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RESIDENTIAL VENTILATION AND ENERGY CHARACTERISTICS

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SYNOPSIS

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. This report ascertains, 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).

LIST OF SYMBOLS

AFUE	gas furnace annual fuel utilization efficiency [-]
COP	air conditioner coefficient of performance [-]
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 [% of cooling energy]
$Elec_{comp}$	Electrical consumption of air conditioner compressor [% of cooling energy]
$Elec_{ffan}$	Electrical consumption of furnace fan [% of heating energy]
FH%	percent of heating load met through free heat (solar and internal gains) [%]
HI	inside enthalpy [kJ/kg]
HO	outside enthalpy [kJ/kg]
IDD	infiltration degree days [°C-day]
N	number of hours [h]
NL	normalized leakage area [-]
Q	heat flow/ load[kJ]
T	temperature [°C]
V	ventilation air flow rate [m^3/s]
ρ	density of air [1.2 kg/m^3]
[h]	indicates hourly value

INTRODUCTION

Infiltration and ventilation in dwellings is conventionally believed to account for 1/3 to 1/2 of the space conditioning energy, although 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, it is important 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 and its derivatives will be used as the basis for the calculation.

EVALUATION CRITERIA

In this report we estimate and evaluate, using various ASHRAE standards, 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[2] 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[1] 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 (ACH), but not less than 7.5 l/s per person. Unfortunately, while the values for residential ventilation are explicit in Standard 62, the interpretation of these values was left vague. 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.

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[3] we can estimate the combined contributions of envelope leakage and other ventilation systems towards meeting Standard 62.

MODELING METHODS AND DATA SOURCES

The modeling methods used in this report have been reported earlier in a preliminary version of this analysis[4] and are similar to ones used in the general analysis of "blower door" data.[3]

Variations and additions to the previous modeling methods are described in our corresponding LBNL report.[2]

Putting available data sources together we can determine for each county the number of houses (from the U.S. Census), the type and sizes of houses (from the Residential Energy Consumption Survey, RECS[5]), the leakage properties (from the LBL Leakage Database[1]) and the representative weather conditions. From the analysis of this data, data average and aggregate quantities are developed for the nation as a whole. Our use of the Census and RECS data is identical to that used in our previous analysis.[4] Based on the RECS data, we have defined 32 different types (or configurations) of houses for use in this analysis: 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. An expanded U.S. leakage database[3] is used in this analysis to develop weighted average leakage values for each climate and house combination (7,680 possible combinations).

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,[6] 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.

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 becomes one of characterizing the infiltration. We first analyze the leakage data and then use it to estimate ventilation and energy issues.

Envelope Leakage

Using our datasets and the approach discussed in a previous paper[3] we can estimate the average normalized leakage (NL) for each county in the U.S., with an average U.S. value of NL=1.2 (std. dev. = 0.34).

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 are reasonably representative and can indicate 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 its given climate. 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.

The databases do not adequately reflect values appropriate for the newest construction which are, in general, much tighter than reflected in the average values. Our comparison of alternative scenarios, however, will have implications for new construction.

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. 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 the constant air change rate that would provide the same pollutant dilution as the actual (time-varying) air change rate.

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.

Energy Impacts

The energy impacts associated with the such high infiltration rates are relatively large. We estimate that the heating load attributable to infiltration and 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 and 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. 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.

As mentioned earlier we are assuming a standard set of behavior for all our scenarios: houses are 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 only when 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 ASHRAE airtightness standard 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, 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.

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 to 1.18 ACH, with a national average of 0.52 ACH. Census division averages range from 0.48 to 0.59 ACH. 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. 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.

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. 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 methods, leading to a requirement of a factor of two tighter than the ASHRAE Case. Operable inlets are assumed to be used, when necessary, to bring the leakage to a minimum of NL=.14 (Standard 119 Class B). 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). The annualized cost is approximately $550/yr for the average house, ranging from $45/yr to $1776/yr per house.

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. Exhaust-only ventilation systems are more predominant than heat recovery ventilators in the Pacific Northwest, Mountain, East South Central and New England regions.

Comparison of Scenarios

The national ventilation energy usage for the various scenarios is summarized in Table 1. Heating, cooling and parasitic energy are essentially the same for the current stock and the base case.

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.

TABLE 1. Energy Consumption (EJ)

	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

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. 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.

DISCUSSION AND SUMMARY

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 lower limit for 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, 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 slightly 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.

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 including the cost of any required ventilation systems), 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 implies that there is not a large economic penalty for over-tightening in the more severe climates, where tightening for 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-only 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.

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 be not how to make the envelopes initially tighter, but how to provide cost-effective ventilation and how to maintain system integrity.

Because the stock characterization data indicate a much larger load than is normally attributed to residential ventilation, there is a clear need to determine the cause of this discrepancy. One possibility is bias in the leakage database. This can be resolved by collection and analysis of additional envelope leakage data. Another cause could be the assumption of no significant infiltration heat recovery. Both of these facets should be investigate further.

The validity of the operating assumptions is an area requiring further investigation, but one that affects more than just ventilation. Scheduling of the set-point and the operation of the HVAC system can have a significant impact on not only how much energy is used but how the energy accounting is done. While we avoided some of this issue by using steady-state indoor conditions (and hence no thermal mass effects), further analysis is needed of representative operating assumptions and their impacts.

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