Chapter 4: Ventilation Systems

4.1 Optimized Mechanical Ventilation with the Residential Integrated Ventilation Controller

Ventilation systems are becoming commonplace in new construction, remodeling/renovation, and weatherization driven by combinations of specific requirements for indoor air quality and health and compliance with standards, such as ASHRAE 62.2. California has required compliance with ASHRAE 62.2 in its residential energy code (Title 24) since 2010. At the same time, there is an effort to reduce energy use in homes and therefore to minimize the energy used to provide ventilation. One way to reduce the energy used to ventilate homes is to use a ventilation controller that ensures equivalence with ASHRAE 62.2 while operating the whole-house ventilation system in such a way as to minimize energy use. The Residential Integrated Ventilation Controller (RIVEC), suitable for use in homes, was initially developed by the California Energy Commission through its Energy Innovation Small Grant program. The initial development of RIVEC was refined and then evaluated in this study.

The RIVEC energy reductions are achieved by:

- sensing the operation of other exhaust and supply fans in the house and reducing the operation of the whole-house fan to account for the extra ventilation these fans provide.
- turning off whole-house mechanical ventilation during times of peak indoor-outdoor temperature differences while ventilating more during off-peak times.
- lowering ventilation rates when there are high levels of outdoor pollutants, e.g., ozone.
- turning off whole-house mechanical ventilation during unoccupied times.
- accounting for infiltration. (This will be of increasing importance for the 2013 version of ASHRAE 62.2, which requires much higher baseline mechanical air flow rates and greater infiltration credit.)

To accomplish these reductions, RIVEC must be able to regulate the state of the installed mechanical ventilation system and sense when all significant exogenous mechanical ventilation systems are operating. For example, if a vented clothes dryer is running it is likely that the minimum whole-house ventilation rate will be satisfied by this alone, and so the RIVEC-controlled device does not need to operate at the same time once the indoor air quality has reached a desirable level. To prevent rapid cycling or switching of the whole-house ventilation fan, the controller makes decisions at fixed times. A reasonable strategy to balance between rapid cycling and overshooting is to use time steps of 10 minutes between decisions about turning the fan on or off. To ensure that RIVEC maintains equivalent indoor air quality to a continuously operating system, it uses the principles and physical relationships from Sherman, Walker and Logue (2012) and Sherman, Mortensen and Walker (2011). Sherman and Walker

(2011) showed specifically how this equivalence principle can be applied to meeting ASHRAE Standard 62.2, and therefore Title 24.

To provide ventilation equivalent to ASHRAE 62.2, RIVEC must be programmed with specific house and system parameters:

- Floor area of the house
- Volume of the house
- Number of bedrooms (a surrogate for the number of occupants)
- Target ventilation rate
- Peak hours for turning off the whole-house fan
- Airflow capacity of the whole-house mechanical ventilation system
- Airflow capacities of each exogenous mechanical ventilation system (e.g., bathroom fans, kitchen range hoods, and vented clothes dryers)

RIVEC uses these inputs in an algorithm to estimate the dose and exposure for the home relative to that provided by a continuously operating fan that complies with ASHRAE Standard 62.2. The fan controlled by RIVEC must be oversized relative to a continuously operating fan to compensate for the times while the fan is off. A fan sized to 125 percent of the ASHRAE 62.2 minimum ventilation rate is required for a fan that will be switched off for at least four hours every day. The relative dose and relative exposure are the ratio of the dose and exposure using the RIVEC controlled fan to the dose and exposure if a continuously operating fan were used.

4.1.1 Development of New RIVEC Algorithms

The RIVEC control algorithm has recently been modified as part of the RESAVE project to dispose of the pre-peak and post-peak shoulder periods, to remove minimum and maximum ventilation rates, and to include occupancy sensing (Turner and Walker 2012). These measures were implemented to both simplify the control algorithm and make it more robust for a larger range of houses with different ventilation strategies.

The new algorithm recognizes only two time periods: a peak energy demand period and a non-peak energy demand period (i.e., normal operation). During normal operation the whole-house ventilation strategy is controlled by controlling the upper limit of both the relative exposure and the relative dose. The values of these upper limits depend on the occupancy of the house. While the house is occupied, the relative exposure is limited to a maximum of 0.95. The relative dose is limited to a maximum of 1.0 such that occupants experience indoor air quality at least as good as if a fan were continuously operating. If the relative dose and exposure are less than these values, RIVEC switches off the ventilation device. As soon as either of these values has been exceeded, the ventilation device is switched back on. During unoccupied periods the algorithm will activate the ventilation system only if the upper limit to the relative exposure is exceeded. This allows the ventilation device to be off for longer periods while the house is unoccupied, as the inhabitants will not be exposed to the higher levels of indoor contaminants, while limiting the peak levels that a returning occupant is exposed to at the beginning of the occupancy period.

The peak periods are hardcoded into the controller. For this study, 4 a.m. until 8 a.m. was used for heating days, and 2 p.m. until 6 p.m. was used for cooling days. As heating and cooling set points were used to control the furnace and the air-conditioning, very occasionally there would be both heating and cooling on the same day. The RIVEC algorithm allows there to be no more than one peak period with reduced whole-house ventilation on these days, to avoid a situation where the ventilation system could be off for two four-hour periods (eight hours total) in any single calendar day.

The 2010 edition of ASHRAE Standard 62.2 has a default infiltration credit of 10 liters per second (L/s) per 100 m^2 (2 cfm/100 ft^2) of floor space. This infiltration credit is used to reduce the installed mechanical fan airflow requirements for the whole-house ventilation system. It does not apply to local exhaust ventilation.

The RIVEC controller cannot sense the contribution of infiltration toward ventilation, but this contribution still needs to be accounted for in the calculations. This study used the ASHRAE 62.2-2010 approach of including the default infiltration credit of 10 L/s per 100 m^2 in the target whole-house ventilation rate. This was to allow easy comparison with the existing ASHRAE 62.2 standard. Consequently, for the simulations the default infiltration credit was used as a baseline ventilation rate in the RIVEC calculations.

Addendum N to ASHRAE 62.2 has recently been published (and will be part of the 2013 version of the standard). It revises the standard to:

- explicitly include the default in the total airflow requirements,
- include the full infiltration credit (rather than the current half-credit),
- update the weather factors (including adding many hundreds more weather stations), and
- move all the required calculations into Standard 62.2, thus eliminating the references to Standards 119 and 136.

The difference between the old ASHRAE 62.2 method and new Addendum N in terms of total ventilation rate is usually small, but tighter homes will require more mechanical ventilation.

It is envisioned that the RIVEC controller will have a preprogrammed look-up table that will allow the appropriate ventilation credit to be set by selecting a building envelope leakage and weather factor. The infiltration credit will be a fixed value dependent on climate zone and independent of local fluctuations in the weather data.

Currently ASHRAE 62.2 only allows the use of intermittent ventilation operating to a *fixed* schedule. This prohibits the use of RIVEC as it operates to a *non*-fixed, adaptive schedule based on levels of relative dose, exposure, and occupancy, so further amendments to the standard are being proposed as a result of the RIVEC work. Because Title 24 references the 2007 version of ASHRAE 62.2, it does not include changes made to later versions of ASHRAE 62.2 that allow the use of the equivalence principle that RIVEC is based on. The next version of Title 24 will use a more recent version of ASHRAE 62.2 that allows the use of controllers like RIVEC.

4.1.2 Simulations of Ventilation Systems Controlled by RIVEC

Four different residential ventilation strategies were simulated, operating with and without the RIVEC controller incorporated into the system:

1. Whole-house exhaust ventilation fan sized to meet ASHRAE 62.2 that operated either continuously or under RIVEC control.
2. Heat Recovery Ventilator (HRV) sized to twice the ASHRAE 62.2 minimum ventilation rate and synched to the air handler, operating on a timer (30 minutes out of every hour so as to meet ASHRAE 62.2 intermittent ventilation requirements) or under RIVEC control.
3. Central Fan Integrated Supply (CFIS) system sized to meet ASHRAE 62.2 flow rates when the heating or cooling system operates combined with a whole-house exhaust fan (that also meets 62.2). The whole-house exhaust fan operated continuously or under RIVEC control.
4. Economizer system that uses the air handler and an outside air vent to provide night cooling, combined with a whole-house exhaust fan sized to meet ASHRAE 62.2 that operated either continuously or under RIVEC control.

Each ventilation strategy was simulated for three house sizes based on the prototypes in Title 24, for three different house envelope air leakage levels, and for all 16 California climate zones.

The energy consumption and IAQ of the modeled houses was evaluated by minute-by-minute simulations of the heat and mass balances of the home for a year. The airflows, heat transfer, heating and cooling system operation, and energy use were simulated using the REGCAP residential building simulation tool. REGCAP was modified to simulate RIVEC in previous studies (Sherman, Walker and Dickerhoff 2009; Sherman and Walker 2011). The simulation tool has been validated by comparison to measured data in homes in previous studies (summarized in Walker and Sherman, 2007). The simulation program treats the attic volume and house volume as two separate well-mixed zones, but connected for airflow and heat transport, and includes heating and cooling system airflows. It combines mass transfer, heat transfer, and moisture models. The program allows the modeling of distributed envelope leakage and mechanical system airflows for ventilation and heating and cooling, as well as individual localized leaks such as passive stacks. Inputs are building air leakage characteristics (total leakage and leakage distribution), minute-by-minute weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules.

4.1.3 Energy and IAQ Results of RIVEC Simulations

For all simulations the estimated relative dose and exposure were controlled by RIVEC, so in none of the cases was the annual relative dose greater than one. The results showed that the RIVEC controller provided equivalent (or better) ventilation compared to ASHRAE Standard 62.2.

On average across all climate zones, house sizes, and envelope leakages (Figure 4.1.1), the RIVEC controller reduced the ventilation-related energy by 46 percent for strategy 1 (whole-house exhaust), 31 percent for strategy 2 (HRV), 43 percent for strategy 3 (CFIS plus whole-house exhaust), and 53 percent for strategy 4 (Economizer plus whole-house exhaust). This is an average of 43 percent across all mechanical ventilation strategies. The changes in ventilation-related energy reductions had greater climate variability than the fractional savings but small variability between house sizes and envelope leakage. The following results for climate variability are averaged over all house sizes and envelope leakages. For the whole-house exhaust, CFIS, and economizer systems the ventilation-related energy reductions were similar, ranging from a little over 300 kilowatt-hours (kWh)/year in Los Angeles to about 1,000 kWh/year in Arcata and Mount Shasta. For the HRV, RIVEC reduced the ventilation energy penalty in colder climates. The smallest reductions in ventilation-related energy were about 600 kWh/year in Oakland, and the greatest reductions were 1,600 kWh/year in El Centro.

4.1.4 Recommendations for RIVEC Algorithms for Use in California Homes and Requirements for Acceptability in Building Codes

The RIVEC advanced ventilation controller will:

- typically reduce the ventilation-related energy from whole-house ventilation systems by at least 40 percent, while maintaining equivalence to ASHRAE Standard 62.2.
- ensure that exposures to constantly emitted indoor pollutants are within limits for acute exposure.
- provide ventilation energy reductions that are robust across climate, house size, and air leakage.
- provide absolute energy savings per household of 500 to 7,500 kWh/year, depending on climate—with more temperate climates at the lower end of energy savings estimates.
- allow significant peak power reductions of up to 2 kW for a typical home.

A RIVEC type advanced ventilation controller could provide an energy saving compliance option if it were allowed by Title 24. The annual energy savings could be included in Title 24 compliance calculations using the results of this study. Given that the savings are robust across climate zones, house size and air leakage a relatively simple approach is justified. If the Title 24 compliance software calculates the energy due to mechanical ventilation separately from other building loads, then the use of RIVEC should reduce this energy use by 40 percent. If the mechanical ventilation loads are not calculated separately, then the savings could be set at a fixed number of kilowatt-hours that varies by climate zone, as shown in Turner and Walker (2012).

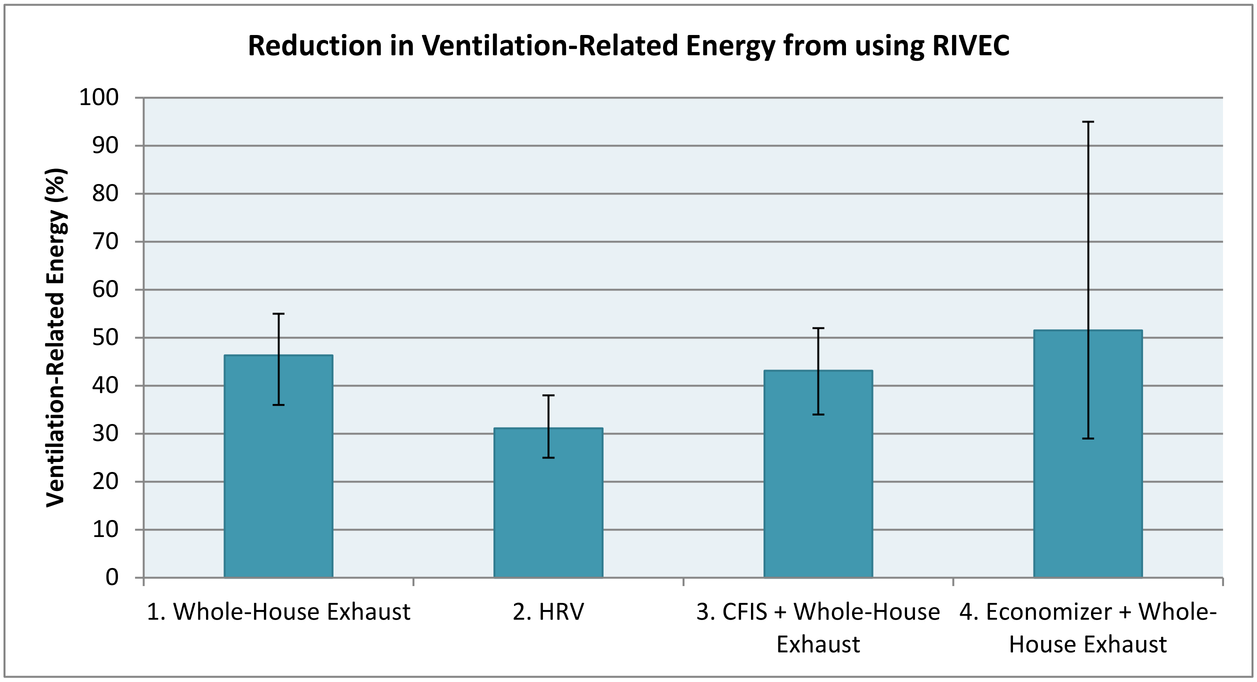

Figure 4.1.1: The Reduction in Ventilation-Related Energy from Using RIVEC Averaged Across All House Sizes, Envelope Leakages, and Climate Zones (with Maximums and Minimums Shown)

4.2 Sustainable Ventilation

Another approach to reducing the energy costs of ventilation is to use passive systems that reduce fan power requirements and installation costs. Passive ventilation has been used for centuries and is still popular in many European countries as a way to provide local exhaust and whole-house ventilation. The principle behind passive stack is that no fan is used, instead a vertical vent from inside to outside is used. A combination of stack and wind pressures on the vent cause air to be drawn from the house—specifically from the room in which the base of the vent is located (usually kitchens and bathrooms). Passive stacks have the advantage of not needing any electrical supply or maintenance of a fan. However, the airflow is much less controlled, and so this study also investigated the use of flow-limiting devices and auxiliary fans to create hybrid systems. The flow-limiting devices in this study limited airflow to 125 percent of that required by ASHRAE 62.2 for whole-house mechanical ventilation. In hybrid systems a fan is only used when the airflow in the stack is too low to provide sufficient ventilation. More details can be found in Turner and Walker (2012).

4.2.1 Summary of Passive and Hybrid Ventilation Techniques

Passive Stack Ventilation

Natural ventilation utilizes naturally occurring renewable energy sources such as wind and stack effects to achieve the same goal of bringing fresh air inside. The wind blowing over the top of the stack depressurizes the stack relative to the house. The magnitude of this wind pressure depends on the stack height and rain cap design, as well as the wind speed. The stack effect is due to differences in hydrostatic pressure between the inside and outside of the house due to the air being at different temperatures. The density of air is inversely proportional to its temperature, such that warm air is less dense than cold air, and the hydrostatic pressure in air depends on its density. With two columns of air—one inside and one outside the house—at different temperatures we can determine the resulting pressure difference between the two columns of air.

A *passive stack* is a device that exploits the wind and stack effect to provide ventilation. It is usually a vertical pipe or duct that extends upwards from the ceiling inside the occupied zone, and then protrudes through the roof. It provides an airflow pathway for ventilation air and protrudes above the roof of the house to maximize exposure to wind effects.

The naturally occurring pressure differences due to wind and the stack effect lead us to a residential ventilation strategy that requires zero energy expenditure on mechanical driving forces such as fans. However, the variable nature of the wind and the outdoor temperature mean that passive stack ventilation is both unpredictable and potentially unreliable. There will be times throughout the year of large, naturally occurring pressure differences resulting in over-ventilation. There will also be times of under-ventilation when these pressure differences are low. It is therefore important to have an appropriately sized passive stack to minimize the times of over- and under-ventilation. The airflow rate through the stack can also be augmented to desirable levels via the deployment of control strategies, such as flow dampers, to limit high ventilation rates, or auxiliary fans to increase it.

A *hybrid* or *mixed-mode* ventilation system utilizes both mechanical and natural ventilation. To overcome the unpredictable nature of natural ventilation, some form of mechanical control is used to regulate the airflow rate. The mechanical and natural components may be used in conjunction with each other or used separately at different times of the day. While acting as a control measure, the mechanical component may be used to regulate the natural ventilation process by restricting the airflow rate during periods of high natural driving forces or to provide additional ventilation at times of low natural driving forces (Buonomano and Sherman 2009).

4.2.2 Simulations of Passive and Hybrid Systems

The same REGCAP simulation tool was used for passive and hybrid systems as for the optimized mechanical ventilation systems. REGCAP includes algorithms for determining airflows through passive stacks, so it was ideally suited to these simulations. The same range of climates, house size, and envelope leakage that was used for the RIVEC simulations was used for the passive and hybrid simulations.

Two cases of passive stacks were simulated. The first was sized so that the daily average airflow would meet ASHRAE 62.2 airflow rates for at least 80 percent of the year (based on Mortensen Walker, and Sherman 2011a). The second used oversized passive stacks that would meet ASHRAE 62.2 for more of the year, but included an automatic damper to limit the maximum airflow to 125 percent of the ASHRAE 62.2 airflow rate to reduce over-ventilation.

The hybrid ventilation system used the same oversized passive stacks as the passive systems, but mechanically limited to 100 percent of the ASHRAE 62.2 minimum airflow rate, and in conjunction with a whole-house exhaust fan operating under RIVEC control, so that airflow rates never dropped below the ASHRAE 62.2 requirements.

4.2.3 Energy and IAQ Results for Passive and Hybrid Systems

In the simulations, the relative dose for several passive and hybrid systems was tracked during occupied times and then averaged over the year (Figure 4.2.2). The results for relative dose show that a passive stack sized to meet ASHRAE 62.2 for 80 percent of the year would be compliant with ASHRAE 62.2 on an annual basis. The occupied dose for the passive stack ventilation with no flow limiting was 12 percent lower than the baseline ASHRAE 62.2 complaint mechanical exhaust. This indicates over-ventilation, which results from there being no control over the ventilation rate. For the oversized and flow-limited and hybrid strategies, the airflow-limiting control measures mean that the relative dose was much closer to unity.

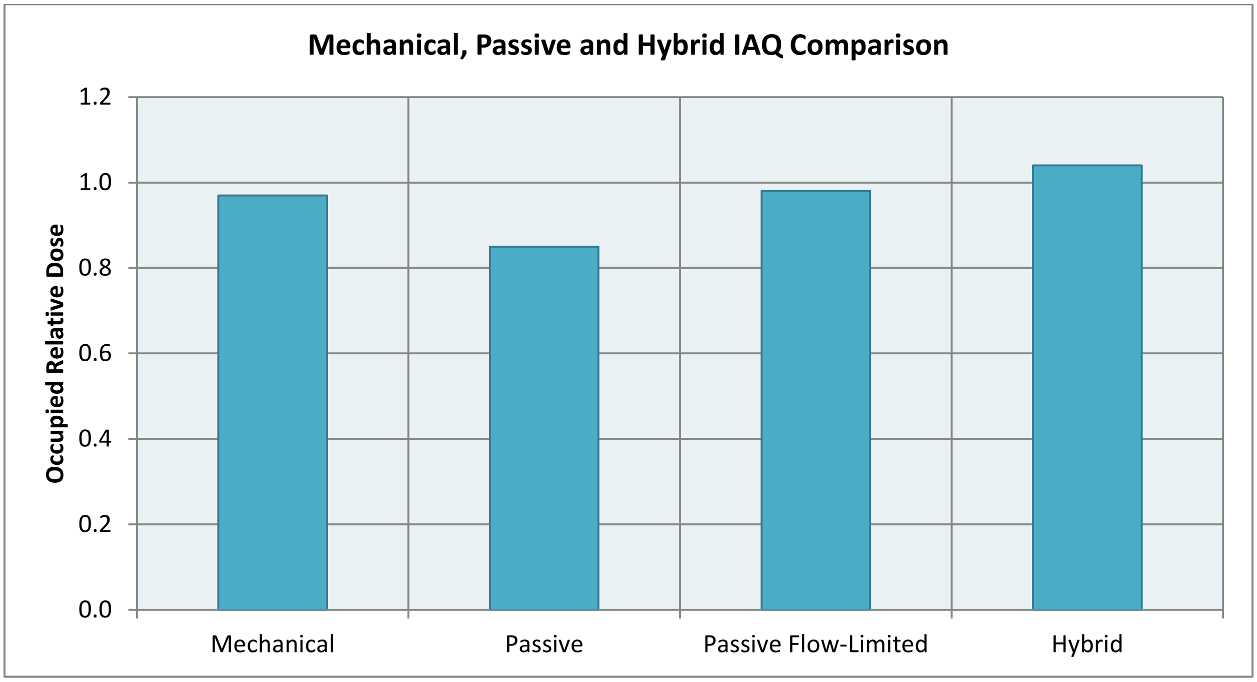

Figure 4.2.2: Mean Annual Occupied Relative Dose Averaged over All House Sizes, Envelope Leakages, and Climate Zones

It is important to ensure that acute exposure levels are not exceeded too often or for too long. For example, asthmatics or rhinitis sufferers sensitive to contaminants such as formaldehyde could face considerable discomfort when exposed to high pollutant levels over short time scales, even though the annual averages are below the acceptable levels. The maximum occupied relative exposures averaged over 1-hour time periods for the passive stack ventilation systems were far below the maximum allowed value of 4.7, outlined by Sherman, et al., (2011). Consequently, the 8-hour and 24-hour maximums were also not exceeded, as the peak hourly occupied relative exposure over the year never exceeded 1.93.

Figure 4.2.3 shows the fractional ventilation energy for the mechanical, passive, and hybrid ventilation strategies averaged over all climate zones. The results have been normalized so that the ventilation-related energy for the mechanical strategy represents 100 percent. The passive stack, on average, used 69 percent more ventilation-related energy than the mechanical exhaust strategy. The lack of flow regulation for the passive stack meant that the space-conditioning load increased considerably. The oversized and flow-limited passive stack strategy used 6 percent less ventilation-related energy than the mechanical exhaust strategy. This is a difference of 75 percent between the non-flow-limited passive system and the flow-limited passive system. The over- and under-ventilation tended to cancel each other out over the year. The remaining difference can be attributed to the fan energy, which was not required by the passive stacks. The hybrid strategy used 24 percent less ventilation-related energy than the whole-house exhaust. There was reduced fan energy compared to the mechanical exhaust strategy, and the airflow was limited to 100 percent of the ASHRAE 62.2 whole-house rate, so there was no over-ventilation with a subsequent increase in space-conditioning load. Combining the flow limiting in the passive stacks with the RIVEC-controlled whole-house exhaust fan successfully limited the extra ventilation-related energy use that results from over- and under-ventilation. The hybrid strategy used less energy than the mechanical strategy because the RIVEC controller prevented the whole-house exhaust fan from operating while the auxiliary exhaust fans operated, thus saving both fan energy and ventilation-related space-conditioning energy.

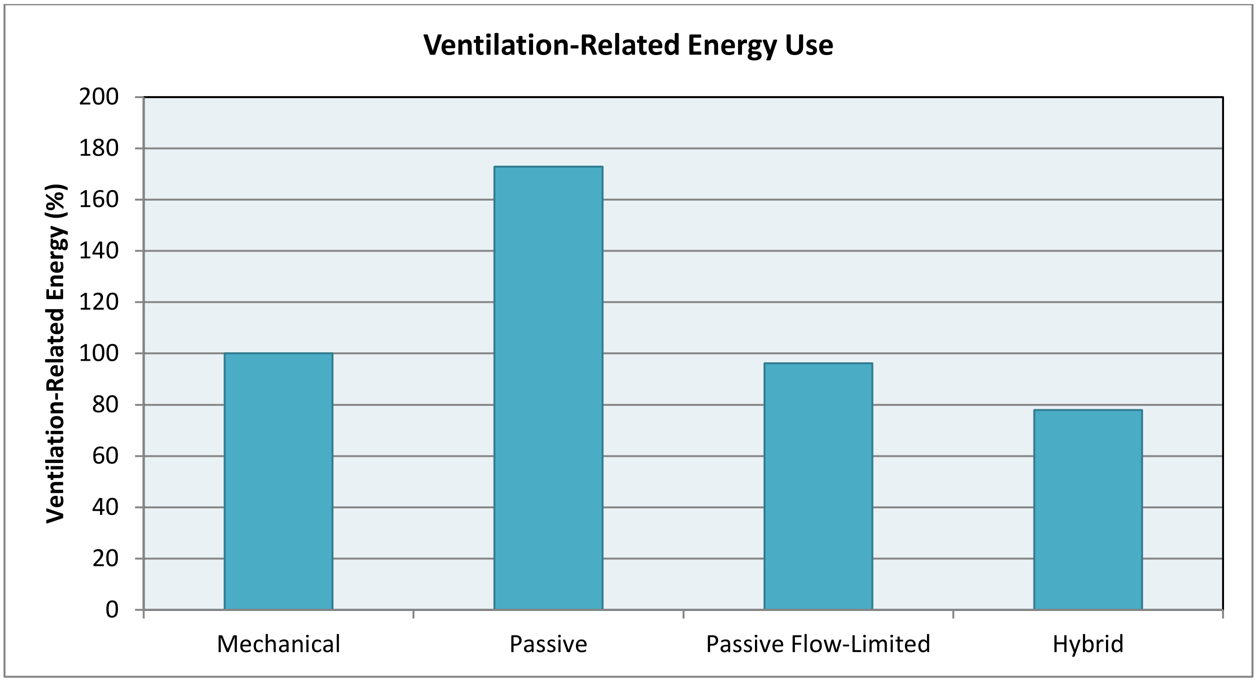

Figure 4.2.3: Fractional Ventilation Energy for the Four Whole-House Ventilation Strategies, Averaged over All Climate Zones and Normalized to the Mechanical Exhaust Strategy

For most California climate zones there was very little difference in absolute energy use between the ventilation strategies; most of the difference in the averages is dominated by the climate zones with severe weather, such as Arcata and Mount Shasta. A decision to use passive or hybrid ventilation instead of mechanical ventilation would then come down to user preference, or installation and maintenance costs. More details of these simulation results can be found in Turner and Walker (2012).

4.2.4 Recommendations on Optimizing Passive and Hybrid System Sizing and Controls and Requirements for Acceptability in Building Codes

If passive systems are to be adopted, it is recommended that they include damper controls to limit over-ventilation to 125 percent of the ASHRAE 62.2 airflow rates. Table 4.2.1 can be used to determine the appropriate size of passive stacks for the three Title 24 Prototype Homes (Pro B, C, and D). The table gives the total required stack size that can be made up of one or more individual stacks of 15 cm and 20 cm diameter (these sizes are used as they are commonly available vent sizes that fit in typical construction). A table entry of 20 corresponds to a single 20 cm diameter stack, an entry of 35 is for a 20 cm diameter stack and a 15 cm diameter stack, an entry of 40 is for two 20 cm stacks, an entry of 55 is for two 20 cm stacks and a 15 cm stack, and the 60 entry is for three 20 cm stacks.

Table 4.2.1: Oversized and Flow-Limited Passive Stack Diameters for the Prototype Houses

	Flow Limited Passive Stack Diameter* [cm]															
CZ	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Pro B (1200 ft^2)	20	35	20	35	20	20	35	40	40	40	40	35	40	40	60	35
Pro C (2100 ft^2.)	20	35	20	35	20	20	35	40	40	35	35	35	40	40	60	35
Pro D (2700 ft^2)	20	35	20	35	35	35	35	55	40	35	40	40	40	40	60	35

4.3 Ventilation System Commissioning

4.3.1 Introduction

Beginning with the 2008 version of Title 24, new homes in California needed to comply with the ASHRAE Standard 62.2 (2007) requirements for residential ventilation. These requirements include minimum airflows for whole-house mechanical ventilation, as well as minimum airflows for local ventilation, maximum total exhaust airflow for combustion safety, garage and duct air-tightness, and maximum specific fan power. Designs that comply with prescriptive requirements or manufacturer's criteria do not require field verification of airflows or power, but central-fan-integrated systems do require these field tests. These requirements do not account for the fact the many homeowners are already running exogenous ventilation systems (including economizers, direct evaporative coolers, dryers, or kitchen hoods). They also do not consider that low-emission materials may be used to reduce ventilation needs or that high-emission materials lead to increased ventilation needs.

Currently, few California houses have mechanical ventilation systems. Where installed, the limited data available indicate that ventilation systems do not always perform at the expected level based on system specifications, or even as many codes and forecasts predict. Deficiencies occur in part because there is no consistent process to identify and correct problems, and also because the value of such activities in terms of reducing energy use and improving IAQ is unknown. Commissioning such systems when they are installed or during subsequent building retrofits is a step toward eliminating deficiencies and optimizing the trade-off between energy use and acceptable IAQ.

Work funded by the Energy Commission about a decade ago at LBNL documented procedures for residential commissioning and demonstrated the value of the overall process, but it did not focus on ventilation systems and did not disaggregate the related potential savings. Since then, standards and approaches for commissioning ventilation systems have been an active area of work in support of European standards, and new analytical methods have been developed to assess the potential value of energy use and IAQ benefits on a common scale. To take advantage of these opportunities, we:

- collected new literature on commissioning procedures and identified information that can be used to support the future development of residential-ventilation-specific procedures.

- determined the combined energy and IAQ potential value of commissioning systems that are intended to comply with the whole-house ventilation component of the California Title 24 residential ventilation requirements.

The following sections provide background about the residential ventilation commissioning process that we envision, describes the literature review findings and potential value assessment (i.e. the monetization of potential energy and health costs and benefits), summarizes this study's findings and the benefits to California, and lists recommendations for future work.

4.3.2 Procedures and Standards for Commissioning

4.3.2.1 The Residential Ventilation System Commissioning Process

Every commissioning process includes three principal elements: metrics, diagnostics, and norms. The following bullets define these elements and offer examples to aid understanding:

- *Metrics*: For whole buildings, there are two broad performance objectives of interest: energy performance and indoor environmental performance (e.g., indoor air quality and comfort). Each objective can be represented by various performance metrics, which are defined as a quantification of the performance of relevant components or systems. Three examples are: (1) unbalanced ventilation airflow, which represents the difference between supply and exhaust ventilation airflows, (2) specific leakage area, which represents the air-tightness of the building envelope, and (3) house depressurization, which is often used to represent the backdrafting potential for combustion appliances. Each of these metrics has implications in terms of energy and indoor environmental performance. However, the importance of a particular metric to each performance objective may be weighted differently, and therefore each must be able to stand on its own.
- *Norms*: A metric itself does not indicate good or bad performance. However, when quantified, each metric forms the basis for developing the norms against which component or system performance is compared. As with the metrics, the norms will vary depending on the objective of the commissioning. They will also depend on the stage of the house in its life cycle. For the metrics related to building performance, consider that various building standards could specify requirements for maximum airflow imbalance, for minimum or maximum specific leakage area, and for maximum house depressurization levels.
- *Diagnostics*: Diagnostics are defined here as relatively quick, short-term field procedures involving measurements (and perhaps analyses) to evaluate performance metrics for a system or component under a functional test or actual building site conditions. While it is also possible and sometimes preferable to evaluate metrics using data taken over an entire season, time limitations make it impractical to collect and analyze such long-term information during ventilation system commissioning. Such limitations will be largely dependent on the value of the commissioning process to the involved parties. In some rare cases, for an existing house, commissioning might be able to use readily available

historical data, either as part of diagnostics or to set norms, if appropriate measurement equipment was already installed. From the building performance examples above, consider ventilation airflows. A possible diagnostic is to use airflow measuring equipment, such as a commercially available flow capture hood.

The same metrics and diagnostics can be used in new and existing houses, although some diagnostics may not be appropriate early in the construction process. However, the norms for existing houses will have to be adjusted to account for the economic viability of meeting stricter standards than those in place at the time of construction. For example, a house built in 1930 does not come close to meeting current Title 24 specifications for air-tightness and mechanical ventilation. The retrofitting required to meet Title 24 air-tightness levels in this example would be prohibitively expensive.

Published commissioning processes for commercial buildings are too onerous for houses. The ventilation system commissioning process proposed here is simpler and has three main phases that combine auditing, testing, and implementing improvements to enhance component and system performance:

- *Audit and Diagnostic*: In the first phase of commissioning, metrics for the house are surveyed using instrumented and non-instrumented techniques. The survey results are then compared with the house norms. For new construction, the norms will be those of the Title 24 compliance material or of the equivalent local building codes. For an existing house, the norms may be based on design intent (in the rare cases where any was documented) or on what a particular component should be able to do compared to other similar houses.
- *Tuning and Tweaking*: The performance of many components and systems may not meet the norms, but it will be possible to improve their performance by making minor adjustments, repairs, or retrofits on the spot. An example is adjusting airflows so that they balance. Tuning and tweaking can often provide significant performance improvements for very little marginal cost. The purpose of this step is to improve house performance to at least the design intent. Sometimes that intent will be unknown. In those cases, the optimization will be to other norms, such as the best performance achievable without repair or retrofit.
- *Opportunity Identification*: After tuning and tweaking, there still may be components that are not performing to their potential. This commissioning step provides the client with information about potential repair or retrofit opportunities that could be investigated further (e.g., sealing the garage-house interface). Even when components are performing to their norms, newer technology may make replacement worth considering.

4.3.2.2 Literature Review

We carried out a topical literature review related to ventilation system commissioning and produced an annotated bibliography to build upon our past literature review and to support related work (Stratton and Wray 2013). Full details of the literature search are available in Wray

2012. The focus was on metrics, norms, and diagnostics related to mechanical ventilation systems, which include:

- Airflow through and pressure rise across fans.
- Airflow through, pressure loss, and leakage of ducts and associated components.
- Ventilation controls.

A substantial amount of new information related at least peripherally to ventilation system commissioning has been published over the past decade. In particular, about 300 new documents were identified but only a limited number of documents were relevant to developing commissioning protocols for residences. .

The most advanced and relevant references are European: the eight parts of CEN 13141 (*Ventilation for buildings – Performance testing and installation checks of residential ventilation systems*.) related to "Ventilation for buildings – Performance testing of components / products for residential ventilation" and CEN 14134:2004.

Each of the eight parts of CEN 13141 describes methods specifically for *laboratory* performance testing of residential ventilation components and products. CEN 14134 describes *field* installation completeness checks and functional tests for commissioning installed mechanical and passive ventilation systems in dwellings. The rest of the literature reviewed remains relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. For example, ASHRAE Standard 111-2008, "Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilation and Air-Conditioning Systems," describes many field diagnostic techniques for use in commercial building test and balance (TAB) activities. However, many of these diagnostics are not suitable for residential ventilation system commissioning because:

- the diagnostic is impractical or takes too long (e.g., pitot-static tube traverses of ducted airflows, where the ducts are often inaccessible, too short, or not straight enough),
- the information provided relates to flows that are much larger than those typically found in residential systems (i.e., it does not address increased inaccuracies at low flows), or
- the guidance is not applicable (e.g., suggestions that flow hoods cannot be relied upon for accurate measurements).

If relevant information from each of the reviewed references was combined together along with the European work and the results of our work described in Sections 3.3.3 and 3.4 of this report, it could be used as the basis to prepare a future stand-alone residential ventilation system commissioning guide for practitioners.

4.3.3 Assessing the Potential Value of Commissioning

4.3.3.1 Approach

To demonstrate the potential value of commissioning residential ventilation systems, computer simulations were used to assess energy use and IAQ for new homes in California over a range of climate zones. Turner et al. (2012) describes these simulations in detail.

In summary, the energy and airflow simulations used REGCAP; LBNL's in-house residential building energy and ventilation simulation tool with mass, heat, and moisture transport models. A key aspect of REGCAP is that it explicitly accounts for HVAC system-related airflows (including duct leakage and grille flows), as well as airflows attributable to the effects of weather and leak location, and the interactions of HVAC system flows with house and attic envelope tightness. Three houses were simulated based on Title 24 housing prototypes in three California climate zones (Oakland, Sacramento, and Blue Canyon). The small- and medium-sized houses were single-story and had occupied floor areas of 1,200 ft^2 and 2,100 ft^2, respectively; the large house was two stories with an occupied floor area of 2,700 ft^2.

As described in the bullets below, we considered two ventilation systems with various malfunctions that could be identified or rectified by commissioning: a whole-house exhaust system and a heat recovery ventilator (HRV) system.

- The ASHRAE 62.2 minimum airflow was used as a baseline for normal operation of the mechanical whole-house exhaust system. The airflow was then simulated at 25, 50, and 75 percent of this airflow to represent underperforming ventilation strategies with inadequate airflows. Airflows of 200 and 300 percent of the 62.2 flow were also simulated to represent malfunctioning intermittent fans, to determine if there were any advantages or disadvantages to over-ventilation compared to the 62.2 minimum.
- A balanced and stand-alone (i.e., not integrated into the central forced air heating and cooling system) HRV system was simulated as a baseline. The HRV was sized to twice the 62.2 airflow and operated for the first 30 minutes of every hour. Airflow restrictions were then applied to the supply side of 50 percent and 100 percent to simulate blockages in the HRV ducts or supply registers. For the 100 percent blocked case (0 percent supply side airflow rate), there was no heat exchange with the incoming and outgoing ventilation air.

A simple time-step mass balance approach was used to calculate indoor concentrations and occupant exposures over the course of a year as a function of building air change and pollutant emission rates. Because this analysis focused on commissioning airflows for whole-house ventilation systems, we only considered the impact of controlling two continuously emitted pollutants that are dominant contributors to the chronic burden of indoor health: formaldehyde and acrolein (emitted by materials, combustion, and cooking). Although particulate matter with an aerodynamic diameter of less than 2.5 microns ($PM_{2.5}$) is also a dominant contributor, it was not considered because it is not continuously emitted. For each of the three homes in each of the three climate zones, three levels of pollutant loading (low, medium and high) were used, as shown in Table 4.3.1. The low, medium, and high emission rate for formaldehyde represent the 5th, 50th (median), and 95th percentile of household emission rates found in the California new homes field study by Offermann (2009). The low, medium, and high emission rates for acrolein represent the 5th, 50th, and 95th percentile emission rates measured by Seaman et al. (2007) in homes.

Table 4.3.1: Emission Rates for Formaldehyde and Acrolein

Pollutant	Emission Rate [μg/(h m^2)]		
	Low	Medium	High
Formaldehyde	9.7	30.3	88.2
Acrolein	1.3	1.9	6.1

Energy and IAQ impacts were converted to monetary values using a Time Dependent Valuation (TDV) approach for energy and a Disability Adjusted Life Year (DALY) impact assessment approach for IAQ, assuming a discount rate of 3 percent. The monetary impacts were combined over a 30-year period to represent the net present value (NPV) in 2011 U.S. dollars of the fiscal cost/benefit to the endpoint user (not including the actual cost of commissioning).

The TDV approach is used by the Energy Commission to preferentially weight California energy saved during peak periods, while the distribution grid is operating at or close to capacity. It uses factors applicable for a 30-year time period.

DALYs are a measure of overall disease burden and incorporate both disease likelihood and severity. They are reported as the equivalent number of years lost from premature death and disability. To determine the NPV of changes in exposure for each simulation for 30 years (to allow comparison with the 30-year TDV energy NPV), we determined the annual cost of DALYs lost or gained relative to a system that was operating at the level specified by ASHRAE 62.2. For these analyses, we assumed a central cost of $100,000 per DALY lost. The projected values for DALYs are on the order of $50,000 - $160,000 US. References for this range are provided in Turner et al. (2013).

4.3.3.2 Energy and Air Quality Potential Values

Results for the different house sizes and climate zones showed insufficient variability to justify independent discussion. As a consequence, the results described below are only for the medium-sized house in Sacramento and may be applied to other regions.

Figure 4.3.1 shows the monetized relationship between energy (represented by ΔTDV) and IAQ (represented by ΔDALY) at 0, 25, 50, 75, 100, 200, and 300 percent of ASHRAE 62.2 ventilation rates standard for three emission rates, low, medium and high (see Table 4.3.1). The net present value is set at $0 at the ASHRAE 62.2 ventilation rate standard. Figure 4.3.2 demonstrates the combined energy and IAQ benefit (i.e., the ΔTDV plus the ΔDALY from Figure 4.3.1) those three emission rates. A positive dollar value represents money saved (benefit), while a negative dollar value represents money lost (cost, or negative benefit). Under-ventilation represents an energy benefit from reduced mechanical ventilation energy and reduced heating and air conditioning loads, and an IAQ cost from higher contaminant levels. Conversely, over-ventilation represents an energy cost from higher fan energy use and increased space-conditioning loads, and an IAQ benefit from reduced contaminant levels.

As an example, consider the 50 percent airflow case in Figure 4.3.1 (whole-house exhaust delivering only half the ASHRAE Standard 62.2 flow). The TDV energy financial benefit is $576 over 30 years. This represents money saved on energy bills due to decreased ventilation. For the medium contaminant emission house with the same 50 percent airflow, the IAQ financial benefit is a *negative* $1,639 over 30 years. This represents money lost (or a cost) due to reduced air quality from increased exposure to indoor contaminants. When the energy and IAQ costs are combined in Figure 4.3.2, the net benefit is a *negative* $1,063, which represents an overall loss (the financial value of the energy saved is less than the financial value of life lost due to exposure to higher contaminant levels).

The worst case is a non-functioning (0 percent of the ASHRAE 62.2 airflow) whole-house exhaust system in the high-emission house. This will cost the occupants approximately $8,700 net over 30 years. Over-ventilating the same high-emission house with an airflow three times the 62.2 minimum will gain the occupant approximately $7,100 net (a $15,800 difference). In the latter case, fixing the system to meet the norm (ASHRAE 62.2) would actually be detrimental to the occupants because the value of the energy saved from reducing the system airflow rate is vastly outweighed by the benefit from improved IAQ.

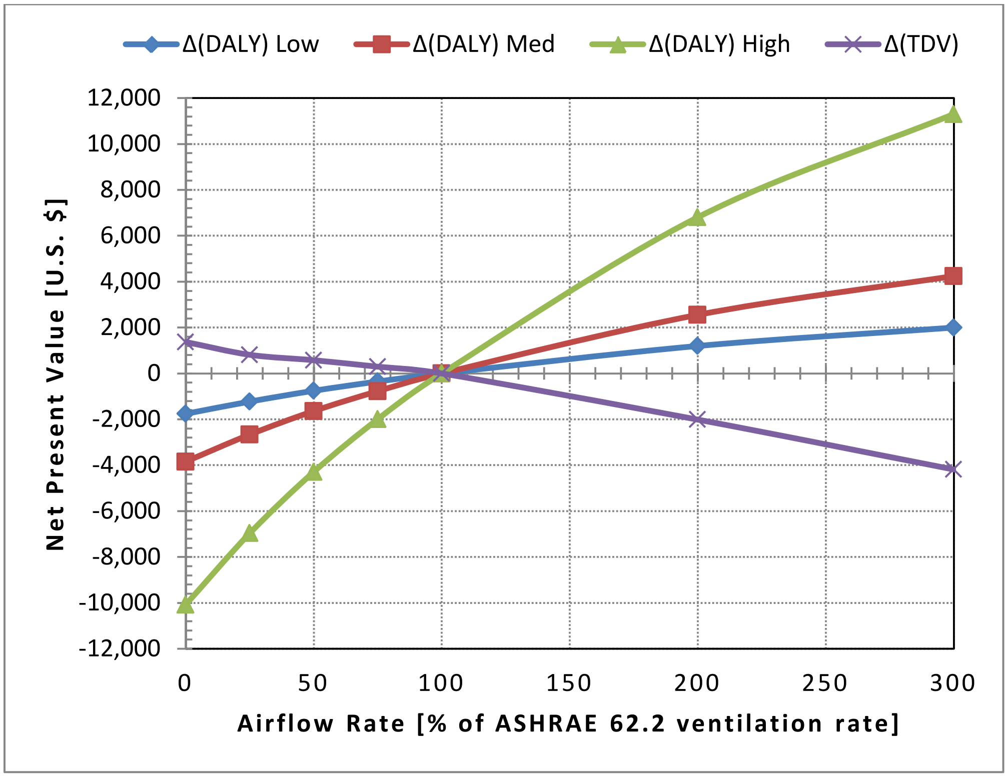

Figure 4.3.1: IAQ and Energy Components, Relative to 100 Percent ASHRAE 62.2 Airflow, for the NPV of Commissioning a Malfunctioning Title 24 Whole-House Exhaust System for Three Contaminant Emission Rates. Results are for the medium-sized house in Sacramento.

However, the cost to the occupants of the low-emission house with a non-functioning whole-house exhaust system is approximately $390, which is comparatively small over a 30-year time period. The low-emission house sees a net loss of $2,200 from over-ventilating by 300 percent, due to increased energy consumption. In both cases, repairing the system to meet the norm would be beneficial.

Because HRV systems are less common, detailed results are not shown here (available in Turner et al. 2013). In summary, 0 and 50 percent supply-side airflow increase the TDV estimated energy cost due to reduced heat exchange between incoming and outgoing air, thus increasing the building heating load. The DALY estimated health cost also increases, due to reduced building air exchange rates (and higher indoor contaminant levels) from the imbalance in mechanical ventilation. As a result, there is no financial benefit to be had from an HRV system with blocked filters or supply registers relative to an HRV that operates as required by ASHRAE 62.2. A benefit might be seen if the HRV were to operate for longer than the intended time period each hour, but this was not simulated. Commissioning a blocked HRV would always be worthwhile, provided that the cost of commissioning is less than the combined cost of the energy used and life lost over 30 years (or some other acceptable payback period to the occupant).

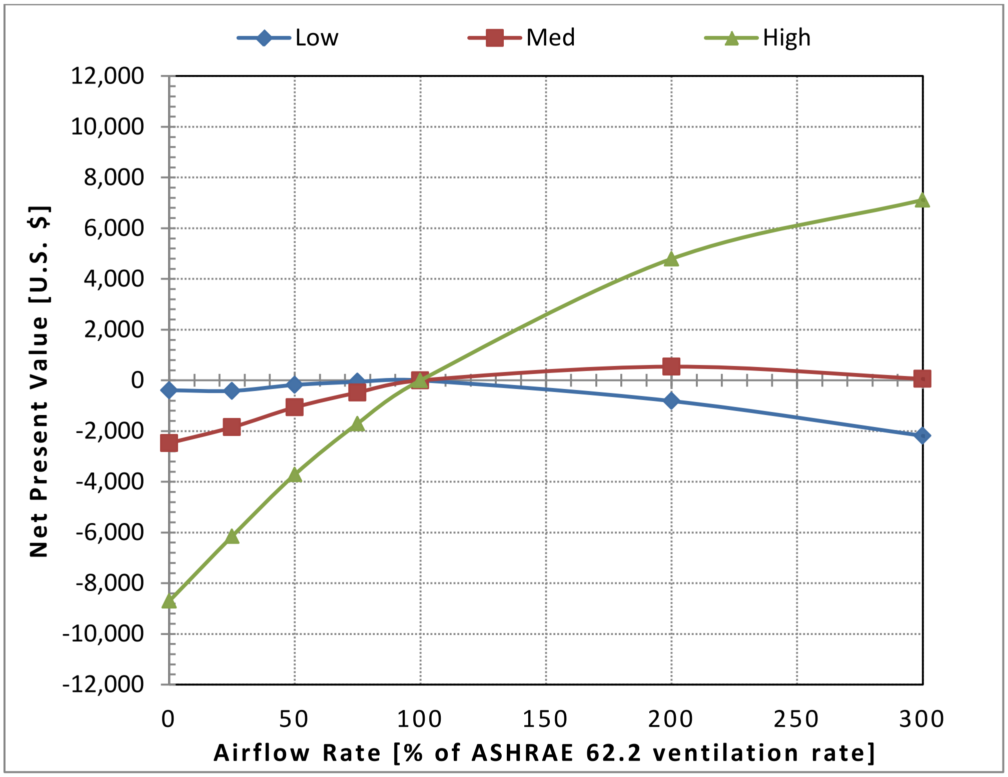

Figure 4.3.2: Combined IAQ and Energy NPV from Commissioning a Malfunctioning Title 24 Whole-House Exhaust System for Three Contaminant Emission Rates (Low, Medium, and High). Results are for the medium-sized house in Sacramento.

4.3.3.3 Ventilation Rate Optimization

Health benefits dominated energy benefits, and there was a strong dependence of IAQ on indoor contaminant emission rates. As a result, providing minimum airflow rates to comply with ASHRAE 62.2 alone was not a sufficient metric for commissioning whole-house ventilation systems. Instead, the metric should be net present value of the combined energy and IAQ benefits to the consumer, and commissioning cost decisions should be made relative to that value, even if that means ventilating to exceed the ASHRAE 62.2 minimum.

Using the results of these simulations, it is possible to attempt to optimize the ventilation rate to find the most cost-effective IAQ level. Assuming a binomial relationship, the curves in Figure 4.3.3 have been extrapolated past the 300 percent modeled ASHRAE 62.2 airflow.

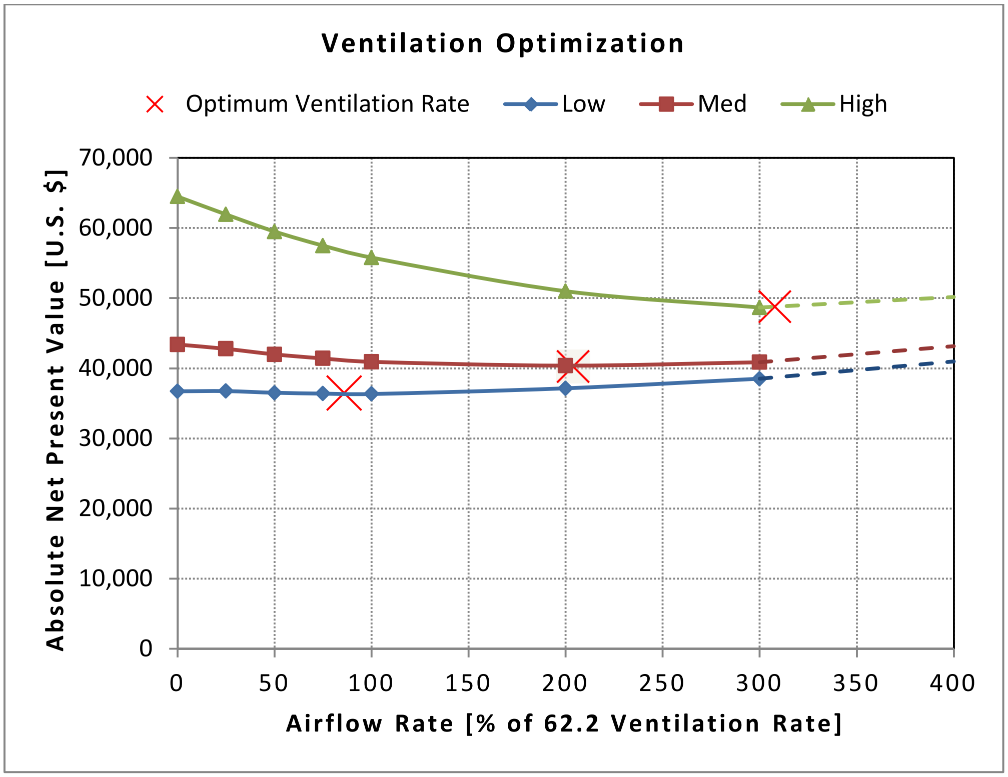

Figure 4.3.3: Optimization Curves for IAQ and Energy. The previous graphs show the net present value (NPV) relative to a base case of the home operating as specified by Title 24. This graph shows the absolute NPV.

The local minima are the points representing the minimum cost to the occupants.

As the ventilation rate increases, the NPV decreases, due to lower indoor contaminant concentrations. At higher airflows, energy costs begin to dominate and cause the NPV to increase. The optimum ventilation rates are at the local minima, or where the differentials of the curves are equal to zero. For the various emission rates considered, the optimum airflows were approximately 85 percent of the ASHRAE 62.2 minimum (low emission), 200 percent of the minimum (medium emission), and 310 percent of the minimum (high emission). These results indicate that, for the medium- and high-emission houses, the minimum ASHRAE 62.2 airflow was not high enough. For the low-emission house, the minimum 62.2 airflow rate was slightly too high, suggesting over-ventilation. Clearly, this approach is highly dependent on emission rates, but the high and low emission rates used in this study should act as boundary conditions.

4.3.4 Benefits to California

Commissioning is performed in steps, and whether or not to perform each step should be evaluated along the way. The ideal commissioning process uses appropriate, calibrated diagnostic tools and standardized procedures to determine the total energy and IAQ cost or benefit for a given home as a function of system airflow, followed by identification of the tuning options for that home, cost analysis of those options, and then finally implementing those options dependent on the cost benefit to the homeowner.

Based on the home characteristics considered for this study, the first step of performing diagnostics appears to be justified in the majority of new homes. For low-emission homes, assuming the proper use of task ventilation, tuning the airflow will always be of value, so long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. For homes with higher emission rates, currently, it would be difficult and potentially costly for a commissioning professional to perform the diagnostics required to estimate household emission rates for the pollutants of concern, especially as these are house-specific and subject to change, in part due to occupant behavior.

Identifying that diagnostics are needed to quantify emission rates will hopefully spur industry to develop appropriate tools and guidelines for the commissioning community. Our results suggest that controlling and limiting the levels of continuous emissions may also be an important tuning tool for residential ventilation systems. Labeling schemes now exist for products that meet low emission standards. Addressing emission rates in the commissioning process might be as simple as the auditor looking for labeled products in the house to help quantify the levels of continuous emissions.

4.3.5 Recommendations for Future Work

Relevant information in the references listed in our annotated bibliography should be combined with an energy and IAQ benefit assessment tool and the results of the diagnostic tool evaluations described in Section 4.4 of this report to develop a standardized commissioning process and a residential ventilation system commissioning guide for practitioners.

Further work is specifically needed to identify diagnostics for quantifying emission rates, which could be as simple as the auditor looking for labeled products in the house to help quantify the levels of continuous emissions. The guide should include guidance regarding these diagnostics, as well as related norms. Where needed, an emissions database also should be developed and made available to support such assessments.

As a consequence of combining energy costs with monetized IAQ costs, we now have the beginnings of an approach to optimize ventilation rates for homes. Future work should be carried out to further develop this method and to incorporate it into standards such as ASHRAE 62.2.

4.4 Airflow Diagnostics

Although ASHRAE Standard 62.2 and Title 24 require homes to have minimum ventilation airflows, they specify neither the device nor the procedure that is to be used to measure these flows. Devices for measuring ventilation (or space conditioning) airflows in buildings are generally referred to as flow capture hoods, or “flow hoods” for short. Typically, these hoods capture the flow entering or exiting a terminal and funnel it through some kind of measurement mechanism. Most flow hoods purportedly can measure flows in either direction (both inlet and outlet), and many have the capability to perform time averaging.

There is a wide range of residential mechanical ventilation flows. In homes with fully ducted heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs), the flows at each terminal can be as low as 10 cubic feet per minute (cfm). At the high end, flows from commercial-style residential range hoods can exceed 1,200 cfm. However, most residential ventilation flows are in the range of 15 to 200 cfm, so this is the range used for this study.

Acceptable measurement accuracy differs depending on the intended use for the results. Previous LBNL studies have described measurement accuracy requirements in terms of evaluating residential heating and cooling systems. For those studies, the required minimum accuracy ranged from a broad ±50 percent for identifying large leaks and disconnected ducts to a narrow ±3 percent for determining total system leakage. Currently, there is no accepted accuracy range for ventilation airflows required by residential building standards, and there is no minimum accuracy required for measuring ventilation flows. To evaluate residential ventilation airflows, we decided on a minimum required accuracy of ±5 cfm or ± 10 percent of measurement reading, whichever was greater.

4.4.1 Laboratory Calibration and Evaluation of Field Measurement Techniques and Technologies for Ventilation Airflow Measurement

There is currently no standard for calibrating flow hoods that reflects their use in realistic field measurement situations. ASHRAE standards 41.2 and 51 discuss how to use a specific laboratory apparatus to perform laboratory evaluations of airflows through conditioning and ventilation equipment, but they do not establish how to calibrate devices that are used to make flow measurements in the field. This situation has left each device manufacturer to develop its own calibration procedure. Flow hoods are often calibrated in a laboratory using an apparatus that produces an approximately uniform flow field that covers the entry of the flow hood. These calibration procedures do not necessarily account for the primary causes of measurement inaccuracy, the non-uniform flow fields common in residential buildings. Therefore, a new standard for flow hood calibration needs to be developed, along with a new measurement standard to address field use of flow hoods. These standards would help to ensure that flow hoods are capable of measuring all flows to an acceptable accuracy, so that homes receive the proper ventilation rates.

For the laboratory calibration (Stratton et al. 2012), we evaluated seven flow hoods that represent a range of types, manufacturers, sizes, weights, measurement mechanisms, complexity, and price. Six were commercially available hoods, and one was a research-grade powered hood constructed by LBNL. This LBNL hood is referred to in this study as "EPB" and has a previously determined accuracy of ±2 percent. The other six hoods were: a powered flow hood from The Energy Conservatory (TECFB), a powered flow hood from Europe (DIFF), a passive exhaust-only device from The Energy Conservatory (TECEFM), a rotating vane anemometer (testo417), and two traditional flow hoods from TSI/Alnor: ABT701 and EBT721.

Our laboratory experiments were designed to ascertain each flow hood's accuracy for measuring various outlet and inlet ventilation airflows under controlled conditions where a well-known reference measurement could be employed. The test apparatus combined an inline fan with two calibrated reference airflow measurement devices that were connected to a baffle into which was inserted a range of air inlets and outlets that are used with ventilation systems. A total of nine inlets and outlets were used, including both exterior and interior terminals. Sensitivity to flow hood placement over the terminals was evaluated by first centering the flow hood, then placing the terminal along one edge ,and finally placing the terminal in the corner of the flow hood.

In general, the three powered hoods yielded more reliable and accurate measurements than did the non-powered hoods. The average mean absolute difference for the three powered hoods was 4.2 percent, versus 11.6 percent for the four non-powered hoods. Two of the non-powered hoods—the ABT701 and the TECEFM—had overall results that were comparable to the powered hoods in terms of mean absolute difference.

The overall accuracy difference between the powered and non-powered hoods is due primarily to their respective abilities to measure outlet flows. The overall mean absolute differences of the inlet flow measurements for the powered hoods (5.1 percent) and non-powered hoods (2.9 percent) were similar, with the non-powered hoods overall yielding slightly more accurate results for inlet flows. However, the powered hoods were much more accurate when measuring outlet flows. For outlet flows, the powered hoods' mean absolute difference was 3.6 percent and the non-powered hoods' was 20.8 percent.

The type of terminal being used, which determines the angle of the flow relative to the mounting face, affected the accuracy of outlet flow measurements more than it affected inlet flow measurements. The standard deviation of mean average differences for all inlet flow terminal measurements was 0.5 cfm, versus 3.0 cfm for outlet flow terminal measurements. For comparison, the standard deviation of the mean average differences of flows sorted by flow location (middle, edge, and corner) was 1.8 cfm. The standard deviation of the mean average differences of flows sorted by flow direction (inlet, outlet) was 4.2 cfm. This reinforces our finding that the direction of flow has a greater effect on measurement accuracy than does the flow location.

Most of the hoods are relatively unaffected by the location of the flow relative to the face of the hood. Two exceptions are the testo417 and the EBT721, both of which are noticeably less accurate the farther the flow is from the center of the hood face. In the case of the testo417, this sensitivity to flow location is especially pronounced; its mean absolute difference is 7.8 percent for middle flows, 11.4 percent for edge flows, and 17.5 percent for corner flows.

In this laboratory study, we did not evaluate insertion losses: that is, the effect the hood has on the flow it is measuring. In particular, we did not compare the flow measurements from hoods to the reference flow as measured *before* the terminal was covered by the hood, because the test apparatus does not represent the system response of an actual ventilation system. Future studies could evaluate the effect of hoods on the flow they are measuring. One way to quantify this effect could be to measure the static pressure within the duct near the terminal before and then during the measurement.

4.4.2 Field Measurements of Whole-House and Local Exhaust Ventilation Air Flows in 15 New California Homes

The goal of this component of the study was to evaluate compliance with the ventilation requirements of ASHRAE Standard 62.2-2007 and Title 24. ASHRAE Standard 62.2 requires mechanical ventilation for both whole-building and local exhaust. ASHRAE 62.2-2007 states that whole-building and local exhaust flows can be measured or can meet prescriptive ducting and fan labeling requirements that use ratings provided by the Home Ventilating Institute. The 2013 version of the Title 24 will refer to ASHRAE 62.2-2010, which requires that whole-building airflows be measured. To show compliance with the ASHRAE Standard, we need a reliable way of measuring ventilation system airflows. This study (Stratton, Walker and Wray 2012) evaluated ASHRAE 62.2 compliance for fifteen California homes, both for whole-building ventilation flows and for local exhaust flows. It also evaluated the accuracy of six commercially available flow hoods, based on our experience using the devices to take field measurements of ventilation flows.

The homes included in the study were all within a 100-mile radius of LBNL. Nine were unoccupied new homes in Manteca and Napa, in new housing developments. Two of the fifteen homes studied were built prior to the implementation of Title 24 2008 (which made ASHRAE 62.2 mandatory) but were designed to be compliant with ASHRAE 62.2. Twelve of the fifteen homes used the exhaust fan in the laundry room for whole-building ventilation. The remaining three homes used a fully ducted ERV to provide whole-building ventilation. In addition to an ERV, one home also has a hole-in-the-return ventilation system. Thirteen of the fifteen homes had range hoods vented to outdoors. Two of the three homes with ERVs had recirculating range hoods. The recirculating range hoods do not count as kitchen exhaust for compliance with ASHRAE 62.2. Instead, these kitchens need to comply with the alternative to local exhaust ventilation, which is five kitchen air changes per hour that would be provided by the ERVs that have pickups in the kitchen.

The airflows were measured using the same flow hoods that were evaluated in the laboratory calibration and evaluation part of the RESAVE study (described in Section 4.4.1).

4.4.3 Summary of Results of Compliance with Title 24/ASHRAE 62.2 Ventilation Requirements in 15 New California Homes

Thirteen of the fifteen homes met or exceeded the minimum whole-house airflow rates required by ASHRAE 62.2 and Title 24. The two homes that did not meet the requirements failed substantially—by 20 cfm (36 percent) and 38 cfm (54 percent). It should be noted that both these homes were built prior to ASHRAE 62.2 being adopted by Title 24. The homes that exceeded the minimum airflow rates did so by a significant margin—averaging an additional 28 cfm (50 percent excess) over the minimum requirements.

There was less consistency for the local exhaust requirements. A key issue is that some exhausts were difficult to measure—in particular kitchen range hoods. The hardest to measure from inside the house are combined microwave/range hoods that have multiple air entry points for exhaust air—often on more than one face of the range hood. These kitchen exhausts need to be measured at their outlets, and that can lead to access-related safety issues, e.g., high exterior wall mounts or roof mounts.

All four of the homes for which kitchen range hood flows were measured met or exceeded the relevant ASHRAE 62.2 requirement. Some kitchens had no range hood, so that they need to meet a continuous kitchen exhaust airflow rate based on kitchen volume. The kitchens without flow hoods were not able to meet this whole kitchen exhaust requirement.

Of the 44 bathroom exhaust fans evaluated for this study, 23 (52 percent) met or exceeded the ASHRAE 62.2 required flow rates for local exhaust. The continuous bathroom exhaust fans used in some homes (with ERV) were required to be 20 cfm, rather than the 50 cfm required for the other homes' intermittent bathroom exhaust fans. Two of the three ERV systems met this requirement.

Without further investigation, it is not possible to say with any certainty why the failing fans failed. It is worth noting that in several instances the same fan model in the same house provided flow rates that differed by as much as a factor of four. This suggests that duct type, length, and installation change flow rates considerably, and that design and installation quality is a factor that determines the flow of an exhaust assembly as much as the fan's HVI-rated airflow.

4.4.3 Recommendations for Measurement Techniques to Be Used in Building Codes in California

At present, there is no industry consensus standard for assessing flow hood accuracy. For several of the hoods, there was little resemblance between the manufacturer's claimed accuracy and the accuracy that we determined in the course of our measurements. This would suggest that the accuracy evaluation protocols that manufacturers use are both different from our own protocol and from each other's. To ensure that hoods are evaluated uniformly on their ability to measure flows in the field, there needs to be a standard method of test for accuracy evaluation that incorporates "actual use" considerations, such as terminal type, flow direction, and flow location.

Included in this standard, or perhaps in a separate rating standard, should be acceptable accuracy ranges for each flow hood application. Based on results from the standard accuracy evaluation, a hood could then be rated and listed for certain flow measurement applications. In turn, codes might state, for example, that "a rated and listed hood with an accuracy of ±5 cfm or 10 percent shall be used to measure ventilation flows to evaluate a home's compliance with ASHRAE Standard 62.2."

The compliance testing indicated that, although compliance with whole-house ventilation was generally good, the kitchen and bathroom exhaust airflow rates were below requirements about half the time. This indicates that more attention needs to be paid to these intermittent fans and that field measurements need to be performed as part of a commissioning process to show compliance with build codes and standards (Title 24). Kitchen range hoods—particularly those with integrated microwave ovens—present a significant challenge for field verification, due to the complexity of airflow entering the range hood and location of building exhausts in hard to access places. In addition, some flow hoods had openings that were too small for typical exhaust fan inlets. Such a misfit leads to large errors in measurement that will have to be addressed through product development or commissioning specifications that disallowed such measurements.

The field testing did not cover as wide a range of terminals as the laboratory studies, so the comparisons between different flow hoods showed less variability. However, two of the tested devices (both passive hoods) had significant errors. The testo417 had average errors greater than 20 percent and only was acceptable (±10 percent or 5 cfm) in about half the tests. The EBT 721 only had poor results when measuring flows entering the flow hood, for example when measuring kitchen exhausts on the exterior of the home.

Until a new testing standard is completed, we can only give broad recommendations for acceptable methods of showing compliance:

1. For inlet flows, use any hood except one with a rotating vane anemometer
2. For outlet flows, use only powered flow hoods

If range hood flows are to be measured to verify compliance with the local kitchen exhaust requirements, guidance needs to be established with regard to the methods and flow hoods that are to be used to make these measurements.

Because they are usually installed on the face of continuous flat surfaces such as walls and ceilings, flows at terminals for bathroom exhaust fans and fully-ducted HRV/ERV systems tend to be more readily measureable than range hood flows. However, these terminals present their own measurement challenges. Tight spaces or obstructions immediately in front of the terminal face can make flow measurement difficult or impossible. If the wall or ceiling surface surrounding the terminal is inadequately sized or irregular, it may not be possible to create a seal with the flow hood and make an accurate measurement.

Given that ASHRAE 62.2 requires measurement of the ventilation flows at these terminals, it is imperative that efforts are made to ensure that flows at these terminals are in fact measurable. Possible strategies for ensuring the measurability of these flows may include a building code stipulation requiring an adequately-sized flat surface bordering the terminal and a requirement that flow hoods have an adjustable flow capture mechanism that can establish a good seal under a range of common terminal conditions.