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Authors

Turiel, I.
Fisk, W.J.
Seedall, M.

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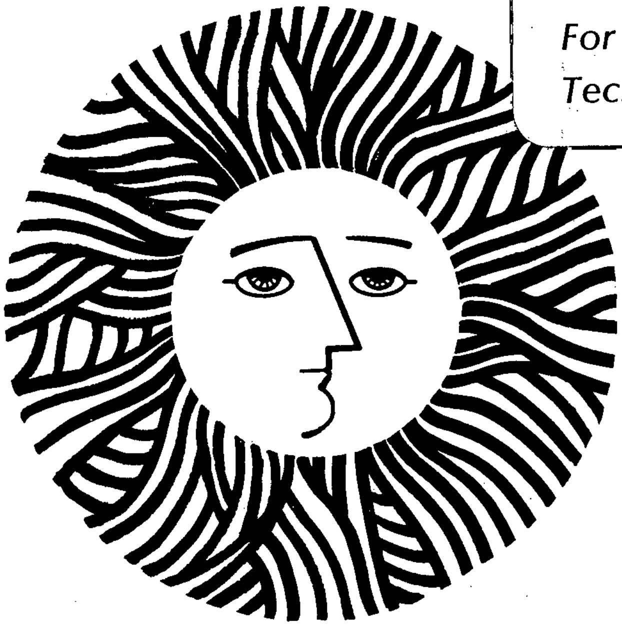

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Isaac Turiel, William J. Fisk, and Mark Seedall

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Energy Savings and Cost-Effectiveness of Heat Exchanger Use as an Indoor Air Quality Mitigation Measure in the BPA Weatherization Program[†]

Isaac Turiel, William J. Fisk, and Mark Seedall

Energy and Environment Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

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ABSTRACT

The Bonneville Power Administration (BPA) has proposed a ten year program to encourage the weatherization of electrically heated homes in the Pacific Northwest. The purpose of this program is to reduce residential electrical energy demand for space heating. If air infiltration rates are reduced by employing house tightening measures, indoor air quality mitigation measures may be required in residences with significant sources of indoor air contaminants. The use of residential air-to-air heat exchangers has been proposed as a possible strategy to assure that indoor air quality is not substantially degraded by house tightening.

We examine the energy impact and cost effectiveness of heat exchanger utilization in tightened homes in the BPA region. Significant energy savings are predicted if homes are tightened and heat exchangers are utilized. From the homeowner's perspective, the results of our economic analysis indicate that, at the relatively low residential electric rates in the BPA region, the use of heat exchangers in existing homes that are tightened is not economically viable. On the other hand, from the utility perspective, it may be cost effective to use heat exchangers in the weatherization program if the marginal cost to the utility is compared with the cost of conserved energy.

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1. INTRODUCTION

The Bonneville Power Administration (BPA) is engaged in a weatherization program designed to reduce electricity use in existing homes that use electricity for space heating. A number of the measures that are included in the program have the effect of reducing the ventilation rate in the structures in question, thereby not only saving energy but also increasing the concentrations of indoor-generated airborne pollutants. The pollutants of most concern in these electrically heated residences are radon, formaldehyde, and combustion products from wood-burning stoves and fireplaces.[1]

The environmental assessment prepared by BPA, in connection with the weatherization program, provided that measures that substantially affect infiltration (and therefore the concentration of pollutants indoors) would not be offered to certain classes of homes in order to avoid having a significant adverse impact on the health of occupants.[2] These homes were excluded from infiltration reducing measures on the basis of house characteristics that suggest the presence of higher-than-average sources of indoor pollutants.

One of the procedures by which presently excluded homes may be permitted to be tightened would be to install air-to-air heat exchangers in such residences. These devices can be utilized to increase the ventilation rate to its original magnitude (before the tightening) while recovering much of the heat energy that would otherwise be lost if this ventilation is provided without heat recovery (e.g. by infiltration or exhaust fans). We discuss the energy savings and cost-effectiveness of heat-exchanger use in electrically heated houses in the BPA region. We consider only the energy savings resulting from heat exchanger use during the winter heating season and only a heat exchanger of the type that is designed for installation through walls or windows. In a previous report, we discussed the energy savings and cost-effectiveness of heat exchanger use in newly constructed homes.[3]

2. BPA WEATHERIZATION PROGRAM

A. Weatherization Measures

It is expected that 312,000 electrically heated residences (790,000 occupants) in the states of Washington, Oregon, Idaho, and western Montana (the BPA region) will be weatherized. The weatherization measures can be divided into two groups. The following will be offered to owners of all houses eligible for weatherization: insulation of ceiling and attic; insulation of floor; insulation of unfinished walls; installation of a vapor barrier in the floor; insulation and sealing of air ducts; insulation of water pipes; installation of a dehumidifier; installation of clock thermostat;

Only measures (4) and (5) alter the infiltration rate (i.e., the rate at which inside air is replaced by outside air due to leakage through the building envelope) significantly and, thus, directly affect indoor contaminant levels. Measure (5), sealing of air ducts that are located in non-space-conditioned areas, can substantially reduce the amount of outside air reaching living areas of a residence. Measure (4), installation of a vapor barrier in the floor of a residence, may also reduce infiltration.

In homes where significant sources of indoor air pollutants are not expected to be present, the following measures will also be offered: (9) caulking (10) weatherstripping (11) storm windows and doors (12) outlet and switchbox gaskets. These measures may decrease the amount of air infiltrating into the residence and thus may increase the indoor concentrations of contaminants generated within the residence. The effects of these four measures on infiltration rate is discussed below.

B. Infiltration Rate Reduction from Weatherization

A key factor in determining the potential impact of the weatherization program on indoor air quality is the reduction in infiltration rate achieved by weatherization of existing homes. We use the estimated reduction in infiltration rate to indicate the amount of mechanical ventilation that must be supplied by the heat exchanger to assure equal average ventilation rates in untightened and tightened homes. Actually, the weatherized home will have less fluctuation in its ventilation rate during the heating season since the heat exchanger fans provide some constant amount of ventilation regardless of effects of weather on infiltration. Therefore, peak concentrations of indoor generated pollutants may be lower in weatherized homes.

Data from weatherization studies in Medford, (Oregon), Midway, (Washington), and Walnut Creek, (California) have been analyzed. These are the only weatherization studies for which carefully documented data are available on leakage areas or infiltration rates before and after weatherization and for which the level of effort expended in the weatherization is specifically accounted for and within the range of effort in the BPA weatherization programs. In some cases, infiltration rates were measured directly by a tracer gas decay method but, in most cases, the effective leakage area was determined.

The concept of effective leakage area is central to a predictive model of infiltration developed at LBL, which assumes that the infiltration rate is proportional to the effective leakage area.[4,5] The effective leakage area is determined by the use of a fan (i.e., blower door) which pressurizes or depressurizes a house to indicate the relationship between air leakage through the building envelope and the indoor-outdoor pressure differential. Given the effective leakage area, local windspeed and temperature, building height, and various shielding factors, the infiltration rate can be estimated by use of a model that relates infiltration rate to all of these factors.

The results of the three weatherization studies are displayed in Table 1, which shows the reduction in infiltration rate or leakage area achieved by the specified weatherization measures. The first two houses in Medford, (Oregon) showed average infiltration rate reductions of 20 and 30%, respectively, for measures A, B, and C. These measures do not involve caulking or use of a blower door to identify leakage paths.[6] The infiltration rate in the first house was reduced from an average (over two weeks) of 0.62 to 0.49 air changes per hour (ach) with the addition of storm doors and windows, the replacement of two sliding glass doors and the weatherstripping of doors. For the second house, the infiltration rate was reduced from 0.82 to 0.58 ach with the addition of storm doors and windows and the replacement of one sliding glass door. The doors were already weatherstripped in this house. The other seven houses in Medford showed no statistically significant reduction in leakage area (which is assumed to be proportional to infiltration rate) when measures A and C were carried out. The researchers concluded that the full potential for reducing air leakage was not realized because the ductwork for the heating system, which was located in unconditioned spaces, was very leaky.

In Midway, (Washington), twelve relatively tight houses (all having air infiltration rates less than 0.5 ach for the heating season) were weatherized in two phases.[7] In Phase I, 6 houses had storm doors and windows added, and caulking was applied around the foundation sill. The average reduction in leakage area was 14% with a range of 0 to 43%. In Phase II, a house-tightening technique was used where, in addition to weatherstripping, a blower-door, smokesticks and an infrared scanner were used to detect air leaks that were then plugged by caulking and taping. When the Phase II procedure was carried out in the first six houses, an additional 20% reduction in leakage area was achieved for a total of a 31% reduction. In six other unweatherized houses, a similar approach was used to achieve an average reduction in infiltration rate of 27%. In this case, twice as much time (2 person-days) was spent weatherizing the houses.

The last weatherization study listed in Table 1 took place in Walnut Creek, (California).[8] One day of house-tightening resulted in a 25% average reduction in leakage area in 19 houses. The range of reduction was 8 to 61%. As might be expected, the 61% reduction took place in a very leaky house.

Summarizing these results, it appears that tightening measures can be expected to reduce effective leakage area on average about 20 to 30%, with a range for individual houses of 0 to 60%. Since the leakage area approach does not include natural ventilation from door and window openings, we should expect a somewhat smaller percentage reduction in total ventilation rate than given by the leakage area reduction. We now discuss residential air-to-air heat exchangers and describe the analysis utilized to predict energy savings and cost-effectiveness.

3. DESCRIPTION OF RESIDENTIAL HEAT EXCHANGERS

The device used to provide residential mechanical ventilation with heat recovery is called a residential air-to-air heat exchanger. A residential heat exchanger generally consists of a core, two fans, and two filters all mounted in an insulated case (Fig. 1). One fan brings outdoor air (supply air) through the core and into the house while the second fan causes an equal amount of house air (exhaust air) to pass through the core and out of the house. As the air passes through the core, heat is transferred from the warmer to the cooler airstream (without mixing). Thus, in the winter, the supply air is warmed before entering the house and the exhaust air is cooled before leaving the house. Residential heat-exchanger characteristics and performance are described for several models in two reports.[9,10] One of the performance parameters described in these reports is the heat exchanger effectiveness. The effectiveness is defined as the ratio of actual heat transfer to the heat transfer that would occur in an infinitely large counterflow heat exchanger. It indicates approximately the amount of preheating of the supply airstream. Thus, a 70% effective heat exchanger would preheat the supply airstream by approximately 70% of the difference between indoor and outdoor temperatures.

Most models of residential heat exchangers are used with a duct system for air distribution. Supply ductwork carries outdoor air to the exchanger and then distributes it to various locations throughout the residence. In many houses, the furnace duct system can be used for a portion of the supply ductwork. Exhaust ductwork carries house air to the heat exchanger and then out of the house. In the BPA area, approximately 30% of electrically heated homes have ductwork to supply hot air from a central furnace.[11]

Some models of residential heat exchangers can be mounted in a wall or window (much like a window air conditioner), avoiding the need for a system of ductwork. Two-thirds of electrically heated residences in the BPA area have no ductwork. Thus, window units may be more cost-effectively employed in these residences because they are less expensive to install.

A concern with window- and wall-mounted heat exchangers is that they may not ventilate all spaces within a residence at an equal rate and they may provide less ventilation than expected. To address this issue, the ventilation efficiency of two commercially available heat exchangers designed for installation through walls or windows was determined in a series of tests.[12] A tracer gas (SF_6) was introduced into the multi-room test spaces and the SF_6 concentration was measured vs. time at a number of indoor locations as the ventilation air provided by the heat exchanger reduced the SF_6 concentration. The ventilation efficiency is defined here as the ratio of the average observed rate of change in tracer gas concentration (at six indoor locations) to the rate of change in concentration that would be predicted if the heat exchanger supplied its rated amount of ventilation air, perfect mixing of indoor air existed, and no short circuiting or cross-stream leakage occurred between exhaust and supply air streams. The term short circuiting is utilized to describe the entrainment of air exiting from the exchanger at locations interior and exterior to the house into the corresponding airstreams entering the exchanger, and is a special case of poor mixing near the heat exchanger. At a medium fan speed (65 cfm), the Mitsubishi VL-1500 heat exchanger had an average ventilation efficiency of approximately 50%, with a range from 36 to 65% for seven tests. Tests performed with another heat exchanger (Sharp GV-120) at the high fan speed (56 cfm) also indicated an average ventilation efficiency of approximately 50% with a range from 44 to 56% for four tests. Based on these data, we have assumed a 50% ventilation efficiency for our analysis.

A second concern with the performance of commercially available models of window- or wall-mounted heat exchangers is the transfer of contaminants from the exhaust to the supply airstream. The ventilation efficiency, measured by the tracer gas decay method, accounts for contaminant transfer due to air leakage and short circuiting. However, the cores of some commercially available window- or wall-mounted heat exchangers (and some other exchangers) are designed so that both moisture and heat are transferred between airstreams and in these exchangers some contaminants may be transferred by a mechanism similar to that for moisture transfer. This type of contaminant transfer, if it occurs, would decrease the effectiveness of the exchanger in reducing indoor contaminant concentrations. For our analysis, we have assumed that contaminant transfer is not a problem. However, some evidence exists for the transfer of formaldehyde in one model of window-mounted heat exchanger,[13] and further research is required to study this potential problem.

4. METHODOLOGY FOR CALCULATING ENERGY SAVINGS

A. Introduction

Both natural infiltration and mechanical ventilation with heat recovery impose a heat load on the home heating system and the sum of these heat loads is called the ventilation heat load. Ventilation with heat recovery imposes a smaller heat load than ventilation due to natural infiltration because the heat recovery system preheats the incoming air. To determine the energy savings resulting from the use of mechanical ventilation with heat recovery, we compare the energy required to heat ventilation air for the untightened house to that for the tightened house with additional ventilation provided by a heat exchanger. In the untightened house, all ventilation is uncontrolled and occurs without heat recovery. In the tightened house, a smaller amount of uncontrolled ventilation occurs and some of the ventilation is provided mechanically and passes through an air-to-air heat exchanger. By subtracting the ventilation heat load in the tightened house from that in the untightened or base case house, a ventilation heat-load reduction can be determined. The details of the calculation of ventilation heat load are described in Sec. 4B.

B. Calculation of Ventilation Heat Load in the Untightened House

To calculate the ventilation heat load of an untightened house, we utilized weather data from the Engineering Weather Data Manual of the U.S. Air Force[14]. This manual contains a list by month of the average number of hours the outdoor temperature falls within consecutive 2.8°C (5°F) temperature bins for cities throughout the United States. Equation (1) is utilized to calculate the ventilation heat load, Q:

$$Q = \rho C p V \text{ (ach) } \sum_j (T_i - T_j) \theta_j \qquad (1)$$

where ρ and Cp are the density and specific heat at constant pressure, respectively, of indoor air, V is the house volume, ach is the air exchange rate for the house expressed in air changes per hour, T_i is the indoor temperature, T_j is the outdoor temperature at the midpoint of a bin, and θ_j is the number of hours that the outside temperature falls within the corresponding temperature bin. The degree hour summation in Eq. (1) is computed only for those hours when the outside temperature is less than the balance point temperature of the house.[+] We did not take into account night setback of the thermostat setpoint. If this were done, there would be a reduction in the predicted ventilation heat load and energy savings.

[+] The balance point is the minimum outdoor temperature for which heat is required from the home heating system. For an average existing house, this temperature is approximately 60°F. We assumed a balance point temperature of 55°F which may be slightly low; however, the resuling error in our analysis is not significant.

C. Calculation of Ventilation Energy Requirements for a Tightened House with Heat Exchanger

In a tightened house employing mechanical ventilation with heat recovery, four factors must be accounted for when calculating the ventilation heat load: (1) uncontrolled ventilation (e.g. infiltration) in the tightened house imposes a heat load, (2) operation of the heat exchanger contributes to the ventilation heat load because the heat-exchanger effectiveness is not 100%, (3) some fraction of the heat released by the heat exchanger fan system is delivered to the house and thus reduces the ventilation heat load, and (4) characteristics of the heat exchanger freeze protection system affect the ventilation heat load. We consider the ventilation heat load to be only the load imposed on the home furnace system; the energy requirements for operating the heat exchanger fan system and freeze protection system (discussed later) are considered separately.

For the tightened house, most of the ventilation is still provided by natural infiltration and occupant's activities (e.g. door openings). Equation (1) is used to determine the corresponding portion of the ventilation heat load.

The ventilation heat load due to ventilation through the heat exchanger depends on the effectiveness of the heat exchanger; the effectiveness is described more fully elsewhere.[9,10] We assume that the heat exchanger operates continuously during the specified heating season and that it is turned off during other times of the year when windows are likely to be open. This portion of the ventilation heat load is calculated using Eq. (1) with an air-exchange rate corresponding to the increase in air exchange rate provided by the heat exchanger. To account for preheating of the air by the heat exchanger, the result from Eq. (1) is then multiplied by the factor $(1-\epsilon)$ where ϵ is the effectiveness of the heat exchanger.

The third factor that affects the ventilation heat load in the tightened house is the generation of heat by the heat exchanger fans and fan motors. Some fraction of this heat energy is delivered to the residence and thus reduces the ventilation heat load. Commercially available models of residential heat exchangers that are designed for installation through walls or windows use one fan motor to drive both fans. For this configuration, it is difficult to estimate the fraction of the generated heat energy that is saved; however, based upon the location of the fan motor, we assume that 50% of the fan energy consumption is delivered to the residence in the form of heat.

During cold weather, a freeze-protection system is required to prevent deterioration in heat exchanger performance due to freezing in the core, and the performance of the freeze-protection system is a fourth factor that affects the ventilation heat load. For our analysis, we assume that heat exchangers installed in Spokane, Lewiston, and Helena employ an electric resistance preheater to prevent freezing. In Portland, the weather is sufficiently warm so that a freeze-protection system is probably not required. We further assume, based upon the design of a freeze protection system for the Mitsubishi VL-1500 exchanger, that the electric preheater is thermostatically controlled such that outdoor air is heated to -9.4°C (15°F) before entering the core[15]. Presently, little information is available on freeze protection systems; however, a sensitivity analysis by Fisk and Turiel[3] indicates that reasonable changes in the assumed performance of the freeze protection system will have a small effect on our results.

The total ventilation heat load for the tightened house is calculated by summing the loads due to infiltration and mechanical ventilation (with heat exchanger inefficiency and preheat freeze protection accounted for) and subtracting the amount of fan energy delivered to the house.

The two other, energy-related parameters calculated for the tight house are the fan energy consumption and the energy required for the electric resistance preheater used for freeze protection. The energy consumed by the fan system equals the product of the fan power and the period of time the heat exchanger is operated. The energy required for the electric resistance preheater is calculated using weather data and the rate of air flow through the heat exchanger. Because the ventilation efficiency of the exchangers was assumed to equal 50%, the air flow rates are twice that indicated by the product of house volume and increase in air exchange rate.

Using the results for both the tightened and untightened houses, two additional energy parameters are calculated. The ventilation heat load reduction is the ventilation heat load in the untightened house minus that in the tightened house with a heat exchanger. The net energy saving equals the reduction in ventilation heat load minus the energy required for the heat exchanger fan and freeze protection systems.

4. METHODOLOGY FOR COST/BENEFIT ANALYSIS

The economic desirability of employing a mechanical ventilation system and heat exchanger in a residential building can be assessed by comparing the savings in energy costs derived from the use of such a system to the incremental costs incurred from its purchase, installation, maintenance, and operation. There are a number of economic criteria that may be used to rank potential capital investments. These include rate of return, net present benefit or reduction in life-cycle cost, discounted payback period, and benefit to cost ratio[16]. All of these, except discounted payback period, yield the same rank ordering when potential investments of equal lifetime and initial cost are compared.

Net present benefit (NPB) is calculated by subtracting capital, operating and maintenance costs from the energy cost savings. Equation (2) is the equation we have used for calculating NPB in this study:

$$\mathrm{NPB} = (\mathrm{FBS}) \sum_{i=1}^{N} \left[\frac{1+f}{1+d}\right]^{i} - (\mathrm{OPC}) \sum_{i=1}^{N} \left[\frac{1+f}{1+d}\right]^{i} - \mathrm{CC} - M \sum_{i=1}^{N} \frac{1}{(1+d)^{i}} \qquad (2)$$

where FBS = fuel bill savings in year 1, OPC = operating cost of fans and freeze protection system in year 1, CC = incremental capital cost of conservation measure, M = annual maintenance cost, f = real escalation rate for electricity price, N = lifetime of heat exchanger, and d = real discount rate. The value of future cash flows is discounted by an appropriate discount factor (d) that corrects for the lost opportunity to invest resources otherwise.

The benefit-to-cost ratio is equal to the sum of the discounted energy cost savings [i.e., the first term in Eq. (2)] divided by the sum of capital costs and discounted maintenance and operating costs [i.e., the sum of remaining terms in Eq. (2)]. The discounted payback period is defined as the length of time required to recover an initial investment taking into account fuel price escalation rates and the time value of money. Thus, it equals the amount of time required for the NPB to become positive. We also calculated the initial fuel price at which the investment in house-tightening and heat exchanger use would just become cost-effective to a homeowner. From the homeowner's perspective, it can be thought of as a break even fuel price (BEFP). It is derived by setting the NPB equal to zero and solving for the fuel price, given an assumed fuel price escalation rate, discount rate, and lifetime.

There are two other economic parameters that we have calculated that are not usually used in cost-benefit analyses. The first parameter, the cost of conserved energy (CCE), is calculated from the utility company's perspective. It is a useful parameter for comparison of energy costs from utility financed programs such as new power plant construction and energy conservation measures. We have defined the CCE to equal the capital cost of the investment in energy conservation (house-tightening plus heat exchanger purchase and installation) divided by the net energy saved over the heat exchanger lifetime. In our calculations, we have assumed that the utility company borrows the money needed for the investment in conservation, at a real interest rate i. Therefore, the CCE is given by Eq. (3) where CC is the capital cost of the conservation measure, ΔE is the net energy saved by the measure, and N is the lifetime of the measure,

$$CCE = \frac{CC}{\Delta E}\left[\frac{i}{1 - (1+i)^{-N}}\right] \quad (3)$$

The quantity in brackets (the uniform capital recovery factor), when multiplied by CC, gives the annual payment needed to pay off a loan of CC dollars at interest rate i, in N equal installments.

The cost of conserved energy, as we have defined it, is independent of energy costs. If the CCE is less than the marginal cost of electricity, then the investment in conservation by the utility is worthwhile. Even though the CCE does not change over time, it is important to note that the marginal cost of electricity does change. Therefore, when comparing conservation measures to new power plant production, the weighted average marginal cost of electricity over the lifetime of the measure should be used[17]. This requires knowledge of the escalation rate of marginal electricity prices.

Some homeowners may be considering the following two alternatives: (1) tighten their house and not utilize a heat exchanger (i.e., accept any resulting degradation in indoor air quality) or (2) tighten their house and utilize a heat exchanger. For these residents, the cost of heat exchanger utilization (CHEU) has been calculated. This parameter equals the present value of capital, installation, maintenance, and operation costs over the 20 year life of the heat exchanger. The cost of operation consists of the cost to operate the heat exchanger fan and freeze protection systems and the cost to heat the ventilation air supplied by the heat exchanger. The cost of tightening the house is not included as a component of the capital cost when calculating the CHEU because the calculation is based upon a comparison of the tightened house with and without additional ventilation provided by the heat exchanger.

5. ASSUMPTIONS FOR ENERGY AND ECONOMIC ANALYSIS

To perform the energy analysis and evaluate the various economic parameters, that are indicators of the cost-effectiveness of using heat exchangers in low infiltration houses, a number of assumptions were required. We estimated the incremental capital cost of the conservation measure which consists of the cost for the labor and materials necessary to tighten the house and the purchase price plus the installation cost of the heat exchanger as discussed below.

The cost of weatherstripping doors and windows and applying caulking to cracks and joints throughout the building envelope has been estimated to be $330 per house based upon data from previous weatherization studies.[7] This process (which takes one person day) includes the use of a blower door to pressurize the house and smokesticks and an infrared scanner to locate infiltration leaks. The estimated heat exchanger costs are based upon quotes from the distributor of the Mitsubishi VL-1500 exchanger and are applicable when heat exchangers are purchased in large quantities.[16] The heat exchanger costs we used are $350 and $250 with and without a freeze protection system, respectively. The installation cost is estimated to be $120 based upon installation costs in two field studies performed by LBL. Thus, the total capital investment, for the heat exchanger, in 1982 dollars, is estimated to equal $700 in cities which do not need freeze protection such as Portland, (Oregon) and $800 in cities requiring freeze protection.

There is presently little experience with maintenance costs for residential heat exchangers. We estimated that filters will need periodic cleaning or replacement and that the core may also need periodic cleaning. We have assumed a maintenance cost of $10 per year that grows at the rate of inflation.

All other major assumptions are shown in Table 2. We have assumed that the average house had an infiltration rate of 0.65 ach before weatherization. This infiltration rate is approximately equal to the average infiltration rate predicted for the heating season, primarily from leakage area measurements, in 224 U.S. houses.[18] For the four cities in the BPA region chosen for our analysis, the heating seasons are assumed to extend: from October 1 to April 30 in Spokane, (Washington) and Lewiston, (Idaho), from September 1 to April 30 in Helena, (Montana), and from November 1 to April 30 in Portland, (Oregon). We assumed an average infiltration rate of 0.50 ach after weatherization which corresponds to about a 25% decrease in infiltration. The average house floor area (1500 ft^2) was obtained from a survey of residential buildings in the BPA area[11] and a floor to ceiling height of 2.4m (8 ft) was assumed.

The assumed total fan power (42W) is the fan power measured for the Mitsubishi VL-1500 heat exchanger when operating at medium fan speed and is similar to the fan power required for the Sharp GV-120 heat exchanger when operating at high fan speed (41W)[10,12]. The increase in ventilation of 0.15 ach in a 340m^3 house corresponds approximately to the amount of ventilation provided by the Mitsubishi and Sharp exchangers (taking ventilation efficiency into account) when operating at medium and high fan speeds, respectively.[12] A heat-exchanger effectiveness of 60% is based upon performance measurements.[10,19]

Residential electricity prices utilized are current as of July 1, 1982, for the four cities studied (see Table 3). We assumed a real (after inflation) escalation rate of 1% for the price of electricity consistent with projections by BPA and the Energy Information Administration. We assumed a real discount rate of 3%.

6. RESULTS OF ENERGY AND ECONOMIC ANALYSIS

Results of our energy analysis are presented in Table 4. Ventilation heat loads are tabulated for both the untightened and tightened homes. These loads equal the amount of energy that must be supplied by the home heating system to heat ventilation air during the specified season. Also shown in Table 4 is the reduction in ventilation heat load and the total electrical energy consumed annually by the heat exchanger fan system and freeze protection system. The estimated net annual energy savings is equal to the ventilation heat load reduction minus the energy consumed by the fans and preheat system and is listed in the final column of Table 4.

The reduction in ventilation heating load ranged from 2.4 to 4.1 GJ (23 to 39 therms) with the largest reduction in Helena, (Montana). The percentage reduction in ventilation heat load (i.e., heat load reduction divided by heat load in the untightened house) is nearly uniform for the four cities ranging from 14 to 17%. The energy required for preheat protection was 0.1, 0.2, and 0.5 GJ (0.8, 1.6 and 4.5 therms) in Spokane, Lewiston, and Helena, respectively. The estimated annual energy savings vary from 16.5 therms in Portland to 25.9 therms in Helena.

Table 5 summarizes the results of our economic analysis for the four cities for houses using electricity as the heating source. The net present benefit (NPB), discounted benefit-to-cost ratio (B/C ratio), discounted payback period, break even fuel price (BEFP), cost of conserved energy (CCE) and net present value of costs (NPVC) are shown. The analysis assumes a 20 year life for the heat exchanger with a zero salvage value. None of the cities have a positive NPB or B/C ratio greater than one, and all of the cities have discounted payback periods greater than 30 years. While Portland has the mildest climate of the four cities considered, it also has the largest NPB at -$534. This result is not surprising since Portland also has the largest electric prices at 4¢/kWh and a lower capital cost for the heat exchanger. Helena has the coldest climate of any of the four cities considered but is ranked second by the NPB criteria since there is an additional capital cost in Helena (relative to Portland) due to freeze protection and, in Helena, residential electricity rates are lower than in Portland. Since all net present benefits are negative in the BPA region, the utilization of heat exchangers, from the homeowner's perspective, is not cost effective at this time.

This conclusion is reinforced by the results of the break even fuel price analysis. The electricity prices in the four cities studied would have to increase by a factor of 2.5 to 3 before investment in house tightening and a heat exchanger would be cost-effective for a homeowner.

To determine whether or not the energy conservation measure is cost-effective to the utility (BPA in this case), we have calculated the cost of conserved energy. The values of the CCE found in Table 5 are calculated with the assumption that the utility company pays for the capital investment ($700 in Portland, $800 in the other cities), with money it could have used to earn a 3% real return. The CCE varies from 7.1 to 9.7¢/kWh in the four cities which is significantly higher than present cost of electricity in the BPA region. However, the CCE should be compared to a weighted average marginal cost of electricity to the utility.

If the CCE is compared to average marginal costs (the cost of providing electricity from new power plants), then, from the utility perspective, the use of heat exchangers in the weatherization program may be cost-effective. That is, it would be beneficial for the utility companies to subsidize heat exchanger installation, if marginal electricity prices are significantly higher than the cost of conserved energy. This may be the case in the BPA area, where several new nuclear power plants are under construction.

The cost of heat exchanger utilization (CHEU) ranged from $837 in Portland to $1035 in Helena. Some homeowners will find this cost too high to justify the improvement in indoor air quality that results when a heat exchanger is utilized. Other homeowners may feel that the value of improved indoor air quality exceeds the CHEU and proceed with heat exchanger utilization.

In summary, all four cities show net energy savings from house tightening and heat exchanger installation. However, from the homeowner's perspective, the economic benefits derived from the energy savings for the four cities are not greater than the economic costs at present energy prices.

Sensitivity Studies

The results of the economic analysis depend on estimates for several factors. These include discount rate, appliance lifetime, electricity price escalation rate, and initial capital cost. There is always some uncertainty in determining the values for these parameters. A sensitivity analysis was performed to evaluate the relative importance of the key assumptions. The sensitivity studies are centered around our base case assumptions which are a 3% real discount rate, 1% electricity price escalation rate, the given fuel prices (Table 3), a 20 year lifetime, and the primary assumptions in Table 2.

A 3% real discount rate implies that new home buyers, as an alternative to investing in a more energy efficient house, could choose to invest differently and earn 3% more than the inflation rate. If the inflation rate were 10%, consumers could obtain a 13% nominal return for a given investment. Adjustments in the discount rate to 1% and 5% did not change the signs of the NPB in any of the four cities. In Portland, a 5% discount rate (67% increase) resulted in only a 13% decrease in the B/C ratio, while a 1% discount rate (67% decrease) increased the B/C ratio by only 16%.

The analysis assumed a 1% real residential electric fuel price escalation rate over the 20 year lifetime of the heat exchanger. Use of 2 and 3% real escalation rates leaves the NPB for the four cities still highly negative. The increases in the price escalation rate to 2% and 3% per year, respectively, resulted in only a 9% and 18% increase in the B/C ratios in Helena.

A change in the capital cost will change the NPB by the amount of the change in the capital cost. For instance, if the initial capital cost is $200 lower than assumed, the NPB is increased by $200. If initial costs are $200 more than assumed, the NPB is decreased by $200. Even with a $200 change in initial capital costs, the B/C ratio will remain less than one for all cities.

An adjustment in the assumed life of the heat exchanger to 10 or 30 years does not change the sign of any of our NPB results; they all remain negative. In Spokane, a decrease in heat exchanger life to 10 years results in a 40% reduction in B/C ratio while an increase in heat exchanger life to 30 years results in a 26% increase in B/C ratio to 0.44.

Adjustment of heat-exchanger effectiveness from the assumed rate of 60 to 85% increases the ventilation heat load reduction for the tightened houses with heat exchangers by approximately 38% for each of the four climates considered. Even with this significant heat exchanger performance improvement, all of the cities studied still have highly negative NPB. Given an 85% heat exchanger effectiveness, the NPB criterion would rank Helena first with a NPB of -$443 and Portland second with a NPB of -$476, the reverse of the order with the assumed 60%

effectiveness.

7. Summary and Conclusions

Based on the set of assumptions previously stated, from the homeowner's perspective, the use of window unit heat exchangers in the BPA weatherization program is not presently cost effective. The present situation could change if average electricity prices rise to the level of the break-even fuel price (~8¢/kWh) in regions with 3000 degree-days (^{o}C) or colder climates. From the viewpoint of BPA, the use of heat exchangers would be cost-effective when the weighted average marginal cost of electricity reached the cost of conserved energy. It should be noted that the price of electricity in the BPA area is lower than most other parts of the United States. In cities where electricity prices are already at the 8¢/kWh level, the use of window unit heat exchangers in retrofit programs would presently be cost-effective from both the homeowner's and utility's perspectives in regions with cold climates.

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REFERENCES

1. A.V. Nero, I. Turiel, W.J. Fisk, J.R. Girman, and G.W. Traynor, "Exclusion Methodology for Weatherization Program in the Pacific Northwest," Lawrence Berkeley Laboratory Report, LBL-14467 (May 1982), Berkeley, CA 94720.

2. "Revised Environmental Assessment", Proposed BPA Regionwide Weatherization Program, Division of Energy Conservation, Bonneville Power Administration (September 1981), Portland, Oregon, 97208.

3. W.J. Fisk and I. Turiel, "Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics", Lawrence Berkeley Laboratory Report LBL-13843 (February 1982), Berkeley, CA 94720 submitted to Energy and Buildings.

4. M.H. Sherman and D.T. Grimsrud, "Measurement of Infiltration Using Fan Pressurization and Weather Data," Lawrence Berkeley Laboratory Report, LBL-10857 (October 1980), Berkeley, CA 94720.

5. D.L. Krinkel, D.J. Dickerhoff, J. Casey, and D.T. Grimsrud, "Pressurization Test Results: Bonneville Power Administration Energy Conservation Study," Lawrence Berkeley Laboratory Report, LBL-10996 (December 1980), Berkeley, CA 94720.

6. J.V. Berk, R.A. Young, S.R. Brown, and C.D. Hollowell, "Impact of Energy-Conserving Retrofits on Indoor Air Quality in Residential Housing," Lawrence Berkeley Laboratory Report, LBL-12189 (January 1981), Berkeley, CA 94720.

7. J.B. Dickinson, D.T. Grimsrud, D.L. Krinkel, and R.D. Lipschutz, "Results of the Bonneville Power Administration Weatherization and Tightening Projects at the Midway Substation Residential Community," Lawrence Berkeley Laboratory Report, LBL-12742 (January 1982), Berkeley, CA 94720.

8. Energy Efficient Buildings Program, Chapter from Energy and Environment Division Annual Report 1980, pp 4-57 to 4-61, Lawrence Berkeley Laboratory Report, LBL-11985 (May 1981), Berkeley, CA 94720.

9. W.J. Fisk, G.D. Roseme, and C.D. Hollowell, "Performance of Residential Air to Air Heat Exchangers: Test Methods and Results," Lawrence Berkeley Laboratory Report LBL-11793 (September 1980), Berkeley, CA 94720.

10. W.J. Fisk, K.M. Archer, P. Boonchanta, and C.D. Hollowell, "Performance Measurements for Residential Air-To-Air Heat Exchangers", presented at the International Symposium on Indoor Air Quality, Amherst, Massachusetts, October 13-16, 1981, Lawrence Berkeley Laboratory Report LBL-12559, Berkeley, CA 94720.

11. Elrich and Lavidge Inc., Consultants, "The Pacific Northwest Residential Energy Survey" (July 1980), Bonneville Power Administration, P.O. Box 362, Portland, Oregon, 97208.

12. F.J. Offermann, W.J. Fisk, B. Pederson, and K.L. Revzan, "Residential Air-to-Air Heat Exchangers: A study of Ventilation Efficiencies," Lawrence Berkeley Laboratory Report, LBL-14358, (May 1982), Berkeley, CA 94720 in draft.

13. F.J. Offermann, J.B. Dickinson, W.J. Fisk, D.T. Grimsrud, C.D. Hollowell, D.L. Krinkel, G.D. Roseme, R.M. Desmond, J.A. deFrees, and M.C. Lints, "Residential Air Leakage and Indoor Air Quality in Rochester, New York," Lawrence Berkeley Laboratory Report, LBL-13100, (June 1982), Berkeley, CA 94720.

14. "Facility Design and Planning Engineering Weather Data", Air Force Manual 88-29, (1978).

15. Personal communication on July 20, 1982 with Mike Thomas, Mitsubishi Electric Sales America Inc., 30330 East Victoria Street, Compton, California 90221.

16. R.J. Brown and R.R. Young, "Life Cycle Costing: A Practical Guide for Managers", Fairmount Press, Atlanta, Georgia (1980).

17. A. Meier, "The Cost of Conserved Energy as an Investment Statistic", Energy and Resources Group (1982), University of California, Berkeley, CA 94720.

18. D.T. Grimsrud, et al., "Calculating Infiltration: Implication for a Construction Quality Standard," Lawrence Berkeley Laboratory Report, LBL-9416, in draft.

19. A Persely, "Understanding Air Infiltration in Homes", The Center for Energy and Environmental Studies, Princeton University, Report PU/CEES #129 (February 1982), Princeton, N.J.

Table 1. Summary of infiltration and leakage area reductions from weatherization

City	Number of Houses	Infiltration rate reduction, %	Average leakage-area reduction, %	Weatherization measures
Medford, Oregon	2	20,30		A + B + C
	7		0	A + C
Midway, Washington	6		14	A + D
	6		27	F
	6†		20	E
Walnut Creek, California	19		25	E

†Same six houses that already received A + D weatherization measures were used.

A = add storm doors and windows; B = weatherstrip doors; C = replace sliding glass doors; D = caulk around foundation sill; E = one day "house doctor" program which includes use of blower door to find and plug leaks in building shell; F = same as E but two days taken.

Table 2. Major assumptions for energy and economic analysis

	untightened house	tightened house
1 Infiltration rate (ach)	0.65	0.50
2 Ventilation through HX[†] (ach)	---	0.15
3 House Volume (m^3 ($ft^3 \times 10^{-3}$))	339.6 (12)	339.6 (12)
4 Balance Point (^oC (^oF))	12.8 (55)	12.8 (55)
5 Indoor temperature (^oC (^oF))	20 (68)	20 (68)
6 Apparent HX effectivenesss	---	0.60
7 Total HX fan power (w)	---	42
8 Percent of total fan power that is delivered to residence in the form of heat (%)	---	0.50
9 Outdoor temperature at onset of freezing in HX (^oC (^oF))	---	-9.4 (15)
10 Initial capital cost ($)	---	800[‡]
11 Yearly maintenance Cost ($)	---	10

[†] HX = heat exchanger

[‡] In Portland, the initial capital cost is $700.

Table 3. June 1982 electricity prices

City	$/GJ	($/10^6 Btu)	¢/kWh
Portland[†]	11.02	(11.63)	3.968
Lewiston[‡]	6.67	(7.04)	2.402
Spokane[‡]	6.28	(6.62)	2.259
Helena[§]	8.07	(8.51)	2.905

[†] Source: Portland General Electric; [‡] Source: Washington Water and Power; [§] Source: Montana Power Company.

Table 4. Results of energy analysis for houses in four pacific northwest cities.

	†Ventilation heat load in untightened house		‡Ventilation heat load in tightened house with heat exchanger		§Ventilation heat load reduction		Fan energy consumption		Preheat System Energy consumption		¶Annual energy savings	
	GJ	Therms	GJ	therms	GJ	therms	GJ	therms	GJ	therms	GJ	therms
Portland	15.2	144.3	12.8	121.5	2.4	22.8	.66	6.3	na	na	1.7	16.5
Lewiston	21.1	200.5	17.7	168.3	3.4	32.2	.77	7.3	.2	1.6	2.5	23.3
Spokane	22.7	214.9	19.1	181.3	3.6	33.6	.77	7.3	.1	0.8	2.7	25.6
Helena	24.4	231.2	20.3	192.6	4.1	38.6	.86	8.2	.5	4.5	2.7	25.9

†The heat load imposed on the heating system during the specified heating season due to uncontrolled ventilation. ‡The ventilation heat load in the tightened house with heat exchanger is equal to the heat load imposed on heating system due to uncontrolled ventilation, and heat exchanger inefficiency, minus the amount of energy that is released by fan system and delivered to the residence. §The ventilation heat load reduction is equal to the ventilation heat load in the tightened house minus that in untightened house. ¶The annual energy savings equals the ventilation heat load reduction minus fan energy and preheat energy.

Table 5. Results of cost/benefit analysis

City (Heating °C Days)[†]	Net[‡] present benefit	Discounted[‡] benefit/cost ratio	Discounted payback period (years)	break-even[§] fuel price, ¢/kWh	Cost of[¶] conserved energy, ¢/kWh	Cost of Heat[‖] exchanger utilization ($)
Portland (2644)	-534	.45	>30	10.7	9.7	837
Lewiston (3018)	-689	.34	>30	8.8	7.9	893
Spokane (3779)	-676	.35	>30	7.9	7.1	884
Helena (4532)	-621	.45	>30	8.4	7.1	1035

[†] The yearly total degree-days are computed for an, 18.3°C base temperature. [‡] The benefit to cost ratio and the net present benefit are based on a 20-year life for the heat exchanger and zero salvage value. [§] The break-even fuel price is the electricity price which sets the NPB = 0 in 20 years.
[¶] The cost of conserved energy is the amortized capital cost divided by the net energy saved. [‖] The cost of heat exchanger utilization is the present value of heat exchanger purchase price, installation, maintenance and operation.

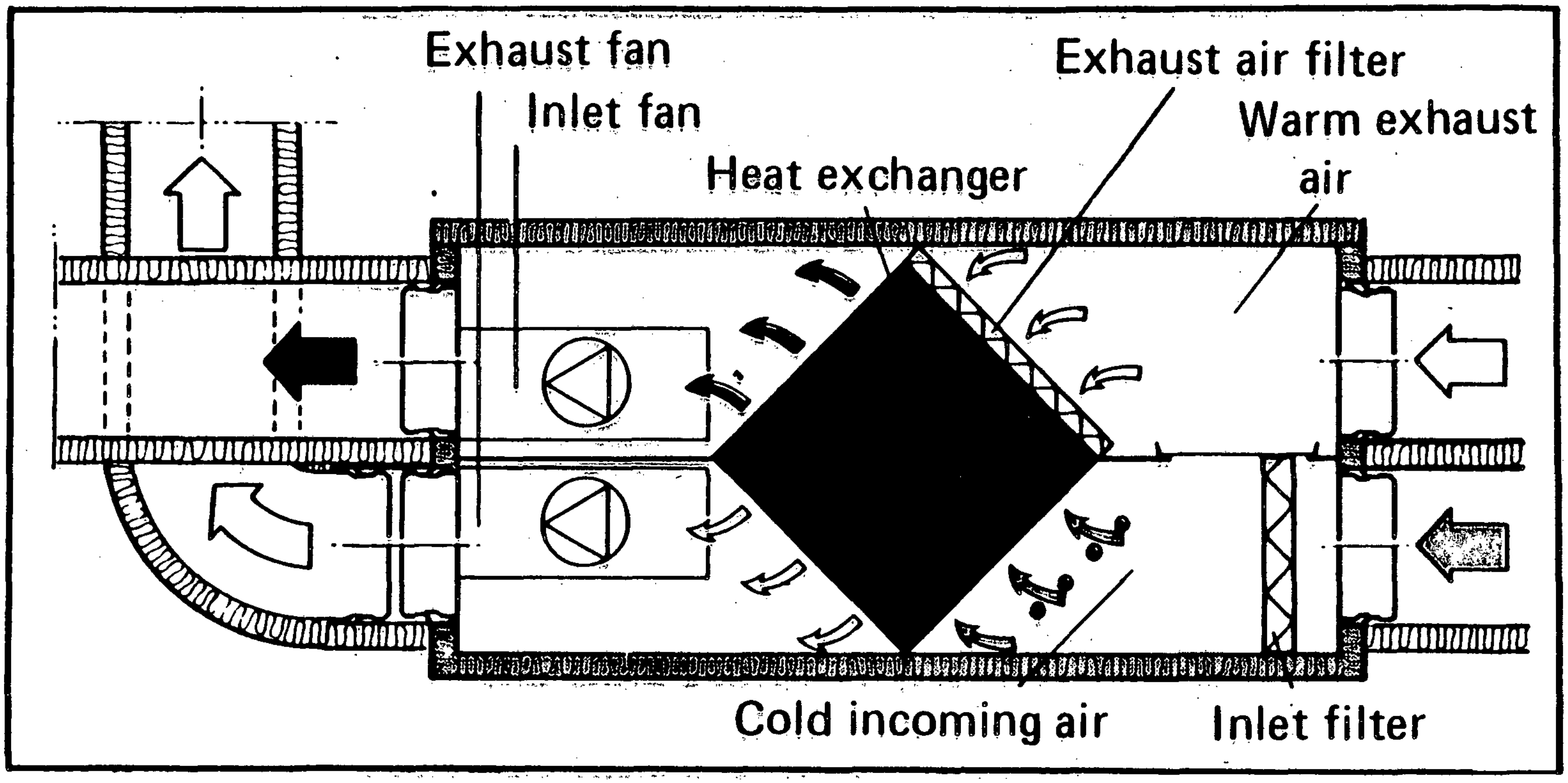

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Figure 1. Schematic diagram of an air-to-air heat exchanger.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720