ENERGY IMPACTS OF ENVELOPE TIGHTENING AND MECHANICAL VENTILATION FOR THE U.S. RESIDENTIAL SECTOR

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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 talk presents estimates of the potential energy savings of implementing air tightness improvements along with mechanical ventilation throughout the US housing stock. We used a physics-based model to simulate population energy impacts of varying levels of air tightness improvements and providing ventilation according to standards. 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 at their current tightness levels. Improving air tightness of all homes at current average retrofit performance levels would decrease site energy demand by 7% or 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 the air tightness specifications of IECC 2012, Canada's R2000, and Passive House standards.

KEYWORDS

HVAC, weatherization, ASHRAE 62.2, retrofit, WAP

1. 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. (US EIA 2009). Heating and cooling accounts for an estimated 5 quads of site energy (5.3 EJ), about half of the site energy used in residences (US EIA 2005). 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 (Sherman and Walker 2008; Chua and Chou 2010; Mortensen, Walker et al. 2011) or comparisons of pre- and post- retrofit energy bills of homes (Schweitzer and Berry 2001; Schweitzer 2005). 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 (Sherman and Matson 1997). 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?

2. 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.

2.1 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. (2012) 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.

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

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:

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

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

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

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

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

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 (J kg^{-1} 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 (CEC 2008), 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.

When applying this model to existing databases of home characteristics, we used the algorithm developed by Walker and Wilson (1998) for infiltration through the building envelope as a function of a limited number of home characteristics, outdoor weather data, and home leakage area. We used the reference method given by ASHRAE Standard 136 (1993) to combine mechanical ventilation and natural infiltration.

2.2 Virtual Cohort of Representative Homes

The Residential Energy Consumption Survey (RECS) is a survey of U.S. housing units performed by the U.S. Energy Information Agency (EIA). The RECS has been conducted every one to five years since 1979. The survey is conducted for a representative subset of the U.S. housing stock. The 2009 RECs database (US EIA 2009) contains characteristics for 12,083 homes including home location; type; number of rooms; occupancy characteristics; cooking frequency; heating and cooling equipment system types, ages and fuel type; and thermostat settings. We used the 2009 RECS database to create a virtual cohort of 50,877 homes to represent the U.S. residential housing stock. Full details of this are presented in Logue, Sherman et al. (2013).

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. Chan et al. (2012) 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 Meteorological Year (TMY) data for the weather station located closest to the IECC identified representative city for the specified climate zone for the home (NREL 2008). We used the model developed by Chan et al. (2012) to determine a normalized leakage value for each of the homes in our virtual cohort.

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 (Mills and Energy Analysis Department 2005). Energy costs were taken from the US Energy Information Administration (USEIA 2005) 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.

2.3 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 current ASHRAE 62.2-2010 (ASHRAE 2010) requirements, 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. <u>Upgrade current housing stock to comply with ASHRAE 62.2.</u>

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. <u>Average Tightening: Improve envelope air tightness of all homes at levels currently achieved by Weatherization Assistance Program (WAP) and non-WAP energy efficiency programs while complying with ASHRAE 62.2.</u>

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. (2012) 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 (Garcia 2012). The remaining houses were tightened by 20% to reflect the impact of non-WAP efficiency programs. For each home the level of mechanical ventilation was adjusted to reflect the lower infiltration credit due to the tighter envelope.

3. <u>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.</u>

The Chan et al. (2012) 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 ventilation 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. <u>IECC: Tighten all homes to achieve the standards specified in the 2012 IECC standard while complying with ASHRAE 62.2</u>

In this scenario, the envelope airtightness of each home was set to the level recommended by the 2012 IECC standard (BECP 2011): 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. <u>R2000: Tighten all homes to achieve the standards specified in the Canadian R2000 standard while complying with ASHRAE 62.2</u>

In this scenario, the envelope airtightness of each home was set to the level required in Canada's R2000 standard (NRC 2012): 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 air tightness of each home was set to the level required the Passive House standard (PHI 2012): 0.6 ACH50. This was selected as an upper limit air tightness 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) (HVI 2009).

3. RESULTS

We determined the impact of the six ventilation scenarios at the U.S. and IECC climate zone levels. We estimate 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. 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 1 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 (Deru and Torcellini 2007). 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.

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%. Offermann (2009) 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 (PHI 2012), 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 would be helpful in evaluating the benefits associated with various building airtightness standards and targets.

Figure 1 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 1 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.

Table 1. 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)
Baseline: Making Stock Comply with 62.2			
Exhaust	0.07	$1.60	0.18
HRV	0.1	$2.60	0.27
Savings compared to baseline: Average Tightening			
Exhaust	-0.72	-$11.80	-1.37
HRV	-0.72	-$11.50	-1.32
Savings compared to baseline: Advanced Tightening			
Exhaust	-1.42	-$22.90	-2.69
HRV	-1.41	-$23.20	-2.6
Savings compared to baseline: IECC Standard			
Exhaust	-2.1	-$33.80	-3.83
HRV	-2.23	-$35.00	-4.19
Savings compared to baseline: R2000 Standard			
HRV	-2.63	-$41.80	-4.78
Savings compared to baseline: Passive House Standard			
HRV	-2.86	-$45.50	-5.18

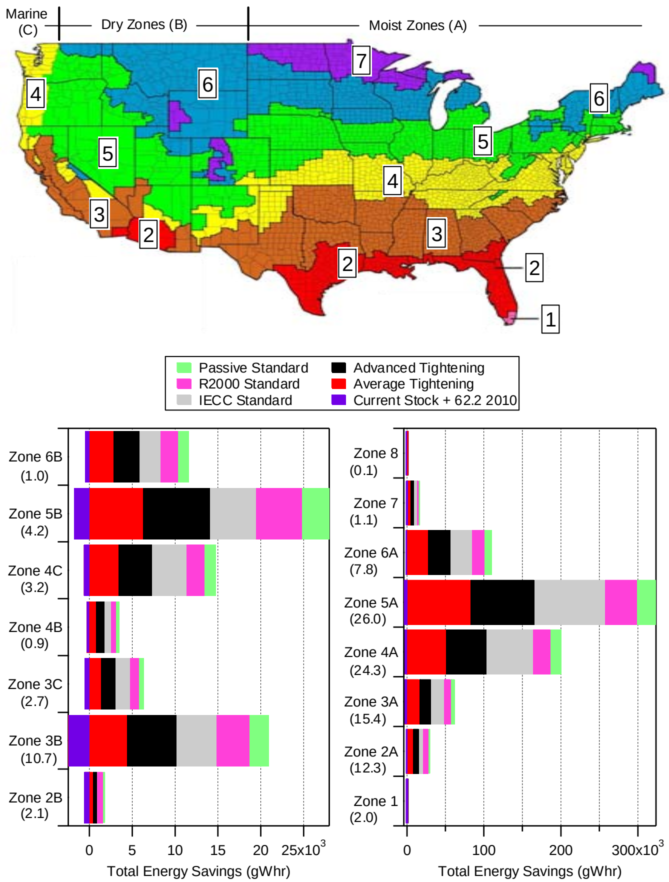

Figure 1. Impact of ventilation scenarios on change in annual residential site energy use in the US housing stock. Each bar represents the total energy impact of each ventilation scenario in each IECC climate zone. The scenarios are ordered from the least energy savings to the most. The savings for each 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 number of millions of homes in the zone.

Figure 2 shows the distributions of annual site energy impacts of Average and Advanced 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 2 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.

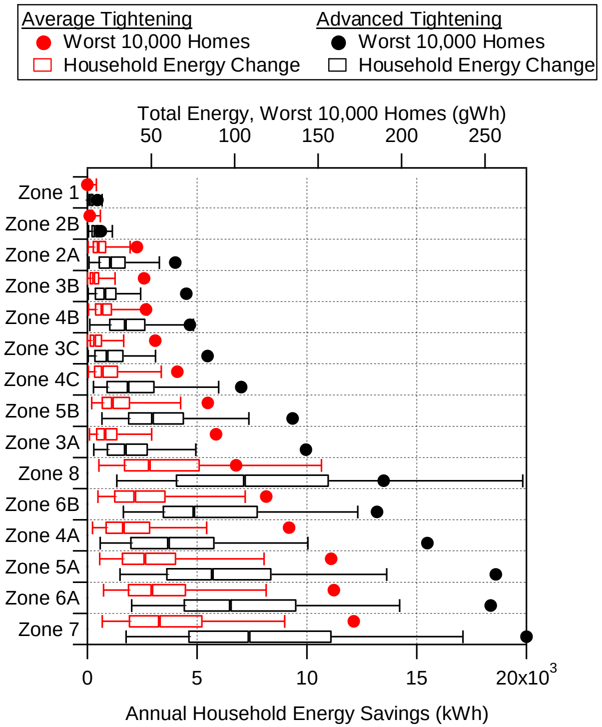

Figure 2. Impact of average and advanced tightening on change in home site energy demand by IECC climate zone. The graph shows the distribution (shown in the box-whisker plots) of home energy savings for the stock in each climate zone as well as the total energy savings from tightening the worst 10,000 homes in each climate zone (10,000 per climate zone) to the specified level.

4. 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 captures 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. When choosing which standard to implement in each region of the country, the proposed homes location and the relative costs and benefits of reaching various tightness levels should be taken into account.

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