

Evaluating Ventilation Systems for Existing Homes

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February 2013



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Evaluating Ventilation Systems for Existing Homes

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Definitions and Abbreviations

АСН	Air changes per hour
ACH ₅₀	Air changes per hour when building is depressurized to 50 Pascals
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air- Conditioning Engineers
BAS	Building airflow standard
BPI	Building Performance Institute
CARB	Consortium for Advanced Residential Buildings
CCCRD	Clark County Community Resources Division
CFIS	Central fan-integrated supply (ventilation)
CFM	Cubic feet per minute
DER	Deep energy retrofit (or reduction)
ECM	Electronically commutated motor
ERV	Energy recovery ventilator (for sensible and latent heat)
HERS	Home Energy Rating System
HRV	Heat recovery ventilator (recovers sensible heat only)
HVAC	Heating, ventilation, and air conditioning
HVI	Home Ventilating Institute
IEQ	Indoor environmental quality
LEED	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
OA	Outdoor air
RAoA	Reciprocal age of air [hr ⁻¹]
w.g.	Water gauge

Executive Summary

In an effort to improve housing options near Las Vegas, Nevada, the Clark County Community Resources Division (CCCRD) performs substantial renovations to foreclosed homes. After dramatic energy, aesthetic, and health and safety improvements are made, homes are rented or sold to qualified residents. This report describes the evaluation and selection of ventilation systems for these homes.

Ventilation is clearly a key component in an efficient, healthy home. When improving the energy performance of homes—often with increased envelope tightness and insulation—selecting ventilation systems is not always straightforward. The ideal ventilation system should be reliable, address indoor environmental quality concerns appropriately, be affordable and practical to install, consume little energy, and be relatively easy to maintain.

Not surprisingly, such an "ideal" system is hard to come by. Selecting a system involves optimizing features depending on the project location, scope, and budget. This report outlines key considerations when selecting a ventilation system and reviews findings of several past and current studies on the subject. The report then describes CCCRD's decision process with respect to ventilation.

After performing detailed evaluations of several systems, CCCRD has chosen to use local energy recovery ventilators in many of its homes. The total installed cost of these systems is manageable (\$700–\$1,600), the operating costs are reasonable, and the Consortium for Advanced Residential Buildings and CCCRD are confident that these systems will adequately address internal environmental quality concerns.

1 Introduction

As new home envelopes have become more and more airtight, most in the homebuilding industry have come to understand that proper ventilation is critical. With the revisions of ASHRAE Standard 62.2 in 2003 (ASHRAE 2003), building scientists and designers had a more meaningful standard for single-family ventilation. Many home building programs, such as Leadership in Energy and Environmental Design (LEED) for Homes and regional ENERGY STAR[®] initiatives, required compliance with ASHRAE 62.2 in new homes.

Building America researchers have been evaluating ventilation systems for more than a decade. While there is still not universal consensus about which systems perform the best, are the most reliable, are most cost-effective for certain homes, there is a wide array of acceptable—if not "ideal"—ventilation options.

Until quite recently, most ventilation research efforts have focused on new construction. When improving the energy performance of existing homes, ventilation must not be overlooked. Many older homes may not experience moisture or indoor environmental quality (IEQ) problems because the homes have high levels of uncontrolled infiltration; as envelopes are tightened, proper local and whole-building ventilation becomes increasingly important.

Although the basic goals and principles of ventilation are similar in new and existing homes, selecting and installing ventilation systems in existing homes can be more complex and costly than in new construction. Local ventilation (e.g. exhaust fans in baths and kitchens) may perform poorly—if they are present at all. Some whole-building ventilation strategies require new ducting which can be intrusive and expensive in existing homes.



Figure 1. One of the homes in Las Vegas, Nevada tested with several ventilation systems

In this research effort, the Consortium for Advanced Residential Buildings (CARB) has been working with Clark County (Nevada) Community Resources Division (CCCRD) to evaluate optimal ventilation systems in retrofit homes. Through the U.S. Department of Housing and Urban Development's Neighborhood Stabilization Program, CCCRD is purchasing foreclosed properties, performing audits, and implementing health, safety, and energy improvements. The renovated homes are then rented or sold to qualifying residents. CARB has performed field testing, energy modeling, and cost analyses to help CCCRD select ventilation systems that reliably provide higher levels of IEQ and minimize first costs, operational costs, and maintenance.

Research questions:

- What are the optimal ventilation systems for CCCRD homes with respect to:
 - IEQ?
 - First costs and ease of installation?
 - Energy and operating costs?
 - Reliable operation and maintenance?
- What gaps remain in cost and performance of these ventilation systems?
- What additional ventilation products or systems might address some of these gaps?

This report discusses these issues in some detail. Although it focuses on CCCRD homes undergoing renovation, the authors hope that the background given and decision-making processes will be useful to decision-makers in many other projects.

2 Background: Key Ventilation Considerations

2.1 Ventilation Levels and Needs

In CARB's experience, ANSI/ASHRAE Standard 62.2-2010 (ASHRAE 2010a) 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 2010b). Some programs (such as those using Building Performance Institute [BPI] Building Analyst Standards [BPI 2012b]) still reference the much older ASHRAE Standard 62-89 (ASHRAE 1989). However, many weatherization and home performance programs are moving toward the more recent Standard 62.2.

Standard 62.2 requires local ventilation in bathrooms (with capacity of at least 50 cubic feet per minute [CFM] intermittently or 20 CFM continuously) and kitchens (with capacity of at least 100 CFM intermittently or 5 air changes per hour [ACH] continuously). These local exhaust systems are required to remove odors and pollutants—especially water vapor—from these key areas. Although exhaust fans are common in many older homes, in CARB's experience older fans often perform very inefficiently and poorly—exhausting a very small fraction of the design or desired flow rates.



Figure 2. Convoluted or extremely long duct runs can dramatically reduce exhaust fan flow rates.

While local exhaust fans can remove water and other pollutants from these heavy source areas, Standard 62.2 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 2010a). Required whole-building ventilation capacity (outdoor air [OA] flow rates) depends on home size and number of bedrooms; this is summarized in Equation 1.

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

where

 $Q_{fan} = W$ Whole-building ventilation flow rate (continuous) [CFM] $A_{floor} = F$ Floor area [ft²] $N_{br} = N$ Number of bedrooms

ASHRAE 62.2 is a standard for ventilation capacity. Although many whole-building ventilation systems are designed to operate continuously or on a timer (e.g. several minutes during each hour), ASHRAE 62.2 mandates system capacity only—not how a system is operated.

While ASHRAE 62.2 has been accepted by many builders, designers, and certification programs, it is clear that there are situations where the ventilation levels in ASHRAE 62.2 are too high or too low. Kitchens in which a great deal of cooking takes place, for example, can benefit from higher exhaust levels to keep 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 or pollutant generation could save energy by reducing ventilation levels.

The performance of a fan—especially the delivered flow rate—is 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 rates in homes (HVI 2011). HVI's recommended ventilation levels are typically higher than those recommended by ASHRAE 62.2. With kitchen ranges, for example, HVI recommends 100 CFM per linear foot of range width (e.g., 250 CFM for a standard 30-in. range). This is considerably higher than the 100 CFM minimum specified in ASHRAE 62.2.

2.2 Installation and Integration With Existing Systems

As discussed in Section 1, most past Building America research has focused on ventilation systems in new construction. In existing homes, installing whole-building ventilation systems can be much more involved and costly—especially with more complicated ventilation systems.

The level of effort, and ultimately the cost, required to install a ventilation system in an existing home depend on many factors, including:

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

In many instances, existing ventilation systems—especially local ventilation in bathrooms, for example—are operable and can be used in the renovated home. Often, however, older fans do not deliver desired flow rates—either because the fans themselves operate poorly or because the ducts are constricted or obstructed. If the fan is the problem—and the ducts are intact—a replacement exhaust fan can often be installed with minimal hassle. A small part of a ceiling or wall may need to be refinished, but existing wiring and ducting can minimize the invasiveness, and ultimately the cost.

In homes with existing forced-air heating or cooling, it's possible that a central fan-integrated supply (CFIS) ventilation system (discussed in Section 4.2) can use the ducts and the central air handling unit (AHU).

When there is no existing duct system—or at least none that is appropriate for the desired ventilation system—installing new ducts and running electrical service to fans can be time consuming and costly. These costs can be minimized when there is access to ventilated areas from basements, crawlspaces, or attics. If ducts or electrical lines must be run between floors or within walls, sections of wall board or ceilings must generally be removed and replaced. If other aspects of the renovation do not necessitate this level of intrusion, this can dramatically increase the cost of ventilation installation and integration.

When ventilation is part of very thorough renovations (gut rehabs or deep energy retrofits [DERs]), these issues may be largely moot. In some large-scope rehab projects, the effort of installing and integrating ventilation systems is very similar to what it would be in new construction. While running electrical and extensive ducting still represents a substantial cost, the incremental costs are much lower in a gut rehab. In practical terms, gut rehabs may allow for more intricate or sophisticated ventilation systems that would be impractical or too costly in smaller scope renovations.

2.3 Distribution and Mixing of Outdoor Air

Local ventilation is properly targeted toward areas where pollutants, especially moisture, are generated intermittently. Whole-building ventilation is intended to reduce pollutants that are continuously generated throughout the home. Some ventilation strategies use point-source or local ventilation systems to meet whole-building ventilation requirements (e.g., a bath exhaust fan running continuously). There is no consensus in the industry about if—or, more accurately, when—point-source ventilation is an IEQ liability.

Certainly providing OA to every room in a home is ideal, but the installed costs of such systems can be quite high. Below are summaries of several research efforts to evaluate the impact of distributing OA or mixing air within a home.

• Rudd (1999) documents tests of two supply-only ventilation systems in new Las Vegas homes. The tests revealed 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) include the results from Rudd (1999) 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 (or 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 central fan integrated supply ventilation, local RAoA values differed from the home average by less than 10%.
- Hendron et al. (2006) document 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 Standard 62.2. Multipoint tracer gas tests consistently showed that central fanintegrated supply ventilation provided the lowest variability in age of air from room to room (RAoA differences of 0.02 hr⁻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 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 as 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. Tests also included preliminary tests of trickle-vent effectiveness.



Figure 3. 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. When this fan was not running, bedrooms with closed doors experienced RAoA values nearly 50% lower than in central spaces. When the mixing fan was running, however, bedroom RAoA values were only 10%–15% lower than in central spaces.
- Testing of a CCCRD 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 energy recovery ventilator (ERV) (described in Section 4.4). With the local ERV, a key goal 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.

This list of research is certainly not exhaustive. While the conclusions of the researchers vary (as to the viability or appropriateness of various systems), there are some consistent conclusions about non-distributed (local or point) ventilation systems. Point ventilation (either exhaust-only or H/ERV) provides fairly uniform distribution of fresh air within a home when:

• Doors are open,

- A central air handler operates intermittently, or
- A mixing system operates continuously at low volume.

In these three cases, RAoA values in all spaces appear to be similar to RAoA values where fully ducted or distributed ventilation is installed. The volumes and duty cycles required in the second and third bullets above require more investigation. In the mixing study (CARB 2010), 20–30 CFM of continuous mixing proved adequate. It stands to reason that a central AHU providing 100 CFM for 15 minutes each hour would provide similar results.

• When doors are closed and there is no central air handler operation, air change rates with point ventilation vary much more throughout a home. Some areas (especially some bedrooms) commonly experience RAoA values 50% lower than do areas where point ventilation systems are located.

2.4 Source of Outdoor Air

Certainly OA brought into a home as part of a ventilation system should—as much as possible be free from pollutants. With active air intakes, published guidelines (often included as part of a manufacturer's installation instructions) give required clearances from combustion exhausts, operable doors and windows, ground or snow level, etc. This concern about the source of OA is much more problematic when dealing with exhaust ventilation.

In larger buildings, ventilation systems typically 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 International Residential Code, for example, any local exhaust fans with capacity of 400 CFM or higher must include makeup 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. This may not be ideal, but there is not widespread consensus on whether this practice is acceptable in any circumstance. Most professionals do agree, however, that these situations or configurations are far from ideal:

- 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. This potential problem was identified during tracer gas testing of a CCCRD home (CARB 2011).
- In a home with a moist or moldy crawlspace or basement, makeup air coming through such a space may bring mold spores, humidity, or other undesirable pollutants.
- 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.

All homes require exhaust ventilation, if only intermittently (e.g., to meet local ventilation requirements of ASHRAE 62.2). The concerns above become somewhat more pressing when exhaust ventilation is used for whole-building ventilation and runs continuously.

2.5 Energy Implications

Mechanical ventilation systems have two key energy impacts:

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

Electrical fan energy varies widely. Typical range for bath exhaust fan power is 6–40 Watts. Conventional HRV and ERV power consumption ranges from 40 to 200 Watts. The fan in a central air handler or furnace—used in some ventilation strategies—can use 200–700 Watts. These are very general ranges, and power consumption certainly varies with air flow and system curves. Power consumption also, not surprisingly, varies with cost. Typically the lowest power ventilation products use fans with electronically commutated motors (ECMs) which often mean higher costs.

The second point—conditioning the introduced OA—is climate dependent. HRVs and ERVs can certainly mitigate this effect. The sensible effectiveness of ERV and HRV heat exchangers typically ranges from 55% to 85%. Again, the higher values typically come with a higher cost. More extreme outdoor temperatures result in greater benefits from heat recovery. In humid climates, the latent transfer of ERVs can help significantly to manage the latent loads introduced by a ventilation system.

For CCCRD homes in Las Vegas, the energy-related specifications of the ventilation systems investigated—along with the modeled energy impacts—are outlined in Section 4.

2.6 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 maintenance requirements. Typical maintenance instructions are—at least once per year—to clean and/or wipe the exhaust fan grille, vacuum dust and dirt from the fan body, wipe the fan body clean, and replace the grille (Panasonic).

Some of the higher performing ERVs, by contrast, require quarterly checking or cleaning of filters, heat exchange media, and exterior duct terminations. While exhaust fan maintenance instructions may consist of four or five short bullets, instructions for checking and cleaning ERV components are typically several pages (UltimateAir 2006). This increased level of maintenance is not a design flaw; it is simply necessary with more complex systems.

CARB has worked with several builders and developers who are 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 often 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. Costs are discussed in Section 4.

3 What Systems Are Being Installed?

Through direct experience and literature reviews, CARB has documented trends in how mechanical ventilation is addressed when improving existing homes. Substantial information is available for two main types of home improvement efforts:

- Weatherization (or similar): typically lower cost, nonintrusive energy and IEQ improvements.
- Deep energy retrofits (or similar): usually much more intensive—and expensive improvements to existing homes. These are often custom projects and sometimes gut rehabilitation projects.

There is, of course, a wide spectrum of home improvement efforts, but these two areas currently have increased focus in the home energy improvement markets.

3.1 Weatherization and Similar Programs

The term *weatherization* can broadly refer to improving the energy and comfort performance of a home, but *weatherization programs* typically offer modest home improvements for lower income occupants. Generally speaking, these programs often include basic safety tests and diagnostics, air sealing, added insulation, efficient lighting, water saving measures, and possible appliance upgrades. Weatherization is usually performed on occupied homes, and the home improvement efforts are not usually extensive or intrusive.

How weatherization programs address ventilation certainly varies, but many programs use standards developed by the Building Performance Institute (BPI) or similar standards. The core BPI standard (BPI 2012b) references ASHRAE 62-89 (ASHRAE 1989). Such weatherization standards require whole-building ventilation only when natural infiltration is lower than a defined benchmark. This benchmark, referred to as the Building Airflow Standard (BAS) in BPI Standards, is the greater of:

- 0.35 air changes per hour (ACH)
- 15 CFM per occupant.

These values are converted to equivalent envelope leakages as measured with a blower door. For example, a 1,500-ft², 12,750-ft³, two-occupant, single-story home in Las Vegas would have a BAS of 74 CFM. When depressurizing with a blower door at 50 Pa, the BAS becomes 1,599 CFM₅₀ (see BPI 2012b for information on these calculations).

Following the BPI standards, when testing this example home a weatherization contractor should follow this protocol:

- If blower door test show infiltration above 1,599 CFM₅₀, no action need be taken concerning ventilation.
- If blower door tests show infiltration less than 1,599 CFM₅₀ but higher than 1,119 CFM₅₀ (70% of BAS), ventilation must be recommended.

• If blower door tests show infiltration less than 1,119 CFM₅₀ (70% of BAS), a ventilation system must be installed as part of weatherization work.

The requirements are fairly clearly laid out, but most home performance and weatherization contractors are equipped to handle air sealing, insulating, lighting upgrades, etc. They are not equipped to handle HVAC improvements. In fact upgrading ventilation is outside the scope of many home performance programs (it is an IEQ measure, not strictly an energy-saving measure, and is therefore often outside the approved scope of services). With these caveats, the effective weatherization guidelines (with respect to ventilation) become:

- Do not air seal a home below the BAS value.
- If initial tests of a home show envelope leakage below the BAS, walk away from the home.

Although this is rarely publicized, in CARB's experience this is the de facto rule for many weatherization and home performance programs. Building America goals require reaching for higher levels of efficiency and envelope tightness. To reach these higher levels, ventilation cannot be ignored. Fortunately, there seems to be a growing trend to address ventilation differently. Several agencies are aligning program rules with ASHRAE 62.2 or similar standards. In response, BPI has announced adjusting its standards in 2013 (BPI 2012a).

3.2 Deep Energy Retrofits and Similar Projects

While weatherization programs often do not result in envelope tightness where standards would require whole-building ventilation, more intense energy improvement efforts—such as DERs—certainly do achieve lower infiltration levels where whole-building ventilation is necessary.

There are several regional DER programs. One nation-wide (and beyond) effort is the "1000 Home Challenge" sponsored by Affordable Comfort, Inc. (<u>thousandhomechallenge.com</u>). This initiative encourages reductions in home energy consumption of at least 70%. Achieving these reductions typically requires dramatic envelope improvements, HVAC system upgrades, efficient lights and appliances, and changes in occupant awareness and behavior. Good ventilation is critical in such tight envelopes.

A survey of the case studies on the 1000-Home Challenge site (ACI 2012) shows that more than 75% of DER projects incorporate HRVs or ERVs to provide whole-building ventilation. Cost information is not consistently available for these projects, but the scope of the home energy improvements shows that overall budgets are considerable. The higher budgets—along with the intensive nature of the energy improvements—allows for easier incorporation of more complicated HRV or ERV systems.

In Massachusetts, National Grid, one of the largest utilities in the state, recently sponsored a DER pilot project. Among the first three completed projects (with case studies available), two homes use ERVs and one uses a CFIS system (BSC 2010, BSC 2011a, BSC 2011b).



Figure 4. With significant space and ducting requirements, fully ducted ERV or HRV systems are often more practical in major renovation projects.

3.3 Midrange Energy Improvement Efforts

The examples above—weatherization efforts and DERs—represent a fairly broad spectrum in home energy improvements. Building America goals target efforts somewhere in the middle of this range. Most DERs certainly meet Building America energy goals, but the high cost of most of these efforts limits widespread adoption or duplication. On the flip side, weatherization often addresses only the very low-hanging fruit; Building America is pushing for more significant energy improvements.

The CCCRD homes in Las Vegas fit squarely in the middle of this range: CCCRD has much more rigorous energy goals than most weatherization programs (HERS 50, though that is not consistently attained), but with smaller scope (and certainly budget) than many DER projects. One of CARB's efforts with CCCRD has been evaluating and helping to optimize its approach to ventilation.

4 Systems Evaluated and Cost Analysis

Below are descriptions of four ventilation systems considered for CCCRD homes along with associated advantages, disadvantages, installation costs, and operating costs:

- Exhaust only
- CFIS (central fan-integrated supply)
- Ducted ERV or HRV
- Local ERV.

4.1 Exhaust Ventilation

Most exhaust fans in existing homes are not terribly efficient, quiet, or rated for continuous operation. In such cases, if exhaust ventilation is to be used as a whole-building ventilation strategy, exhaust fans must be replaced or added as appropriate.

CCCRD's standard practice with local exhaust ventilation is to keep the fans in place when they are working adequately to provide local ventilation. However, it is rather rare to find local exhaust fans working properly. In some instances, CCCRD has replaced older bathroom exhaust fans with Panasonic WhisperGreen fans designed to run continuously to provide whole-building ventilation. The installed cost of these fans is approximately \$400; this exhaust only strategy has the lowest first-cost of all systems considered.



Figure 5. New bathroom exhaust fan installed in a CCCRD home

Power consumption of these fans is very modest—typically 6–8 Watts when exhausting 50 CFM. Running continuously over an entire year, the fan would require 50–70 kWh of electric energy. Thermal impacts are discussed in Section 4.5.

The key advantages of the exhaust-only approach have already been mentioned: low first-cost, ease of installation, low maintenance, and modest operating cost. The drawbacks are:

- OA is not distributed evenly to all parts of the home. Past research has shown that when doors are open or when a forced-air heating or cooling system is operating, this point is moot. As all CCCRD homes use forced-air heating and cooling systems (and typically new, properly sized, well-balanced systems), this was not a major concern.
- By depressurizing the home, there is potential to draw air from undesirable spaces. Because there is no atmospheric combustion appliance in the conditioned space, there is no risk of backdrafting or similar combustion problems. Most of these homes do, however, have attached garages, and rigorous sealing of the walls and ceilings of the garages is typically not in the project scope or budget. As CARB's testing showed (CARB 2011), infiltration through the garage likely accounts for some portion of the makeup air from an exhaust system.

CCCRD has used exhaust-only ventilation in some homes, but concerns about drawing in air from garages—and about not achieving any heat recovery—have led them to explore other options.

4.2 Central Fan Integrated Supply

As all CCCRD homes have forced-air heating and cooling systems, CFIS was an obvious system to investigate. Its installed cost is relatively modest: approximately \$650. CFIS addresses two concerns with exhaust ventilation: (1) drawing in contaminated air from the garage, and (2) not distributing OA throughout the home. The key detriment of CFIS is the electricity required to operate the air handler fan. Even with a very efficient fan—which may consume 300 Watts—operating a CFIS system on a 50% duty-cycle would result in additional electricity use of 750–1000 kWh/yr. This added operating cost—along with its associated impact on HERS indices—was the reason CCCRD did not pursue this strategy.



Figure 6. Simple schematic of CFIS ventilation system

4.3 Ducted Energy or Heat Recovery Ventilator

In a hot, humid climate, an ERV is recommended as it will remove some of the moisture in the incoming airstream (transferring it to the relatively cool, dry exhaust stream). In a dry climate

such as Las Vegas, this benefit is largely moot, and the choice between ERVs and HRVs is not always clear (Holladay 2009). In this arid climate, the indoor humidity (both relative and absolute) will usually be higher than the OA humidity. When this is the case, an HRV, recovering only sensible heat, will tend to reduce indoor humidity year-round. An ERV, on the other hand, will tend to retain some of this interior moisture. This may be a benefit or a detriment, depending on lifestyles and occupant behavior.

Installation costs of the systems, however, are quite similar. CARB and CCCRD estimated that a fully ducted ERV/HRV system (separate from the heating and cooling duct system) would cost \$1,000–\$1,500 to install in a single-story home. Installation requires supply and exhaust ducts to outdoors with exterior terminals as well as ducts and registers supplying and exhausting from several parts of the home. In the Las Vegas homes evaluated, most ducts would be installed in the attic; installation could be considerably more costly if portions of walls or ceilings were removed for installation.

This installation cost is separate from the cost of the core hardware: the HRV or ERV unit. These hardware costs can vary greatly. One more affordable HRV which CARB has seen used in several homes is the FanTech SH704. Although performance varies based on the installation and duct system, this delivers approximately 60 CFM, consumes 40 Watts, has a sensible recovery efficiency of 55%, and has an apparent sensible effectiveness of 63%. This unit costs approximately \$450.

One of the more efficient—though more costly—ERVs that CARB has used on several projects is the Ultimateair Recoupaerator. This unit has variable-speed motors, and at 70 CFM it consumes approximately 40 Watts. This unit has a published sensible recovery efficiency of 83%, apparent sensible effectiveness of 96%, total recovery efficiency of 55% (during cooling), and a list price of approximately \$1,800.

HRVs and ERVs with ducted distribution address most ventilation performance issues:

- Balanced distribution avoids drawing in air from unknown or unsafe sources.
- Ducted distribution brings OA to all parts of the home.
- Heat recovery limits additional load on the heating and cooling systems.

Operating costs of HRVs are very dependent on climate and the benefits of heat recovery. Operating a 40-Watt appliance on a 70% duty cycle consumes 245 kWh/yr. The thermal impacts for an example Las Vegas home are discussed in Section 4.5. In addition to costs, maintenance for these systems is not insignificant. Most HRV/ERVs have filters and/or media that need to be cleaned or replaced regularly; failure to do this can result in dramatic drops in performance (air flow rates, heat exchange efficiency, and equipment durability).

The key drawbacks of these systems—and the reasons CCCRD did not actively pursue any of these options—are first cost and installation requirements. Depending on equipment chosen and configuration, such a system would cost \$1,450–\$3,300 for a single-story home. In a two-story home, if ducts were run from the attic to supply or exhaust from the first floor, installation costs would certainly be higher. The amount of this increase would vary greatly depending on the

home layout, areas of wall board or ceilings, etc. needing to be removed and patched; and the scope of the renovation project.

4.4 Local Energy Recovery Ventilator

The final system considered by CCCRD, and the system CCCRD started to use quite often, is a new, local ERV. This product, the Panasonic WhisperComfort, is installed in a ceiling cavity. It requires one fresh air duct and one exhaust duct, both run to outdoor terminations. The fresh air is supplied to the home and the indoor air is exhausted from the ceiling-mounted unit.

The immediate concern for many is short-circuiting—fresh air immediately being exhausted as the delivery and exhaust locations are so close together. CARB's testing of the unit, however, showed that this was not a significant concern (CARB 2011).

The WhisperComfort costs CCCRD \$700–\$800 to purchase and install. On its highest speed, the unit draws 23 Watts, exhausts 40 CFM, and supplies 30 CFM (both at 0.1 in. w.g.). Published heat recovery efficiencies are 66% during heating season (apparent sensible effectiveness) and 36% during cooling (total recovery efficiency).

Figure 7. Images of Panasonic's WhisperComfort ERV. At right, installed (with cover removed) in the ceiling of a CCCRD home

The unit is compact, relatively simple to install (especially in the top floor of a home where the attic is accessible), does not consume a large amount of electricity, and offers some heat recovery (although at modest efficiencies). There are several limitations to using this product for whole-building ventilation, some of which are evident from the specifications.

- The maximum exhaust flow rate is 40 CFM (the maximum supply is 30 CFM). There are few single-family, detached homes for which 40 CFM meets the whole-building ventilation rates prescribed by ASHRAE 62.2. Some CCCRD homes employing this strategy require two local ERVs.
- Unlike some of Panasonic's exhaust fans, WhisperComfort units do not use ECMs. Rated flows are at 0.1-in. w.g., and relatively short, straight duct runs are important.

• The device avoids freezing and defrosting problems by switching to exhaust only when outdoor temperatures are below 20°F. When outdoor temperature is between 20° and 32°F, it cycles between balanced and exhaust-only ventilation.

Continuous exhaust ventilation may lead to issues as discussed in Section 2.4, but issues would likely be much less severe with this ERV unit. Natural-draft combustion appliances have much better draft during cold weather, and introduction of pollutants (from garages, etc.) would be much less frequent than with dedicated exhaust-only systems. In Las Vegas, where the heating design temperature is 32°F, these concerns are trivial.

• As mentioned above, the unit's design does not allow a significant amount of fresh air to short-circuit (and be immediately exhausted). CARB's and NREL's tracer gas testing confirmed this. However, this unit certainly is a local ventilator. It provides fresh air to one location; it does not actively distribute fresh air throughout a home.

Cable 1. Overview of Whole-Building Ventilation Systems Evaluated and	
Considered in CCCRD Homes	

System	Power	Approximate Installed Cost (\$)	Advantages	Disadvantages
Exhaust Fan Operating Continuously	6 W	400	 Low first cost Simplest installation Low operating cost Lowest maintenance 	 May draw air in from garage OA not actively distributed
CFIS	Depends on AHU, 250 W minimum	650	 Low first cost Simple installation Distributed OA	• High operating cost
Distributed ERV/HRV	Varies, at least 40 W	1,450–3,300	 Distributed OA Heat recovery Potential for low operating cost 	 High first cost More complex installation Highest maintenance
Local ERV	23 W	750	Heat recoveryLow operating cost	• OA not distributed

4.5 Cost Comparisons

To compare the costs of these ventilation systems in the context of this report, CARB has performed modeling on an example CCCRD home: 1,780 ft², two-story, three-bedroom, with blower door tests showing infiltration of 810 CFM₅₀. The home has a 92%-AFUE gas furnace and a 16-SEER air conditioner. In this example, all local ventilation systems (bathroom and kitchen) are assumed to be installed and operational (therefore they do not enter into whole-building ventilation cost analyses).

Per ASHRAE 62.2-2010, this home requires a whole-building ventilation capacity of 48 CFM. Table 2 describes four systems evaluated along with approximate installed, operating, and annualized costs. Operating costs include fan electricity and additional space conditioning loads (\$0.109/kWh, \$1.09/therm). Annualized costs include operating costs as well as annualized cost of the installed system over 15 years with a discount rate of 3%.

Whole-Building Ventilation System	Description	Installed Cost	Annual Operating Cost	Annualized Cost
None	For reference only	\$0	\$0	\$0
Exhaust Only	Panasonic WhisperGreen FV- 08VKS3 operating continuously at 50 CFM, 7 W	\$400	\$30	\$64
CFIS	OA duct provides 80 CFM, set to run 15 h/day, AHU fan uses 300 W	\$650	\$146	\$200
Ducted HRV	Fantech SH704 running continuously at 60 CFM, 40 W	\$2,250	\$64	\$252
Local ERVs	Two Panasonic WhisperComfort ERVs, each running continuously at 30 CFM, 21 W each	\$1,500	\$61	\$187

Table 2. Cost Comparisons for Several Ventilation Systems Considered in an Example Las Vegas Home

5 Conclusions

In the examples shown in Table 2, the low annualized cost of the exhaust-only system is striking. Cost is not, however, the only criterion. The risk of drawing in air through attached garages is a significant concern. The lack of OA distribution—another common drawback to the exhaust-only approach—is a lesser concern with the forced-air heating and cooling systems in these homes. Of course, the forced-air heating and cooling system will operate only when there is a thermal load. Adding controls for intermittent mixing operation was not considered here, but this practice may have merit.

While the annualized cost of the CFIS system is quite comparable to that of the local ERV, the high energy consumption of this system eliminated it from consideration. The two ERV/HRV options have very similar operating costs, but the simpler installation and lower installed costs of the local ERV give this system an edge.

Moving forward, CCCRD has chosen to use the local ERV system in most of its renovation projects. The lack of fresh air distribution may be the largest drawback of this system, but this concern is reduced with forced-air heating and cooling systems in all homes.

6 Discussion

6.1 Other Projects and Climates

Section 2 attempted to present much previous and current work and to outline many issues related to ventilation systems. The authors hope that this information is useful to many users in many climates, but the focus of the study was on CCCRD homes in and near Las Vegas, Nevada. The results could be considerably different for a single-family home in south Texas or for an apartment in Chicago.

There is a group of key questions that should be asked when selecting a whole-building ventilation system for an existing home. Several of these questions, and some example implications, are presented here:

- What climate? The benefits of HRVs and ERVs will increase in extreme climates. In hot, humid climates, the latent load introduced by ventilation may influence design of other HVAC systems.
- What is the scope of the rehab/renovation project? More intensive projects may allow for more robust ventilation systems at more reasonable costs. In a gut rehab, it is usually much simpler to incorporate new duct systems. If renovations are more modest, any removal (and replacement) of ceilings or wallboard may increase costs considerably.
- Will any natural draft combustion appliances be inside the home's pressure boundary? This is a key concern for any exhaust ventilation.
- Is there a crawlspace, attached garage, or other attached space that may contain pollutants? This again may be a concern for exhaust ventilation
- What type of heating and cooling system? A forced-air heating and cooling system may reduce concerns related to non-distributed ventilation.
- What is the expected energy performance level of the home? Providing ventilation—and fresh air mixing or distribution—may be even more important in a very low-load, airtight home.

In conjunction with questions about the project, the goals of the project should also be considered:

- What is the budget?
- What ventilation rates or standards or program requirements are targeted?
- How important is energy/operating cost? In relation to first cost?
- What maintenance levels are appropriate or acceptable?

There is no one-size-fits-all solution to ventilation, especially in existing homes. CARB plans to develop guidelines—useful to remodelers, contractors, and programs—for addressing ventilation in existing homes. The guidelines will step through these questions above, among others, and present viable ventilation system options along with the advantages, disadvantages, and costs that go with them.

6.2 Gaps and Additional Systems

All the ventilation systems discussed have advantages and disadvantages, and there's rarely a "silver bullet" approach that solves all cost and performance concerns. In working with builder and manufacturer partners, CARB has identified several systems or product needs that might alleviate some concerns.

6.2.1 Larger Capacity Local Energy Recovery Ventilator

Test results of Panasonic's WhisperComfort ERV were quite positive. One limiting aspect of the device is its flow rates: maximum exhaust rate is 40 CFM, maximum supply rate is 30 CFM. Although 40 CFM can meet ASHRAE 62.2 whole-building ventilation rates for many two-bedroom homes (up to 1,750 ft²), three-bedroom homes and larger typically require higher flow rates.

Installing two local ERVs, as CCCRD does in many homes, is certainly a solution, and this practice helps to address concerns about OA distribution. But a larger capacity unit could significantly reduce costs in some scenarios. CARB believes that the capacity of this ERV is limited by its size; it is designed to fit in a floor cavity of 2×6 joists at 16 in. on center. Larger air flow capacity would require a bigger unit, larger dimensions, and larger ducts (likely moving to 6 in. diameter from 4 in.). The larger size may make such a unit impractical for many installations.

6.2.2 Energy Recovery Ventilator With Limited Ducting

Perhaps the biggest potential disadvantage of the local ERV is the lack of OA distribution. The Panasonic WhisperComfort exhausts from and supplies OA to a single location. There is no consensus among building scientists about the importance of distributing or mixing fresh air (see Section 2.3), but distributing OA more evenly is certainly preferred.

Panasonic has discussed the development of a modified version of the WhisperComfort: a ceiling-mounted unit that supplies air directly to the room below but exhausts air through a 4-in. duct connection. By running this exhaust duct to one or two separate locations within the home—keeping pressure drop in mind—OA distribution or mixing could be dramatically improved. CARB had hoped to install and test a prototype of this system, but the product's development has been delayed.

6.2.3 Mixing

Several tracer gas studies (see Section 2.3) have shown that when a home's central air handler operates for heating or cooling, concentrations of tracer gas "pollutants" are equalized throughout the home. Homes without forced-air heating or cooling (hydronic heating, mini-split heat pumps, etc.) are much more prone to variations in pollutant concentrations. Some of these same tests, however, have shown that a very modest level of distribution or "mixing" of air within the home can alleviate these concerns. In one study (CARB 2010), delivering 20–30 CFM to each bedroom from a central living space dramatically reduced—nearly eliminated—variations in tracer gas concentrations. CARB believes that more study is merited to determine what minimum levels of mixing are appropriate to alleviate IEQ concerns. Similarly, more study on how often a central forced-air heating/cooling system must operate—and at what flow rates—to alleviate IEQ concerns would be very helpful in designing and selecting ventilation systems.

The term *mixing* is used here to describe simply moving conditioned, indoor air from one space to another. Conventional distribution, on the other hand, delivers heated, cooled, or fresh air directly to spaces in a home. Several Building America teams have been investigating the impacts of such mixing systems on temperature and comfort in homes with simple, non-distributed heating and cooling systems (ductless heat pumps, room heaters, etc.).

These mixing systems can be smaller and less costly than conventional distribution systems. When thermal loads are small enough, local heating, cooling, and ventilation systems combined with mixing systems—can provide efficiency and comfort at much lower costs. CARB is investigating this further with several partners.

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