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Authors
Logue, J.M.
Turner, W.J.N.
Walker, I.S.
et al.

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# A simplified model for estimating population-scale energy impacts of building envelope air-tightening and mechanical ventilation retrofits

J.M. Logue[1], W.J.N. Turner, I.S. Walker, B.C. Singer

[1] Corresponding author: jmlogue@lbl.gov

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Abstract

Changing the air exchange rate of a home (the sum of the infiltration and mechanical ventilation airflow rates) affects the annual thermal conditioning energy. Large-scale changes to air exchange rates of the housing stock can significantly alter the residential sector's energy consumption. However, the complexity of existing residential energy models is a barrier to the accurate quantification of the impact of policy changes on a state or national level.

The Incremental Ventilation Energy (IVE) model developed in this study combines the output of simple air exchange models with a limited set of housing characteristics to estimate the associated change in energy demand of homes. The IVE model was designed specifically to enable modellers to use existing databases of housing characteristics to determine the impact of ventilation policy change on a population scale. The IVE model estimates of energy change when applied to US homes with limited parameterisation are shown to be comparable to the estimates of a well-validated, complex residential energy model.

Connection between this LBNL report and a and previous LBNL Report: In 2012 we published a previous LBNL Report:

Logue, Jennifer M., William J. N. Turner, Iain S. Walker, and Brett C. Singer. Evaluation of an Incremental Ventilation Energy Model for Estimating Impacts of Air Sealing and Mechanical Ventilation., 2012.

A subset of the work presented in the previous LBNL report was developed into a journal publication for the Journal of Building Performance Simulation. This publication contains the text of the accepted journal paper.

1. Introduction

Thermal conditioning of US residences is estimated to require approximately 1500 TWh of energy, accounting for approximately 50% of residential site energy (US Energy Information Administration 2009). Estimates attribute one-third to one-half of this energy use to uncontrolled infiltration (Sherman & Matson 1997). Air tightening of building envelopes and ducts to reduce air leakage is a core element of energy-efficiency programmes and residential retrofit practices that aim to reduce energy consumption, costs and greenhouse gas emissions.

Current best practise in construction 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). ASHRAE publishes Standard 62.2, a residential ventilation standard for low-rise residential buildings (ASHRAE 2010), the provisions of which have been incorporated into various professional protocols, guidelines, and building codes (Building Performance Institute 2010; RESNET 2012; CEC 2013b). Providing mechanical ventilation requires electrical energy to operate the mechanical system and thermal energy to condition the ventilation air. 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 financial costs and IAQ benefits of various ventilation system designs and technologies is important to inform policy decisions and for the development of protocols for practitioners. The potential benefits of air tightening and the costs of mechanical ventilation vary widely across individual homes due to differences in the following factors:

1) Climate
2) Baseline air-tightness and other building structural/envelope characteristics
3) Heating, ventilation and air conditioning (HVAC) equipment
4) Occupant use of HVAC equipment (e.g. heating/cooling set points).

One approach to assessing the energy impacts of air tightening and mechanical ventilation options for new homes or retrofits is to use a building simulation model (e.g. EnergyPlus (US DOE 2013), DeST (Designer's Simulation Toolkit Group 2011), EnergyGauge (Florida Solar Energy Center 2012), and DOE-2 (Birdsall et al. 1990)) to calculate total energy use for each configuration of interest and then compare the results. The simulation models typically require inputs to define the building geometry, envelope, materials, loads, and HVAC systems. One residential energy model, REGCAP (Walker 1993; Walker & Sherman 2007) requires over 100 individual input parameters in order to perform a simulation.

Many of the parameters required to model an existing building can be determined or estimated only through an extensive on-site audit. Some parameters require detailed diagnostics (such as envelope leakage) and some cannot be determined with the tools typically available to home auditors (such as whole-building thermal conductance). Since values for all parameters must be specified for each simulation, applying these models for population-scale analysis requires assumptions to be made for many of the model inputs. These assumptions can greatly influence the accuracy of analytical results. Additionally, modelling large numbers of homes with complex building

simulation tools can be very processor intensive. Without significant investment in system development to optimize parametric simulation and data processing, the setup and runtimes for analysing results for large databases of homes can be prohibitive. For these reasons, complex building energy modelling tools are not well suited for assessing the specific impacts of air tightening and ventilation systems at the population scale for most building researchers.

Empirically-derived airflow models have been used to estimate the impacts of changing envelope air-tightness on natural and mechanical ventilation rates in homes using a relatively limited set of housing characteristics (Wilson & Walker 1990; Chan et al. 2005; Chan et al. 2003; Sherman & McWilliams 2007). These airflow models have also been used to estimate the ventilation impacts of adding mechanical ventilation to homes (Sherman et al. 2011; Sherman 2008). However, there are no analogous energy models that can estimate the energy impact of changes in air exchange rate using a similarly limited set of housing characteristics.

This paper introduces a new model called the Incremental Ventilation Energy (IVE) model. The IVE model attempts to address the above issues by developing a physics-based approach to modelling the *incremental* change in energy demand associated with an *incremental* change in air exchange rate (the sum of the infiltration and mechanical ventilation airflow rates (ASHRAE 2013a)). The IVE model predicts the energy impacts of air tightening (also called 'weatherization' in North America) and of adding different mechanical ventilation systems to homes. Results from the model can be used to inform policy makers and building practitioners.

This paper has three main objectives:
1) Describe the IVE model.
2) Describe how to apply the IVE model to databases of housing characteristics to estimate population energy change due to changes in ventilation.
3) Compare the energy impacts calculated by the IVE model to those calculated by an existing, well-validated residential energy simulation model.

2.   The Incremental Ventilation Energy (IVE) Modelling Approach

2.1   *Rationale*

There exist a number of residential simulation models that calculate energy demand by solving a series of coupled time-dependent equations representing the physical processes of heat (and sometimes moisture) transfer (Florida Solar Energy Center 2012; Fairey, Vieira, and Parker 2000; Halrecht, Zmeureanu, and Beausoleil-Morrison 1999; RESNET 2014; Crawley et al. 2001). The models can 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 (Figure 1a).

A key rationale for the IVE model is that many of the processes of energy transfer shown in Figure 1**Figure 1**a are not necessarily affected by changes to building air exchange rate. If indoor temperature schedules do not change and the building HVAC equipment is able to meet the heating and cooling set points, then the impact of changes to building airflow rate on the conductive, radiative, and convective losses at

the envelope should be minimal (Ackerman, Wilson, et al. 2006; Ackerman, Dale, et al. 2006). Solar and internal gains should also be unaffected. Therefore, when considering *changes* in building energy due to changes in air exchange rate, only two mechanisms need to be considered to capture the majority of the effect: the change in heating/cooling equipment load required to thermally condition incoming infiltration or ventilation air, and any fan energy used to drive ventilation air (Figure 1b).

The IVE model calculates the following:
1) Thermal heating/cooling loads associated with incremental changes to the air exchange rate of the building due to changes in infiltration and mechanical ventilation
2) The operation and energy use of mechanical ventilation equipment.

The IVE model *does not* calculate building air exchange rates. Instead, it takes building air exchange rates calculated by separate simulation tools as inputs, and then calculates the energy penalty or benefit associated with the change in air exchange rate.

A) Energy flows to consider for analysis of total home energy

Attic

Heat transfer to and from attic

Home
Indoor Temperature
Controled by Thermostat

Solar Gains

Convective and Radiative Losses from exterior

Energy added or removed from conditioned space to maintain temperature

Conduction and air flow through envelope

Home Conditioning Equipment

Heat transfer to and from slab/basement/ground

B) Energy flows to consider for analysis of change in home energy

Attic

Home
Indoor Temperature
Controled by Thermostat

Energy added or removed from conditioned space to maintain temperature

Air flow through envelope

Home Conditioning Equipment

Figure 1: (a) Energy transfer mechanisms that must be accounted for when calculating total home energy use annually, and (b) energy transfer mechanisms that are included in the IVE model when calculating the change in energy demand resulting from a change in airflow. Fan energy is not included in Figure 1. The IVE model does not include energy impacts from potential changes in airflow pathways in the home due to envelope tightening.

2.2   Description

Input parameters for the IVE model, and sources for those parameters are described in Table 1. The IVE model uses the change in hourly air exchange between two conditions for one home to calculate the overall change in HVAC energy use. The change in HVAC energy use, ΔE_{HVAC}, is calculated as the sum of four contributions: energy changes associated with heating (ΔE_{heat}) and cooling (ΔE_{cool}), changes to the

energy used by the air distribution fan/blower for a forced air system (ΔE_{blower}), and changes to energy use for ventilation fans (ΔE_{fans}), as shown in Equation 1.

$$\Delta E_{HVAC} = \Delta E_{Heat} + \Delta E_{cool} + \Delta E_{blower} + \Delta E_{fans} \tag{1}$$

The first three terms are all proportional to changes in air exchange rate that occur when each piece of equipment is in use. Blower and ventilation fan energy are tracked separately because they are calculated in fundamentally different ways and are part of two distinct and separate systems – the space conditioning system (ΔE_{blower}), and the ventilation system (ΔE_{fans}).

The incremental change in heating or cooling energy is calculated for discrete time intervals using the following equations:

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

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

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

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

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

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

Where:

- Δt time step (h)
- $\dot{m}_t$ mass flow of air through the home during the time step (kg s^{-1})
- C_p heat capacity of air (J kg^{-1} K^{-1})
- $T_{set,t}$ indoor temperature (thermostat setting) (K)
- $T_{out,t}$ outdoor temperature at time t (K)
- fan_{heat} heat added by the air distribution system fan and air supply fans (W)
- ε_{heat} and ε_{cool} heating and cooling total system efficiencies (-)
- ΔA_t change in the air exchange rate at time step t (h^{-1})
- V_{cond} conditioned volume of the house (m^3)
- ρ_{water} absolute humidity (the density of water vapour) in the air indoors and outdoors (kg m^{-3})
- ρ_{air} air density (kg m^{-3})
- L_v latent heat of water vaporization (J kg^{-1})
- $\varepsilon_{equipment}$ efficiency of the heating or cooling equipment (-)
- ε_{ducts} efficiency of the ducts (-)

The cooling load is the sum of the sensible ($\Delta E_{thermal}$) and latent (ΔE_{latent}) loads. An hourly time step allows tracking of weather variations throughout each day using TMY3

meteorological data. Changes to energy demand due to an increased or decreased air exchange rate are calculated every hour for a year, and then summed to calculate the total annual change in energy use for the home.

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 interest.
ΔA	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.
ε_{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.
ΔE_{fans}	Energy use of additional fans	Fan power specified based on flow rate using energy and airflow relationships from the Certified Home Ventilating Products Directory (HVI) handbook (HVI 2009).
ΔE_{blower}	Energy use of air distribution blower	Proportionality coefficients determine air handler energy change based on heating and cooling energy change and presence of ducts. The CEC's 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.

Heat generated by the forced air distribution blower is included in fan_heat, which is calculated as the energy consumption of the blower motor (ΔE_{blower}) multiplied by 1 minus the fan efficiency. The wasted power is added as heat directly to the distribution airstream (Walker & Lutz 2006; Walker 2008). Heat from the blower reduces the heating load in winter, but increases the cooling load in summer.

Blower energy changes associated with heating and cooling system operation time are calculated using proportionality coefficients (Equation 8):

$$\Delta E_{blower} = 0.023 * \Delta E_{Heat} + 0.058 * \Delta E_{cool} \tag{8}$$

Coefficients were calculated from system specifications included in the California Energy Commission's (CEC) Alternative Calculation Method (ACM) (CEC 2013a). The ACM is used for compliance testing with the California Building Energy Efficiency Standards. The coefficients reflect the sizing relationship between the recommended blower size and heating/cooling system sizes for new California homes, and are calculated using the ratio of the specified fan efficacy and the specified heat/cooling airflow. These coefficients are variables that can be changed when analysing housing stocks with varying characteristics.

The IVE model can be applied to homes that have 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 used even if one of the systems is a non-ducted system (such as a wall furnace or ductless mini-split system) simply by assigning zero duct losses and zero blower energy to the fraction of thermal conditioning that is associated with that system.

The heating and cooling system efficiencies, ε_{heat} and ε_{cool}, account for efficiencies of equipment (air conditioner or furnace, $\varepsilon_{equipment}$) and supply ducts (ε_{ducts}). The IVE model will accept system efficiencies that are constant throughout the year, or system efficiencies that vary as a function of outdoor air temperature and relative humidity. Duct efficiency, ε_{ducts}, is the fraction of distributed air that is not lost to the unconditioned space during distribution (1 minus the percentage of supply duct leakage). If either heating or cooling is supplied with a ductless system or the ducts are located within the conditioned space, this efficiency is 1. The IVE model can 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. The model does not account for conductive losses from the ducts, however these could be included as an additional efficiency term or as a reduction in the duct efficiency term.

The IVE model can be run for many homes, with individual house specifications based on documented characteristics (when available), or by using specifications based on established relationships to characteristics that are documented. Figure 2 describes how to use the IVE model to determine the population energy change due to ventilation changes in a cohort of homes. The variables that must be specified for Equations 1-9 and how to derive them for each home are summarized in Table 1. The IVE model can be applied for all types of ventilation scenarios where the time-varying change in residential air exchange rate can be determined. The algorithm developed by Walker and Wilson (1998) can be used to calculate infiltration as a function of data on outdoor weather, limited building characteristics, and building leakage. This method is recommended for calculating infiltration in Chapter 16 of the ASHRAE Handbook-

Fundamentals (ASHRAE 2013a). The ASHRAE Handbook also provides methods for combining mechanical and infiltration ventilation rates to determine total residential air exchange rates. Other inputs to the IVE model are based on the building characteristic data available in the Residential Appliance Saturation Survey (RASS) (Palmgren et al. 2010) and Residential Energy Consumption Survey (RECS) (US Energy Information Administration 2009) databases for tens of thousands of homes representing the California and US housing stocks respectively. Building leakage area is found using the algorithms developed by Chan et al. (2012) based on parameters available in these databases. TMY3 weather data (Wilcox & Marion 2008) is used based on reported home location.

Analysis of Cohort of Homes

Select Characteristics from existing data sources:
- RASS
- RECS
- American Housing Survey Data
- Other

Assign parameters not included in cohort data.
Includes:
- Normalized leakage
- Duct leakage
- System efficiencies
- Fan sizes and power
- Other

Decide on two ventilation scenarios to compare:
Options:
- Adding whole house fan
- Tightening building envelope
- Other scenarios
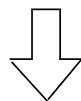
Analyze each home in cohort.
See description on right.

Aggregate results from each home to determine population statistics.

Analysis of Individual Home

Determine the change in air exchange rate (AER) for every hour of a given year for the home.
Steps:
- Calculate AER before ventilation change for a typical year (see appendix)
- Calculate AER after ventilation change for a typical year (see appendix)
- Determine the change in AER after intervention
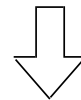
Run IVE model for home
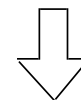
Output annual change in energy use by prefered metric
Options:
- kWh of electricity, BTUs of natural gas, etc.
- Energy dollars spent (multiply use by state prices)
- Carbon dioxide emissions

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

2.3   *Limitations*

A limitation of the IVE model is that it assumes that all additional ventilation and infiltration air is coming from outdoors and not just outside the conditioned space. In real homes, adding unbalanced fans or changing the building envelope may affect the relative pressures in the home and any attached unconditioned spaces (such as attics, crawl spaces and basements). The subsequent change in pressure fields may lead to additional air coming from spaces that are not at the same temperature as the outdoor air. This air may be preheated due to duct leakage in winter or solar gains in the summer. In these cases, the IVE model would overestimate the heating load in winter and underestimate the additional cooling load in summer.

An additional limitation is that the IVE model assumes that the heating and cooling equipment can meet the required loads of the home. If a building's HVAC system is undersized the IVE model will overestimate the energy impact of air tightening the building envelope. If the HVAC system becomes undersized because of increased air exchange rate of the home, then the IVE model will overestimate the energy impact of that additional air leakage.

3.   **The REGCAP Modelling Approach**

The REGCAP model, developed and validated at the University of Alberta (Walker 1993) and the Lawrence Berkeley National Laboratory (Walker & Sherman 2007), 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. REGCAP has been used in previous studies of residential ventilation and energy use, e.g. Turner et al. (2013). The IVE modelling results were compared to those from REGCAP because REGCAP is currently the best available model for residential HVAC operation that includes parameters of interest in this study. Commercially-available software such as EnergyGuage (Florida Solar Energy Center 2012), and programmes like HOT2000 (Halrecht et al. 1999) have been developed for use in home energy ratings methodologies (RESNET 2012). However, these software packages do not have very sophisticated ventilation models. EnergyPlus (Crawley et al. 2001), developed by the US Department of Energy (DOE) is used for both commercial and residential building energy simulations, but has been shown to have deficiencies in modelling infiltration impacts in residential modelling (Spencer 2010).

REGCAP performs a heat, mass and moisture balance on the modelled house and HVAC system with a time resolution of one minute. REGCAP includes all HVAC system-related airflows (including duct leakage and at registers), models of air conditioner performance that include the effects of coil airflows, indoor and outdoor air temperature, and humidity. REGCAP 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. The REGCAP model calculates the house conditions for each minute and operates the thermal conditioning equipment based on the calculated indoor temperature and set points. The conditioning equipment is modelled as adding/removing energy from the space at a specified rate. The air temperature and energy output of the conditioning equipment from the previous time step, combined with any building heat gains or losses, are used to compute the indoor

temperature for the next time step. At the end of the simulation the annual HVAC system energy use and building air exchange rate are calculated.

REGCAP has been extensively verified and been shown to predict HVAC equipment energy consumption within 4% of measured systems. Ventilation rates are predicted within approximately 5% over a wide range of house leakage distributions and weather conditions (Walker & Sherman 2007; Wilson & Walker 1992; Siegel 1999; Siegel et al. 2000; Walker et al. 1999; Walker et al. 2001; Walker et al. 2005).

4.   Simulations

To assess the performance of the IVE model, we compared its predictions to the energy changes estimated by the REGCAP model. REGCAP was first used to calculate the reference energy for three simulated homes in seven climate zones. The home specifications were then changed to represent four retrofit scenarios. REGCAP was used again to simulate the retrofitted homes. The IVE model was then run to calculate the impact of those same retrofits on each of the homes in all of the climate zone for comparison. Hourly ventilation airflow rate changes used as inputs for the IVE model were obtained by calculating the difference between the reference cases and the retrofit scenarios from the REGCAP runs.

4.1   Climates

Each home was modelled in the representative city of seven IECC climate zones (Briggs et al. 2003), covering the range of US weather (Table 2).

Table 2: Modeled IECC climate zones

Climate Zone	Climate	Representative City
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
7	Very cold	Duluth, Minnesota

4.2   Simulation Homes

Specifications were developed for three reference houses to represent archetypal new, average, and old US homes with variations in relevant characteristics (e.g. insulation levels and conditioning system sizes etc.). Details of home characteristics are included in the online supplement. According to the RECS (US Energy Information Administration 2009), as of 2009 the average US home was built in 1971, with 13% of homes built before 1940, 57% built before 1980, and 86% built before 2000. The new home was based on specifications in the CEC's ACM (2013b) for the 200 m^2 Prototype C home, which is broadly representative of new homes across the US. The specifications for the average and old home were based on RECS data for homes built in the 1980s and 1940s, respectively. The RECS database includes home size,

heating/cooling appliance type and age, and whether or not ducts were present; 71% of US homes have ducted heating systems and 76% have ducted cooling systems. All three modelled homes were therefore assumed to have ducted heating and cooling systems. The average size of US homes built between the 1940s and the 1980s did not vary significantly. However, for the older home a small 1940s home was modelled in order to increase the variability of the comparison houses.

4.3   *Envelope Leakage and Insulation Levels*

Envelope leakage levels were taken from the Lawrence Berkeley National Laboratory (LBNL) Residential Diagnostics Database (ResDB) (Chan et al. 2012). Insulation values for the new home were taken from the CEC's ACM (2013b). We assumed that the old home had minimal levels of insulation. The average home was assigned insulation R-values that are between those for the old and new homes. These values are intended to represent broadly the characteristics of non-retrofitted homes from each era. Building characteristics for each of the modelled homes is included in the online supplement.

4.4   *Heating and Cooling Equipment*

For each home type in each climate zone, the Wrightsoft Right-Suite software (Wrightsoft 2012) was used to calculate the heating and cooling loads as per ACCA Manual J (ACCA 2006). Conditioning system efficiencies were assigned as a function of system type and age (DOE 2010; Johnson et al. 1994; Lekov n.d.) based on the calculated load. Air conditioning systems were oversized by 15% and heating systems by 40% relative to Manual J calculations as prescribed by ACCA Manual S (ACCA 2009). A blower efficiency of 15% was used (based on Walker (2008)), i.e. only 15% of the electricity consumed by the blower is actually used for moving air, while the remaining 85% is wasted as heat added to the airstream.

Time-dependent thermostat set points are inputs for both the IVE and REGCAP models. For all comparisons, the same thermostat schedules are used for the compared IVE and REGCAP model runs. For all homes, cooling thermostats were set to 27°C from 9 a.m. to 5 p.m. and 25°C at all other times. For the average and new homes, heating thermostats set to 21°C from 9 a.m. to 12 a.m. and 20°C otherwise. Thermostat settings were based on the work by Lstiburek et al. (2007). 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. For old homes heating thermostats were set to 20°C from 7 a.m. to 8 a.m. and 9 p.m. to 12 a.m., and 18°C at all other times.

Supply and return duct leakage rates were assumed to be 3, 10, and 15% for new, average and old homes respectively (Kruse et al. 2004).

4.5   *Retrofit Scenarios*

The IVE and REGCAP models were applied to analyse four retrofit scenarios. The first two scenarios explore the impacts of air tightening buildings to different levels of envelope tightness. The second two scenarios are used to investigate the effects of installing mechanical ventilation systems

Scenario 1: Weatherization

In this scenario the old and average home envelopes were tightened by 25% and ducts were tightened by 43% - typical levels achieved by weatherization programmes (Offermann et al. 2011; Chan et al. 2012). The new homes were omitted because their envelopes were already at the required level of air leakage. For all homes, the air exchange rate is decreased.

In summary:
- Old and average homes
- Envelopes tightened by 25%
- Ducts tightened by 43%
- Tightened homes compared to untightened homes.

Scenario 2: ASHRAE 62.2

Building envelopes in Scenario 2 were tightened to the limit at which ASHRAE Standard 62.2 (2010)[2] requires mechanical ventilation.

This scenario is relevant to assessing whether the benefit of air tightening outweighs the costs of mechanical ventilation at the margin. To allow a home not to have mechanical ventilation, ASHRAE requires a sufficient envelope leakage area that provides twice the ASHRAE-required level of mechanical ventilation plus 10 Ls^{-1} per 100 m^2 of floor area of the home. The ASHRAE-required level of mechanical ventilation airflow rate, Q (Ls^{-1}), is defined as:

$$Q = 0.05 A_{floor} + 3.5(N + 1) \tag{11}$$

Where A_{floor} is the house floor area in m^2, and N is the number of bedrooms (ASHRAE 2010).

The necessary leakage area can be calculated using ASHRAE 136 (ASHRAE 2006), which estimates the annual air exchange rate as a function of normalised leakage and a weather factor. For all homes, the air exchange rate is decreased.

In summary:
- Old and average homes
- Envelopes tightened to the ASHRAE 62.2 mechanical ventilation limit
- Ducts tightened by 43%
- Tightened homes compared to untightened homes.

Scenario 3: Whole-House Exhaust

For this scenario, the envelopes of the old and average homes were tightened to the better of the levels achieved by Scenario 1 or Scenario 2 (the new home was already at this level of air tightness), and then a continuously-operating whole-house exhaust

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[2] ASHRAE Standard 62.2-2010 was in effect when this study was performed. Since then the 2013 version of Standard 62.2 (ASHRAE 2013b) has been published. This new version increases the required ventilation airflow rate (Q), but simplifies the relationship used to offset this requirement with natural infiltration. Although the newer standard will change the envelope leakage levels for Scenario 2, the changes are not expected to significantly change the evaluation of the IVE model

fan was added to each home. The airflow rate of the whole-house exhaust fan was determined using Equation 11.

Fan power consumption was calculated as a function of the required airflow based on specifications for the Broan QDE30BL exhaust fan (on average 0.7 WL^{-1}s^{-1}) (HVI 2009).

In summary:
- Old, average and new homes
- Envelopes tightened to the better level of Scenario 1 or Scenario 2 (old and average homes only)
- Ducts tightened by 43% (old and average homes only)
- Whole-house exhaust fan added
- Tightened homes *without* whole-house exhaust fan compared to tightened homes *with* whole-house exhaust fan. All homes had HVAC systems that were able to meet increased load demand.

Scenario 4: HRV

Scenario 4 is the same as Scenario 3 except a balanced, fully-ducted heat recovery ventilator (HRV) was added to the homes rather than a mechanical exhaust fan.

Because HRVs usually have airflow rates greater than the ASHRAE 62.2 minimum requirements, they can be operated on a timer for some fraction of each hour. For this scenario 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%. HRV power consumption was calculated as a function of the required airflow based on the average ratio of the reported airflow and energy use data for the Amana Brand HRV150 HRV (1.8 WL^{-1}s^{-1}) (HVI 2009). The change in air exchange rate with HRV operation was calculated as ΔA_t minus HRV recovery efficiency multiplied by the hourly airflow rate of the HRV.

In summary:
- Old, average and new homes
- Envelopes tightened to the better level of Scenario 1 or Scenario 2 (old and average homes only)
- Ducts tightened by 43% (old and average homes only)
- HRV system added
- Tightened homes *without* HRV compared to tightened homes *with* HRV. All homes had HVAC systems that were able to meet increased load demand.

5.   Results and Discussion

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 model components. IVE and REGCAP estimates of component energy change and total energy change were compared for each of the four retrofit scenarios.

5.1   Overview of REGCAP Model Results

For the three reference cases (the new, average and old homes without air tightening or mechanical ventilation), REGCAP-estimated total annual HVAC energy use ranged from 10.6 to 78.2 MWh across the seven climate zones. Climate had a larger impact on building HVAC energy than housing characteristics, with the old home using 16.8 to 78.2 MWh, the average home using 15.2 to 57.9 MWh, and the new home using 10.7 to 46.3 MWh depending on climate zone.

Air tightening the average and old homes decreased annual energy use between 0.1 and 7.8 MWh. The smallest change was seen when air tightening the average home to the ASHRAE 62.2 limit because the tightness of the homes was already close to that limit. Adding mechanical ventilation increased the annual energy demand by 0.4 MWh up to 4.4 MWh. In the more extreme climates, the largest contribution to the change in energy was the additional conditioning energy used to heat and cool the increased airflow. Increasing blower and exhaust fan loads were more significant in milder climates than colder climates.

5.2   Comparison of IVE and REGCAP Model Results

Figure 3**Figure 3** shows the annual pattern of total and incremental cooling and heating energy estimated by REGCAP for the average home in Houston and Chicago for the reference case and Scenario 1 (Weatherization). Results are presented with fortnightly resolution. Each column shows the estimated reference energy, and the solid part represents the energy savings from improving air tightness by the average improvement achieved in the weatherization programme. 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 efficiencies of cooling equipment (that transfer heat) compared to heating equipment (that generate heat via combustion). For the two conditions presented in Figure 3, IVE model calculations were compared to the solid bars representing the change in energy demand.
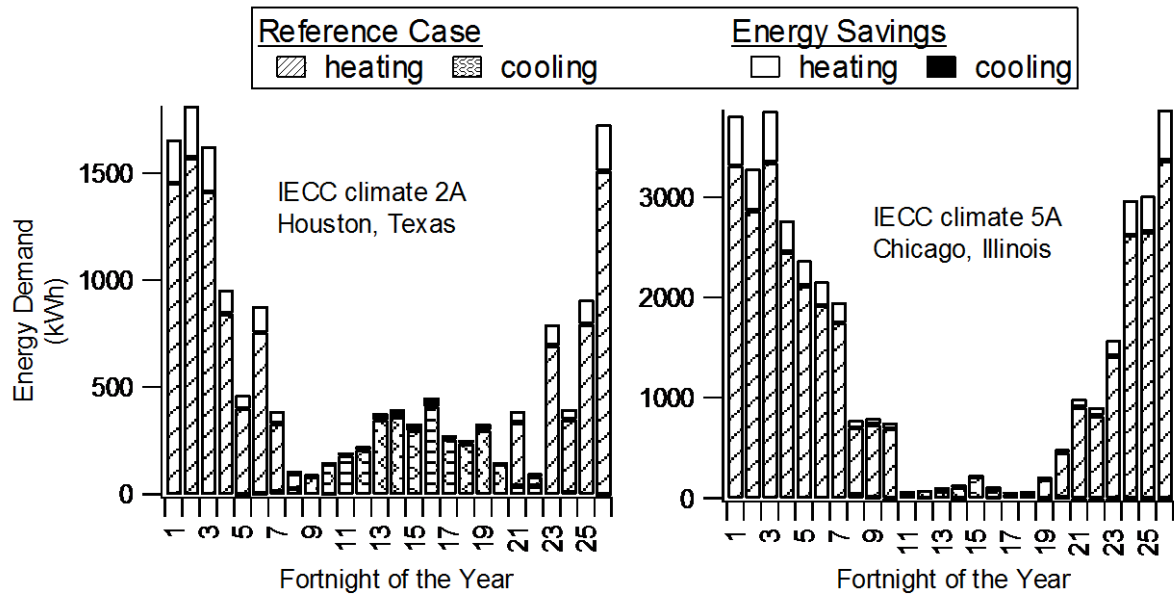
Figure 3: Annual cooling and heating energy consumption for average homes for the reference cases in two climate zones, and the change in energy consumption due to envelope air sealing, as estimated by REGCAP. The solid black and white bars show the difference between the reference cases and Scenario 1 (Weatherization). Note the different y-axis scales for the two climate zones.

Figure 4 compares the IVE and REGCAP estimates of energy change per unit air entering the conditioned space for the homes in Figure 3 for Scenario 1 as a function of indoor-outdoor temperature difference. 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.
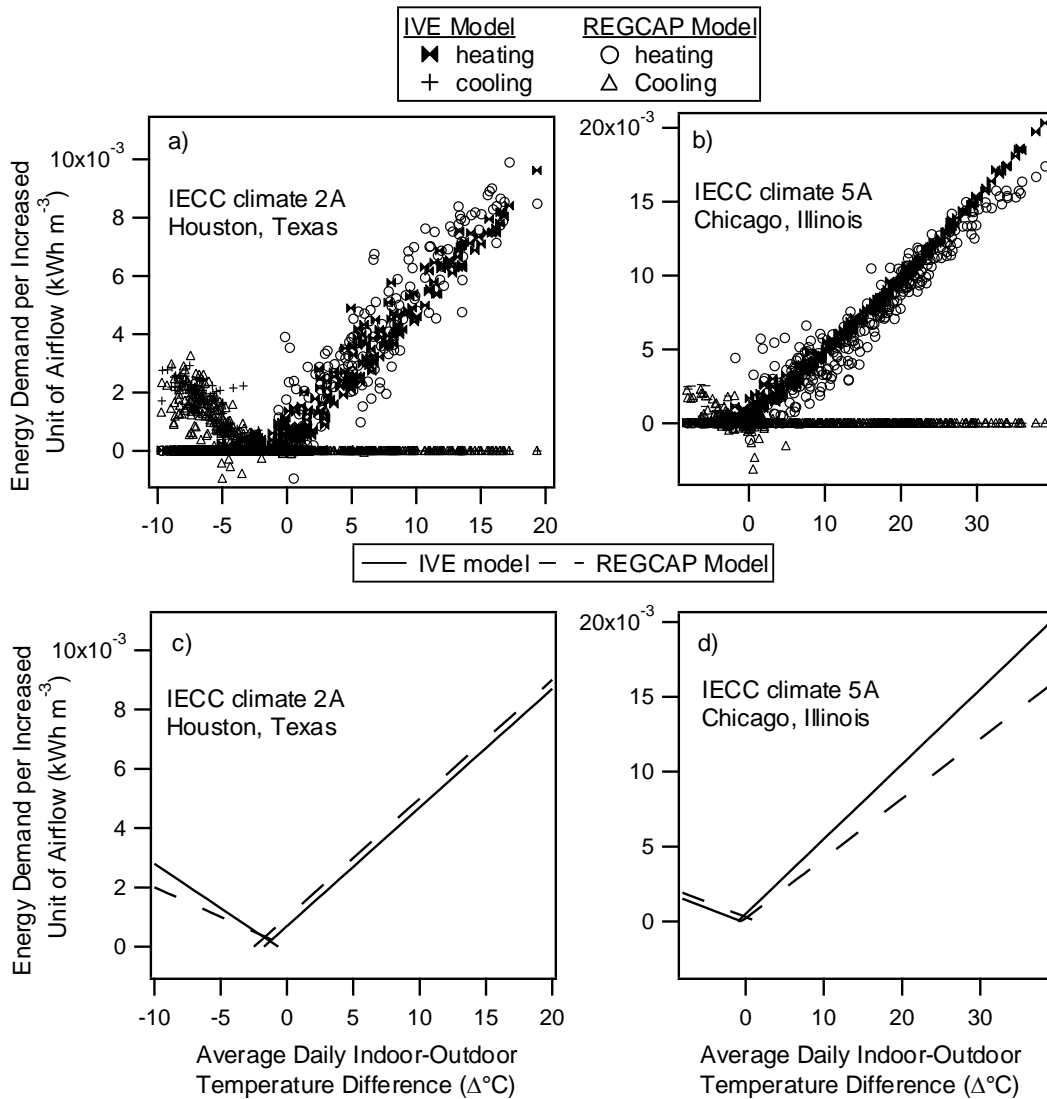
Figure 4: Increase in energy demand per unit of air entering the conditioned space as a function of daily average indoor-outdoor temperature difference are shown in figures 4a and 4b. Figures 4c and 4d show the best-fit linear regression for IVE and REGCAP heating and cooling energy demand per unit airflow. 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 climate zones. Cooling contributions are zero when outdoor temperatures are lower than indoor set points, and heating contributions are zero when outdoor temperatures are higher than indoor set points.

Figure 5 shows IVE and REGCAP predictions for HVAC energy savings resulting from air tightening old and average homes in each of the seven climate zones for Scenarios 1 (Weatherization) and Scenario 2 (ASHRAE 62.2). Results are presented separately for heating, cooling, and forced air system 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. Figure 5 indicates that reduced heating loads account for the vast majority of total HVAC energy savings of air tightening 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.
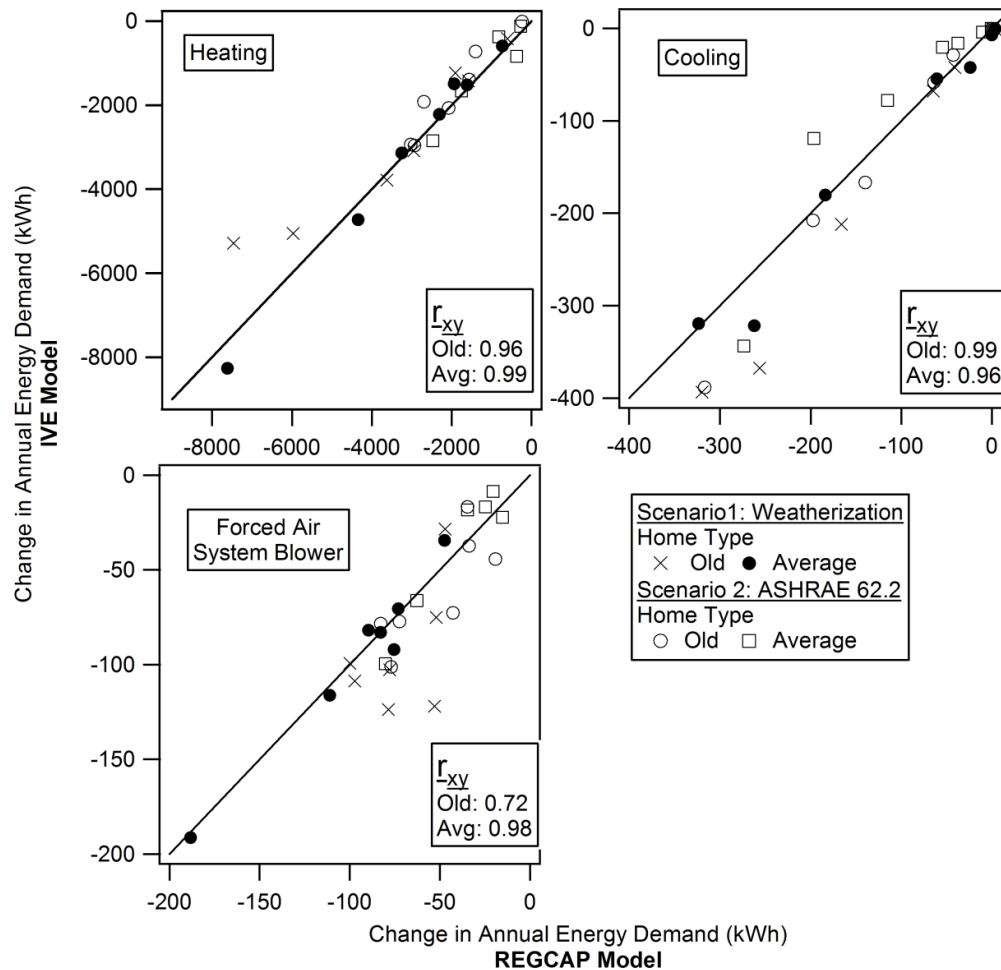
Figure 5: Changes in annual energy demand associated with air sealing the building envelope and HVAC ducts, as estimated by IVE and REGCAP models for Scenario 1 (Weatherization) and Scenario 2 (ASHRAE 62.2). Each data point represents one house (old or average) in one climate zone. New homes are not included in this analysis because they do not need to be retrofitted; they are already airtight. The 1:1 line is shown for reference. Note the different scales for the change in energy demand.

Figure 6 compares the annual total HVAC energy change estimated by the IVE and REGCAP models for each home in each of the four retrofit scenarios. Across climate zones, the REGCAP and IVE models correlate very strongly for each home archetype for all of the scenarios ($r_{xy} \geq 0.95$). The IVE model predicts smaller HVAC energy impacts for the exhaust fan and larger impacts for the balanced HRV as compared to the REGCAP model results. For both Scenario 3 (Whole-House Exhaust) and Scenario 4 (HRV), heating is the largest contributor to the energy cost with cooling and fan energy each requiring an order of magnitude less energy for Scenario 3 and two-thirds less energy for Scenario 4. Differences in IVE and REGCAP results are due to differences in how the two models account for where infiltration air enters the home. The IVE model assumes that all infiltration air enters the home from outside and at outdoor air temperature. REGCAP tracks airflow pathways based on pressure differences between the home, attic and outside so infiltration air can be at different temperatures depending on where the air originated before entering the conditioned space. Changes in airflow pathways would impact energy demand of heating and cooling.
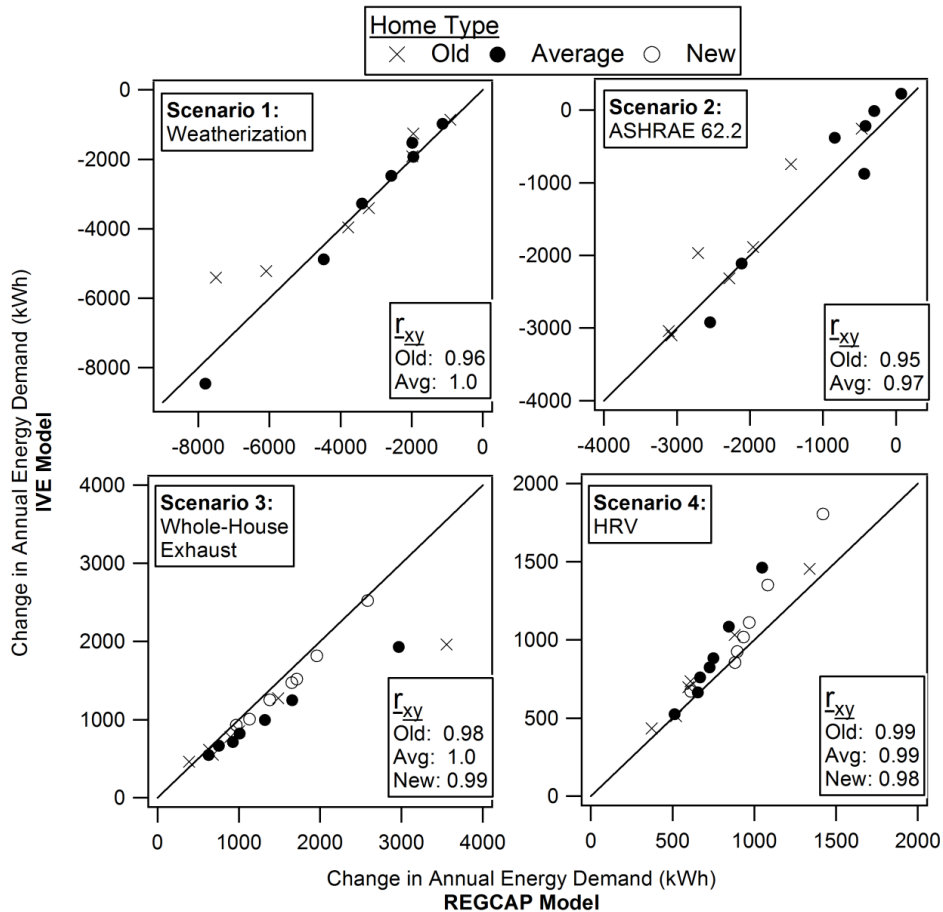
Figure 6: Changes in annual energy demand associated with air tightening and the addition of mechanical ventilation as estimated by the IVE and REGCAP models. Each data point represents one house (old, average, new) in one climate zone. The 1:1 line is shown for reference. Note the different scales for the change in energy demand.

Table 3 presents summary statistics comparing IVE model results to REGCAP model results. Table 3 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 3 are simple averages of all the homes in each category. 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. 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 3, RMSE and bias values also are normalised, CV(RMSE) and CV(bias), by the mean value of the incremental energy change estimated by REGCAP, mean(R).

Table 3: 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 normalised 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
Scenario 1:	RSME (kWh)	721	43	28	NA	697
Weatherization	BIAS (kWh)	-407	24	16	NA	-367
	r_{xy}	0.96	0.99	0.72	NA	0.95
	mean(R)	-2716	-114	-62	NA	-2892
	CV(bias)	27%	38%	45%	NA	24%
	CV(RSME)	15%	-21%	-25%	NA	13%
Scenario 2:	RSME (kWh)	322	36	10	NA	332
ASHRAE 62.2	BIAS (kWh)	-1	-2	-1	NA	-4
	r_{xy}	0.99	0.96	0.98	NA	0.99
	mean(R)	-1960	-110	-65	NA	-2135
	CV(bias)	16%	33%	16%	NA	16%
	CV(RSME)	0.0%	2.0%	1.0%	NA	0.0%
Scenario 3:	RSME (kWh)	451	32	14	0	447
Whole-House	BIAS (kWh)	266	-10	-1	0	255
Exhaust	r_{xy}	0.93	0.95	0.48	1.00	0.92
	mean(R)	1159	78	35	123	1395
	CV(bias)	39%	41%	39%	0%	32%
	CV(RSME)	23%	-12%	-3%	0%	18%
Scenario 4:	RSME (kWh)	139	32	14	0	168
HRV	BIAS (kWh)	-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(bias)	33%	58%	100%	0%	21%
	CV(RSME)	-21%	-42%	-78%	0%	-15%

Table 3 shows that IVE predictions for heating, cooling, and overall HVAC energy reductions by air tightening were highly correlated ($r_{xy} \geq 0.90$) with REGCAP predictions. On average, IVE estimated the total annual energy change within 9% of the REGCAP estimates. The greatest bias and RMSE values were seen for heating, but the largest normalised error, CV(RMSE), was seen for cooling, potentially due to not including internal gains in the IVE model. Internal gains impact heating and cooling loads when temperatures are near the thermostat set point. When outdoor temperatures are only slightly lower than thermostat set points, additional cooling may be needed to remove energy from internal gains when the building air exchange rate is reduced (for which the IVE model does not account). The greatest fractional difference between the REGCAP and IVE model predictions of air tightening impacts was seen for old homes in cold climates. As above, REGCAP is capable of determining changes in airflow pathways which may impact where air enters the home (i.e. potentially from the attic which is preheated due to duct leaks instead of through walls) whereas the IVE model assumes all air is coming from outside. Changes in airflow pathways can affect energy demands associated with airflow changes.

For Scenario 3 (Whole-House Exhaust) the IVE and REGCAP predictions 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 all home-climate combinations is 18% lower for IVE relative to REGCAP (CV(bias) = 18%). Since the models estimate energy in very different ways, it is not clear what is causing the 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 scenario case. The IVE model does not account for varying indoor air and duct temperatures as the heating and cooling systems turn on and off, and changing airflow pathways due to air tightening.

For Scenario 4 (HRV), the IVE predictions of total HVAC energy use are 15% higher than the REGCAP predictions averaged across all home-climate combinations. The normalised RMSE is only 21%, indicating good agreement across simulated homes. The IVE model consistently predicted higher incremental conditioning energy use compared to REGCAP for the HRV.

5.3   *Estimating IVE/REGCAP differences on a Population-Scale*

We have characterized the IVE/REGCAP differences in energy estimates for four retrofit scenarios in three home types, and in seven home locations. The IVE model was developed to estimate energy impacts of changes to large numbers of homes where applying a more complex energy model would be prohibitive. To obtain an estimate of the magnitude of the difference between the two model results when extrapolated to the US housing stock scale, IVE and REGCAP estimates of total energy change for each of the three simulated homes were weighted by an estimate of the prevalence of these types of homes and their locations. The estimates were based on statistics in the 2005 RECS. The estimates are not intended as robust predictions of the energy impacts of instituting the modelled retrofit scenarios across the US housing stock (for that, see Logue et al. (2013)). Rather, the results are intended to explore how differences between IVE and REGCAP results for individual homes will impact results when extrapolated to the population scale.

The home count for each climate zone/home type combination was multiplied by the estimated energy change determined by REGCAP and IVE models for each retrofit scenario. The results are presented in Table 4, which shows that the IVE model produces similar energy impact estimates to those obtained using the more detailed and complex REGCAP model.

Table 4: Population-scale extrapolation of IVE- and REGCAP-predicted energy impacts (in gigawatt-hours, GWh) of the four retrofit scenarios. The values shown are not robust estimates of population-scale impacts of air sealing or ventilation. Rather, the results are intended to demonstrate the agreement between IVE and REGCAP model estimates when extrapolated to the population scale.

IECC Climate Zone	Millions of homes			Scenario 1: Weatherization			Scenario 2: ASHRAE 62.2		
	Old	Average	New	REGCAP	IVE	Ratio	REGCAP	IVE	Ratio
2A	1.8	4.84	0.92	-13,018	-12,782	0.98	-13,742	-13,599	0.99
2B	0.29	0.95	0.19	-1,338	-1,184	0.88	-420	-87	0.21
3A	2.51	6.43	1.28	-24,596	-24,478	1	-8,393	-7,218	0.86
3C	0.6	0.88	0.07	-2,926	-2,106	0.72	-1,602	-782	0.49
4A	5.38	8.61	1.49	-49,665	-49,505	0.95	-15,928	-14,765	0.93
5A	8.14	7.91	1.06	-84,979	-81,075	0.95	-28,742	-31,670	1.1
7	0.23	0.32	0.05	-4,164	-3,897	0.94	-1,417	-1,367	0.96
Weighted average IVE/REGCAP Ratio						0.97			0.99

IECC Climate Zone	Scenario 3: Whole-House Exhaust			Scenario 4: HRV		
	REGCAP	IVE	Ratio	REGCAP	IVE	Ratio
2A	5,830	5,246	0.9	5,127	5,778	1.13
2B	889	827	0.93	709	750	1.06
3A	10,516	8,850	0.84	7,401	8,443	1.14
3C	1,341	1,065	0.78	953	954	1
4A	19,324	15,430	0.8	11,264	13,127	1.17
5A	27,245	22,168	0.81	14,968	18,398	1.23
7	1,876	1,185	0.63	708	885	1.25
Weighted average IVE/REGCAP Ratio		0.82				1.2

6.   Conclusions

A simplified physics-based Incremental Ventilation Energy (IVE) model was developed. The model uses a limited number of inputs to predict the energy impacts of building envelope air tightening and mechanical ventilation retrofits for large-scale populations of homes. Results from the IVE model were compared to results from REGCAP (a well-validated, physics-based, residential building simulation tool) to evaluate the potential for the IVE model to predict 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 US nation-wide energy impacts were within 18% of the REGCAP predictions for all mechanical ventilation cases, and within 3% for the envelope air tightening cases.

The IVE model is a useful tool for estimating population-scale changes in energy demand where limited data on homes are available. The IVE model can be applied using existing databases of home characteristics and existing computationally-inexpensive airflow models. The model can be used to estimate the impact of policy directed toward changing home ventilation including weatherization programmes and ventilation standards. The IVE model can also be used as an initial screening tool to identify homes for further analysis using a more advanced energy model such as REGCAP.

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Supplemental Material: A simplified model for estimating population-scale energy impacts of building envelope air-tightening and mechanical ventilation retrofits

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 impacted 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 range 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 SM-1 to SM-3. REGCAP requires input parameters that were determined for these characteristics. If a parameter was not available, its relationship to the available parameter was assumed to be the same as for the highly-specified Prototype D house in the California Energy Commission's Alternative Compliance Method.

Table SM-1. Abbreviated inputs for REGCAP and IVE model inputs for new, tight homes

New Home								
IECC Climate Zone	2A	2B	3A	3C	4A	5A	7	**Data source**
Representative City	Houston	Phoenix	Atlanta	San Francisco	Baltimore	Chicago	Duluth	
Home Characteristics								
Floor area (m^2)	195	195	195	195	195	195	195	T24-Prototype C (CEC 2009)
NL	0.14	0.14	0.14	0.14	0.14	0.14	0.14	T24-Prototype C (CEC 2009)
Floors	1	1	1	1	1	1	1	T24-Prototype C (CEC 2009)
Insulation U-Values								
Walls (Wm^{-2}K^{-1})	0.014	0.014	0.014	0.014	0.014	0.008	0.008	High insulation
Floor (Wm^{-2}K^{-1})	0.009	0.009	0.009	0.009	0.009	0.009	0.006	High insulation
Ceiling (Wm^{-2}K^{-1})	0.006	0.006	0.006	0.006	0.006	0.005	0.004	High insulation
Windows (Wm^{-2}K^{-1})	0.070	0.070	0.070	0.068	0.070	0.070	0.070	High insulation
Heating								
AFUE	0.80	0.80	0.80	0.80	0.80	0.80	0.80	Highest market efficiency
Total Heating Efficiency	0.78	0.78	0.78	0.78	0.78	0.78	0.78	Total system efficiency (system + ducts)
Airflow Rate (Ls^{-1})	345	357	520	240	345	527	723	Manual J&S-Wrightsoft (ACCA2006)
Heating System (kW)	14.7	14.7	22.0	8.2	14.7	22.0	29.3	Manual J&S-Wrightsoft (ACCA2006)
Fan power (W)	365	379	551	255	365	558	766	Walker (2008)
Cooling								
COP	3.4	3.4	3.4	3.4	3.4	3.4	3.4	T24-Prototype C (CEC 2009)
EER	11.0	11.0	11.0	11.0	11.0	11.0	11.0	T24-Prototype C (CEC 2009)
Total Cooling Efficiency	3.33	3.33	3.33	3.33	3.33	3.33	3.33	Total system efficiency (system + ducts)
Airflow Rate (Ls^{-1})	637	1015	614	256	510	415	318	Manual J&S-Wrightsoft (ACCA2006)
Cooling System (kW)	11.9	18.9	11.4	4.8	10.0	7.7	5.9	Manual J&S-Wrightsoft (ACCA2006)
Fan power (W)	675	1075	650	272	540	440	337	Walker (2008)
Ducts								
Return Leakage	3%	3%	3%	3%	3%	3%	3%	T24-Prototype C (CEC 2009)
Supply Leakage	3%	3%	3%	3%	3%	3%	3%	T24-Prototype C (CEC 2009)
Insulation (Wm^{-2}K^{-1})	0.029	0.029	0.029	0.029	0.029	0.022	0.022	High insulation
Mechanical Ventilation								
MV 62.2 (Ls^{-1})	24	24	24	24	24	24	24	Constant Exhaust Fan Broan QDE30BL fan (HVI 2009)
Exhaust fan (W)	18	18	18	18	18	18	18	
MV 62.2 (Ls^{-1})	48	48	48	48	48	48	48	HRV 30 minutes every hour
HRV (W)	92	92	92	92	92	92	92	HVI (HVI 2009)

Table SM-2. Abbreviated inputs for REGCAP and IVE model inputs for old, small homes

Old Home, Low Insulation								
IECC Climate Zone	2A	2B	3A	3C	4A	5A	7	**Data source**
Representative City	Houston	Phoenix	Atlanta	San Francisco	Baltimore	Chicago	Duluth	
Home Characteristics								
Floor area (m^2)	84	84	84	84	84	84	84	(RECS 2009)
NL	1.20	0.75	1.00	0.80	1.00	0.80	0.75	(RECS 2009)/(Chan 2012)
Floors	1	1	1	1	1	1	1	(RECS 2009)
Insulation U-Values								
Walls (Wm^{-2}K^{-1})	0.044	0.044	0.044	0.044	0.044	0.025	0.018	Low insulation
Floor (Wm^{-2}K^{-1})	0.035	0.035	0.035	0.035	0.035	0.018	0.015	Low insulation
Ceiling (Wm^{-2}K^{-1})	0.016	0.016	0.016	0.016	0.016	0.012	0.009	Low insulation
Windows (Wm^{-2}K^{-1})	0.176	0.176	0.176	0.176	0.176	0.176	0.176	Low insulation
Heating								
AFUE	0.58	0.70	0.57	0.67	0.70	0.57	0.57	(RECS 2009)/Efficiency References
Total Heating Efficiency	0.49	0.60	0.48	0.57	0.60	0.48	0.48	Total system efficiency (system + ducts)
Airflow Rate (Ls^{-1})	396	258	486	259	452	705	864	Supplies 140% of Manual J Calcs (ACCA 2006)
Heating System (kW)	17.0	11.1	20.9	11.1	19.4	30.3	37.1	Supplies 140% of Manual J Calcs (ACCA 2006)
Fan power (W)	419	274	515	275	479	747	915	Walker (2008)
Cooling								
COP	2.4	2.4	2.8	2.8	2.8	2.8	2.8	Calculated from EER
EER	7.7	7.7	9.1	9.1	9.1	9.1	9.1	RECS/Efficiency References
Total Cooling Efficiency	2.41	2.41	2.85	2.85	2.85	2.85	2.85	Total system efficiency (system + ducts)
Airflow Rate (Ls^{-1})	416	417	359	200	366	349	251	Supplies 140% of Manual J Calcs (ACCA 2006)
Cooling System (kW)	6.7	6.7	5.6	2.4	5.7	5.4	3.4	Supplies 140% of Manual J Calcs (ACCA 2006)
Fan power (W)	441	442	380	212	388	370	266	Walker (2008)
Ducts								
Return Leakage	15%	15%	15%	15%	15%	15%	15%	High leakage
Supply Leakage	15%	15%	15%	15%	15%	15%	15%	High leakage
Insulation (Wm^{-2}K^{-1})	0.176	0.176	0.176	0.176	0.176	0.088	0.088	Low insulation
Envelope Air Tightening								
NL (33% tighter)	0.80	0.50	0.67	0.53	0.67	0.53	0.50	Tightening (Weatherization)
Ducts (43% tighter)	9%	9%	9%	9%	9%	9%	9%	Leakage database
W ASHRAE 136	0.81	0.68	0.75	0.92	0.82	0.93	1.00	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 (Ls^{-1})	15	15	15	15	15	15	15	Constant Exhaust Fan
Exhaust fan (W)	11	11	11	11	11	11	11	Broan QDE30BL fan (HVI 2009)
MV 62.2 (Ls^{-1})	30	30	30	30	30	30	30	HRV 30 minutes every hour
HRV (W)	57	57	57	57	57	57	57	HVI (HVI 2009)

Efficiency Reference: Efficiencies were calculated as a function of system age and type for the average 1940s home reported in the RECs based on Mills (2005).

Table SM-3. Abbreviated inputs for REGCAP and IVE model inputs for average homes

Average Home								Data source
IECC Climate Zone	2A	2B	3A	3C	4A	5A	7	Data source
Representative City	Houston	Phoenix	Atlanta	San Francisco	Baltimore	Chicago	Duluth	
Home Characteristics								
Floor area (m^2)	144	144	144	144	144	144	144	(RECS 2009)
NL	1.00	0.60	0.60	0.55	0.50	0.50	0.50	(RECS 2009)/(Chan 2012)
Floors	2	2	2	2	2	2	2	(RECS 2009)
Insulation U-Values								
Walls (Wm^{-2}K^{-1})	0.022	0.022	0.022	0.022	0.022	0.013	0.013	Moderate insulation
Floor (Wm^{-2}K^{-1})	0.018	0.018	0.018	0.018	0.018	0.018	0.012	Moderate insulation
Ceiling (Wm^{-2}K^{-1})	0.012	0.012	0.012	0.012	0.012	0.009	0.008	Moderate insulation
Windows (Wm^{-2}K^{-1})	0.088	0.088	0.088	0.088	0.088	0.088	0.088	Moderate insulation
Heating								
AFUE	0.76	0.76	0.76	0.76	0.76	0.76	0.76	(RECS 2009)/Efficiency References
Total Heating Efficiency	0.68	0.68	0.68	0.68	0.68	0.68	0.68	Total system efficiency (system + ducts)
Air flow (L/s)	327	259	385	266	454	557	709	Supplies 115% of Manual J Calcs (ACCA 2006)
Heating System (kW)	14.0	11.1	16.5	11.4	19.5	23.9	30.4	Supplies 115% of Manual J Calcs (ACCA 2006)
Fan power (W)	347	274	408	282	481	590	751	Walker (2008)
Cooling								
COP	2.8	2.8	2.8	2.8	2.8	2.8	2.8	Calculated from EER
EER	9.1	9.1	9.1	9.1	9.1	9.1	9.1	RECS/Efficiency References
Total Cooling Efficiency	2.56	2.56	2.56	2.56	2.56	2.56	2.56	Total system efficiency (system + ducts)
Airflow Rate (Ls^{-1})	634	663	578	349	574	556	410	Supplies 115% of Manual J Calcs (ACCA 2006)
Cooling System (kW)	11.1	11.6	10.0	5.4	9.9	9.5	6.6	Supplies 115% of Manual J Calcs (ACCA 2006)
Fan power (W)	671	703	613	369	608	589	435	Walker (2008)
Ducts								
Return Leakage	10%	10%	10%	10%	10%	10%	10%	Medium Leakage
Supply Leakage	10%	10%	10%	10%	10%	10%	10%	Medium Leakage
Insulation (Wm^{-2}K^{-1})	0.059	0.059	0.059	0.059	0.059	0.044	0.044	Moderate insulation
Envelope Air Tightening								
NL (33% tighter)	0.67	0.40	0.40	0.37	0.33	0.33	0.33	Tightening (Weatherization)
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	1.00	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 (Ls^{-1})	18	18	18	18	18	18	18	Constant Exhaust Fan
Exhaust fan (W)	13	13	13	13	13	13	13	Broan QDE30BL fan (HVI 2009)
MV 62.2 (Ls^{-1})	36	36	36	36	36	36	36	HRV 30 minutes every hour
HRV (W)	68	68	68	68	68	68	68	HVI (HVI 2009)

Efficiency Reference: Efficiencies were calculated as a function of system age and type for the average 1980s home reported in the RECs based on Mills (2005).

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