RESIDENTIAL VENTILATION AND ENERGY CHARACTERISTICS*

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The role of ventilation in the housing stock is to provide fresh air and to dilute internally-generated pollutants in order to assure adequate indoor air quality. Energy is required to provide this ventilation service, either directly for moving the air or indirectly for conditioning the outdoor air for thermal comfort. Different kinds of ventilation systems have different energy requirements. Existing dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by mechanical ventilation systems. The purpose of this report is to ascertain, from best available data, the energy liability associated with providing the current levels of ventilation and to estimate the energy savings or penalties associated with tightening or loosening the building envelope while still providing ventilation for adequate indoor air quality. Various ASHRAE Standards (e.g., 62, 119, and 136) are used to determine acceptable ventilation levels and energy requirements. Building characteristics, energy use, and building tightness data are combined to estimate both the energy liabilities of ventilation and its dependence on building stock characteristics. The average annual ventilation energy use for a typical dwelling is about 61 GJ (roughly 50% of total space conditioning energy usage); the cost-effective savings potential is about 38 GJ. The national cost savings potential, by tightening the houses to the ASHRAE Standard 119 levels while still providing adequate ventilation through infiltration or mechanical ventilation, is $2.4 Billion. The associated total annual ventilation energy use for the residential stock is about 4.5 EJ (ExaJoules).

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INTRODUCTION

Infiltration and ventilation in dwellings is conventionally believed to account for 1/3 to 1/2 of the space conditioning energy. There is not a great deal of measurement data or analysis to substantiate this assumption. As energy conservation improvements to the thermal envelope continue, the fraction of energy consumed by the conditioning of air may increase. Air-tightening programs, while decreasing energy requirements, have the tendency to decrease ventilation and its associated energy penalty at the possible expense of adequate indoor air quality.

In evaluating energy efficiency opportunities, the United States Department of Energy and others need to put into perspective the energy and indoor air quality liabilities associated with residential ventilation. The purpose of this report is to use existing data to estimate these liabilities in the current U.S. housing stock as well as scenarios based on energy conservation and ventilation strategies.

Because of the lack of direct measurements, we cannot approach this as a direct data analysis task. Rather, we approach this objective as a simplified modeling task using the existing sources of data as inputs to the model. The LBL infiltration model[15] and its derivatives will be used as the basis for the calculation.

EVALUATION CRITERIA

In this report we estimate ventilation rates, envelope tightness, and energy consumption of the stock and some potential alternatives. Various ASHRAE Standards are used to assist us. ASHRAE Standard 119-1988[5] classifies the envelope tightness of buildings and sets maximum leakage levels based on energy considerations and we use this standard to evaluate the tightness of the housing stock.

ASHRAE Standard 62-1989[4] sets minimum ventilation rates for providing acceptable air quality in all kinds of buildings. For residential buildings the standard specifies 0.35 Air Changes per Hour.[*] Unfortunately, while the values for residential ventilation are explicit in Standard 62, the interpretation of these values was left vague.

There is a spectrum of possible interpretations for Standard 62. The most severe interpretation might be to assume that each room had a minimum of 0.35 air changes at all times; this interpretation would mandate a continuously operating balanced mechanical ventilation system. The most liberal interpretation would only require that the building have the capacity for providing an average of 0.35 ACH; virtually all residential buildings would meet this criterion by having openable windows. The former solution gives no credit to infiltration or natural ventilation, while the latter assumes that occupants are good determinants of indoor air quality and that windows can be opened at any time or weather and in any amount.

[*] But not less than 7.5 l/s per person

Our approach is more moderate: to assume that infiltration contributions can be used to provide ventilation, but that the contribution of natural ventilation will be limited to milder weather conditions and that any whole-house mechanical ventilation system will be sized to meet the 0.35 air change criteria and is run continuously. Using an approach similar to ASHRAE Standard 136-1993[6] we can estimate the combined contributions of envelope leakage and other ventilation systems towards meeting standard 62.

For there to be any ventilation there must be air entering and leaving the space of interest. To accomplish this there must be both an air flow path and a driving force for each air flow direction. The air flow paths are either building leakage sites or designed ducts or vents and the air flow drivers can be either mechanical or natural. Under this definition, infiltration is the simplest ventilation system using the adventitious leakage and the natural driving forces of the weather.

MODELING METHODS AND DATA SOURCES

The modeling methods used in this report have been reported earlier in a preliminary version of this analysis[17] and are similar to ones used in the general analysis of "Blower Door" data[14]. For convenience these equations are included in the "APPENDIX: MODELING TOOLS" on page 21.

For any one house, a straightforward modeling approach can be used to determine the heating and cooling demand as well as the effective air change rate. Applying this to each of the almost 75 million single-family households in the U.S. would require more data and manpower resources than currently exist. The approach we use instead is to take the sources of data available and combine them at an appropriate level of detail using database management tools.

Putting all of the data sources together we can determine for each county the number of houses (from the U.S. Census[7]), the type and sizes of houses (from the Residential Energy Consumption Survey, RECS[19]), the leakage properties (from the LBL Leakage Database[10]) and the representative weather conditions.[2,8] From the analysis of this data, data average and aggregate quantities are developed for the nation as a whole. Following are descriptions of each of the data sources.

CENSUS DATA

The Constitution of the United States[20] requires that a complete population census be completed every decade. The results of the 1990 Census[7] are used to extract information on the number, type (single-family detached, single-family attached, etc.) and location of each building. The data is broken down into nine census divisions as well as down to the state, county and, eventually, the block level. We can use this data to determine the number of each type of buildings on any geographic scale we desire; however, the data does not contain information about specific building characteristics.

As the census dataset contains more geographic detail than could profitably be used in this project, we decided to use the county-level of detail as our finest detail. There are 3,413 counties which span the U.S., typically having an average of 33,000 residential buildings (23,000 single family buildings). For each county we use the census data to determine the building stock and the number of buildings broken down by the number of units in each building. We will only be using single-family buildings (single family detached, single family attached and mobile homes) for this study, which make up 86% of the total U.S. residential building floor area.

WEATHER DATA

Representative weather data is necessary to run any infiltration model. LBL has a library of approximately 240 representative weather sites (or locations) across the country. These weather files have been selected to be representative of typical years for each location and are derived from the WYEC (Weather Year for Energy Calculations), TMY (Typical Meteorological Year), TRY (Typical Reference Year)[2] and CTZ (California Climate Zones)[8] weather tapes. For each county, the most representative weather location was chosen, based primarily on geography. Each weather file contain outside temperature and humidity, wind speed and direction and barometric pressure.

RECS DATA

The Residential Energy Consumption Survey[19] was conducted by the Energy Information Administration for the U.S. Department of Energy and is a statistically significant representation of the U.S. housing stock as it pertains to energy. The RECS data consists of approximately 4,800 single-family dwelling observations, each of which has approximately 900 reported survey values regarding energy conservation and building characteristics. The survey contains information on building size and shape, the type, details, and use of heating and cooling systems, indications of the level of air tightness and age and geographic location of each representative building.

CONFIGURATIONS

Based on the RECS data, we have defined 32 different types (or configurations) of houses: old vs. new (using 1980 as a dividing point); single-story vs. multistory; poor condition vs. good condition; duct systems vs. none; and floor leakage vs. no floor leakage. The RECS data is used to determine, for each census division, the floor area and percentage of air conditioning use for each of the 32 house types. The smallest, statistically significant geographical breakdown in the RECS data is the census division. Therefore the properties of the housing stock are separately determined for each of the nine census divisions. Every county within a given division is assumed to have the same relative distribution of house configurations, where the number of houses in each county is determined from the Census data.

LEAKAGE DATA

While the RECS data contains some indications of air tightness, it does not contain quantitative values which could be used as part of this modeling effort. Over the last several years LBL has compiled a database on measured air tightness for the U.S.[10] The dataset contains the measured air tightness (NL), as well as a general description of the building which allows estimates of leakage distribution (R & X) and envelope conditions. Modeling techniques described in the appendix are used to find representative leakage values for the locations and configurations desired. As described in the appendix, NL is the effective leakage area of the envelope normalized by the size of the house.

Our analysis calculates both heating and cooling loads separately. For heating we use a regional estimation of percent of free heating energy, due to solar and internal gains,[21] to reduce the heating energy impact. On the cooling side, we only account for cooling load for those fraction of houses having central air conditioning and only when the outdoor temperature and humidity are outside the comfort zone, presuming that ventilative cooling (i.e natural ventilation) will be used to provide comfort otherwise.

COST DATA

In order to perform economic analyses, it is necessary to obtain ventilation equipment costs and efficiencies as well as fuel price information. The (mechanical) ventilation strategies modeled in this project are exhaust-only and heat recovery. The annualized equipment costs were determined based on equipment and installation first costs, obtained from a 1995 survey of California and New York ventilation equipment distributors[22], and are summarized in Table 1. Residential electricity and natural gas price information for the 1993 calendar year was obtained from the Energy Information Agency.[23] [23] Annual average fuel costs (electricity and natural gas) were determined for each state, weighted by consumption. Based on this data, the national average fuel prices for 1993 are $0.08/kWh (electricity) and $0.62/therm (natural gas).

Table 1: Ventilation Equipment Cost Inputs

Equipment and Installation First Cost Inputs	Exhaust-Only System	Heat Recovery Ventilator
First Cost[22]	$785	$2,298
Annualized Cost	$187	$247
Annual Interest Rate	7%	7%
Years in Service	5	15
Annual Heat Recovery Efficiency	0%	70%
Fan Wattage	0.6 watts/cfm	1.0 watts/cfm

CHARACTERISTICS OF CURRENT STOCK

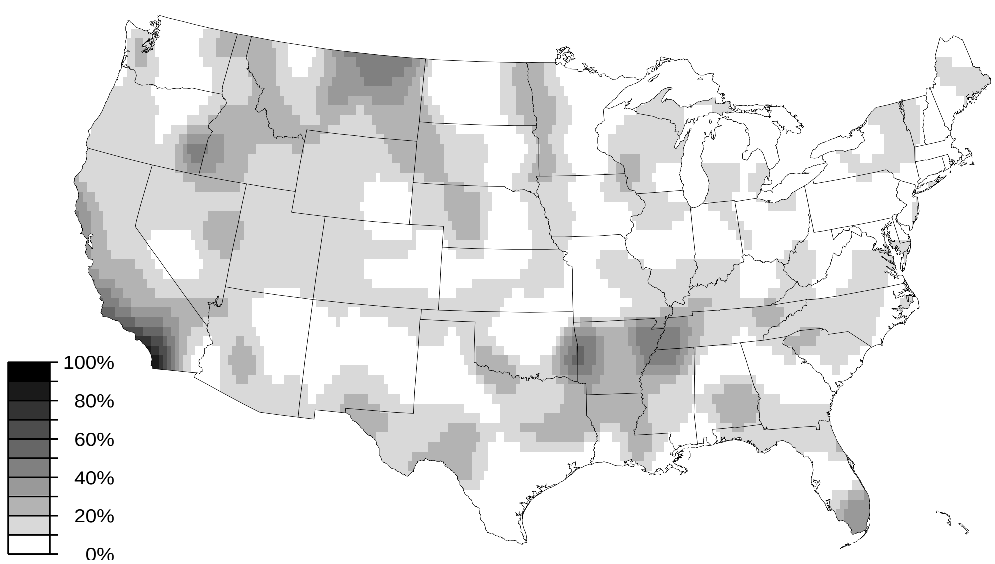
The housing stock represented by our datasets contains a negligible number of dwellings using whole-house ventilation systems. The task of characterizing the ventilation-related aspects of the stock then bcomes one of characterizing the infiltration. We first analyze the leakage data and then use it to estimate ventilation and energy issues.

It should also be noted that the databases do not adequately reflect values appropriate for the newest construction. “Brand new” houses are, in general, much tighter than reflected in the average values and some of them have whole-house ventilation systems. Our comparison of alternative scenarios, however, will have implications for new construction.

Envelope Leakage

Using our datasets and the approach from the “DISTRIBUTED LEAKAGE” section of the appendix we can estimate the average normalized leakage for each county in the U.S. Doing so leads to an average U.S. value of NL=1.2, with regional average values being approximately 20% around that average.

FIGURE 1: Percentage of Housing Stock Meeting Standard 119



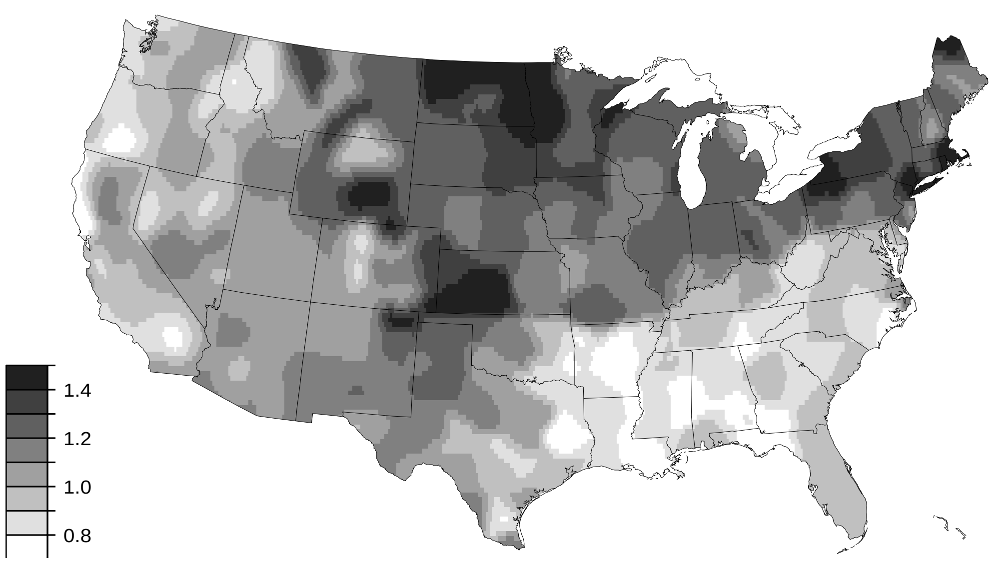
Leakage measurements demonstrate a huge variation across house type and age. The statistical distributions are quite wide and do not allow predictions to be made for any single house, but the average values as displayed above are reasonably representative and can indicate clear trends. Because the leakage values are the heart of infiltration calculations, this conclusion follows for them as well. While this level of tightness allows for uncontrolled natural ventilation, it corresponds to much higher (looser) levels than that suggested by the ASHRAE tightness standard (119) and contributes to higher, uncontrolled infiltration-related space conditioning loads. Only 15% of the housing stock is tight enough to meet the tightness standard for their given climate. Figure 1 shows the national distribution of the percent of houses meeting Standard 119. Houses in the milder climates, such as the West Coast, South East and South Central portions of the country, are more apt to meet the tightness standard while houses in the colder climates do not meet the standard.

Ventilation Rate

The ventilation rate in the stock is dominated by infiltration due to envelope leakage and is calculated from the leakage distribution and the weather using the LBL infiltration model included in the appendix. The concern in this section is only with ventilation rates for providing acceptable indoor air quality and not for energy calculations. Thus we use the effective air change rate which is that constant air change rate that would provide the same pollutant dilution as the actual (time-varying) air change rate. (See the appendix for a detailed definition.)

Although our analysis incorporates the effects of kitchen and bath exhaust fans, these have a negligibly small impact. Our analysis also allows for the use of natural ventilation during mild weather conditions. We estimate the average effective air change rate is 1.09 ACH for the U.S. as a whole and that approximately 95% of current stock meets the intent of ASHRAE Standard 62.

FIGURE 2: Average Annual Air Change Rates of Current Stock

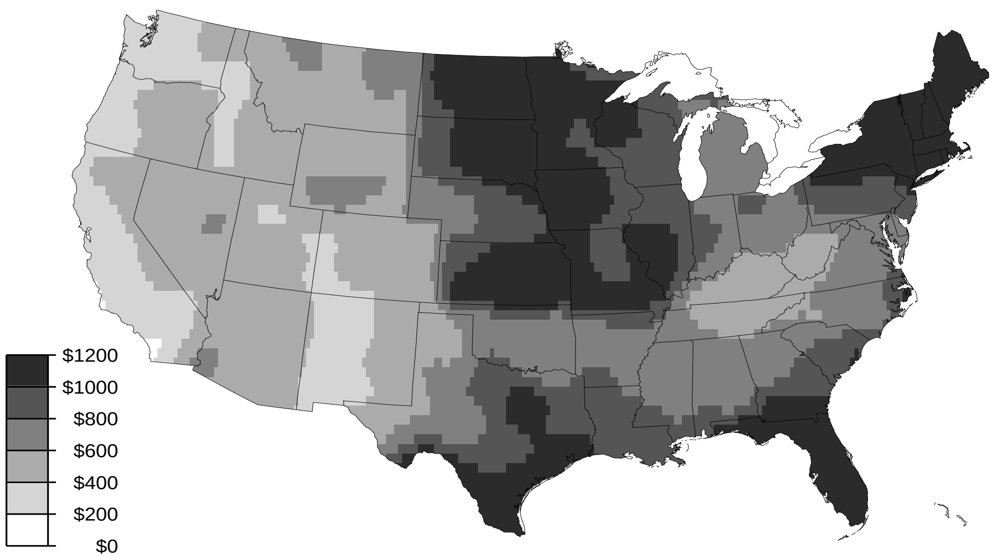


Energy Impacts

The energy impacts associated with the such high infiltration rates are relatively large. We estimate that the heating load attributable to infiltration/residential ventilation in the current stock is 3.4 EJ and the cooling load is 0.8 EJ. Electrical energy required for parasitics (furnace and air conditioner circulation fans) attributable to infiltration/residential ventilation is 0.3 EJ. The northern and eastern climates (Mid Atlantic, East North Central, West North Central and South Atlantic) have the highest ventilation-related energy loads, ranging from 0.6 to 0.9 EJ per region. The South Atlantic and West South Central regions (more humid regions) have the highest ventilation cooling-related energy loads, ranging from 0.2 to 0.4 EJ.

Using our air leakage and other databases, we estimate that the national annual cost to provide this much ventilation is $6 Billion/year. Average annual costs are shown nationally in Figure 3. The average annual cost per house would thus be $820/year, with costs ranging from $50/yr to $7,000/yr per house. Higher annual costs correspond to areas with colder or more humid climates as well as areas with higher local energy rates.

FIGURE 3: Annual Average Ventilation Costs of Current Stock[[$]



As mentioned earlier we are assuming a standard set of behavior for all our scenarios. We are assuming that the houses are intended to be occupied and conditioned full time; therefore, there is no allowance for energy saving strategies such as "set back." This assumption is likely to slightly overstate the energy usage in all our analyses. We also assume that people will use their windows whenever, but only whenever, it is comfortable outdoors.

ALTERNATIVE SCENARIOS

Although it appears that the vast majority of the U.S. has sufficient residential ventilation, the high cost associated with it suggests that there may be cost effective ways to reduce the infiltration rate and, if necessary, consider mechanical ventilation to meet ASHRAE Standard 62. We shall consider three different scenarios: the "*Base Case*" scenario, the "*ASHRAE*" scenario and the "*Scandinavian*" scenario. For each scenario the most cost-effective means to meet our interpretation of ASHRAE Standard 62 will be found assuming different tightness levels and corresponding infiltration contributions.

The **Base Case** scenario is very similar to the existing stock. But in order to fairly compare other alternatives, the less than 5% under-ventilated stock is modified. In the **ASHRAE** scenario the goal is to also meet the ASHRAE airtightness standard we have been discussing (119). The envelope will be tightened as needed to meet Standard 119 and then if required, mechanical ventilation will be supplied. The **Scandinavian** scenario is similar except that the tightness level will be increased by approximately a factor of two.

We consider two mechanical ventilation systems: simple exhaust and heat recovery ventilation. The simple **exhaust** system assumes that a continuously operating exhaust fan will extract air from the house at all times at a rate of 0.35 air changes per hour. Although various heat recovery strategies such as dynamic insulation or heat pumps are possible, we assume no heat recovery from this system. The Heat Recovery Ventilator (**HRV**) is a balanced air-to-air heat exchanger also sized to provide 0.35 ach at all times. The HRV recovers some of the energy of the air passing through it, and is modeled with an annual recovery efficiency of 70%. Although other types of mechanical ventilation systems could be considered, these two are the most representative and the only ones we will analyze.

The Base Case

In the base case we wanted to find the minimal change that would provide adequate ventilation. As such, we allowed for some *loosening* of the envelope as an option. For the less than 5% of the houses that did not have sufficient ventilation from infiltration, we ran an economic optimization to determine which of our three options (loosen the envelope, exhaust-only ventilation and heat recovery ventilation) would be more cost effective. Of the stock houses, ventilation systems are necessary in less than four percent of the houses (exhaust fans [1.9%], heat recovery ventilators [1.9%]). Essentially, then the base case has no mechanical ventilation.

The national average effective air change rates in the base case scenario are essentially the same as that for the stock. The heating and cooling loads increase slightly over that of the stock characterization by loosening the envelope or adding mechanical ventilation. The national annual cost to provide this ventilation is essentially the same as that for the stock, with similar average costs distributions as seen for the stock in Figure 3.

The “ASHRAE” Scenario

For this scenario we looked at the housing stock and tightened any envelopes necessary to meet ASHRAE Standard 119 and then analyzed the modified stock to determine which houses no longer met ASHRAE Standard 62. Tightening the houses without any mechanical ventilation would reduce the energy cost by almost a factor of four, but some of that gain must be “given back” to provide adequate ventilation. For those 51% of the houses that did not have sufficient ventilation from infiltration we ran an economic optimization to determine which of our two mechanical ventilation options would be more cost effective. (Loosening was not, of course, an option.)

The effective air change rates for the ASHRAE scenario range from 0.35 ach to 1.18 ach, with a national average of 0.52. Census division averages range from 0.48 to 0.59. The relatively small range is due to the fact that the variation in infiltration has been reduced through tightening and that mechanical ventilation is necessary in more of the housing stock. These air change rates are all higher than the 0.35 ach minimum due to the fact that we are assuming that the mechanical ventilation system is on continuously. While it is quite likely that the majority of users would not operate these systems at all times, we have used this assumption to avoid overstating the savings associated with the alternative scenarios.

The total energy load for the U.S. for the ASHRAE scenario is about 1.8 EJ. The national annual cost is $3.6 Billion, a reduction of $2.4 Billion over that of the base case. Average annual costs are shown in Figure 4. The annualized cost of ventilation is $490/yr for the average house, ranging from $20/yr to $2,200/yr per house. The annualized cost reduction achieved is not as large as the energy reduction due to the costs associated with purchasing and operating the mechanical ventilation system. Our annualized cost calculations take into account these costs but do not incorporate any costs associated with tightening. (Note that the shading scales for figures 3,4 & 6 are the same.)

FIGURE 4: ASHRAE Scenario Annualized Operating Costs

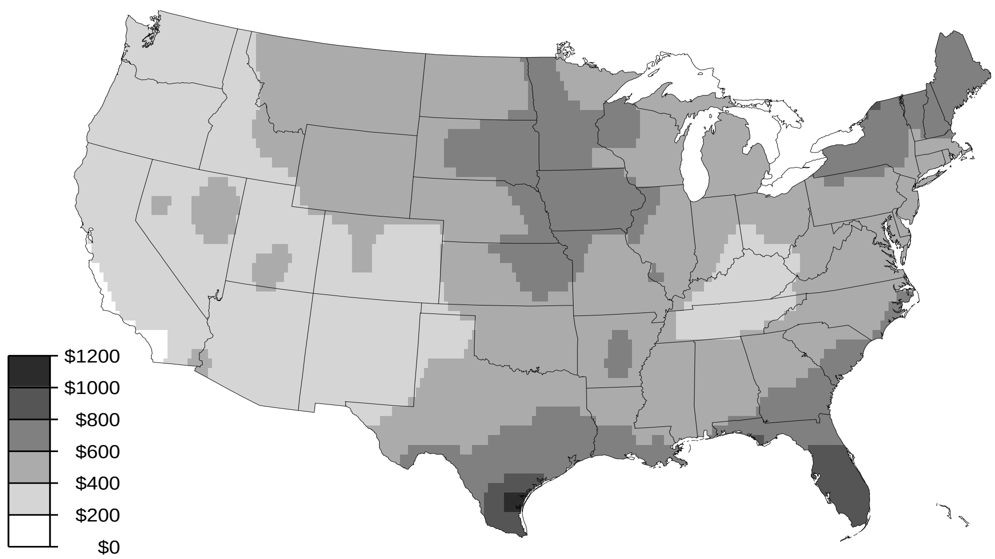
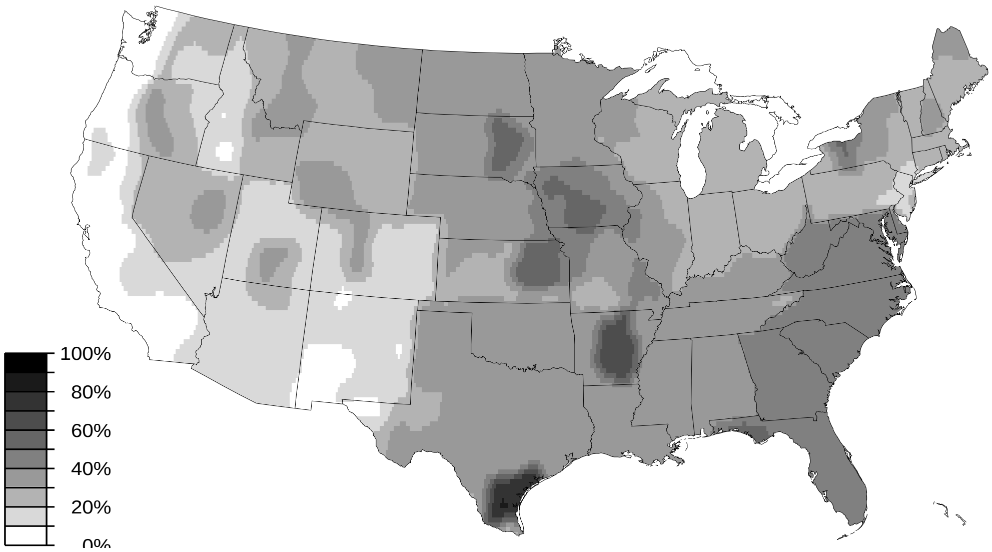


FIGURE 5: Percent of ASHRAE-Scenario Houses with Heat Recovery Ventilation



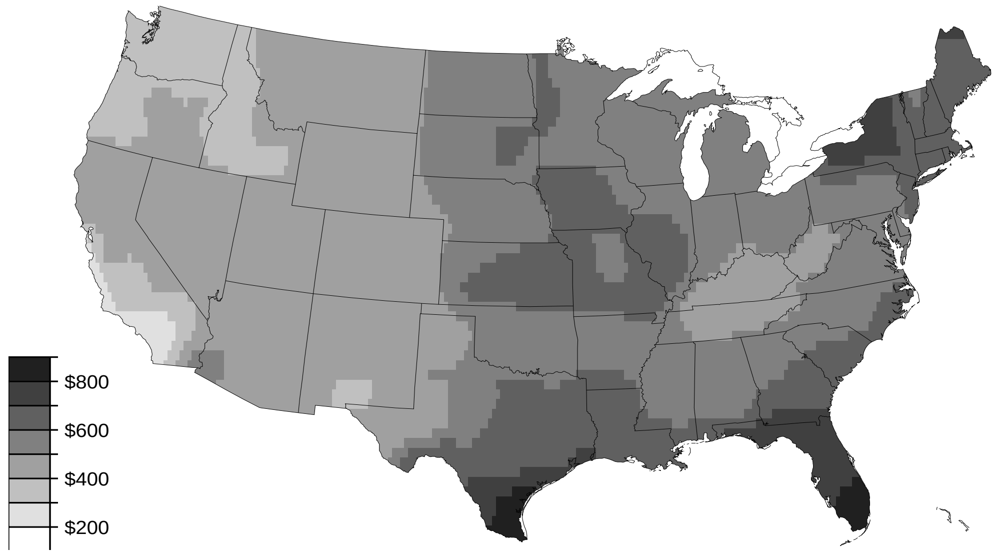
Of the 51% of the houses that need mechanical ventilation in the ASHRAE scenario houses, exhaust fans represent 22% and heat recovery ventilators, 29%. The optimal system type varies with house type and fuel costs, but more importantly with climate; the need for mechanical systems is quite minimal on the Pacific Coast but quite significant in the more extreme climates. The distribution of the percentage of houses requiring heat recovery ventilators is shown in Figure 5, where one can see that HRVs are cost-effective in some of the more humid or extreme climates. For the remainder of the country, the general trend is that exhaust fans are used in the frost belt but infiltration alone is used in the sun belt.

The “Scandinavian” Scenario

This scenario is modeled after the northern European shift towards tighter building envelopes and a small amount of operable air inlets. The origin of this trend was in the Swedish standard mandating no more than 3 air changes of envelope leakage at 50 Pascals of depressurization. We have adapted this approach to U.S. climates and our formalism, leading to a requirement of a factor of two (two classes) tighter than Standard 119 with operable inlets having the ability to bring the leakage to NL=.14 (Class B) if necessary. As with the ASHRAE case we assume that any mechanical ventilation system is running and that the operable inlets are open.

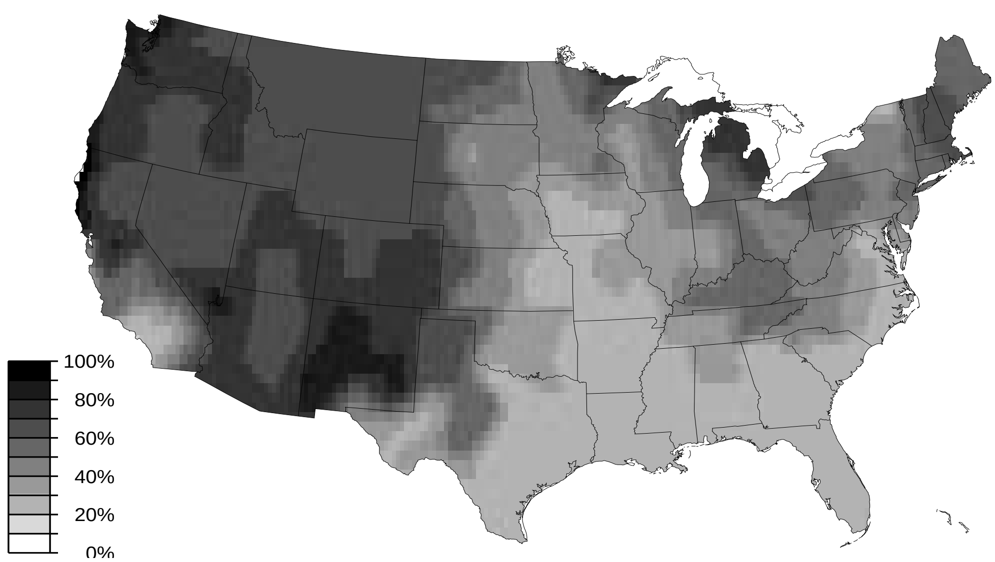
Ventilation systems are needed in 95% of the houses (exhaust fans [44%], heat recovery ventilators [51%]). The corresponding average air change rates are quite similar to the ASHRAE case, but with smaller regional variation. The optimal system configuration uses 1.6 EJ and has a national annual operating cost of $4 Billion (a reduction of $2 Billion over the stock characterization and over the base case). Average annual operating costs are shown in Figure 6. The annualized cost is approximately $550/yr for the average house, ranging from $45/yr to $1776/yr per house.

FIGURE 6: Scandinavian Scenario Annualized Operating Costs



The only areas that have a significant amount of infiltration-only systems are the Southern California region and, to some extent, the West Texas / Southern New Mexico region. For the remainder of the country, exhaust-only systems and heat recovery ventilators are favored. The distribution of the percent of houses with exhaust-only ventilation systems is shown in Figure 7.

FIGURE 7: Percent of Scandinavian-Scenario Houses with Exhaust-Only Ventilation



Comparison of Scenarios

The national ventilation energy usage for the various scenarios is summarized in Table 2. Heating, cooling and parasitic energy are essentially the same for the current stock and the base case.

TABLE 2. National Total Ventilation Energy Usage - EJ/Year

	Current Stock	Base Case Scenario	ASHRAE Scenario	Scandinavian Scenario
Heating Energy	3.41	3.43	1.15	0.93
Cooling Energy	0.77	0.78	0.34	0.25
Parasitic Energy	0.29	0.31	0.33	0.40
Total Energy	**4.47**	**4.52**	**1.82**	**1.58**
Free Heating	1.30	1.31	0.64	0.74
Free Cooling	0	0.01	0.19	0.26
Total Free Heating and Cooling	1.30	1.32	0.83	1.00

Heating and cooling energy usage decreases from that of the base case for the ASHRAE and Scandinavian scenarios (65% and 72%, respectively) while parasitic energy requirements increase (6% and 29%, respectively). The total ventilation energy usage decreases 2.7 EJ (60%) for the ASHRAE case and 2.9 EJ (65%) for the Scandinavian case.

We can compare the ASHRAE and Scandinavian scenarios to the base case to attempt to determine cost effective levels. Since all of the costs related to the mechanical systems are included, savings represent the income stream available to pay for the required tightening either as a retrofit or in new construction.

FIGURE 8: ASHRAE Scenario Ventilation Cost Savings

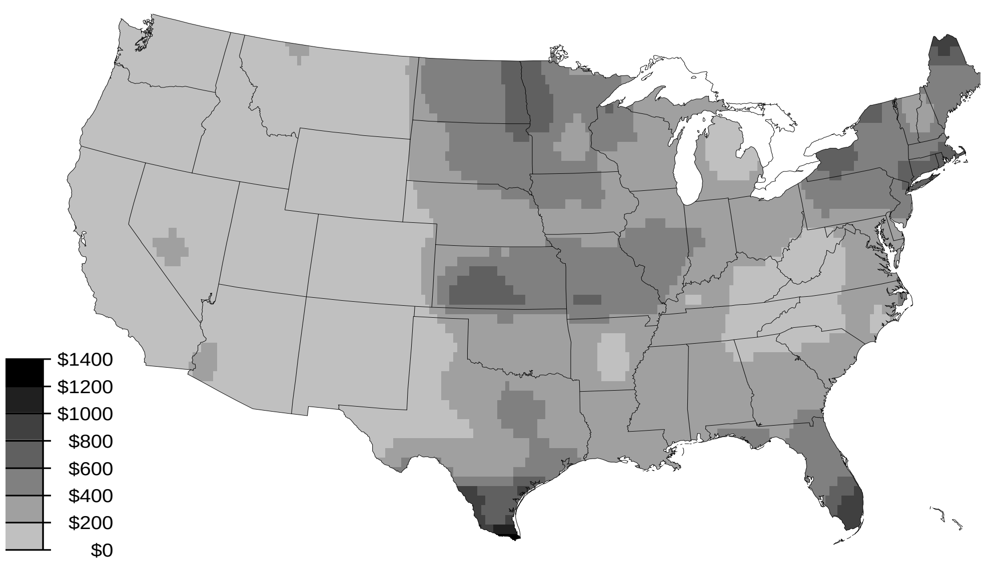
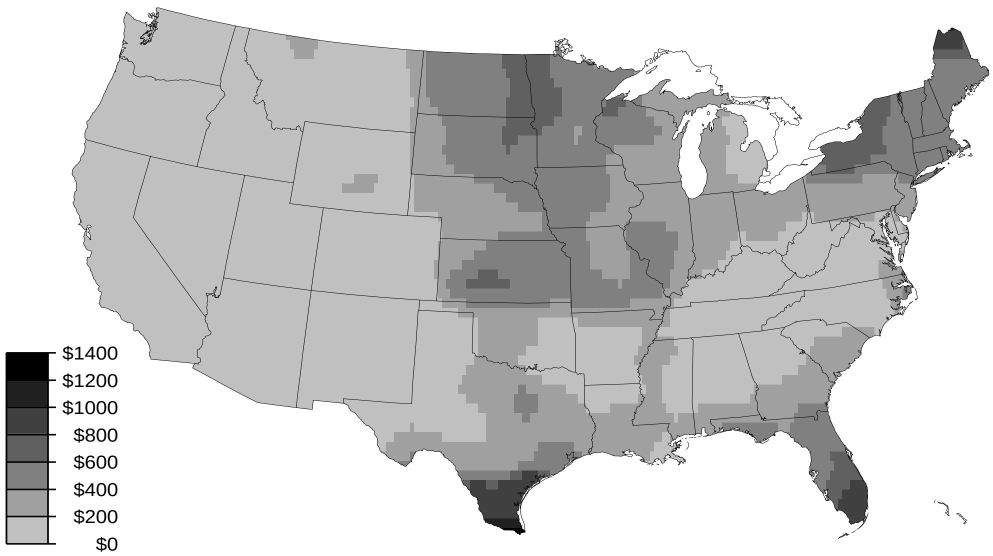


FIGURE 9: Scandinavian Scenario Ventilation Cost Savings

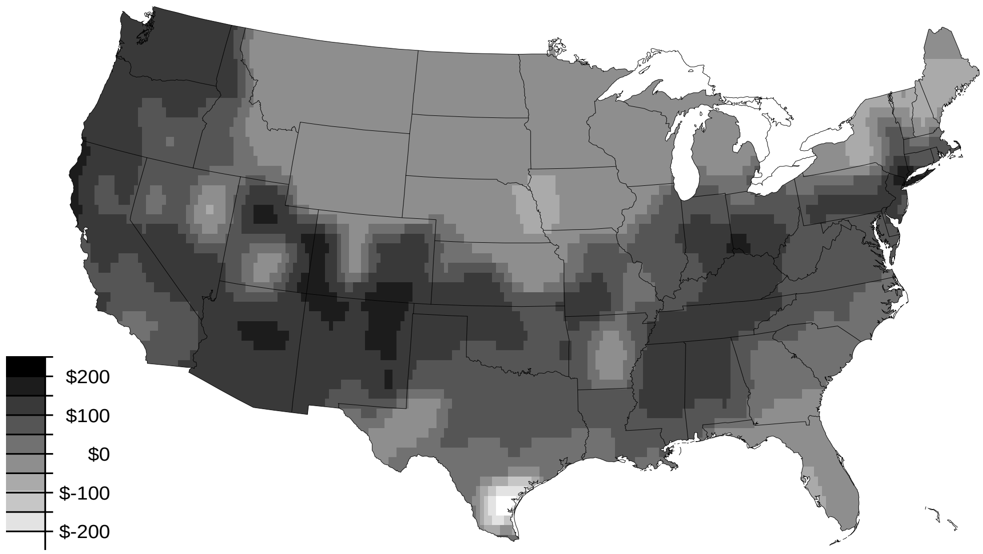


The annual cost savings, over that of the base case, are shown for the ASHRAE and Scandinavian scenarios in Figure 8 and Figure 9, respectively. One can see that for most of the west savings are small and often additional net costs are required for our tightest scenario, even though there is some net savings of energy.

For the country as a whole the average cost saving is $290 per house for the ASHRAE case and $240 per house for the Scandinavian case. Operating cost savings are higher ($300 to $450 per house) in the colder northern and northeastern climates as well as in the hot humid climates. Assuming that, on average, house air-tightening costs $1,000 per house and that the ventilation system operating cost savings are applied to this effort, a typical homeowner could expect a payback of less than five years for the air-tightening efforts needed for either scenario.

It is interesting to note that neither the ASHRAE nor Scandinavian scenarios are always superior. Figure 10 shows the annualized cost difference between the two. For most of the country the ASHRAE scenario is more cost-effective; in these areas additional tightening beyond that level is not warranted. In the Northern Plains, New England and parts of the hot humid South, the Scandinavian scenario is more cost-effective. Since this analysis does not include the cost of tightening, it is unlikely that the Scandinavian scenario would be practical as a *retrofit* strategy anywhere in the continental U.S.

FIGURE 10: Operating Cost Savings Comparison: Scandinavian Scenario - ASHRAE Scenario



Implications for Alaska and Hawaii

Though Alaska and Hawaii are not included on the maps shown, their housing stocks' building and leakage characteristics were taken into account when undertaking this analysis and are appropriately reflected in the national totals. We will briefly summarize their trends as follows:

Alaska, being a colder climate, follows the same patterns as the northern U.S. in terms of the most cost-effective ventilation systems for the various scenarios. Similar to the majority of the country, the current stock Alaska houses are able to meet the ASHRAE ventilation Standard 62 recommendations using natural ventilation. The Alaska current stock average annual infiltration/ventilation energy costs are $600/year, ranging from $200 to $2,400. When the Alaska houses are tightened for the ASHRAE scenario, 80% of the houses need exhaust fans and the remaining, heat recovery ventilation. When tightened to meet the Scandinavian scenario, 72% of the houses need exhaust fans and the remainder, heat recovery ventilators. Annual operating costs decrease to an average of $470 for both the ASHRAE and Scandinavian scenarios, with the Scandinavian scenario having a slightly lower operating cost.

The Hawaiian housing stock acts similarly to that of California, where the current stock uses infiltration and natural ventilation to meet the ventilation standard. Our analyses *would* suggest that the average annual infiltration/ventilation energy costs are $1,270/year for the Hawaiian stock and would decrease to approximately $480 for the ASHRAE and $580 for the Scandinavian scenarios. These values are, however, unrealistically high because our analysis predicts a much lower usage of natural ventilation and ventilative cooling than is typically observed. This artifact is due to a strong disagreement between the occupants and ASHRAE Standard 55 over the temperature and humidity ranges at which comfort can be achieved. Technically this flaw effects climates other than just

Hawaii, but its practical impact is small in other climates because of the low numbers of hours in which this weather would occur and for which people would open their windows.

DISCUSSION AND CONCLUSIONS

The U.S. housing stock currently has a negligible number of houses using whole-house ventilation systems. Infiltration is the dominant ventilation system. Infiltration is often viewed as a poor ventilation mechanism because the flow paths are diffuse and unknown while the driving mechanism is both unstable and variable over the year. While these qualities do little for those who strive for certainty, they do have some advantages. Averaged over any time longer than a day, infiltration provides a floor on the ventilation rate even when no ventilation systems operate. Infiltration rates are the highest during the times of the year when window opening is least desirable. Although infiltration may have a relatively low ventilation efficiency,[18] it is at times the optimal system or, more often, a component of an optimal system.

Stock Characteristics

Typical ventilation rates in the stock average over one air change per hour. Because we allow open windows to contribute towards this value, this number is not indicative of the energy impacts of ventilation, only its ability to dilute pollutants. Nevertheless, this number is higher than is often quoted. The representativeness of the leakage data used to make this calculation is not known. While there is no a-priori reason to assume the dataset is biased, it is not impossible for it to be so. The predicted ventilation rates indicate that meeting ASHRAE Standard 62 will not be difficult for most of the stock.

The data implies that the total energy use for residential ventilation is over 4 EJ annually. This number would represent a significantly larger fraction than is normally attributed to residential ventilation. This fact may indicate that some of the assumptions of the analysis should be tested in subsequent efforts. Key factors that could affect the total include air tightness of the stock, temperature preferences and operating strategies; under-conditioning could be a significant contributor. Another key factor to consider is whether or not there is any heat exchange occurring during the infiltration and exfiltration through envelope leaks.

The diffuse nature of infiltration allows for some heat transfer to temper incoming air during more extreme weather conditions and for exfiltrating air to reduce heat transfer through interior surfaces; thus forming a kind of distributed heat exchanger. Theoretically this effect is well known and has even being used as a design approach in Scandinavia. What is not known is whether adventitious leakage in the envelopes of U.S. buildings would have any appreciable heat recovery. We have assumed no such heat recovery in our analysis, but if such an effect did, in fact, contribute, it would lower the energy impact of infiltration.

Stock Optimization

As has been discussed in this and other papers, purposely building a house loose in order to provide sufficient natural ventilation by infiltration alone most often results in high energy bills from excessive infiltration. The challenge of building a house to the exact tightness level to balance energy and ventilation through infiltration is an exacting (or exasperating) activity. Likewise, air-tightening an existing house while still providing sufficient natural ventilation is a challenge.

In undertaking this study, we have examined the trade-offs between tightening the building envelope for energy efficiency while adding supplemental mechanical ventilation when necessary to meet ventilation requirements. For most of the U.S. tightening much below the ASHRAE (119) tightness standard does not afford any additional savings, thus implying that from a life-cycle cost perspective there exists an optimal tightness level.

When tightening the envelope to meet the ASHRAE tightness standard, 51% of the houses need some type of supplemental ventilation system. 95% of the houses need supplemental ventilation systems if the houses are tightened to our version of the Scandinavian standard. The trade-offs are found in the energy savings due to lowered, yet still sufficient, ventilation rates with supplemental ventilation equipment.

For the existing stock, these results can be used to evaluate retrofit measures and to develop programs for determining optimal ventilation systems designed to provide adequate ventilation at the lowest cost. The energy savings over that of the existing stock houses with higher ventilation rates ($240 to $290/year), can be applied directly to the tightening and weatherization efforts of a given house,[*] resulting in a least cost effort and minimal financial impact on the homeowner.

Implications for New Construction

Our results have implications for new construction as well as for retrofit efforts, even though our leakage data under-represents the new construction stock. In new construction, the cost of building tighter is principally that of a learning curve, so that the vast majority of our predicted savings can be realized. By treating the base case as a construction option (i.e. design it to leak) rather than as the current state of affairs, we can evaluate new construction options. The optimal level of tightness will vary by region but, overall, the ASHRAE levels do a good job in specifying that level.

Natural ventilation can be used for a significant fraction of the year in the mild parts of the Pacific and SouthWest. Thus our economic optimum is not very sensitive to the tightness level in these areas as long as the appropriate ventilation system (if required) is chosen. Typical current construction practices are providing tight enough building envelopes for these climates and the only concern may be insufficient ventilation during those parts of the year when natural ventilation is not appropriate.

In the most extreme climates, tightening beyond the level of the ASHRAE Standard may be warranted in order to better utilize the heat recovery of the HRV, but for most of the country this effect is small. Conversely, this flatness implies that there is not a large economic penalty for over-tightening in the more severe climates, where tightening for

[*] The cost of any required ventilation system is already included.

thermal comfort reasons may be desirable. The striking difference when moving to the Scandinavian scenario is the change in which systems are optimal: there is a sharp drop in the infiltration-only systems in the sunbelt and the rise of HRV systems in the greater Mississippi Valley area and the Northeast with most of the West moving towards exhaust fan systems.

Discussion of Errors

The economic conclusions are, of course, sensitive to the price assumptions and specific scenarios we chose. We did not, for example, consider passive ventilation systems, heat-pump heat recovery systems, or dynamic insulation systems; we did not consider high efficiency or variable flow fans, nor did we consider any of the proposed control strategies. Furthermore, the system and fuel price assumptions are unlikely to be universally applicable. Nevertheless, the results indicate clear trends. More specific analyses may be warranted before making localized policy or program recommendations.

Similarly, we have focused on mean values for the technical quantities rather than their distribution. Representative measurements of infiltration and air leakage are known to have large standard deviations (e.g. as big as their mean value) due to inherent inhomogeneities of such samples. Examination of the tails of these broad distributions would require more detailed data than is available nationwide. For mechanically dominated systems, the variation in envelope properties has a less pronounced influence and the distributions become significantly narrower.

Areas for Further Work

The conclusions of this study have clear national implications. The data indicates regional trends, but the specific policies, pricing, and practices of each region are not included in detail. While it appears that leakage retrofit programs may be cost effective over much of the country, the specifics should be incorporated for each locale.

This analysis covers only single-family buildings. It is tempting to say that we would use the same energy intensity for multifamily buildings, which represent only 14% of the U.S. residential floor area, and scale up our values. Future work should attempt to ascertain the accuracy of such an assumption. Future work should also attempt to ascertain whether or not heat exchange is contributing to the energy impact of infiltration.

As mentioned earlier, an important need is to extend this work more into new construction by improving the database on newly and recently constructed houses. Anecdotal evidence clearly indicates that much of the new construction is already sufficiently tight enough that infiltration and a reasonable amount of natural ventilation will not provide adequate ventilation. The issues in new construction may not necessarily be how to make the envelopes initially tighter, but how to provide cost-effective ventilation and how to maintain system integrity.

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LIST OF SYMBOLS

A	stack coefficient [-]
A_f	building floor area [m^2]
ACH	effective air change rate (ach) [h^{-1}]
B	wind coefficient [-]
C′	generalized shielding coefficient [-]
C_p	heat capacity of air [1.022 kJ/kg-°K]
E	annual or seasonal energy load [kJ]
$Elec_{ahu}$	Electrical consumption of air handling unit as a percentage of cooling energy
$Elec_{comp}$	Electrical consumption of air conditioner compressor, as a percentage of cooling energy
$Elec_{ffan}$	Electrical consumption of furnace fan, as a percentage of heating energy
ELA	effective leakage area [m^2]
f_s	stack factor [(m/s)(°K)$^{1/2}$]
f_w	wind factor [-]
g	gravity [9.8 m/s^2]
H	building height [m]
HI	inside enthalpy [kJ/kg]
HO	outside enthalpy [kJ/kg]
IDD	infiltration degree days [°C-day]
L	heating or cooling load [kJ]
N	number of hours [h]
NL	normalized leakage area [-]
Q	heat flow/ load[kJ]
R	fraction of total leakage area in the floor and ceiling [-]
s	specific infiltration [m/s]
s_o	average specific infiltration [0.71 m/s]
ΔT	inside-outside temperature difference [°C]
T_o	(absolute) reference temperature [298 °K]
V	ventilation air flow rate [m^3/s]
v	measured wind speed [m/s]
X	difference in ceiling/floor fractional leakage area [-]
w	air change rate factor accounting for effect of local weather (ACH) [$^{-h}$]
ρ	density of air [1.2 kg/m^3]
[h]	indicates hourly value

APPENDIX: MODELING TOOLS

In order to use this information we must have a way of predicting instantaneous ventilation rates and deriving the corresponding seasonal and annual air change rates and ventilation energy requirements. The fundamental relationship between the infiltration and the house and climate properties is expressed by the LBL infiltration model[16], which is incorporated into the ASHRAE Handbook of Fundamentals[1]. The LBL infiltration model is used to generate, on an hourly basis, specific infiltration and air flow rates. From these hourly results, seasonal average air change rates and corresponding energy consumption, as well as overall measures of tightness (ASHRAE Standard 119)[5] and rates for adequate ventilation (ASHRAE Standard 62)[4] are determined.

LBL INFILTRATION MODEL

The LBL infiltration model[16] calculates specific infiltration rate, $s[h]$, as:

$$s[h] = \sqrt{f_s^2 \cdot \Delta T[h] + f_w^2 \cdot v^2[h]} \qquad \text{(EQ 1)}$$

where the stack and wind factors (f_s and f_w respectively) are a function of building properties and are calculated as shown in Equation 2 and Equation 3.

$$f_s = \left(\frac{1 + \frac{R}{2}}{3}\right)\left(1 - \frac{X^2}{(2-R)^2}\right)^{\frac{3}{2}}\left(\frac{g \cdot H}{T_o}\right)^{\frac{1}{2}} \qquad \text{(EQ 2)}$$

where R and X are measures of leakage distribution, H is the height of the building and T_o is the outside drybulb temperature.

$$f_w = C'(1-R)^{\frac{1}{3}} A\left(\frac{H}{10m}\right)^B \qquad \text{(EQ 3)}$$

where C’ can be found from Table 3, “Shielding Parameters,” as a function of shielding class, and A and B can be found from Table 4, “Terrain Parameters,” as a function of terrain class.

Table 3: Shielding Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
C’	0.34	0.30	0.25	0.19	0.11

Table 4: Terrain Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
A	1.30	1.00	0.85	0.67	0.47
B	0.10	0.15	0.20	0.25	0.35

The hourly infiltration rate is calculated using the following relationship:

$$V[h] = ELA \cdot s[h] \tag{EQ 4}$$

The effective leakage area, *ELA*, quantifies the absolute size of the openings in the building and for the LBL infiltration model is determined by summing the respective component leakage areas of a specific building. A better measure of the relative tightness, however, is the normalized leakage as defined in ASHRAE Standard 119.[5]

$$NL = 1000\frac{ELA}{A_f}\left(\frac{H}{2.5m}\right)^{0.3} \tag{EQ 5}$$

Effective Air Change Rate

The equations above allow the calculation of instantaneous air change rates. A simple average of these values has, unfortunately, no physical significance whatsoever; the effective air change rate is calculated using the procedures of Sherman and Wilson[18] which are similar to, but more accurate than ASHRAE Standard 136-93[6]:

To accommodate the potential use of natural ventilation it is assumed that the occupants will open their windows anytime the outside conditions are in the comfort zone[3] or when no energy penalty would occur from doing so. Thus the effective air change rate will be raised for ventilation considerations.

Seasonal Energy Use

The energy used to condition air depends on the temperature or enthalpy difference between the infiltrating and exfiltrating air. Because the driving forces for infiltration also depend on the temperature difference, the relationship is non-linear.

A simplified method for treating this non-linearity is to create a statistic that quantifies the infiltration-related climate. One method[13] creates such a statistic, called Infiltration Degree-Days(*IDD*). During the heating season the IDDs can be calculated by summing over each heating hour:

$$IDD_{heating}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (TH - T[h]) \quad \text{(EQ 6)}$$

where *TH* is the indoor heating temperature setpoint (19 ° C), *T[h]* is the outside drybulb temperature and s_o=0.71 m/s.

For the cooling season, as latent cooling loads may be quite important, both latent and sensible cooling loads must be considered. The cooling IDDs for each hour should be taken as the larger of the two values:

$$IDD_{cooling(sensible)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (T[h] - TC) \quad \text{(EQ 7)}$$

where *TC* is the cooling setpoint temperature (25°C).

$$IDD_{cooling(latent)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot \frac{HO[h] - HI}{C_p} \quad \text{(EQ 8)}$$

where *HO* is the enthalpy of the outside air and *HI* is the enthalpy of the indoor air (set to a default for each census division, based on DOE-2[9] modeling results).

Hours of heating, cooling and ventilation are determined based on outside temperature conditions. The building is modeled in heating mode when the outside temperature is below 19 ° C and in cooling mode when the outside temperature is greater than 25°C. When the external conditions meet the ASHRAE comfort requirements[3], it is assumed that the occupants open their windows. When in ventilation mode, the effective leakage area is increased by a factor of 100 to reflect the opening of windows.

The annual energy intensity, reflecting heating and cooling energy consumption, can also be calculated from the combined total infiltration and ventilation air flow, V_{tot}, calculated as in Equation 9

$$V_{tot} = \sqrt{V_{infil}^2 + (V_{supply} - V_{exhaust})^2} + V_{balanced} \quad \text{(EQ 9)}$$

The corresponding loads are calculated for each hour using the appropriate load calculations (Equation 10 [heating], Equation 11 [sensible cooling], and Equation 12 [latent cooling]). The Ventilation mode, as modeled with natural ventilation, does not carry any energy liabilities. Corresponding energy liabilities are calculated by applying heating and cooling equipment efficiency factors (annual fuel utilization efficiency [AFUE] and coefficient of performance [COP], respectively) to the resulting seasonal loads. Electrical energy consumption (furnace fan and air conditioner compressor and air handler) is calculated as a percentage of the corresponding seasonal energy consumption. Table 5 summarizes the equipment efficiency and electrical assumptions.

$$Q_{heating}[h] = \rho \cdot C_p \cdot V_{tot} \cdot (T_{heating} - T_{out}) \quad \text{(EQ 10)}$$

$$Q_{cooling}(sensible)[h] = \rho \cdot C_p \cdot V_{tot} \cdot (T_{out} - (T_{heating} + T_{deadbamd})) \quad \text{(EQ 11)}$$

$$Q_{cooling}(latent)[h] = \rho \cdot C_p \cdot V_{tot} \cdot (HO[h] - HI) \quad \text{(EQ 12)}$$

TABLE 5. Equipment Efficiency and Parasitic Electricity Assumptions

Furnace AFUE	80%
Furnace Fan Electrical Energy (% of Heating Energy) [$Elec_{ffan}$]	3%
Air Conditioner COP	3.18
Air Conditioner Compressor Electrical Energy (% of Cooling Energy) [$Elec_{comp}$]	45%
Air Conditioner Air Handler Electrical Energy(% of Cooling Energy) [$Elec_{ahu}$]	6.5%

$$E_{heating}[h] = \frac{Q_{heating}[h] \cdot (1 - FH\%)}{AFUE} \quad \text{(EQ 13)}$$

$$E_{cooling}[h] = Q_{cooling} \cdot COP \quad \text{(EQ 14)}$$

$$E_{electrical}[h] = \frac{1}{3600} \cdot \left(E_{cooling}[h] \cdot \frac{Elec_{comp} + Elec_{ahu}}{100} + E_{heating}[h] \cdot \frac{Elec_{fan}}{100}\right) \quad \text{(EQ 15)}$$

Compliance with ASHRAE Standards

Compliance is checked with two ASHRAE standards: Standard 119[5], the tightness standard, and Standard 62[4], the ventilation standard.

ASHRAE Standard 119 relates normalized leakage to infiltration degree-days. The standard can be expressed[12] in the following form:

$$NL \leq \frac{2000}{IDD} \quad \text{(EQ 16)}$$

where the denominator is the total number of IDDs for heating and cooling. A building is considered to be in compliance with the tightness standard when the above relationship is true.

The effective air change rate is the value of the air change rate that should be used in determining compliance with minimum ventilation requirements. ASHRAE Standard 62 sets minimum air change rate requirements, for residences, of 0.35 air changes per hour. It should be noted, for smaller residences, that the additional requirement of a minimum of 7.5 l/s per occupant must also be met in order to meet compliance.

DISTRIBUTED LEAKAGE

The leakage database used is one of convenience and can safely be assumed to be non-representative of the housing stock. So it is necessary to reduce the raw data into a form that is. The objective to calculate the average leakage for each *configuration* and for each *location.* There are 32 configurations and over 240 weather sites to determine from the over 12000 measured leakage values.

The approach is to construct a weighted average of all of the leakage data for each of the desired combinations. The weights will be determined by how relevant the measured value is for the combination of interest. The desired combination is called the **T**arget and the raw data is referred to as the **S**ource. The combination of the five conditions is referred to as the **C**onfiguration and is determined for each **L**ocation. (For example C_T represents the configuration of the target area.)

For any given target configuration and location the normalized leakage (*NL*) can be expressed as the following weighted average:

$$NL(C_T, L_T) = \frac{\sum_S FC(C_T, C_S) NL(C_S, L_S) W(C_T, L_T, C_S, L_S)}{N(C_T, L_T)} \qquad \text{(EQ 17)}$$

where the denominator tells us how many equivalent points have contributed to the weighted average

$$N(C_T, L_T) \equiv \sum_S W(C_T, L_T, C_S, L_S) \qquad \text{(EQ 18)}$$

and the correction factor, *FC*, corrects for the difference in configurations.

This reduces most of the problem to that of finding appropriate weights. The weighting comes from the two parts:

$$W(C_T, L_T, C_S, L_S) = \frac{1}{DL(L_T, L_S) + DC(C_T, C_S)} \qquad \text{(EQ 19)}$$

The location difference is defined using the longitude and latitude and infiltration degree days of each weather site:

$$DL(L_T, L_S) \equiv \left(\frac{lat_T - lat_S}{2^o}\right)^2 + \left(\frac{long_T - long_S}{8^o}\right)^2 + \left(\frac{IDD_T - IDD_S}{1000C^o days}\right)^2 \qquad \text{(EQ 20)}$$

The configuration difference (and correction factor) are products that depend on the difference between the source configuration and the target configuration. Both *DC* and *FC* start out at unity and are then multiplied by one factor for each component as indicated in the table below:

TABLE 6. Configuration Difference Weighting

Component	$DC^a = DC^*$		
	Same	Different	Unknown
Multistory?	1	10	3
Floor Leakage?	1	4	2
Ducts?	1	10	1000
Good Condition?	1	25	5
New?	1	1000	10

a. depending on whether the source and target conditions are same different or unknown, respectively

The output of this calculation is 32x240 *NL*s and *N*s.