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Energy Impacts of Effective Range Hood Use for all U.S. Residential Cooking

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Abstract

Range hood use during residential cooking is essential to maintaining good indoor air quality. However, widespread use will impact the energy demand of the U.S. housing stock. This paper describes a modeling study to determine site energy, source energy, and consumer costs for comprehensive range hood use. To estimate the energy impacts for all 113 million homes in the U.S., we extrapolated from the simulation of a representative weighted sample of 50,000 virtual homes developed from the 2009 Residential Energy Consumption Survey database. A physics-based simulation model that considered fan energy, energy to condition additional incoming air, and the effect on home heating and cooling due to exhausting the heat from cooking was applied to each home. Hoods performing at a level common to hoods currently in U.S. homes would require 19–33 TWh [69–120 PJ] of site energy, 31–53 TWh [110–190 PJ] of source energy; and would cost consumers \$1.2–2.1 billion (U.S.\$2010) annually in the U.S. housing stock. The average household would spend less than \$15 annually. Reducing required airflow, e.g. with designs that promote better pollutant capture has more energy saving potential, on average, than improving fan efficiency.

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Introduction

Cooking is one of the largest sources of air pollutants in residences (Kamens et al. 1991; Lewis and Zweidinger 1992; Chao and Cheng 2002). Both the burners – including gas and electric (Dennekamp et al. 2001; Wallace et al. 2008) – and cooking of food (Thiebaud et al. 1995; Bein and Leikauf 2011) emit pollutants in amounts that can reach hazardous concentrations in both the kitchen space as well as throughout the whole home. Fortmann et al. (2001) found that cooking events produced concentrations of criteria pollutants and air toxics in a test home that exceeded acute outdoor standards. Simulation modeling by Logue, Klepeis et al. (2013a) estimated that roughly 20% of U.S. homes regularly exceeded the USEPA 1-hour NO₂ standard due to the use of unvented natural gas for cooking. Seaman, Bennett et al. (2007) showed that food emissions during cooking produce acrolein concentrations that exceed health based chronic and acute standards in homes.

Venting residential range hoods can mitigate the impact of cooking-related emissions by venting pollutants to the outdoors before they mix into the indoor air. ASHRAE Standard 62.2 (ASHRAE 2010), which addresses residential ventilation, has requirements for manually operable source control ventilation in kitchens. The standard has requirements for flow rate and noise yet currently includes no explicit requirement for pollutant removal effectiveness. ASHRAE 62.2 is only required in states and municipalities that have adopted the standard as part of their building code, including the state of California (CEC 2010). Currently, not all homes have range hoods and, of those that do, not all vent to the outside. A study by Klug and Singer (2011) that analyzed photos for 1002 California homes to estimate range hood prevalence characteristics noted that 7% of homes did not have range hoods. It is unclear whether this limited study is representative of the over 13 million households in California and there is no available data that we could find on range hood presence in the national housing stock. For those homes that do have hoods, it was not clear what fraction of hoods currently successfully exhaust pollutants to the outside. Some hoods are re-circulating hoods which are designed to capture grease, but release pollutants back into the home and some homes have range hoods that are connected to a vent that goes outdoors but the vent is either blocked or the fan is not powerful enough to move air to the outdoors for the given vent. For the remainder of this paper, when we refer to range hoods we are referring to operational outdoor venting range hoods.

Singer, Delp et al. (2012) reported pollutant capture efficiency (PCE) – the fraction of pollutants produced by a cooking burner that are removed by an installed range hood or downdraft exhaust – based on measurements in 15 homes. Delp and Singer (2012) found similar results in 7 lab analyzed hoods. Analysis of data from the range hoods they studied indicated that flow rates of roughly 200 cfm [95 LPS] are necessary but not always sufficient to achieve PCE of 75% on front burners. Singer, Delp et al. (2012) also found that similarly high PCEs are achieved at lower flows for some hood designs and when cooking occurs on back rather than front burners. Data on range hood use rates are limited. A survey of 372 homes predominately in California (Klug et al. 2011) found that range hoods are used for only about a third of cooking events in homes. Mullen, Li et al (2012) measured concentrations of nitrogen dioxide, formaldehyde, acetaldehyde and carbon monoxide in homes with natural gas appliances in California. Of 65 homes that reported cooking at least 7 times during the 6-day sampling period and that had a range hood, 34% used their hoods during all cooking events, 21% used the hoods

sometimes, and 45% never used their range hoods. Given the potential health benefits, insuring the availability and encouraging the use of venting range hoods should be a priority for healthy homes initiatives.

Increasing range hood presence and use increases household energy use. Like all fans, range hoods use energy to move air. We refer to this energy as fan energy. Additional energy is required to thermally condition the make-up air entering the home. We refer to this energy as conditioning energy. Additionally, range hoods exhaust air heated by the stove. If the heated air were not discarded it would heat the home. Removing this heat via the range hood would increase furnace energy use in winter and decrease air conditioning energy use when cooking in the summer. We refer to this energy as replacement energy. Fan energy is dependent on the system curve of the range hood duct system, on the available power settings, and on the fan curve of the device. Determining fan efficacy (air flow rate per unit power), the key parameter for fan power, requires extensive knowledge of the system being characterized. Replacement energy is dependent on the heat capture efficiency (HCE). HCE is the fraction of burner heat output that is removed by the range hood or exhaust fan. Since the buoyant plume contains the pollutants that are being exhausted, the PCE should correlate with the HCE with an offset in HCE due to losses from the stove including conductive and radiative losses. The additional air that needs to be conditioned is a function of the original tightness of the home envelope. The tighter a home is, the larger the impact of an additional exhaust fan on home air change rate. This is due to the non-linear, sub-additive interaction between natural and mechanical ventilation, as described below.

Range hood energy use can be reduced through the use of energy efficient products. Energy Star is a U.S. developed voluntary efficiency standard that is widely accepted in the residential appliance market. For a range hood to be Energy Star rated the fan efficacy must be above 2.8 cfm W^{-1} at a flow rate of 100 cfm measured at a static pressure of 25 Pascals, a pressure drop relevant to a short duct system. However, this may not be the most effective method to reduce energy use since it only addresses the fan energy. If the PCE per unit airflow were to increase, the airflow required for good IAQ could be reduced which would in turn lower the energy needed to condition that air as well as fan energy. Additionally, decreasing the HCE, without decreasing PCE, could reduce losses from hood use in the winter.

This study sought to estimate the annual energy requirements and costs for venting range hoods to be used during all cooking events in U.S. homes, with the hoods used at flow rates required to adequately protect residents from cooking related IAQ issues. This is a theoretical calculation as many homes do not have venting hoods installed and many of the venting hoods that are installed likely do not have the capacity to achieve air flow rates required for effective pollutant capture. Additionally, we sought to explore the potential to reduce the energy demand of venting range hood use through technology improvements. It was not our objective to determine the actual energy burden associated with use of currently installed venting range hoods. There are insufficient data about the prevalence of venting range hoods, the capabilities of hoods that are in homes and of range hood usage patterns to develop estimates of actual energy use. This paper explores the following questions: What would be the aggregate and average household energy and consumer costs if all U.S. homes were to have and occupants were to operate a venting range hood at 200 cfm [95 LPS] during all cooking events? What is the potential energy savings of increasing fan efficacy? What is the potential energy savings of using

hoods with better PCE and of users preferentially selecting back burners to achieve the same PCE at 100 cfm [47 LPS]? We present results for changes in site and source energy demand, and consumer cost for the U.S. housing stock relative to no range hood use.

Methods

To accomplish this analysis, we utilized the Population Impact Assessment Modeling (PIAM) framework. Generically, the PIAM framework involves the application of a physics-based simulation model to calculate one or more environmental or energy performance parameters for each individual home in a sample cohort selected or developed to represent a population. The weighted results for individual homes are aggregated to determine population impacts. A key feature of the approach is that sample cohorts are developed from representative databases such as the Residential Energy Conservation Survey (RECS) (US EIA 2009b) or the American Housing Survey (AHS)(US Census Bureau 2011). Key characteristics not specified in these datasets are assigned from other data sources based on trends by demographics or other specified home characteristics. Results from the individual homes are compiled to provide the statistics for population impacts. The framework can be applied at varying temporal or spatial scales. Recent applications of the PIAM framework examined the impact of air sealing and ventilation on annual energy use for homes across the U.S. (Logue et al. 2013b) and the impact of gas cooking on indoor pollutant concentrations (Logue et al. 2013a).

The PIAM framework was applied to assess the site and source energy and consumer cost of range hood use during cooking in the U.S. housing stock. An energy balance model was used to determine time-dependent range hood related site energy use for a typical year in each cohort home based on home characteristics. We calculated annual impact on source energy and cost based on state specific utility costs and source energy multipliers.

Analysis Scenarios. We applied the PIAM framework to estimate range hood energy requirements for the U.S. housing sector for four scenarios. In each scenario, we assumed that a venting range hood is present in each home and operated coincident with burner operation for every cooking event. A schedule of cooking events for each home was determined using household characteristics as described in the sub-section on the representative sample of homes. The scenarios varied in the specified range hood airflow rate and fan efficacy, as described below. The results are presented as ranges of energy impacts corresponding to estimated ranges of input parameters.

1. Base case: performance typical of current models. Following the finding of Singer, Delp et al. (2012), we used 200 cfm (95 L/s) as the baseline flow rate required to achieve adequate PCE (75%) with the range hood designs most commonly observed in homes currently. Observations about hoods commonly installed in homes are based on a study of real estate web sites as reported by Klug and Singer (2011). For very airtight homes, the addition of a range hood exhausting even 200 cfm in combination with other exhaust fans could lead to “worst-case” depressurization that exceeds thresholds for ensuring safety in homes with natural draft combustion appliances. This hazard can be mitigated using an interlocked make-up air system or a pressure relief damper.

We used a fan efficacy of 1-2 cfm W⁻¹ for these hoods based on the measurements reported by Delp and Singer (2012). Delp and Singer's measurements indicated that the low cost hoods that Klug found to be typical have high efficacies at very low pressure drops, but the efficacy is quite low in the range of static pressures expected in homes. Additionally, the Home Ventilation Institute (HVI) reports airflow (in steps of 10 cfm) and power usage for a limited number of hoods and settings that have been tested using HVI procedures (HVI 2013). HVI allows members to express efficacies (cfm W⁻¹) for their products based on these reported values (HVI 2009). However the vast majority of range hoods that are not energy star rated do not report fan power at specific flow rates. The 1-2 cfm W⁻¹ efficacy range corresponds to lowest 10% of calculable efficacies from data reported in the HVI guide.

2. Improved fan efficiency. Energy Star currently requires that fans have an efficacy of greater than 2.8 cfm W⁻¹ (1.4 L/s/w) at 100 cfm (47 L/s). Although this fan efficacy is higher than low-end fans on the market, it still represents a relatively low level of overall fan efficiency. This scenario estimates the potential benefits of improving fan efficacy by assuming all range hoods operate at an efficacy of 3-4 cfm W⁻¹ at the base case flow rate of 200 cfm. This range of fan efficacies are comparable to the median to 90th percentile range of fan efficacies calculated from data reported for Energy Star rated fans in the HVI (HVI 2013).
3. Improved pollutant capture efficiency. PCE depends on the geometry and other design features of the range hood, type of pollutant, cooking practices (e.g. preferentially using back versus front burners), and installation height. Improving any combination of these features to increase capture efficiency – e.g., requiring range hoods that cover the entire stove top and educating occupants to cook on back burners – could significantly improve pollutant removal per unit air flow. These changes would allow for lower flow rates while providing equivalent indoor air quality. For this scenario, we assumed that flow rates could be halved while maintaining the base case PCE based on the findings of Singer, Delp et al. (2012). We did not specify how this reduction in flow rate would be achieved in homes.
4. Improving PCE and fan efficacy. This scenario quantifies the potential benefit of both reducing airflows to 100 cfm through improved PCE and improving fan efficacy to 3-4 cfm W⁻¹.

Range Hood Energy Model. The energy impact of range hood ventilation is a combination of the energy to run the fan, ΔE_f , the energy to thermally condition the additional incoming air, ΔE_c , and the conditioning energy impact of removing the heat produced by the range that would normally enter the space that is vented along with the pollutants, ΔE_r . The annual change in energy demand from using a range hood in a single home is:

$$\Delta E_{annual} = \Delta E_f + \Delta E_c + \Delta E_r \quad (1)$$

The three components of Equation 1 were calculated separately to estimate the impact of each component on total energy demand.

Energy impact of fans (ΔE_f). The operating condition of a range hood is a function of the fan setting, the fan curve, and the range hood and ducting system curves. A limited number of studies have measured fan curves for range hoods (Kuehn et al. 1989; Delp and Singer 2012). For the more expensive fans with centrifugal impellers, fan efficacy and fan flow rates do not vary greatly with pressure. For low cost models with simple propeller-shaped fan blades, the shape of the system curve has a large impact on both fan flow rate and fan efficacy. While methods for calculating system curves for duct systems are relatively straightforward, we have little information on duct systems attached to range hoods in homes. The presence of elbows, offsets, and the loading of grease screens drastically change the curve and these parameters are often field modified or unattainable. There is also very limited information on range hood prevalence in U.S. homes or if fans that are present are exhausting to the outside (Klug and Singer 2011; Mullen et al. 2012).

For this analysis we assumed that fan efficacy did not vary as flow rate varied. We additionally assumed that all of the range hoods met the required airflows exactly. Due to the speed settings and different system / fan curves, actual flows will vary in homes. We assumed that the hoods ran during all cooking events in each home. Given these assumptions, a simplified equation for fan energy is:

$$\Delta E_f = \frac{FR}{FE} * \Delta t \quad (2)$$

where FR is the fan flow rate, FE is the fan efficacy, and Δt is the time that the fan is operating.

Energy impact of conditioning additional airflow (ΔE_c). For each individual home simulation, we determined the additional airflow, ΔA_t , for every cooking hour of a representative year by comparing the home with no range hood use to the same home with a range hood operating during all cooking events. We treated the range hood as an unbalanced exhaust device that increased total airflow through the home by quadrature, not by addition; therefore it has a greater effect on total airflow at low levels of infiltration and has a decreasing effect as infiltration increases. ASHRAE Handbook of Fundamentals (ASHRAE 2013a) gives the following relationship for combining mechanical ventilation and natural infiltration:

$$A_i = A_{bal,i} + \sqrt{A_{unbal,i}^2 + A_{inf,i}^2} \quad (3)$$

In this model, $A_{bal,i}$ is the air change rate at time step i contributed by balanced mechanical ventilation system(s), $A_{unbal,i}$ is the air change rate at time step i that would result solely from operation of unbalanced mechanical ventilation system(s), and $A_{inf,i}$ is the air change rate at time step i due to natural infiltration in the absence of unbalanced mechanical ventilation. Infiltration is natural ventilation that is driven through envelope leaks by the indoor-outdoor temperature difference and outdoor wind speed. In this model, range hood use has a greater impact on total airflow at low levels of infiltration and a decreasing effect as infiltration increases. For our analysis, for every hour of the year, the additional air exchange rate due to exhaust range hood use is:

$$\Delta A_i = f_{fan\ on,i} \left(\sqrt{A_{range\ hood,i}^2 + A_{inf,i}^2} - A_{inf,i} \right) \quad (4)$$

where $f_{fan\ on}$ is the fraction of the hour the fan is on and $A_{range\ hood}$ is the unbalanced range hood flow. We determined the infiltration air change rate using the enhanced model for infiltration developed by Walker and Wilson (1998).

$$A_{inf,t} = \frac{Q}{V_{house}} = \frac{1}{V_{house}} \sqrt{Q_{stack,t}^2 + Q_{wind,t}^2} \quad (5)$$

$$Q_{stack,t} = cC_s \Delta T_t^{2/3} \quad (6)$$

$$Q_{wind,t} = cC_w (sU_t)^{4/3} \quad (7)$$

$$c \left(\frac{m^3}{sPa} \right) = \frac{ELA}{\sqrt{\frac{\rho_{air}}{2} \Delta P^{(.67-.5)}}} \quad (8)$$

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, ELA is the estimated leakage area, Q_{stack} is the infiltration airflow due to the stack effect, Q_{wind} is the infiltration airflow due to wind, V_{house} is the volume of the house, and ELA is the estimated leakage area of the home. Typically ELA is calculated from measurements of c using a blower door in individual homes. Since we are using database derived estimates of ELA as a function of home characteristics, we must then calculate the c for the home to determine changes in airflow due to range hood use. We assume that windows are only open at times when the space is not being conditioned; therefore they are not considered in the energy calculation.

We used the Incremental Ventilation Model (IVE) to determine the additional energy required to condition the extra airflow over the course of the year. 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 IVE model has been described in detail and compared to a comprehensive physics-based residential energy, moisture and airflow model by Logue, Turner et al. (2012) and will be described briefly here.

The change in total conditioning energy used, ΔE_c , is calculated as the sum of three contributions: changes to (1) heating (ΔE_{heat}), (2) cooling (ΔE_{cool}), and (3) air distribution fan for a ducted, forced air system (ΔE_{blower}) if the system is ducted.

$$\Delta E_c = \Delta E_{heat} + \Delta E_{cool} + \Delta E_{blower} \quad (9)$$

Each of the three terms on the right hand side is proportional to the change in airflow. The incremental change in heating or cooling energy is calculated for discrete time intervals using the following equations:

$$\Delta E_{Heat} = \max[\Delta t([\dot{m}_t C_p (T_{set,t} - T_{out,t})]/\epsilon_{heat}), 0] \quad (10)$$

$$\Delta E_{cool} = \Delta E_{thermal} + \Delta E_{latent} \quad (11)$$

$$\Delta E_{thermal} = \max[\Delta t([\dot{m}_t C_p (T_{out,t} - T_{set,t})]/\epsilon_{cool}), 0] \quad (12)$$

$$\Delta E_{latent} = \max[\Delta t(\Delta A_t * L_v * V_{cond} * (\rho_{water,out,t} - \rho_{water,in,t})/\varepsilon_{cool}), 0] \quad (13)$$

$$\dot{m}_t = \Delta A_t * V_{cond} * \rho_{air} \quad (14)$$

The symbols in equations 10 through 13 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 change rate at time step t .
- V_{cond} (m³) 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 includes both sensible ($\Delta E_{thermal}$) and latent (ΔE_{latent}) components. An hourly time step allows tracking of weather variations throughout each day in concert with Typical Meteorological Year data (TMY3) 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 energy use of a residential blower system is a function of the home conditioning system size and run times. Since we did not have information about the sizes of the home conditioning systems and blower sizes or run times, 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). The coefficients reflect a sizing relationship between the recommended blower and heating and cooling system sizes for new California homes. We applied these coefficients for all systems that were ducted. When more than one heating system was reported as providing a significant fraction of the annual heat demand ($\geq 25\%$), we applied these coefficients to only the fraction of the heating or cooling energy that was reported to be provided by a ducted system.

$$\Delta E_{blower} = 0.023 * \Delta E_{Heat} + 0.176 * \Delta E_{cool} \quad (15)$$

Energy impact of removing heat generated by the cooking device (ΔE_r). In addition to removing pollutants, venting range hoods also capture and remove some fraction of the heat generated by the cooking device. In the absence of range hood use, this heat would reduce the conditioning energy load during heating season and add to the load during times requiring cooling. The heat capture efficiency (HCE) differs from the PCE for several reasons. A

substantial fraction of the heat generated by the cooking appliance is transferred to the cooking container and food; and when the oven burner is used, some of heat is temporally stored in the mass of the oven. Some of this heat radiates beyond the exhaust plume during cooking, some will remain in the pot or oven after burner and exhaust fan use have ceased, and some may be transferred to the kitchen if the pot is removed from the stove during cooking. Even for the limited question of HCE for a pot on a stovetop during burner use, we found only one report of measurements for residential range hoods (Farnsworth et al. 1989). We therefore had to estimate HCE.

We estimated HCE from the reference point that even with 100% PCE, heat capture would be less than complete because of the heat transfer processes noted above. As another reference, we used estimates of heat gain in commercial spaces due to commercial cooking appliances. The ASHRAE Handbook of Fundamentals publishes a table of radiative heat factors for commercial cooking appliances (ASHRAE 2013b) indicating a radiative loss of roughly 15% when the appliances are idle (e.g. the burner/range is on, but not cooking food). Since commercial range hoods are designed to ensure complete capture with some margin of safety and since actually cooking would further remove heat from the plume, we took this value as an unrealistic lower bound of the heat that would escape from the exhaust plume in a residential setting. We therefore estimate that with 100% PCE the HCE would be roughly 60-80%, corresponding to a 20-40% heat transfer to the indoor environment. We then assume that HCE is reduced proportionally to PCE. Based on the measured values of PCE reported by Singer, Delp et al. (2012) and Delp and Singer (2012), we estimate that the use-averaged PCE of currently available and installed hoods is in the range of 50-80%. Multiplying these PCEs by the proportional HCE range of 60-80%, we estimate that use-averaged absolute HCE is in the range of 30-65%.

For each hour of the year for each home we determined if the heating system or cooling system was on by comparing the heating or cooling thermostat temperature to the outdoor temperature during cooking times. Replacement energy was calculated by:

$$\Delta E_r = Power_{burner} * HCE \left(\frac{\Delta t_{heat}}{\varepsilon_{heat}} - \frac{\Delta t_{cool}}{\varepsilon_{cool}} \right) \quad (16)$$

Where $Power_{burner}$ is the power output of the burner, Δt is time the burner and conditioning system are simultaneously on, HCE is the heat capture efficiency of the range hood, and ε is the efficiency of the conditioning system (heating or cooling). Using the thermostat settings instead of the balance temperature to determine when conditioning systems are on will likely overestimate the energy impact when the thermostat setting is close to the outdoor temperature.

Representative Subset of U.S. homes

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 2009b) 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. (2013b) and in the supplemental material.

The current application of the IVE and the PIAM framework 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 (which was used to derive ELA for equation 8) of the building envelope, home size, heating and cooling system efficiencies, hourly weather conditions, stove type and burner energy use, and thermostat temperatures for RECS entries that did not have specified values. Chan, Joh 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. We used hourly weather data from the National Solar Radiation Data Base (NSRD) (NREL 2008). The NSRD reports data for a typical Meteorological Year (TMY3) for 1020 weather stations nationwide. For each home, we used the TMY3 data from the weather station closest to the IECC identified representative city for the climate zone the home is located in.

We used the model developed by Chan, Joh et al. (2012) 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 the corresponding 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 set of homes represented by a disaggregated RECs database entry. We used the mean values in the analysis so that we could multiply the calculated site energy demand of each set of home characteristics by the weight for that entry to determine the aggregate change in energy use.

The heating and cooling system in each home was assigned a system efficiency based on system type and age using the algorithm of the Home Energy Saver calculation engine (Mills and Energy Analysis Department 2005). Energy costs for electricity, natural gas, heating oil, and liquid petroleum gas (lpg) were taken from 2010 USEIA data reported by state (USEIA 2012). Source energy demand was calculated using the electrical grid interconnection source energy factors for each state (Deru and Torcellini 2007). Most of the homes in RECS reported heating and cooling thermostat temperatures for periods when occupants are home, away, or sleeping. For the homes that did not report these values, the median temperature reported by other RECS homes was used. These default temperature settings for cooling were 75°F, 73°F, and 73°F (24°C, 23°C, and 23°C) for away, home and overnight. Default settings for heating were 67°F, 70°F, and 68°F (19°C, 21°C, and 20°C) for away, home and overnight.

Stove type (electric, natural gas, or propane) was assigned to each home such that the ratio of stove types in our sample was consistent with the 2005 RECS nationwide ratios of stove type (US EIA 2005). Power output values for natural gas stoves assume an average cooktop burner firing rate of 123 kJ/min (7 kBtu/h). Propane ranges and stoves were assumed to have the same burner rate as natural gas stoves. Electric stoves were assumed to have a per burner range energy rate of 1800 watts and stove burner energy rate of 3000 watts, based on manufacturers published outputs. Oven use durations must be translated to burner operation times to account for on/off cycling. We used the oven burner patterns developed by Logue, Klepeis et al. (2013a) to determine burner firing time as a function of overall duration of oven use.

The RECS database contains household-provided data on the frequency of cooking with a stovetop or oven, but does not resolve separate stovetop and oven use and does not report which meals are cooked. The RECS database also contains no information about cooking duration. We assigned which meals were cooked, cooking duration, whether or not the oven was used, what fraction of time the oven burners were on, and cooking start time using the methodology developed by Logue, Klepeis et al. (2013a). These activity patterns were assigned as a function of home occupancy based on results of cooking behavior surveys.

Limitations of modeling analysis

Given the lack of data about actual home performance and prevalence of range hoods, there are several limitations to this analysis. The analysis undertaken was designed to estimate population wide energy impacts of venting range hood use in all U.S. homes if all homes in the stock were outfitted with venting range hoods. The analysis does not estimate the current energy use of range hoods in homes or the incremental energy use that would result if all households with venting range hoods would use them during all cooking events. Additionally, some homes may use alternative ventilation, such as opening windows, when cooking if no range hood is present. Those impacts are not included in this analysis. Our model did not account for variations in cooking patterns throughout the year. To the extent that people use their indoor cooking appliances less during the hot weather / cooling season, the benefit of removing heat via the range hood will be less than calculated. This analysis assumes that heat emitted by the stove/oven is effectively used to heat the home and removing that heat results in an even tradeoff in the increase in heat demand and reduction in cooling demand. If this is not the case, we are overestimating the impact of replacement energy.

Results

We estimate that comprehensive use of range hoods having the performance characteristics of devices that are currently most common in homes would require annual expenditures of 19–33 TWh [69–120 PJ] of site energy (about 1% of current annual US residential site energy use), 31–53 TWh [110–190 PJ] of source energy, and \$1.2–2.1 billion for the U.S. housing stock (Note that all cost estimates are provided as US\$ in 2010). The impact on individual homes varies based on weather and cooking patterns; however the cost of range hood use is relatively low in the vast majority of homes.

Table 1 lists the representative city and climate description for each IECC climate zone (CZ). Figure 1 shows the total and house average energy use and cost impacts of range hood use in each CZ for the base case, Scenario 1. Results are presented for each component load – fan energy, conditioning energy, and replacement energy – and for the total load. Fan and replacement energy loads are each shown as a range to reflect uncertainty in fan efficacy (1-2 cfm W⁻¹) and heat capture efficiency (30-65%). The average total energy demand is shown with bars extending from the minimum energy impact (low HCE and high fan efficacy) to maximum energy impact (high HCE and low fan efficacy). The large climate zone to climate zone variation in total energy/cost impact is due to large variations in the number of homes in each climate zone as shown in Table 1. The home average energy/cost impacts increase on average as the indoor-outdoor temperature difference for a give climate zone increases. Across zones, estimated contributions to total site energy demand were 5-16% for fans, 20-35% for conditioning, and 52-

74% for replacement energy. The relative importance of each component load varies across CZ and with estimated HCE and fan efficacy. Conditioning energy was higher in colder climates, and replacement energy depends on the temporal coincidence of cooking and thermal conditioning.

In CZ-1 the cost of range hood use is estimated to be small, requiring an estimated -4 to 25 kWh of annual site energy per home. These tiny overall load estimates are due in part to the calculated net benefit of saving on replacement energy during the cooling season. Replacement energy did not have as large an impact in CZ-2A through CZ-3B as it did in the other zones. The large impact of replacement energy in CZ-3C results because unvented cooking in this area, which predominately represents the marine/coastal region of California, provides a substantial fraction of the energy required to condition the house when burners are used. In this CZ, a large fraction of the hours of the year are below the reported thermostat setting but only by a small amount. It is possible that in CZ-3C that this approach does not accurately estimate the impact of removing cooking heat and that a more advanced modeling technique may be needed.

Figure 2 shows the distribution of household source energy and consumer cost due to range hood use as described in Scenario 1 with a fan efficacy of 1 cfm W⁻¹ and an HCE of 65%. These values represent the upper limit on the energy and cost impacts of range hood use. Estimated cost impacts vary within each CZ even though the average cost increases from warmer to colder CZs. Even in the coldest CZ-8, range hoods use as described in Scenario 1 costs less than \$75 for 75% of homes. The vast majority of homes would pay less than \$40 annually. The low calculated costs indicate that range hood use is an affordable method of controlling the potentially quite high health burden from cooking pollutants from an annual energy cost standpoint. Given the low average annual energy demand, the initial cost of range hood installation could play a large role in the decision of which range hood to install in new construction and whether or not to install a range hood in retrofits. Costs of range hoods vary widely, and those on the lower cost end tend to have lower performance (Delp and Singer 2013). Delp and Singer conducted an internet search that indicated range hood costs ranging from \$40 for economy hoods and \$300 for a hood that meets ASHRAE 62.2. A home cost calculator estimated that range hood installation would require 3 hours and cost around \$160 (Homewyse 2013), although not specified, we understand this cost to apply to replacement in a home with existing ductwork for venting or potentially a direct through the wall venting. The cost would be substantially greater in a home that requires venting to be installed or replaced. In some homes – especially in multiunit buildings - the location of the kitchen may make it extremely expensive or otherwise infeasible to install a vent to the outside."

Cooking in homes occurs for limited time frames at regular intervals. This type of activity will have an impact on daily patterns of electricity use and could potentially impact peak energy demand. For this analysis, we used limited data on behavior patterns of cooking that do not reflect seasonal or potentially regional variability in cooking behavior patterns limiting our ability to make any specific assumptions on peak electricity use. Analyzing our limited results for daily variability in electricity use in the cohort indicates that in summer months range hood use would, on average, reduce electricity demand during peak hours by reducing the cooling load when cooking heat is removed from the home. In winter months, range hood use would increase demand. Total residential electricity demand is currently higher in summer than winter,

indicating that range hood use would likely not increase summer peak load issues. Further work is needed to fully assess or access? peak electricity impacts of range hood use.

The low cost of range hood use indicates that it will likely not be cost effective to retrofit homes to replace range hoods with more efficient appliances based on energy savings alone. However, as new homes are built or range hoods are replaced or installed for other reasons including improvements in IAQ, there is the opportunity to introduce new products to the market that use less energy.

Scenarios 2 and 3 present two methods of reducing range hood energy use. Scenario 2 is the current approach taken by the Energy Star program. Scenario 3 assumes airflow is reduced by half while achieving the same pollutant capture efficiency. Both of these scenarios were assumed not to impact replacement energy since the fraction of the buoyant plume being captured is assumed to not change. Figure 3 shows the scenario / strategy that more frequently leads to greater energy savings by climate zone. The analysis compares Scenario 2 savings assuming that all homes saw an increase of fan efficacy from 1 to 4 cfm W⁻¹ to Scenario 3 savings, with fan efficacy assumed to be 1.5 cfm W⁻¹ and airflow being reduced by half, to 100 cfm. In most CZs the majority of homes will save more energy with Scenario 3 even when we assume maximum improvement in fan efficacy for Scenario 2. Reducing the required airflow rate reduces both the fan energy and the conditioning energy requirements. In cold climates, Scenario 2 saves more source energy in homes that are leaky enough that the additional mechanical fan use does not significantly impact total airflow. If these homes are weatherized to reduce home leakiness, it is likely that Scenario 3 will save more energy. In moderate climates, Scenario 2 saves more energy than Scenario 3 in homes that have low levels of conditioning either due to not conditioning at all or setting the thermostat temperature to a level that is close to the outdoor temperature. Given the low annual cost of range hood operation, it is unlikely that a dedicated heat exchanger, like a heat recovery ventilator (HRV), would be cost effective. Also, heat exchangers do not operate well in dirty/greasy environments. However, range hoods could potentially be designed to inexpensively reduce the energy exhausted to the outside by using materials and design elements that increase heat loss from the exhaust stream back to the home. Designing range hoods that minimize HCE while increasing PCE at lower flow rates has the greatest potential to reduce the energy impact of range hood use on an annual average basis.

Figure 4 shows the total and house average annual energy and cost savings, relative to base case of Scenario 1, resulting from improvements to fan efficacy (Scenario 2), capture efficiency (Scenario 3), or both (Scenario 4). Implementing Scenario 2 would save 0.6–2.5 TWh [2.0–8.9 PJ] of site energy, 1.8–8.3 TWh [6.6–30 PJ] of source energy, and \$68–304 million annually. Implementing Scenario 3 would save 5.4–6.3 TWh [20–23 PJ] of site energy, 10–13 TWh [37–47 PJ] of source energy, and \$390–490 million annually. Implementing both scenarios would save 5.7–7.5 TWh [21–27 PJ] of site energy, 11–17 TWh [40–60 PJ] of source energy, and \$425–645 million annually. In all scenarios, average household savings would be less than \$6 annually. Both Scenario 2 and 3 have similar impacts on daily patterns of electricity use.

As a check, we compared our bottom-up estimates of residential cooking fuel energy to estimates developed by the U.S. Energy Information Agency (USEIA). With the assumptions used in our model, we calculated total cooking fuel site energy use of 41 TWh [150 PJ] of electricity, 26 TWh [94 PJ] of natural gas, and 2.2 TWh [8.0 PJ] of propane for the U.S. housing sector. The USEIA estimated that electric burners and stoves use 53 TWh annually based on the

results of the 2001 RECS (US EIA 2009a). In the 2013 Annual Energy Outlook (USEIA 2013), the USEIA estimated an annual residential energy use for cooking of 32 TWh [120 PJ] of electricity, 65 TWh [232 PJ] of natural gas, and 8.7 TWh [32 PJ] of propane. Our estimates for electricity use fall between the two USEIA estimates. Our estimates of natural gas and propane are lower than the estimates from the USEIA. The USEIA natural gas estimates are double the estimates for electricity despite the fact that more than 60% of residential stoves are electric and energy use rates of electric and gas stoves are similar. It may be that the additional natural gas and propane use is due to non-stove cooking such as outdoor grills or that the USEIA estimates, which are a disaggregation of nationwide energy use, are uncertain at this level of resolution.

Conclusions

Range hood use is essential to maintaining indoor air quality in homes where cooking occurs. Our assessment indicates that effective range hood use during all U.S. residential cooking events would increase residential energy demand by 19.3–33.4 TWh [69–120 PJ], on the order of 1% of the total site energy for the U.S. housing sector. Source energy demand would increase by 30.5–52.8 TWh [110–190 PJ] and the cost to consumers would be \$1.2–2.1 billion (US\$2010) annually. The range in estimated energy use and costs is due to uncertainty in fan efficacy and heat capture efficiency that would apply across the population. While small relative to total home use, an aggregate change of 1% of residential energy use is equivalent to adding five constantly running 600 MW power plants to the US.

Range hood use will impact peak electricity use. A detailed analysis of time varying electricity demand would require more information than we currently have on cooking behavior in homes. Our initial results indicate that range hood use would reduce peak electricity demand in summer and increase peak electricity demand in winter.

Increasing fan efficacy to levels that exceed current minimum requirements of the Energy Star program would reduce site energy demand related to range hood use by 3–7%, significantly less than the 20–40% reduction that is the nominal target of the program. This is because fan energy accounts for only a minority of total energy load associated with range hood use and reducing the required flow rate also reduces fan energy. Improved range hood designs and changing practice to preferentially use back, rather than front burners would reduce the airflow rates for effective pollutant capture; the potential benefit of such changes is estimated to reduce site energy demand by 19–28% relative to the baseline case. Reducing required flow rates and improving fan efficacy could reduce site energy demand by 22–30%.

The cost per home for range hood use is relatively low: the average cost per home is estimated to be less than \$15 annually. The low cost indicates that range hood use is a fairly inexpensive way to improve indoor air quality, but also means that energy savings will not pay back the cost of replacing an operational hood with a more efficient model purely for purpose of saving energy. There is opportunity to reduce energy use by requiring new range hoods to be more energy efficient. The current Energy Star approach of focusing exclusively on fan efficacy is less effective than a requirement to ensure efficient capture efficiency at lower airflow rates. There is also significant energy savings potential for range hoods that are designed to both increase pollutant capture efficiency and to reduce the amount of stove energy exhausted to the outside.

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Table 1. List of IECC climate zones along with representative city for each climate zone, qualitative description, and number of homes in that climate zone.			
IECC Climate Zone	Representative City	Climate Description	RECS estimated Homes in Climate zone
1	Miami, Florida	hot, humid	1,978,975
2A	Houston, Texas	hot, humid	12,267,510
2B	Phoenix, Arizona	hot, dry	2,069,784
3A	Atlanta, Georgia	hot, humid	15,406,999
3B	Los Angeles, California	hot, dry	10,686,455
3C	San Francisco, California	marine	2,662,390
4A	Baltimore, Maryland	mild, humid	24,300,108
4B	Albuquerque, New Mexico	mild, dry	877,109
4C	Seattle, Washington	marine	3,242,353
5A	Chicago, Illinois	cold, humid	25,957,160
5B	Denver, Colorado	cold, dry	4,194,726
6A	Minneapolis, Minnesota	cold, humid	7,795,736
6B	Helena, Montana	cold, dry	1,027,399
7	Duluth, Minnesota	very cold	1,053,574
8	Fairbanks, Alaska	extreme cold	59,881

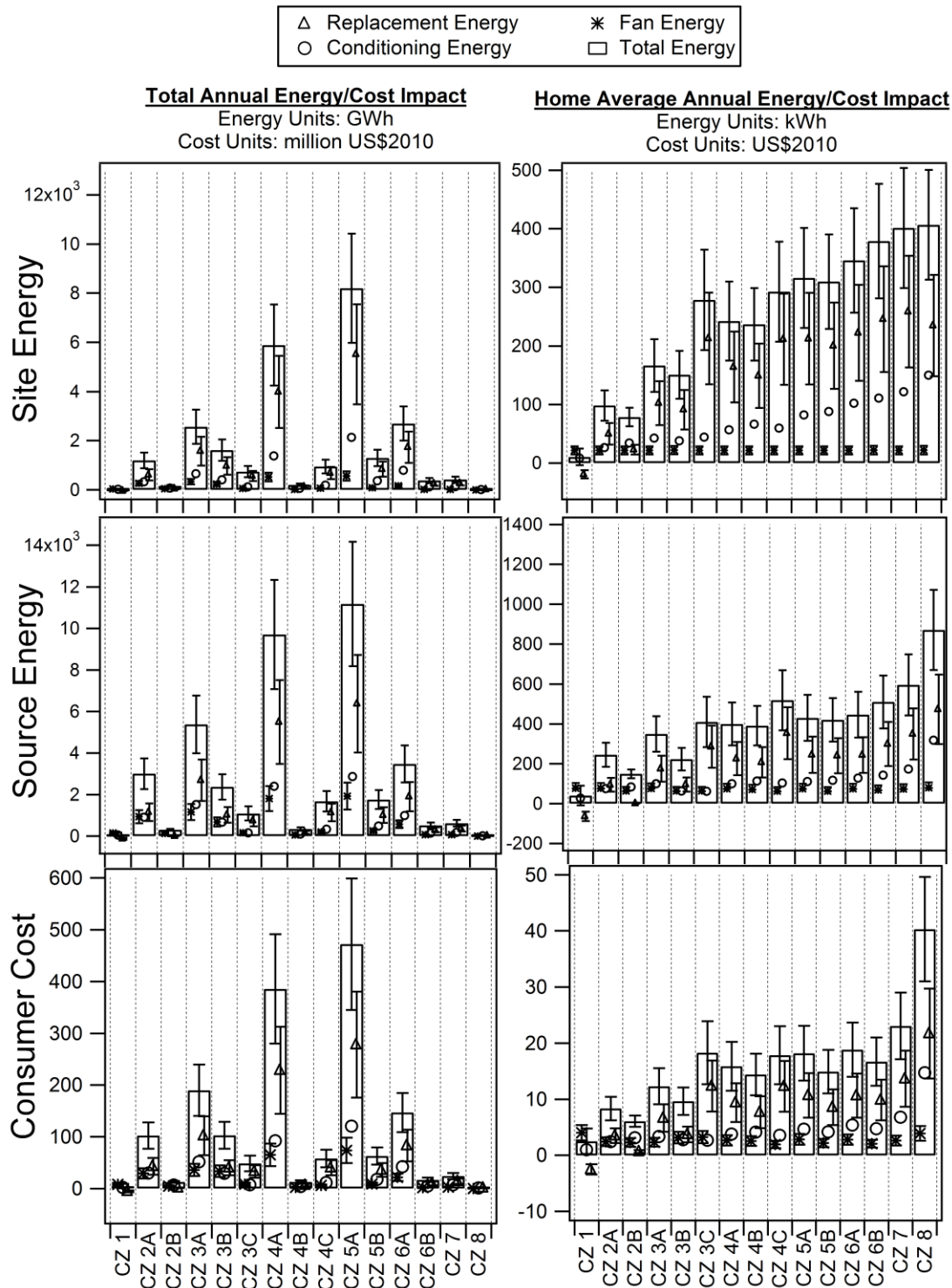


Figure 1. Estimated energy use and consumer cost impacts of using range hoods during all U.S. residential cooking with performance as specified in Scenario 1. Left side shows total impacts by climate zone (CZ). Right side shows house average impacts. Ranges reflect uncertainty in heat capture efficiency (HCE) and fan efficacy. Black outlined bars use central estimates of HCE and fan efficacy. Whiskers show bounding estimates, based on ranges of HCE and fan efficacy.

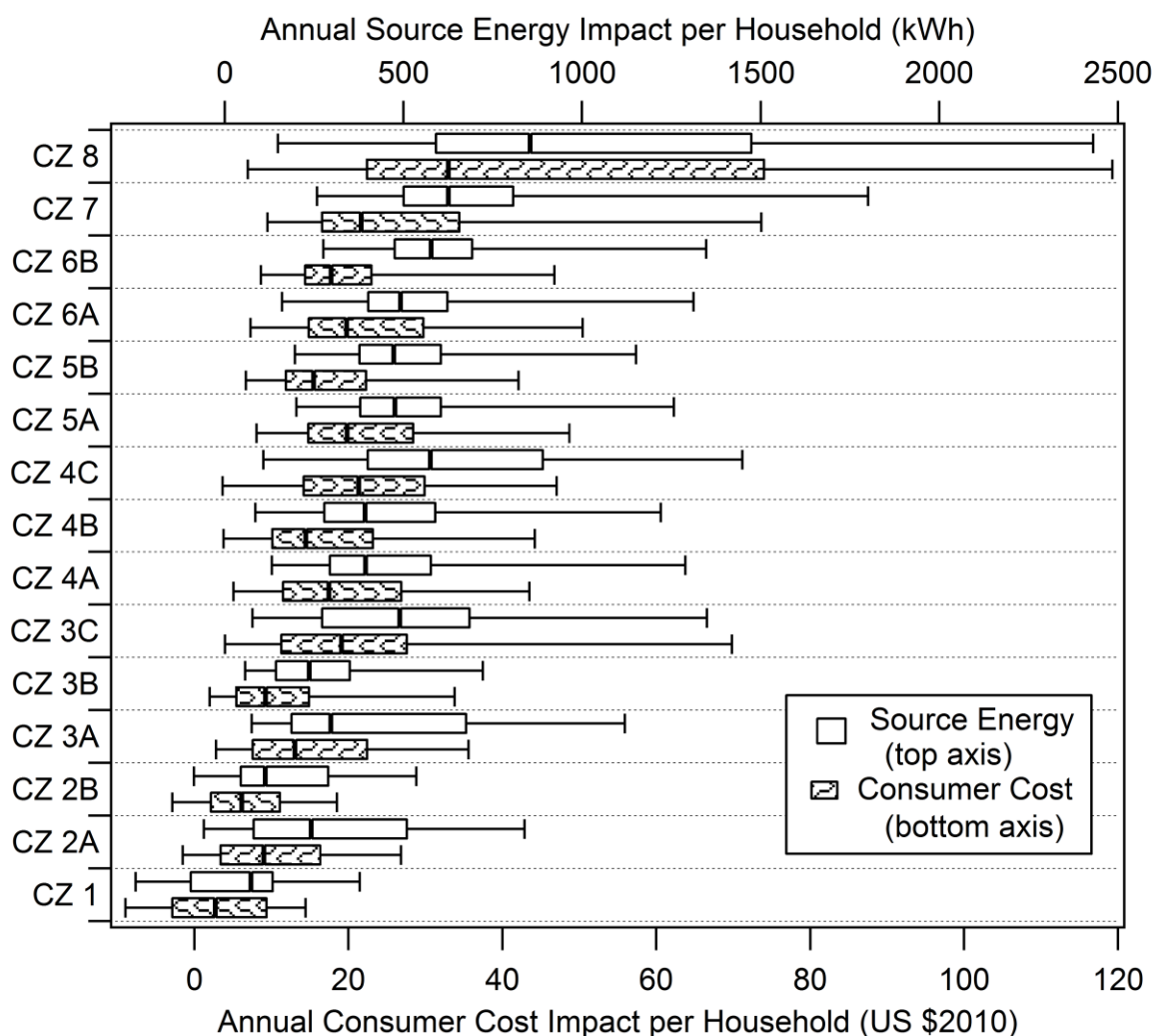


Figure 2. Distributions of household source energy and cost of range hood use in Scenario 1 assuming heat capture efficiency of 65% and fan efficacy of 1 cfm W^{-1} . Boxes range from 25th to 75th percentiles with center lines at 50th percentiles. Whiskers show 5th to 95th percentiles.

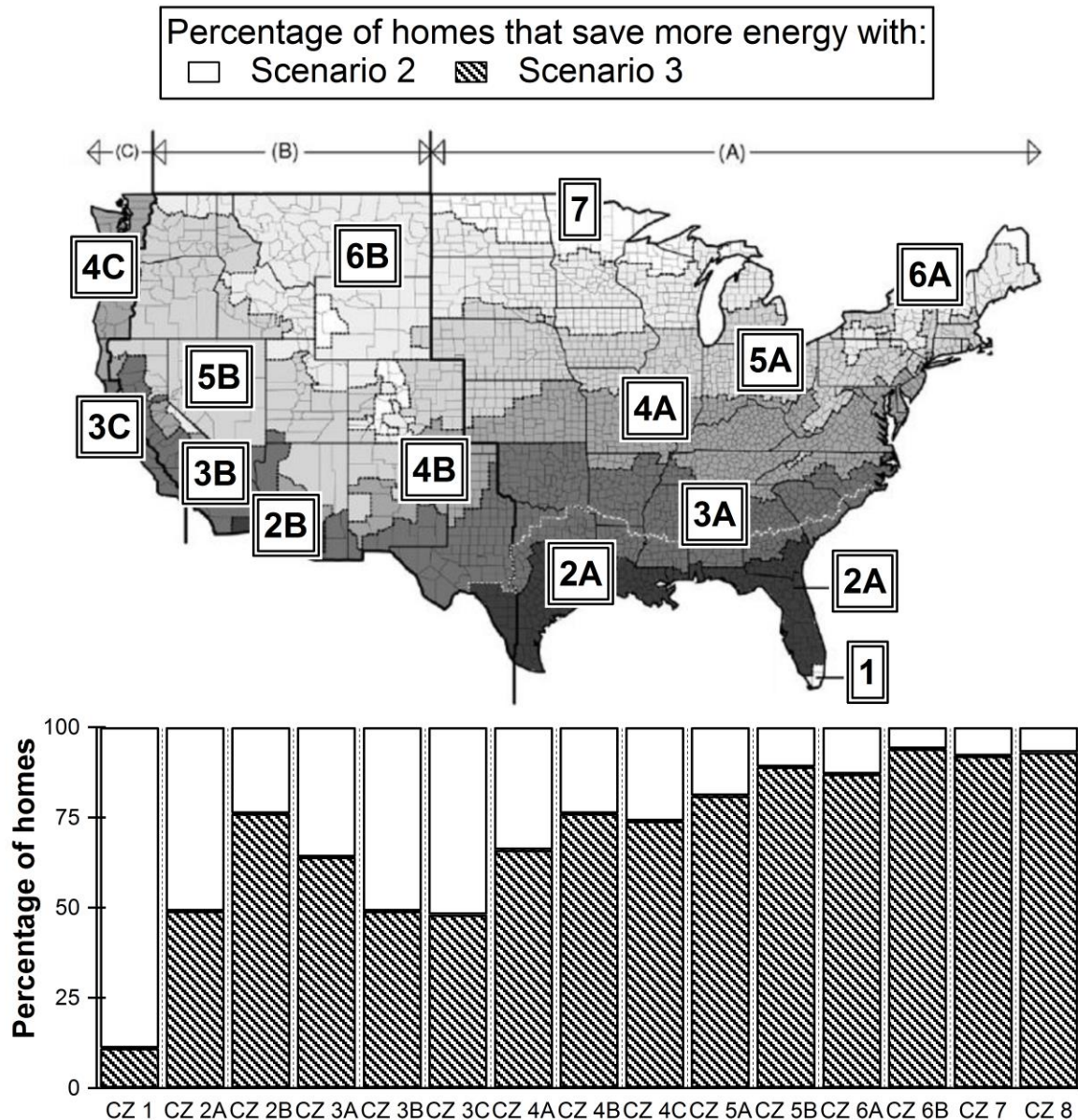


Figure 3 Percentage of homes in each climate zone that would save more source energy by using a higher efficacy fan (Scenario 2) compared to achieving the same PCE at half of the flow of the base case (Scenario 3). The energy savings for Scenario 2 assumed maximum improvement from 1 to 4 cfm W⁻¹ and the energy savings for Scenario 3 were calculated using the mid-value of the fan efficacy range (1.5 cfm W⁻¹). The same trend was seen for the impact on consumer cost.

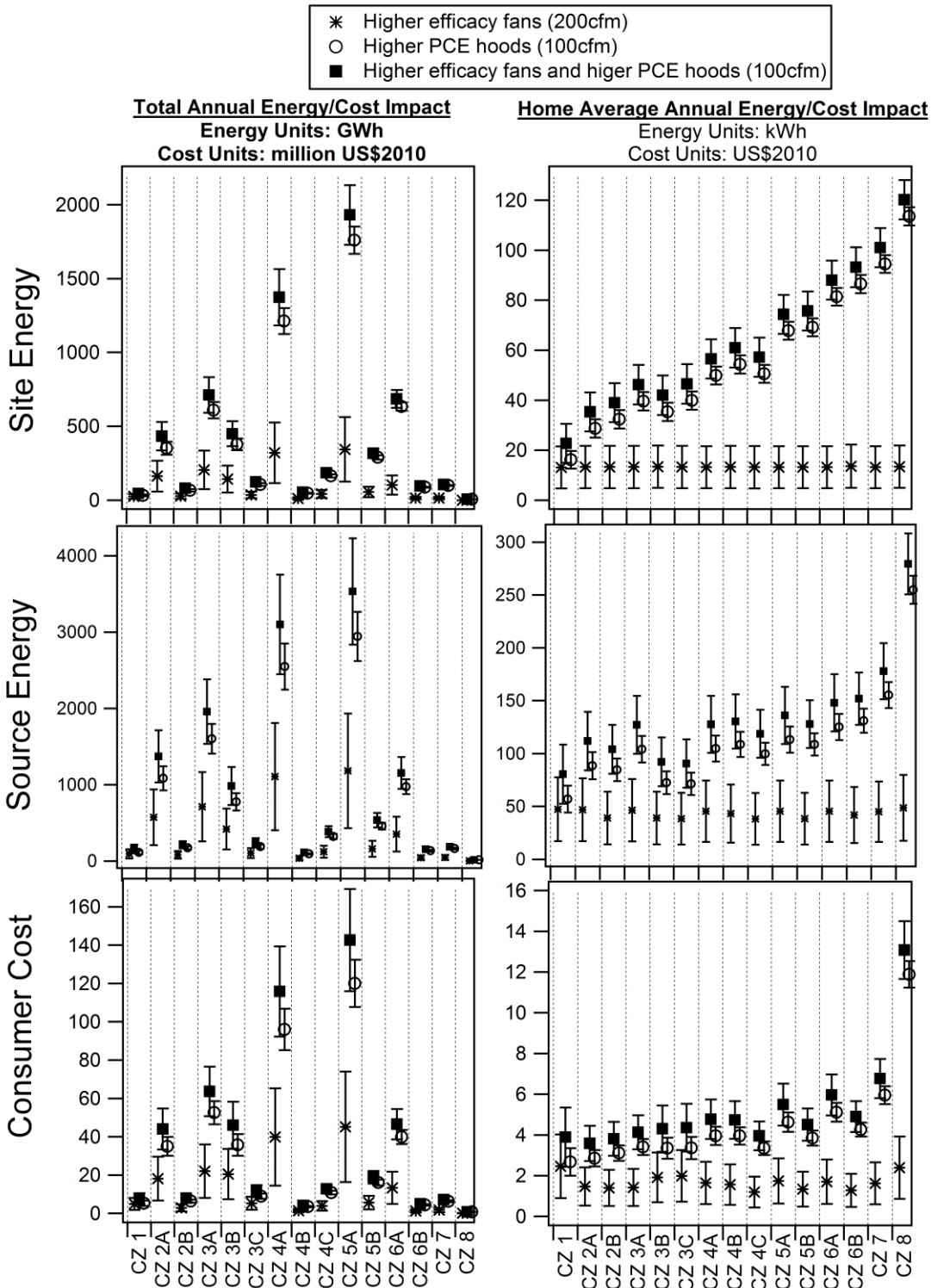


Figure 4 Site energy, source energy, and consumer cost savings compared to Scenario 1 (base case). The total annual energy impact per climate zone and house average energy impact per climate zone is shown. The ranges represent the uncertainty in HCE and fan efficacy.