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Houses are Dumb without Smart Ventilation

Iain Walker, Max Sherman and Brennan Less, Lawrence Berkeley National Laboratory

ABSTRACT

As we move to high performance housing and especially toward zero-energy homes, ventilation represents a larger and larger fraction of the space conditioning energy requirements. Ventilation standards, such as ASHRAE Standard 62.2 (or codes that use it, such as California Title 24), are typically met by continuous ventilation for their whole-house requirements, but met intermittently for their local exhaust requirements. Higher indoor air quality (IAQ) performance, as well as lower HVAC power and energy consumption, can be achieved by being smarter about how and when ventilation occurs. Numerous smart ventilation strategies are possible in high performance homes, such as increasing ventilation when the outdoor temperature is less extreme, scheduling ventilation during off-peak hours, avoiding ventilation during periods of poor outdoor air quality, and reducing whole house ventilation operation in response to incidental ventilation (e.g., bathroom or kitchen fan operation) and occupancy. Smart ventilation, in the form of a ventilation controller, can be used to implement all of these strategies and more. In this paper, we outline the theoretical requirements of a smart controller, discuss the real-world practicalities of control input options, and provide some actual examples of smart ventilation controls for residences. Ventilation controllers are flexible, and they can be used to fulfill the varied needs of building occupants, designers, policy makers, and program managers. Furthermore, as web-connected devices, the operation of a smart ventilation controller could be changed at will, in response to changes in policy, climate conditions, or grid dynamics.

Introduction

Smart ventilation systems would use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This would be done in a manner that provides improved home energy and IAQ performance, relative to a ”dumb” base case. We define as our base case the most typical situation of a continuously running whole-house ventilation system with on-demand local exhaust, but other base cases could be considered. We define “smart” controls as those best able to balance system energy use and IAQ. Fans would be controlled in response to inputs from local sensors or remote data sources (e.g., outdoor IAQ monitoring stations), and the smart control algorithm could be as simple or complex as desired. The most common application is likely to be control of whole house mechanical ventilation systems, intended to reduce exposure to pollutants generated throughout a home (i.e., from furnishings, carpeting and occupants). While rudimentary controls (e.g. humidistats) currently exist, there could also be smart controls on *local* exhaust systems, intended to remove pollutants generated indoors at high concentrations (i.e., from kitchens and bathrooms). Whole house ventilation has the advantage of the ability to be varied with time, unlike local exhaust, which needs to be coincident with the actions of occupants (e.g., cooking, showering, etc.). Conversely, control of local exhaust fans has the potential to most effectively reduce acute exposures, such as those during cooking. Flexible scheduling of a whole house smart ventilation system often requires over-sizing of the central ventilation fan. In principle, air cleaning and filtration could be used to improve IAQ rather than dilution ventilation, but current standards to not allow for such a trade-off and we will not consider that further herein.

Smart ventilation systems could provide the following benefits to home occupants, utility companies, and efficiency program managers: (1) reductions in energy use and energy costs, (2) equivalent or enhanced IAQ, (3) reductions in peak load (or equivalently time-of-use pricing), (4) ability to respond to demand response events, (5) flexibility that allows a wide variety of goals to be implemented on one platform, without expensive hardware/equipment changes, and (6) a cloud-connected platform that facilitates future adjustments to control algorithms in response to ongoing changes in climate, regulation, energy prices, grid dynamics, or occupant behavior. Both new and existing homes have the potential to benefit from smart controls. Many of the benefits accrue to utilities. Residential cooling, in states such as California, is a major contributor towards summer peak load, and adjusting the ventilation to off-peak time periods shifts a significant fraction of that cooling demand—and in some cases eliminates it. This is particularly true for the existing housing stock.

Some controls, smart and otherwise, currently exist in the U.S. residential and commercial building markets. Ventilation systems in commercial buildings often have controls that can be thought of as smart that depend on occupancy (demand controls) and outdoor air conditions. Controls currently found in some homes include timers, motion sensors, and humidistats; all of which operate almost exclusively in bathrooms. Other home ventilation controls are designed to save energy, such as outdoor air economizers, but they lack any IAQ components and either miss further energy saving opportunities or possibly worsen IAQ, due to introduction of outdoor pollutants. Smart controls are not commonly found in homes for the following reasons: deliberate mechanical ventilation is relatively new idea for homes, adding advanced controls increases system cost, control equipment on the market is not suitable for homes, and the typical homeowner is not accustomed to the necessary maintenance.

Currently, the most common implementation of whole house mechanical ventilation is to install a small, quiet fan (usually replacing a bath or laundry fan) that operates continuously, in accordance with the requirements of the current U.S. ventilation standard—ASHRAE 62.2-2013. These fans tend to require less than 20 watts to operate (HVI (2013)), and the vast majority of their energy impact is due to conditioning of the ventilation air. Yet, as high performance homes become the norm in U.S. new construction, demand has grown for ways to limit the energy impacts of these systems, while still providing the same benefits. A recent interpretation to 62.2-2013 allows use of smart ventilation technologies, but neither California, nor any other jurisdiction has approved its use.

We can estimate the magnitude of ventilation related energy from some recent simulation studies that examined the impacts of smart ventilation controls. Looking at natural infiltration only, for several prototype homes across all US climate zones that met IECC 2009 envelope requirements, tightening from 8 ACH50 to 2 ACH50 reduces energy use by about 20% (Turner, Walker and Sherman (2014)) – which implies that ventilation contributes about a quarter of the building load in a new home that has not been tightened. The envelope loads can be decreased with the use of more insulation and better windows but the ventilation has a limit imposed by minimum ventilation requirements. Saving 20% by tightening to 2 ACH50 in this example, would not be acceptable because a 2 ACH50 house would not have sufficient natural infiltration to maintain indoor air quality. A tight house therefore needs mechanical ventilation to maintain indoor air quality. For new well insulated homes (with a range of envelope leakage from 5 to 9 ACH50) built to meet California Title 24 or IECC 2009 the effect of adding mechanical ventilation to meet ASHRAE Standard 62.2-2010 is an increase in total HVAC energy use of about 10% (Turner and Walker (2012) and Turner, Walker and Sherman (2014)). Therefore, as envelope performance increases with improvements to energy codes and standards, the contribution of ventilation to overall energy use increases and presents an opportunity for energy savings.

One method to reduce ventilation loads in a home is to install mechanical ventilation with heat recovery (MVHR), but the first costs of these systems limit their cost-effectiveness in many situations. Another option is to simply reduce mechanical ventilation rates, but that may negatively impact IAQ and health. Smart ventilation systems have the potential to reduce the energy consumption resulting from ventilation, as well as to ensure equivalent or even enhanced IAQ. First costs will be greater than in a simple on-off system, but they are likely to be lower than MVHR systems. Furthermore, due to its potential flexibility, a smart ventilation controller can be implemented with varying strategies across building types, climate zones, and regulatory frameworks, making it a crosscutting solution in the built environment. Our focus herein is to find the energy and power savings associate with using smart ventilation system to minimally meet ventilation requirements, and thus our results are presented in energy terms. One could also use the same approaches to get better IAQ with the same energy consumption and thus the results would come out in a health-related metric.

Desired Characteristics of a Generic Smart Ventilation System

An effective smart ventilation controller must have the following generic attributes: understand and calculate IAQ in some manner, operate in real-time, be capable of sensing relevant control factors (e.g., building operation, pollutant levels, or occupancy), and be able to change ventilation rates or scheduling in response to inputs. In order to optimally balance system energy use and IAQ, a smart controller could leverage any of the following inputs.

Outdoor air quality: Unless (active or passive) air cleaning occurs, indoor air quality cannot be better than outdoor air quality on average (i.e. it can be better when short-term outdoor contaminant spikes occur). Nevertheless, when intermittent periods of poor outdoor air quality occur (e.g. afternoon ozone spikes), one can improve IAQ by lowering ventilation rates during these periods and increasing ventilation rates at other times.

Outdoor thermal conditions: Conditioning ventilation air takes more energy when the outdoor temperature and humidity are extreme. If infiltration is a factor, it too will be larger when the temperature difference is larger. Hence knowing outdoor thermal conditions can help to optimize ventilation by reducing controlled ventilation during the short-term extremes and compensating at other times.

Utility rates: The cost of each unit of energy may vary, for example, because of time of use rates. Therefore, it may be optimal to shift the ventilation away from high-cost periods. This can be done using both current and anticipated rates.

Occupancy: Limiting pollutant levels is only necessary when a space is occupied. Knowing when the space is or is not occupied can help reduce the amount of energy necessary to provide equivalent ventilation when it is occupied. If human bioeffluents are a contaminant of concern, knowing the number of occupants can also be important.

Exogenous ventilation: Many pieces of equipment that may be used around the house can impact whole-building ventilation rates as a side-effect, including kitchen exhaust, bathroom exhaust, economizers, direct evaporative coolers, dryer venting, etc. Monitoring such exogenous ventilation and crediting it towards whole house airflows can save energy by reducing excess ventilation.

Key contaminants: Limiting exposure to contaminants of concern below health-relevant levels is ultimately the purpose of ventilation. Key contaminants might include particles, aldehydes (such as acrolein or formaldehyde), products of combustion, ozone, radon, second-hand smoke, human bioeffluents, etc.

Infiltration: If the building leakage is known, then simple models (such as those in the ASHRAE Handbook of Fundamentals) can be combined with measured temperatures (and possibly wind speed) to estimate infiltration and turn off whole house mechanical systems when there is sufficient infiltration. Control algorithms to take advantage of infiltration are currently being studied by DOE's Building America program.

What we can detect reasonably?

While the items noted above are potential control inputs to a smart ventilation controller, current options for integrating many of them into a real-world controller are limited. The following are options that we consider currently practical for use as control inputs.

Occupancy: Due to low occupant density, the CO_2 sensors used in commercial buildings cannot be applied in residences. Motion sensors are another option, but if occupants do not move enough, such as when sleeping, they will not activate the sensor, resulting in incorrectly reducing ventilation. In addition, in a home with pets they may continue to activate the ventilation system even if no people are present. Thermal sensors could be used to detect occupancy, but, like the motion sensor, these would need to be in every room. Another possibility is to use the locator function of personal electronic devices (PEDs) (e.g., smartphones) to determine presence in the home. Finally, a smart ventilation system could use combinations of heat, motion and PEDs as is used in some residential HVAC controls.

Humidity: For the accuracy required in conditioning homes (±3%), humidity sensors are commercially available that could be used to control a ventilation system based on indoor humidity. Sensing outdoor humidity can be more difficult, but real-time weather reported by third parties (e.g. weather information) can often be a superior substitute.

Temperature: Detecting indoor and outdoor temperature is relatively easy and can be used to control ventilation. Sensors exist and are already being used in some commercially available residential HVAC systems (e.g., economizers and advanced air-conditioner/heat pump outdoor units). Measuring the temperature of the air above the cooking surface can also be used to control automatic range hoods.

Third party signals: A smart ventilation controller could synchronize to third party signal providers. Examples of external third party signals are an alarm when outdoor ozone or particle concentrations are high, or a utility signal for demand responsive ventilation.

User/Occupant Interactions

What does a smart ventilation system need to look like to the occupant? Preferably the automation and smarts are hidden and do not require occupant interaction. People are poor detectors of most pollutants that pose chronic health hazards (e.g., formaldehyde, acrolein, etc.), while they are generally able to detect odors and irritants. Furthermore, they generally do not have the time or inclination to be IAQ or energy managers. Therefore, the systems likely to be successful will be independent of occupant interaction. Having said that, acceptance will be more likely if occupants are allowed some override ability, as is currently required in any non-smart, ASHRAE 62.2-2013 compliant system. The excess fan capacity noted in the introduction as a requirement for many smart control strategies would also allow occupants to demand higher rates of ventilation when desired, such as during social gatherings and hobby activities with high emissions. Systems with occupant-override ability should provide means of restarting smart control after an instance of occupant intervention, such as an automatic reset every 24-hours.

Smart Ventilation and IAQ

Whole house ventilation is intended to reduce exposure to pollutants that are continuously emitted by building materials, household contents, and occupant activities. In principle, one could have active ventilation to control the exposure of occupants to contaminants of concern. In fact, this is done in high-occupancy spaces where people are the dominant contaminant source. Such demand controlled ventilation uses carbon dioxide (CO_2) as a surrogate for human bioeffluents and changes the ventilation system airflow to keep it below a desired level. Such an approach would be less useful in homes, as Logue et al (2011) showed that other contaminants dominate indoor exposure and health impacts.

Yet, as outlined above, there are no currently available pollutant sensors upon which we can base ventilation control in homes. Nevertheless, the entire concept of smart ventilation, as we have defined it, is the ability to best balance the energy use of a system with its resultant level of IAQ. Accordingly, another metric is needed in order to facilitate assessment of IAQ provided by different smart ventilation systems. In response, LBNL developed the concept of *equivalent ventilation* (Sherman (2006) and Sherman et al. (2010) and (2012)). The equivalent ventilation approach provides a method for comparing time-varying and fixed ventilation rates, in terms of the dose and exposure of the home and its occupants. The dose and exposure are expressed relative to the fixed airflow rate of a continually operating, ASHRAE 62.2 compliant, whole house exhaust fan, which makes determination of actual pollutant levels unnecessary. Dose and exposure are calculated in real-time, but efforts to-date have focused mostly on equivalence in chronic exposure (i.e., over a one-year period).

The principle of equivalent ventilation is a recent addition to ASHRAE Standard 62.2 and is an accepted method of showing compliance with ASHRAE 62.2-2013 in section 4.6:

"4.6 Equivalent Ventilation. A whole-building ventilation system shall be designed and operated in such a way as to provide the same or lower annual exposure as would be provided by complying with Section 4.1. The calculations shall be based on a single zone with a constant contaminant emission rate. The manufacturer, specifier, or designer of the equivalent ventilation system shall certify that the system meets this intent and provide supporting documentation."

Recent interpretations of this standard (available on the ASHRAE website) have confirmed that smart, real–time controllers are in fact allowed as a means of compliance, as long as they are certified by the manufacturer, designer or installer to be equivalent. Furthermore, only periods of occupancy need be considered.

The concept of equivalent ventilation allows us to adjust ventilation in time, while still providing IAQ indistinguishable from that provided by a continuously operated, “dumb” fan. This moving of ventilation in time allows us to preferentially ventilate at times when energy impacts are reduced, as well as to make a residence more demand-responsive (a key issue for utilities). Additional benefits include the ability to take credit for ventilation provided by other systems (e.g., kitchen and bathroom exhaust fans, as well as clothes dryers and economizers), thus reducing the required whole house airflow rate. Smart ventilation can also be used to deliberately reduce ventilation if outdoor pollutant levels are high—for example, during times of high outdoor ozone, humidity, or particulate levels.

Equivalent ventilation calculations have been used to:

- Demonstrate 40% energy savings while maintaining equivalence to ASHRAE 62.2 and prevent exposure to acute pollutant levels (Turner and Walker 2012).
- Compare constant air volume to demand controlled ventilation designs (Mortensen et al. 2011).
- Design passive stack ventilation systems (Turner and Walker 2013).
- Simulate a smart ventilation control strategy to reduce ventilation at times of high outdoor ozone levels, with demonstrated reductions of 10-40% in ratios of indoor-to-outdoor ozone (Walker and Sherman 2012).

While equivalency has been used mostly in assessments of chronic exposure, acute pollutant exposures (i.e., short-term, high-concentration exposure) also pose serious health risks, and are not necessarily controlled by accounting for annual average exposures. If smart ventilation systems are turned off during periods of no occupancy or peak demand, then occupants may be exposed to unacceptably high pollutant concentrations upon entering a previously unoccupied space. A smart ventilation controller can take this into account by limiting exposure (i.e., occasionally operating ventilation system), even if the space is unoccupied. Turner and Walker (2013) used ratios of acute-to-chronic standards reported in Logue et al. (2011) to set an increased maximum relative exposure for use by a smart controller during unoccupied times. Turner and Walker showed that $PM_{2.5}$ has the lowest ratio of acute-to-chronic reference exposure levels (2.5). This represents the most conservative exposure limit that a smart ventilation controller might use for unoccupied times.

Limited Ability to Detect Pollutants

We currently cannot control residential ventilation based on real-time pollutant measurements for two reasons: (1) we do not know precisely which pollutants are the most important to measure in any given home, and (2) no sensors are currently available on the market that are appropriate for long-term residential ventilation control. The first issue could be overcome to some extent by detecting what are considered to be the most significant pollutants of concern in residences (Logue et al. (2011))—particles, acrolein, formaldehyde, & NO_2—but doing so to some extent eliminates the ability to tailor system operation to the needs of a specific home. As for existing sensors, most continuous detection/measurement methods are neither affordable nor robust (i.e., working well over periods similar to the lifetimes of HVAC equipment). Furthermore, no specifications exist outlining the acceptable accuracy and precision of sensors for use in residential ventilation control. As a result, we feel that it is unlikely that significant progress will be made in the near future.

Smart Ventilation and Energy

Both fan energy and (except for economizer uses) space conditioning energy are reduced any time the mechanical ventilation system is shut off. Smart ventilation controls can do this in several ways. The energy used to condition air can be reduced by increasing airflow rates and shifting ventilation to times of day with lower temperature differences. Similar controls could be used to control humidity levels. The total ventilation rate for the home can be reduced by sensing operation of other mechanical systems in the home and turning the central fan on or off in response. In all but the very tightest of homes, being able to account for infiltration to shut off mechanical ventilation prevents over-ventilation, which is most likely to occur when temperature differences are largest and the energy penalty for over-ventilating is highest.

Smart ventilation can also facilitate reductions in ventilation-related peak load, which can be a about third of the HVAC peak load, and it can also integrate with the demand response needs of utility companies. Smart controls allow us to easily shift the time of ventilation away from peak demand periods, when loads on the gas and electricity distribution infrastructures reach a maximum (typically 4-8 am during winter months and 2-6 pm during summer months). Reducing peak demand benefits both utility companies and consumers, through lower prices and greenhouse gas emissions, as well as increased grid stability and avoidance of service outages. Through smart ventilation, the contributions of ventilation fans and space conditioning loads can be entirely eliminated during peak periods. Furthermore, due to their flexibility, smart ventilation systems allow ongoing dynamic response to grid conditions.

Examples of Smart Ventilation Control

Smart Ventilation for Local Exhaust

Cooking activities in kitchens are considered important sources of pollutants in all homes where cooking occurs. Studies have shown that occupants are unreliable operators of local kitchen exhaust (Klug et al., 2011a; Mullen et al., 2013), with only about a quarter of people regularly using exhaust fans. Furthermore, recent studies have shown that kitchen range hoods have highly variable capture efficiency (Delp and Singer (2012) and Singer et al. (2012)), and on average they only capture about half of the emitted pollutants. Unfortunately, smart controls cannot fix this problem, as it is an issue of aerodynamics and improved hood design to capture the pollutant plume above a cooking surface. Nevertheless, smart controls can be used to ensure reduced exposure to cooking pollutants by automatically operating local kitchen exhaust when needed. Automatic control of kitchen exhaust systems will in most cases increase, rather than decrease system operation and energy use. Yet, increased use of kitchen exhaust will reduce pollutants in the home, and local systems generally do so at higher levels of ventilation effectiveness. This could allow a reduction in the whole-house ventilation rate, while still maintaining acceptable or enhanced IAQ.

Some currently available kitchen range hoods have some level of automatic control, but most are not suitable for ongoing operation of the exhaust fan, in response to cooking activities. These range hoods use temperature or smoke sensing to automatically turn on, however several of these do so as a safety feature to prevent the hood overheating, rather than as a continuous pollutant control feature. Some hoods have thermal sensors for control, but the range hood usually has to be turned on manually at low speed before the controls activate. This is not very useful from our smart ventilation perspective. Preliminary laboratory testing by LBNL has found that the thermal controls in existing products have slow response—taking up to half an hour to activate even with all burners turned on. A single burner, or burners set on low or operating the oven, will not activate the range hood, even though pollutants are entering the home. These unsatisfactory performance results are due to slow sensor response, as well the positioning of the thermal sensors (e.g., being located in the controls area of the range hood rather than the air directly over the cooking area). Clearly, further research and product development efforts are needed in order to automate range hoods for control of IAQ.

Residential Integrated Ventilation Energy Controller

Another specific embodiment of a real-time controller is the Residential Integrated Ventilation Energy Controller (RIVEC). The RIVEC controller performs real-time calculations of relative dose and exposure and controls the whole house ventilation fan in a manner that ensures equivalent IAQ to a continually operated ventilation fan. The controller includes: the effects of exogenous ventilation (e.g., kitchen range hood, economizer, dryer), periods of time when ventilation is forced to be off during times when the energy penalty is highest for ventilation, reduction in ventilation during unoccupied times, and control of acute pollutant exposures.

Preliminary studies of RIVEC (Sherman and Walker 2011) showed that at least 40% ventilation energy reductions (500-7,500 kWh/year) were possible, or reductions of about 15% of total HVAC energy use. Some of this savings came from deferring ventilation during peak times and some came from taking account of exogenous ventilation sources, thus reducing over-ventilation. Turner and Walker (2012) extended this effort by using simulations to: investigate the use of occupancy-based ventilation that included limits on acute exposures, show that substantial peak power reductions (of about 2 kW) could be achieved, and optimize the design of passive stack and hybrid systems. Finally, Walker, Sherman and Dickerhoff (2012) performed a field test in order to validate the functioning of the RIVEC system in an actual home. The test house was chosen because it had a mechanical ventilation system and an economizer in addition to the usual household appliances. The results in the test home showed that RIVEC reduced overall ventilation fan operation by 55% and delivered a calculated relative dose 20% less than that of a continually operating ventilation system. Ventilation fan operation was reduced particularly during periods of economizer operation, because its large outdoor airflows offset substantial operation by the smaller ventilation fan.

As an illustration of RIVEC activity in real-time, Figure 1 illustrates the operation of the RIVEC controller during a 48-hour period where both chronic and acute exposures are being controlled. For the first four hours and from hours 17 to 28, nothing else is happening in the home and RIVEC cycles the whole house ventilation fan to maintain relative dose and exposure below one (the whole house ventilation fan is on when the RIVEC Fan ON/OFF indicator is high – at 0.8). The pink shaded areas are when the ventilation system is deliberately shut off in the early hours of the morning to reduce building loads when it is coldest outside (in this winter example). During these periods, the relative dose and exposure increase. The blue shaded area indicates when the home is unoccupied. During this time the relative dose and exposure for the occupants (designated by (Occ)) goes to zero as they are not in the home. The relative dose and exposure are still calculated during this time and the controller limits the relative exposure to a higher level (see Smart Ventilation and IAQ section above)—with the RIVEC fan operating for less of the time than when controlling to a lower level of pollutant. This prevents the returning occupants (at hour 40) from being exposed to too high a level of pollutant. In the first day, from hours 11 to 14, a dryer fan operates (indicated by the higher value of 0.6 for the Dryer ON/OFF indicator) that increases the ventilation rate for the home and drives down the relative dose and exposure, such that after this time the RIVEC fan may be turned off for a couple of hours.

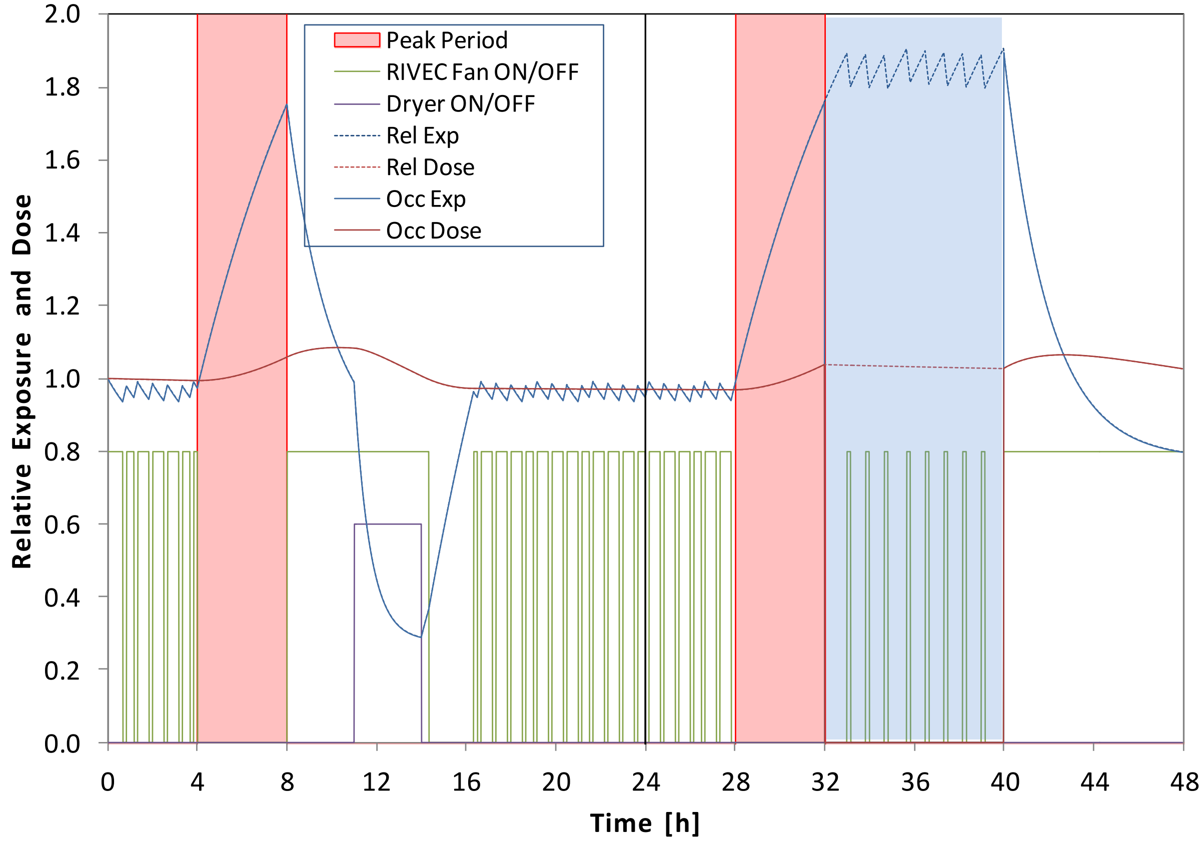

Figure 1. Example of smart ventilation (RIVEC) control operation.

With these preliminary results in hand, LBNL simulated the RIVEC control strategies in three house types, with four different whole house ventilation systems, across all eight U.S. DOE climate zones. The results showed ventilation energy savings of about 40% with economizer use leading to higher savings (48%). Heat recovery ventilation showed reduced energy savings potential (34%), due to their reduced ventilation energy impact. In absolute terms, the energy savings were about 1,000 kWh with significant climate zone variation. Peak load reductions had even stronger climate dependence, as illustrated in Figures 3 and 4 for heating and cooling, respectively. These peak load reductions, of up to 1,600 W for cooling, represent a big savings potential for utility demand reduction programs.

Temperature Controlled Ventilation

The simple controlling of mechanical ventilation in a manner that accounts for wind and stack-driven infiltration is another smart ventilation strategy. LBNL recently performed simulations in all U.S. DOE climate zones, assessing the implications of turning off mechanical ventilation fans (sized to ASHRAE 62.2-2013) when a simple infiltration model predicted that weather factors alone would provide equivalent air exchange. Airtightness was varied in the simulations from 0.6 ACH_{50} to 10 ACH_{50}. (Existing homes leakier than this do not normally need mechanical ventilation systems.) Homes with airtightness of 3 ACH_{50} or less were never able to achieve infiltration equivalent to 62.2-2013 requirements, so fans in these homes were never turned off, and no energy savings occurred. As expected, results were highly variable by climate zone, as shown in Figure 3. This type of ventilation temperature control strategy becomes more effective as homes become leakier and climates more severe. Just greater than half of all test homes had no benefit from this strategy, due to levels of infiltration in very airtight homes that never meet 62.2-2013. So, other temperature control strategies should be developed for these advanced projects. For example, ventilation rates could be controlled on a daily basis, using the prior day's average or median temperature as a control point.

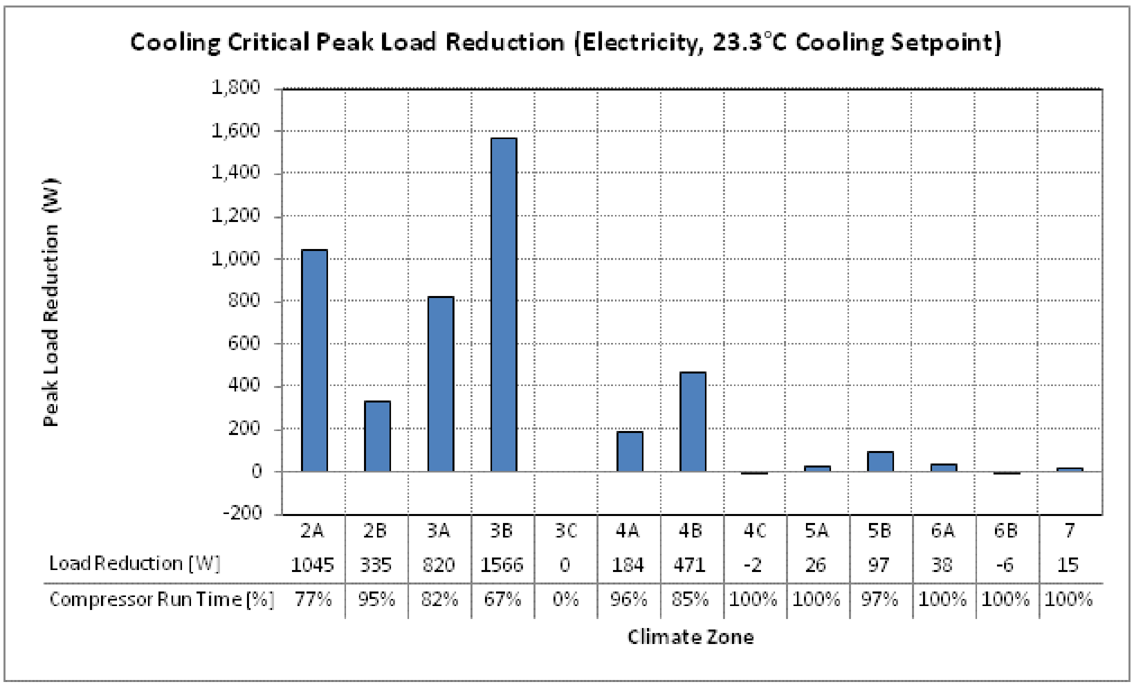

Figure 2. Simulation results for RIVEC on cooling critical peak load reduction.

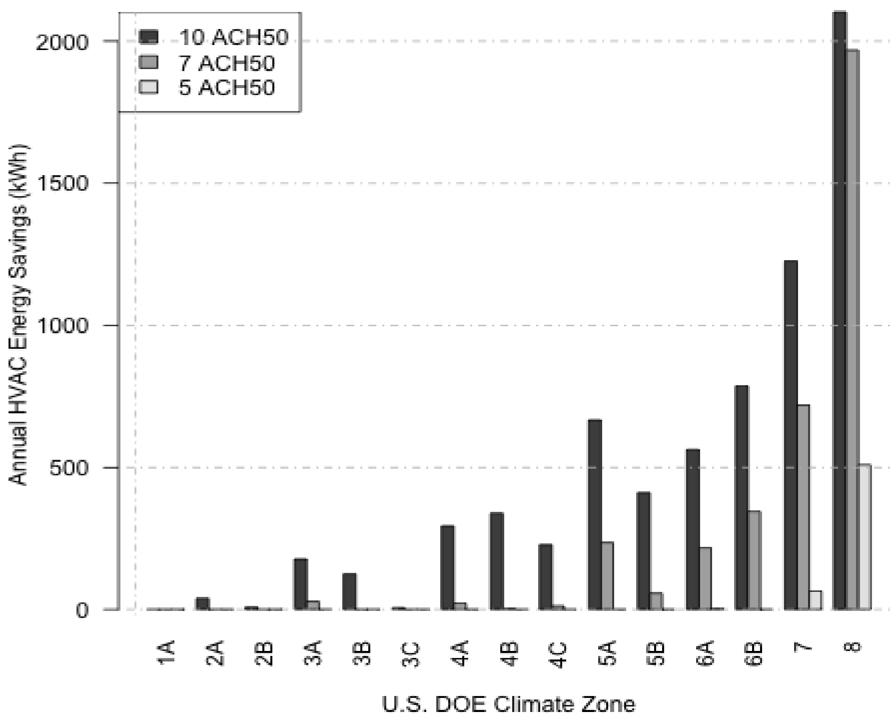

Figure 3. Estimated energy savings for temperature controlled ventilation in different U.S. DOE climate zones for a single-story home.

Summary and Perspectives

With conductive and convective loads decreasing in homes, the ventilation load is becoming more important as a fraction of HVAC energy requirements. Technologies such as heat recovery ventilation can mitigate that load, but there are also many opportunities to make ventilation systems smart–reducing ventilation loads while increasing IAQ performance. In this paper, we've outlined the theoretical requirements of a smart controller, the real-world practicalities of control input options, and some actual examples of smart ventilation controls for residences. Prototype smart controllers have been shown to potentially reduce ventilation-related energy use by an average of 40%, while maintaining equivalent or enhanced IAQ.

There are rudimentary systems on the market now, but zero net-energy buildings will require further advancements in smart ventilation control technology. We've identified the following innovations that will make smart ventilation controllers viable and relevant going forward: (1) innovations in sensor technologies, including pollutants and occupancy detection, (2) development of software, hardware, and communication protocols that will facilitate secure communication with the cloud and sensor networks in new and existing homes, (3) adjustments to current codes and standards, so that smart controllers are explicitly acknowledged as paths to compliance, (4) development of effective automatic range hoods, and (5) exploration of low-cost systems that can still capture substantial savings (i.e., temperature controlled ventilation).

We are making our houses smarter and smarter every day by putting brains in appliances, connecting them to the web, having them learn the thermal comfort preferences of their occupants, and having inter-appliance communication. Our residential ventilation systems now have the capacity to be smart. They can save energy while improving IAQ, as well as responding to grid needs, all without negatively impacting human comfort.

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