + \Delta E_{cool} + \Delta E_{blower} + \Delta E_{fans} \quad (1)$$

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The first three terms are all proportional to changes in airflow that occur when each piece of equipment is in use. The incremental change in heating or cooling energy is calculated for discrete time intervals using the following equations:

$$\Delta E_{Heat} = \max[\Delta t([\dot{m}_t C_p (T_{set,t} - T_{out,t})]/\epsilon_{heat}), 0] \quad (2)$$

$$\Delta E_{cool} = \Delta E_{thermal} + \Delta E_{latent} \quad (3)$$

$$\Delta E_{thermal} = \max[\Delta t([\dot{m}_t C_p (T_{out,t} - T_{set,t})]/\epsilon_{cool}), 0] \quad (4)$$

$$\Delta E_{latent} = \max[\Delta t(\Delta A_t * L_v * V_{cond} * (\rho_{water,out,t} - \rho_{water,in,t})/\epsilon_{cool}), 0] \quad (5)$$

$$\dot{m}_t = \Delta A_t * V_{cond} * \rho_{air} \quad (6)$$

The symbols in equations 2 through 6 are defined as follows:

- Δt is the time step in hours.
- \dot{m}_t is the mass flow of air through the home during the time step.
- C_p ($\text{J kg}^{-1} \text{K}^{-1}$) is the heat capacity of air.
- $T_{set,t}$ (K) is the indoor temperature at time t . (thermostat setting).
- $T_{out,t}$ (K) is the outdoor temperature at time t .
- ϵ_{heat} and ϵ_{cool} are the heating and cooling system efficiencies, respectively.
- ΔA_t (h^{-1}) is the change in the whole house air exchange rate at time step t .
- V_{cond} (m^3) is the conditioned volume of the house.
- ρ_{water} (kg m^{-3}) is the absolute humidity (the density of water vapor) in the air indoors and outdoors.
- ρ_{air} (kg m^{-3}) is the air density.
- L_v (J kg^{-1}) is the latent heat of water vaporization.

The cooling load included both sensible ($\Delta E_{thermal}$) and latent (ΔE_{latent}) components. An hourly time step allowed tracking of weather variations throughout each day in concert with meteorological data (TMY3 or Typical Meteorological Year) with the same resolution. Changes to energy demand due to an increased or decreased airflow rate were calculated every hour for a year then summed to calculate the total annual change in energy use for each home. The change in fan energy was simply the energy demand of any additional fans (ΔE_{fans}) added to move air.

The power use of a residential blower system is a function of the home conditioning system size. Since we did not have information about the sizes of the home conditioning systems and blower sizes, we used coefficients derived from residential modeling guidance to determine the impact of changes in heating and cooling energy on blower energy when ducts were present. We used coefficients derived from the modeling design manual used to assess whether new homes in California comply with the energy-efficiency elements of the state building code [10], as shown in Equation 7. The coefficients reflect a sizing relationship between the recommended blower and heating and cooling system sizes for new California homes. The suitability of these coefficients for older systems has not been assessed. We were not able to find sufficient data to do so. We applied these coefficients for all systems that were ducted. When more than one heating system was present, we applied these coefficients to

only the fraction of the heating or cooling energy that was reported to be provided by the ducted system.

$$\Delta E_{blower} = 0.023 * \Delta E_{Heat} + 0.176 * \Delta E_{cool} \quad (7)$$

The IVE model was designed for use in population-level assessments of air-sealing and ventilation energy impacts, with the goal of informing policy and program planning. For this purpose, IVE can be run for many homes, with individual home specifications assigned based on documented characteristics of a home (when available) or by assigning specifications based on established relationships to characteristics that were documented.

One limitation of the model is that it does not account for the impact of ducts and duct tightening on the change in energy use. When ducts are tightened in the home, without changing the envelope, the base load energy demand will decrease. Tightening ducts increases the HVAC system efficiency and reduces the total air exchange rate of the home. Duct leakage also impacts the incremental energy demand since supply duct leakage represents a direct reduction in the system efficiency. Since the IVE does not calculate the total energy demand of the building, we cannot use it to estimate the impact of duct tightening on the home cohort. Adding the impact of duct tightening to the analysis would increase the energy savings of envelope tightening.

Determining Change in Airflow

When applying this model to existing databases of home characteristics, we used an existing, simple airflow model to determine the hourly air exchange rate before and after a change was made to the building envelope and ducts. Walker and Wilson [11] developed an algorithm to calculate infiltration through the building envelope as a function of a limited number of home characteristics, outdoor weather data, and home leakage area. The infiltration air leakage model by Walker and Wilson [11] is described in equations 8-11 below:

$$A_{inf,t} = \frac{Q}{V_{house}} = \frac{1}{V_{house}} \sqrt{Q_{stack,t}^2 + Q_{wind,t}^2} \quad (8)$$

$$Q_{stack,t} = cC_s \Delta T_i^{2/3} \quad (9)$$

$$Q_{wind,t} = cC_w (sU_i)^{4/3} \quad (10)$$

$$c \left(\frac{m^3}{sPa} \right) = \frac{ELA}{\sqrt{\frac{\rho_{air} * dP^{(.67-.5)}}{2}}} \quad (11)$$

The symbols are as follows: $A_{inf,t}$ is the infiltration air exchange rate at time t , V_{house} is the volume of the house, Q_{stack} is the infiltration airflow due to the stack effect, Q_{wind} is the infiltration airflow due to wind, C_w , s , and C_s are constants based on shelter class, number of stories, and number of flues, ΔT is the difference between indoor and outdoor temperature, U is the wind speed, and ELA is the estimated leakage area. The ELA was calculated from the normalized leakage (NL) for each home in the cohort using the following relationship[12]:

$$ELA = \frac{FloorArea * NL}{1000} \left(\frac{2.5m}{Height} \right)^{0.3} \quad (12)$$

In this equation, $FloorArea$ is the floor area of the house and $Height$ is the height of the home. For many of the comparisons we added mechanical ventilation. ASHRAE Standard 136 [13] gives a reference method for combining mechanical ventilation and natural infiltration:

$$A_t = A_{bal,t} + \sqrt{A_{unbal,t}^2 + A_{inf,t}^2} \quad (13)$$

Where $A_{bal,t}$ is the air exchange rate at time step t due to balanced mechanical ventilation alone (such as HRVs and ERVs), $A_{unbal,t}$ is the air exchange rate at time step t due to unbalanced mechanical ventilation alone (this includes exhaust and supply fans), and $A_{inf,t}$ is the air exchange rate at time step t due to natural infiltration alone. Balanced mechanical ventilation uses mechanical equipment to provide both supply and exhaust airflow at roughly equal rates. When mechanical equipment is used to provide only supply or exhaust airflow, airflow in the other direction through the building envelope is induced through the resulting pressure differential and the system is described as unbalanced. Infiltration is natural ventilation that is driven by the indoor-outdoor temperature difference and outdoor wind speed through envelope leaks.

Virtual Cohort of Representative Homes

The Residential Energy Consumption Survey (RECS) is a survey of U.S. housing units performed by the Energy Information Agency (EIA). The RECS has been conducted every one to five years since 1979. The RECS uses a multi-stage area probability design method of sampling, a complex form of cluster sampling, that selects a sample of homes that is representative of the entire population of occupied housing units in the United States. The 2009 RECS database [1] contains data for 12,083 homes including home characteristics that are needed to determine the impact of air tightness on residential energy use including location; number of rooms; thermostat settings; building age; heating and cooling equipment system types, ages and fuel type; home income; and if ducts are present. Each entry is weighted to indicate how representative that home is of the US housing stock.

We used the 2009 RECS database to create a virtual cohort of 50,877 homes to represent the U.S. residential housing stock. The RECS database assigns each of the 12,083 surveyed homes to a reportable domain (a subset of states for which the home is considered typical) and also assigns a weighting for how common the home is within the domain. We used this information to build a sample of homes for each International Energy Conservation Code (IECC) climate zone within each state then used the weightings associated with each entry to develop population statistics by state and separately by climate zone. Each RECS entry was assigned to be part of the representative sample of homes for each climate zone within each of the states within the domain. The RECS weighting associated with each entry, which is the number of homes represented by the entry, was subdivided first among all the states in the domain, then among all the IECC climate zones within those states. The assignment of RECS weighting to climate zones within each state is based on the reported number of homes in each county, which is in turn used to estimate the breakdown of homes among climate zones within the state [14-15]. An example of this is shown in Figure 1 for a specific entry in the RECS database: DOEID 4. Reportable domain 7 includes two states (Indiana and Ohio) and each state includes 2 climate zones (4A and 5A). The original RECS entry (DOEID 4) is used to create 4 virtual homes each representing some number of homes within each climate zone and state combination. Simulation results for each of these 4 virtual homes are multiplied by the weightings to calculate the aggregate contribution of this sample home to the housing stock by state and climate zone. The number of states in a reportable domain varies from 1 to 5, and the number of climate zones per state varies from 1 to 7. Subdividing all the database entries into individual states and climate zones resulted in a virtual cohort of 50,877 homes with weightings to indicate how widely representative each home is. The overall sample

cohort was built from data and information about real homes that are considered representative of their climate zones and regions.

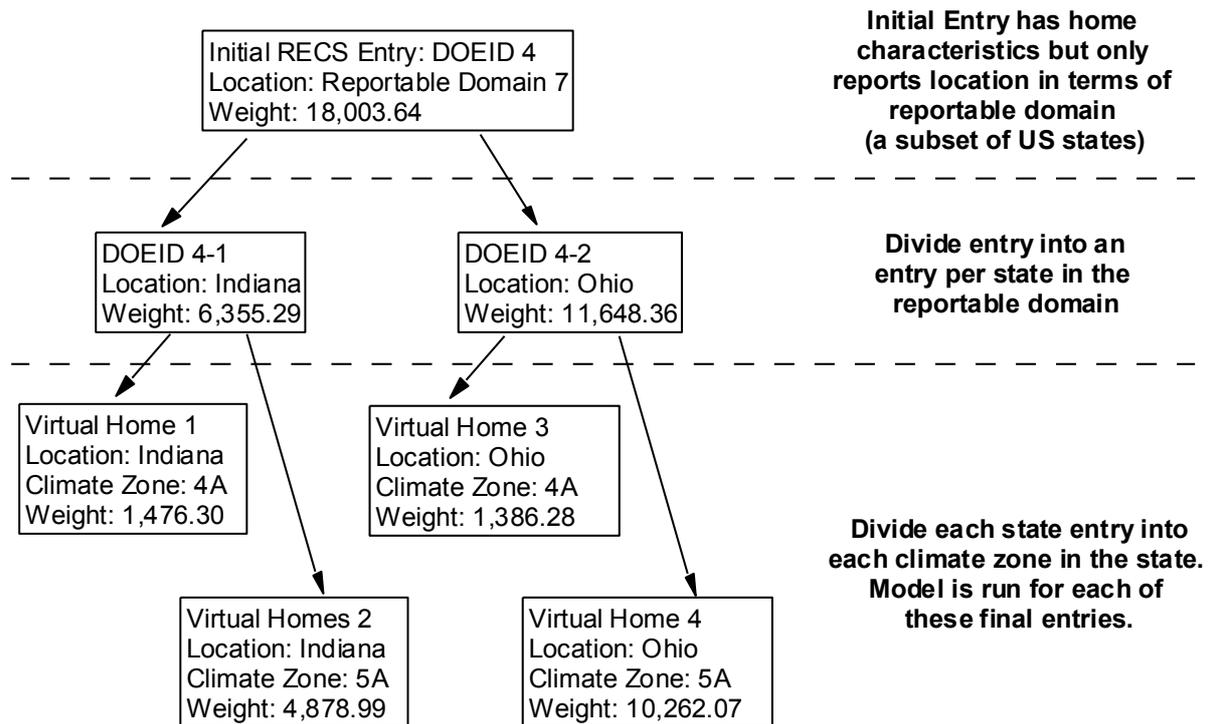


Figure 1. Assignment of an individual RECS entry to serve as a representative home for each combination of climate zone and state within the reportable domain. The figure shows an example of a single home entry in the RECS being split into four virtual home entries, one for each state and climate zone combination in the reportable domain of the original RECS entry. The weight of the initial entry is split between the final four entries according to the number of homes in each county and the IECC assigned climate zones for each county in the U.S.

Most of the reportable domains cover one or two states with relatively similar climates; the exception to this is reportable domain number 27, which includes Alaska, Hawaii, Oregon, and Washington. For this reportable domain, we assigned all homes that reported not heating to Hawaii and subdivided the remaining homes between Alaska, Oregon, and Washington using the method shown in Figure 1. This method resulted in an estimated number of homes in Hawaii that was comparable to the US Census Bureau estimates for Hawaii (4% more homes in our cohort).

The IVE model requires several housing parameters that are not available in the RECS; these parameters were estimated or assigned based on home characteristics that were specified in the RECS. The estimated or assigned parameters include normalized leakage of the building envelope, home size, heating and cooling system efficiencies, hourly weather conditions, and thermostat temperatures for RECS entries that did not have specified values. Table 1 lists the data sources for parameters used in the model. The RECS reports the number of rooms in each home but does not currently report the floor area of the homes. Chan et al [16] established a relationship between room number and home size. We used this same relationship to assign a house size to each home in the RECS. For each home, we used the National Solar Radiation Data Base Typical Meteorologically Year (TMY) data for the weather

station located closest to the IECC identified representative city for the specified climate zone for the home [17].

Table 1. Sources of input parameters for incremental ventilation energy model.

Parameter	Description	Assignment or Selection Scheme
V_{cond}	Conditioned Volume	Calculated based on the number of rooms reported to be conditioned for each home in the RECS. [16]
V_{house}	House Volume	Calculated based on the number of rooms reported in the home for each home in the RECS. [16]
NL	Normalized leakage	Calculated for each virtual cohort home as a function of home age (from the RECS), foundation type (from the RECS), size, and location using the model of [16]
T_{set}	Thermostat setting	If available, taken from the RECS database for each home entry. If data was not reported, we assumed that the thermostat settings to be the median values reported by homes in the RECS for each time period.
T_{out}	Outdoor temperature	Representative meteorological year based on home location (TMY3).
$\epsilon_{heat/cool equipments}$	Heating / cooling equipment efficiency	Assigned based on system type and age of system. The RECS reports conditioning system ages and type. We assigned efficiencies for the systems based on these data. [18]
$\rho_{water,out}$	Outdoor water density in air	Data taken from representative meteorological year based on home location (TMY3).
$\rho_{water,in}$	Indoor water density in air	Assumed a constant 60% relative humidity in all mechanically cooled homes.
ΔE_{fans}	Energy use of additional fans	Fan power specified based on flow rate using energy and airflow relationships from the Certified Home Ventilating Products Directory (HVI) handbook [19].
ΔE_{blower}	Energy use of air distribution blower	For homes with a forced air system and ducts, proportionality coefficients from the ACM were used to determine the change in blower energy use based on heating and cooling energy change.
<i>Location</i>	Climate zone or ZIP code	Each RECS entry indicates the reportable domain of the home. Each entry is subdivided into state and IECC climate zone specific entries for the virtual cohort.

Normalized leakage is a dimensionless term that represents the fraction of the home that is open to airflow normalized for the effects of house size and height and is required to estimate the infiltration airflow. The RECS survey method does not include measurements of home leakage. We used the model developed by Chan et al. [16] to determine a normalized leakage value for each of the homes in our virtual cohort as a function of home location, foundation type, age, size, and the income status of the residents. The Chan model determines, as a function of home characteristics, the median of the distribution of normalized leakages for a home of that type. Since each entry in our cohort represents a set of homes, we used the distribution characteristics from the Chan model to determine the arithmetic mean of the normalized leakages for each entry so that we could multiply the calculated energy demand of each set of home characteristics by the weight for that entry to determine the aggregate change in energy use for the collection of homes represented by the home in our virtual sample. Chan et al. determined that on a population basis, their model accurately estimates the normalized leakage of single family detached homes and multi-family homes, but underestimates the leakage of single family attached homes and mobile homes. According to the RECS, the US housing stock contains 63.2% detached houses, 24.8% multi-family homes,

5.9% attached homes, and 6.1% mobile homes. Applying this model may underestimate the initial normalized leakage for 12% of the housing stock.

For each heating and cooling system in each home we assigned a system efficiency as a function of system type and age based on assignments used by the Home Energy Saver calculation engine [18]. Energy costs for kerosene, electricity, natural gas, heating oil, kerosene, and liquid petroleum gas (lpg) were taken from the US Energy Information Administration (USEIA) reports of state costs. Costs for 2010 were used in the analysis. Most of the homes reported a heating and cooling temperature for when occupants are home, away, or sleeping. For the homes that did not report these values, the median temperature reported by the other homes was used. This default temperature setting for cooling and heating are (away: 75°F, home: 73°F, overnight: 73°F) and (away: 67°F, home: 70°F, overnight: 68°F) respectively.

The RECS included a question about the presence of ducts, but for most homes included in the database this information is not present. The RECS reports the heating and cooling system types. Based on the heating and cooling system types we either assigned the homes to have ducts or not. Central cooling systems, heat pumps, and central warm-air furnaces were assumed to have ducts. The remaining heating and conditioning systems were assumed not to have ducts.

ASHRAE 62.2 Compliance

ASHRAE Standard 62.2 has requirements for manually operable source control ventilation in kitchens and baths, and for whole house ventilation. The current ventilation code is ASHRAE 62.2-2010 [20]. The current code-required whole-house mechanical ventilation rate is based on the assumption that infiltration contributes 2 cubic feet per minute (cfm) per 100 square feet (ft^2) or $0.1 \text{ L s}^{-1} \text{ m}^{-2}$. In addition to this infiltration, the standard prescribes the whole-house mechanical ventilation rate given by Equation 14:

$$Q(\text{cfm}) = 0.01A_{\text{floor}}(\text{ft}^2) + 7.5(N + 1) \quad (14)$$

where Q is the required ventilation rate, A_{floor} is the house floor area, and N is the number of bedrooms. Standard 62.2 also allows for specific infiltration credits and for intermittent operation of mechanical ventilation systems with some restrictions. Standard 62.2-2010 allows the required mechanical ventilation rate to be reduced under certain circumstances when the air leakage has been measured. Based on this credit, the airflow rate of the designed mechanical ventilation system can be reduced by half of the estimated infiltration (calculated using ASHRAE Standard 136) above the assumed rate of 2 cfm/100 sq. ft (from Section 4.1.3 of Standard 62.2).

The proposed standard for ASHRAE 62.2-2013 follows a similar pattern but with a few distinct differences. The proposed standards does not include an assumption of any infiltration. The proposed whole-house mechanical flow rate is given by Equation 15:

$$Q(\text{cfm}) = 0.03A_{\text{floor}}(\text{ft}^2) + 7.5(N + 1) \quad (15)$$

The proposed standard also allows for more of an infiltration credit when the envelope leakage is measured. The airflow rate of the designed mechanical ventilation system can be reduced by the calculated level of infiltration (calculated using Section 4.1.2 of proposed Standard 62.2-2013). For the ventilation simulations analyzed in this paper we applied both the current ASHRAE 62.2 standard and the proposed 62.2-2013 standard.

To calculate the infiltration credit required a weather factor, w , for each house. The ASHRAE 136-2010 and proposed 62.2-2013 standards provide w factors for a limited set of cities. The cohort entries included in this work were only specified at the state level. For each state we determined a population weighted w factor for 2010 and 2013 by assigning each of the US counties the w factor that was located closest to the county.

Analysis Scenarios

Simulations were conducted to assess impacts of five retrofit or upgrade scenarios on the US housing stock. All scenarios included upgrades to ensure that all homes meet 62.2, and most include envelope air tightening. Mechanical ventilation was provided either by an exhaust fan or a heat recovery ventilator (HRV). HRVs reduce the amount of heat need to condition the extra airflow, however they also require more power to operate than an exhaust fan. The six scenarios are described below:

1. Upgrade current housing stock to comply with ASHRAE 62.2.

We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan (1a) or an HRV (1b). For each scenario we reduced the required mechanical flow for each of the homes by the calculated infiltration credit using infiltration calculations in the current 2010 or proposed 2013 standards.

2. Average Tightening: Improve envelope airtightness of all homes at levels currently achieved by Weatherization Assistance Program (WAP) and non-WAP energy efficiency programs while complying with ASHRAE 62.2.

The envelope of each home was tightened using the relationship of pre- and post- retrofit homes that have participated in WAP or other energy efficiency retrofit programs. Chan et al. [16] determined that for non-WAP energy efficiency programs, home tightening typically reduced the normalized leakage by 20% and that for WAP homes the normalized leakage was typically reduced by 30%. The WAP is for low-income homeowners; on average, WAP homes are thought to be in worse condition than non-WAP homes. For this scenario we applied the WAP level of envelope tightening to all homes that had income below 200% of the poverty limit as this is one of the WAP eligibility requirements [21]. The remaining houses were tightened by 20% to reflect the impact of non-WAP efficiency programs. For each home the level of mechanical infiltration was adjusted to reflect the lower infiltration credit due to the tighter envelope.

3. Advanced Tightening: Tighten envelopes as necessary to ensure that each house reaches the current 90th percentile tightness for homes with similar key characteristics while complying with ASHRAE 62.2.

The Chan et al. [16] model determines the median normalized leakage for a home with a given set of parameters. Using the characteristics of the distribution we were able to calculate the 10th percentile normalized leakage value for each home in our cohort, i.e. the tightness level met or exceeded by the 10% tightest home having a similar set of characteristics associated with air tightness. The assumption of this scenario is that the 90th percentile performance (10% most tight homes) is a level that is achievable in practice with effective air sealing retrofit work. This recognizes that even with air-sealing retrofits, air tightness likely will still vary with the age, vintage, construction style and factors related to home quality and maintenance as indicated (imperfectly) by household income. For each home the level of mechanical infiltration was adjusted to reflect the lower infiltration credit due to the tighter envelope. We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan or an HRV.

4. IECC: Tighten all homes to achieve the standards specified in the 2012 IECC standard while complying with ASHRAE 62.2

In this scenario, the envelope airtightness of each home was set to the level recommended by the 2012 IECC standard[22]: 5 air changes per hour at an induced 50 Pascal indoor-outdoor pressure difference (ACH50) for IECC climate zones CZ1 and CZ2; 3 ACH50 for all other climate zones. This is a theoretical scenario that imagines a housing stock of the future that is comprised of homes built or renovated to the 2012 standard. Mechanical ventilation was added in the same manner as the previous scenarios. We added the required amount of mechanical ventilation to the housing stock using either an exhaust fan or an HRV.

5. R2000: Tighten all homes to achieve the standards specified in the Canadian R2000 standard while complying with ASHRAE 62.2

In this scenario, the envelope airtightness of each home was set to the level required in Canada's R2000 standard [23]: 1.5 ACH50. As with scenario 4, this considers a theoretical stock that has been built or renovated to a specific air tightness performance standard. Mechanical ventilation was added in the same manner as the previous scenarios but only HRVs were added to these homes.

6. Passive House: Tighten all homes to achieve the standards specified in the Passive House standard while complying with ASHRAE 62.2

In this scenario the envelope airtightness of each home was set to the level required the Passive House standard [24]: 0.6 ACH50. This was selected as an upper limit airtightness target. Mechanical ventilation was added in the same manner as the previous scenarios but only HRVs were added to these homes.

We specified an HRV Apparent Sensible Effectiveness (ASE) of 82%. Power consumption for the exhaust fan and HRV was calculated as a function of the required airflow based on the specifications for the Broan QDE30BL exhaust fan (on average 0.35 W/cfm) and the Amana Brand HRV150 HRV (0.9 W/cfm)[19].

RESULTS

We determined the impact of the six ventilation scenarios at the U.S., IECC climate zone, and state levels. Each of the scenarios impacted the distribution of air exchange rates in the home cohort. Adding ventilation increased the airflow through the home and increased the home energy use, while tightening the building envelope decreased airflow and energy use. Figure 2 shows the impact of each of the analysis scenarios on the annual average minimum air exchange rate, i.e. the estimated air exchange rate resulting from infiltration and mechanical ventilation. The values are the annual average of the air exchange estimated using the Walker and Wilson airflow model. The values would be increased due to any window or door opening activities. It was assumed that windows and doors are not left open during home conditioning, and therefore this extra airflow does not impact the energy demand of the home.

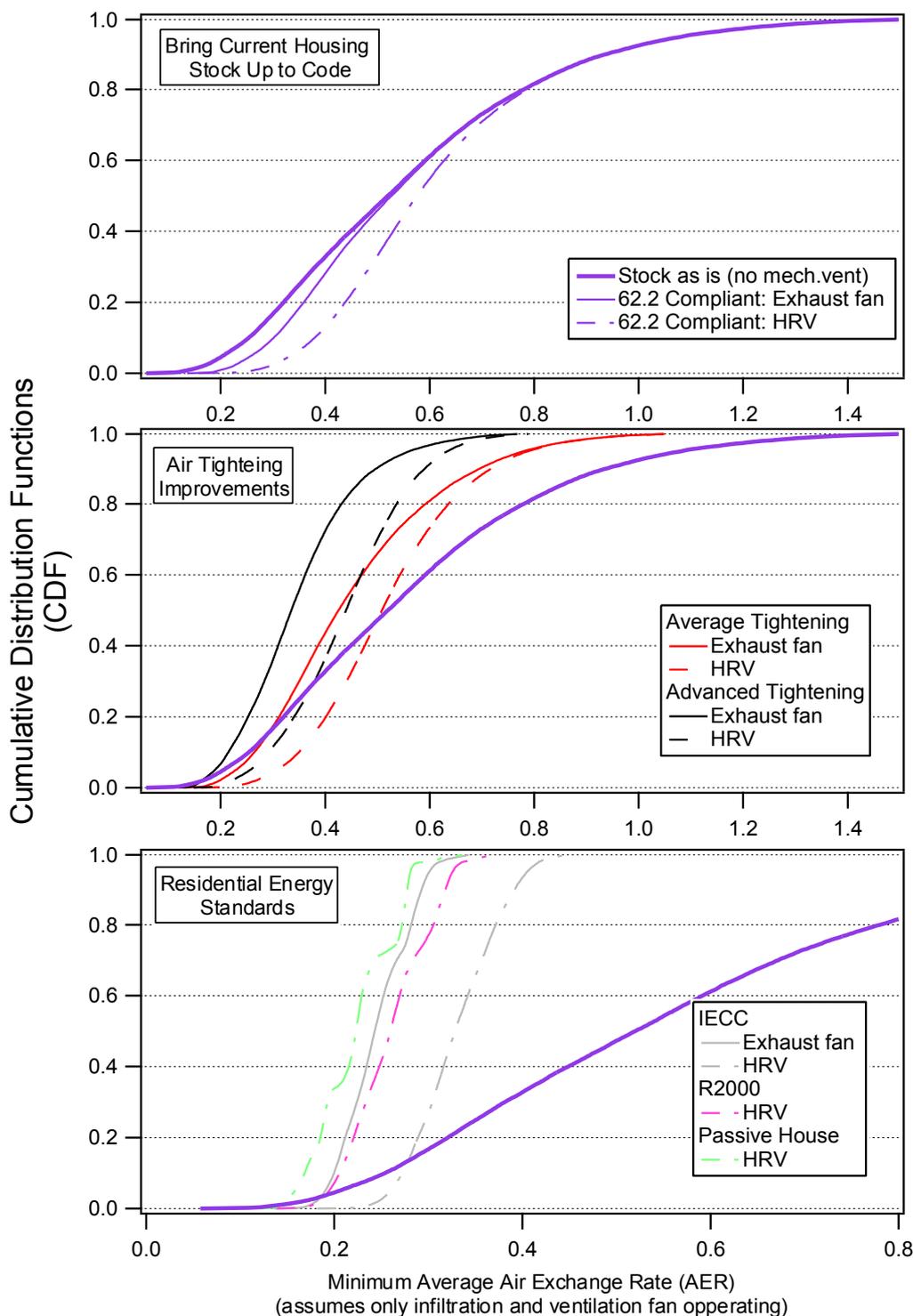


Figure 2. Impact of ventilation scenarios on minimum annual average air exchange rate. These graphs present the distribution of minimum annual ventilation rates for the US housing stock as-is, entirely in compliance with ASHRAE 62.2, after air sealing at average and advanced levels, and when various standards for tightness are applied. Except for the “as is” plot, all plots include compliance with ASHRAE 62.2-2010.

Figure 2 shows that making the current housing stock compliant with ASHRAE 62.2 would appreciably impact the average airflow in 45-80% of homes depending on whether an HRV or exhaust fan was used. Both the HRV and exhaust fan are run at the same flow rate. The HRV has a larger impact on total air exchange rate because it is a balanced fan versus the

unbalanced exhaust fan. As Equation 13 shows, unbalanced flows are added to infiltration by quadrature whereas balanced flows are added directly resulting in higher total air exchange rates in homes using HRVs at the same flow rate. Tightening the stock with Average and Advanced improvements would reduce the median annual average air exchange rate by up to 0.2 air changes per hour depending on the type of ventilation used. Applying increasingly strict standards could lead to an additional median reduction of up to 0.3 air changes per hour.

Table 2 shows the aggregate site and source annual impact of applying each of the ventilation scenarios to the US housing stock. Source energy demand was calculate using the reported electrical grid interconnection source energy average factor for electricity in the United States [25]. The table shows operating costs only; these values do not include the cost or energy to build and install the products required for these air tightness improvements (e.g. the embedded energy in materials and installed equipment, energy related to construction). The energy cost of complying with ASHRAE 62.2 is relative to the current housing stock. The savings due to tightening the envelope are relative to the existing housing stock after it complies with ASHRAE 62.2. The savings of tightening and adding the exhaust fan are relative to the stock complying with ASHRAE 62.2 using exhaust fans and the savings of tightening and adding an HRV are relative to the stock complying with ASHRAE 62.2 and using an HRV. In other words, each tightening scenario is linked to the ventilation only (no tightening) baseline with the same type of ventilation system.

Table 2. The annual increase in site energy demand, consumer energy cost, and source energy demand of the US housing stock in quads for the explored ventilation scenarios. The savings for tightening the building envelope are in comparison to the existing stock that has complied with ASHRAE 62.2. (1 Quad= 1.055 Exajoules)

	Site Energy Demand (Quads)		Energy Cost (billion\$ 2010)		Source Energy Demand (Quads)	
	ASHRAE 2010	ASHRAE 2013	ASHRAE 2010	ASHRAE 2013	ASHRAE 2010	ASHRAE 2013
Baseline: Making Stock Comply with 62.2						
Exhaust	0.07	0.06	\$1.6	\$1.3	0.18	0.16
HRV	0.10	0.08	\$2.6	\$2.2	0.27	0.22
Savings compared to baseline: Average Tightening						
Exhaust	-0.72	-0.72	-\$11.8	-\$11.7	-1.37	-1.31
HRV	-0.72	-0.72	-\$11.5	-\$11.5	-1.32	-1.33
Savings compared to baseline: Advanced Tightening						
Exhaust	-1.42	-1.39	-\$22.9	-\$21.2	-2.69	-2.53
HRV	-1.41	-1.41	-\$23.2	-\$21.9	-2.60	-2.67
Savings compared to baseline: IECC Standard						
Exhaust	-2.10	-1.89	-\$33.8	-\$29.8	-3.83	-3.44
HRV	-2.23	-2.12	-\$35.0	-\$32.2	-4.19	-3.87
Savings compared to baseline: R2000 Standard						
HRV	-2.63	-2.44	-\$41.8	-\$36.7	-4.78	-4.42
Savings compared to baseline: Passive House Standard						
HRV	-2.86	-2.62	-\$45.5	-\$39.3	-5.18	-4.82

The annual energy impact of bringing the entire current stock into compliance with ASHRAE 62.2 is relatively small; it would increase the annual site energy demand of the residential sector by less than 1%. Ofermann et al [26] showed that many installed mechanical whole house exhaust systems operate below levels required by ASHRAE 62.2. Care should be taken to meet ASHRAE 62.2, however it should be noted that exceeding the standard by requiring or using oversized fans will have energy penalties. In this work we found if we brought the current stock into compliance but installed fans in each home that provided 50% more air than needed, the cohort energy penalty for meeting ASHRAE 62.2 for exhaust only ventilation doubled and the energy penalty for HRV use increased by 50%.

Average tightening was predicted to reduce the residential energy sector demand by 0.72 quads (0.76 EJ) annually. Advanced tightening to get all homes to the level of the tightest 10% currently would achieve roughly twice the benefit of tightening at current average improvement levels. This result is scalable. Increasing the effectiveness of WAP and non-WAP retrofits to ensure that all homes reach 90th percentile air-tightness levels for homes of similar age and construction could double the energy impact of air sealing in these programs.

The final three scenarios focused on the potential benefits of air tightness standards for residential buildings. Though such standards typically focus on new construction or “down to the studs” renovations, it is useful to overlay the standards on the current stock of homes to assess their potential benefits. The Passive House tightness standard has been shown to be difficult to achieve [24], and it can be considered as a theoretical upper limit. Thus, the result for the Passive House scenario indicated an upper bound annual energy savings from air tightening (with ventilation provided by HRVs) of roughly 2.6-2.8 quads (2.7-3.0 EJ) site energy. This is more than half of the residential sector site conditioning energy demand and a quarter of the total residential sector site energy demand. The R2000 standard would achieve 92-93% of this maximum benefit and the IECC standards would achieve 78-81% of the maximum possible benefit. Advanced tightening to get all homes to the performance level of current top 10% would achieve about half of the theoretical maximum benefit of air tightening. The cost of reaching these levels of home tightness are not explored in this work, however the estimates of annual energy and energy cost savings are helpful in evaluating the benefits associated with various building airtightness standards and targets.

Figures 3-7 present variations in home tightening impacts by IECC climate zone. Similar results are shown in the online supplement resolved to a state by state basis. The energy results present the site energy impact.

Figure 3 shows the estimated average annual impact of tightening on the total housing stock in each of the IECC climate zones. The top of the graph shows a map of the continental US IECC climate zones. Hawaii is climate zone 1 and Alaska is climate zones 7 and 8. Each bar in Figure 3 shows the total energy impact of the scenarios in the order described above, corresponding to increasing levels of air tightness. Aggregate impacts are larger in the Eastern (a) climate zones predominately due to larger populations in those areas.

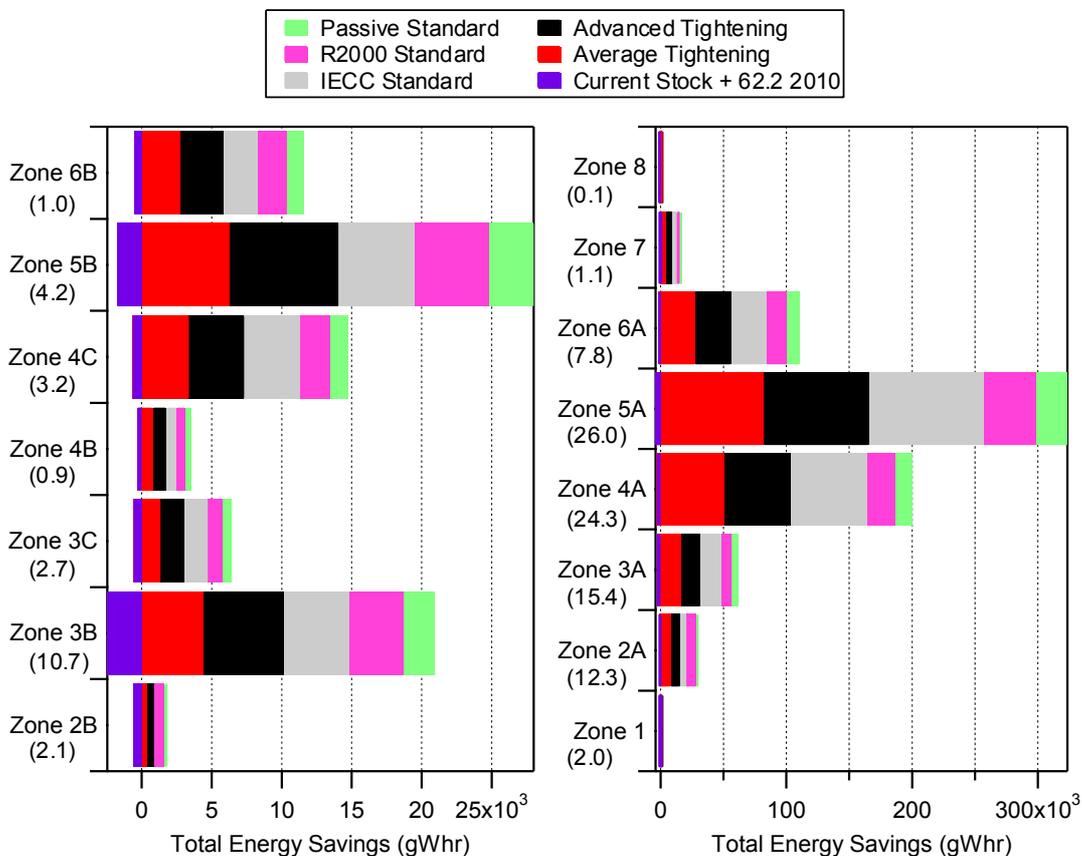
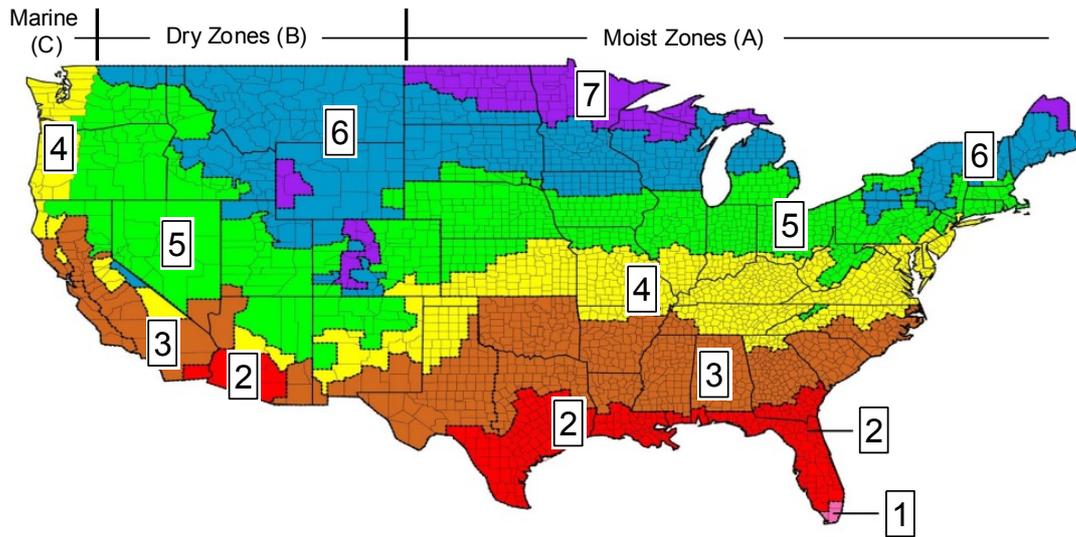


Figure 3. Impact of ventilation scenarios on change in annual residential site energy use in the US housing stock. Each bar represents the total energy impact of each ventilation scenario in each IECC climate zone. The scenarios are ordered from the least energy savings to the most. The savings for each scenario is indicated by the upper value on the colored bar, reflecting the additional benefit of implementing that scenario. In parentheses below the zone name is the millions of homes in the zone.

Figure 4 shows the average energy impact for a home in each climate zone. As expected, the colder the climate, the larger the annual energy impact. On an average basis, the energy impact per home appears to be dominated by the weather variation. However, Figure 5 indicates that there is significant overlap between energy impact distributions for homes in many of the climate zones.

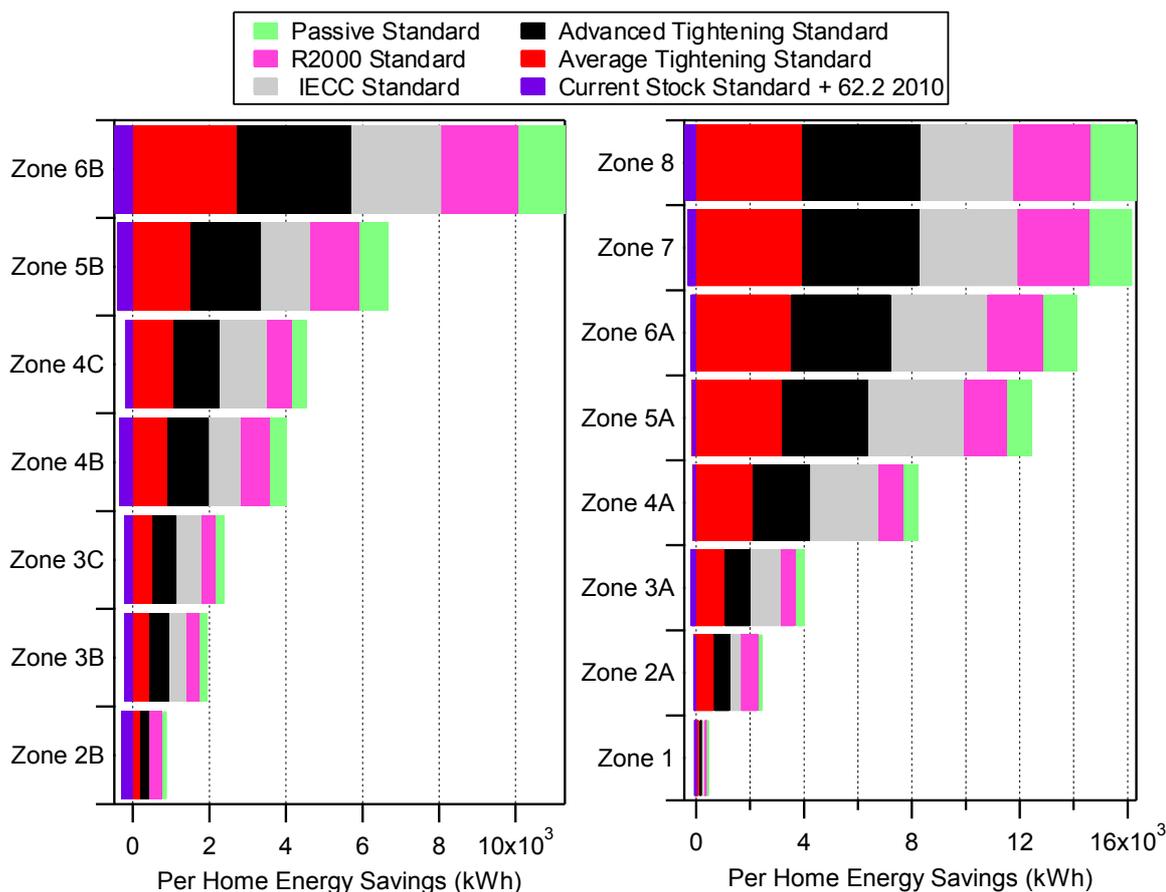


Figure 4. Impact of ventilation scenarios on house average change in annual residential site energy use in the US housing stock. Each bar represents the average per house demand impact of each of the ventilation scenario in each IECC climate zone. The scenarios are ordered from the least energy savings to the most. The savings for each scenario is indicated by the upper value on the colored bar, reflecting the additional benefit of implementing that scenario.

Figure 5 shows the distributions of annual site energy impacts of Average and Advance tightening on the housing stock in each of the IECC climate zones. The distributions were made using the weighted results from the virtual cohort of representative homes analyzed for each climate zone. Since each home was assigned the mean normalized leakage for that home type, the distributions are not as wide as they would be in distributions of actual homes. Figure 5 also shows the impact of tightening the worst 10,000 homes in each climate zone (10,000 homes were tightened per climate zone). There is significant overlap for the distributions for zones 5-8. Tightening the worst 10,000 homes in zone 8 resulted in lower total energy impacts than tightening homes in zones 6B, 4A, 5A, 6A, and 7. This is because the worst 10,000 homes in climate zone 8 are, on average, tighter than the worst 10,000 homes in climate zone 7.

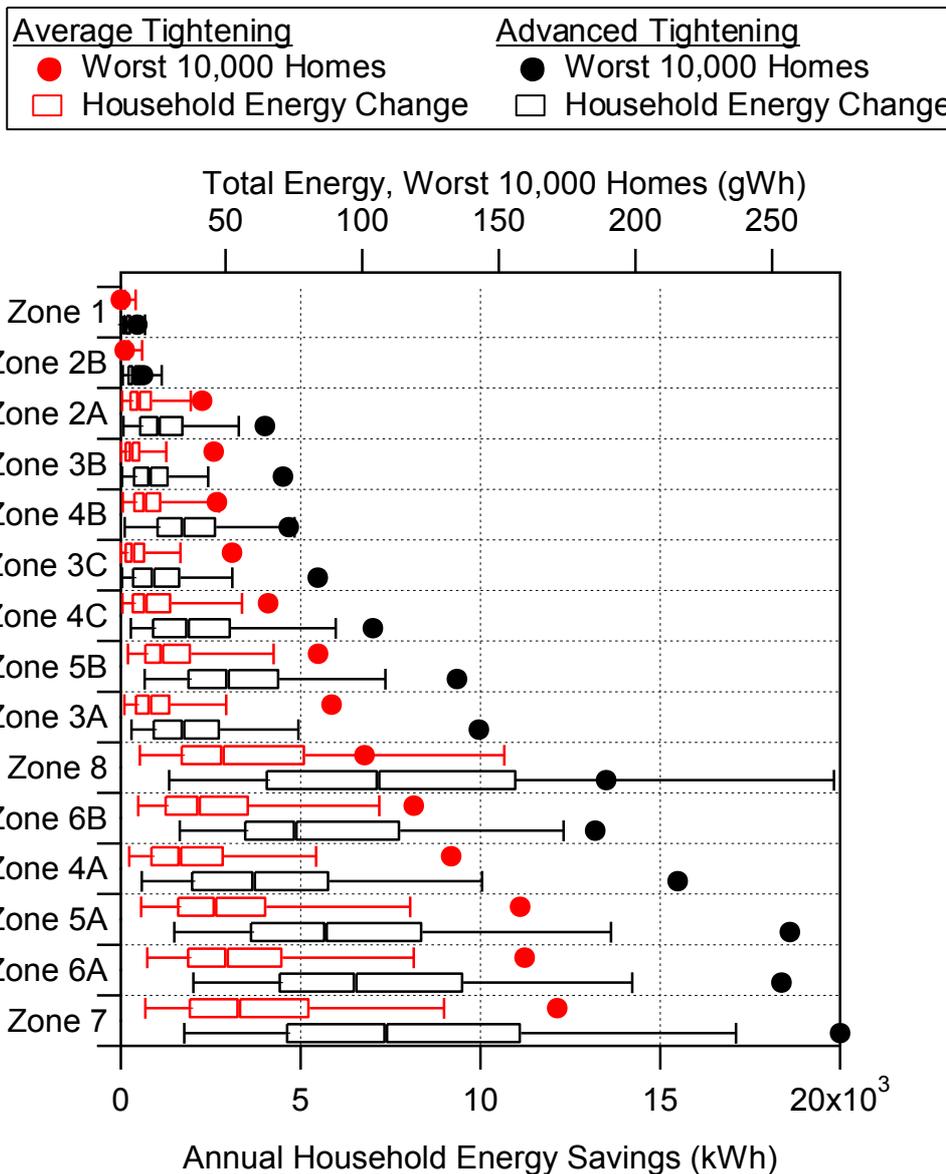


Figure 5. Impact of average and advanced tightening on change in home site energy demand by IECC climate zone. The graph shows the distribution (shown in the box-whisker plots) of home energy savings for the stock in each climate zone as well as the total energy savings from tightening the worst 10,000 homes in each climate zone (10,000 per climate zone) to the specified level.

Figure 6 presents the annual cost savings corresponding to the energy savings presented in Figure 5. These results include state-by-state variations in energy pricing and include natural gas, kerosene, electricity, heating oil, and liquefied petroleum gas (LPG). A very limited number of homes used other fuels such as wood or solar to heat or cool. The costs savings presented here are solely the annual energy benefit of changes. They do not include the cost of the retrofit or the impact of any payment schemes. Determining the net benefit or cost of a retrofit would include an assessment of the costs. The benefits shown in Figure 6 could be compared to the costs of various retrofits and financing methods.

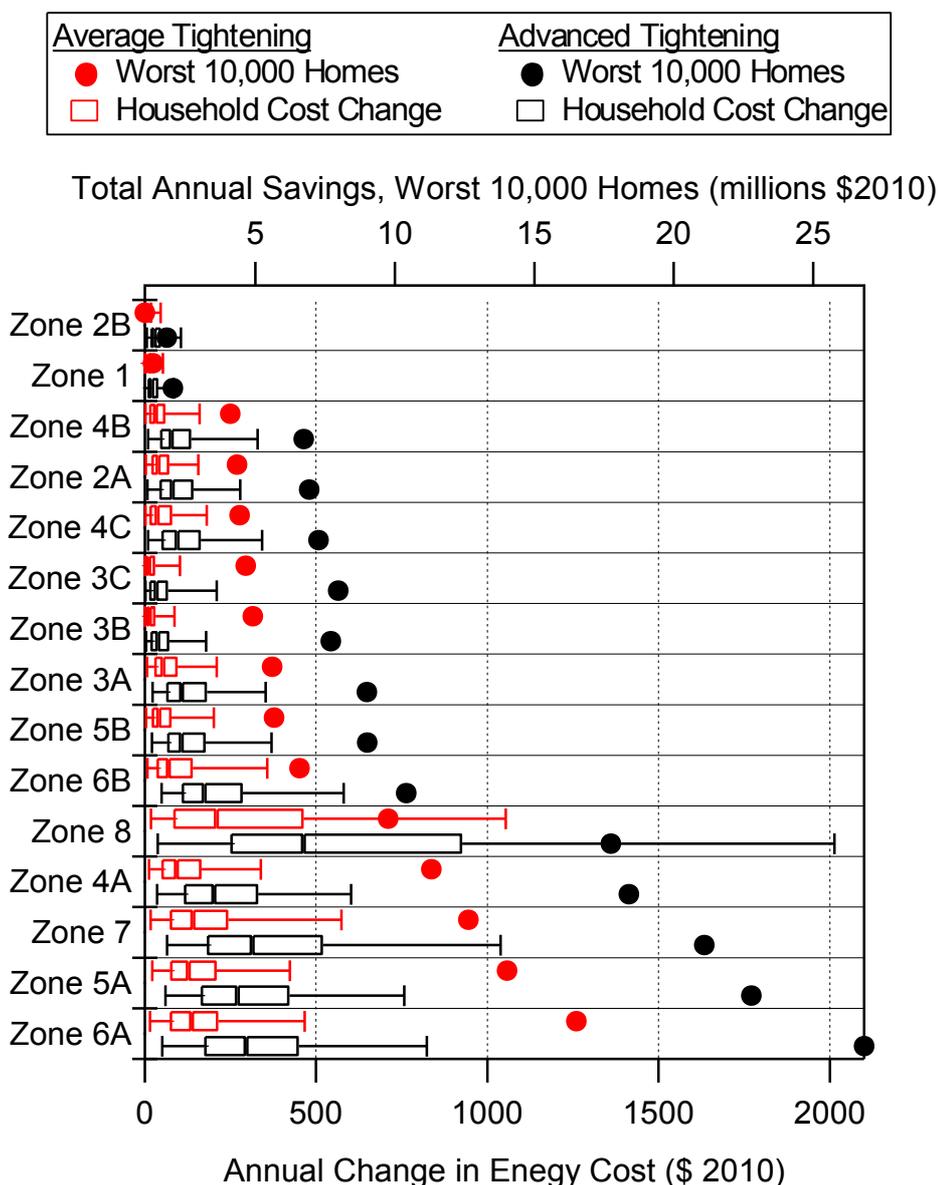


Figure 6. Impact of tightening on change in home energy cost by IECC climate zone. The graph shows the distribution (shown in the box-whisker plots) of consumer cost savings for the stock in each climate zone as well as the total savings from tightening the worst 10,000 homes in each climate zone (10,000 per climate zone) to the specified level.

Currently, much of the residential energy retrofit focus in the U.S. is on low-income homes through the WAP program. Figure 7 compares the energy impact of Average and Advance tightening on the U.S. housing stock for homes with income above and below 200% of the poverty line. The graph shows that air tightening at performance levels currently achieved by WAP and non-WAP programs has greater potential benefits when targeted at low-income homes. The annual energy benefit is greater for increasing tightness in low income homes but for some climate zones there is considerable overlap in the distribution; this indicates that both home income and other parameters, such as home age and foundation type, should be included when selecting homes to tighten if a home audit is not possible. Interestingly, improving tightening efficiency to the specified advanced level has a larger impact on non low-income homes and for some climate zones results in a similar distribution for low income and non-low income homes. If higher levels of tightening are possible, there may be advantages to providing incentives for non-low income homes to retrofit.

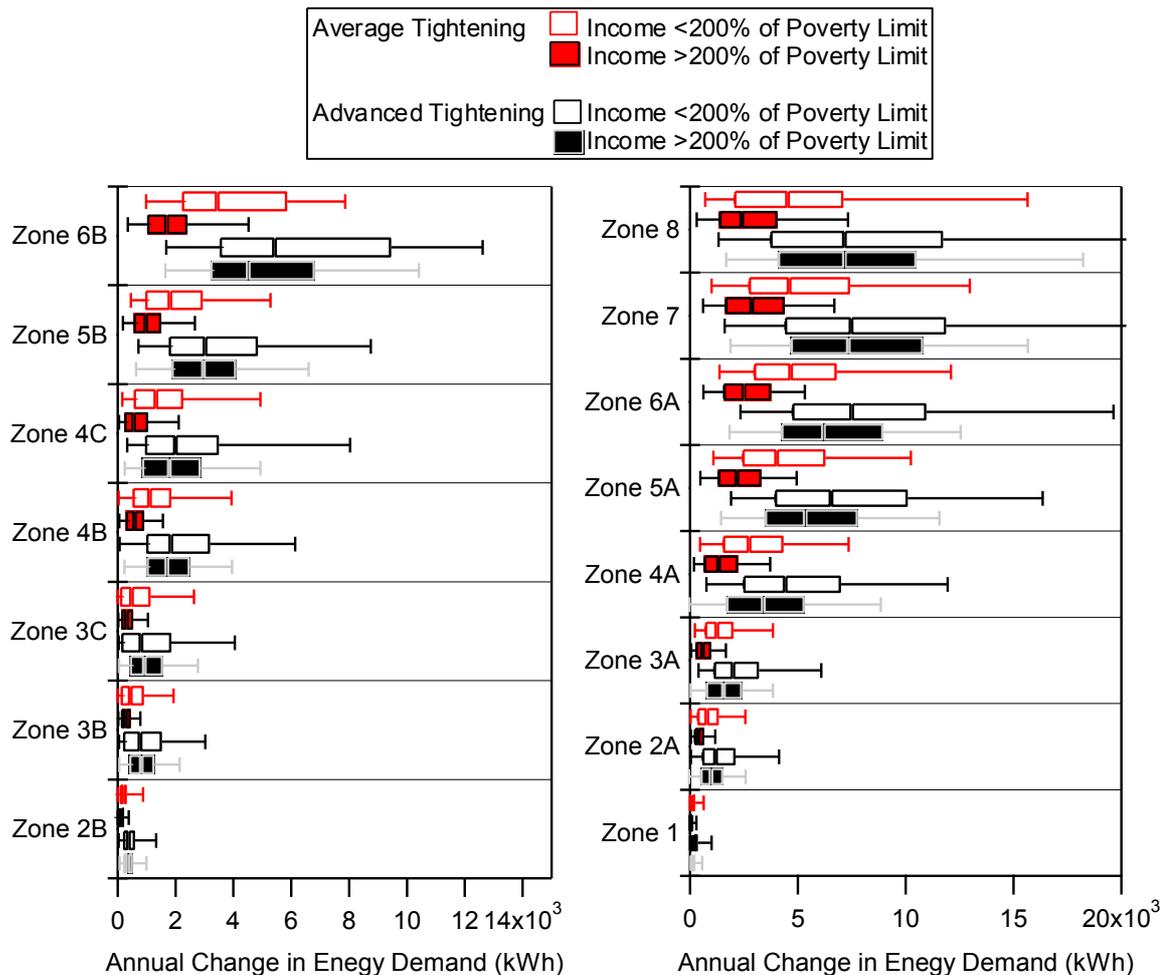


Figure 7. Impact of average and advanced tightening on low income and non low income homes. The graph shows the distribution (shown in the box-whisker plots) of home energy savings for the stock in each climate zone for low income and non low income homes.

CONCLUSIONS

We used a physics-based modeling approach to assess the energy impact of envelope tightening on the U.S. housing stock. Envelope tightening alone has the potential to reduce the residential sector site energy demand by 2.9 quads (3.1 EJ). However, this would require the leakage of all homes to be reduced to the level specified by the Passive House standard which is not reasonable for the existing stock. Current levels of tightening seen in WAPs and energy efficiency programs could reduce the energy demand by 0.7 quads (0.74 EJ). We estimate that advanced methods of tightening could potentially double that energy savings, achieving half of the savings that could be achieved with stock wide application of the Passive House standard. Substantial additional energy savings are possible by improving air sealing practice to what has to be regarded as an achievable goal – to get all homes up to the current 90th percentile performance level of homes of the same type. This analysis considers the characteristics of the home that may limit air tightness and compares each home only to homes of the same age, type, and income class. There is a clear need to develop and apply the most effective methods of envelope tightening in home retrofits.

As new homes replace the existing stock, increasing tightness will reduce the energy demand of the residential sector, however these new homes will likely have higher efficiency systems for heating and cooling reducing the envelope tightness specific energy reductions to the

stock. The cost of achieving progressively tighter building standards should be considered when deciding the level of air tightness required for new construction. It is considerably more difficult to reach the Passive House standard than the IECC standard and the energy benefit of doing so would be modest. The IECC 2012 seems to capture most of the energy savings of the tightness standards explored and more aggressive tightness levels may not be worth requiring if the cost is significant. Which standard to implement in each region of the country should take into account the proposed homes location and the relative costs and benefits of reaching various tightness levels.

REFERENCES

1. US EIA, *Residential Buildings Energy Consumption Survey (RECs)*. 2009, U.S. Energy Information Administration.
2. US EIA, *Residential Buildings Energy Consumption Survey (RECs)*. 2005, U.S. Energy Information Administration.
3. Mortensen, D.K., I.S. Walker and M.H. Sherman, *Energy and air quality implications of passive stack ventilation in residential buildings*, in *ACEEE 16th Biennial Summer Study*. 2011: Asilomar Conference Center, Pacific Grove, California.
4. Sherman, M.H. and I.S. Walker, *Energy Impact of Residential Ventilation Standards in California*. ASHRAE Journal, 2008. **114**: p. 482-493.
5. Chua, K.J. and S.K. Chou, *Energy performance of residential buildings in Singapore*. *Energy*, 2010. **35**(2): p. 667-678.
6. Schweitzer, M., *Estimating the National Effects of the U.S. Department of Energy's Weatherization Assistance Program with State Level Data: A Metaevaluation Using Studies from 1993-2005*. 2005, Oak Ridge National Laboratory: Oak Ridge, TN.
7. Schweitzer, M. and L.G. Berry, *Evaluation of the Washington State Weatherization Assistance Program*. 2001, Oak Ridge National Laboratory: Oak Ridge, TN.
8. Sherman, M.H. and N. Matson, *Residential Ventilation and Energy Characteristics*. ASHRAE Transactions, 1997. **103**(1): p. 717-730.
9. Logue, J.M., W.J.N. Turner, I.S. Walker and B.C. Singer, *Evaluation of an Incremental Ventilation Energy Model for Estimating Impacts of Air Sealing and Mechanical Ventilation*. 2012, Lawrence Berkeley National Laboratory: Berkeley, CA.(LBNL-5796E)
10. CEC, *Residential Alternative Calculation Manual (ACM) Approval Method*. 2008, California Energy Commission.
11. Walker, I.S. and D.J. Wilson, *Field validation of equations for stack and wind driven air infiltration calculations*. HVAC&R Research, 1998. **4**(2).
12. Chan, W.R., W.W. Nazaroff, P.N. Price, M.D. Sohn and A.J. Gadgil, *Analyzing a database of residential air leakage in the United States*. *Atmospheric Environment*, 2005. **39**(19): p. 3445-3455.
13. ASHRAE, *A Method of Determining Air Change Rates in Detached Dwellings*. 1993, American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta, GA.
14. US Census Bureau. *County Housing Unit Estimates for States: 2010 to 2011*. 2012 Accessed:[6/27/2012]; Available from: <http://www.census.gov/popest/data/housing/totals/2011/HU-EST2011-3.html>.
15. US DOE, *VOLUME 7.1 Building America Best Practices Series: High-Performance Home Technologies, Guide to Determining Climate Regions by County*. 2010, US Department of Energy: Washington DC. p. 34.
16. Chan, W.R., J. Joh and M.H. Sherman, *Analysis of Air Leakage Measurements from Residential Diagnostics Database*. 2012, Lawrence Berkeley National Lab: Berkeley, CA. (LBNL-5967E)
17. NREL. *Typical Meteorological Year*. 2008 Accessed:[March 15, 2012]; Available from: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

18. Mills, E. and Energy Analysis Department, *The Home Energy Saver: Documentation of Calculation Methodology, Input Data, and Infrastructure*. 2005, Lawrence Berkely National Laboratory: Berkely, CA. p. 197.
19. HVI, *Certified Home Ventilating Products Directory*. 2009, Home Ventilating Institute Wauconda, IL.
20. ASHRAE, *Ventilation and Accetable Indoor Air Quality in Low-Rise Residential Buildings Standard 62.2*. 2010, American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta, GA.
21. Garcia, A.M., *2012 Poverty Income Guidelines and Definition of Income*, Department of Energy, Editor. 2012: Washington, DC.
22. BECP, *Building Technologies Program: Air Leakage Guide*. 2011, Prepared by DOE's Building Energy Codes Program (BECP) for the U.S. Department of Energy under Contract DE-AC05-76RLO 1830 Washington, DC.
23. NRC, *2012 R-2000 Standard*, in *4. Building Enevelope Requirements*. 2012, National Resources Canada: Canada.
24. PHI. *Passive House Requirements*. 2012 Accessed:[8/29/2012]; Available from: <http://www.passivehouse-international.org/>.
25. Deru, M. and P. Torcellini, *Source Energy and Emission Factors for Energy Use in Buildings*. 2007, National Renewable Energy Laboratory: Golden, Colorado.
26. Offermann, F.J., *Ventilation and indoor air quality in new homes*. 2009, California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program. Collaborative Report. CEC-500-2009-085.

SUPPLEMENTAL MATERIAL:**Characteristics of Housing stock**

Figures S.1 and S.2 display the two characteristics of low income and non-low income homes that have significant impacts on conditioning energy use: normalized leakage and heated floor area.

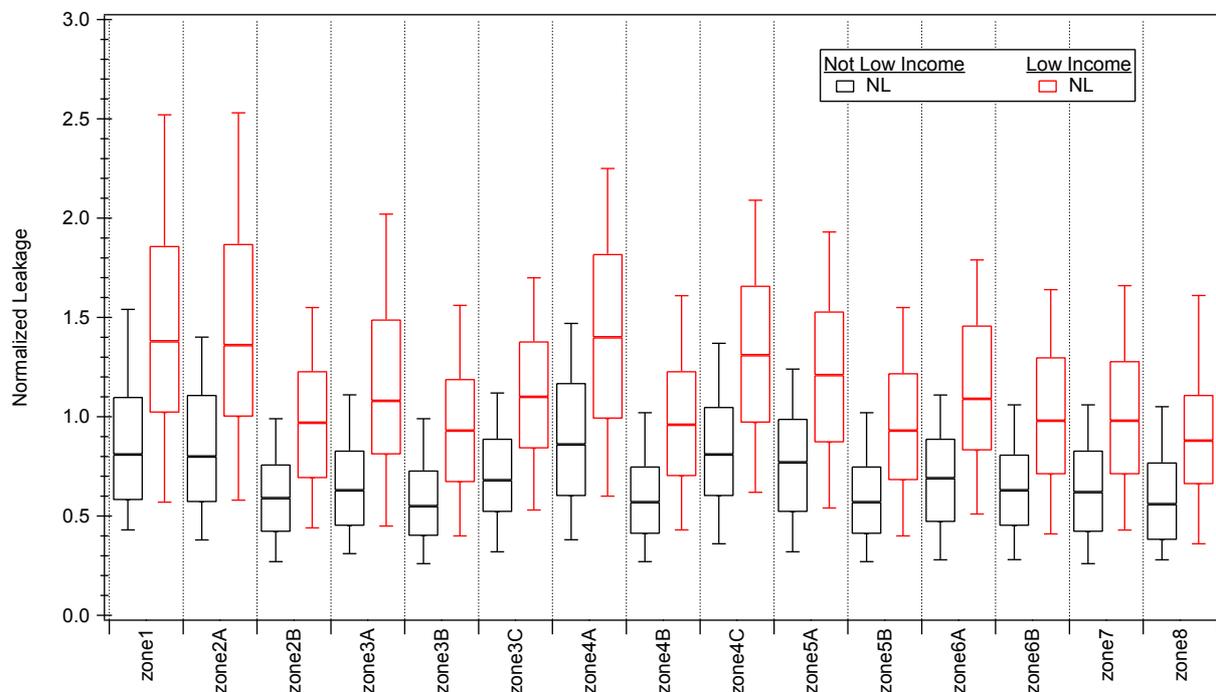


Figure S1. Envelope tightness characteristics of low income and non low income homes. The graph shows the estimated distribution of home normalized leakage values for low income homes and non-low income homes.

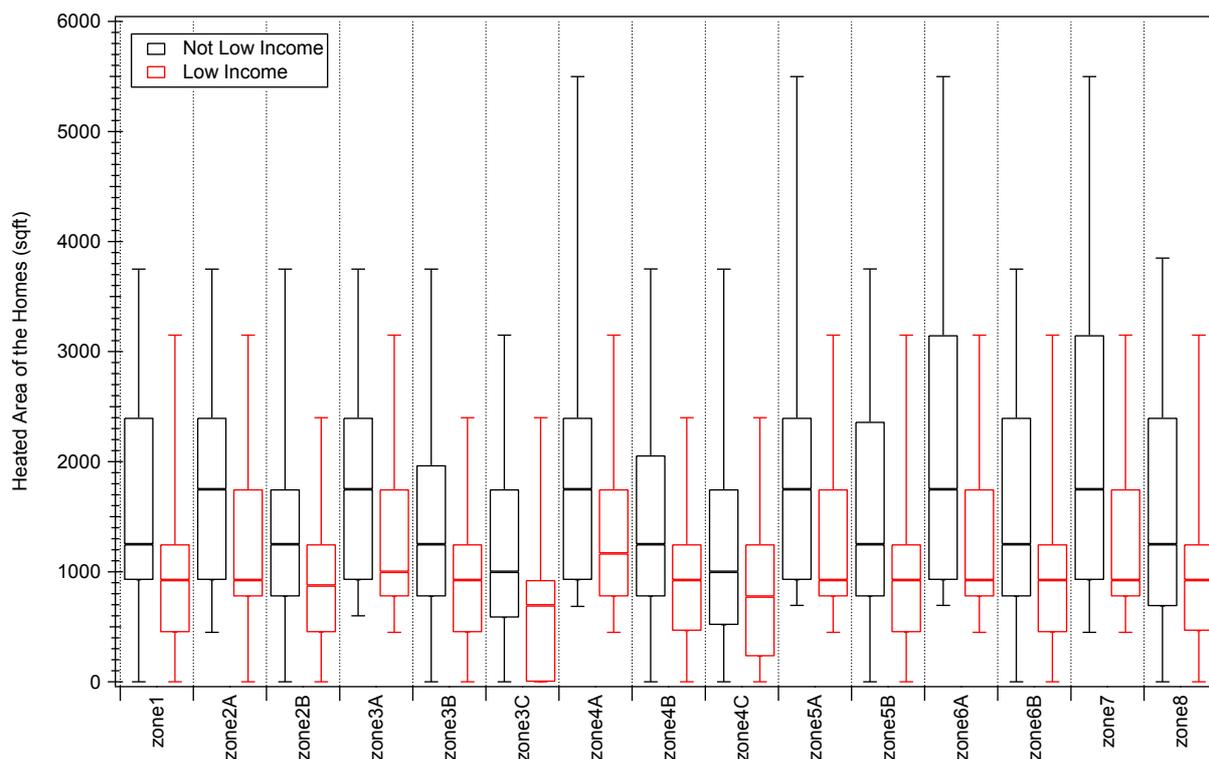


Figure S2. Home size characteristics of low income and non low income homes. The graph shows the estimated distribution of home heated floor areas (square feet) for low income homes and non-low income homes.

Impact of Home Tightening on a State by State Basis

Figures S3-S5 have similar information to Figures 5-7 but on a state by state basis. Figure S3 shows the distribution of home energy impact of average tightening on the housing stock in each state. The figure also shows the total energy impact of tightening the worst 10,000 homes in each state. Figure S4 shows the same information for advanced tightening. Figure S5 shows the distribution of the annual energy cost impact of applying the average and advanced level of tightening to the housing stock in each state.

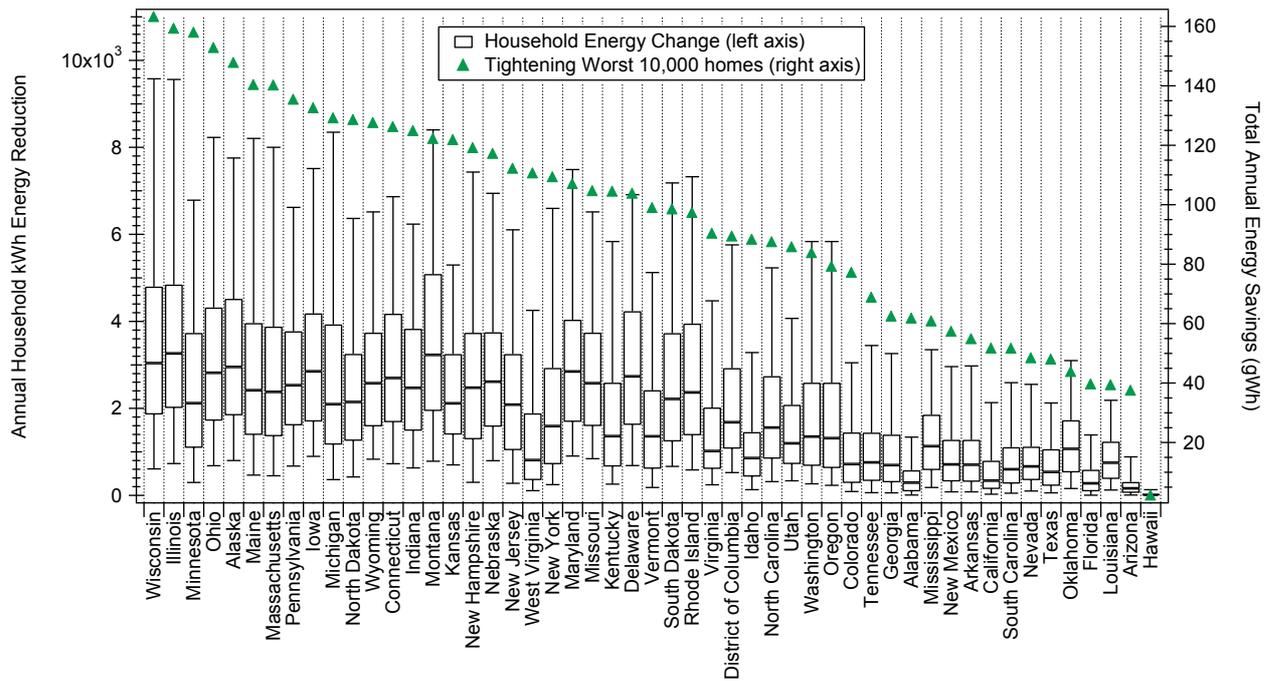


Figure S3. Impact of average tightening on change in home energy demand by state. The graph shows the distribution of annual home energy savings from tightening the entire stock at the ‘average’ current level of tightening. The graph additionally shows the total energy savings from tightening the worst 10,000 homes in each state.

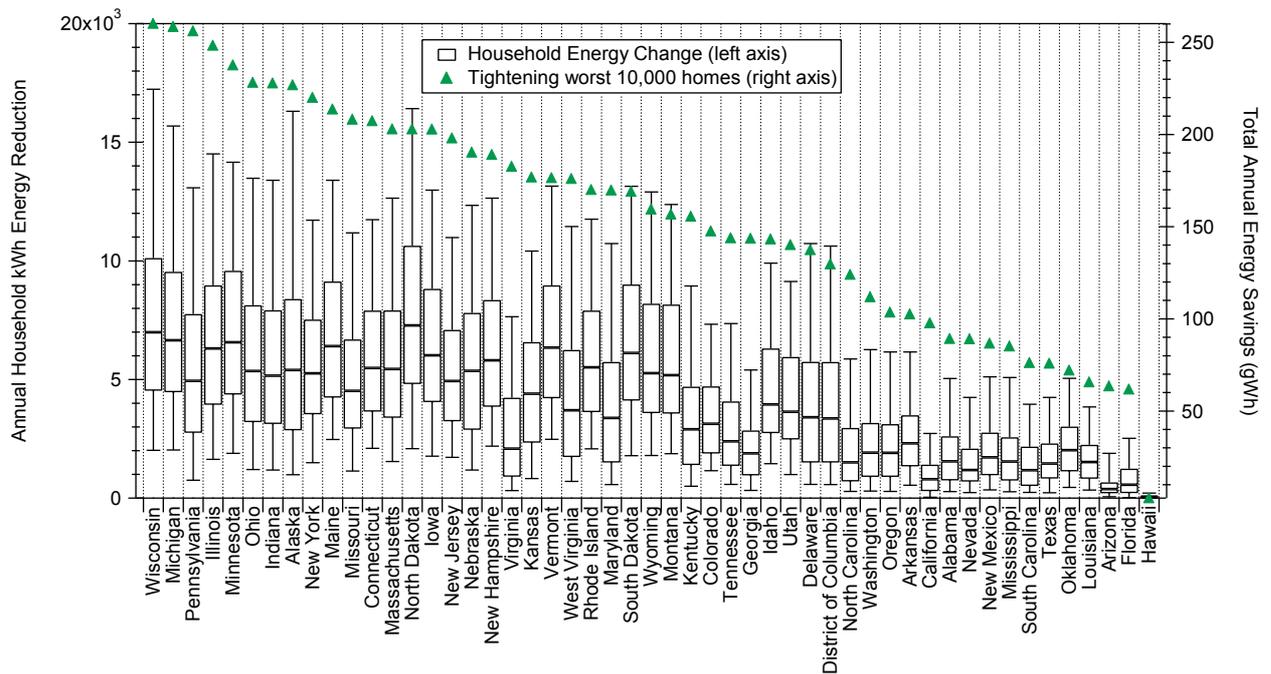


Figure S4. Impact of advanced tightening on change in home energy demand by state. The graph shows the distribution of home energy savings from tightening the entire stock at the ‘average’ current level of tightening. The graph additionally shows the total energy savings from tightening the worst 100,000 homes in each state.

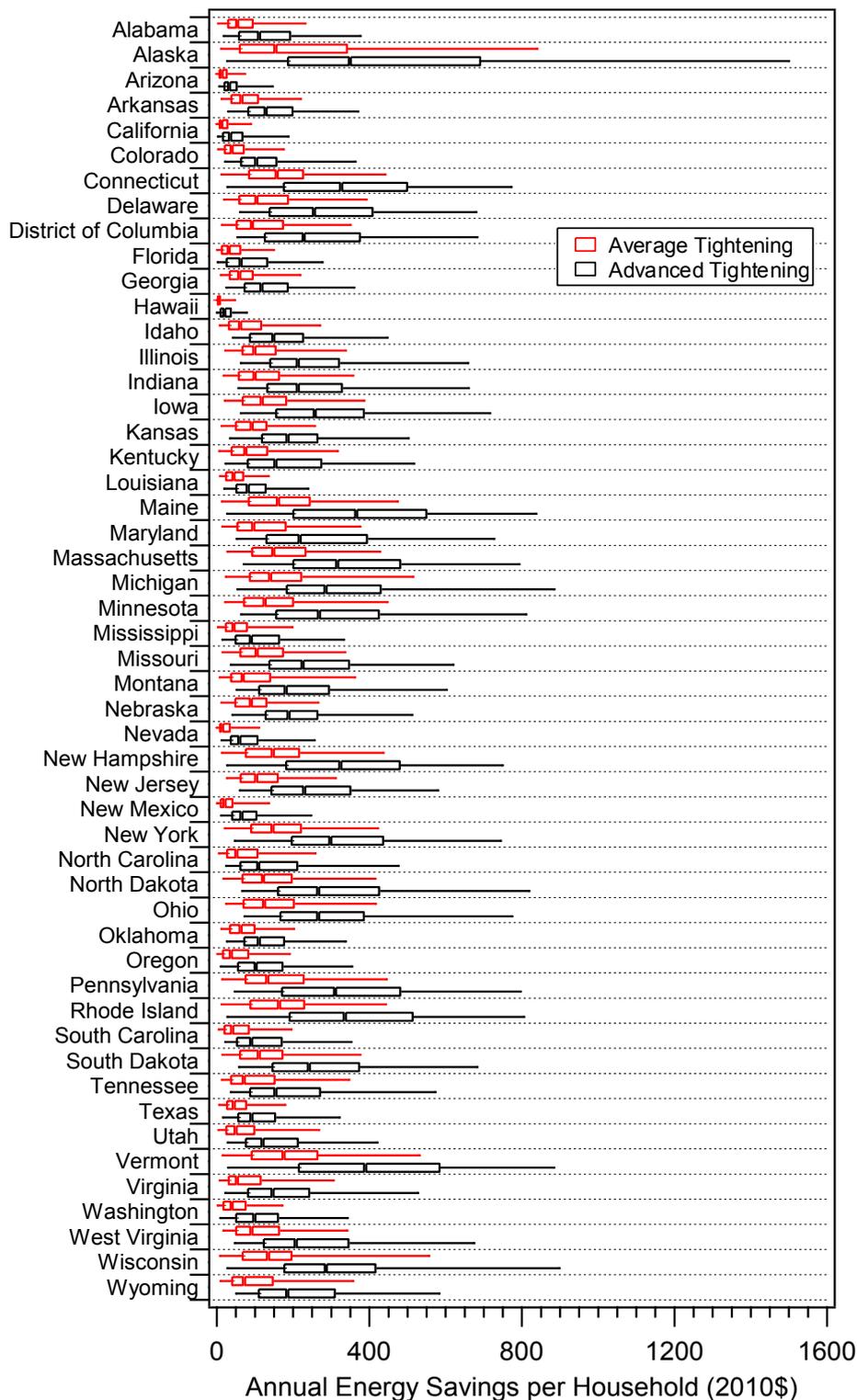


Figure S5. Impact of tightening on change in home energy cost by state. The graph shows the distribution of home cost savings from tightening the entire stock at the ‘average’ current level of tightening and the estimated ‘advanced’ level of tightening for the existing stock.