Lawrence Berkeley National Laboratory



# Evaluation of an Incremental Ventilation Energy Model for Estimating Impacts of Air Sealing and Mechanical Ventilation



**Author**
Logue, Jennifer M.

**Publication Date**
2012-09-28

LBNL-XXXX

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

# Evaluation of an Incremental Ventilation Energy Model for Estimating Impacts of Air Sealing and Mechanical Ventilation

Jennifer M. Logue, William J. N. Turner, Iain S. Walker, and Brett C. Singer

Environmental Energy Technologies Division

June 2012

## Acknowledgments

Funding was provided by the U.S. Dept. of Energy Building Technologies Program, Office of Energy Efficiency and Renewable Energy under DOE Contract No. DE-AC02-05CH11231; by the U.S. Dept. of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070, by the U.S. Environmental Protection Agency Office of Air and Radiation through Interagency Agreement DW-89-92322201-0 and by the California Energy Commission through Contract 500-08-061.

## Abstract

Changing the rate of airflow through a home affects the annual thermal conditioning energy. Large-scale changes to airflow rates of the housing stock can significantly alter the energy consumption of the residential energy sector. However, the complexity of existing residential energy models hampers the ability to estimate the impact of policy changes on a state or nationwide level.

The Incremental Ventilation Energy (IVE) model developed in this study was designed to combine the output of simple airflow models and a limited set of home characteristics to estimate the associated change in energy demand of homes. The IVE model was designed specifically to enable modelers to use existing databases of home characteristics to determine the impact of policy on ventilation at a population scale. In this report, we describe the IVE model and demonstrate that its estimates of energy change are comparable to the estimates of a well-validated, complex residential energy model when applied to homes with limited parameterization. Homes with extensive parameterization would be more accurately characterized by complex residential energy models. The demonstration included a range of home types, climates, and ventilation systems that cover a large fraction of the residential housing sector.

## 1. Introduction

Thermal conditioning of U.S. residences is estimated to require roughly 5.2 quads of energy, accounting for roughly 49% of site energy (US EIA 2005). Estimates attribute one-third to one-half of this energy use to uncontrolled infiltration (Sherman and Matson 1997). Tightening of building envelopes and ducts to reduce air leakage is therefore a core element of energy-efficiency programs and residential retrofit practices that aim to reduce energy consumption and associated costs, including greenhouse gas emissions.

Current best practice seeks to make homes as airtight as possible (within reasonable costs) and provide controlled ventilation with mechanical systems. Ventilation is required to remove indoor-generated pollutants and excess moisture, and to provide a sufficient supply of outdoor air to ensure acceptable indoor air quality (IAQ). The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) publishes a residential ventilation standard (ASHRAE 2010) whose provisions have been incorporated into various professional protocols, guidelines, and energy codes (BPI 2010; CEC 2010; RESNET 2012). Providing ventilation requires energy for thermal conditioning and mechanical system operation. Minimizing these loads while maintaining acceptable IAQ is a key challenge for energy-efficiency retrofits.

The analytical capability to predict the benefits of increasing residential envelope air tightness, and the costs and IAQ benefits of various ventilation system designs and technologies, is important for program design and for the development of protocols for practitioners. The potential benefits of air sealing and the costs of mechanical ventilation vary widely across individual homes and for sub-populations by climate; baseline air-tightness and other building structural characteristics; the performance characteristics of existing or replacement heating, ventilating and air conditioning (HVAC) equipment; and occupant-influenced equipment operational schedules and settings.

Physics-based models exist and have been applied to estimate the impacts of envelope air sealing on natural and mechanical airflows in homes (Wilson and Walker 1990; Chan et al. 2003; Chan et al. 2005; Sherman and McWilliams 2007). These airflow models have been applied to estimate the ventilation impacts of adding mechanical ventilation to homes (Sherman 2008; Sherman et al. 2011). Lawrence Berkeley National Laboratory (LBNL) has developed modeling tools to assess population-level impacts of ventilation changes on pollutant concentrations and exposures in homes. It additionally has shown that health impacts of in-home air pollutant exposures can be quantified with the metric of disability-adjusted life years (DALYs) (Logue et al. 2012). DALYs are a measure of equivalent years of life lost due to illness or disease that quantifies overall disease costs (impacts) due to both mortality and morbidity. DALYs can be used to quantify benefits of ventilation improvements that reduce air pollutant exposures.

One approach to assessing the energy impacts of air sealing and mechanical ventilation options for new homes or retrofits is to use a simulation model to calculate annual total energy use for each configuration of interest (including the baseline) and compare the results. There exist a number of residential energy simulation models that calculate energy demand by solving a series of coupled time-dependent equations representing physical processes of heat, and in some cases moisture transfer, into and out from the home. The models account for radiative and convective heat transfer at the various surfaces of the building envelope (including solar gains); conduction through walls, floors, and ceilings; heat transfer to and from the attic; convective transfer with airflow, heat, or enthalpy addition/removal by HVAC equipment; and internal heat generation. These energy flows are summarized in Figure 1a.

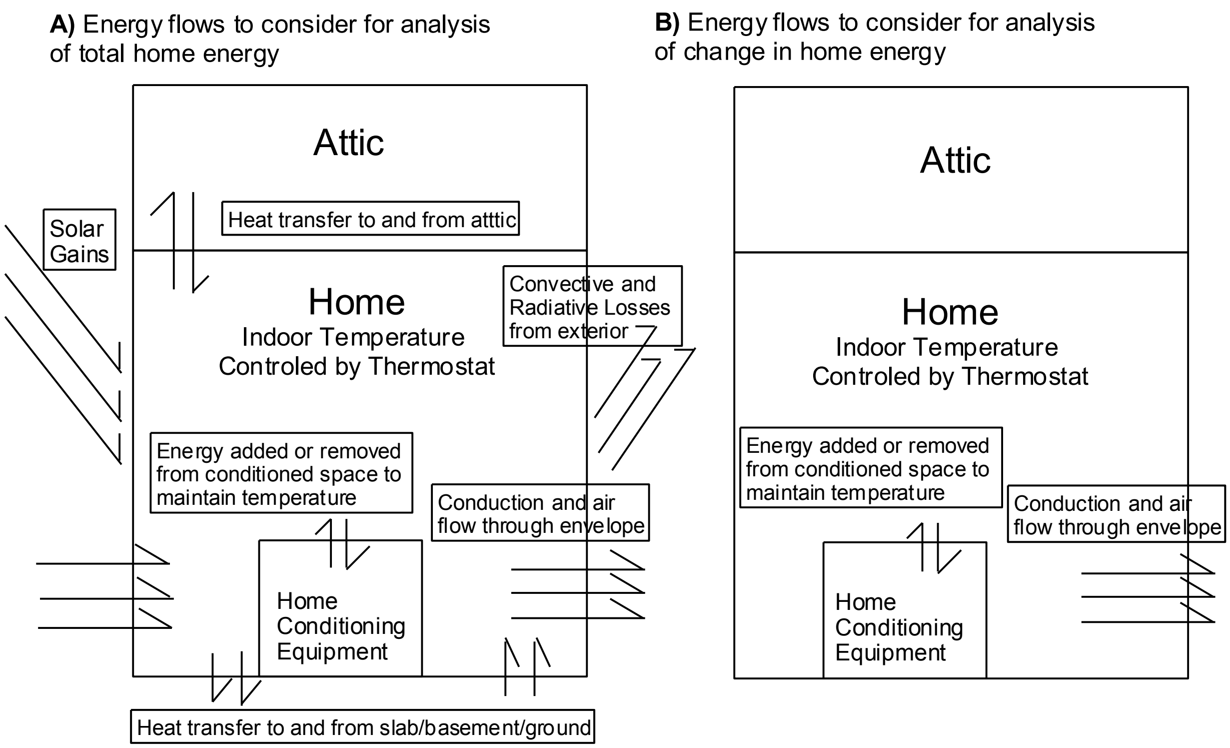


**Figure 1. Energy transfer mechanisms that must be accounted for when calculating (a) total home energy use annually, and (b) the change in energy demand resulting in a change in airflow.**

HVAC operation is based on loads, thermostat settings and schedules. Time-dependent outdoor conditions, which are critical to the model calculations, are incorporated through hourly resolved weather files for representative cities within each climate zone. The physical simulation algorithms require specification of physical characteristics and parameters such as model geometry; heat transfer coefficients (U-values); solar reflectance; internal loads; and heating, cooling, and ventilation system capacities and efficiencies. One residential energy model, REGCAP, requires over 80 parameters per run. The complexity and number of parameters that must be specified increases with the scope of physical processes and potential structural configurations (e.g., attic, basement versus slab) included in the model. A discussion of existing energy models is included in the appendix.

For existing buildings, many of the required parameters can be determined or estimated only through an extensive on-site audit. Some would require research-level diagnostics and some could not be ascertained with any degree of certainty. Since all parameters must be specified for each model calculation, applying these models for population-level analysis requires assignment assumptions to be made for many of the physical characteristics that can influence analytical results. Additionally, the complex nature of existing modeling tools results in model setup and runtimes that make analysis of a large number of homes time consuming. Existing residential energy modeling codes therefore, are not well suited for assessing the specific impacts of air sealing and ventilation systems at the population level.

In recognition of the analytical need, we developed a modeling framework to focus on incremental energy impacts of changing infiltration through envelope air-tightness and adding mechanical ventilation to ensure acceptable IAQ. A key rationale for this model is that many of the processes of energy transfer shown in Figure 1 are not necessarily affected by changes to outdoor air exchange rates or airflow pathways (infiltration or mechanical). If indoor temperature schedules do not change and HVAC equipment is able to achieve thermostat settings, the conductive, radiative, and convective losses at the envelope should be minimally affected by changes to airflow (Ackerman et al. 2006; Ackerman et al. 2006). Solar and internal gains should also be unaffected.

The Incremental Ventilation Energy (IVE) model described in this report calculates (1) thermal energy impacts associated with incremental changes to airflow through the home due to changes in infiltration and mechanical airflow, and (2) loads associated with the operation of mechanical ventilation equipment. The IVE model is designed to calculate energy impacts for large numbers of homes with varied characteristics, so that users can explore the statistics of energy impacts across various sub-groups within the population. The IVE model does not calculate building airflow rates. Instead, it takes building airflow rates (calculated by separate simulation tools) as inputs and then calculates the energy penalty/benefit associated with going from one airflow rate to another for the same building. The model is designed (1) to be run in conjunction with models that estimate the impact of air tightening on infiltration and mechanical airflows on total home air exchange rate, and (2) to select or assign the required home and HVAC equipment parameters based on large, existing databases of U.S. residence characteristics.

This report's aims are to describe the IVE model, describe how to apply IVE to databases of home characteristics to estimate population energy change due to ventilation changes, and compare energy impacts calculated with the IVE to those obtained with a comprehensive residential energy simulation model. The REGCAP model used for this comparison tracks heat, moisture, and airflow; includes algorithms to account for attic and HVAC duct leakage impacts; and has been extensively validated (Wilson and Walker 1992; Wilson and Walker 1992; Siegel 1999; Walker et al. 1999; Siegel et al. 2000; Walker et al. 2002; Walker et al. 2004; Walker and Sherman 2007). The results of IVE and REGCAP were compared for three archetypal homes being operated within five air-sealing and ventilation scenarios across seven continental U.S. climate zones.

## 2. Methods

This section includes a description of the IVE model and details about the house, ventilation, and climate scenarios that were used to compare IVE results to those of the REGCAP model. In describing the model, we first present the overall framework and parameterizations for the physical processes included in the model. We then discuss the sources of data available for assigning or selecting parameter values and note the values used in the application of IVE presented in this report.

### 2.1 Incremental Ventilation Energy (IVE) Modeling Approach

The IVE model calculates the hourly change in energy demand associated with changes to airflow and mechanical ventilation system operation. Energy impacts include changes to thermal conditioning loads and electrical power to operate ventilation equipment. The thermal energy load is a function of the change in mass flow of air, outdoor air temperature and humidity, indoor temperature setting, and the efficiency of the heating or cooling system. The model does not account for internal gains. Hourly incremental airflow is an input to IVE that can be calculated using a variety of approaches, as described below. Changes to incremental airflow and energy for a given hour do not affect subsequent hours. The IVE model is designed to execute this hourly calculation over a full year using standard weather data files (NREL 2008). The IVE model assumes that the change in airflow does not affect indoor temperature and consequently does not impact other heat loss or gain mechanisms such as solar gain, conduction, and internal gains. The assumption of no change in indoor temperature limits IVE application to scenarios in which the installed heating and cooling equipment has adequate capacity to meet the thermostat schedule. In the model, thermostat schedules for the home can be specified as a function of time of year and time of day.

When applying this model to existing databases of home characteristics, we can use existing simple airflow models to determine the hourly air exchange rate. Walker and Wilson (Walker and Wilson 1998) developed an algorithm to calculate the infiltration as a function of data available in databases of home characteristics such as the Residential Appliance Saturation Survey (RASS) and Residential Energy Consumption Survey (RECS), outdoor weather data, and home leakage area. Walker and Wilson did not initially develop their algorithm for use with databases of home characteristics, but the information required to use their model is available in these databases. Lawrence Berkeley National Laboratory has also developed algorithms to estimate building leakage area based on parameters available in home databases (Chan et al. 2012). ASHARE Standard 136 (1993) gives a reference method for combining mechanical ventilation and natural infiltration. Details of applying these models to the homes in the existing databases are discussed in the appendix.

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 HVAC energy use, $\Delta E_{HVAC}$, is calculated as the sum of four contributions: energy changes associated with heating ($\Delta E_{heat}$) and cooling ($\Delta E_{cool}$), changes to the energy used by the air distribution fan for a forced air system ($\Delta E_{blower}$), and changes to energy use for fans ($\Delta E_{fans}$), 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:

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

$$\Delta E_{cool} = \Delta E_{thermal} + \Delta E_{latent} \tag{3}$$

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

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

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

$$\varepsilon_{cool/heat} = \varepsilon_{equipment} * \varepsilon_{ducts} \tag{7}$$

The symbols in equations 2 through 7 are defined as follows:

- $\Delta t$ 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 (thermostat setting).
- $T_{out,t}$ (K) is the outdoor temperature at time *t*.
- $fan_{heat}$ is the heat added by the air distribution system fan and any air supply fans.
- $\varepsilon_{heat}$ and $\varepsilon_{cool}$ are the heating and cooling system efficiencies, respectively.
- $\Delta A_t$ (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.
- $\rho_{water}$ (kg m$^{-3}$) is the absolute humidity (the density of water vapor) in the air indoors and outdoors.
- $\rho_{air}$ (kg m$^{-3}$) is the air density.
- $L_v$ (J kg$^{-1}$) is the latent heat of water vaporization.
- $\varepsilon_{equipment}$ is the efficiency of the conditioning equipment.
- $\varepsilon_{ducts}$ is the efficiency of the ducts, as further described below.

The cooling load includes both sensible ($\Delta E_{thermal}$) and latent ($\Delta E_{latent}$) components. An hourly time step allows 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 are calculated every hour for a year, then summed to calculate the total annual change in energy use for the home.

In calculating heating energy loads, the IVE model accounts for heat generated by the air distribution blower ($fan_{heat}$). This parameter is calculated as the energy consumption of the blower ($\Delta E_{blower}$) motor multiplied by 1 minus the fan efficiency. In the current application, we assumed 15% efficiency for this fan, with the other 85% of the power adding heat directly to the distributed airstream (Walker 2006; Walker 2008). Heat from the blower reduces the load on the heating equipment and increases the load on the cooling system.

The heating and cooling system efficiencies, $\varepsilon_{heat}$ and $\varepsilon_{cool}$, account for efficiencies of equipment (air conditioner or furnace, $\varepsilon_{equipment}$) and supply ducts ($\varepsilon_{ducts}$). Duct efficiency is the fraction of distributed air that is not lost during distribution (1 minus the percentage of duct leakage in supply). If either heating or cooling is supplied with a ductless system, this efficiency is 1. The IVE model can therefore account for the first-order benefits of reducing supply duct leakage. The model does not currently account for return duct leakage or leakage due to depressurization of the house due to supply leaks. This type of leakage affects HVAC energy use by bringing air at different conditions than the indoors into the duct system and increasing the airflow through the envelope due to pressure differences. The IVE does not account for changes in air exchange rate due to supply and return duct leaks. Existing, simple airflow models do not account for this increase in airflow. Methods for estimating this extra airflow are discussed in the appendix.

The IVE model accounts for two processes that can affect blower energy use, $\Delta E_{blower}$:
(1) changes to the operation time of the heating or cooling system ($\Delta E_{blow,con}$), and (2) the use of the air distribution system for ventilation ($\Delta E_{blow,vent}$).

$$\Delta E_{blower} = \Delta E_{blow,con} + \Delta E_{blow,vent} \tag{8}$$

Blower changes associated with heating and cooling system operation time are calculated using proportionality coefficients, as shown in Equation 9 below. For the model application presented in this report, we used coefficients 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. These coefficients are variables that can be changed if more appropriate relationships between system and air handler size are determined. The suitability of these coefficients for older systems has not been assessed. We have not been able to find sufficient data to do so.

$$\Delta E_{blow,con} = 0.023 * \Delta E_{Heat} + 0.176 * \Delta E_{cool} \tag{9}$$

The IVE modeling approach can be applied to homes having multiple heating and/or cooling systems with different efficiencies by assigning to each system a set fraction of any incremental conditioning energy impact. This approach can be applied even if one of the systems is a non-ducted system (such as a wall furnace or ductless mini-split) simply by assigning zero duct losses and zero blower energy to the fraction of thermal conditioning that is associated with that system. The IVE model is not set up to readily track energy impacts on supplemental heating or cooling devices since the model does not track total heating and cooling loads as would be needed to determine when a supplemental system operates.

For ventilation systems that operate in conjunction with the forced air system blower, determining the change in blower energy for ventilation ($\Delta E_{blow,vent}$), requires estimating the fraction of the time the blower is on due to heating and cooling ($f_{heat/cool}$). The change in blower energy due to ventilation is

$$\Delta E_{blow,vent} = max\left[\Delta t * P_{blower} * f_{venting} * \left(1 - f_{heat/cool}\right), 0\right] \tag{10}$$

where $f_{venting}$ is the fraction of each time step that the system is venting, and $P_{blower}$ is the power of the blower. Lstiburek et al. (2007) determined the annual heating and cooling hours (i.e., hours when the conditioning system was operating) for six International Energy Conservation Code (IECC) climate zones for the standard-performance IECC reference house. We used these calculated values to fit linear relationships between heating and cooling degree-days and heating and cooling hours, then used the trend lines to estimate cooling and heating hours for the remaining IECC climate zones. We used these relationships for all homes.

It was assumed that for all hours the indoor temperature was below the heating set point or above the cooling set point and that the forced air system blower was running for conditioning purposes for a set fraction of that hour. The fraction of the hour that the forced air system blower was assumed to be running for conditioning purposes was the ratio of the heating or cooling hours to the number of hours a year that the outdoor temperature was below or above the heating or cooling set point. The remaining fraction of the hour was assumed to be available for running the forced air system blower for ventilation purposes. Heat supplied by the fan reduces the amount of heat that needs to be delivered to the space by the furnace to maintain temperature and increases the cooling load. Unlike heat supplied by the furnace, the heat supplied by the forced air system blower is provided whether or not the thermostat indicates that additional heating energy is required. The IVE model includes the fan heat in the $fan_{heat}$ term in Equations 2 and 4.

The IVE model is 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 are documented. Figure 2 describes how to use IVE to determine the population energy change due to ventilation changes in a cohort of homes. The variables that must be specified from Equations 1–9 for each home are summarized in Table 1, below. Information about home characteristics is available from surveys of the housing stock, such as the U.S. Energy Information Administration's RECS (US EIA 2005) and the California Energy Commission's RASS (Palmgren et al. 2010).

One limitation of the IVE model is that it assumes that all additional airflow is coming from the outside. In real homes, adding unbalanced fans or changing the building envelope may affect the relative pressures in the home and attached unconditioned spaces such as the attic and crawl spaces. This change in pressure fields may lead to additional air coming from spaces that are not at the outdoor temperature, such as attics, and this air may be preheated due to duct leakage in winter and heated due to solar gains in the summer. In these cases, IVE would overestimate the heating load of the extra air due in winter and underestimate the cooling load in summer.

**Figure 2. Steps for using the IVE model to analyze population changes in energy use due to changes in ventilation in a cohort of homes.**

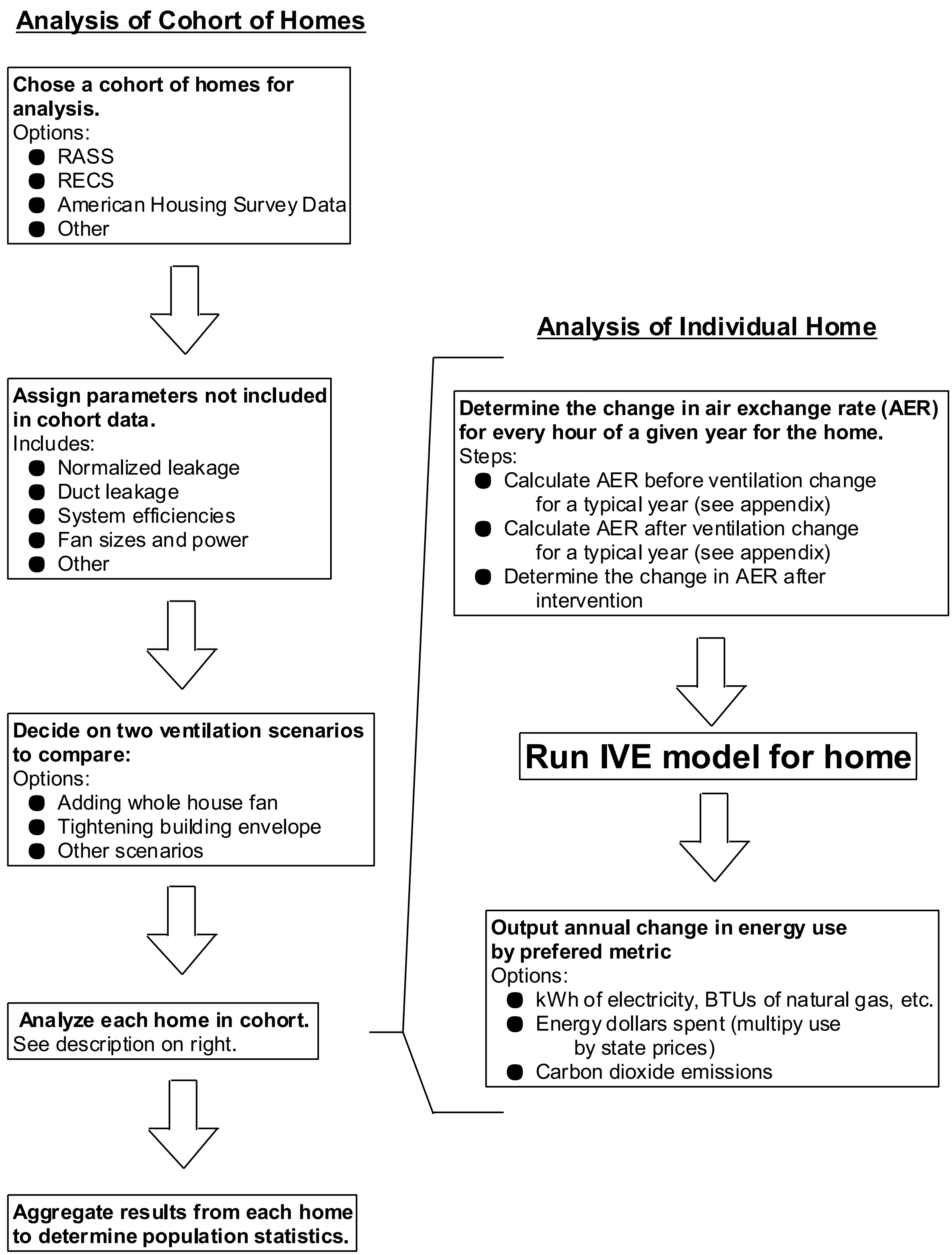

**Table 1. Sources of input parameters for a home-by-home IVE analysis to assess ventilation-related energy impacts for a population of homes**

| Parameter | Description | Assignment or Selection Scheme |
|---|---|---|
| $V_{cond}$ | Home Volume | Selected from available databases (RASS, RECS) to reflect population of interst. |
| $\Delta A$ | Time-resolved change in air exchange rate | Calculated from airflow models that account for air-tightness, building height, and weather-driving forces from representative meteorological year (TMY3). |
| $T_{set}$ | Thermostat setting | Select from available databases (RASS, RECS). If data is not reported, can be assigned from thermostat settings reported by similar homes. |
| $T_{out}$ | Outdoor temperature | Representative meteorological year based on home location (TMY3). |
| $fan_{heat}$ | Fan heat | In this application, assigned as 0.85*energy use of fans and blowers supplying air to the space for ventilation. Assign a specific value if the blower efficiency is known or specified. |
| $\varepsilon_{heat/cool\ equipments}$ | Heating / cooling equipment efficiency | Assigned based on system type and age of home. The RASS and RECS report conditioning system ages and if ducts are present. These parameters can be used to estimate the efficiencies of the systems. |
| $\varepsilon_{duct}$ | Duct efficiency | Assigned based on system type and age of home, or specific value if appropriate. |
| $\rho_{water,out}$ | 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 or based on measured humidity of air-conditioned homes and home temperature. In this application, assumed a constant 60% relative humidity in all mechanically cooled homes. |
| $\Delta E_{fans}$ | 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 (HVI 2009). |
| $\Delta E_{blower}$ | Energy use of air distribution blower | Proportionality coefficients determining air handler energy change based on heating and cooling energy change and presence of ducts, ACM provides one set of coefficients. RASS and RECS report if ducts are present. |
| *Location* | Climate zone or ZIP code | Selected from available databases and used to determine location-based parameters. RASS and RECS databases report location information for each home. |
| $P_{blower}$ | Power of the blower | Can be determined from Manual J calculations (ACCA 2006) . When analyzing a large number of homes, this value can be extrapolated from a limited set of Manual J calculations for representative homes in each climate zone. |
| $f_{venting}$ | Fraction of the hour blower is on for venting only | This parameter is specified when you choose a ventilation scheme that is interlocked with the air handler. We ran an HRV for 30 mins of each hour ($f_{venting}$ =0.5), but user can specific what they want. |
| $f_{heat/cool}$ | Fraction of the hour blower is on for heating/ cooling | We used the values determined by Lstiburek et al. (2007) for the IVE/ REGCAP comparison. The analysis here yielded new estimates of system on time for each home type in each climate that we will use for further analysis. |

## 2.2 Comparison Between IVE and REGCAP Incremental Energy Predictions

To assess the performance of the IVE model, we compared its predictions to the energy changes estimated by the REGCAP airflow, energy, and moisture simulation model. Model predicted impacts were compared for air sealing and ventilation system additions for three houses in seven climate zones. Details of the REGCAP model can be found in the appendix.

Specifications were developed for three residences, to represent archetypal new, average, and older U.S. homes with variations in relevant characteristics (e.g., insulation levels and conditioning-system sizes) appropriate for seven different IECC climate zones. Simulations were conducted for the three homes being affected by air sealing and the installation of mechanical ventilation systems. Detailed specifications for the three homes are provided in the appendix. Below, we provide a summary description of how the home characteristics were selected and specified.

The **new** home parameters were based on specifications in the California Energy Commission's *Alternative Calculation Manual* (ACM) for Prototype C (CEC 2008). While this home was designed to determine the impact of various changes on energy use in new California homes, the home design is broadly representative of new homes across the United States.

As available, **average** and **old** home specifications were based on data available from the RECS database (US EIA 2005). The average home uses characteristics of homes built in the 1980s and the **old** home uses characteristics from homes built in the 1940s. The RECS database includes home size, heating/cooling appliance type and age, and whether or not ducts were present. According to data in the RECS, average home size did not vary significantly from the homes built in the 1940s to the 1980s. For the older home, we chose a small 1940s home to increase the variability of the comparison homes.

For parameters not explicitly specified in the ACM or available in RECS, we assigned values based on relationships and data described elsewhere. We assumed that the envelope leakage for the old and average homes was equivalent to levels predicted for homes of this age in each climate zone by the Lawrence Berkeley National Laboratory Residential Diagnostics Database (ResDB) (Chan et al. 2012). We assigned conditioning system efficiencies to these two homes based on values reported in the literature as a function of system type and age (Lekov ; Johnson et al. 1994; DOE 2010). We assumed low (3% on supply and return), medium (10% on supply and return), and high (15% on supply and return) levels of duct leakage on the new, average, and old homes, respectively (Kruse et al. 2004). Insulation values are specified for the new home in the ACM. We assumed that the old home had minimal levels of insulation. For the average home we assigned insulation R-values that are between those for the other two homes. These values are intended to represent broadly the characteristics of non-retrofitted homes from each era.

For each home type in each climate zone, we used the Wrightsoft Manual J software (ACCA 2006) to calculate the heating and cooling loads. For the new homes, the software recommended system sizes based on the specifications of existing home equipment. For the older homes, we specified equipment sizes to meet the calculated load based on the assigned system efficiency. As with the insulation, we recognized that the specified equipment may not have ever been available. The intent was to specify values that are broadly relevant to the home type and age. As allowed by Air Conditioning Contractors of America (ACCA) Manual S, all of the systems were oversized by 15% for air conditioning systems and by 40% for heating systems. System and thermostat settings are shown in the appendix. Since the old homes could not meet the initial thermostat settings due to the high rate of heat loss of the buildings, the old home thermostat settings were lowered, as shown in the appendix. As previously stated, for all homes the pre- and post-ventilation thermostat settings remained the same.

Each home type was modeled in the representative city for each of the seven IECC climate zones that represent the expanse of U.S. weather. The following climate zones and representative cities were used: 2A hot/humid (Houston, Texas); 2B hot/dry (Phoenix, Arizona); 3A warm/humid (Atlanta, Georgia); 3C warm/marine (San Francisco, California); 4A mixed/humid (Baltimore, Maryland); 5A cool/humid (Chicago, Illinois); and 7 very cold (Duluth, Minnesota).

Since the IVE model is designed to estimate differences in energy use resulting from some change to infiltration and/or mechanical airflow, results of the IVE model were compared to differences between REGCAP predictions for two scenarios. REGCAP was first used to estimate the base energy for each specified home in each climate zone. Home specifications were then changed to simulate a retrofit or upgrade, as described below. The IVE model was then run to calculate the impact of that same upgrade on each home in each climate zone.

Simulations were conducted to assess impacts of five retrofits or upgrade scenarios. The first two involve air sealing to different levels of envelope tightness. The other three involve installation of mechanical ventilation systems. The mechanical systems were added to homes that were also air-sealed. Comparisons for the mechanical ventilation scenarios (3–5) are between tightened homes without ventilation and tightened homes with one of the three ventilation system designs. Since the new home was assumed to be airtight already, only three comparison scenarios were run for this home: each of the three mechanical ventilation systems were compared to the case of the baseline (already airtight) home with no mechanical ventilation.

1. <u>Air sealing improvements at levels achieved by weatherization programs</u>

The envelopes of old and average homes each were tightened by 25%, based on an analysis of the average effectiveness of weatherization programs (Offermann et al. 2011). Ducts were tightened by 43%, which is the level of duct leakage reduction seen in Weatherized homes (Chan et al. 2012).

2. <u>Air sealing to the limit at which ASHRAE 62.2 requires mechanical ventilation</u>

This scenario is relevant to assessing whether the benefit of air sealing outweighs the costs of mechanical ventilation at the margin. To allow a home to not have mechanical ventilation, ASHRAE requires a sufficient leakage area to provide twice the ASHRAE-required level of mechanical ventilation plus 2 cubic feet per minute (cfm) per 100 square feet of floor area of the home. The necessary leakage area can be calculated using ASHRAE 136, which estimates an annual air exchange rate as a function of normalized leakage and a weather factor (1993). Ducts were tightened by 43% in this scenario.

3. Adding a constant exhaust fan
For this scenario, an exhaust fan was added to the new home and to the tightened old and average homes. The fan was added after the home has been tightened to the better of the two air-sealing scenarios noted above. The airflow rate was set to meet ASHRAE 62.2 requirements, as described in the appendix.

4. Adding a balanced HRV
Because heat recovery ventilators (HRVs) usually have airflow rates greater than those needed to meet the minimum requirements in ASHRAE 62.2, they can be operated on a timer to reduce their effective airflow rate to just meet the ASHRAE 62.2 minimum requirements. For the simulations described in this report, the HRV operated at twice the airflow rate specified by ASHRAE 62.2 for 30 minutes of each hour. We specified an HRV Apparent Sensible Effectiveness (ASE) of 82%, and power consumption was calculated as a function of the required airflow (HVI 2009). The change in air exchange rate with HRV operation was calculated as $\Delta A_t$ minus HRV recovery efficiency times the hourly flow rate of the HRV.

5. Adding a balanced HRV interlocked with the forced air system blower
This is the same as case 4, but when the forced air system blower is not running to condition the space during HRV operation, it is turned on at the cooling fan speed to provide ventilation air to the space. The IVE modeling approach description in Section 2.1 describes how we estimated the blower system run time for ventilation.

Since the focus of this comparison is on IVE calculations of energy impacts, we used the airflow calculations from pairs of REGCAP runs to calculate hourly incremental airflows for the IVE model. Generally IVE will use the airflow estimation models noted in the model description section.

## 3. Results

For each of the REGCAP and IVE model runs, the change in energy demand was tracked for heating, cooling, forced air system blower, and exhaust fan components. We compared IVE- and REGCAP-estimated energy changes for each component and for total energy demand for each air tightening or ventilation scenario for each house and climate zone combination.

For the three reference cases—homes without air sealing or mechanical ventilation—REGCAP-estimated total annual HVAC energy use ranged from 10.6 to 78.2 megawatt-hours (MWh) across climate zones. Climate had a larger effect than home characteristics, with the old home requiring 16.8 to 78.2 MWh, the average home needing 15.2 to 57.9 MWh, and the new home requiring 10.7 to 46.3 MWh across climate zones.

Tightening the average and old homes decreased annual energy use between 0.1 and 7.8 MWh. The lowest change was seen for tightening the average home to the ASHRAE limit because the tightness of the homes was already close to that limit. Adding mechanical ventilation increased the annual energy demand by 0.4 to 4.4 MWh. In the more extreme climates, the largest part of the change was for conditioning energy to heat and cool the increasing airflow. Increasing blower and exhaust fan loads were more important in milder climates.

Figure 3 shows the annual pattern of total and incremental cooling and heating energy estimated by REGCAP for the archetypal average home in the distinctly different climates represented by Houston and Chicago. Results are presented with bi-weekly resolution. Each column shows the estimated baseline energy, and the solid part represents the energy savings from improving air tightness by the average improvement achieved in the Weatherization program. As expected, heating loads are higher in colder climates, and the most substantial cooling loads occur in hot climates. Heating loads are higher in Chicago, with 5,873 heating degree-days (HDD), compared to Houston, with 1,812 HDD; and cooling loads are higher in Houston, with 3,116 cooling degree-days (CDD) compared with Chicago's 555 CDD. Yet even in the warmer climate of Houston, more site energy is required for heating than for cooling. This is predominately because of the much higher system efficiencies of cooling compared to heating equipment.

Figure 4 shows the effect of indoor-outdoor temperature difference on the energy required to condition each unit of additional air brought into the home with increased ventilation. Results are again presented for Houston and Chicago. The figure shows a similar functional relationship for both IVE and REGCAP models. As the temperature difference increases, more energy input is required to condition each volume of air that enters the home.

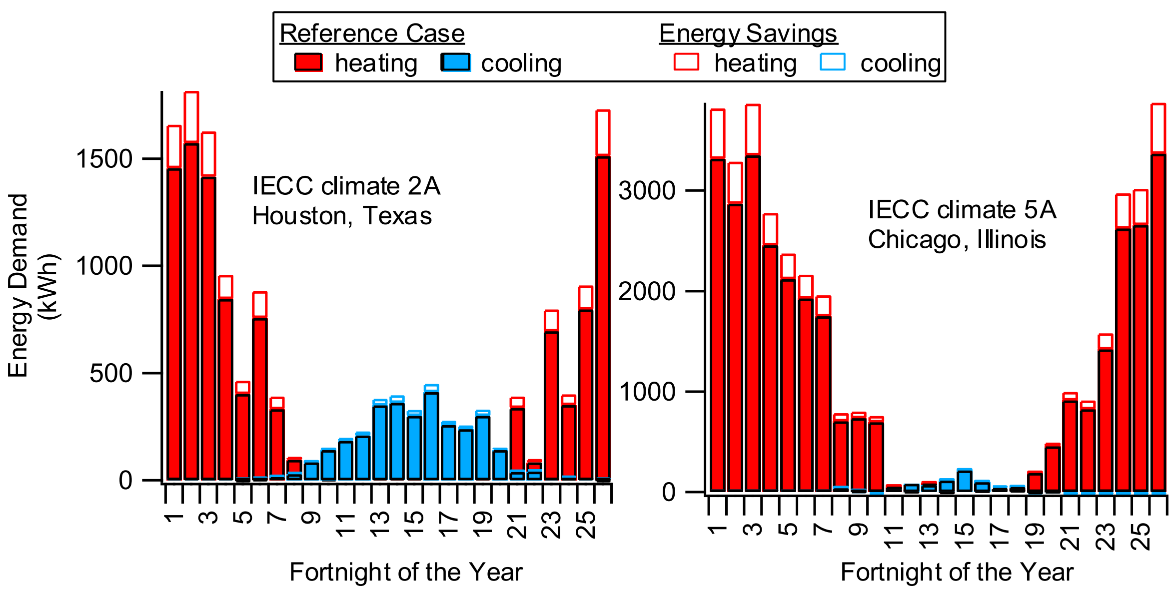


**Figure 3. Baseline annual cooling and heating energy consumption and change in energy consumption with envelope air sealing for average home in two climate zones, as estimated by REGCAP.** The solid bars show the difference between baseline and air sealing scenarios. Note the different y-axis scales for the two scenarios.

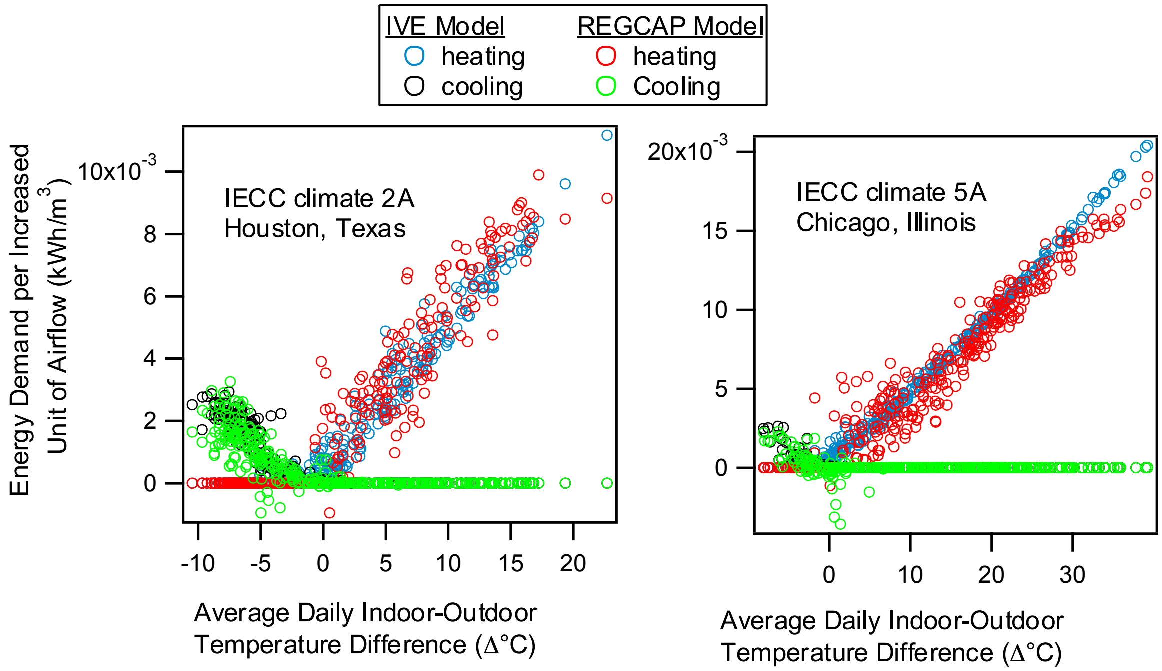


**Figure 4. Increase in energy demand per unit of airflow as a function of daily average indoor-outdoor temperature difference.** REGCAP and IVE show very similar functional dependence between indoor-outdoor temperature difference and increase in energy demand with increase in volumetric airflow. Note the different scales for the two scenarios.

The next series of figures compares IVE and REGCAP model predictions of incremental energy by scenario, with each home and climate zone combination shown as one data point for an annual run. Summary statistics about the agreement between IVE and REGCAP incremental energy predictions are presented in Table 2, following the presentation of the figures for each scenario.

Figure 5 shows IVE and REGCAP predictions for energy savings resulting from air sealing of average and old homes in each of the seven climate zones. Results are presented separately for heating, cooling, and blower energy savings. The scale is adjusted in each panel to elucidate the comparison for each system. The scale of each panel indicates the relative importance of the component to total annual energy change. The plots indicate that reduced heating loads account for the vast majority of total HVAC energy savings of air sealing these homes. The Pearson correlation coefficient ($r_{xy}$) between IVE and REGCAP predictions is provided in each panel. Overall, predictions of the two models are highly correlated.

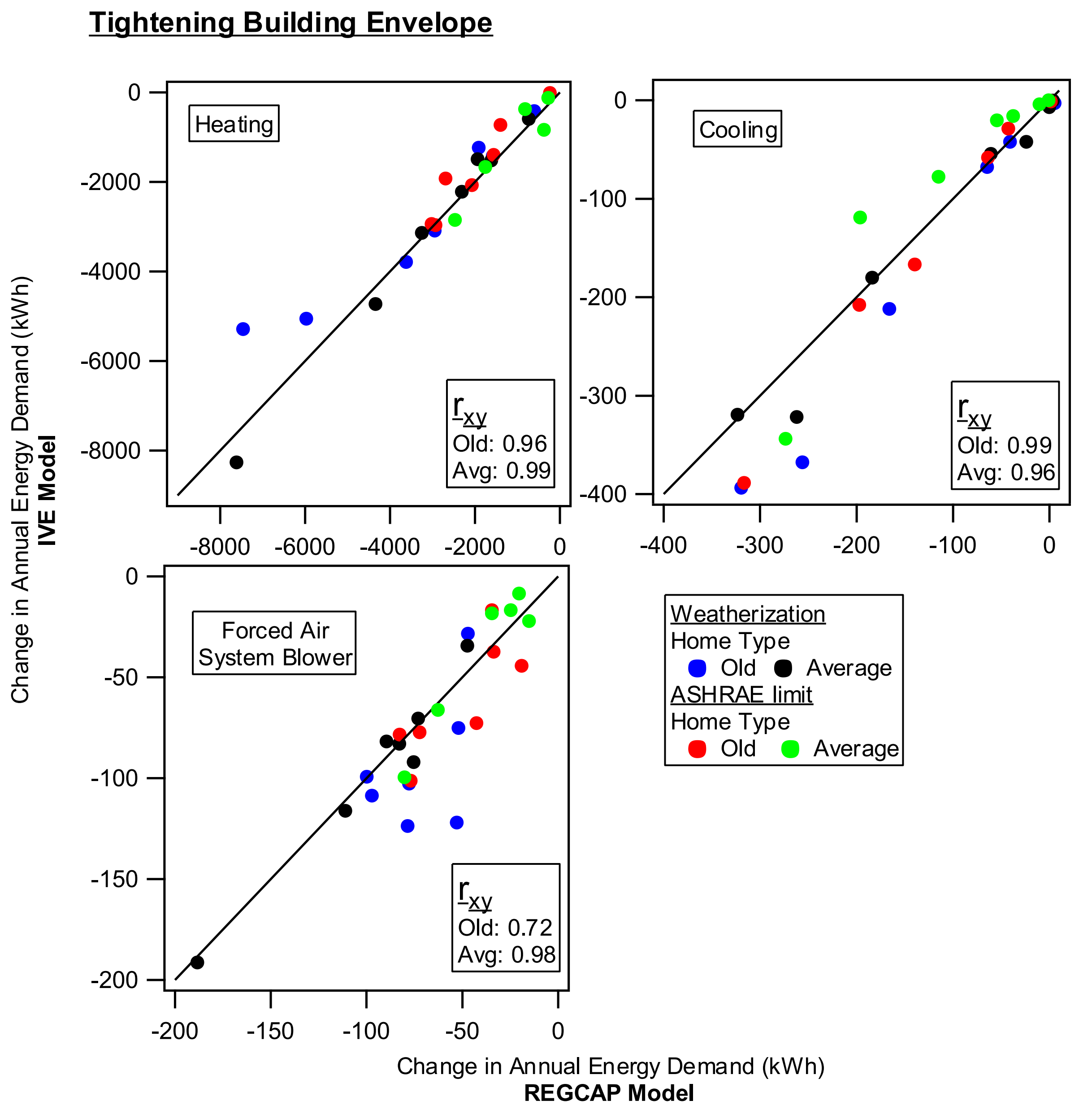


**Figure 5. IVE and REGCAP estimated annual change in energy demand associated with air sealing the building envelope and HVAC ducts.** Each dot represents one house (old, average) in one climate zone, as described in the methods. The 1:1 line is shown for reference. The next three figures display IVE and REGCAP predictions for energy requirements of the three ventilation systems: continuous exhaust fan, independent HRV, and HRV interlocked with the forced air system blower. It was assumed that the indoor environment was at 60% relative humidity during all air cooling periods. Note the different scales for the scenarios.

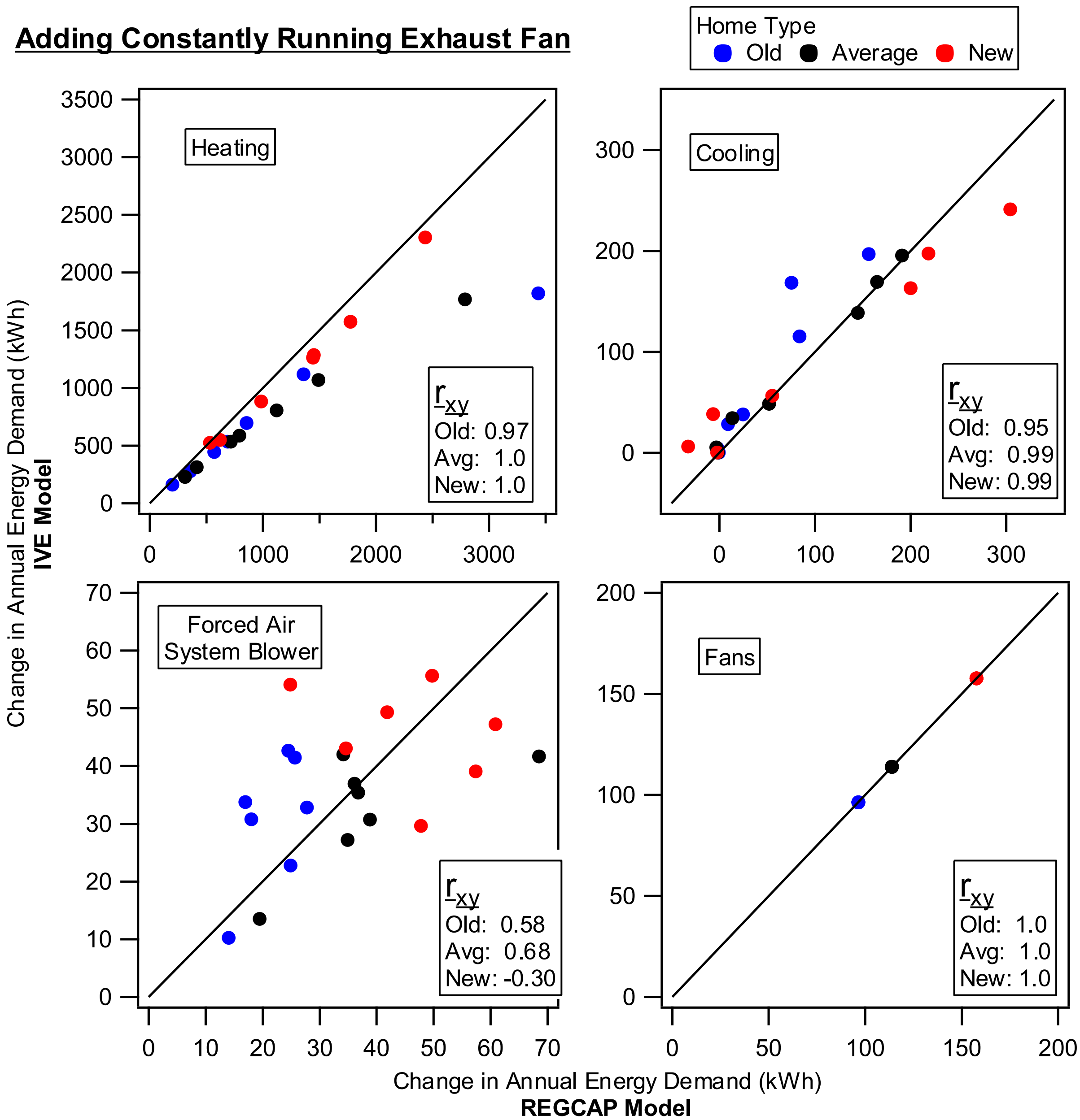


**Figure 6. IVE and REGCAP estimated annual change in energy demand associated with adding a continuous exhaust fan for ventilation.** Each dot represents one house (old, average, new) in one climate zone, as described in the methods. The 1:1 line is shown for reference. Note the different scales for the scenarios.

Figure 6 shows that heating is the largest contributor to the energy cost of adding a constant exhaust fan for ventilation, with cooling and the exhaust fan each requiring an order of magnitude less energy input. For the constant exhaust ventilation fan, IVE estimates of energy impacts clearly trend below those calculated by REGCAP. For most of the scenarios the agreement is close. The two points that are farthest from the 1:1 line are for the old and average homes in the coldest climate of Duluth, Minnesota. In the Results section, we explore the effects of various specifications on predictions of incremental energy impacts for the old home in Duluth. There is precise agreement for the exhaust fan impacts because the two models calculate this parameter with the same equation using the same specification for fan power.

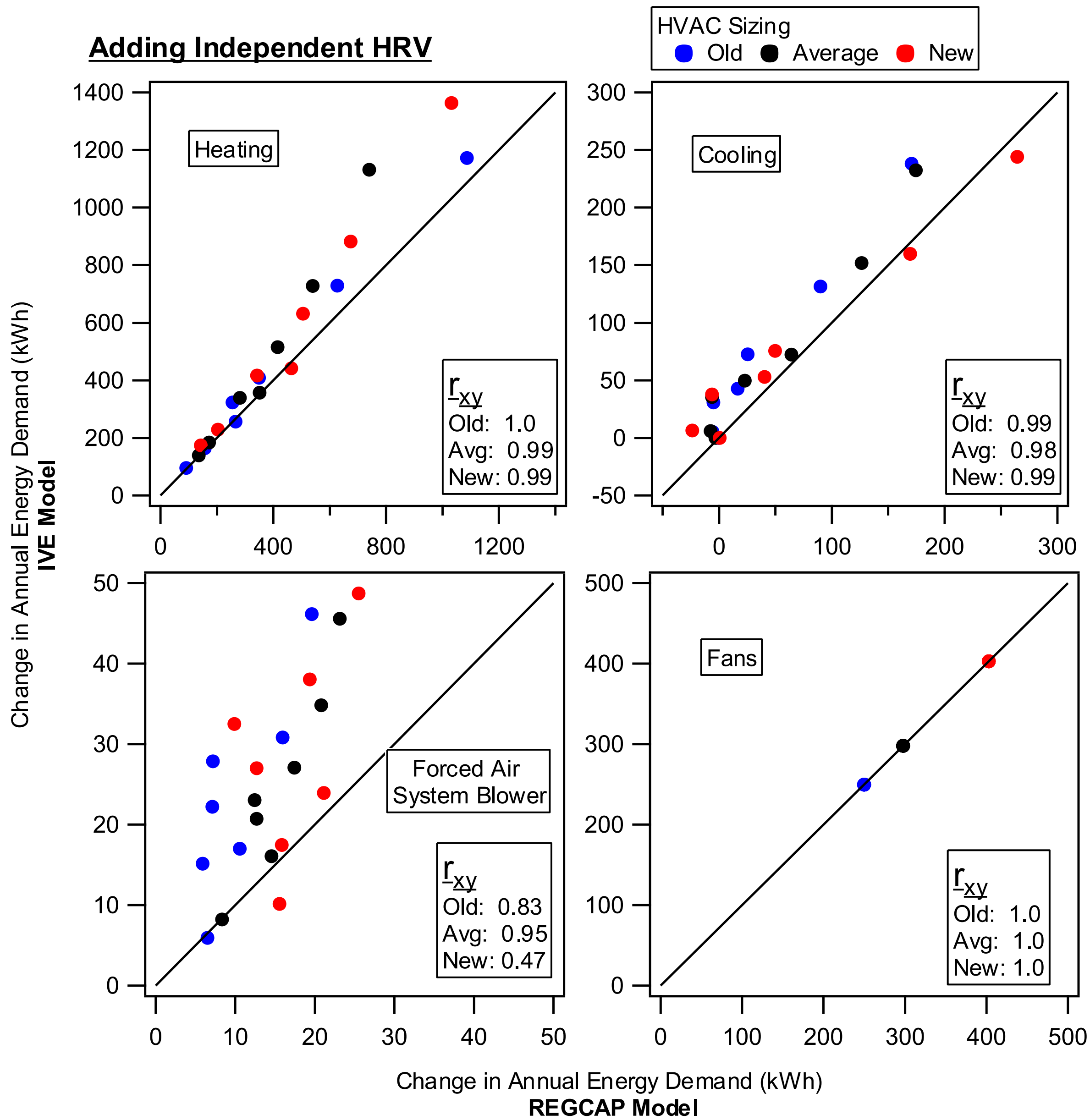


**Figure 7. IVE and REGCAP estimated annual change in energy associated with adding an independent heat recovery ventilator (HRV).** Each dot represents one house (old, average, new) in one climate zone, as described in the methods. The 1:1 line is shown for reference. Note the different scales for the scenarios.

Adding the independent HRV for ventilation (Figure 7) resulted in lower incremental energy demand for heating, roughly similar demand for cooling, and higher energy demand for fans, relative to the exhaust ventilation scenario. In contrast to results for the continuous exhaust fan, the IVE model predicted higher incremental heating energy use compared to REGCAP for the independent HRV. On a relative basis, IVE predicted much higher blower energy impacts for this scenario. But this discrepancy is unimportant, since blower energy impacts are small relative to heating, cooling, and ventilation fan energy impacts.

For the remaining ventilation case, an HRV was interlocked to the forced air system blower. When the forced air system blower runs in conjunction with heating or cooling equipment, the change in blower fan energy is counted as forced air system blower energy. When the blower runs for the purpose of supplying ventilation, it is counted as ventilation fan energy.

The IVE and REGCAP predictions of the energy cost of installing this system in air-sealed homes are shown in Figure 8. Notable for this system are the substantially larger loads for ventilation fans and the generally poor agreement between REGCAP and IVE for heating energy impacts. The red dots in the lower part of the top left panel indicate that IVE estimates for heating energy impacts are much lower than REGCAP estimates. The IVE model calculates correspondingly higher energy use for ventilation fans. These discrepancies appear to result from the different algorithms used by each model to attribute blower fan use to ventilation. Whenever the blower operates, it adds heat to the home via the HVAC air distribution ducts in both IVE and REGCAP. That heat reduces the load on the furnace.

The two models do not yield highly correlated predictions for the HRV interlocked to the air distribution system. The error for this system is likely to be in the IVE estimate, since the IVE model does not explicitly track heating system running time and adjust the attribution of blower fan energy accordingly.

Figure 9 compares the annual total HVAC energy change estimated by the IVE and REGCAP models for each home in each of the air-sealing and ventilation scenarios. Across climate zones, the REGCAP and IVE models correlate very strongly for each home archetype for both air-sealing scenarios and for the first two ventilation scenarios ($r_{xy} \geq 0.95$). The IVE model predicts smaller HVAC energy impacts for the exhaust fan and larger impacts for the independent HRV, as compared to the REGCAP model results.

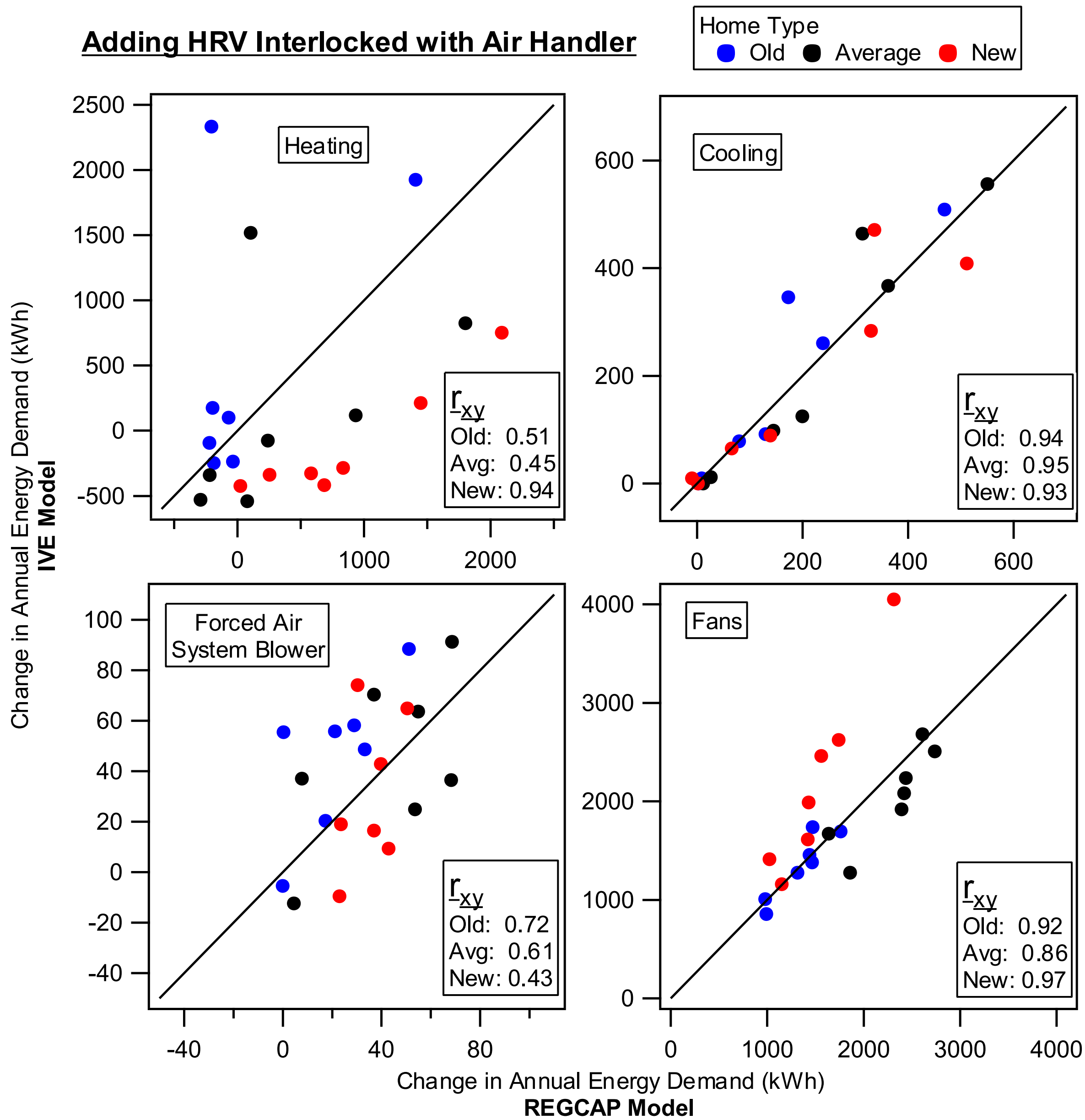


**Figure 8. IVE- and REGCAP-estimated annual changes in energy demand associated with adding a heat recovery ventilator (HRV) interlocked with the forced air system blower.** Each dot represents one house (old, new, average) in one climate zone, as described in the methods. The 1:1 line is shown for reference. Note the different scales for the scenarios.

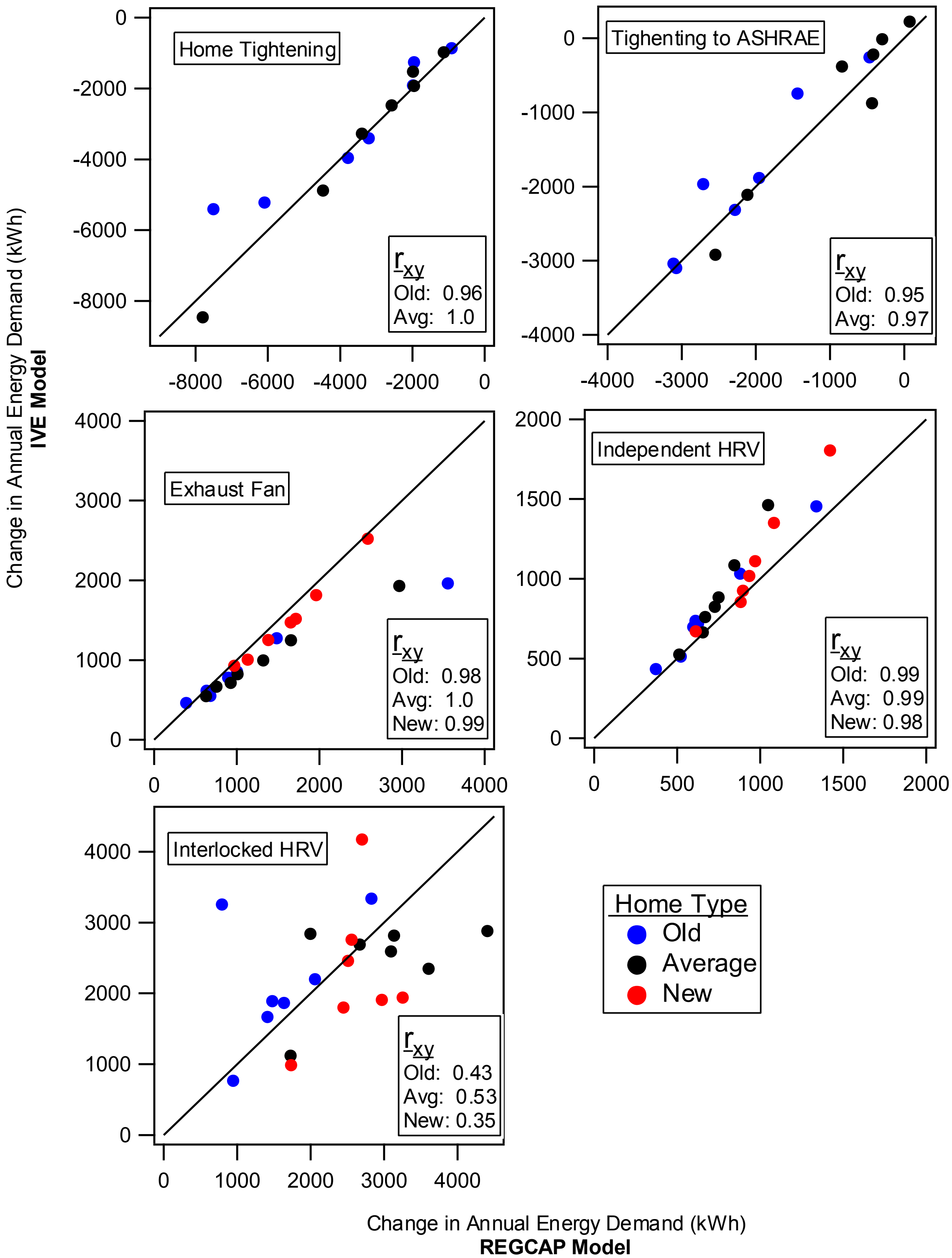


**Figure 9. IVE- and REGCAP-estimated annual changes in energy demand associated with air sealing and addition of mechanical ventilation.** Each dot represents one house (old, average, new) in one climate zone, as described in the methods. The 1:1 line is shown for reference. Note the different scales for the scenarios.

Table 2 presents summary statistics comparing IVE to REGCAP results shown in the preceding figures. Table 2 first provides the root mean squared error (RMSE) and mean bias of the IVE model results compared to REGCAP for each scenario. The values in Table 2 are simple averages of all the homes in each category. Weighted averages that consider the breakdown of old, average, and new homes in the population are presented in Table 3 and discussed later in the Results section.

The RMSE is an indicator of how far apart the two models are in calculating impacts across home and climate combinations, without considering systematic differences. A negative bias means that IVE estimates are on average lower than REGCAP. If each IVE estimate is far from the corresponding REGCAP estimate, the RMSE will be large. But if some IVE estimates are higher and some are lower than REGCAP, the mean bias could be close to zero. Both statistics are relevant. RMSE tells us how close the models are across home and climate combinations. The bias indicates how closely the average of the IVE calculations for all the homes compares with the average of the REGCAP calculations across all homes. In Table 2, RMSE and bias values also are normalized (CV[RMSE] and CV[bias]) by the mean value of the incremental energy change estimated by REGCAP (mean[R]).

The top rows of Table 2 show that IVE predictions for heating, cooling, and overall HVAC energy reductions by air sealing were highly correlated ($r_{xy} \geq 0.9$) with REGCAP predictions. For this ventilation change, IVE estimated the total annual energy change within 9% of the REGCAP estimates on average. The greatest bias and RMSE values were seen for heating, but the largest normalized error, CV(RMSE), was seen for cooling, potentially due to not including internal gains. The greatest fractional difference between the REGCAP and IVE model predictions of air-sealing impacts was seen for old homes in cold climates.

The IVE and REGCAP predictions of the impacts of adding a continuous exhaust fan are highly correlated for heating and cooling energy and well correlated for total HVAC energy use. Yet the average prediction of total HVAC energy impact for the 21 home-climate combinations is 18% lower for IVE relative to REGCAP (CV[bias] = 0.18). Since the models estimate energy in very different ways, it is not clear what is causing the fairly consistent bias in the results. One major difference between REGCAP and IVE is that IVE assumes that conditioning losses (i.e., heat transfer to the outside independent of the change in airflow) are the same for both the reference case and the variation. The IVE model is not complex enough to take into account that the indoor and duct temperatures are actually varying with time as the heating and cooling systems turn on and off.

**Table 2. Bias and root mean squared error (RMSE) of the IVE model estimates of incremental energy for each of the ventilation cases compared with REGCAP estimates of the same parameters.** The bias (kWh) and RMSE (kWh) values are also shown normalized by the average REGCAP estimate (mean[R]) of the incremental energy. The Pearson coefficient ($r_{xy}$) is also reported.

| | | All Results | | | | |
|---|---|---|---|---|---|---|
| | | Heating | Cooling | Blower | Fan | Total |
| Envelope Tightening Weatherization | RMSE | 721 | 43 | 28 | NA | 697 |
| | BIAS | -407 | 24 | 16 | NA | -367 |
| | $r_{xy}$ | 0.96 | 0.99 | 0.72 | NA | 0.95 |
| | mean(R) | -2716 | -114 | -62 | NA | -2892 |
| | CV(RMSE) | 27% | 38% | 45% | NA | 24% |
| | CV(bias) | 15% | -21% | -25% | NA | 13% |
| Envelope Tightening ASHRAE | RMSE | 322 | 36 | 10 | NA | 332 |
| | BIAS | -1 | -2 | -1 | NA | -4 |
| | $r_{xy}$ | 0.99 | 0.96 | 0.98 | NA | 0.99 |
| | mean(R) | -1960 | -110 | -65 | NA | -2135 |
| | CV(RMSE) | 16% | 33% | 16% | NA | 16% |
| | CV(bias) | 0% | 2% | 1% | NA | 0% |
| Exhaust Fan | RMSE | 451 | 32 | 14 | 0 | 447 |
| | BIAS | 266 | -10 | -1 | 0 | 255 |
| | $r_{xy}$ | 0.93 | 0.95 | 0.48 | 1.00 | 0.92 |
| | mean(R) | 1159 | 78 | 35 | 123 | 1395 |
| | CV(RMSE) | 39% | 41% | 39% | 0% | 32% |
| | CV(bias) | 23% | -12% | -3% | 0% | 18% |
| Independent HRV Fan | RMSE | 139 | 32 | 14 | 0 | 168 |
| | BIAS | -88 | -23 | -11 | 0 | -123 |
| | $r_{xy}$ | 0.98 | 0.96 | 0.70 | 1.00 | 0.97 |
| | mean(R) | 420 | 55 | 14 | 317 | 807 |
| | CV(RMSE) | 33% | 58% | 100% | 0% | 21% |
| | CV(bias) | -21% | -42% | -78% | 0% | -15% |
| Interlocked HRV Fan | RMSE | 933 | 68 | 28 | 534 | 927 |
| | BIAS | 235 | -8 | -7 | -140 | 80 |
| | $r_{xy}$ | 0.29 | 0.94 | 0.49 | 0.69 | 0.40 |
| | mean(R) | 430 | 194 | 33 | 1721 | 2379 |
| | CV(RMSE) | 217% | 35% | 84% | 31% | 39% |
| | CV(bias) | 55% | -4% | -23% | -8% | 3% |

For the independent HRV, the IVE predictions of total HVAC energy use are 15% lower than the REGCAP predictions averaged across the 21 home-climate combinations. And the normalized RMSE is only 21%, indicating good agreement across simulated homes. It is interesting to note that the overall energy impacts of adding an HRV are estimated to be small relative to the other two ventilation systems.

The IVE versus REGCAP comparison statistics for the HRV interlocked with the forced air system blower reflect the points noted previously. The estimates of heating energy impacts are very far apart for the two models (CV[RMSE] = 217%). The estimates for the other large energy use component—the blower being used for ventilation—are much closer with a CV(RMSE) = 0.31. Interestingly, the relative bias is very small, at 3%.

The comparison statistics in Table 2 were calculated with an equal weighting of results for each of the three homes in each of the seven climate zones. To obtain a rough estimate of how the limited results obtained with the two models would extrapolate to the U.S. housing stock, we weighted IVE and REGCAP estimates of total energy change for each home by an estimate of the prevalence of each of these archetypal home and locations based on statistics in the 2005 RECS (US EIA 2005). New homes were considered to be those built since 2000. Average homes were those built between 1960 and 2000. Pre-1960s homes were considered to be represented by our old home archetype.

The number of homes in each category are shown in Table 3. The RECS includes the home size, location, and weighting. The weighting is the actual number of homes that each entry represents. The RECS database indicates which of the nine U.S. census regions each of the homes is in. To assign the homes to one of the 13 IECC climate zones, we assumed that the fraction of homes in each IECC climate zone in each census region was equivalent to the fraction of the population in each IECC climate zone in each census region (US Census Bureau 2009). The weighting for the original home entry was divided among each of the IECC climate zones as a function of the relative population in each of the climate zones in the specified census region (US Census Bureau 2009).

We multiplied the home count for each climate and home size by the estimated energy change determined by REGCAP and IVE models for each ventilation scenario. The results are shown in Table 3. These estimates are not intended as robust estimates of the energy impacts of instituting the modeled scenarios across the U.S. housing stock. Rather, the calculation is intended to explore how differences between IVE and REGCAP results for individual homes will impact results when extrapolated to the population level. The results in Table 3 suggest that the IVE model will produce similar energy impact estimates as the more detailed and complex REGCAP model.

**Table 3. Population-level extrapolation of IVE- and REGCAP-predicted energy impacts (in gigawatt-hours, GWh) of air-sealing and ventilation scenarios examined in this study.** The values shown in this table are not thought to be robust estimates of population-level impacts of air sealing or ventilation. Rather, the calculations are intended to explore the agreement between IVE and REGCAP model estimates when extrapolated to the population levels.

| | | Millions of Homes | | | Tight: Weatherization | | | Tight: ASHRAE | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IECC CZ | Representative City | Old | Average | New | REGCAP | IVE | Ratio | REGCAP | IVE | Ratio |
| 2A | Houston, Texas | 1.8 | 4.8 | 0.92 | -13,018 | -12,782 | 1.0 | -13,742 | -13,599 | 1.0 |
| 2B | Phoenix, Georgia | 0.29 | 0.95 | 0.19 | -1,338 | -1,184 | 0.9 | -420 | -87 | 0.2 |
| 3A | Atlanta, Georgia | 2.5 | 6.4 | 1.3 | -24,596 | -24,478 | 1.0 | -8,393 | -7,218 | 0.9 |
| 3C | San Francisco, California | 0.60 | 0.88 | 0.07 | -2,926 | -2,106 | 0.7 | -1,602 | -782 | 0.5 |
| 4A | Baltimore, Maryland | 5.4 | 8.6 | 1.5 | -49,665 | -49,505 | 1.0 | -15,928 | -14,765 | 0.9 |
| 5A | Chicago, Illinois | 8.1 | 7.9 | 1.1 | -84,979 | -81,075 | 1.0 | -28,742 | -31,670 | 1.1 |
| 7 | Duluth, Minnesota | 0.23 | 0.32 | 0.05 | -4,164 | -3,897 | 0.9 | -1,417 | -1,367 | 1.0 |
| Weighted Average IVE/Regcap Ratio | | | | | | | 0.97 | | | 0.99 |

| | | Exhaust fan | | | HRV Interlocked | | | Independent HRV | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IECC CZ | Representative City | REGCAP | IVE | Ratio | REGCAP | IVE | Ratio | REGCAP | IVE | Ratio |
| 2A | Houston, Texas | 5,830 | 5,246 | 0.9 | 21,227 | 20,110 | 0.9 | 5,127 | 5,778 | 1.1 |
| 2B | Phoenix, Georgia | 889 | 827 | 0.9 | 3,465 | 3,882 | 1.1 | 709 | 750 | 1.1 |
| 3A | Atlanta, Georgia | 10,516 | 8,850 | 0.8 | 27,215 | 24,494 | 0.9 | 7,401 | 8,443 | 1.1 |
| 3C | San Francisco, California | 1,341 | 1,065 | 0.8 | 2,216 | 1,517 | 0.7 | 953 | 954 | 1.0 |
| 4A | Baltimore, Maryland | 19,324 | 15,430 | 0.8 | 42,316 | 31,891 | 0.8 | 11,264 | 13,127 | 1.2 |
| 5A | Chicago, Illinois | 27,245 | 22,168 | 0.8 | 61,012 | 51,951 | 0.9 | 14,968 | 18,398 | 1.2 |
| 7 | Duluth, Minnesota | 1,876 | 1,185 | 0.6 | 979 | 1,735 | 1.8 | 708 | 885 | 1.3 |
| Weighted Average IVE/Regcap Ratio | | | | 0.82 | | | 0.86 | | | 1.2 |

## 4. Putting IVE and REGCAP Differences in Context

The IVE and REGCAP models do not predict the same energy impacts for some of the home and climate combinations. Since REGCAP tracks more of the physical processes that determine energy use, this model is expected to provide a more accurate estimate of energy impacts for any home for which enough key characteristics and physical parameters are known. The rationale for the IVE model is that many of the key parameters required for REGCAP are not known for large numbers of U.S. homes and would therefore need to be assumed or estimated—in many cases without a data basis—when conducting a population-level analysis of energy impacts. The effect of errors in assumed or estimated parameters on energy impact predictions is unknown.

With the goal of exploring the effect of parameter assignment on REGCAP-based estimates of air sealing or ventilation impacts, we executed several series of simulations of the old home in Duluth, Minnesota. In this series, we varied the following parameters: levels of insulation and conditioning system efficiency. For the first group of simulations we specified insulation at the levels used in the new home. For the second group, we specified heating and cooling systems with higher efficiencies and smaller capacities (0.8 AFUE [annual fuel utilization efficiency] for heating and SEER [seasonal energy efficiency ratio] 11 for cooling; systems sized to provide the load needed to condition the space) and with both smaller systems with higher efficiencies and insulation levels at the level used in new homes. We ran REGCAP for each of these homes for four conditions: tightening the home at the level seen by weatherization, adding an exhaust fan to the tightened home, adding an independent HRV to the tightened home, and adding an interlocked HRV. The goal was to quantify the variation in incremental energy estimates obtained with each set of specifications. If variations between REGCAP runs with one different parameter specification are large relative to the IVE/REGCAP difference, then IVE should be considered a suitable substitute for REGCAP for population-wide analyses.

The results are shown in Table 4. The parameters that we varied are ones that will not be readily available in home databases. Table 4 shows that for this limited list of parameters, assigning the wrong level of insulation or the wrong system size leads to potential errors (the Maximum Difference in Table 4) in the estimated change in energy use. The potential errors are for the most part comparable or larger than the average RSME values for the IVE and REGCAP comparison in Table 2.

**Table 4. The impact of parameter specification variations on REGCAP estimates of incremental energy impacts of air-sealing and ventilation scenarios.** The table includes the results from the old home in Duluth from the IVE/REGCAP comparison presented earlier in the Results (Old home), as well as the following variations: the home has the same insulation as the new home in Duluth, the heating and cooling systems have the same efficiency as the new home, and there is added insulation with higher efficiency equipment.

| | Change in Energy Use (kWh) | | | |
|---|---|---|---|---|
| | Tight | T & UF | T & HRV | T&SHRV |
| Old home | 11,919 | 4,144 | 3,542 | 1,075 |
| Same insulation as new home | 11,004 | 3,900 | 3,137 | 1,165 |
| Same efficiency as new home | 8,085 | 2,565 | 2,170 | 884 |
| Same insulation and efficiency as new home | 7,621 | 2,807 | 2,322 | 938 |
| **Maximum Difference (kWh)** | 4,298 | 1,579 | 1,372 | 281 |

**Tight** = tightened home, **T & UF** = tightened home with unbalanced exhaust fin, **T & HRV** = tightened home with independent HRV, **T & SHRV** = tightened home with HRV interlocked with conditioning system

## 5. House Type and Weather Impacts on Conditioning System Run Times

As previously stated, we assumed a constant fractional run time for the heating and cooling systems if the outdoor temperature was above (for cooling) or below (for heating) the thermostat setting based on the work by Lstiburek et al. (2007). Analyzing the REGCAP runs indicated, as expected, that the fractional run time of the system for each hour was a function of the outdoor-thermostat temperature difference. The general shape of the relationship was fairly linear for all homes for heating and cooling but had slightly different parameters for each house in each climate zone. Figure 10 shows an example of the heating system fractional on time as a function of temperature difference. For each home in each climate zone, the ventilation changes made to the homes did not significantly impact this relationship. From these runs we developed linear relationships between the temperature difference and fractional on time for each of the characteristic house types in each climate. In future applications of the IVE model, we will use these relationships to estimate the fraction of the time the blower is on due to heating and cooling

($f_{heat/cool}$) when analyzing ventilation systems interlocked with the conditioning system. The relationships are shown in Table 5.

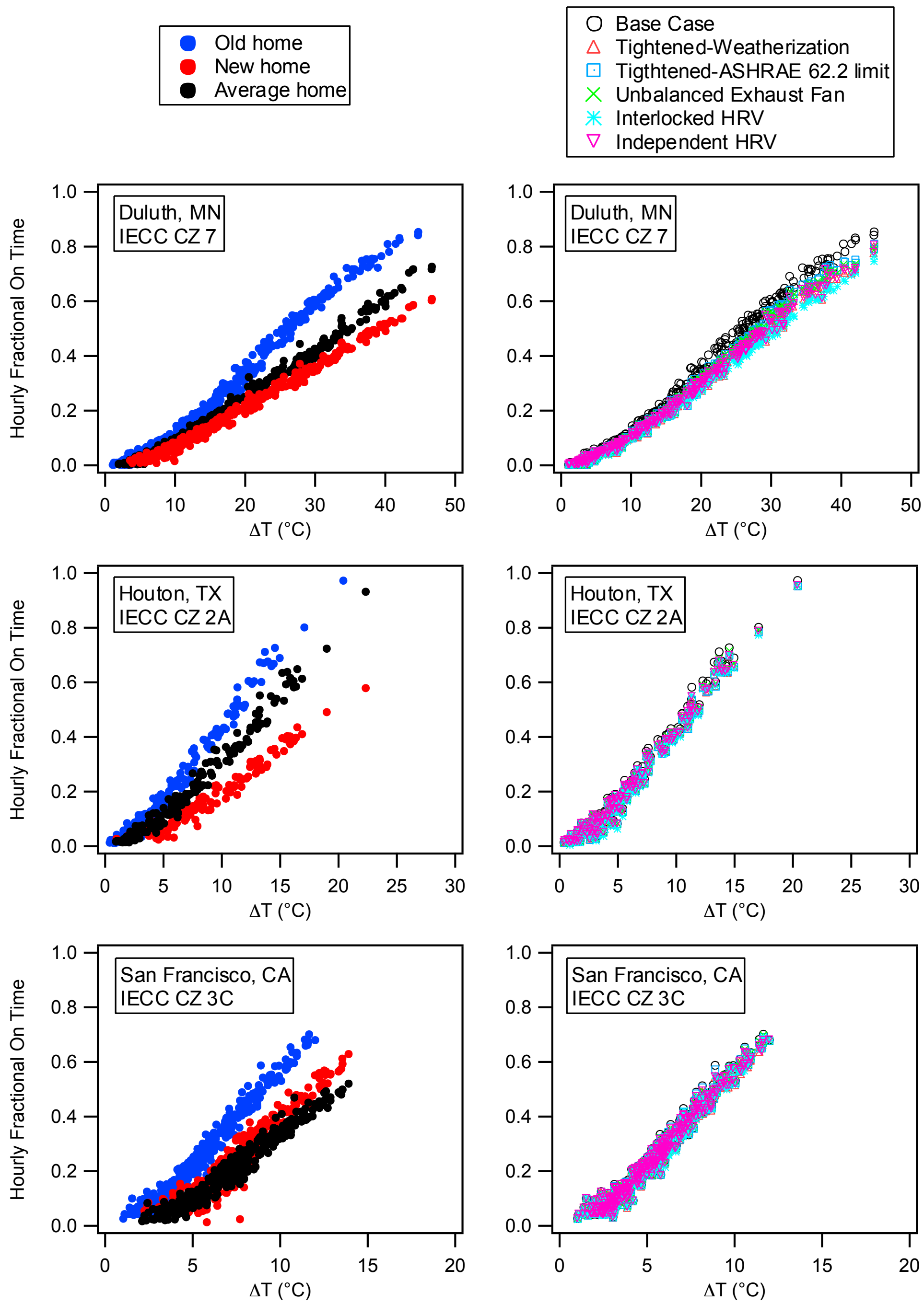


**Figure 10. Fractional on time of heating system as a function of temperature difference**. The graphs shows the hourly fractional on time of the heating system in the old, average, and new homes in IECC climate zones 3C, 2A, and 7 from the REGCAP modeling results. The graphs on the right side show the fractional on time for the old home in each climate for the base case and all of the ventilation variations. The temperature difference is the difference between the outdoor temperature and the heating thermostat set point.

**Table 5. Parameters for fractional on time of heating and cooling**. The parameters for the linear best fit line (y = mx + b) for the hourly fractional on time of the conditioning system (y) as a function of the absolute difference between the thermostat setting temperature and the outdoor temperature in degrees Celsius (x). Equations are only valid when y is between 0 and 1. The heating equation is only valid when the outdoor temperature is below the heating thermostat setting. The cooling equation is only valid when the outdoor temperature is higher than the cooling thermostat setting.

| | New | | Average | | Old | |
|---|---|---|---|---|---|---|
| IECC CZ | m (slope) | b (intercept) | m (slope) | b (intercept) | m (slope) | b (intercept) |
| **Heating System** | | | | | | |
| 2A | 0.03 | -0.07 | 0.04 | -0.08 | 0.05 | -0.07 |
| 2B | 0.03 | -0.07 | 0.04 | -0.08 | 0.05 | -0.07 |
| 3A | 0.02 | -0.07 | 0.03 | -0.08 | 0.04 | -0.06 |
| 3C | 0.06 | -0.17 | 0.04 | -0.12 | 0.07 | -0.10 |
| 4A | 0.03 | -0.10 | 0.03 | -0.08 | 0.04 | -0.06 |
| 5A | 0.02 | -0.08 | 0.02 | -0.06 | 0.02 | -0.06 |
| 7 | 0.01 | -0.07 | 0.01 | -0.06 | 0.02 | -0.07 |
| **Cooling System** | | | | | | |
| 2A | -0.04 | 0.08 | -0.04 | 0.10 | -0.10 | 0.10 |
| 2B | -0.04 | 0.08 | -0.04 | 0.10 | -0.10 | 0.10 |
| 3A | -0.04 | 0.09 | -0.05 | 0.09 | -0.11 | 0.13 |
| 3C | -0.07 | 0.29 | -0.04 | 0.19 | -0.03 | 0.19 |
| 4A | -0.05 | 0.11 | -0.05 | 0.10 | -0.11 | 0.13 |
| 5A | -0.05 | 0.16 | -0.03 | 0.10 | -0.09 | 0.12 |
| 7 | -0.06 | 0.25 | -0.05 | 0.17 | -0.11 | 0.23 |

## 6. Conclusion

We developed and applied a simplified physics-based, easily applied Incremental Ventilation Energy (IVE) model that uses a limited number of inputs to estimate the nationwide energy impact of changes to the housing stock that affects ventilation. The model was designed to use existing databases of home characteristics and existing computationally inexpensive airflow models as inputs. We compared the results from the IVE model to REGCAP, a well-validated, physics-based, ventilation, heat transfer and moisture model to evaluate if the IVE model could capture home performance changes on a population scale. Considering a weighted sample of the archetypal homes for which simulations were conducted, IVE model predictions of potential nationwide energy costs/savings were within 18% of the REGCAP predictions for all ventilation cases and within 3% for the tightening cases. For scenarios where the ventilation is interlocked to the forced air system blower, the IVE model does not predict performance in individual homes well, but it predicts global behavior fairly accurately. The difference between the IVE and

REGCAP results is small relative to the uncertainty introduced by varying a limited set of estimated input parameters in REGCAP.

The IVE model is a useful tool for estimating population-wide changes in energy demand where limited data are available about each home and can efficiently be used to estimate the impact of policy directed toward changing home ventilation including weatherization programs and ventilation standards. The IVE tool can also be used as an initial screening tool to identify homes for further analysis using a more advanced energy model such as REGCAP.

## 7. References


ACCA (2006). Manual J Residential Load Calculation 8th Edition, Air Conditioning Contractors of America

Ackerman, M. Y., D. Wilson, D. Dale and R. Bailey (2006). "Infiltration Heat Recovery, Part IField Studies in an Instrumented Test Building." Ashrae Transactions **112, pt 2**: paper no. QC-06-056 (RP-1169), 1597-1608.

Ackerman, M. Y., D. Wilson, D. Dale and R. Bailey (2006). "Infiltration Heat Recovery, Part II Laboratory Studies of Two Test Panel Geometries." ASHRAE Transactions **112, pt. 2**: paper no. QC-06-057 (RP-1169), 1609-1621

ASHRAE (1993). A Method of Determining Air Change Rates in Detached Dwellings. Atlanta, GA, American Society of Heating, Refrigerating and Air Conditioning Engineers. **Standard 136**.

ASHRAE (2010). Ventilation and Accetable Indoor Air Quality in Low-Rise Residential Buildings Standard 62.2. Atlanta, GA, American Society of Heating, Refrigerating and Air Conditioning Engineers. **Standard 62.2**.

BPI (2010). Home Energy Auditing Standard, Building Performance Institute, Inc.

CEC (2008). Residential Alternative Calculation Manual (ACM) Approval Method, California Energy Commision**:**CEC-400-2008-002-CMF

CEC (2010). 2008 Building Energy Efficiency Standards for Residential and Non-Residential Buildings. Sacramento, CA, California Energy Comission**:**CEC-400-2008-001-CMF

Chan, W. R., J. Joh and M. H. Sherman (2012). Analysis of Air Leakage Measurements from Residential Diagnositcs Database. Berkeley, CA, Lawrence Berkeley National Lab**:**LBNL number pending

Chan, W. R., W. W. Nazaroff, P. N. Price, M. D. Sohn and A. J. Gadgil (2005). "Analyzing a database of residential air leakage in the United States." Atmospheric Environment **39**(19): 3445-3455.

Chan, W. R., P. N. Price, M. D. Sohn and A. G. Gadgil (2003). Analysis of US residential houses air leakage database. Berkeley, CA, Lawerence Berkeley National Laboratory**:**LBNL-53367

Chau, C. K., W. K. Hui and M. S. Tse (2008). "Valuing the health benefits of improving indoor air quality in residences." Science of the Total Environment **394**(1): 25-38.

DOE (2010). Preliminary Technical Support Document (TSD): Energy Efficiency Program for Consumer Products and Industrial Equipment: Residential Central Air Conditioners and Heat Pumps. Washington, DC, This Document was prepared for the Department of Energy by staff members of Navigant Consulting, Inc., Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory

Fairey, P., R. Vieira and D. Parker (2000). Validation of EnergyGauge® USA Using the HERS BESTEST Procedure. Cocoa, FL, Florida Solar Energy Center**:**No. FSEC-RR-55-00

Halrecht, D., R. Zmeureanu and I. Beausoleil-Morrison (1999). Defining the Methodology for the Next-Generation HOT2000 Simulator. Ottawa, Canada, National Resources Canada http://www.inive.org/members_area/medias/pdf/Inive%5CIBPSA%5CUFSC682.pdf

HVI (2009). Certified Home Ventilating Products Directory. Wauconda, IL, Home Ventilating Institute HVI 911

Johnson, F. X., R. E. Brown, J. W. Hanford, A. H. Sanstad and J. G. Koomey (1994). Residential HVAC Data, Assumptions and Methodology for End-Use Forecasting with EPRI-REEPS 2.1. Berkeley, CA, Lawerence Berkeley National Lab**:**LBNL-34045 http://enduse.lbl.gov/info/LBNL-34045.pdf

Kruse, E., P. Francisco, L. Palmiter and B. Davis (2004). Measured Duct Leakage at Operating Conditions in 48 Homes. ACEEE's Summer Study on Energy Efficiency in Buildings,

Lekov, A. Personal Communication: Natural gas and oil boiler and furnace efficiencies. J. Louge. Berekeley

Logue, J. M., P. N. Price, M. H. Sherman and B. C. Singer (2012). "A Method to Estimate the Chronic Health Impact of Air Pollutants in US Residences." Environmental Health Perspectives **120**(2): 216-222.

Lstiburek, J., B. Petit and A. Rudd (2007). Whole House Ventilation Systems Options – Phase 1 Simulation Study. Arlington, VA, Air-Conditioning, Heating and Refrigeration Institute**:**ARTI Report No. 30090-01 http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Technical%20Results/ARTI-Rpt-30090-01.pdf

NREL. (2008). "Typical Meteorological Year." Retrieved March 15, 2012, from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

Offermann, B., W. J. Fisk, J. M. Logue, P. Francisco, L. Kolb and J. Hughes (2011). Workshop: Energy Conservation in IAQ and Residences. Indoor Air 2011, Austin, TX,

Palmgren, C., N. Stevens, M. Goldberg, R. Barnes and K. Rothkin (2010). 2009 California Residential Appliance Saturation Study. Oakland, CA, Prepared by KEMA, Inc. for the California Energy Commission; Contract number 400-07-031

RESNET (2006). Procedures for Certifying Residential Energy Efficiency Tax Credits for New Homes. Oceanside, CA, RESNET. **RESNET publication No. 06-001:** 30.

RESNET (2012). 2006 Mortgage Industry National Home Energy Rating Systems Standards. Oceanside, CA, Residential Energy Services Network (RESNET).

Sherman, M. H. (2008). On the valuation of infiltration towards meeting residential ventilation needs. Berkeley, CA, Lawrence Berkeley National Laboratory**:**LBL-1031E

Sherman, M. H., J. M. Logue and B. C. Singer (2011). "Infiltration effects on residential pollutant concentrations for continuous an dintermittent mechanical ventilation approaches." HVAC&R Research **17**(2): 159-173.

Sherman, M. H. and N. E. Matson (1997). Residential Ventilation and Energy Characteristics. Berkeley, CA, Lawerence Berkeley National Laboratory**:**LBNL-39036

Sherman, M. H. and J. A. McWilliams (2007). Air Leakage of U.S. Homes: Model Predictions. Berkeley, CA, Lawerence Berkeley National Laboratory**:**LBNL-62078

Siegel, J., I. S. Walker and M. H. Sherman (2000). "Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems." Proceedings of

American Council for Energy Efficiency Economy Summer Study 2000, LBNL-45315 **1**: 295-306.
Siegel, J. A. (1999). The REGCAP Simulation: Predicting Performance in New California Homes. Berkeley, CA, University of California at Berkeley. **Masters Thesis**.
Spencer, J. (2010). Analysis of EnergyPlus for use in residential building energy optimization. Department of Civil, Environmental, and Architectural Engineering. Boulder, Co., University of Colorado at Boulder. **M.S.:** 133.
US Census Bureau (2009). County population, population change and estimated components of population change: April 1, 2000 to July 1, 2009 (CO-EST2009-alldata) US Census Bureau.
US EIA (2005). Residential Buildings Energy Consumption Survey (RECs), U.S. Energy Information Administration.
Walker, I. S. (1993). Attic Ventilation, Heat and Moisture Transfer. Department of Mechanical Engineering. Alberta, Canada, University of Alberta. **Ph.D.**
Walker, I. S. (2006). Residential Furnace Blower Performance. Berkely, CA, Prepared by Lawrence Berkely National Laboratory for PG&E**:**LBNL-61467
Walker, I. S. (2008). "Comparing Residential Furnace Blowers for Rating and Installed Performance." ASHRAE Transactions **114**(Pt. 1): 187-195.
Walker, I. S., G. Degeneais and J. A. Siegel (2002). Simulations of Sizing and Comfort Improvements for Residential Forced Air Heating and Cooling Systems. Berkeley, CA, Lawerence Berkeley National Laboratory**:**LBNL 47309
Walker, I. S., T. W. Forest and D. J. Wilson (2004). "An Attic-Interior Infiltration and Interzone Transport Model of a House." Buildign and Environment **40**(5): 701-718.
Walker, I. S. and M. H. Sherman (2006). Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements. Berkeley, CA, Environmental Energy Technologies Division, Lawrence Berkeley National Lab**:**LBNL-59998
Walker, I. S. and M. H. Sherman (2007). Humidity Implications for Meeting Residential Ventilation Requirements. Berkeley, CA, Lawerence Berkeley National Laboratory**:**LBNL-62182
Walker, I. S., M. H. Sherman and J. Siegel (1999). Distribution Effectiveness and Impacts on Equipment Sizing. Berkeley, CA, Lawrence Berkeley National Laboratory
Walker, I. S. and D. J. Wilson (1998). "Field validation of equations for stack and wind driven air infiltration calculations." HVAC&R Research **4**(2).
Wilson, D. J. and I. S. Walker (1990). Combining Air Infiltration and Exhaust Ventilation. Indoor Air '90, Toronto, Canada, 467-472.
Wilson, D. J. and I. S. Walker (1992). Feasibility fo Passive Ventilation by Constant Area Vents to Maintain Indoor Air Quality in Houses. Proceedings of Indoor air Quality '92. San Francisco, CA.
Wilson, D. J. and I. S. Walker (1992). Passive Ventilation to Maintain Indoor Air Quality. Alberta, University of Alberta, Department of Mechanical Engineering**:**Report 81

# Appendix

**A.1 Existing Residential Energy Models**

Existing residential HVAC energy models estimate a home's total energy demand for conditioning the space. Modeling or estimating the total annual HVAC energy use of a home requires a complex analysis to account for heat transfer to and from the building (solar gains, airflow through the home, conduction losses to the walls and floor), moisture transfer, and HVAC equipment performance. Various modeling platforms and programs have been established to model total energy use in buildings. The best known of these is Energy Plus and its predecessor, DOE II, both developed by the U.S. Department of Energy (DOE). Energy Plus is used for both commercial and residential building energy simulations, but has been shown to have deficiencies in modeling infiltration impacts in residential modeling (Spencer 2010). Some modeling platforms have been designed to address residential energy use specifically. Commercially available software, such as EnergyGuage, developed and validated by the Florida Solar Energy Center (Fairey et al. 2000), or programs like HOT2000 (Halrecht et al. 1999) have been developed for use in home energy ratings (RESNET 2006). However, these software packages do not have very sophisticated ventilation models.

**A.2 REGCAP Model Description**

The REGCAP model, developed and validated at the University of Alberta (Walker 1993) and Lawrence Berkeley National Laboratory (Walker and Sherman 2007), contains a sophisticated ventilation and general HVAC model combined with a model for building loads. We compared the IVE modeling results to those from REGCAP because REGCAP is currently the best available model for HVAC operation, including parameters of interest in this study.

The REGCAP modeling framework is a residential HVAC model that combines ventilation, heat transfer, and moisture models to determine annual residential energy use as a function of building characteristics and location (Walker and Sherman 2006). REGCAP was developed because existing models of residential HVAC system performance either had too many simplifying assumptions or did not adequately model the ventilation, thermal, and moisture performance of the ducts and the spaces containing ducts combined with heating and cooling equipment performance. REGCAP is capable of simulating any level of time resolution, as long as the differential equations in the model remain stable, but it is predominately used to simulate minute-by-minute HVAC system operation. REGCAP performs a heat and mass balance on the house and HVAC system at each time step. REGCAP includes all the HVAC system-related airflows, including duct leakage and registers, and models of air conditioner performance that include the effects of coil airflows and indoor and outdoor air temperature and humidity. The REGCAP model calculates the home conditions for each minute and turns the thermal conditioning equipment off and on based on the temperature calculated for the home. The conditioning equipment is modeled as adding/removing energy from the space at the rate specified for the conditioning equipment in the home. The previous minutes' temperature and the energy output of the conditioning system, along with other heat gains or losses, is then used to compute the temperature in the house in the next minute, and the conditioning equipment is turned on or off accordingly. The REGCAP model accounts for thermal losses and gains from the home due to conduction, radiation, and heat transfer to the outside from the building envelope and duct system, as well as solar gains. REGCAP determines the HVAC system energy use and air exchange rate of the home on a minute-by-minute basis and also produces annual summaries.

The model has been extensively verified and been shown to predict equipment energy consumption within 4% of measured system capacity and predicted ventilation rates within about 5% over a wide range of house leakage distributions and weather conditions [15] (Wilson and Walker 1992; Wilson and Walker 1992; Siegel 1999; Walker et al. 1999; Siegel et al. 2000; Walker et al. 2002; Walker et al. 2004; Walker and Sherman 2007). The REGCAP model requires a minimum of 87 input parameters, which are listed in Table A.1.

**Table A.1. REGCAP input list.** This is a list of common REGCAP inputs needed to run the model for one set of home conditions.

| **REGCAP Run Inputs** | |
|---|---|
| Envelope leakage coefficient, m3/sPa^n | Attic volume, m3 |
| Envelope pressure exponent | Attic leakage coefficient |
| Eave height, m | Attic pressure exponent |
| R = ceiling floor leakage sum | Fraction of attic leakage above wall 1 |
| X = ceiling floor leakage difference | Fraction of attic leakage above wall 2 |
| Number of flues | Fraction of attic leakage above wall 3 |
| Cflue | Fraction of attic leakage above wall 4 |
| Flue height, m | Fraction of attic leakage in the two pitched roof surfaces |
| Flue gas temperature | Soffit height above wall 1, m |
| Cflue | Soffit height above wall 2, m |
| Flue height, m | Soffit height above wall 3, m |
| Flue gas temperature | Soffit height above wall 4, m |
| Fraction of leakage in wall 1 - N | Number of added attic vents |
| Fraction of leakage in wall 2 - S | Attic vent wall |
| Fraction of leakage in wall 3 - E | Attic vent height |
| Fraction of leakage in wall 4 - W | Attic vent area |
| Fraction of leakage at floor level below wall 1 | Attic vent pressure exponent |
| Fraction of leakage at floor level below wall 2 | Attic vent wall |
| Fraction of leakage at floor level below wall 3 | Attic vent height |
| Fraction of leakage at floor level below wall 3 | Attic vent area |
| Wind shelter for roof and flue | Attic vent pressure exponent |
| Number of passive vents | Roof pitch, degrees |
| Floor height above grade, m | Roof peak orientation |
| House site info | Roof peak, m |
| Building volume, m3 | Number of attic vent fans |
| Floor area , m2 | Roof R-value |
| Plan area, m2 | Roof type |
| Length of house, m | Duct location, 1= inside, 0= attic |
| Width of house, m | Supply insulation thickness, m |
| Heating house UA w/C | Return insulation thickness, m |
| Cooling house UA w/C | Supply R value, m^2k/w |
| Number of open windows and doors | Return R value, m^2k/w |
| Number of mechanical vent fans | Supply leakage fraction, % or fraction |
| Fan 1 power, w | Return leakage fraction, % or decimal fraction |
| Fan 1 Q, m^3/s | Supply ducts length, m |
| Fan 1 schedule | Return ducts length, m |
| Fan 2 power, w | Mean supply diameter, m |
| Fan 2 Q, m^3/s | Mean return diameter, m |
| Fan 2 schedule | Cooling air flow |
| Fan 3 power, w | Heating air flow m^3/s |
| Fan 3 Q, m^3/s | Supply duct leak pressure exponent |
| Fan 3 schedule | Return duct leak pressure exponent |
| Fan 4 power, W | Supply duct leak coefficient, m3/sP^n |
| Fan 4 Q, m^3/s | Return duct leak coefficient, m3/sP^n |
| Fan 4 schedule | Fraction of ducts buried in insulation |
| E/W window area m2 | Raw capacity, tons (really only applies to cooling) |
| North facing window area, m2 | Cooling capacity, kBtu/h |
| South facing window area, m2 | EERari cooling (Energy Efficient Ratio) [Btu/Wh] |
| Window shading coefficient, SHGC | Heating capacity, kBtu/h |
| Heating R value of ceiling, m2K/W | Heating fan power consumption, W |
| Cooling R value of ceiling, m2K/W | Cooling fan power consumption, W |
| Latent load, kg/s | Charge, fraction of full charge |
| Internal gains, W | Heating system AFUE |

## A.3 Applying Simplified Airflow Models

When applying this model to existing databases of home characteristics, we can use exiting simple airflow models to determine the hourly air exchange rate. Walker and Wilson (1998) developed an algorithm to calculate the infiltration as a function of home characteristics available in databases of home characteristics such as the RASS and RECS, outdoor weather data, and home leakage area. Lawrence Berkeley National Laboratory has developed algorithms to estimate building leakage area based on parameters available in home databases as well. ASHARE Standard 136 (1993) gives a reference method for combining mechanical ventilation and natural infiltration. The infiltration air leakage model by Walker and Wilson is (1998):

$$A_{inf,i} = \frac{Q}{V_{house}} = \frac{1}{V_{house}}\sqrt{Q_{stack,i}^2 + Q_{wind,i}^2} \quad \textbf{(A.1)}$$

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

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

$$c(\frac{m3}{sPa}) = \frac{ELA}{\sqrt{\frac{\rho_{air}}{2}} * dP^{(.67-.5)}} \quad \textbf{(A.4)}$$

$A_{inf,i}$ is the infiltration air exchange rate at time *i*, $V_{house}$ 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, *Cw, s*, and *Cs* are constants based on shelter class, number of stories, and number of flues, $\Delta T$ is the difference between indoor and outdoor temperature, *U* is the wind speed, and *ELA* is the estimated leakage area. Using characteristics available in the RASS and RECS, the normalized leakage area (NL) of each home can be estimated using the LBNL leakage model (Chan et al. 2005; Sherman and McWilliams 2007; Chau et al. 2008). ELA can be calculated from NL using the following relationship.

$$ELA = \frac{FloorArea * NL}{1000}\left(\frac{2.5m}{Height}\right)^{0.3} \quad \textbf{(A.5)}$$

Where *FloorArea* is the floor area of the house and *Height* is the height of the home. For many of the comparisons we will be adding mechanical ventilation. ASHARE Standard 136 (1993) gives a reference method for combining mechanical ventilation and natural infiltration:

$$A_i = A_{bal,i} + \sqrt{A_{unbal,i}^2 + A_{inf,i}^2} \quad \textbf{(A.6)}$$

Where $A_{bal,i}$ is the air exchange rate at time step *i* due to balanced mechanical ventilation alone (such as HRVs and ERVs), $A_{unbal,i}$ is the air exchange rate at time step *i* due to unbalanced mechanical ventilation alone (this includes exhaust and supply only fans), and $A_{inf,i}$ is the air exchange rate at time step *i* due to natural infiltration alone. Balanced mechanical ventilation uses mechanical equipment to provide both supply and exhaust airflow at 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.

### A.4 Estimating Additional Airflow Due to Supply Duct Leakage

Efficiency of system is reduced by the air infiltration due to leakage in return ducts. When applying the IVE methodology to databases of home characteristics, using simplified air models, the extra infiltration should be calculated to estimate the total additional energy required. One method of doing this would be to iteratively solve the energy demand for each time step of the model if ducts are present in the home being modeled. You would first calculate the additional airflow due to mechanical ventilation using the simple airflow models. Then calculate the energy required to condition that volume of added air. You would then use that energy calculation to solve for the extra airflow due to infiltration using available proportionality constants. The California Energy Commission's *Alternative Calculation Manual* (ACM)(CEC 2008) specifies recommended system airflow sizes as a function of the home heating and cooling system (400 feet per minute [cfm]/ ton cooling and 16.8 cfm/ kBtuh). These values can be used to derive estimates of the airflow required to flow through the blower and duct system per unit energy output by the heating and cooling systems (6,824 cubic feet [$ft^3$] per kWh cooling and 3,439 $ft^3$ per kWh heating). You would then multiply the total system airflow by the homes estimated return side duct leakage to determine the percentage of outside air that enters the home per kWh of cooling and heating. You would then recalculate the energy needed to condition the total airflow (duct leakage plus airflow difference from simplified airflow models) for that time step. This could be done iteratively until the difference between two iterations is negligible.

### A.5 Ventilation Standards and Equipment

The ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, is the industry standard for residential ventilation (ASHRAE 2010). ASHRAE Standard 62.2 has requirements for source control ventilation in kitchens and baths, and for whole-house ventilation. The required whole-house mechanical ventilation rate is based on the assumption that infiltration contributes 2 cfm per 100 square feet ($ft^2$) or 0.1 liters per minute per square meter (L $s^{-1}$ $m^{-2}$). In addition to this infiltration, the standard prescribes the whole-house mechanical ventilation rate given by Equation 1:

$$Q(cfm) = 0.01A_{floor}(ft^2) + 7.5(N + 1) \qquad \textbf{(A.7a)}$$
$$Q(L/s) = 0.05A_{floor}(m^2) + 3.5(N + 1) \qquad \textbf{(A.7b)}$$

where $Q$ is the required mechanical ventilation rate, $A_{floor}$ is the house floor area, and $N$ is the number of bedrooms. The floor area of the house is a surrogate for pollutants from materials intrinsic to the building, and the number of bedrooms is a surrogate for occupant activities and associated emissions.

The standard allows for flexibility in the method in which the ventilation is delivered. In practice, the most common method is a continuous exhaust fan. Other systems combine ventilation with the the forced air thermal conditioning system or use heat recovery or enthalphy recovery ventilators (HRV or ERV). HRV and ERV systems are balanced systems that exhaust air from the space at the same rate that they supply air into the home. The inflow and outflow streams flow though a heat or heat and moisture exchanger to recover some of the energy that would be lost from just exhausting the air. When ventilation is combined with the forced air system blower, the system turns on the blower when ventilation is required if the blower is not already opperating in conjunction with the home conditioning equipment.

## A.6 Input Parameters for the IVE/REGCAP Comparison

To compare the IVE and REGCAP models, we specified three home types for each of seven IECC climate zones. The home types are (1) a **new** home impacted by ventilation standards, (2) an **average** U.S. home impacedt by weatherization and ventilation standards, and (3) an **old** small home impacted by weatherization and ventilation standards. Each home type was designed for the representative city for each of seven IECC climate zones that represent the expanse of U.S. weather. The climate zones and representative city for each climate are: 2A hot/humid (Houston, Texas), 2B hot/dry (Phoenix, Arizona), 3A warm/humid (Atlanta, Georgia), 3C warm/marine (San Francisco, California), 4A mixed/humid (Baltimore, Maryland), 5A cool/humid (Chicago, Illinois), and 7 very cold (Duluth, Minnesota). The home characteristic for each of these homes is shown in tables A.2–A.4. RECAP required input parameters that were determined from these listed parameters. If a parameter was not available, its relationship to the available parameter was assumed to the same as for the highly specified Prototype D house in the ACM. Table A.5 shows the thermostat settings for both the REGCAP and IVE model runs.

**Table A.2.** Abbreviated inputs for REGCAP and IVE model inputs for **new,** tight homes

| New Home | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CZ2A Houston | CZ2B Phoenix | CZ3A Atlanta | CZ3C San Francisco | CZ4A Baltimore | CZ5A Chicago | CZ7 Duluth | Data source |
| Home Characteristics | | | | | | | | |
| Size(cuft) | 2100 | 2100 | 2100 | 2100 | 2100 | 2100 | 2100 | T24-Prototype C |
| NL | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | T24-Prototype C |
| Floors | 1 | 1 | 1 | 1 | 1 | 1 | 1 | T24-Prototype C |
| Insulation | | | | | | | | |
| walls | R13 | R13 | R13 | R13 | R13 | R21 | R21 | High insulation |
| floor | R19 | R19 | R19 | R19 | R19 | R19 | R30 | High insulation |
| ceiling | R30 | R30 | R30 | R30 | R30 | R38 | R44 | High insulation |
| windows | R2.5 | R2.5 | R2.5 | R2.6 | R2.5 | R2.5 | R2.5 | High insulation |
| Heating | | | | | | | | |
| AFUE | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | highest market efficiency |
| Heating Eff | 0.776 | 0.776 | 0.776 | 0.776 | 0.776 | 0.776 | 0.776 | total system efficiency |
| Air flow(cfm) | 730 | 757 | 1102 | 509 | 730 | 1116 | 1531 | Manual J&S-Wrightesoft |
| Heating (kBtu/h) | 50 | 50 | 75 | 28 | 50 | 75 | 100 | Manual J&S-Wrightesoft |
| Fan power (W) | 365 | 379 | 551 | 255 | 365 | 558 | 766 | 0.5watts /cfm |
| Cooling | | | | | | | | |
| COP | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | T24-Prototype C |
| EER | 11 | 11 | 11 | 11 | 11 | 11 | 11 | T24-Prototype C |
| Cooling Eff | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | total system efficiency |
| air flow (cfm) | 1350 | 2150 | 1300 | 543 | 1080 | 880 | 673 | Manual J&S-Wrightsoft |
| Cooling (kBtu/h) | 41 | 65 | 39 | 16 | 34 | 26 | 20 | Manual J&S-Wrightsoft |
| Fan power (W) | 675 | 1075 | 650 | 272 | 540 | 440 | 337 | 0.5w/cfm |
| Ducts | | | | | | | | |
| %return | 3% | 3% | 3% | 3% | 3% | 3% | 3% | T24-Prototype C |
| %supply | 3% | 3% | 3% | 3% | 3% | 3% | 3% | T24-Prototype C |
| insulation | R6 | R6 | R6 | R6 | R6 | R8 | R8 | High insulation |
| Mechanical Ventilation | | | | | | | | |
| MV 62.2 (cfm) | 51 | 51 | 51 | 51 | 51 | 51 | 51 | Constant Exhaust Fan |
| Exhaust fan (W) | 18 | 18 | 18 | 18 | 18 | 18 | 18 | Broan QDE30BL fan (HVI 2009) |
| MV 62.2 (cfm) | 102 | 102 | 102 | 102 | 102 | 102 | 102 | HRV 30min/hour |
| HRV (W) | 92 | 92 | 92 | 92 | 92 | 92 | 92 | HVI (HVI 2009) |

**Table A.3.** Abbreviated inputs for REGCAP and IVE model inputs for **old**, small homes

| Old home, low insulation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CZ2A Houston | CZ2B Phoenix | CZ3A Atlanta | CZ3C San Francisco | CZ4A Baltimore | CZ5A Chicago | CZ7 Duluth | Data source |
| Home Characteristics | | | | | | | | |
| Size(cuft) | 900 | 900 | 900 | 900 | 900 | 900 | 900 | RECS |
| NL | 1.20 | 0.75 | 1.00 | 0.80 | 1.00 | 0.80 | 0.75 | RECS/NL model |
| Floors | 1 | 1 | 1 | 1 | 1 | 1 | 1 | RECS |
| Bedrooms | 2 | 2 | 2 | 2 | 2 | 2 | 2 | RECs |
| Insulation | | | | | | | | |
| walls | R4 | R4 | R4 | R4 | R4 | R7 | R10 | Low insulation |
| floor | R5 | R5 | R5 | R5 | R5 | R10 | R12 | Low insulation |
| ceiling | R11 | R11 | R11 | R11 | R11 | R15 | R20 | Low insulation |
| windows | R1 | R1 | R1 | R1 | R1 | R1 | R1 | Low insulation |
| Heating | | | | | | | | |
| AFUE | 0.58 | 0.7 | 0.57 | 0.67 | 0.7 | 0.57 | 0.57 | RECS/Efficiency Reference |
| Heating Eff | 0.49 | 0.60 | 0.48 | 0.57 | 0.60 | 0.48 | 0.48 | total system efficiency |
| Air flow(cfm) | 838 | 547 | 1031 | 549 | 957 | 1495 | 1830 | Supplies 140% of Manual J Calcs |
| Heating (kBtu/h) | 58 | 38 | 71 | 38 | 66 | 103 | 126 | Supplies 140% of Manual J Calcs |
| Fan power (W) | 419 | 274 | 515 | 275 | 479 | 747 | 915 | 0.5w/cfm |
| Cooling | | | | | | | | |
| COP | 2.4 | 2.4 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | RECS/Efficiency Reference |
| EER | 7.7 | 7.7 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | RECS |
| Cooling Eff | 2.4 | 2.4 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | total system efficiency |
| air flow (cfm) | 882 | 884 | 760 | 425 | 776 | 739 | 532 | Supplies 115% of Manual J Calcs |
| Cooling (kBtu/h) | 23 | 23 | 19 | 8 | 20 | 18 | 12 | Supplies 115% of Manual J Calcs |
| Fan power (W) | 441 | 442 | 380 | 212 | 388 | 370 | 266 | 0.5w/cfm |
| Ducts | | | | | | | | |
| %return | 15% | 15% | 15% | 15% | 15% | 15% | 15% | High leakage |
| %supply | 15% | 15% | 15% | 15% | 15% | 15% | 15% | High leakage |
| insulation | R1 | R1 | R1 | R1 | R1 | R2 | R2 | Low insulation |
| Tightening | | | | | | | | |
| NL(33% tighter) | 0.80 | 0.50 | 0.67 | 0.53 | 0.67 | 0.53 | 0.50 | Tightening: Weatherizatoin |
| Ducts (43% tighter) | 15% | 15% | 15% | 15% | 15% | 15% | 15% | Leakage database |
| W ashrae 136 | 0.81 | 0.68 | 0.75 | 0.92 | 0.82 | 0.93 | 1 | Determined from ASHRAE 136 |
| ASRAE min Inf (ACH) | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | 0.66 | min infiltration w/o ventilation |
| NL(max) | 0.81 | 0.97 | 0.88 | 0.72 | 0.80 | 0.71 | 0.66 | Tightening: ASHRAE limit |
| Mechanical Ventilation | | | | | | | | |
| MV 62.2 (cfm) | 31.5 | 31.5 | 31.5 | 31.5 | 31.5 | 31.5 | 31.5 | Constant Exhaust Fan |
| Exhaust fan (W) | 11 | 11 | 11 | 11 | 11 | 11 | 11 | Broan QDE30BL fan (HVI 2009) |
| MV 62.2 (cfm) | 63 | 63 | 63 | 63 | 63 | 63 | 63 | HRV 30min/hour |
| HRV (W) | 57 | 57 | 57 | 57 | 57 | 57 | 57 | HVI (HVI 2009) |

**Table A.4.** Abbreviated inputs for REGCAP and IVE model inputs for **average** homes

| Average Home | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CZ2A | CZ2B | CZ3A | CZ3C | CZ4A | CZ5A | CZ7 | Leakage database |
| | Houston | Phoenix | Atlanta | San Francisco | Baltimore | Chicago | Duluth | Data source |
| Home Characteristics | | | | | | | | |
| Size(cuft) | 1550 | 1550 | 1550 | 1550 | 1550 | 1550 | 1550 | RECS |
| NL | 1.00 | 0.60 | 0.60 | 0.55 | 0.50 | 0.50 | 0.50 | RECS/NL model |
| Floors | 2 | 2 | 2 | 2 | 2 | 2 | 2 | RECS |
| Insulation | | | | | | | | |
| walls | R8 | R8 | R8 | R8 | R8 | R14 | R14 | moderate insulation |
| floor | R10 | R10 | R10 | R10 | R10 | R10 | R15 | moderate insulation |
| ceiling | R15 | R15 | R15 | R15 | R15 | R19 | R22 | moderate insulation |
| windows | R2 | R2 | R2 | R2 | R2 | R2 | R2 | moderate insulation |
| Heating | | | | | | | | |
| AFUE | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | RECS/Efficiency References |
| Heating Eff | 0.684 | 0.684 | 0.684 | 0.684 | 0.684 | 0.684 | 0.684 | total system efficiency |
| Air flow(m/s) | 693 | 548 | 817 | 563 | 962 | 1181 | 1502 | Supplies 115% of Manual J Calcs |
| Heating (kBtu/h) | 48 | 38 | 56 | 39 | 66 | 82 | 104 | Supplies 115% of Manual J Calcs |
| Fan power (W) | 347 | 274 | 408 | 282 | 481 | 590 | 751 | 0.5w/cfm |
| Cooling | | | | | | | | |
| COP | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | 2.84 | Calculated from EER |
| EER | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | RECS/Efficiency References |
| Cooling Eff | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | total system efficiency |
| air flow (cfm) | 1343 | 1406 | 1225 | 738 | 1216 | 1179 | 870 | Supplies 115% of Manual J Calcs |
| Cooling (kBtu/h) | 38 | 40 | 34 | 18 | 34 | 32 | 23 | Supplies 115% of Manual J Calcs |
| Fan power (W) | 671 | 703 | 613 | 369 | 608 | 589 | 435 | 0.5w/cfm |
| Ducts | | | | | | | | |
| %return | 10% | 10% | 10% | 10% | 10% | 10% | 10% | Medium Leakage |
| %supply | 10% | 10% | 10% | 10% | 10% | 10% | 10% | Medium Leakage |
| insulation | R3 | R3 | R3 | R3 | R3 | R4 | R4 | moderate insulation |
| Tightening | | | | | | | | |
| NL(33% tighter) | 0.67 | 0.40 | 0.40 | 0.37 | 0.33 | 0.33 | 0.33 | Tightening: Weatherizatoin |
| Ducts (43% tighter) | 6% | 6% | 6% | 6% | 6% | 6% | 6% | Leakage database |
| W ashrae 136 | 0.81 | 0.68 | 0.75 | 0.92 | 0.82 | 0.93 | 1 | Determined from ASHRAE 136 |
| ASRAE min Inf (ACH) | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | min infiltration w/o ventilation |
| NL(ASHRAE) | 0.62 | 0.74 | 0.67 | 0.55 | 0.62 | 0.54 | 0.51 | Tightening: ASHRAE limit |
| Mechanical Ventilation | | | | | | | | |
| MV 62.2 (cfm) | 38 | 38 | 38 | 38 | 38 | 38 | 38 | Constant Exhaust Fan |
| Exhaust fan (W) | 13 | 13 | 13 | 13 | 13 | 13 | 13 | Broan QDE30BL fan (HVI 2009) |
| MV 62.2 (cfm) | 76 | 76 | 76 | 76 | 76 | 76 | 76 | HRV 30min/hour |
| HRV (W) | 68 | 68 | 68 | 68 | 68 | 68 | 68 | HVI (HVI 2009) |

**Table A.5.** Thermostat settings for homes.

| | Average and New Home | | Old Home | |
|---|---|---|---|---|
| Hour | Heating | Cooling | Heating | Cooling |
| 1 | 68 | 77 | 65 | 77 |
| 2 | 68 | 77 | 65 | 77 |
| 3 | 68 | 77 | 65 | 77 |
| 4 | 68 | 77 | 65 | 77 |
| 5 | 68 | 77 | 65 | 77 |
| 6 | 68 | 77 | 65 | 77 |
| 7 | 68 | 77 | 68 | 77 |
| 8 | 68 | 77 | 65 | 77 |
| 9 | 70 | 80 | 65 | 80 |
| 10 | 70 | 80 | 65 | 80 |
| 11 | 70 | 80 | 65 | 80 |
| 12 | 70 | 80 | 65 | 80 |
| 13 | 70 | 80 | 65 | 80 |
| 14 | 70 | 80 | 65 | 80 |
| 15 | 70 | 80 | 65 | 80 |
| 16 | 70 | 80 | 65 | 80 |
| 17 | 70 | 80 | 65 | 80 |
| 18 | 70 | 77 | 65 | 77 |
| 19 | 70 | 77 | 68 | 77 |
| 20 | 70 | 77 | 68 | 77 |
| 21 | 70 | 77 | 68 | 77 |
| 22 | 70 | 77 | 68 | 77 |
| 23 | 70 | 77 | 68 | 77 |
| 24 | 70 | 77 | 68 | 77 |