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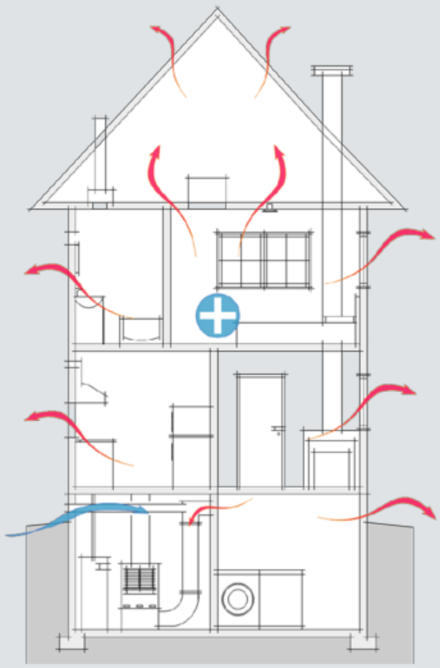

Measure Guideline: Selecting Ventilation Systems for Existing Homes

R. Aldrich
Consortium for Advanced Residential Buildings

February 2014

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Measure Guideline: Selecting Ventilation Systems for Existing Homes

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Definitions

AHU	Air handling unit
ASEF	Apparent Sensible Effectiveness
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPM	Brushless, permanent magnet (motor)
CARB	Consortium for Advanced Residential Buildings
CFIS	Central fan integrated supply
CFM	Cubic feet per minute
DC	Direct current
ECM	Electronically commutated motor
ERV	Energy recovery ventilator (recovers both latent and sensible heat)
HRV	Heat recovery ventilator (recovers only sensible heat)
HVAC	Heating, ventilation, and air conditioning
HVI	Home Ventilating Institute
IAQ	Indoor air quality
IEQ	Indoor environmental quality
IECC	International Energy Conservation Code
in. w.g.	inches of water gauge
IRC	international residential code
LBNL	Lawrence Berkeley National Laboratory
RAoA	reciprocal age of air
TEL	Total equivalent length
TRE	Total Recovery Efficiency

Abstract

This document addresses adding—or improving—mechanical ventilation systems to existing homes. The purpose of ventilation is to remove contaminants from homes either directly or by dilution. This report discusses where, when, and how much ventilation is appropriate in a home, including some discussion of relevant codes and standards. Advantages, disadvantages, and approximate costs of various system types are presented along with general guidelines for implementing the systems in homes.

CARB intends for this document to be useful to decision-makers and contractors implementing ventilation systems in homes. Choosing the "best" system is not always straightforward; selecting a system involves balancing performance, efficiency, cost, required maintenance, and several other factors. It is the intent of this document to assist contractors in making more informed decisions when selecting systems.

Ventilation is an integral part of a high performance home. With more air-sealed envelopes, a mechanical means of removing contaminants is critical for indoor environmental quality and building durability.

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Progression Summary

Determine what levels of ventilation are appropriate or necessary for the home.

- Section 1, Preliminary Planning
- Section 2, Codes and Standards

Address local ventilation as appropriate.

- Section 3, Implementing Local Ventilation—Bathroom Exhaust
- Section 4, Implementing Local Ventilation: Kitchen Exhaust

Determine the most practical type of whole-building ventilation system.

- Section 5, Whole-Building Ventilation Considerations

Implement whole-building ventilation.

- Section 6, Implementing Whole-Building Ventilation: Exhaust-Only
- Section 7, Implementing Whole-Building Ventilation: Fan Integrated Supply
- Section 8, Implementing Whole-Building Ventilation: Recovery Ventilator and Energy Recovery Ventilator

1 Preliminary Planning

Before delving into the various technologies and types of ventilation systems, it's worth considering details of the home, scope of the project, and project goals. The "best" or most appropriate ventilation systems—with respect to first cost, efficiency, indoor air quality (IAQ), etc.—will depend on many aspects of the home and the overall renovation or weatherization project. The Consortium for Advanced Residential Buildings (CARB) recommends reviewing the following questions before deciding on a ventilation system.

Do I need mechanical ventilation?

In short, the answer is almost always yes. Mechanical ventilation has become a practical and prescribed necessity in nearly all homes—certainly in efficient, high performance homes.

In any occupied home, contaminants are being generated. Contaminants come directly from people and pets (hair, dander, perspiration, etc.) and from occupant activities (cooking, showering, etc.). Contaminants also come from building materials and furnishings (paint, adhesives, etc.). Of course, limiting the sources of these contaminants is an excellent step in improving IAQ, but some contaminants are unavoidable. The purpose of ventilation is to remove contaminants and/or dilute them by bringing in outdoor air.

What code or program requirements must be met?

Many home improvement and weatherization programs have requirements related to ventilation. Be clear on these requirements before choosing a system.

What is the scope of the renovation project?

The incremental cost and levels of effort needed to install ventilation systems can vary dramatically with the overall scope of a project. In a gut rehabilitation, for example, ducts and fans can often be installed rather easily—often similar to new home applications.

In a much more modest project, running ducts and installing fans can require extra drywall or finishing work. Such costs can add up for complex systems, significantly increasing the cost of adding ventilation.

What heating, air conditioning, and ventilation systems currently exist in the home?

If ventilation systems exist in a home, these may already meet—or can be fairly easily modified to meet—ventilation goals and requirements. Some ventilation systems can also make use of existing forced-air heating and cooling systems.

What type of heating and air conditioning systems will be in the renovated home?

If home improvements include changes to the heating and cooling systems, keep in mind possible synergies between space conditioning and ventilation. Also keep in mind combustion safety requirements.

Does the home have an attached garage, crawlspace, or basement?
When planning for ventilation systems, be mindful of drawing in air from spaces such as these which may contain higher levels of contaminants.

What is the project budget?
Installed costs for new ventilation systems can range from a couple hundred to several thousand dollars. As with many building systems, cost will very often be a factor in system selection.

What are the project goals with respect to ventilation?
Other than codes or program requirements, are there any other ventilation requirements in the project? Are there areas of the home that have greater or specialized ventilation needs? Is there a desire or need to have outdoor air supplied to each room? Is a system that provides rigorous filtration desired? Are there any heat recovery goals?

What levels of maintenance are acceptable?
All ventilation systems require some form of maintenance. Some maintenance is as simple as wiping off the grille of an exhaust fan from time to time; other systems require quarterly changing or cleaning of filters and heat exchange media. Without proper maintenance, performance of systems can be dramatically reduced.

In what climate is the home?
The practicality, comfort, and energy implications of various ventilation systems can vary greatly depending on climate.

2 Codes and Standards

2.1 ASHRAE Standard 62.2-2010

A growing number of codes and home performance programs are starting to address ventilation in a more meaningful way. While requirements can vary considerably, ANSI/ASHRAE Standard 62.2 is—or is becoming—the most common standard referenced for ventilation requirements in homes (ventilation in high-rise apartments is covered in Standard 62.1, ASHRAE 2010a). The most recent version of the standard 62.2 was published in 2013 (ASHRAE 2013), but Standard 62.2-2010 (ASHRAE 2010b) is still referenced by many programs.

ASHRAE 62.2-2010 requires local ventilation in bathrooms (with capacity of at least 50 CFM intermittently or 20 CFM continuously) and kitchens (with capacity of at least 100 CFM intermittently or 5 ACH of kitchen volume continuously). These local exhaust systems are required to remove odors and pollutants—especially water vapor—from these key areas. While exhaust fans are common in many existing homes, older fans often perform very poorly—exhausting a very small fraction of the design flow rates—and consume a large amount of electricity.

While local exhaust fans can remove water and other pollutants from these heavy source areas, ASHRAE 62.2-2010 also requires whole-building ventilation. Whole-building ventilation "is intended to dilute the unavoidable contaminant emissions from people, from materials, and from background processes" (ASHRAE 2010b). The required whole-building ventilation capacity (expressed in outdoor air flow rate) depends upon home size and number of bedrooms. This is summarized in Equation 1.

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br}+1) \quad (1)$$

where

Q_{fan} = Whole-building ventilation flow rate (continuous) [CFM]

A_{floor} = Floor area [ft^2]

N_{br} = Number of bedrooms

ASHRAE 62.2-2010 assumes a home will have a baseline level of infiltration—2 CFM/100 ft^2 of floor area. If blower door tests of existing homes show infiltration rates above this level (per ASHRAE Standard 136, ASHRAE 1993), then the amount of whole-building ventilation can be reduced.

ASHRAE 62.2-2010 has a special provision for ventilation in existing homes (Appendix A). If adding or improving local ventilation (kitchen or bathroom) to meet ASHRAE 62.2-2010 requirements is impractical or beyond the project's budget, the standard can be met by increasing the whole-building ventilation rate. To determine the amount by which the whole-building ventilation rate must be increased, the local ventilation deficit is summed. In the example shown in Figure 1, there is no kitchen ventilation (deficit of 100 CFM) and the existing bath fan delivers only 30 CFM (deficit of 20 CFM). Having operable windows in these spaces can reduce the deficit by 20 CFM (per space—not per window). In the example below, the total local ventilation deficit is 100 CFM. If a contractor did not improve any local ventilation, the home could still comply with ASHRAE 62.2-2010 if the whole-building ventilation system capacity were increased by 25% of this deficit—25 CFM in this example.

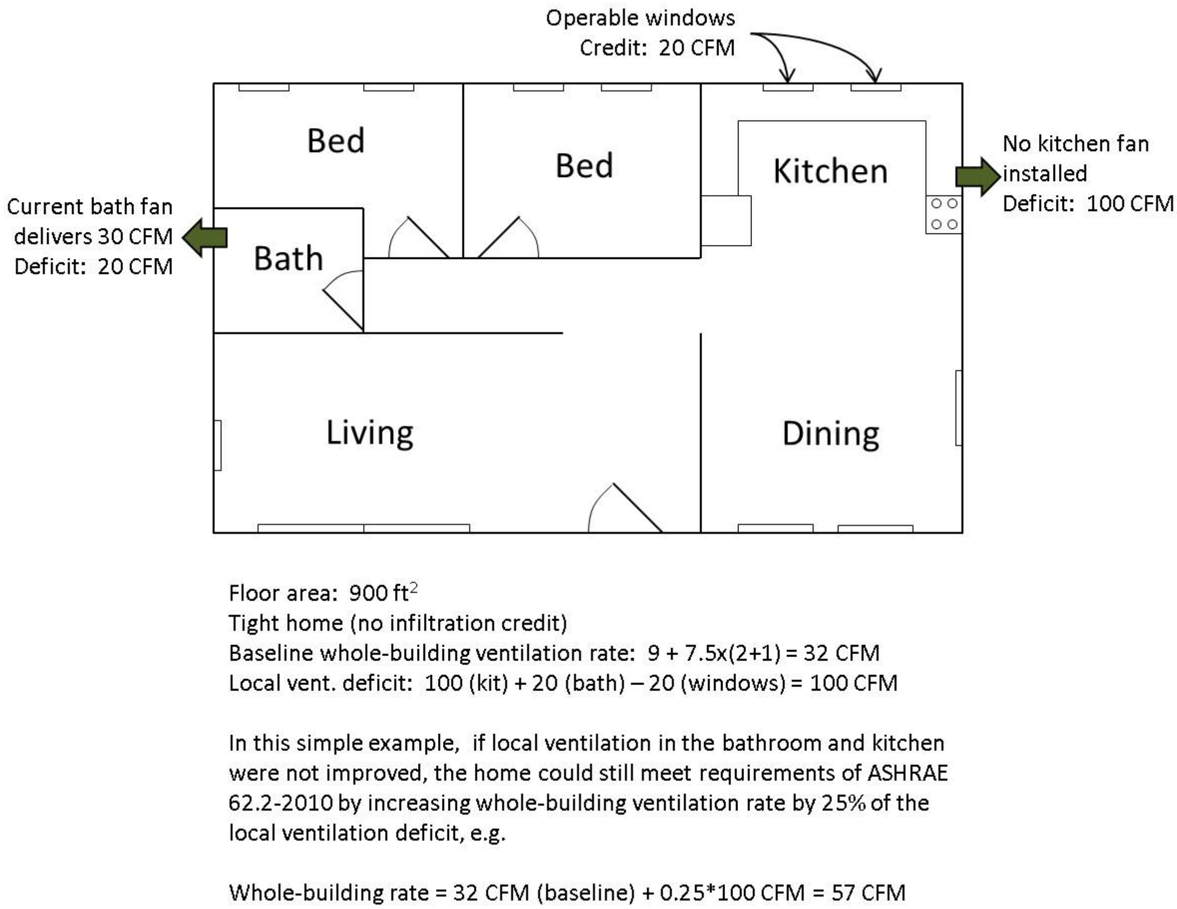

Figure 1. Simple example of increasing whole-building ventilation rates to offset lack of local ventilation in an existing home

This addendum does not obviate the need for whole-building ventilation. Whole-building ventilation is always required by ASHRAE 62.2-2010 unless the envelope is extremely leaky. For the example home in Figure 1, blower door tests would need to show infiltration above 17–20 ACH_{50} to avoid the need for baseline whole-building ventilation. Even then, local ventilation would still need to be addressed.

It's important to reiterate that ASHRAE 62.2-2010 is a minimum standard for ventilation capacity. While many whole-building ventilation systems are designed to operate continuously or on a timer (e.g., several minutes during each hour), ASHRAE 62.2-2010 mandates system capacity only—not how home occupants actually use the system.

2.2 ASHRAE 62.2-2013

The primary change in the 2013 version of Standard 62.2 is the elimination of the built-in "infiltration credit" discussed above. The new formula for calculating whole-building flow rate is:

$$Q_{tot} = 0.03A_{floor} + 7.5(N_{br}+1) \qquad (2)$$

where:

Q_{tot} = Total required whole-building ventilation rate [CFM]

A_{floor} = Floor area [ft^2]

N_{br} = Number of bedrooms

If a blower door test is done on a single-family home, however, it's likely this ventilation flow rate can be reduced.

$$Q_{fan} = Q_{tot} - Q_{inf} \qquad (3)$$

where Q_{inf} is the "Effective Annual Average Infiltration Rate". Calculating Q_{inf} is described in the standard (ASHRAE 2013), but there are several online tools where these calculations can be done, such as:

- Residential Energy Dynamics, www.residentialenergydynamics.com/REDCalcFree/Tools/ASHRAE6222013.aspx
- Heyoka Solutions, www.heyokasolutions.com/ASHRAE_62_2_2013_WX_Whole_Building_Laminated_Sheet_p/ashrae6213wxwbcw.htm

Another critical difference in the 2013 version of ASHRAE 62.2 is in the treatment of multifamily buildings. In the examples below, for the two single-family homes, there are modest differences in the rates required by the two standards. For multifamily buildings, however, the rates required by ASHRAE 62.2-2013 are twice as high. The primary reason: ASHRAE 62.2-2013 does not allow infiltration credits for multifamily homes.

Single-Family Example 1	Multifamily Example 1
$2{,}500\ ft^2$, 3 Bedrooms, 2 Stories Albany, New York Blower Door Results: 1,500 CFM_{50} Whole-Building Ventilation Required ASHRAE 62.2-2010, Q_{fan} = **44 CFM** ASHRAE 62.2-2013, Q_{fan} = **42 CFM**	$1{,}400\ ft^2$, 2 Bedrooms, 2 Stories Albany, New York Blower Door Results: 900 CFM_{50} Whole-Building Ventilation Required ASHRAE 62.2-2010, Q_{fan} = **29 CFM** ASHRAE 62.2-2013, Q_{fan} = **65 CFM**
Single-Family Example 2	**Multifamily Example 2**
$1{,}200\ ft^2$, 2 Bedrooms, 1 Story Houston, Texas Blower Door Results: 600 CFM_{50} Whole-Building Ventilation Required ASHRAE 62.2-2010, Q_{fan} = **34 CFM** ASHRAE 62.2-2013, Q_{fan} = **45 CFM**	$800\ ft^2$, 1 Bedroom, 1 Story Houston, Texas Blower Door Results: 600 CFM_{50} Whole-Building Ventilation Required ASHRAE 62.2-2010, Q_{fan} = **20 CFM** ASHRAE 62.2-2013, Q_{fan} = **39 CFM**

Like the 2010 version, ASHRAE 62.2-2013 makes special provisions for existing buildings. If adding local ventilation is beyond the scope of the project, whole-building ventilation rates can be increased to compensate.

2.3 Home Ventilating Institute

The performance of fans—especially the delivered flow rates—are typically tested and verified per HVI (Home Ventilating Institute) Publication 916 (HVI 2009a). These test procedures—and the associated certification procedures in HVI Standard 920 (HVI 2009b)—provide standardized ratings for most mechanical ventilation fan products used in homes.

HVI also publishes guidelines on recommended ventilation practices in homes (HVI 2009c). For whole-building ventilation, HVI references rates from ASHRAE 62.2-2007. HVI's recommended local ventilation levels are, however, typically higher than the minimum rates outlined by ASHRAE 62.2. For kitchen ranges located against a wall, for example, HVI recommends 40–100 CFM/linear foot of range width (e.g., 100–250 CFM for a standard 30-in. range). The 100 CFM minimum specified in ASHRAE 62.2 is on the bottom of this range. HVI recommends higher exhaust rates for "island" ranges.

For bathrooms smaller than $100\ ft^2$, HVI recommends exhaust fan capacity of $1\ CFM/ft^2$. For larger bathrooms, HVI recommends exhaust capacity of 50 CFM for each shower, bathtub, and toilet and 100 CFM for each jetted tub.

2.4 2012 International Residential Code and International Energy Conservation Code

The 2012 International Residential Code (IRC) (ICC 2011b) and 2012 International Energy Conservation Code (IECC) (ICC 2011a) include both local exhaust and whole-building ventilation. Section 303.4 of the IRC stipulates that when air infiltration of a dwelling is less than

5 ACH_{50}, ventilation requirements are very similar to those of ASHRAE Standard 62.2-2010 (Section M1507.3). One key difference in the requirements is that there is no infiltration credit in the IRC.

2.5 Programs and Other Standards

In addition to the standards and guidelines discussed above, many certification or incentive programs have standards for ventilation. ENERGY STAR® Homes version 3, for example, requires compliance with ASHRAE 62.2-2010 (EPA 2012). The Leadership in Energy and Environmental Design (LEED) for Homes program requires compliance with 62.2-2007 (which is very similar to 62.2-2010, USGBC 2008).

The Building Performance Institute (BPI) has announced it is updating its Building Analyst standards to reference ASHRAE 62.2 (BPI 2012a), but currently these standards reference the much older ASHRAE 62-1989 (BPI 2012b). If working with specific rating systems, weatherization programs, or utility initiatives, be clear about ventilation requirements with program managers.

2.6 What Rate is Right?

While ASHRAE 62.2 and similar guidelines have been accepted by many builders, designers, and certification programs, it's important to remember that these standards cannot provide one-size-fits-all solutions. ASHRAE is very clear that Standard 62.2 outlines minimum standards for ventilation rate. For indoor environmental quality (IEQ) reasons, there are certainly situations where higher ventilation levels can be beneficial. Other building scientists maintain that the ventilation rates in ASHRAE 62.2 are too high for many situations (BSC 2013).

It's certainly true that a simplified standard cannot determine optimal levels of ventilation for all situations. Kitchens in which a great deal of cooking takes place, for example, can benefit from higher exhaust levels to keep odors and moisture levels down. New homes with high levels of chemical off-gassing may benefit from higher whole-building ventilation levels. Conversely, homes with very low occupancy and/or contaminant generation could save significant amounts of energy by reducing ventilation rates. Very often, program requirements will determine ventilation system capacity. Designers and contractors, however, may choose to install systems with more versatility—where ventilation rates can be adjusted as needed.

3 Implementing Local Ventilation—Bathroom Exhaust

Installing bathroom exhaust fans has been standard practice for decades. Most often fans are installed in bathroom ceilings with a small duct (most often 4-in. diameter) that carries air to an outdoor termination of some type. While many bathrooms already have exhaust fans, many older fans do not perform at the desired or rated ventilation rates.

3.1 Assessment

If a bath exhaust fan already exists, evaluate how well it works. Measure the airflow using an appropriate flow hood or other device (Figure 2). Discussion of measurement accuracy of these instruments is outside the scope of this document, but keep in mind not all flow hoods are equal. A Lawrence Berkeley National Laboratory (LBNL) study documents accuracy of various instruments (Stratton et al. 2012). Inspect the fan grille for dirt and dust; remove the grille and inspect the fan blades and housing. Simply cleaning the fan housing and grille can sometimes dramatically improve performance. Of course disconnect power before working on any electrical equipment.

Figure 2. Measuring exhaust flow with a flow hood and exhaust fan meter

Locate the outdoor terminal of the duct run. Exhaust ducts should always terminate outdoors—never in an attic or crawlspace, etc. (see Figure 3). If possible, measure the flow rate here at the outdoor termination as well. A large disparity in measured flow rates implies leakage. If possible, trace the exhaust duct run and inspect for disconnects, crimps, leaks, etc. If the fan appears in good working order, flow rates are acceptable, and the duct run terminates outdoors, upgrading the fan may not be necessary.

Figure 3. Exhaust ducts should always terminate outdoors—not in an attic "near" the outdoors.

If fan replacement is necessary, inspect the ceiling cavity for clearances, joist spacing, and mounting configurations. The electrical service to existing fans will often be adequate for newer fans, but as always refer to an electrician or qualified contractor to assess electrical issues.

If a bathroom does not have an existing exhaust fan, evaluate the effort required to install a fan and ducting. If a bathroom is located on the top floor beneath a vented attic, running electrical and ductwork may not be terribly difficult. On lower floors, installing a new duct run may be much more problematic. If the bathroom is on an exterior wall, a fan that exhaust directly through the wall is a possible solution. If installing a new fan is not practical or affordable, many standards (including ASHRAE 62.2) allow for higher whole-building ventilation rates where local ventilation cannot be installed.

3.2 Selecting Fans

Once the desired flow rates are known (refer to appropriate codes or guidelines above), it's usually best to select an exhaust fan that meets these flow rates at pressures of 0.25 in. w.g. Many fans list flow rates at 0.1 in. w.g., but most exhaust duct runs have much higher pressure drops.

ENERGY STAR rated exhaust fans are recommended for several reasons. The most obvious benefit is lower energy consumption. ENERGY STAR requirements for bathroom exhaust fans (with rated flow rates below 90 CFM) call for fans to deliver a minimum of 1.4 CFM/Watt. For fans with rated flows 90 CFM and above, ENERGY STAR fans must deliver at least 2.8 CFM/Watt (EPA 2003).

While these energy requirements represent great improvements over older fans, many current manufacturers have bathroom exhaust fans with draws of more than 10 CFM/Watt (seven times more efficient than ENERGY STAR minimum requirements). These very efficient fans typically use brushless, permanent-magnet motors (BPM

While standards and guidelines vary, CARB generally recommends these exhaust fan rates for bathrooms:

Powder rooms (lavatory and water closet)	50 CFM
Full bathrooms (lavatory, water closet, and tub/shower)	80 CFM
Large bathrooms (additional tubs, whirlpool, etc.)	110 CFM

motors). These motors are also referred to as DC (direct current) motors, ECMs (electronically commutated motors), or variable-speed motors. In addition to lower energy consumption, the variable-speed capabilities of these motors allow many fans to maintain design flow rates over a wide range of static pressures.

In existing buildings, exhaust duct runs are often concealed in walls or ceilings. It's very difficult to determine the state of these runs, and many have twists and turns that result in higher pressure conditions. Fans with BPM motors and advanced controls are excellent choices for such retrofit applications because fans can increase speed and flow to largely overcome duct restrictions. Operating at higher fan speed increases power consumption somewhat, but this is usually a small price to pay for meeting airflow targets.

One additional benefit of efficient bath exhaust fans is lower noise; ENERGY STAR fans must meet noise requirements of 2 sones or less for most products (EPA 2003).

3.3 Fan Installation

When an older exhaust fan is present, replacing the fan—but keeping the existing duct—can be a relatively low-cost project. If possible, the duct run should be inspected for leaks, insulation, obstructions, etc. and repaired as necessary. At a very minimum, the outside terminus of the exhaust run should be located and inspected. Exhaust fans should vent directly outdoors—not to an attic, crawlspace, etc. If an existing fan is terminated inappropriately, a new outdoor termination must be installed. Outdoor terminations should be properly air sealed, flashed, and include proper screens or backdraft dampers to prevent insects and other pests from entering the ducts.

If a new duct must be installed, duct runs should be as short and as straight as possible to an appropriate outdoor termination. If an elbow is required to redirect the ductwork, it is recommended that 2–3 ft of straight run is provided directly off of the fan housing prior to the elbow. Refer to fan literature to determine the proper duct diameter; larger ducts generally result in better flow rates and are more forgiving of long or winding duct runs. Joints in the duct system should be sealed with mastic, and any ducts located outside of conditioned space (e.g., attic) should be insulated to prevent condensation of the humid exhaust air.

Ideally, replacing an existing exhaust fan will require minimal drywall and/or ceiling finishing work. However, the variability in size and configuration of these fans makes this hard to predict. Refer to retrofit installation instructions provided by the manufacturer, and if possible select a new fan with a ceiling opening similar to—or slightly larger than—that of the existing fan. It's also a good idea to inspect the ceiling cavity to make sure clearances are acceptable.

Some manufacturers have begun to offer fans specifically designed for the retrofit market (such as Broan's Ultra models). In the right circumstances, electrical connections, duct connections, and installation of the fan housing itself can be done with minimal finish work.

Most older and single-speed bath fans deliver their rated flow rate at pressures of 0.1 in. w.g. In reality, most exhaust duct runs induce pressures closer to 0.25 in. w.g. A typical fan (non-DC motor) rated at 50 CFM at 0.1 in. w.g. will operate closer to 23–31 CFM at 0.25 in. w.g. Similarly, an 80 CFM fan will deliver only 48–57 CFM at 0.25 in. w.g.

DC or variable-speed fans are more forgiving of duct problems and will often maintain flow over a wide range of pressures. But keeping ducts short and straight—unlike in Figure 4—will result in quieter, more efficient operation.

Figure 4. Tight bends can reduce fan flow rates, increase noise, and increase power consumption.

3.4 Controls

Bathrooms in general—and showers in particular—introduce substantial amounts of moisture into homes. The primary reason for bathroom exhaust ventilation is to remove much of this moisture before it causes problems. Turning on an exhaust fan when taking a shower is certainly a step in the right direction. Ideally, however, an exhaust fan would operate for a time after a bathroom is used. Instead of a conventional switch, a crank timer or a delay-off switch can be used to keep a fan running for an additional period of time.

Many fan manufacturers have started to include more advanced controls into the fans themselves. In addition to integrated delay-off timers, some newer fans feature built-in occupancy sensors that turn on fans when a person enters the bathroom. Other fans feature humidity sensors that keep a fan running whenever humidity levels are above an adjustable threshold. While these features can certainly help control moisture levels, they also add some cost and maintenance to the exhaust fan.

3.5 Measurement, Verification, and Commissioning

Commissioning of exhaust fan operation is usually very straightforward. First, verify that the fan actually turns on when manually switched on and/or when programmed to turn on based on humidity levels, timer, or other controls. Exhaust airflow rate is easily measured with a flow hood or flow meter (e.g., see Figure 2). If delivered flow rates do not match design rates, inspect the duct system (when possible) to see if there are any obstructions, if backdraft dampers are operating properly, etc. It is common to see the exhaust fan backdraft damper restricted due to screws being used to connect ductwork to the fan housing collar. Screws should not be used to make this connection. Instead, clamps plus mastic or approved foil faced tape should be used.

4 Implementing Local Ventilation: Kitchen Exhaust

While kitchen exhaust ventilation is required by many codes and standards, there are few requirements beyond meeting prescribed minimum flow rates (AHSRAE 2010, HVI 2012). One low-cost solution to meet this requirement is simply installing a bathroom-type exhaust fan with flow rates of 100 CFM or higher. Some manufacturers, however, state that their bathroom-type fans should not be used near stoves where exposed to grease and other cooking products.

More often, kitchen ventilation is provided by a range hood. Such hoods can often collect and remove cooking byproducts better than ceiling or wall-mounted fans (Singer and Delp 2010). In addition, range hoods are often equipped with grease filters that protect and extend the life of the fan itself. Many range hoods (such as the one in Figure 5) can either be connected to an exhaust duct or recirculate the air into the kitchen. Exhausting air to outdoors is strongly recommended; recirculating air removes few contaminants and does not comply with most ventilation standards.

Figure 5. Some range hoods, like this one, do not vent outdoors. They simply circulate air back into the kitchen. Such hoods do not meet most ventilation requirements.

4.1 Assessment

If a kitchen exhaust fan is installed in a home already, evaluate its performance. Inspect the fan grille and housing; in some instances simply cleaning accessible parts of a fan (air inlet, grease screens, backdraft damper, outdoor termination etc.) can sometimes dramatically improve performance. Trace the exhaust duct run and locate the outdoor termination. Measure the fan's flow rate (if a range hood, this is often most easily done at the outdoor termination).

If a fan is not installed, assess the kitchen for how and where a fan could be installed. Range hoods—which remove moisture and odors directly above the cook top—are preferred (Singer and Delp 2010). If this is not practical, down-draft fans or even ceiling or wall exhaust fans located in the kitchen are possible (refer to manufacturer instructions when locating a fan). If none of these is practical, many standards (including ASHRAE 62.2) allow for higher whole-building ventilation rates where local ventilation cannot be installed.

4.2 Selecting Fans

As with bathroom exhaust fans, ENERGY STAR certified range hoods are recommended. ENERGY STAR range hoods must deliver a minimum of 2.8 CFM/Watt with a maximum sound level of 2.0 sones (EPA 2003). Most ENERGY STAR rated fan hoods have capacities of 100–200 CFM. For normal residential use, these flow rates are often adequate, though HVI recommends higher flow rates (see Section 2.3 above). While higher volume fans certainly do exhaust more moisture and odors, they can also cause pressure imbalances within the home. Large pressure imbalances can cause comfort problems (such as drafts) and interfere with normal operation of other heating, ventilation, and air conditioning (HVAC) systems (especially combustion systems).

As discussed previously, hoods are much more effective at capturing and removing pollutants than wall- or ceiling-mounted exhaust fans. Research has found that capture efficiency varies widely from hood to hood (Delp and Singer 2012). Currently there is no standard for assessing capture efficiency of hoods, but work on this is underway.

The 2009 and 2012 IRC (ICC 2009, ICC 2012) require makeup air provisions with exhaust fans rated above 400 CFM. Such makeup air provisions can be costly and can cause comfort issues. Unless there is a compelling need for higher rates of exhaust, exceeding HVI guidelines (40–100 CFM/linear ft of cooking range) is not recommended.

4.3 Fan Installation

In the best scenario, when a range is located on an exterior wall, a range hood will exhaust directly through that wall. When this is not practical (because of the location of the outdoor terminal, etc.), the duct run should be as short and straight as possible. Refer to the manufacturer’s instructions on duct sizing, and seal all duct joints with mastic. If the exhaust duct must run in unconditioned space (such as an attic), it should be insulated.

In many instances, running power to a new range hood may be the most challenging part of the process. This should be considered during planning, and wiring and electrical connections should be done by a qualified electrician.

Outdoor terminations should be properly air sealed, flashed, and include proper screens or backdraft dampers to prevent insects and other pests from entering the ducts.

5 Whole-Building Ventilation Considerations

5.1 Installation and Integration With Existing Systems

In existing homes, installing whole-building ventilation systems is often more involved and costly than in new construction—especially with more complicated ventilation systems. The level of effort—and ultimately the cost—required to install a ventilation system in an existing home depends on many factors, including:

- Existing ventilation systems
- Existing ducted heating and/or cooling
- Accessibility to attics and/or basements
- Scope of the renovation/rehabilitation project

One of the most common types of whole-building ventilation is simple exhaust ventilation—where efficient exhaust fans run continuously to remove indoor air. Bathroom exhaust fans are operable in many existing homes, but these older fans are usually not appropriate for whole-building ventilation (for efficiency, noise, and flow reasons as described below, Section 6). The existing duct runs and electrical connections, however, may possibly be reused with the new system.

In homes with existing forced-air heating and/or cooling, it's possible that a central fan-integrated supply ventilation system (CFIS, discussed below in Section 5.7.2) can make use of the ducts and the central air handler.

When there is no existing duct system—or at least no duct system appropriate for the desired ventilation system—installing new ducts and running electrical service to fans can be invasive and costly. These costs can be minimized when there is access from basements, crawlspaces, or attics. If ducts or electrical lines must be run between floors or in existing walls, sections of wall board must generally be removed and replaced. If other aspects of the renovation do not necessitate this level of intrusion, this invasive work can dramatically increase the cost of ventilation installation and integration.

5.2 Distribution and Mixing of Outdoor Air

Local, source-control ventilation is properly targeted toward areas where contaminants, especially moisture, are frequently and intensely generated. Whole-building ventilation is intended to reduce contaminants throughout the entire home by diluting them with outdoor air. Certainly directly removing (or diluting) contaminants in every room in a home is ideal, but the installed costs of such systems can be quite high—especially in retrofit projects. Some ventilation strategies make use of point-source or local ventilation systems to meet whole-building ventilation requirements (e.g., a bath exhaust fan running continuously). There is not yet broad consensus in the industry about if—or, more accurately, when—point-source, whole-building ventilation is an IEQ liability. Researchers are certainly looking into this question, and summaries of several studies are described in the Appendix.

When considering the question of ventilation and distribution, it's important to keep in mind that the primary purpose of ventilation is to reduce indoor contaminant levels. Ventilation systems reduce contaminants by diluting them with outdoor air. The important question to ask about ventilation effectiveness, therefore, is not "Does fresh air get to all parts of the home?" but rather, "Are contaminants in all parts of the home reduced effectively?" These two questions are closely related, but they are not necessary the same.

While research is ongoing, there are some consistent findings from past studies that use tracer gas tests to approximate contaminant diffusion (see the Appendix for more information and references). Several of these studies compare point ventilation (such as a local exhaust fan) to distributed ventilation (such as CFIS or distributed energy recovery ventilator/heat recovery ventilator (ERV/HRV) systems).

- Point ventilation provides fairly uniform dilution of indoor air within a home when:
    A. Interior doors are open
    B. A central furnace or air handler operates intermittently
    C. A mechanical "mixing" system operates continuously at low volume.

  In these three situations, air change rates in all spaces appear to be similar to air change rates when fully ducted/distributed ventilation is installed. The volumes and duty cycles required in configurations B and C above require more investigation.
- When doors are closed and there is no central air handler operation, air change rates with point ventilation vary much more throughout a home. It is common for some areas (especially some bedrooms) to experience air change rates 50% lower than those of areas where point ventilation systems are located.

A summary of some of these studies can be found in the Appendix. Unfortunately, CARB cannot provide definitive advice on when or how important it is to distribute outdoor air throughout a home. Researchers are still investigating this issue. In the meantime, another Building America team (Building Science Consortium) has proposed increasing whole-building ventilation rates by 25% when air is not actively distributed (for new homes only, Bailes 2013).

5.3 Source of Outdoor Air

Outdoor air brought into a home as part of a ventilation system should be—as much as possible—free from contaminants. With active air intakes, codes generally require intakes be at least 10 ft from sources of contaminants (ICC 2011c). Manufacturer installation instructions may also provide clearances from combustion exhausts, operable doors and windows, ground or snow level, etc. As many exhaust-only ventilation systems do not have dedicated air intakes, the concern about the source of outdoor air may be more pressing with these systems.

In larger buildings, ventilation systems often include active makeup air systems to balance air exhausted from buildings. Newer residential codes are also starting to require makeup air in some cases. In the 2009 IRC, for example, any local exhaust fans with capacity of 400 CFM or higher must include make-up air provisions (ICC 2009).

In smaller, existing homes, makeup air provisions are rare. By design or by default, most exhaust ventilation systems force infiltration through building envelopes. While this may not be ideal, there is not widespread consensus as to whether this is acceptable or unacceptable practice in particular circumstances. There are, however, several configurations that most agree are problematic:

- Depressurizing the home can interfere with natural-draft combustion appliances.
- In a home with an attached garage, forced infiltration can enter a home through the garage. With the air can come traces of car exhaust, fuel, or solvents that may be stored in the garage (CARB 2011).
- In a home with a moist, moldy crawlspace or basement, makeup air coming through such a space may bring mold spores, humidity, or other undesirable elements.
- In some cases, depressurizing a home can exacerbate introduction of radon or soil gas through the foundation.

These can be serious issues, and in some of these situations exhaust ventilation—without makeup air provisions—should be avoided. In many cases, however, these issues can be addressed with common-sense solutions:

- Eliminate natural-draft combustion appliances.
- Meticulously air seal the garage from the living space and/or install ventilation in the garage that eliminates the positive pressure with respect to the living space.
- Create a well-sealed, dry, conditioned crawlspace or basement.
- Install a radon mitigation system if soil gas is a problem.

Most homes require exhaust ventilation, if only intermittently, to meet local ventilation requirements. The concerns above become somewhat more pressing when exhaust ventilation is used for whole-building ventilation and runs continuously.

5.4 Energy Implications

Mechanical ventilation systems have two key energy impacts:

- Electricity used to operate fans and ventilation equipment.
- Thermal energy required to condition outdoor air introduced into the space.

Electrical fan energy varies widely. The power range for most bathroom exhaust fans is 5–40 Watts. Power consumption for many HRVs and ERVs ranges from 30–200 Watts. The fan in a central air handler or furnace—used in some ventilation strategies—can use 200–1,000 Watts. These are very general ranges, and power consumption certainly varies with airflow and system configurations. Power consumption also, not surprisingly, varies with system cost. Typically ventilation products with lower power consumption use variable-speed, BPM fan motors; these often carry a cost premium.

The second point—conditioning the introduced outdoor air—is climate-dependent. HRVs and ERVs can certainly mitigate this effect. The sensible effectiveness of ERV/HRV heat exchangers typically ranges from 55%–95%. Again, the higher values typically come with a higher cost. More extreme outdoor temperatures mean greater benefits from heat recovery. In humid climates, the latent transfer of ERVs can help reduce moisture introduced by a ventilation system. See Table 2 in Section 5.7.3 for example energy implications.

5.5 Humidity

As discussed above, bringing outdoor air into a home causes the heating or cooling systems to work harder to condition this air. When humid air is brought into a home, however, air conditioners often cannot remove all of this additional moisture.

This problem is exacerbated in efficient homes: as sensible cooling loads (i.e., energy needed to lower the air temperature) become smaller, air conditioners are smaller and/or need to run less frequently. When air conditioners run less frequently, less moisture is removed. In hot, humid climates, this can lead to real challenges. When ventilation systems bring more outdoor into homes, additional dehumidification systems may be needed to keep indoor humidity at comfortable and healthy levels.

Many researchers have examined—and continue to examine—this conundrum: how to provide adequate fresh air, keep indoor humidity at acceptable levels, and minimize cost and energy needed for dehumidification systems. Several references have much more information and recommendations on this topic (BSC 2009; Chandra et al. 2008; Rudd et al. 2005; Rudd 2013; Shirey et al. 2006).

5.6 Operation and Maintenance

One important—though sometimes overlooked—aspect of a ventilation system is the level of maintenance required. All mechanical systems require some maintenance, but maintenance required on ventilation systems can vary greatly. On one end of this spectrum, local bathroom exhaust fans have very modest requirements. Typical maintenance instructions are—at least once per year—to clean/wipe the exhaust fan grille, vacuum dust and dirt from the fan body, and wipe the fan body clean (Panasonic 2011).

Some of the higher performing ERVs, by contrast, require checking or cleaning filters, heat exchange media, and exterior duct terminations quarterly. While exhaust fan maintenance instructions may consist of four or five short bullet points, instructions for checking and cleaning ERV components can be several pages. This increased level of maintenance is not a design flaw; it is simply necessary with more complex systems with greater functionality.

CARB has worked with several builders and developers who were very sensitive to the level of maintenance required in their homes. Ventilation systems are often of special concern, as a malfunctioning ventilation system in a tight, efficient home can lead to moisture, mold, and other problems. If systems are not maintained, ventilation flow rates will decrease over time—eventually to a small fraction of the design rates. To minimize these risks, some builders actively choose ventilation systems with lower maintenance requirements. Lower maintenance systems also tend to have lower first costs; this certainly factors into decision processes.

5.7 Overview of System Types

While there are many types of ventilation systems and devices, three main types of systems predominate in U.S. homes: exhaust ventilation, CFIS ventilation, and balanced ventilation using an ERV or HRV. Table 1 and Section 5.7.1 through Section 5.7.3 outline some of the major system characteristics, advantages, disadvantages, and costs. Implementation of each of these three types of systems is described in the following sections.

Note that information in this section is general and approximate. The cost ranges presented are costs to contractors or installers. Many specifics, especially installation requirements and costs, can vary significantly from home to home and from region to region.

Table 1. Summary of Advantages and Disadvantages of Ventilation Systems

	Exhaust Only	CFIS	ERV/HRV
Pros	Low first cost Simple installation Low maintenance Low electrical energy	Low first cost Often easy to install Low maintenance Outdoor air filtered and distributed	Heat recovery Air can be filtered and distributed Potential for low energy costs Balanced (pressures)
Cons	No control of air intake No distribution of outdoor air No filtration	High energy use	Higher first cost Higher maintenance Installation may be more difficult

5.7.1 Exhaust Only

With exhaust only systems, exhaust fans operate continuously (or on timers) to remove air from the home. Fresh air is introduced through induced infiltration. Most often these systems make use of an exhaust fan that provides local ventilation as well (most often in a bathroom).

5.7.1.1 Pros

- Exhaust-only, whole-building ventilation is one of the most common systems employed in homes, especially existing homes. The key reasons for this are its **low cost and simplicity**. Nearly all homes have exhaust fans, and upgrading one (or more) fans to an efficient model designed for continuous operation is very straightforward.
- Exhaust fans that use **very little electricity** are available (5–12 Watts for 50–80 CFM).
- Exhaust fans also require very **little maintenance**. Typical maintenance instructions are to vacuum or wipe the fan grille from time to time. In this regard, exhaust-only ventilation can be very **reliable**.

5.7.1.2 Cons

- Depressurizing the home draws in air from outside the home. The key question is: where does this makeup air come from? Are **contaminants being introduced**? Exhaust-only ventilation should **not** be used in homes with atmospheric combustion appliances, homes where makeup air comes from damp, moldy crawlspaces or basements, homes with attached garages (that are not well air-sealed from the home), or other situations where contaminants are likely to be introduced continuously.

- Exhaust-only ventilation is typically **not distributed**. A single exhaust fan removes air from one location, and makeup air enters where it will. With such a system, it is likely different parts of the home will be ventilated to different degrees—especially when interior doors are closed. When doors are open—or when there is a forced-air system operating within the home—differences in air changes throughout the home are minimal (see Appendix).

5.7.1.3 Cost

Efficient exhaust fans themselves range from **$100–$250**—depending on rated flow rates, special features, etc. If installed as an upgrade (e.g., in a bathroom that already has an old exhaust fan, power, ducting, etc.), installation costs may be **$100**. If installed in a location which did not previously have a fan, costs can be much higher. If installed in a ceiling beneath an accessible attic, installation can be **$200-$400**. If drywall or finishes must be removed and repaired, costs can be substantially higher.

5.7.1.4 Energy Implications

A 10-Watt fan running year-round consumes **88 kWh**. At $0.11/kWh, this costs **$10/yr**. As this system has no heat recovery, outdoor air brought into the building must be conditioned. Costs to do this vary with climate and HVAC equipment (see Table 2), but these costs are usually much larger than cost of electricity to operate the fan.

5.7.2 Central Fan Integrated Supply Ventilation

CFIS systems make use of an existing forced-air heating or cooling system (see Figure 6). A duct is run between the return plenum and outdoors. CFIS controllers are programmed to turn on the air handler fan and open the motorized damper. Outdoor air is drawn into the return plenum, mixed with return air, and distributed throughout the home.

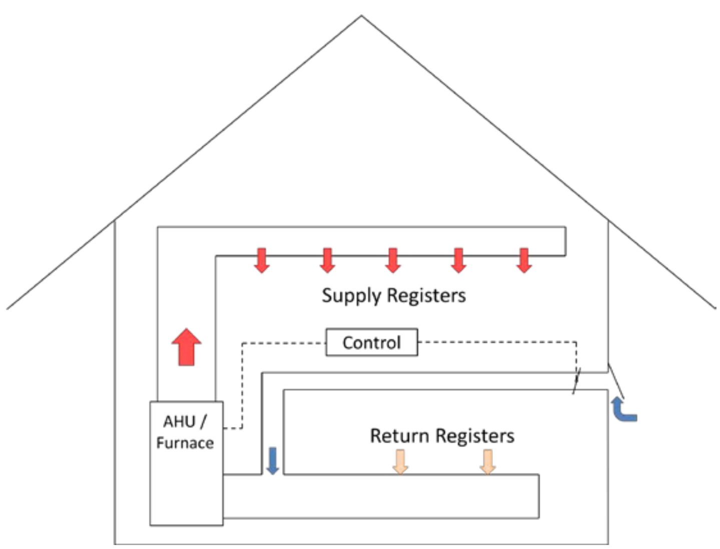

Figure 6. Simple schematic of CFIS ventilation

5.7.2.1 Pros

- Along with exhaust ventilation, CFIS is one of the most **simple and affordable** systems to install in existing homes.
- CFIS systems **distribute outdoor air** to all parts of the home.
- Aside from keeping the air intake free from debris, a CFIS system requires **little maintenance** beyond maintenance of the central heating and cooling system.
- Outdoor air is **filtered** (through the central air handler filter).

5.7.2.2 Cons

- One key limitation is that this system is viable only in homes with **forced-air heating or cooling** systems.
- The largest drawback of CFIS is the **high electricity consumption** from using the air handler fan for modest ventilation needs. This strategy should be considered only when the air handler has an ECM blower.
- If the central **duct system is leaky**, operating costs can be much higher.
- There is potential for **comfort problems** if cool mixed air blows on occupants during the winter (or warm, humid air blows on them during the summer).

5.7.2.3 Cost

If the air handler is accessible in a basement or attic—and a duct can be fairly easily run from outdoors—total CFIS cost may range from **$500–$900** (including controls, motorized damper, and installation). If installing the outdoor air duct is involved or requires removal of drywall, refinishing, etc., costs can increase dramatically.

5.7.2.4 Energy Implications

As mentioned above, CFIS systems can consume tremendous amounts of electricity. If using an efficient AHU fan motor (300 Watts) and run an average of 8 h/day for ventilation (i.e., in addition to operation needed for space conditioning), a CFIS would consume **876 kWh/yr**. At $0.11/kWh, this costs **$96/yr**. Most central air handlers have motors that are not this efficient; it is not uncommon for draws to be **two or three times** higher.

Basic CFIS systems have no heat recovery, and outdoor air brought into the building must be conditioned. See Table 2 for examples of these cost implications. If CFIS is used in a system with considerable duct leakage, these thermal conditioning costs can be much higher.

5.7.3 Heat Recovery Ventilator or Energy Recovery Ventilator

HRVs and ERVs are balanced systems; this means they exhaust air and supply outdoor air simultaneously (see Figure 7). These two airstreams cross in a heat exchanger, so during the winter, much of the heat in the exhaust stream is transferred to the supply stream (the reverse is true in the summer). HRVs transfer sensible heat only; ERVs also transfer moisture (latent heat).

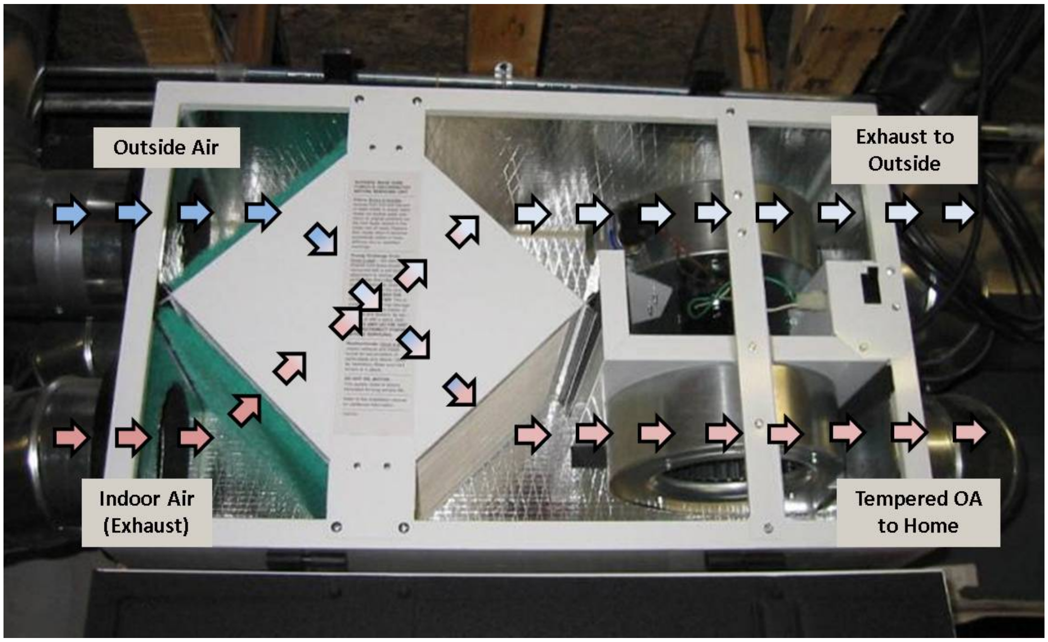

Figure 7. Schematic of exhaust air and outdoor air passing through the heat exchanger in an HRV

5.7.3.1 Pros

- Perhaps the most obvious benefit of ERVs and HRVs is the **heat recovery** that reduces conditioning implications of ventilation. The level of heat recovery (efficiency or effectiveness) varies considerably, however, among various products.
- Depending on how the systems are designed and installed, ERVs/HRVs can **distribute air** to many areas in a home.
- These systems don't induce a large pressure (either positive or negative) on the building.
- Outdoor air can be filtered.

5.7.3.2 Cons

- Of the systems discussed here, these are typically the **most expensive** and can have **more involved installation** procedures.
- These systems typically require **higher maintenance**. Filters and heat exchange media typically need to be cleaned or replaced regularly.
- While heat recovery offers savings, some systems have **high electricity consumption.** As with heat recovery effectiveness, however, this varies tremendously from product to product.

5.7.3.3 Cost

The range of ERV and HRV equipment costs is quite wide. Costs are generally proportional to heat transfer effectiveness and electrical efficiency. Until recently, costs for core hardware ranged from approximately **$400–$2,000**. Not surprisingly, the units with lower electricity consumption (> 1 CFM/Watt) and higher heat recovery effectiveness tend to be most expensive. Recently, some higher end European products have become available in the U.S. market. These systems boast even lower electrical consumption (near 3 CFM/Watt) and higher heat recovery effectiveness but with price tags of $3,000–$5,000.

Installation costs vary tremendously; key factors include:

- Location of the core unit. If installed in an accessible space (such as a basement), core equipment and duct connections may be fairly simple.
- If ducts can be run in an open space (basement or attic), wall and ceiling finishes may be left mostly undisturbed.
- More and longer duct runs translate into higher installation costs.
- Need for a condensate drain and/or pump.

Some contractors have found installation costs of **$1,000–$1,500** when the system is entirely installed in a basement, attic, or other accessible space (i.e., very little ceiling or wall removal or finish work needed). Rules-of-thumb fail with more complex installations requiring ceiling, wall, or floor removal, construction of chases, refinishing, etc.

5.7.3.4 Energy Implications

One of the main benefits of ERVs/HRVs is heat recovery. In colder climates, the savings from heat recovery are more pronounced. The electrical power consumption of these systems can also vary significantly; in milder climates, the electricity costs can actually be greater than the thermal energy savings. More information on ERV/HRV efficiency ratings is presented in Section 7.2.

Table 2 shows example ventilation-related energy costs of four systems in six different climates. The values in this table were generated using BEopt v2.0.0.4; they represent costs induced using a ventilation system delivering 50 CFM continuously (except for the CFIS system that provides the equivalent but runs intermittently). The heating and cooling systems are consistent with the Building America Benchmark (Hendron and Engbrecht 2010), specifically 78% AFUE gas furnace and 13 SEER air conditioner. The home is one story, has three bedrooms, and 1,200 ft^2 of conditioned floor area. There is no duct leakage to the outdoors (especially relevant for CFIS system). All costs are annual and relative to a home with no whole-building ventilation. Costs are also represented in Figure 8.

Table 2. Example Annual Energy Consumption and Operating Costs for Ventilation Systems in Several Climates

Location	Energy Rates		Exhaust, 10 W			CFIS, 8 h/day		
	$/kWh	$/therm	kWh	Therms	Cost ($)	kWh	Therms	Cost ($)
Chicago	0.11	0.85	182	107	111	985	29	134
San Francisco	0.14	0.97	114	55	69	894	21	144
Atlanta	0.10	1.53	264	47	98	914	21	123
New York	0.18	1.33	187	81	142	1,023	30	277
Phoenix	0.10	1.46	469	11	64	1,105	5	121
Orlando	0.12	1.76	419	6	59	1,252	3	151

Location	HRV, 55 W, 70% ASEF			ERV, 30 W, ASEF[a], 55% TRE[b]		
	kWh	Therms	Cost ($)	kWh	Therms	Cost ($)
Chicago	534	42	95	270	18	45
San Francisco	498	33	100	272	22	59
Atlanta	648	22	98	357	13	55
New York	562	36	150	296	17	77
Phoenix	733	5	83	387	3	43
Orlando	850	3	103	487	1	59

a Apparent Sensible Effectiveness
b Total Recovery Efficiency

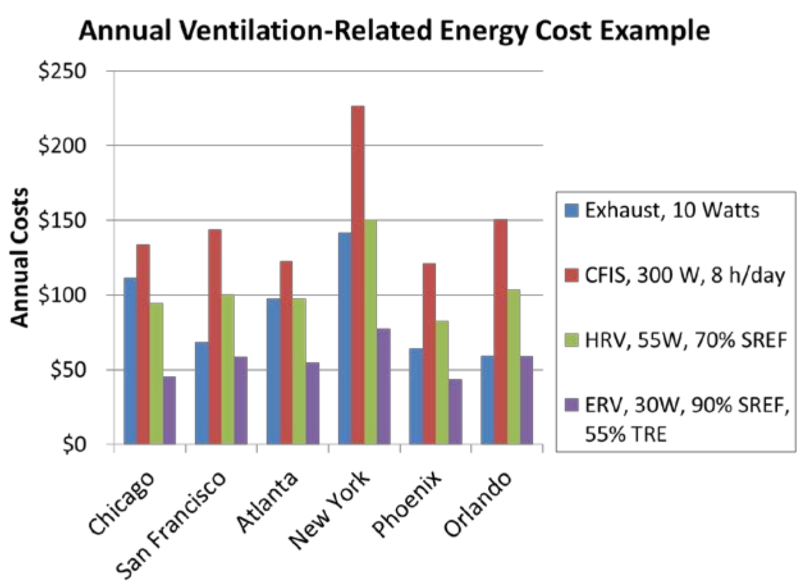

Figure 8. Example ventilation related costs for four systems in six different U.S. climates

6 Implementing Whole-Building Ventilation: Exhaust-Only

6.1 Assessment

Refer to Section 5 above to determine if an exhaust-only ventilation system is appropriate for your building. While these systems are very simple and low cost, they have some significant limitations, and there are situations where exhaust-only strategies are not appropriate.

Before installing fans in a home, evaluate the exhaust fans already in place. Locate the inlets and exhausts for each fan and, if possible, trace and inspect the duct runs. Measure the flow rates—both at the inlets and outlets if practical.

Based on existing conditions and target whole-building ventilation rate, determine the best locations for exhaust fans. In the simplest situations, a single fan—using an existing exhaust duct run—can meet the entire ventilation rate required. In larger homes or when higher flow rates are needed, using multiple fans can be more practical and more effective in removing contaminants from an entire home. If a 3,000-ft^2 home, for example, requires 100 CFM of whole-building ventilation, using two 50-CFM fans may be a better solution than a single 100-CFM fan.

If existing exhaust runs are not sufficient, identify pathways where new exhaust duct runs can be installed. These are usually most easily installed on the top floor of a building where ducts can be run through an attic to a termination at the soffit, gable, roof, etc. Exhaust ducts should never terminate in an attic; exhaust air should always be ducted to the exterior.

6.2 Selecting Equipment

6.2.1 Fans

While some older, existing exhaust fans may be acceptable for local exhaust ventilation, older exhaust fans are typically not appropriate for whole-building ventilation for several reasons:

1. Many older exhaust fans simply do not deliver desired **airflow rates**—or even their rated airflow rates. Poor installation may be largely to blame.
2. Newer fans can be much more **efficient**. While ENERGY STAR fans were recommended for local ventilation (Section 3.2), this is much more important when fans are intended to operate frequently or continuously. In fact, using fans that greatly exceed ENERGY STAR performance standards is strongly recommended. Many newer exhaust fans can operate at 6–9 CFM/Watt while the ENERGY STAR minimum is only 1.4 CFM/Watt (EPA 2003, for exhaust fans rated below 90 CFM). Several manufacturers, for example, make 50–CFM exhaust fans that consume 6–8 Watts.
3. ENERGY STAR fans also have **noise** requirements. If an older (or non-ENERGY STAR) fan is intended to operate continuously, the noise generated may make residents turn off the fan for long periods of time. This can obviously defeat the purpose of continuous ventilation.
4. Finally, older fans likely were not designed to run continuously and have dramatically reduced **longevity** when compared to newer, ENERGY STAR fans.

6.2.2 Controls

In the simplest exhaust-only systems, fans are intended to run continuously at their rated speed. When a home's ventilation target is 50 CFM (or lower), one 50-CFM fan operating continuously can suffice. If the target flow rate is somewhat lower—say 30 CFM for a smaller home—operating a 50-CFM exhaust fan continuously can be overkill. The additional 20 CFM of forced infiltration can be a substantial energy liability, especially in colder climates. Several control strategies and devices are available to address this issue. Some examples of these are shown in Figure 9 through Figure 12. These are presented as examples only; this is certainly not an exhaustive list nor does CARB necessarily recommend these specific devices over others. There are many ways to control the fan speed and/or period of operation to achieve the desired rates.

Figure 9. Many fans have adjustable speed settings (30–70 CFM in this fan) for continuous operation. When the bathroom is in use and more flow is desired, the fan can boost to 80 CFM for a preset time.

Figure 10. Some devices—when wired in series with a fan—will reduce the speed and flow rate delivered.

(Credit: Tamarack)

Figure 11. Many timer controls can be programmed to cycle fans on and off. For an equivalent 30 CFM continuously, a 50-CFM fan can operate 36 minutes per hour. The fan can also be controlled on-demand.

(Credit: AirCycler)

Figure 12. This timer from can be manually programmed or users can enter in home information and the fan will operate to meet 62.2-2010 requirements.

(Credit: Honeywell)

6.3 Installation

See Section 3.3 for guidance on installation of exhaust fans.

6.4 Measurement, Verification, and Commissioning

After fans are installed, adjust controllers (if necessary) to deliver the desired levels of ventilation at the proper times. Measure the exhaust rate flow from the fan. There are several ways to measure exhaust flow, but a flow hood or dedicated exhaust measurement device (e.g., Figure 2) are two fairly simple and reliable methods. Most variable-speed fans should deliver flow rates very close to the nameplate rates. If flows are much lower, it's possible there is a restriction in the duct system. Check the duct runs and outdoor air hoods to remove restrictions if possible.

Finally, ensure that the controls operate as intended (e.g., fans boost to high speed, timers turn on/off at proper times, etc.)

6.5 Operation and Maintenance

As discussed above, exhaust fans require minimal maintenance. To maintain proper flow rates, however, most manufacturers do recommend periodic vacuuming of the exhaust fan grille and wiping/cleaning the fan housing with a damp cloth. Refer to operation instructions for details. On the outside of the home, the exhaust outlet should be checked periodically for obstructions or debris.

7 Implementing Whole-Building Ventilation: Central Fan Integrated Supply

7.1 Assessment

Clearly, CFIS systems are only appropriate in homes with forced-air heating or cooling systems. Examine the air handler and return plenum location. Make sure the area is accessible and that there is adequate room to install an outdoor air duct.

Locate a good air intake location. The air intake should draw in clean outdoor air without restrictions. Outdoor air should **not** be drawn from an attic, basement, garage, or crawlspace. Intake should be well above the ground and snow level, away from garages or parking areas, and away from any exhaust termination. The 2012 International Mechanical Code (ICC 2011c) typically mandates intakes be at least 10 ft from contaminant sources. The intake location should also be close to the return plenum.

Figure 13. Poor location selection for CFIS ventilation intake, as the homeowners placed their outdoor grill in this corner of the patio

Map the duct run. Make sure a duct can be run from the return plenum to the outdoor air intake location within the project's scope. Duct runs should be as short and as straight as practical to provide unrestricted airflow.

Measure airflow and return static pressure. With the air handler in "fan only" mode (i.e., heating and cooling turned off but the fan turned on), measure the system airflow and the static air pressure in the return plenum.

AHU fan motor. Determine the type of air handler fan motor and/or measure the power consumption of the motor. Variable-speed motors (also called ECMs or BPM motors) typically use approximately 50% less electricity than older permanent, split-capacitor (PSC) motors.

While inefficient motors can provide adequate airflow, the energy consumption is substantial. Using CFIS with PSC fan motors is **not recommended**.

Determine the Outdoor Air flow rate and operating schedule. The approximate outdoor air flow rate can be calculated from the measured return static pressure and the total equivalent length (TEL) of the duct run. Each linear foot of outdoor air intake duct counts as 1 ft of TEL, but bends and fittings also increase TEL. Many elbows, for example, add at least 15 ft to TEL; an air intake hood may add 30 ft. See ACCA Manual D (Rutkowski 2009) for more details about calculating TEL. Flow rate can be estimated using a duct calculator tool; examples are shown in Table 3.

Table 3. Approximate Airflow Rates With Varying TELs and Available Static Pressures

		Approximate Airflow (CFM)			
TEL (ft)	**Return Static Pressure (Pa)**	**6-in. Galvanized**	**6-in. Flexible**	**8-in. Galvanized**	**8-in. Flexible**
25	–20	200	150	435	330
50	–20	140	105	310	220
100	–20	84	75	210	160
200	–20	66	54	145	105
50	–40	200	150	435	330
100	–40	140	105	310	220
200	–40	84	75	210	160
50	–60	250	175	540	380
100	–60	170	125	385	270
200	–60	116	85	250	175

The more outdoor air introduced into the system, the less time the air handler must operate to deliver outdoor air. A key limitation, however, is on the temperature of the mixed air (i.e., the mixture of return air and outdoor air) supplied to the home. Cool air can cause comfort problems during the winter, and many furnace manufacturers require that air passing over the heat exchanger be above a minimum temperature (55°–60°F is common; see manufacturer literature). The mixed air temperature can be calculated by the ratio of air temperatures and flow rates. Table 4 shows an example of maximum outdoor air flow fractions to keep mixed air at 60°F or above (assuming 70°F return air). For example, if total system airflow is 1,000 CFM and outdoor air is 10°F, outdoor air flow rate should be no higher than 170 CFM to keep mixed air temperature above 60°F. Some guidelines for CFIS systems cold climates (Pettit et al. 2013) state that outdoor air should not exceed 15% of the total system flow rate.

Table 4. Minimum Outdoor Air Fraction To Provide Mixed Air Temperature of at Least 60°F With 70°F Return Air Temperature

Outdoor Air Temperature	Maximum Outdoor Air Fraction for Mixed Air > 60°F
40°F	33%
30°F	25%
20°F	20%
10°F	17%
0°F	14%
–10°F	13%
–20°F	11%

7.2 Selecting Equipment

7.2.1 Controller

There are several CFIS controllers on the market (see Figure 14). These controllers are available as discrete components, but many are also available as part of a kit that also includes a controller, motorized damper, and transformer. While these devices have very similar functionalities, make sure the device (or kit) used is compatible with the existing air handler and control system.

Figure 14. At least three manufacturers offer CFIS kits: Aprilaire, AirCycler, and Honeywell.

(Credit: Aprilaire, AirCycler, and Honeywell)

7.2.2 Ducts and Dampers

Duct size is covered in “assessment” above. Duct runs should be as short and straight as is practical. Ducts bringing cold outdoor air through conditioned space may cause condensation; to reduce this risk, insulate ducts running through conditioned space in colder climates.

Motorized dampers—which open to allow outdoor air in and close when the ventilation quotas have been met—are often available as part of a CFIS package or kit (see Figure 14). If a different size damper is needed, motorized dampers can certainly be acquired separately. Refer to manufacturer literature to ensure that dampers are compatible with the controller.

Figure 15. A motorized damper (left) and manual balancing damper (right) in CFIS systems

In addition to the motorized damper, a manual balancing damper is recommended in the outdoor air duct. This can be adjusted if necessary to fine-tune the volume of outdoor air introduced into the system.

7.2.3 Air Handler Fan Motors

As mentioned above, CFIS ventilation systems are not recommended with an inefficient AHU fan motor. For older furnaces or air handlers, there are at least two efficient fan motor replacements available (see Figure 16). While electricity consumption of these motors depends a great deal on HVAC system characteristics, these motors may consume 50% less electricity to deliver the same flow rate (Aldrich and Williamson 2013). If central air handlers do not have an efficient motor, and replacing the motor is not possible or practical, CARB recommends a different type of ventilation system.

7.3 Installation

A qualified HVAC contractor should install the controller, ducts, dampers, and other components. The location of the duct run, connection to the return plenum, and location of outdoor air intake should be planned beforehand (see Section 7.1 above).

Ducts should be sealed with approved foil-faced tape or mastic as appropriate (see Aldrich and Puttagunta 2011). In cold climates, ducts running through interior spaces should be insulated to prevent condensation. Outdoor air intakes should be equipped with screens to keep out insects and debris. As mentioned above, intakes should be well above snow level, but it's preferable that they be accessible from the ground for cleaning and maintenance. Outdoor intakes should be integrated with siding and flashed properly to prevent water intrusion, and penetrations through exterior walls or ceilings should be appropriately sealed to limit infiltration.

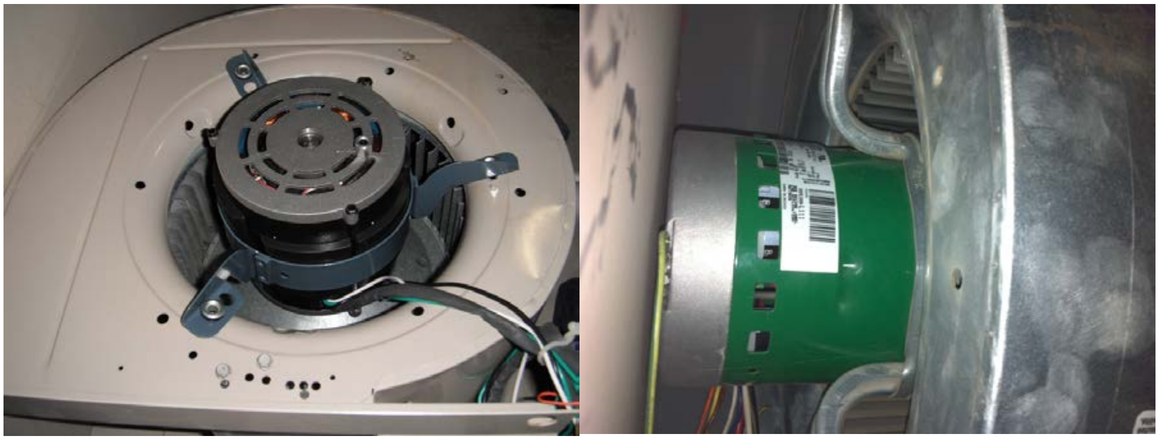

Figure 16. The Fieldpiece LER (left) and the Evergreen IM (right) are two replacement variable-speed motors designed for residential air handlers.

7.4 Measurement, Verification, and Commissioning

After installation, commissioning of the system is critical. The first step is usually checking to ensure that when the controller calls for outdoor air, the air handler turns on and the motorized damper opens (see Figure 15). The outdoor air flow rate should then be measured. This can be accomplished in several ways, but two common methods are:

- A traverse of the outdoor air duct with a pitot tube or anemometer will provide air velocity. Velocity (feet per minute) times the cross-sectional area (square feet) of the duct will yield volume flow rate (CFM).
- At the outdoor air intake, a flow hood can measure airflow being drawn into the system (this typically requires little or no wind for accurate measurements).

Finally, the balancing damper and the controller should be adjusted so that the desired amount of outdoor air is introduced into the system at the desired schedule.

7.5 Operation and Maintenance

As always, refer to manufacturer instructions for maintenance. One of the appealing features of CFIS systems is low maintenance, but this does not mean “no” maintenance. One very common method of failure is clogging of the air intake; regularly check the air intake to make sure it is free from debris (leaves, grass clippings, trash, bird nests, etc.).

8 Implementing Whole-Building Ventilation: Heat Recovery Ventilators and Energy Recovery Ventilators

8.1 Assessment

Most HRVs and ERVs are housed in rectangular cabinets that contain fans, filters, heat exchange media, etc. Four ducts usually connect to this cabinet: outdoor air intake, exhaust to outdoors, outdoor air supply to the home, and exhaust from the home.

Determine location for equipment. The ERV/HRV should be located so that duct runs can be short and straight, power and control wiring can be connected easily, and the unit can be easily accessed for maintenance. Many ERVs/HRVs produce a fair amount of noise; keep this in mind if units will be located near sensitive areas (e.g., bedrooms). Basements and attics are common locations for ERVs and HRVs.

Determine outdoor air intake and exhaust locations. The outdoor air intake should draw in clean outdoor air. Outdoor air should **not** be drawn from an attic, basement, garage, or crawlspace. Intake should be well above the ground and snow level, away from garages or parking areas, and far from any exhaust termination. Per the International Mechanical Code, air intakes should be at least ten feet from contaminant sources (ICC 2011c), but different jurisdictions or programs may have more detailed guidelines.

To help justify the higher costs of ERVs and HRVs, many manufacturers suggest that bathroom exhaust fans can be eliminated. Instead of dedicated exhaust fans, the ERV/HRV can be used to continuously exhaust air from each bathroom. This often meets code or program requirements for local ventilation (20 CFM continuously). While many people have used this strategy successfully, others have had problems. CARB has heard complaints from occupants where this strategy is used: “the bathroom never dries out” or similar.

While ERVs and HRVs all have mechanisms to deal with condensate, putting more moisture through the systems can lead to problems. With ERVs, much of this moisture is recaptured and retained in the home. Very often, this is not desired. When ERVs or HRVs are used in a home, CARB recommends separate bathroom exhaust fans be used to remove moisture quickly and directly.

Determine fresh air supply locations. As discussed above (Section 5), one of the advantages of an ERV or HRV system is the ability to distribute fresh air to several locations. While providing outdoor air to all spaces may seem ideal, it is rarely practical. Especially in an existing home, running ducts to all parts of a home is difficult. If an ERV is installed in a basement, for example, delivering fresh air to first-floor spaces may be straightforward; reaching second-story spaces may be quite challenging. Even a single supply register—located relatively far from exhaust registers—can provide better mixing of fresh air than local ventilation systems.

In their product literature, some manufacturers recommend integrating ERVs/HRVs with the central duct systems used for heating and cooling. This requires much less work, especially in an existing home: short duct runs can bring fresh air to the supply plenum and exhaust can be drawn from the return plenum (Figure 17). CARB has found that this strategy does not work well. When the central air handler fan is not running, the outdoor air follows the path of least resistance. In the first arrangement shown in Figure 17, the path of least resistance is for fresh air to move backwards through the air handler and be exhausted through the duct in the return plenum. In both arrangements; very little fresh air is introduced into the living space.

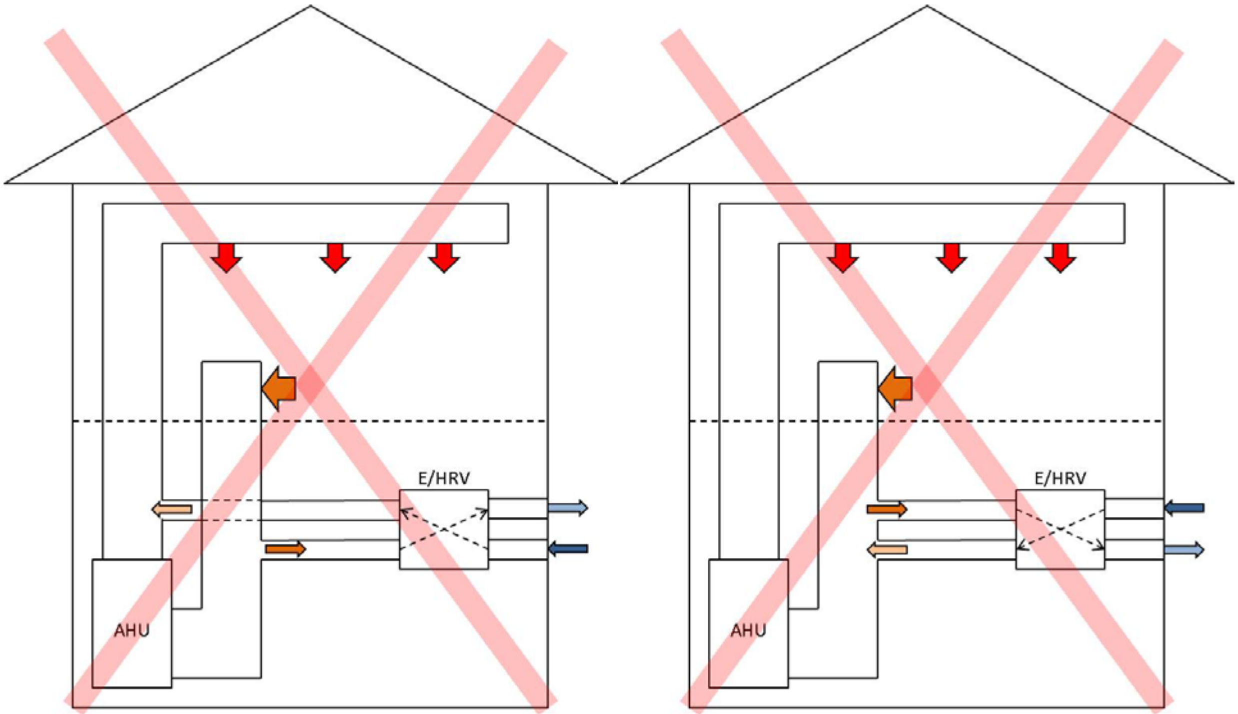

Figure 17. While schematics such as these are often listed as installation options by ERV and HRV manufacturers, these configurations are NOT recommended.

Turning on the air handler when the ERV/HRV operates can solve this short-circuiting problem, but this increases electricity consumption dramatically and is not recommended. If occupants use the air handler to heat or cool when the ERV/HRV is not operating, the ventilation system in these scenarios will introduce large amounts of duct leakage. CARB recommends that *at least* one side of the ERV/HRV system (i.e., either the exhaust or return side) be ducted separately. In Figure 18, for example, air is exhausted through a dedicated run and tempered outdoor air is supplied to the return plenum. This can solve the short-circuiting problem but not the duct leakage problem when the ERV/HRV is not operating. A fully ducted system—where ventilation supply and exhaust ducts are separate from heating and cooling ducts—may offer the best distribution of outdoor air, but this is often impractical in retrofit applications.

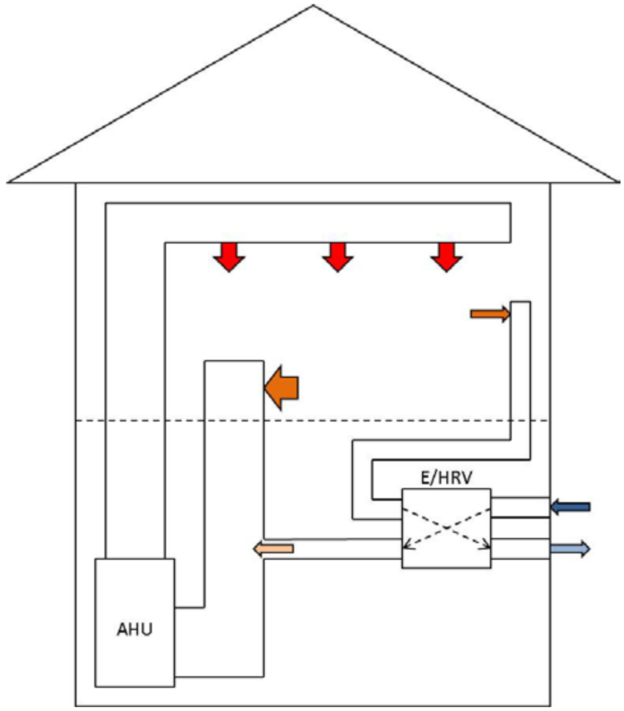

Figure 18. If integrating an ERV/HRV with the heating or cooling duct system, CARB recommends at least one side of the ventilation system (either supply or exhaust) have a dedicated duct run.

Size ducts and map duct runs. To determine duct sizes, refer to manufacturer literature. For more detailed sizing calculations refer to ACCA Manual D (Rutkowski 2009), but for simple duct systems these calculations may not be necessary. For ERVs or HRVs with multiple or variable fan speeds, size duct systems for the higher flow rates. Even if the system is initially intended to run at lower speed, occupants may choose to operate at higher speeds in the future. As always, keep duct runs as short and as straight as practical.

8.2 Selecting Equipment

8.2.1 Energy Recovery Ventilator or Heat Recovery Ventilator?

ERVs transfer moisture (latent heat) as well as temperature (sensible heat). HRVs transfer sensible heat only; they do not transfer moisture. Choosing one type of system or another is not always straightforward, but the key question to ask is: Are typical indoor moisture levels more comfortable than outdoor moisture levels? If so, an ERV may be a more practical choice.

The ERV/HRV question is easiest to answer in hot, humid climates. In Florida, for example, air inside comfortable homes is relatively cool and dry. Outdoor air is quite humid. When outdoor air passes through an ERV, the air will be somewhat cooled and dehumidified by the exhaust air. This does not mean an ERV dehumidifies the home. On the contrary, running an ERV will increase the amount of humidity in the home, but the humidity increase will be less than if an HRV was used.

Outside of hot, humid climates, selecting ERVs or HRVs is not as straightforward. Some manufacturers provide recommendations or even maps of the country designating which type of system is most appropriate, but the recommendations vary from manufacturer to manufacturer. A few example situations are below.

- In relatively leaky homes in colder climates, indoor air during the winter is often uncomfortably dry—so dry that many people use humidifiers. An ERV can help retain moisture within the home, improve comfort, and possibly eliminate the need for humidifiers.
- In very airtight homes in cold climates, especially smaller homes with lots of moisture generation, indoor air humidity can be uncomfortably high. In this a case, an HRV will help reduce indoor humidity.
- In hot, dry climates there is a similar trend: larger or leakier homes with low moisture generation may benefit from ERVs (to retain indoor moisture), while smaller, tighter homes with higher occupancy may benefit from HRVs (to reduce indoor humidity levels).

There is not a hard-and-fast rule about which type of system is more appropriate. Especially in mixed climates, there are many situations where an ERV may be more beneficial during cooling season and an HRV more appropriate during heating season. Installers should use their judgment when selecting systems.

Figure 19. An HRV installed in a cold-climate home

8.2.2 Efficiency

See the previous section for information on when an ERV or an HRV may be more appropriate. HVI publishes standards for testing and rating efficiencies of ERVs and HRVs. **Apparent Sensible Effectiveness (ASEF)** is the most commonly published rating for heat recovery during cold weather. Look for ASEF values above 80%; the most efficient systems have values above 90%. **Total Recovery Efficiency (TRE)** is listed for ERVs, and it accounts for sensible and latent heat recovery during cooling season. For best performance, look for TRE values above 50%. A full listing of certified equipment is available on HVI’s website (HVI 2013).

8.2.3 Power Consumption

Power consumption can vary widely, from below 30 Watts to 200 Watts. Systems with low power consumption often have variable-speed or ECM motors that often allow for better control of ventilation rates. While systems with low power consumption (> 1 CFM/Watt) are often more expensive, they are strongly recommended. In addition to the lower electricity consumption and better controllability, they also usually generate much less noise.

8.2.4 Controls and Features

Most ERVs and HRVs are available with programmable timers of various types. These are usually quite versatile and can be set to various schedules. In ERVs or HRVs with variable-speed fans (ECMs or BPM motors), the flow rate can often be adjusted by changing the fans' speed. Such fans can often be manually boosted to high speed when more air is desired.

The basic timer or variable speed controls are usually all that is required to meet code or program ventilation rates, but some systems offer advanced features (often at a premium). Some examples are:

- Controls with carbon dioxide and/or humidity sensors can boost speed at higher concentrations (which usually indicate higher occupancy).
- Some systems can boost speed and/or bypass the heat exchanger to take advantage of nighttime cooling.
- Higher levels of filtration are sometimes available (including HEPA) to remove airborne allergens and other pollutants.

8.2.5 Cold Weather Performance

With cold outdoor temperatures, moisture in the exhaust air will often condense in the heat exchanger. Under more extreme conditions, this moisture can freeze. Most ERVs and HRVs have condensate drains and frost-protection mechanisms. However, some of these defrost devices or controls must be ordered as add-on features. When selecting a system, make sure you have the necessary features to protect against frost in your climate.

8.3 Installation

Installation should be done by a qualified professional. Follow manufacturer instructions for proper installation. Be sure to install the ERV/HRV unit where it can be easily accessed for maintenance, where power can be safely run to the unit, and where the system's noise will not disturb occupants. Install condensate drains as required by manufacturers.

All duct runs should be as short and straight as is practical. Be sure outdoor penetrations are properly air sealed and flashed and have the appropriate screens for pest protection. Ideally, these penetrations will be easily accessed from the ground so occupants can make sure they stay free of debris.

Duct should be sealed (see Aldrich and Puttagunta 2011), and the ducts running to and from the outdoors should be insulated. If the E/HRV is installed in unconditioned space (e.g., in a vented attic) the ducts carrying exhaust air and tempered outdoor air should also be insulated.

Figure 20. Local ERV (Credit: Panasonic)

Figure 21. Local ERV (cover removed) installed in a home.

Most of the HRVs and ERVs discussed here are ducted systems—i.e., two ducts run from the unit to the indoors, and two ducts run from the unit to outdoors. Cost for installing these duct systems is often a large part of total system cost. To help address this challenge, Panasonic has introduced a local ERV called the WhisperComfort.

This unit is installed in a ceiling—similar to a bathroom exhaust fan. The unit requires two outdoor air ducts (one intake and one exhaust), but the unit exhausts directly from and supplies directly to the room below.

Tests have showed this device to be quite effective (CARB 2011). Compared to conventional ERVs, this system can dramatically simplify installation and reduce costs. There are of course limitations: heat recovery is only moderately efficient, outdoor air is not distributed throughout the home, and it is not recommended for cold climates. Still, CARB believes it may be a practical choice for many rehab projects.

8.4 Measurement, Verification, and Commissioning

As with all ventilation systems, it's important to measure the delivered airflows and make sure they meet specifications or requirements. Flow rates can be measured in several ways. At exhaust registers, a flow hood or exhaust meter (e.g., Figure 2) can measure flow rates. Flow hoods are also useful to measure flow rates at supply registers. In addition to providing a check of total system flow, measuring flow rates at each register is the only practical way to check system balancing.

If indoor supply or exhaust registers cannot all be accessed (e.g., if air is supplied to the return plenum of the central heating and cooling system), flow hoods can be used at the terminations outdoors. This is usually practical only if the terminations are accessible from the ground and if outdoor conditions are calm (i.e., no wind).

As described for CFIS systems, a duct traverse with a pitot tube or anemometer can provide velocity and flow rate. Some ERV and HRV units are, in fact, equipped with pressure taps so that flows can be measured by connecting a manometer directly to the ERV/HRV itself.

If flow measurements do not match specifications or design targets, adjust the controls if appropriate. If the desired flow rates are hard to achieve, inspect the duct system, registers, and exterior terminations for obstructions. If controls have advanced features (e.g., timers, flow boosts, etc.) ensure that these functions are working properly.

8.5 Operation and Maintenance

As always, refer to manufacturer instructions for proper maintenance. Maintenance requirements of HRVs and ERVs are often more rigorous than for other ventilation systems. Many systems require periodic cleaning and/or replacement of heat exchange media, filters, and other parts prone to collect dust and dirt. In addition, outdoor air inlets should be checked periodically to make sure they are free from debris (leaves, grass clippings, trash, etc.).

Some devices are equipped with indicator lights that alert occupants when it’s time for maintenance. If this is not present, residents should be meticulous in maintaining a schedule. Without maintenance, flow rates can drop dramatically; CARB has seen airflow reduced by 50% over twelve months in a system that was not maintained (outdoor intakes blocked with grass/trash, filters and media never cleaned). If possible, checking airflow rates over time (as recommended during commissioning) is an excellent practice to ensure the desired airflow is being consistently delivered.

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Appendix: Summary of Ventilation and Distribution Studies

Below are summaries of several research efforts to evaluate the impact of distributing outdoor air or mixing air within a home. The list is certainly not exhaustive.

- Rudd (1999) documents tests of two supply-only ventilation systems in new Las Vegas, Nevada homes. The tests find that when the ventilation systems are integrated with the central air handler (such as with a CFIS system), all areas in the home experience similar air change levels. Local supply ventilation did not provide even levels of air changes throughout the home; this was especially pronounced when interior doors were closed. When the air handler was operated in conjunction with local ventilation, disparities in air change levels were substantially reduced.
- Rudd and Lstiburek (2000) includes the results from above as well as results from testing ventilation systems in a large new home in Minneapolis, Minnesota. During tests of local exhaust ventilation used as whole-building ventilation, some areas of the home experienced air change rates (reciprocal age of air, RAoA) of nearly 50% less than the average air change rate in the entire home. When the central air handler was operated periodically in conjunction with the exhaust fan, RAoA values were much more uniform. In tests of CFIS ventilation, local RAoA values differed from the home average by less than 10%.
- Hendron et al. (2006) documents tests in two new homes in Sacramento, California. The tests compared exhaust-only ventilation (using a local exhaust fan) and supply ventilation using the central air handler and duct system. Ventilation systems were set to meet airflow required by ASHRAE 62.2-2004. Multi-point tracer gas tests consistently showed that central fan-integrated supply ventilation provided the lowest variability in age of air from room to room (RAoA differences of 0.02 h^{-1} or less). Tracer gas tests for exhaust-only systems provided the following insights:
    - With all doors closed, RAoA values could be quite disparate. In the most extreme case, RAoA values differed by a factor of 2.5 between two spaces in the home.
    - When doors are open, age-of-air uniformity is much greater. During this test, the highest measured RAoA was 15% higher than the lowest RAoA.
    - When the central air handler was operated on a 33% duty cycle (without introducing additional outside air), RAoA values were quite uniform—very nearly as uniform as the central AHU-integrated supply ventilation.
- CARB (2007) describes multipoint tracer gas test results in a Massachusetts home with exhaust-only ventilation using bathroom fans. Results were similar to those described above: when interior doors were open, RAoA values were very similar; when doors were closed, secondary bedrooms had RAoA values nearly double those of central spaces (Figure 20). Tests also included preliminary tests of trickle-vent effectiveness.

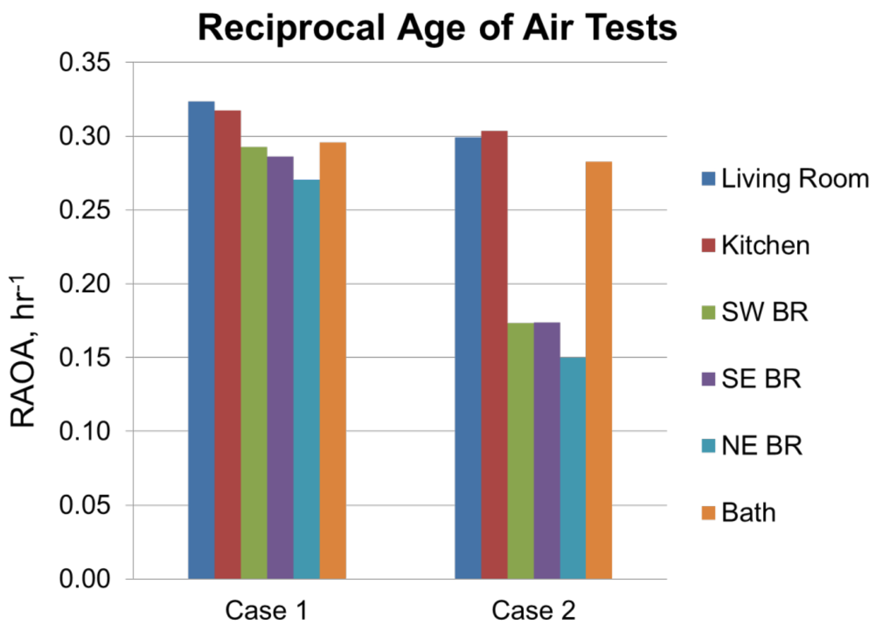

Figure 22. Summary of RAoA tests from (CARB 2010). In both test cases, all interior doors are closed with exhaust ventilation operating continuously. In Case 1, the mixing fan is running.

- The Massachusetts home described in another study (CARB 2010) also had an exhaust-only ventilation system. This home, however, had a separate air "mixing" system. The mixing fan is simply an efficient exhaust fan installed in the ceiling of a central space. This fan moves approximately 20–30 CFM continuously from the central space to each bedroom. Without this fan running, bedrooms with closed doors experienced RAoA values nearly 50% lower than in central spaces. With the mixing fan running, however, bedroom RAoA values were only 10%–15% lower than in central spaces.
- An LBNL paper (Sherman and Walker 2010) reviews several past studies to gauge the IAQ impacts of mixing indoor air. The study concludes that overall, additional mixing of indoor air will not substantially affect IAQ. In some cases added mixing can reduce occurrences of extreme contaminant exposure. To minimize average exposure to contaminants, however, added mixing is not recommended.
- Testing of a Las Vegas home is described in (CARB 2011). Two different whole-building ventilation systems were installed in this home: an exhaust-only system and a local, ceiling-mounted ERV. With the local ERV, a key concern was to evaluate "short-circuiting" potential as the supply and exhaust ports are located in the same ceiling-mounted device. Tracer gas tests showed that this was not a problem in this home.

  Tracer gas tests showed that neither local ventilation system provided equal air change rates throughout the home unless interior doors were open or the central air handler fan was operating. In the test with the exhaust-only system running with all doors closed, the utility room showed RAoA values nearly twice as high as in other spaces; this is concerning as the utility room borders the garage.

- In two new homes in Texas, BSC researchers tested three ventilation systems and found the exhaust only system resulted in more disparate air change rates and higher concentration of volatile organic compounds when compared to the CFIS and ERV systems (Rudd and Bergey 2013).

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