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Smart ventilation energy and indoor air quality performance in residential buildings: A review

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Residential smart ventilation: a review

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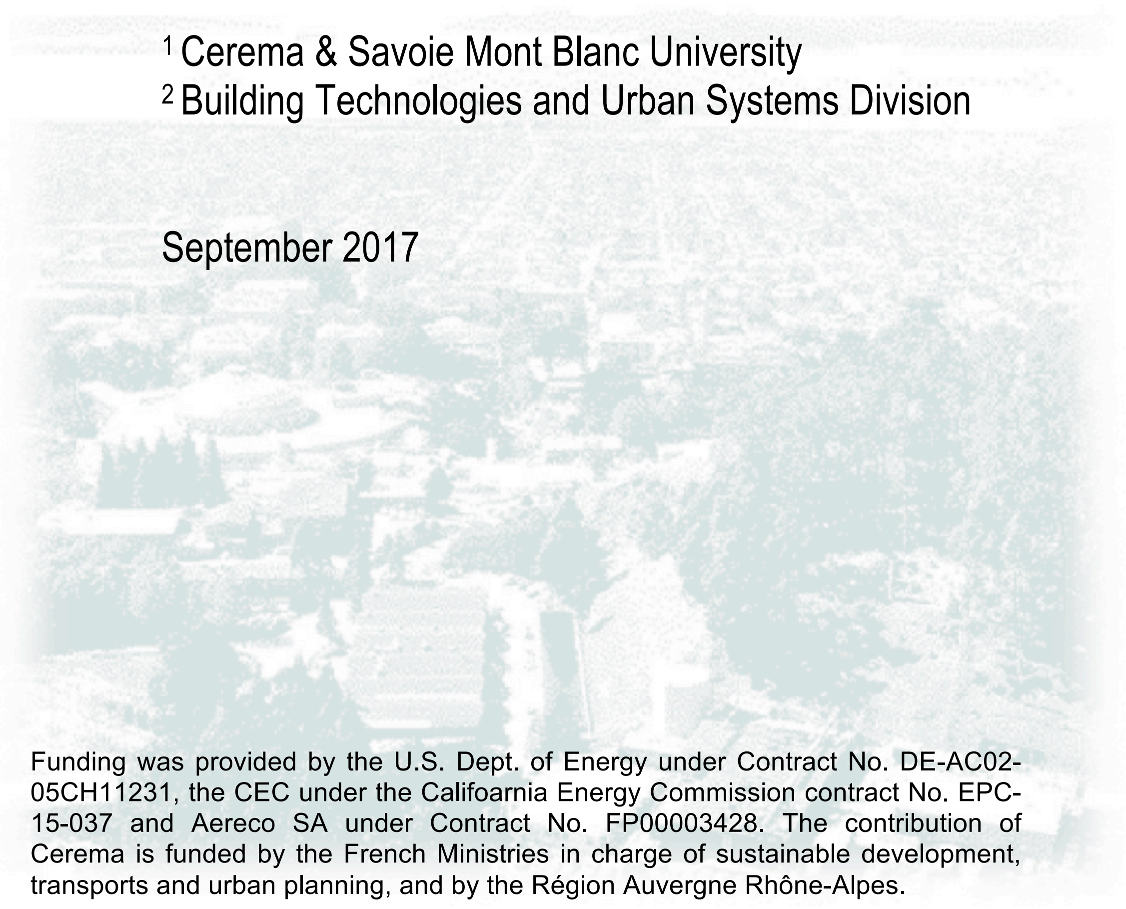

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Disclaimer

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ABSTRACT

Air ventilation is one of the top energy users in residential buildings. Smart ventilation equipment and controls help to reduce the amount of energy use attributable to ventilation in homes while maintaining high indoor air quality. Ventilation can also be used as a resource for utility grid demand response if done intelligently. A key component of the smart ventilation concept is the use of controls to ventilate more when doing so provides an energy or air quality advantage and/or a resource to the power grid, and less when it provides a disadvantage. Unlike demand-controlled ventilation, other smart ventilation concepts involve the addition of several new inputs into control algorithms—namely measured or modeled concentrations of pollutants and signals from the electricity grid. And, unlike demand-controlled ventilation, smart ventilation uses the "equivalent ventilation" principle in the selection of the control strategy, which allows anticipation of future ventilation needs and retroactive compensation for previous ventilation needs.

To determine the best means of controlling ventilation in residences, this study first reviewed literature relating to the:

- Suitability of common environmental variables (pollutants of concern, humidity, odors, CO_2, occupancy) for use as input variables in smart ventilation applications
- Availability and reliability of relevant sensors
- Different control strategies used for a smart ventilation approach.

Results of the review showed that the suitability of each environmental variable is specific to each smart ventilation application, and also that pollutant sensors are currently not robust or accurate enough to be relied upon for residential ventilation controls.

Next, this research assessed the regulatory context in which smart ventilation strategies might be implemented most effectively. The assessment showed that many countries already have a regulatory structure that is favorable for the development of smart ventilation strategies. These countries have regulations and standards in place that propose "equivalence methods" that offer a path to compliance including the use of smart ventilation strategies. These compliance paths have allowed for the development and availability of demand-control ventilation systems in the marketplace; more than 30 such systems have been approved and are available in countries including Belgium, France, and the Netherlands. It seems likely that the more complex smart ventilation strategies would follow a similar path to market acceptance.

Results of the review of smart ventilation in residential buildings is used to:

- Determine and discuss performance of smart ventilation in terms of energy and indoor air quality
- Gather data on occupant behavior
- Assess the suitability of automatically controlled ventilation systems
- Assess the applicability of a multi-zone approach for ventilation.

This meta-analysis of 38 studies of various smart ventilation systems with controls (on either CO_2, humidity, combined CO_2 and TVOC, occupancy, or outdoor temperature) shows that ventilation energy savings of up to 60% can be obtained without compromising IAQ—and sometimes even improving it. In some cases, the smart ventilation strategies did not reduce energy use (showing an increase in energy use of up to 26%).

Occupant behavior was also examined in the review. The examination showed that occupants are rarely aware of the quality of their indoor air, particularly with regard to health issues, and do not necessarily operate the ventilation systems when recommended for optimal indoor air quality or energy efficiency. The applicability of a multi-zone approach is also demonstrated by studies showing a disparity in concentrations between different rooms of a home, and differences between single-zone and multi-zone modeling in residential buildings.

Finally, this report summarizes ongoing developments in smart ventilation strategies and applications, including research into indoor air quality metrics, feedback on the lack of quality in ventilation installations, and source control (filtration and air cleaning) issues.

KEYWORDS

Residential, smart, ventilation, DCV, indoor air quality, health, energy, performance, sensors, pollutants

1. INTRODUCTION

Ventilation is a driver of both 1) indoor air quality (IAQ) considerations in residential buildings and 2) energy use in residential buildings (conditioning ventilation air and fan power requirements). In order to provide both improved IAQ and energy performance in residential buildings, ventilation must become aware of what is happening in the space and its own impact; that is, it must become smarter. *Smarter ventilation* provides higher performance whether that performance is more energy-efficient, conducive to improved IAQ, or it also takes into consideration the needs of the power grid and potential future variable costs of electricity.

Through updates to California building codes, California is leading the way to energy-efficient residential buildings, and is even on the way to mandating zero-net-energy homes. This is also the case in some European municipalities, in response to energy performance building directives from the European Parliament (2010).. For these high-performance homes, envelope airtightness treatment becomes crucial (Erhorn, et al. 2008) and should be combined with efficient ventilation technologies. Ventilation loads in high performance homes represent a significant and increasing fraction of the space conditioning load and thus smart ventilation become an increasingly useful approach.

Great strides have been made in improving envelope airtightness in residential and commercial applications, but sometimes at the cost of IAQ. Because people spend 60%—90% of their life in indoor environments (homes, offices, schools, etc.), IAQ is a critical factor affecting public health and smart ventilation concepts of the future must take it into account (Klepeis, et al. 2001; European commission 2003; Brasche and Bischof 2005; Zeghnoun, et al. 2010; Jantunen, et al. 2011). Logue, et al. (2011b) estimated that current damage to public health from poor IAQ (excluding second-hand smoke (SHS) and radon) was in the range of 4,000–11,000 µDALY per person per year. By way of comparison, this means the damage attributable to poor IAQ is somewhere between the health effects of road traffic accidents (4,000 µDALY/p/yr) and heart disease from all causes (11,000 µDALY/p/yr). According to the World Health Organization (WHO 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household IAQ in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes IAQ requirements, have been estimated at more than 300,000 disability-adjusted life years (DALY) per year. (Jones, et al. 2015) studied air change rates provided by infiltration only and showed that, in order to limit negative health consequences, up to 79% of homes could require additional purpose-provided ventilation.

Tightening building envelopes may increase the likelihood of poor IAQ (Phillips and Levin 2015), but the risk may be exacerbated by the fact that airtight envelopes are sometimes combined with poor quality ventilation installations (Dimitroulopoulou 2012; Stratton, et al. 2012). In the Healthvent project (Seppanen, et al. 2012), experts from 17 European countries were interviewed on the effects of the last update of the Energy Performance Building Directive (EPBD). They concluded that tightening of envelopes combined with a lack of attention to IAQ concerns in the national energy performance regulations must be considered a serious risk.

In order to meet the sometimes-competing desires to provide for proper IAQ and reduce energy use in buildings, interest in a new generation of ventilation systems has been growing. The term “smart ventilation” usually denotes a ventilation system that uses controls to ventilate more when doing so provides an energy or IAQ advantage (or both) and less when it provides a disadvantage (relative to an base case that is insensitive to such issues). The most studied subset of smart ventilation strategies are demand-controlled ventilation (DCV) strategies (Laverge, et al. 2011). Although DCV techniques can be applied to just about any ventilation system, they are particularly useful in allowing relatively simple ventilation systems (such as an exhaust) to have an energy performance that is closer to more complex systems (such as those using energy recovery).

As an example of the growing interest in better ventilation, the *Indoor Environmental Quality Research Roadmap* (Levin and Phillips 2011) recommends that indoor environmental quality (IEQ) be integrated into California’s future plans. The roadmap identified ventilation as a priority research topic. Two specific high-priority research topics were listed:

- Identify and understand the best ventilation systems for high-performance buildings, including ventilation and air cleaning systems that are separate from heating and cooling systems
- Develop and demonstrate IEQ-optimized ventilation, heating, and cooling systems for different building types and different climate zones in California for both new and retrofit applications.

Our review begins to work toward these objectives as part of a project called “Smart Ventilation Advanced for Californian Homes” (SVACH) funded by the California Energy Commission, the U.S. Department of Energy, and the Aereco S.A. The project addresses both of these high-priority project areas for residential buildings first by developing smart ventilation technology approaches, some of which may include the use of air cleaning, and secondly by developing IAQ metrics for optimizing ventilation.

This report is an analysis of the state of the art in smart ventilation, as published in industry literature. Analysis presented here is based on industry publications and published market surveys.

This report addresses several aspects of smart ventilation:

- The definition and description of smart ventilation strategies, including a theoretical background
- The suitability of various environmental variables for use as inputs in smart ventilation applications
- The availability and reliability of the sensors used to measure these variables
- A description of relevant control strategies
- An overview of the regulations and standards proposing “equivalence methods” in order to promote the use of smart ventilation strategies and the available systems on the market in different countries
- A review of smart ventilation as currently used in residential buildings, the associated energy and IAQ performance of these buildings, and occupant behavior

- The applicability of a multi-zone approach for ventilation.

Finally, a summary of ongoing developments in research areas related to smart ventilation is given, including IAQ metrics, feedback from on-site implementations, source control, filtration and air cleaning.

2. BACKGROUND ON “SMART VENTILATION” STRATEGIES

Why Ventilate Buildings?

Appropriate building ventilation provides a healthy and comfortable indoor environment, with attention to occupant health and comfort. Indoor pollutant sources can come from outside air, from occupants themselves and their activities, and from the furnishings and materials installed in buildings. Any first principles evaluation of IAQ needs to include a focus on the contaminants which are likely to impact health.

There are thousands of chemical species in the indoor air—most of them are present at concentrations that do not represent any significant health threat. There are more species added all the time—many of which have very limited data on their health impacts. Thus, it has been difficult to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom, et al., 2016). Instead, prescribed ventilation rates have been used. The limitation to this approach is that, though it displaces human bio-effluents including odors, it assumes that ventilation is a sufficient means of controlling other contaminants (Matson and Sherman 2004). Persily (2006) gives more details. A committee chair of ASHRAE Standard 62-1989 (ASHRAE 1989) noted that the minimum ventilation requirement of 7.5 L/s per person was based on body odor control (Janssen 1989), and that this minimum was increased to 10 L/s per person in many building types to account for contaminants other than human bio-effluents, such as those emitted by building materials and furnishings. However, no specific methodology articulating the justification of this increase is noted. As a result, standards and regulations generally set ventilation rates based on comfort considerations and not on health criteria as suggested in the Healthvent project (Seppanen, et al. 2012; Wargocki 2012).

Regardless of the performance criteria or particular ventilation system, a ventilation strategy should be able to dilute and/or remove both the background emissions and the occupant-related emissions in order to prevent unhealthy chronic and acute exposure. As a result, current standards and regulations, such as ASHRAE 62.2-2016 and others in Europe (Dimitroulopoulou 2012), often prescribe ventilation strategies requiring three constraints on airflow rates:

1. A constant airflow based on a rough estimation of the emissions of the buildings: for instance, one that considers size of the home, the number and type of occupants, or combinations thereof
2. Minimum airflows (i.e., during unoccupied periods)
3. Provisions for short-term forced airflows to dilute and remove a source pollutant generated by activities (cooking, showering, house cleaning, etc.).

It should be noted that even a proper ventilation system should not be seen as a panacea: to achieve good IAQ, source reduction must also be considered (Mansson, et al. 1997; Sherman and Hodgson 2002; Wargocki 2012; Borsboom, et al. 2016). The history of combustion devices changing from open fireplaces to sealed modern fireplaces is a good illustration of a response to the need for source reduction (Matson and Sherman 2004). Public policy that pushes the development of low-emitting building materials and furnishings is another example (composite wood product airborne toxic control measure of California Environmental Protection Agency 2011; compulsory labeling of VOC emission of all construction products and decorative products installed indoors of French Ministry for Ecology 2011).

Smart ventilation definition and examples

The concept of smart ventilation was developed to ventilate properly while reducing energy loads, allow for the provision of grid services, and promote associated renewable power integration (Sherman and Walker 2011; Walker, et al. 2011; Turner and Walker 2012; Walker, et al. 2014). The goal is to reduce the amount of energy that ventilation uses and reduce associated energy costs below that of an analogous continuously operating system while maintaining or improving IAQ. A secondary goal is to allow residential ventilation systems to eventually interact symbiotically with the power grid by reducing electricity use during peak demand period and eventually allowing for grid services such as short-term load shifting. Smart ventilation encompasses some aspects of DCV strategies, which have been employed for years, such as the modulation of ventilation in response to occupancy. But in its most general definition, smart ventilation also includes some other components:

- First, ventilation is provided in response to demand for ventilation rather than in a prescribed, conservative prescription of ventilation rate. In DCV systems, demand is most often quantified in terms of occupancy, or some other measureable quantity, which is usually intended to indirectly estimate occupancy (such as RH or CO_2 concentrations). Smart ventilation can also quantify demand in terms of individual pollutant loads (by sensing individual pollutants and the allowing a reduction in demand based on these measurements)—a critical and often unaddressed issue. Also, smart ventilation can often reduce calculated demand that stems from air infiltration or exhaust due to mechanical equipment used for source removal (i.e., kitchen hoods and bathroom fans).
- A second aspect of a smart ventilation strategy is that it can employ the principle of equivalent ventilation to satisfy demand at times of the day that are not necessarily coincident with the demand itself. The equivalent ventilation principle allows proper IAQ and acceptable levels of exposure to be maintained even if ventilation quantity is not proportional to instantenous demand. This allows for a shift of ventilation from times when the costs (e.g. thermal loads) associated with ventilation are high to those when it will be lower, extending strategies such as night flushing or pre-ventilating before expected occupancy periods.
- Lastly, smart ventilation allows building managers or homeowners to integrate information from many sources to make informed and intelligent decisions about efficient and effective ventilation. These sources of information may include outdoor conditions such as temperature, humidity, pollutant concentrations, wind speed and wind direction; indoor

> conditions such as occupancy, humidity, pollutant concentrations, and control set points (e.g., static pressure reset); whole-house conditions such as predefined schedules and the operation of other mechanical equipment; and global inputs such as community- or regional-scale demand for electricity or the price of electricity. With this information, a building manager or homeowner can then make decisions based not just on current conditions but, conceivably, also predict future conditions and weigh the appropriateness of various control strategies based on financial, energy, and air quality considerations.

One current smart ventilation controller prototype, the Residential Integrated Ventilation-Energy Controller (RIVEC) (Sherman and Walker 2011; Walker, et al. 2011), controls a whole-house ventilation system in real time by continuously calculating pollutant dose and exposure relative to a continuous ventilation system. It is able to:

1. Use timers or temperature sensors to provide ventilation when the impact is the smallest—typically shifting ventilation from times of high temperature differences to times of low temperature difference. This also results in significant peak-demand reduction (Turner, et al. 2015), which increases grid reliability
2. Account for operation of other air-moving equipment such as kitchen and bathroom exhaust fans and clothes dryers
3. Reduce ventilation during unoccupied times
4. Ventilate more at times to compensate for other times when ventilation is reduced.

The prototype was field-tested in an occupied house in Moraga, California. Experimental data were combined with a modeling approach to estimate the energy savings over the year in three Californian climate zones (temperate: Oakland; warm: Fresno; cold mountain: Mt. Shasta). The modeling showed a potential of 13%—44% annual ventilation energy savings, while preserving IAQ and eliminating 100% of the peak power associated with ventilation. RIVEC run-times were 30%—70% of nominal full-time operation. Figure 1 shows an example of RIVEC operation, showing time series of relative dose and exposure, together with the RIVEC-controlled fan operation.

Additional development (Turner and Walker 2012) led to improved and simplified control algorithms. Ventilation energy savings were estimated to be at least 40% by studying diverse climates (16 California climate zones), various home geometries, and values for envelope airtightness to give a good representation of the majority of the Californian housing stock. This reflects absolute energy savings between 500 and 7000 kWh/year per household with a peak power reduction up to 2 kW in a typical house.

More detailed information about LBNL studies on smart ventilation is given in the section *Literature review: smart ventilation performance in residential* buildings, below.

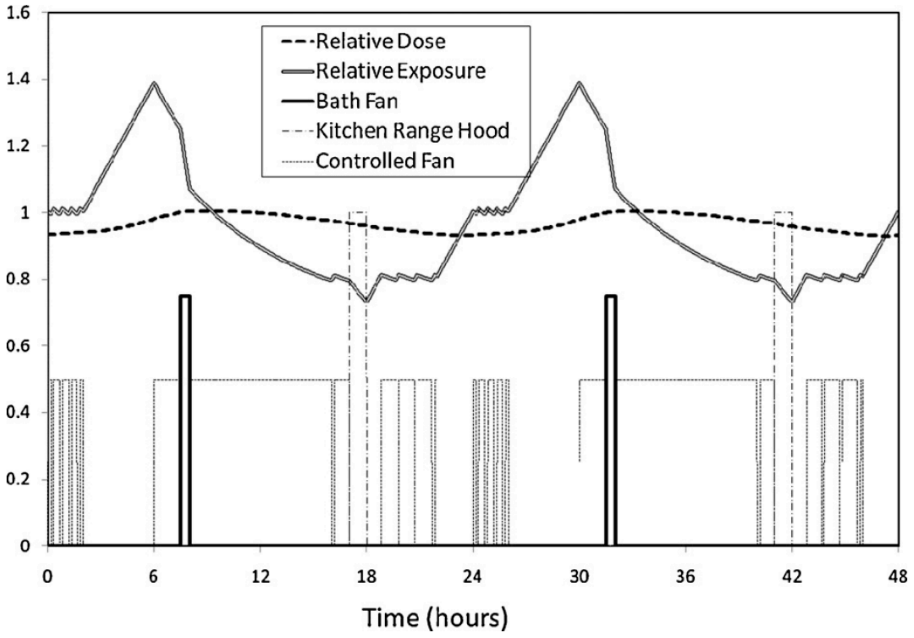


Figure 1: Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter (Sherman and Walker 2011)

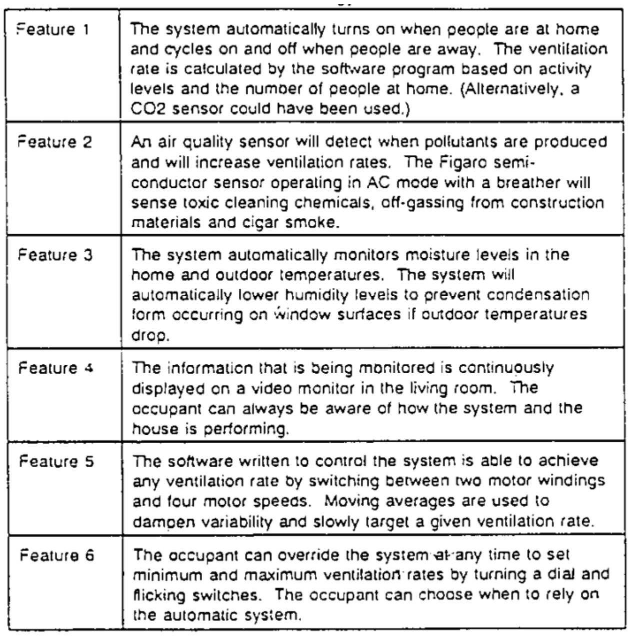
The smart ventilation concept is not fixed and has evolved concurrently with technological progress and scientific knowledge. The next generation of smart ventilation technology will be the focus of a future CEC/LBNL project, *Smart Ventilation for Advanced Californian Homes* (SVACH), that will include variation of airflows with indoor pollutant load and the use of air cleaning systems in response to outdoor pollution levels. Table 1**Error! Reference source not found.** describes the categories of data that were proposed for use inputs in the algorithms controlling the operation of the fan in the SVACH project.

Table 1: Summary description of the advanced smart ventilation strategy

	Goal	Sensor/input	Fan operation
1	Shift ventilation to times of lower temperature difference	Outdoor temperature sensor / timer	$ACH=ACH_{MIN}$ (high ΔT) ; ACH_{MAX} (low ΔT)
2	Avoid peak utility loads; especially when cooling needs are high	Timer + Utility signal	$ACH=ACH_{MIN}$
3	Reduce ventilation in empty rooms/homes	Occupancy sensors	$ACH=ACH_{MIN}$
4	Avoid outdoor pollution peaks	Outdoor pollutant (PM,O_3,HCHO) sensor Or Signals/web connection (sparetheair.com)	$ACH=ACH_{MIN}$ + air cleaning system
5	Adapt ventilation rates to indoor pollutant load, calculating instantaneous exposure and long-term dose	Indoor pollutant sensors	$ACH = f(C_i)$
6	Avoid acute exposure	Indoor pollutant sensors in kitchen (and baths)	$ACH=ACH_{MAX}$ $ACH=ACH_{MIN}$;never 0
7	Take credit for operation of other air systems (bath fans, clothes dryers, economizers, kitchen range hoods)	Electric sensors (on/off + speed detection)	$ACH= ACH_{ASHRAE} - ACH_{others}$
8	Collection of data to anticipate future adjustments	Cloud/connected platform	
9	Take credit for natural infiltration	Weather and house leakage	$ACH= ACH_{ASHRAE} - \Phi ACH_{infi}$

A previous Canadian study (Moffat, et al. 1991) proposed a ventilation strategy in an experimental house called “Helma” that could be considered a precursor to and basis for a smart ventilation strategy. The six features of this strategy are described in Table 2. Only a description of the implemented system was given in the literature: no quantitative results were found.

Table 2: Features of DCV control strategy in Helma House (Moffat, et al. 1991)



Feature 1	The system automatically turns on when people are at home and cycles on and off when people are away. The ventilation rate is calculated by the software program based on activity levels and the number of people at home. (Alternatively, a CO2 sensor could have been used.)
Feature 2	An air quality sensor will detect when pollutants are produced and will increase ventilation rates. The Figaro semi-conductor sensor operating in AC mode with a breather will sense toxic cleaning chemicals, off-gassing from construction materials and cigar smoke.
Feature 3	The system automatically monitors moisture levels in the home and outdoor temperatures. The system will automatically lower humidity levels to prevent condensation form occurring on window surfaces if outdoor temperatures drop.
Feature 4	The information that is being monitored is continuously displayed on a video monitor in the living room. The occupant can always be aware of how the system and the house is performing.
Feature 5	The software written to control the system is able to achieve any ventilation rate by switching between two motor windings and four motor speeds. Moving averages are used to dampen variability and slowly target a given ventilation rate.
Feature 6	The occupant can override the system at any time to set minimum and maximum ventilation rates by turning a dial and flicking switches. The occupant can choose when to rely on the automatic system.

The concept of DCV is a specific subset of smart ventilation. The term DCV is widely used. A clear definition of the concept is necessary to distinguish it from and compare it to the related but different concept of smart ventilation. The IEA Annex 18 defines DCV as the idea of continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson, et al. 1997). Maripuu (2011) defines a DCV system as a ventilation strategy with feedback and/or feed-forward control of the airflow rate in response to a measured demand indicator. AIVC Technical note 36 (Limb, M.J. 1992) defines a DCV strategy as “a ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced. Common pollutants are usually occupant dependent, such as, carbon dioxide, humidity or temperature.”

This study defines DCV more broadly as a ventilation strategy able to adjust real-time airflow, even if with a simple on-off strategy, as a function of some measured (demand) quantity (pollutant, humidity, CO_2, occupancy, temperature), according to a preset relationship. DCV is not a ventilation technique but a strategy that can be applied to most ventilation techniques. Ventilation based on schedules is not considered a DCV strategy, but it can be a part of a smart ventilation strategy.

Hybrid, or natural ventilation, strategies can also be considered smart ventilation strategies. Hybrid ventilation systems need to sense outdoor and indoor parameters and possibly ventilation system air flows in order to determine if the natural ventilation from wind pressure and stack effect is sufficient, or if a fan must be activated. This review includes results from some hybrid ventilation studies (Jreijiry, et al. 2007; Turner and Walker 2013; Less, et al. 2014; Chenari, et al. 2016; Lubliner, et al. 2016) but doesn’t include an extended review of hybrid ventilation strategies in residential buildings.

Three complementary components of smart ventilation in a home can be distinguished, as suggested by Schild (2007) for DCV systems and by Walker, et al. (2014) for smart ventilation:

1. Global demand control, which is called “***smart whole-house strategy***” in this report: involves detection of global variables such as regional energy demand or price of electricity, outdoor conditions, and home occupancy and modulation of ventilation airflows in response to these signals.
2. Zonal demand control, which is called “***smart room strategy***” in this report: as the name implies, responds to variables measured on a per-room or per-zone basis such as occupancy and pollutant concentration. In this strategy, ventilation should still first be considered globally and the mass balance of air in the home controlled, meaning airflow rates into and out of each room are not independent.
3. Local demand control, or “***smart source removal strategy***”: when possible, pollutants are removed at their source (e.g., sources associated with activities as cooking, showering, house cleaning, toilet use, etc.). Several studies in the literature describe these short-term emissions, including indoor particle generation by cooking, toasting, smoking, burning of candles and incense, use of hairdryers and vacuums (Ji 2010), chemical pollutants from cleaning products (Singer, et al. 2006), and NO_2 emissions during gas cooking (Boulanger, et al. 2012). The

ventilation system must be able to detect these pollutants and exhaust them from the home. Recent studies have, however, demonstrated that such devices have widely varying capture efficiencies and may capture only about half of the emitted pollutants (Singer, et al. 2012).

Energy savings from the use of smart ventilation can be of several types. These include:

1. A long-term, global decrease in the constant ventilation airflow rate provided to the home. This somewhat obvious strategy is applicable when oversized constant-speed fans are specified, which occurs in some homes.
2. A decrease in the total amount of ventilation supplied to the home over a day, month, or year through ascertainment of demand and control of systems to provide only as much ventilation as is required.
3. Shifting of ventilation to times during which less heating or cooling is needed, thus decreasing heating and/or cooling loads. The quantification of this third source of energy savings, reducing heating and cooling loads by shifting ventilation times, strongly depends on the local climate.
4. Reduction in fan power through any of these strategies by taking advantage of favorable fan characteristics. Fan brake horsepower is roughly a square function of flow rate, meaning small reductions in flow rate translate to larger reduction in fan energy use. Even if more powerful ventilation fans must be used to meet peak airflow requirements (Smart ventilation could require an increase of 34% in fan size on average (Less, et al. 2014), the fact that those peak airflows are used only if needed leads to a decrease in the energy consumption.

When the goal is saving energy, all types of energy efficiency methods need to be considered. This is especially true when smart ventilation is competitive with balanced heat recovery systems employing constant airflow rates and when electricity use is penalized through primary energy factors higher than two. Previous studies (Turner and Walker 2012) have shown typical combined fan power and conditioning energy savings of 40% available with smart ventilation strategies. Section 5 of this report, *Literature review: smart ventilation performance in residential buildings,* provides other references, most of them on DCV strategies, with estimates of energy savings between -26% and +60%.

Peak-demand reduction. Smart ventilation systems can allow modification of ventilation strategies to provide beneifits to the consumer and to the electricity provider, which don't necessarily come in the form of reduced annual energy consumption. These include:

1. Ability to reduce peak demand by ventilating more at off-peak hours and less or none during peak times.
2. Ability to integrate more renewable sources either at a utility level or that of an individual home. This is made possible by providing more demand in the form of increased ventilation at times when renewable capacity is greatest and ventilating less when renewable supply is lowest, constrained by the need to provide for acceptable IAQ. The ability for the ventilation system to react quickly to changes in price signal or renewable capacity is crucial for realization of this benefit.
3. Reduction in the cost of producing electricity via the reduction of expensive peak loads savings, which can be passed to consumers.

Theoretical background on smart ventilation metrics: Ventilation rate and indoor pollutant concentrations

Successful implementation of any smart ventilation strategy requires understanding the relationships between ventilation rates and indoor pollutant concentrations, whether concerning equilibrium relationships or temporal response. This necessitates an understanding of how exposures to contaminants of concern impact health and IAQ.

The concentration of a pollutant under a time-varying ventilation airflow rate has been described in Sherman and Wilson (1986) and used as the theoretical background of the equivalence principle for smart ventilation described in Walker, et al. (2011) and Sherman, et al. (2012) and used to quantify the preliminary air quality implications of passive stack ventilation (Mortensen, et al. 2011; Turner and Walker 2012).

Sherman and Wilson (1986) showed that the continuity equation describing the conservation of pollutant (Equation 1) can be solved with the single-zone assumption by direct inversion (Equation 2).

$$\frac{dC(t)}{dt} + A(t)C(t) = S(t)$$

Equation 1

Where *C(t)* is the indoor pollutant concentration, *t* is the time variable, *A(t)* is the air exchange rate which is the ratio between the volume airflow and the volume, and *S(t)* is the pollutant source strength including all sources and sinks of the pollutant.

$$C(t) = \int_{-\infty}^{t} S(t')e^{-\int_{t'}^{t} A(t'')dt''}dt'$$

Equation 2

Assuming the source strength is constant, concentration can be expressed as a proportional function of the instantaneous turnover time $\tau_e(t)$ (Equation 3), described as the characteristic time for the pollutant to reach steady-state (Equation 4). This **constant emission assumption** should be re-examined if the pollutant can be stored in materials, as for example formaldehyde can be, so that emission rates are assumed to respond to ventilation rate.

$$C(t) = S \cdot \tau_e(t)$$

Equation 3

$$\tau_e(t) = \int_{-\infty}^{t} e^{-\int_{t'}^{t} A(t'')dt''}dt'$$

Equation 4

Sherman and Wilson (1986) demonstrated a simple recursive relationship for discrete data in order to calculate the current value of the effective turnover time from the value at the previous time step (Equation 5), which will be used later to simplify the analysis

$$\tau_{e,i} = \frac{1 - e^{-A_i \Delta t}}{A_i} + \tau_{i-1} e^{-A_i \Delta t}$$

Equation 5

Where Δt is the time step used in the control algorithm of the smart ventilation system.

The principle of equivalent ventilation is based on the equivalent dose assumption, which states that any ventilation pattern that produces the same dose as the standard is equivalent to the standard. This can be expressed according to Equation 6.

$$k \oint C(t) o(t) dt = k \oint C_{eq} o(t) dt$$

Equation 6

Where k is a constant of proportionality depending of the specific contaminant, o(t) is a function equal to zero or one depending on whether the space is occupied or not, C_{eq} is the equivalent concentration with a constant ventilation rate.

Because the dose used here is the relative dose, the constant of proportionality can be set equal to unity without loss of generality, and with **the constant occupancy assumption** Equation 6 can be simplified in order to define the simple equivalence principle, allowing the ventilation rates and time-steps to vary as long as the long-term average of relative exposure is unity. For a constant ventilation rate A_{eq}, Equation 3 can be used to define the equivalent concentration C_{eq}.

$$C_{eq} = \frac{S_{eq}}{A_{eq}}$$

Equation 7

The **relative exposure R** can then be defined as the ratio between the time-varying concentration and the constant equivalent concentration as the product of the constant equivalent ventilation rate and the instantaneous turn-over time (Equation 9).

$$R(t) = \frac{C(t)}{C_{eq}} = A_{eq} \tau_e(t)$$

Equation 8

Combining Equation 5 and Equation 8, it is possible to express the current value of the relative exposure from the value at the previous time step.

$$R_i = \frac{A_{eq}}{A_i}\left(1 - e^{-A_i \Delta t}\right) + R_{i-1} e^{-A_i \Delta t}$$

Equation 9

The equivalence principle allows for periods when the relative exposure is above unity if ventilation rates can also be increased beyond those of the constant ventilation rate scheme in order to keep the long-term average below unity. This also requires that the ventilation fan should be sized larger than that of the base case.

In addition to long-term dose it is important to not exceed acute exposure limits. Logue, et al. (2011a) looked at ratios of acute to chronic exposure limits for residential pollutants of concern. The limiting case was found to be for particles and they determined the instantaneous value of relative exposure should not be allowed to exceed five.

This theoretical background on equivalence has been integrated into ASHRAE 62.2-2016 and is discussed in more detail later.

With a constant ventilation rate, the concentration of a pollutant emitted at a constant rate independent of other concentrations, in a single-zone building, can be greatly simplified in Equation 10 (Fisk and De Almeida 1998; Nazaroff, et al. 1993). In this equation, both chemical reaction in the indoor air and deposition phenomena are neglected.

$$\frac{dC(t)}{dt} = A_{eq}\left(C_{out} - C(t)\right) + \frac{G}{V}$$

Equation 10

Where V is the indoor volume, C_{out} *is the constant outdoor concentration, G is the constant indoor pollutant generation rate.*

It can be solved to give the transient and the steady state (equilibrium) pollutant concentrations, *C(t)* and C_{ss}, described by Equation 11 and Equation 13.

$$C(t) = (C_{t=0} - C_{\infty})e^{-\frac{t}{\tau}} + C_{\infty}$$

Equation 11

where

$$\tau = \frac{1}{A_{eq}}$$

Equation 12

$$C_{\infty} = C_{ss} = C_{out} + \frac{G}{Q_{\tau}}$$

Equation 13

In Equation 11, τ is a simplified expression of the instantaneous turnover time and can still be considered as the time constant of the system, describing the required time to reach steady state. Applying Equation 11 with a time equal to 1τ, 2τ, 3τ, etc. shows that during times equivalent to one, two, and three time constants, the pollutant concentration will increase to 63%, 86%, and 95% of the difference between the initial and the steady-state concentration, respectively.

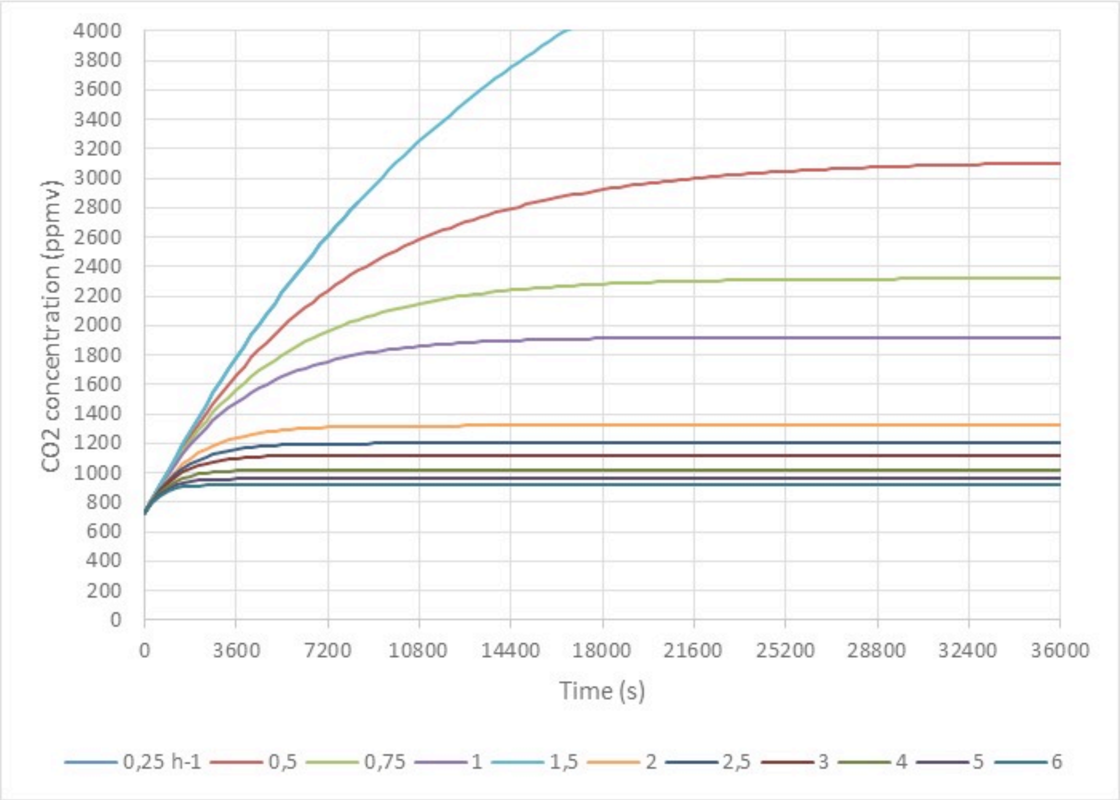


Figure 2: Indoor CO$_2$ in a 30 m^3-zone with two people operating at a low activity level (G=10 m^3/s) for air change rates ranging from 0.25 to 6 h^{-1}

The methods described above have been used in the literature, for instance to estimate ventilation rates from nocturnal CO$_2$ concentrations in bedrooms (Figure 2, Bekö, et al. 2010; Lucas, et al. 2009) and to determine the air change rates of experimental buildings or chambers with tracer gas techniques (Sherman 1990; Persily 1997; Labat, et al. 2013).

Such results and others concerning indoor air pollutants in general must be analyzed carefully, considering the following assumptions made in these equations:

- A pollutant is assumed to be emitted at a constant emission rate and the ventilation rate is assumed to be constant
- The model is a single-zone model
- Chemical reactions in the indoor air are neglected
- Removal by air cleaning systems or deposition is neglected
- The outdoor concentration is assumed to be constant, which can be a poor assumption in a polluted urban area.

Because of these assumptions, it is important to note clearly that there is no clear evidence that measuring indoor air pollutants can allow for precise determination of appropriate ventilation airflows. Rather, advanced smart ventilation proposes a change of paradigm. In this strategy, measurements of indoor air pollutants drive the adjustment of ventilation airflows directly to ensure that the final exposure is acceptable, and not to indirectly calculate airflows and check that they comply with standards.

Current "smarter" ventilation strategies – Demand Controlled Ventilation

The most common subset of smart ventilation technology in the market and in the literature is Demand Controlled Ventilation. The classification of the strategy employed in each application depends on many variables, including the type of regulation, the quantity being measured, and the types of control algorithms. For instance in Belgium, (Caillou, et al. 2014b; Moniteur, Belge 2015) DCV systems have been classified according to quantity measured (CO_2, RH, occupancy); type of space(s) (humid and/or dry); local vs. centralized control; sensor location (distributed vs. central) and airflow direction (exhaust only, supply only, balanced).

Balanced DCV system control can be centralized (at the fans) or decentralized in each room, either by the use of a supply fan in each dry room, or by the presence of dampers controlling airflow in each space. An important point is that such a smart ventilation system must be able to balance the exhaust and supply continuously.

Exhaust-only DCV system controls can also be centralized or decentralized as described above. Such systems containing only regulated air inlets wouldn't be interesting (infiltration would counteract decreased airflow through air inlets). On the other hand, such systems can be centrally regulated by measuring CO_2, for instance, in dry spaces and adjusting centralized equipment accordingly without regulation of the air inlets in these spaces. Other technologies exist, sometimes including additional exhausts in bedrooms which compensate for under-ventilation due to airtightness. Natural smart ventilation systems are, by their very nature, locally regulated.

An issue rarely investigated in the literature on smart ventilation strategies is how a fan coil unit can react to a change in airflows. Mortensen and Nielsen (2011) modeled a centralized DCV system for multi-family homes and tested several strategies for controlling a fan-coil unit. They conclude that a strategy based on resetting the static pressure at part-load conditions could reduce yearly electricity consumption by 20%—30%, compared to the commonly used control strategy with fixed static pressure.

The type of measurements used can also depend strongly on the quantity being measured (CO_2, RH, pollutants, occupancy), the type of measuring technology, the type of spaces (humid and/or dry), the type of airflow control (mechanical or electronic inlet and outlet cross-section variation, direct control of the fan speed, or control of dampers).The type of control algorithm (for example the value of the set-points and the rules for control between set-points) also constitutes an important topic and can have a large impact on IAQ and energy performance.

A later section of this report further describes the types of available sensors and their accuracy, the algorithms controlling the airflows, and the types of available smart ventilation systems on the market. Note that under the umbrella of CO_2-based DCV systems, or humidity-based DCV systems, or the smart ventilation system there can be a wide variety of systems and strategies.

3. RELEVANT PARAMETERS, SENSORS & CONTROLS STRATEGIES

Measurement-based control strategies

Although appropriate sensors are not available for all possible control inputs—particularly for individual pollutants—it is important to consider all possible variables influencing IAQ (pollutants, odors, CO_2, temperature, humidity, occupancy) because future sensor development may make some strategies more viable.

Pollutants of concern in residences from a smart ventilation perspective

As argued above, ventilation is not a panacea capable of ensuring good IAQ but should be considered a method to dilute remaining pollutants once they have been reduced at their source. With this in mind, it is important to separate from among the many pollutants of concern in residential buildings. From this perspective, the recent AIVC technical note 68 "Residential ventilation and health" (Borsboom, et al. 2016) proposes that tobacco smoke and radon should not be considered in establishing ventilation standards. Although they were clearly pointed out in a cumulative risk assessment study (WHO 2011) and in an impact assessment of chronic residential exposure (Logue, et al. 2011b), these pollutants are more impacted by home characteristics (such as the depressurization of subfloors for radon) and occupant behavior than by ventilation strategies (Borsboom, et al. 2016). It is possible that carbon monoxide is, similarly, not a pollutant suitable for control by ventilation as shown by the results in Emmerich, et al. (2005) in which adjusting the stove had a bigger impact than changes in air flows.

AIVC technical note 68 considered existing guidelines and standards, hazard assessment, cumulative risk assessment and impact assessment exposure studies, and proposed a selection of high-priority pollutants for residential ventilation standards. For chronic exposure, they identify the following high-priority pollutants, ranked by population impact: 1-particles, 2-mold and moisture, 3-formaldehyde, 4-acrolein. For acute exposure, they propose the following pollutants without ranking them because of the lack of information in the literature: acrolein, chloroform, carbon monoxide, formaldehyde, NO_2, $PM_{2.5}$ (Logue, et al. 2011a). Also, even if humidity itself is not a pollutant, it must be considered in an exposure and health analysis in homes because of mold development risks.

Table 3: Selection of pollutants in residential ventilation standards (Borsboom, et al. 2016)

High-priority pollutants for chronic exposure (ranked by population impact)	High-priority pollutants for acute exposure
1. Particulate matter	Acrolein
2. Mold and moisture	Chloroform
3. Formaldehyde	Carbon monoxide
4. Acrolein	Formaldehyde
	NO_2
	$PM_{2.5}$

The conclusions of IEA Annex 18 "Demand-controlled ventilating systems" (Mansson, et al. 1997), defined the important pollutants or indicators from a DCV perspective, defined as requiring the highest ventilation rate in order to maintain their concentration below acceptable thresholds. Then, the use of DCV is justified if the driving pollutants emission rates: 1) are significantly transient (e.g., variable occupancy), 2) have a known maximum pollution emission, and 3) are unpredictable: time and location of sources cannot be scheduled. Fisk and De Almeida (1998) added the following condition to make the use of DCV strategies relevant: that the building has one driving pollutant at the most.

In a report from this same IEA Annex 18 (Raatschen 1990), authors contend that particles cannot drive ventilation control approaches. They suggest managing their concentrations through complementary filtration systems—either by filtering indoor air with high efficiency filters treating recirculation air or by filtration of outdoor air. This suggestion is confirmed by Sherman, et al. (2012) citing a previous study (Weisel, et al. 2005) that had shown that, in 100 houses in three cities in the United States, only half of the homes had indoor $PM_{2.5}$ concentrations greater than outdoor concentrations. This shows that additional ventilation may increase $PM_{2.5}$ exposure (e.g., through open windows).

Nevertheless, other research on envelope filtration and deposition shows that extra outdoor air can enter the space at lower-than-outdoor concentrations. In the most popular ventilation system in the United States, which includes exhaust-only ventilation control and no trickle ventilator, outdoor air enters the home through leaks in the envelope. This can lead to an significant infiltration of outdoor particles with penetration factors highly dependent on envelope leakage, the size of the particles, and the size of the leaks (Liu and Nazaroff 2001, 2003; Stephens and Siegel 2012), with typical penetration values for a tight new home of only a few percent (roughly equivalent to a moderate or MERV 8/9 HVAC system filter). Such results are unexpected in most new European homes, which are equipped with trickle ventilators.

In homes equipped with a balanced ventilation system and/or a recirculating air system, the use of efficient filters can also decrease particle concentrations in the home. This issue has been recognized in Addendum k of the current version of ASHRAE 62.2, which allows for a dwelling unit ventilation rate reduction of up to 20% for good filters with minimum clean air delivery rates. The EN779: 2012 standard requires class F7 filters on supply ducts. This EN779 classification is based on the requirement that filtration effectiveness for 0.4 µm particles must be in the 80%—90% range for an average value and higher than 35% as a minimum value. The question of the effectiveness of those filters once installed is an issue of concern not addressed in this report.

Mansson, et al. (1997) suggests that individual VOCs are inappropriate for DCV applications because:

1. The sensitivity of humans to VOCs is unknown (except for select few, such as formaldehyde and acrolein)
2. The concentrations in non-industrial buildings are often well below hygienic limit values
3. Susceptibility to VOCs depends on the individual
4. The composition of VOCs varies from building to building.

The authors instead recommend minimizing emission rates of such chemicals in buildings. These previous recommendations should be considered carefully because the context has changed since their publication in the early 1990s. Specifically, the development of building materials and furnishings has resulted in increased VOC emissions and VOC concentrations measured in non-industrial buildings (Logue, et al. 2011a).

Fisk and De Almeida (1998) recommend using VOC sensors in conjunction with CO_2 sensors. They underlined the difficulties of doing this resulting from the high variability in toxicity of different VOCs as well as the lack of data on acceptable levels for mixtures of VOCs. Nevertheless, they consider that VOC-based DCV strategies could at least avoid peak exposure during scheduled activities such as painting or installation of carpeting. More than 300 VOCs have been measured in indoor air; the total VOC (TVOC) concentration is often used in literature and sensor technologies to simply characterize the total concentration with a single parameter. Several authors have highlighted the lack of a precise definition for this variable and of a standardized procedure for its calculation (Mølhave, et al. 1997).

A synthesis of the literature review suggests that the following pollutants can be considered the most relevant in a smart ventilation approach, disregarding the availability and the accuracy of the corresponding sensors (Table 4).

Table 4: Selection from the literature of relevant pollutant for smart ventilation strategies

Relevant pollutants (chronic exposure)	Relevant pollutants (acute exposure)
1. Particulate matter	Acrolein
2. Mold and moisture	Chloroform
3. Formaldehyde	Formaldehyde
4. Acrolein	NO_2
	$PM_{2.5}$

Odors, CO_2 and humidity

IAQ has also been subjectively evaluated by assessing occupant satisfaction (CEN 2007; Fanger, et al. 1988). Indoor air variables such as odors, temperature, CO_2, and humidity strongly correlate to occupant activities, and can also be important to consider in smart ventilation approaches. CO_2 and relative humidity are the most commonly used parameters in DCV systems. Research on their ability to represent overall IAQ, including their correlation with other types of indoor pollutants, is only minimally available in the literature.

CO_2 is often used in DCV strategies, not to prevent negative health effects directly attributed to it, but because it can be representative of other parameters such as concentrations of bio effluents and other indoor air pollutants or ventilation rates.

Several studies have shown that health effects directly attributable to CO_2 are minimal at concentrations observed in indoor environments, which are commonly in the range of 350 ppm—2000 ppm, but which have been measured at values of 6000 ppm in bedrooms during night periods between 2 am and 5 am (Kirchner, et al. 2006). The American Conference of Governmental Industrial Hygienists considers 5000 ppm the threshold for an 8-hour exposure in indoor environments (ACGIH 2011). The French Agency for Food, Environmental and Occupational Health Safety published results of an analysis of available CO_2 epidemiologic and toxicology studies, and of studies on CO_2's effects on health, performance, and comfort (ANSES 2013). Results concluded that the only health threshold on which several studies converge is an exposure of 10,000 ppm for 30 minutes, corresponding to a respiratory acidosis for a healthy adult with a modest amount of physical load.

The analysis does mention an experimental study (Satish, et al. 2012) of 22 human subjects that suggested an effect on psychomotricity performance above 1,000 ppm attributable to CO_2 but which must still be further investigated according to the authors. The recent study of Zhang, et al. (2016) shows different results. Twenty-five human subjects were exposed for 255 minutes first to only CO_2 (at either 1,000 ppm or 3000 ppm) and then to bioeffluents and corresponding CO_2 levels (of either 1,000 ppm or 3,000 ppm). No statistically significant effects were observed in the first case; the second showed an increase in reported headaches, fatigue, sleepiness, and difficulty in thinking clearly. The authors conclude that moderate concentrations of bioeffluents, but not CO_2, will affect occupants at typical indoor exposure levels. This can also be seen as a study of dose-response relationships between human bioeffluents, including CO_2, and indicators of health, wellbeing, and performance. The authors concluded that complementary studies should still be performed on sensitive groups such as the elderly and infants.

Other studies of specific applications such as bomb shelters, submarines (de Gids and Heijnen 2011), and high-risk industrial facilities and homes (French Ministry For Ecology 2007) have used higher threshold values for CO_2. They confirm that CO_2 is not dangerous by itself at the levels measured in residences. All these threshold values are summarized in Table 5.

Table 5: CO_2 concentrations thresholds in the literature

Effects	CO_2 threshold (ppm)	Comments	Source
Comfort	1000	To prevent odors from bio effluents	(Von Pettenkofer 1858)
No effect	3000 for 255 min	Pure CO_2	(Zhang, et al. 2016)
Increasing intensity of reported headache, fatigue, sleepiness, and difficulty in thinking clearly	3000 for 255 min	Metabolic CO_2+ bio-effluents	(Zhang, et al. 2016)
Hygienist threshold in indoor environments	5000	For 8 hour exposure	(ACGIH 2011)
Respiratory acidosis for a healthy adult with a modest amount of physical load	10.000	For 30 minutes	Several studies reviewed in (ANSES 2013)
Bomb shelters	20.000		(de Gids and Heijnen 2011)
Submarine	30.000		(de Gids and Heijnen 2011)
Irreversible effects	50.000		(French Ministry For Ecology 2007)
Mortality level **1% lethal effects threshold**	100.000		(de Gids and Heijnen 2011) (French Ministry For Ecology 2007)
5% lethal effects threshold	200.000		(French Ministry For Ecology 2007)

Nevertheless, several authors agree that CO_2 is a good indicator of occupant emissions including bio-emissions and odors (Von Pettenkofer 1858; Cain and Berglund 1979; Cain, et al. 1983; Fanger, et al. 1988) as well as some VOC and particle emissions from office equipment used by occupants (Emmerich and Persily 2001; Fisk and De Almeida 1998; Mansson, et al. 1997). Von Pettenkofer (1858) proposed 1,000 ppm, assuming that the outside concentration was 500 ppm, as a threshold for CO_2 level to prevent odors from bioeffluents. The recent study of Zhang, et al. (2016) suggests that indicators based on CO_2 are a good basis for IAQ standards and ventilation requirements where the most important sources of pollution are the occupants and their activities.

Recent studies (ANSES 2013; Ramalho, et al. 2015) have demonstrated that CO_2 concentrations in homes were significantly correlated with concentrations of other pollutants such as acetaldehyde, formaldehyde, benzene, acrolein, $PM_{2.5}$, and PM_{10} but that the correlations were weak (sometimes very weak). Moreover, in these field studies, CO_2 was measured every 10 minutes while other pollutant measurements were passively performed over seven days. These conclusions should also be considered carefully in the context of smart ventilation strategies. Research on this field needs to be consolidated before concluding with a high degree of confidence that CO_2 concentrations are significantly correlated with other indoor air pollutants for smart ventilation applications.

In his review on DCV, Raatschen (1990) affirms that, according to the analyzed literature, “there is no doubt that CO_2 is the best gas to use in a ventilation system when a building is occupied and no other large pollution sources such as smokers are present.” Ten years later, in their review on CO_2-based DCV, Emmerich and Persily (2001) underline the limitation of using CO_2 because of its inadequacy as an overall indicator of IAQ, especially for pollutant emission from sources other than occupants such as building materials and furnishings. This is confirmed by other authors in the literature (Raatschen and Trepte 1987; Emmerich, et al. 1994; Fisk and De Almeida 1998). Nevertheless, Emmerich and Persily (2001) justify the use of CO_2 as an indicator of ventilation rate per person based on regulations or standards. Indeed, these controls have largely been based on CO_2, and the threshold of 1000 ppm (Von Pettenkofer 1858) and the relationship between indoor CO_2 concentration and ventilation rates is well understood and described in (Persily 1997; Persily and Dols 1990), as discussed earlier in this report.

Humidity is one of the prioritized pollutants of concern identified in Table 3. Unlike CO_2, humidity is, itself, interesting as an input variable for controlling smart ventilation systems. Variables associated with humidity are relative humidity and absolute humidity. Relative humidity is the ratio of water vapor in the air at a given temperature to the water vapor in saturated air at the same temperature. Absolute humidity is the amount of water vapor in the air per unit mass of air. Relative humidity is the most commonly measured parameter. Relative humidity is more difficult to work within the context of a control strategy, as IAQ concerns necessitate controlling both the value (recommended 30%—70%) (CEN 2007) and the time it remains above a threshold. The threshold value depends on climate and can be fixed at values as low as 45%, as is done in Nordic countries in order to prevent growth of house dust mites (Nielsen 1992). Moreover, from a health perspective, only a metric combining humidity, time above a limit, and temperature can adequately quantify the condensation risk. Finally, from a comfort perspective, a metric combining temperature and humidity must be used, as shown by the Mollier diagram. CEN (2007) recommends that absolute humidity stays below 12 g/kg.

This research also set out to answer the related question of whether relative humidity can be representative of other parameters, such as occupant-related emissions. The literature review showed that some studies found a positive correlation and other studies found a negative one. The moisture buffering effect and the dependence of relative humidity on temperature and air moisture content reduces the relationship between moisture and occupancy. As a result, several studies (Anon 1983; Barthez and Soupault 1984; Sheltair Scientific, Ltd. 1988; Parekh and Riley 1991) show a poor relationship between relative humidity and the occupant load in a room. Fisk and De Almeida (1998) confirmed that other residential pollutants are not correlated with humidity. A two-week monitoring study of a house reported by Mansson (1993) showed no correlation between the value given by an RH sensor and a mixed gas sensor in the living room.

On a related note, Van den Bossche, et al. (2007) showed that taking into account the moisture buffering effects in modeling studies of the efficiency of humidity-controlled ventilation systems would very slightly (by 0.75%) lower the energy performance of those systems. Woloszyn, et al. (2009) confirmed that taking into account the buffering effect does not affect the global performance of humidity-based DCV systems, but that it is possible, by the combined effect of ventilation and buffering by wood, to keep indoor RH at a very stable level (between 43% and 59%).

In contrast, the Performance Project (Air, H. 2010; Bernard 2009) highlighted a strong correlation between CO_2 concentrations and the relative humidity levels measured in 31 apartments over the duration of more than two complete heating seasons. To quantify this correlation, the authors plotted the average degree of opening of humidity-controlled air inlets against CO_2 concentrations between 300 ppm and 2000 ppm, and observed a clear correlation between degree of inlet opening and concentration of CO_2 in bedrooms. These results confirm previous ones from 26 apartments equipped with humidity-controlled ventilation in France, Belgium, and the Netherlands (Mansson 1993). Moffat, et al. (1991) observed in one house that CO_2 levels and relative humidity tend to track each other, but that CO_2 peaks occurred three hours later. This was confirmed by research by Parekh and Riley (1991). Raatschen and Trepte (1987) showed that, in a three-occupant living-room, air change rates necessary to remove moisture are higher than those necessary to keep CO_2 concentrations below 1000 ppm. They showed also that in an unoccupied bathroom the hourly air change rate needed to remove moisture was higher than the one needed to remove formaldehyde; the opposite was observed in the living room. In residential buildings, Raatschen and Trepte conclude that the need for ventilation in occupied rooms is dominated by moisture; in unoccupied rooms the need to ventilate for formaldehyde control is more important and must be considered when setting minimum airflows.

The correlation between absolute humidity and CO_2 might be stronger than the correlation between relative humidity and CO_2; however, it has a lag time due to sorption characteristics of the building materials and furniture in the home (Moffat, et al. 1991; Savin and Jardinier 2009).

Odor, when defined as excluding olfactory irritation, is regarded more as comfort parameter rather than a health impact. Because occupant sensitivity to odors is much lower for an “acclimated” occupant (Olesen 2007), this parameter is considered less important for residential ventilation applications (Figure 3). Moreover, design requirements such as the presence of an exhaust device in the bathroom and kitchen can easily control odor to avoid discomfort, and, unlike most other pollutants, occupants can easily sense odors. Nevertheless, Sherman, et al. (2012) contend that body odors constitute a special issue because they are diffuse in the home and suggest that the relative exposure should stay below a value R_{occ}, a function of occupant density per 100 m² (Occ, Equation 14). In Belgium, odors are taken into account in DCV performance evaluation through the modeling of tracer gas emission in bathrooms (Caillou, et al. 2014b).

$$R_{occ} = 1.5 + {}^{6}\!/_{Occ}$$

Equation 14

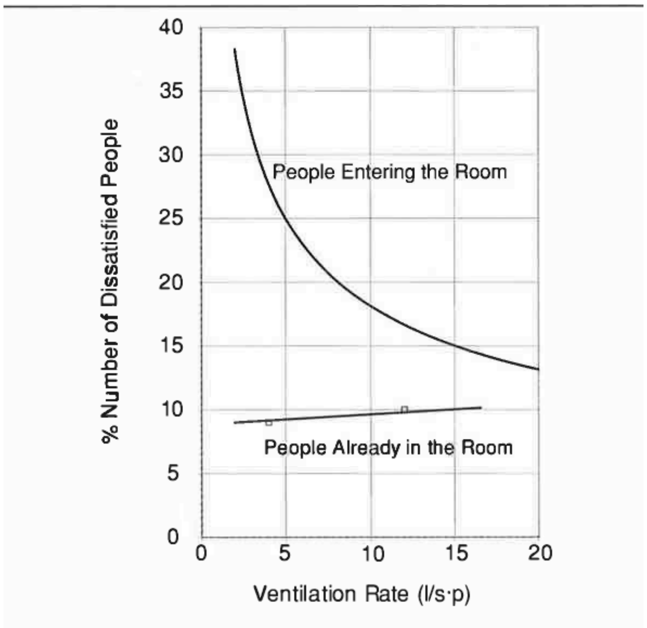


Figure 3: Relationship between ventilation rate and odor dissatisfaction for visitors and occupants (Mansson, et al. 1997)

Temperature has been recognized as the primary parameter for quantifying comfort (Fanger 1974). Because of its impact on relative humidity and on indoor pollutant concentrations such as formaldehyde, temperature is clearly a parameter of interest when considering ventilation. Researchers have investigated temperature as a suitable variable for controlling ventilation in homes. Homod and Sahari (2013) developed a model to study the performance of natural and hybrid ventilation systems controlled by indoor temperatures and Predicited Mean Vote (PMV) in a single-family house in Kuala Lumpur, Malaysia. By turning off the air conditioning when it is not needed, 24 hour cooling needs were reduced at least 8% in the cross-flow strategy and at least 28% in the optimized hybrid strategy. Nevertheless, indoor temperature-controlled ventilation is not further investigated here, because smart ventilation is clearly not focused on comfort only.

Occupancy

Because CO_2 or relative humidity measurements are often considered indicators of occupancy in the literature, some wish to use it to directly measuring occupancy. Moffat, et al. (1991) concludes that passive infrared activity sensors had a poor short-term correlation with CO_2 but an excellent long-term correlation.

A strategy based on occupancy sensing in bathrooms has been recognized as the most efficient way to remove short emissions in such a room at their source (Caillou, et al. 2014b). These authors showed also that using occupancy sensors in all dry rooms (bed- and living-rooms) can save approximately 33% less energy than a strategy based on monitorin CO_2 in dry rooms, but 20% more energy than a reference system.

Availability and reliability of pollutant-and occupancy-sensors

In smart ventilation strategies, sensors need to have a real-time output signal to allow the system to react and adjust the airflow. The choice of sensor could depend on the existing ventilation system. In 2005, *State-of-the art in sensor technology for demand-controlled ventilation* was published by Won and Yang, which included previous studies by Fahlen, et al. (1991); Mansson, et al. (1997); De Almeida and Fisk (1997); and Emmerich and Persily (2001). This extensive review of the state of the art included sensors for CO_2, humidity, VOCs, formaldehyde, NO_2, SO_2, ozone, particulate matter (PM) and radon. Won and Yang recommended that selection of sensors for DCV applications consider three criteria:

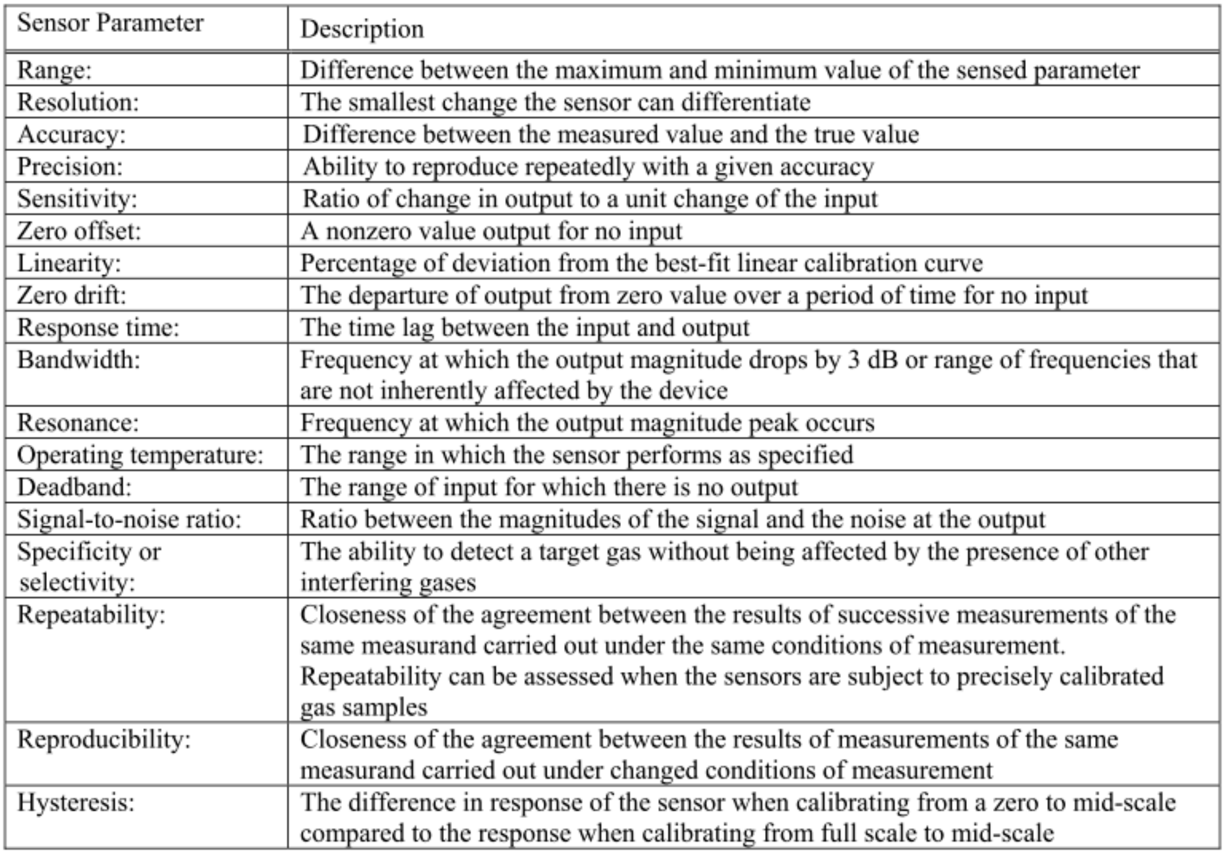
1. **Performance**: whether the performance range can cover the typical IAQ range or guideline thresholds, whether resolution can meet the suggested level, and if the calibration frequency is not more than once a year
2. **Cost**: if the sensor is affordable
3. **IAQ**: if, for this pollutant, there is a greater risk that typical indoor levels exceed IAQ guideline thresholds.

Won and Yang's report was updated in 2011 with modifications to sections on sensors for formaldehyde, radon, and VOCs, titled *Commercial IAQ Sensors and their Performance Requirements for Demand-Controlled Ventilation*. The following sections summarize the content of that report and:

1. Give an overview as it relates to residential buildings
2. Add to it a discussion of products available in other parts of the world such as in Europe
3. Review recent studies including *Real-time sensors for indoor air quality monitoring and challenges ahead in deploying them to urban buildings* (Kumar, et al. 2016)
4. Include some dynamic IAQ sensors, which could be implemented in smart ventilation systems in the short, medium, or long term.

The word "sensor" can refer to a single direct sensor or several components (filters, amplifiers, modulators of other signals) (Bishop 2002). Many factors can affect sensor performance and should be considered in the choice of a sensor for smart ventilation applications (Table 6), along with other factors such as size, extent of signal conditioning, reliability, robustness, maintainability, and cost (Bishop 2002).

Table 6: Sensor Summary (Won and Yang 2005) from (Bishop 2002)



Sensor Parameter	Description
Range:	Difference between the maximum and minimum value of the sensed parameter
Resolution:	The smallest change the sensor can differentiate
Accuracy:	Difference between the measured value and the true value
Precision:	Ability to reproduce repeatedly with a given accuracy
Sensitivity:	Ratio of change in output to a unit change of the input
Zero offset:	A nonzero value output for no input
Linearity:	Percentage of deviation from the best-fit linear calibration curve
Zero drift:	The departure of output from zero value over a period of time for no input
Response time:	The time lag between the input and output
Bandwidth:	Frequency at which the output magnitude drops by 3 dB or range of frequencies that are not inherently affected by the device
Resonance:	Frequency at which the output magnitude peak occurs
Operating temperature:	The range in which the sensor performs as specified
Deadband:	The range of input for which there is no output
Signal-to-noise ratio:	Ratio between the magnitudes of the signal and the noise at the output
Specificity or selectivity:	The ability to detect a target gas without being affected by the presence of other interfering gases
Repeatability:	Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. Repeatability can be assessed when the sensors are subject to precisely calibrated gas samples
Reproducibility:	Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement
Hysteresis:	The difference in response of the sensor when calibrating from a zero to mid-scale compared to the response when calibrating from full scale to mid-scale

CO_2 sensor technologies are not new; DCV strategies have existed for more than 30 years. Available technologies are mostly non-dispersive infrared sensors (called also photometric CO_2 sensors), but also include photoacoustic CO_2 sensors.

The first extensive study validating the performance of such sensors in residences was published by Fahlen, et al. (1991). They tested two CO_2 sensors, nine humidity sensors, and five mixed-gas sensors in lab tests under variable environmental conditions. CO_2 sensor performance was found to be acceptable for ventilation applications. The authors identified problems due to the time-consuming calibration process and the sensitivity to humidity at low CO_2 levels. The need for periodic calibration of CO_2 sensors was stressed in the literature, which contains several accounts of sensor drift over time (Fisk, et al. 2006; Kesselring, et al. 1993).

Next, Fisk (2010) studied the accuracy of 208 single-location CO_2 sensors in 34 commercial buildings. For 90 of these sensors, the accuracy was checked at multiple CO_2 concentrations using primary standard calibration gases. Even if the average errors were small (i.e., 26 ppm and 9 ppm, respectively, at 760 and 1,010 ppm), they found occasional respective absolute of errors of 118 at 760 ppm (16%) and 138 at 1,010 ppm (14%). At 760 ppm, 47% of the sensors had error magnitudes greater than 75 ppm and 37% greater than 100 ppm. At 1,010 ppm, 19% of sensors had errors greater than 200 ppm and 13% greater than 300 ppm. Authors showed that there were also statistically significant differences between different technologies and manufacturers, and that sensor age was not statistically significant.

Complementary laboratory testing of nine sensors with large measurement errors could not prove the causes of sensor failures. These observations were confirmed by another study by the Iowa Energy Center (Shrestha and Maxwell 2009), which tested the accuracy of 15 models of new, single-location CO_2 sensors. They reported numerous errors greater than 75 ppm; cases of errors greater than 200 ppm were not uncommon.

More recently, semiconductor-based (metal oxide) sensors are being developed, though not yet commercialized (Barsan, et al. 2007; Presmanes 2015).

Unlike other pollutant sensors, CO_2 sensors can be considered quite easy to calibrate, since gas mixtures with necessary CO_2 concentrations can be accurately and readily manufactured using pure CO_2.

In the Belgian regulation for DCV strategies, a CO_2-based DCV system must include CO_2 sensors with a maximum uncertainty of 40 ppm + 5% of the target value, in the 300 ppm—1,200 ppm] range (Moniteur Belge 2015). The non-residential requirements of California's Title 24 regulations state that "the CO_2 sensors must be factory certified to have an accuracy of no less than 75 ppm over a five-year period without recalibration in the field."

The 2005 market survey (Won and Yang, 2005) gave precise product references with prices around $500 CAD (~$400 US, ~350 EUR) for sensors in the range [0 ppm—2,000 ppm] with an accuracy of ±50 ppm, often with a self-calibration system. Response times were found to be between 1 and 2 minutes. Adding temperature and RH sensors increase the price to more than $2,000 CAD. Costs were evaluated in 2011 (Mortensen 2011) and found to be approximately 3000 DKK$ (~$450 US, ~400 EUR).

Humidity sensors are not new either, as such DCV strategies have been used at large scale, notably in France, for more than 30 years.

Won and Yang's review (2005) refers to a previous study (Roveti 2001) that reviews the wide variety of sensors available on the market. Formerly, mechanical methods used the dimensional change in characteristics of fibers such as hair, plastics, or wood to quantify humidity. Won and Yang note that, in most cases, mechanical methods of measuring humidity have been replaced by electronic RH sensors, thanks to progress in semiconductor technologies. According to Won and Yang, such RH sensors have greater accuracy; this is not confirmed by other authors in the literature, as described below. Other available technologies include capacitive sensors, resistive humidity sensors, and thermal conductivity sensors (measuring the absolute humidity) and are also presented in Won and Yang's review with their limits. Won and Yang also discusses dew-point sensors that are used to quantify the absolute humidity.

In France, for more than 30 years, the market has largely been dominated by humidity-based DCV systems with mechanically variable inlet and outlet cross-sections (Savin, et al. 2014). Advanced materials are used, such as polyamidic fibre, which varies in length with the relative humidity. Polyamidic fibres are not classical sensors, but they could be described as "sensor-actuators"—worthwhile in a whole house ventilation strategy, but not interesting just as sensors. The proper operation of this type of inlet/outlet has been deomonstrated in laboratories and the field by the project Performance (Air, H. 2010; Bernard 2009), through measurements over two complete heating seasons in 31 new occupied apartments. An analysis of the correlation between the area of each outlet and the relative humidity of the room was performed, at each 1-minute time-step. The measurements showed good performance when compared to the tolerances given by the manufacturer and to the measurements performed in the laboratory. Depending on the manufacturer, lifetimes could be up to 30 years, including a warranty of approximately 10 years, without need for recalibration. These products are used not only in France but also in other European countries such as Spain, Poland, and Germany.

Classical humidity sensors are already used for air conditioning applications in residential buildings and are commercially available for use with smart ventilation strategies with an accuracy of ±3 % (Walker, et al. 2014). Belgian regulations for DCV strategies state that a relative humidity DCV system must include relative humidity sensors, each with a maximum uncertainty of 5% of the target value, in the 10%—90% RH range (Moniteur Belge 2015).

In their market survey, Won and Yang (2005) found that humidity sensors were usually combined with temperature sensors. The average measurement range was found to be between 0% and 90% with an accuracy of +-2%—3%. A majority were thin film capacitive sensors, with a cost below that of CO_2 sensors ($500 CAD, ~$400 US, ~350 EUR). Dew-point sensor cost was found to be in the range $100—$5,000 CAD, depending on the technology. A sensor requiring calibration every 1-2 years cost $100—$250 CAD. The humidity sensor-actuators described above are not reported in this market survey. They are very low-cost with a long warranty (10 years)[1].

Particle sensors are used to control ventilation rates in buildings or rooms with high particle emissions (e.g., smoking rooms). The technology behind them consists of optical particle counters, working on a light scattering principle, with laser power used depending on the size of the particle being counted. Faulkner, et al. (1996) tested such a $PM_{2.5}$ sensor in a clean room, at a time when an optical particle counter costing 2,500 USD was considered "low-cost." The price of such existing sensors can be up to several thousand dollars for large residential applications (Coeudevez 2016; Fisk and De Almeida 1998; Won and Yang 2005) but their price may decrease with recent technological developments. Semple, et al. (2013) recently validated a "low-cost" (400 USD) $PM_{2.5}$ optical counter, monitoring with a time-step of one minute over 24 hours in 34 homes, comparing results with those of another more expensive sensor (3,000 USD). Semple underlined the necessity for such a photometric device to be calibrated against a gravimetric reference standard. The most powerful lasers are used to count particles under 0.1 µm (Won and Yang 2005) with costs starting at 10,000 USD. Kumar, et al. (2016) further investigated nanoparticle sensors.

VOC sensing in demand-controlled ventilation is relatively new because, until recently, VOCs could not be measured separately; multi-gas sensors were used instead. VOC sensors have notably been used in the car industry to monitor cabin air, and they are progressively being used more in buildings. Available technologies include electrochemical, infrared, catalytic bead, photo ionization, solid state, and surface acoustic wave sensors (detailed in Won and Yang 2005). Won and Schleibinger (2011) noted cross-sensitivity (also referred to as specificity or interference) as a major issue for VOC sensors. Datasheets

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[1] http://www.e-novelec.fr/303-entrees-d-air

published by manufacturers allow quantification of this cross-sensitivity issue. They propose a project to calculate cross-sensitivity requirements for formaldehyde and toluene sensors. Common technologies are either semiconducting metal oxide (SMO) sensors or infra-red optical sensors (Galatsis and Wlodarsk 2006), which are used for better selectivity between pollutants.

The selectivity issue with SMO sensors has also been highlighted by (Barsan, et al. 2007). Fundamental theory behind SMO sensors was described in Yamazoe and Shimanoe (2009). A semi-conductor VOC sensor was tested in a house (Moffat, et al. 1991) and appeared to be a good indicator of overall IAQ for DCV applications. The authors point out the need to periodically flush the sampling chamber in the sensor to zero. In their laboratory testing, Fahlen, et al. (1991) found various levels of performance among the five sensors tested. They were all found to be sensitive to humidity. A Total Volitile Organic Compound (TVOC) sensor and a formaldehyde sensor were tested to evaluate a DCV strategy in a lecture room in Hong Kong and had accuracies of 10% of the reading or 20 ppb in the measurement range 0 ppb—999 ppb and 10 μppm in the range of 0 ppm—2 ppm (Chao, et al. 2004). Caron, et al. (2016) experimentally validated two SMO sensors with decay tests of pure toluene, o-xylene, acetone, acetaldehyde, and formaldehyde. They drew positive conclusions about the sensors' ability to describe single VOC concentrations compared to analytical measurements, but underlined the problem with mixed VOC concentrations.

In their market survey, Won and Yang (2005) found that the most commonly used sensors were SMO sensors and photoionization detectors (PID), but that they were still not completely adapted to building ventilation applications. They consider the SMO sensors less expensive (\$600—\$1200 CAD, ~\$480—\$960 USD, ~420—840 EUR) with better selectivity of individual VOCs but with an inadequate range of measurement (1 ppm—10,000 ppm for TVOCs or 5 ppm—5,000 ppm for an individual VOC). The PID-based sensors have some advantages in the 0.02 ppm—20 ppm measurement range, even if they are considered less selective, and are much more expensive (\$5000 CAD—\$7000 CAD). This high price is also explained by the fact that they include relative humidity, temperature and/or CO_2-monitoring capability. Six years later, the same researchers found same level of performance for lower-priced PID-based sensors (\$1,500—\$5,000 CAD) and better performance for SMO-sensors with a detection range of 0 ppm—50 ppm, again for lower prices (Won and Schleibinger 2011). They found that those sensors have a response time of around one minute with a resolution still about a factor of 20 different from that required (100 ppb at best for a 5 ppb requirement). They concluded that no commercial VOC sensor was yet precise and specific enough for ventilation applications.

Kumar, et al. (2016) reviewed compact, light-weight, inexpensive sensors up to \$500 USD, with some under \$100 USD measuring carbon monoxide, benzene, and VOCs. Advanced technologies have been reviewed (Kumar, et al. 2016), including a miniaturized gas chromatography system for monitoring single volatile compounds in indoor air (Zampolli, et al. 2005).

In Belgium, those wishing to employ a VOC sensor in bathrooms in a DCV system must prove that there is a correlation between the measured signal and human occupancy (Moniteur Belge 2015). Before beginning to study implementation of such a sensor on a large scale, Caillou, et al. (2014b) consulted several international experts in the field. In 2014, VOC-sensing technology was considered mature enough to be integrated into DCV technologies. A commonly cited problem is the difficulty associated with directly controlling and calibrating such a sensor, as opposed to a CO_2 sensor, for instance.

Formaldehyde sensors were examined in an important part of the Won and Yang's review (2005), as formaldehyde has been specifically identified as a priority pollutant (Table 3). They described that the most appropriate method is photoelectric photometry. They report a detection limit of 0.05 ppm within a sampling time of five minutes, with no interference from various aldehydes and other VOCs. In their market analysis, they found three available technologies: SMO, electrochemical, and photoelectric. The last one provided the best sensitivity (0 ppm—0.06 ppm or 0 ppm—1 ppm) at relatively low cost ($1200 CAD, ~$960 USD, ~840 EUR). Six years later, they believed electrochemical sensors and photoelectric photometry sensors may be applicable for DCV applications (Won and Schleibinger 2011), with a similar detection range 0—5 ppb or 0—10 ppb. Interference was found to be lower than photoelectric photometry sensors, but with the disadvantage of replacing the coloring tape or tab every month. Such sensors had a cost between $1,000 CAD and $7,000 CAD.

The formaldehyde sensors under development seem to be improving (Chung, et al. 2013) but are still rarely tested in typical indoor air environment with hundreds of other compounds.

NO_2 sensors have been commonly used, combined with CO-sensors, for non-residential application such as ventilating parking areas. Won and Yang (2005) reported that three available technologies are available: electrochemical, chemiluminescence, and colorimetric-sensors. Electrochemical technology was found to be the cheapest ($500 CAD—$1,000 CAD, ~$400—$800 USD, ~350—$700 EUR) while offering a large detection range of 0-20 ppm. The two technologies have much higher costs (more than $10,000 CAD) but offer detection ranges of 0-5 ppb and 50 ppb, respectively. Calibration is recommended every six months with a pure standard gas and costs $200 CAD—$500 CAD. Recent research showed a cross-sensitivity issue for the electrochemical sensors with the NO compound (Viricelle, et al. 2016).

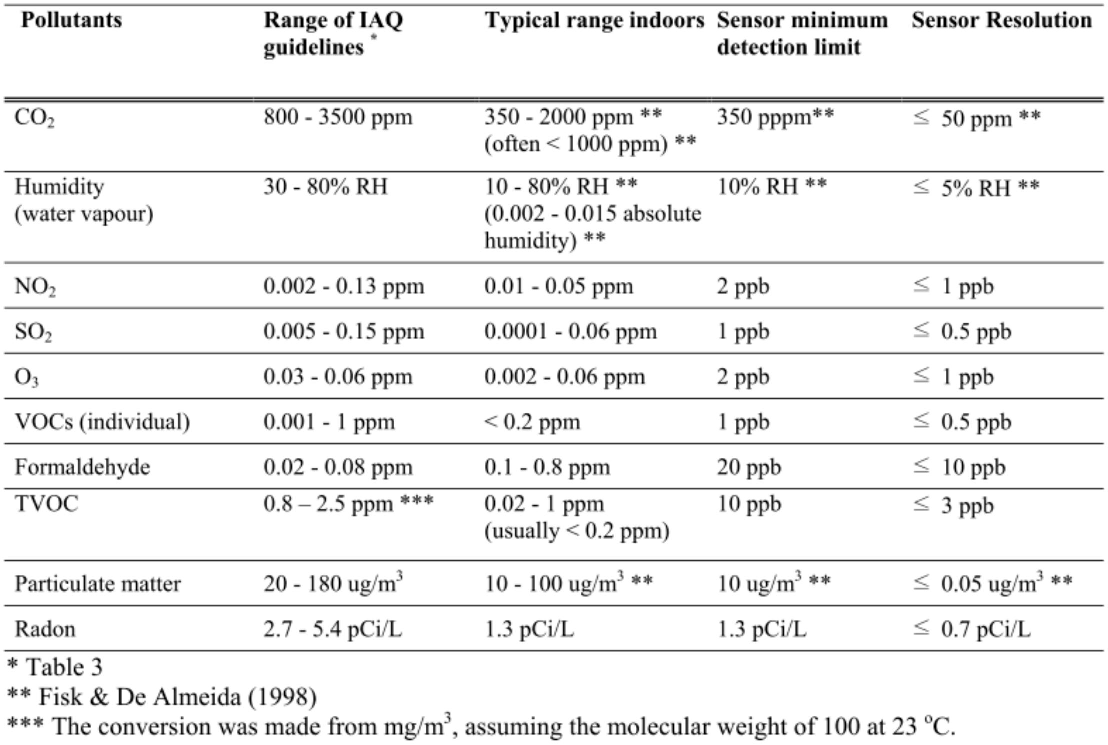
Other emerging sensors, such as microelectronic mechanical sensors (MEMS) and nanosensors, were also described in Won and Yang's market survey (2005) and are promising for future smart ventilation applications. Notably, they report that nanosensors tested for formaldehyde and NO_2 measurements with rapid response at extremely low concentration (20 ppb) and recovery time less than several minutes (Shi, et al. 2005). They cite other studies showing that nanosensors could be promising for VOC measurements. Yamazoe and Shimanoe (2009) further investigated MEMS and concluded that micro-platforms with MEMS techniques were almost ready to be used in gas sensors. Kumar, et al. (2016) further investigated the emerging sensor technologies that have been developed since.

Multiple-parameter sensors were also recognized as promising in Won and Yang's report (2005) and have experienced substantial development since. In the Clear-up project, Ulmer and Herberger (2011) developed metal oxide semiconductor sensors combining CO_2 and VOC sensors. By monitoring airflow rates in HVAC or ventilation systems and measuring in various places during correlated emissions of CO_2 and VOCs, they were able to develop an empirical algorithm able to capture not only the occupant-generated CO_2 events but also all other events generating VOC in a defined metric. They guarantee the performance of their sensor for more than 50,000 operating hours.

Other types of sensors such as electronic nose, ozone, sulfur dioxide, and radon were described in Won and Yang's market survey (2005) and are not reported here.

The following two tables give the characteristics of pollutant sensors used for smart ventilation strategies and available sensors from the 2005 Canadian review (Won and Yang 2005). Fisk and De Almeida (1998) were the first to provide such a table, recommending that: 1) sensor minimum detection thresholds should be equal to the lower concentrations expected inside buildings, 2) sensor resolution and maximum drift between calibrations should be less than 10% of a typical indoor concentration, and 3) 30 minutes is a typical ventilation time constant and acceptable sensors should reflect this.

Table 7: Suggested performance levels of sensors for DCV (Won and Yang 2005)



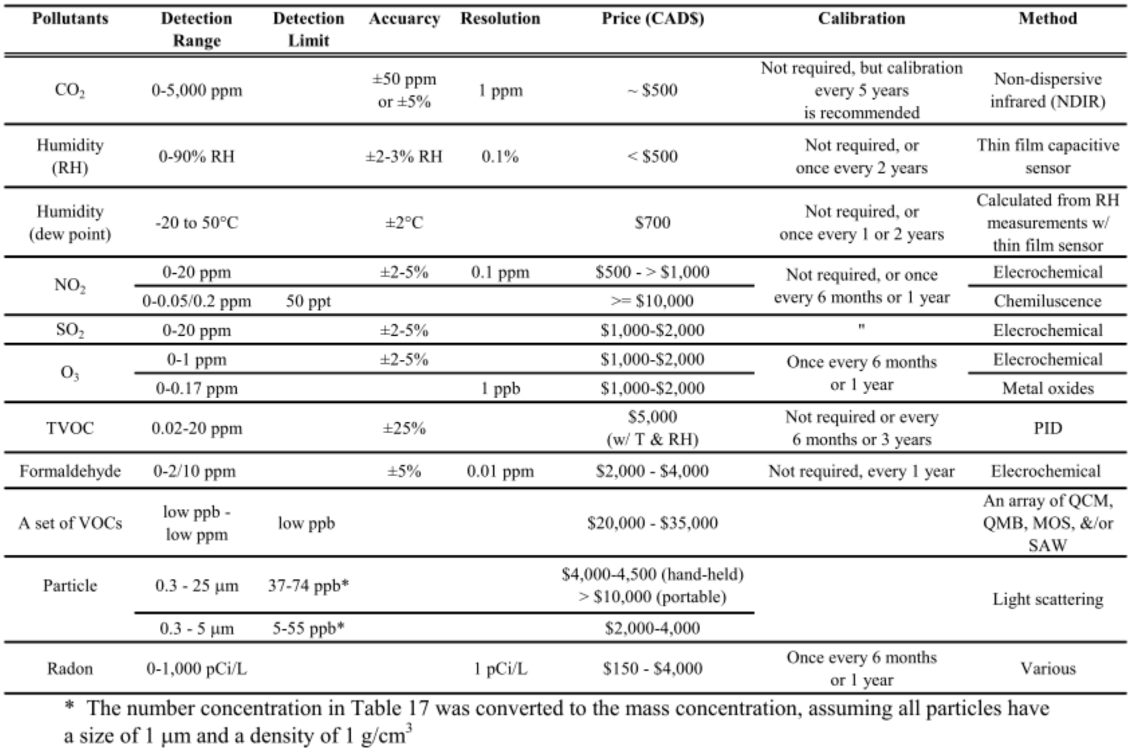
Pollutants	Range of IAQ guidelines *	Typical range indoors	Sensor minimum detection limit	Sensor Resolution
CO_2	800 - 3500 ppm	350 - 2000 ppm ** (often < 1000 ppm) **	350 pppm**	≤ 50 ppm **
Humidity (water vapour)	30 - 80% RH	10 - 80% RH ** (0.002 - 0.015 absolute humidity) **	10% RH **	≤ 5% RH **
NO_2	0.002 - 0.13 ppm	0.01 - 0.05 ppm	2 ppb	≤ 1 ppb
SO_2	0.005 - 0.15 ppm	0.0001 - 0.06 ppm	1 ppb	≤ 0.5 ppb
O_3	0.03 - 0.06 ppm	0.002 - 0.06 ppm	2 ppb	≤ 1 ppb
VOCs (individual)	0.001 - 1 ppm	< 0.2 ppm	1 ppb	≤ 0.5 ppb
Formaldehyde	0.02 - 0.08 ppm	0.1 - 0.8 ppm	20 ppb	≤ 10 ppb
TVOC	0.8 – 2.5 ppm ***	0.02 - 1 ppm (usually < 0.2 ppm)	10 ppb	≤ 3 ppb
Particulate matter	20 - 180 ug/m^3	10 - 100 ug/m^3 **	10 ug/m^3 **	≤ 0.05 ug/m^3 **
Radon	2.7 - 5.4 pCi/L	1.3 pCi/L	1.3 pCi/L	≤ 0.7 pCi/L

* Table 3

** Fisk & De Almeida (1998)

*** The conversion was made from mg/m^3, assuming the molecular weight of 100 at 23 ^oC.

Table 8: General specifications of commercial sensors (Won and Yang 2005)



Pollutants	Detection Range	Detection Limit	Accuarcy	Resolution	Price (CAD$)	Calibration	Method
CO_2	0-5,000 ppm		±50 ppm or ±5%	1 ppm	~ $500	Not required, but calibration every 5 years is recommended	Non-dispersive infrared (NDIR)
Humidity (RH)	0-90% RH		±2-3% RH	0.1%	< $500	Not required, or once every 2 years	Thin film capacitive sensor
Humidity (dew point)	-20 to 50°C		±2°C		$700	Not required, or once every 1 or 2 years	Calculated from RH measurements w/ thin film sensor
NO_2	0-20 ppm		±2-5%	0.1 ppm	$500 - > $1,000	Not required, or once every 6 months or 1 year	Elecrochemical
	0-0.05/0.2 ppm	50 ppt			>= $10,000		Chemiluscence
SO_2	0-20 ppm		±2-5%		$1,000-$2,000	"	Elecrochemical
O_3	0-1 ppm		±2-5%		$1,000-$2,000	Once every 6 months or 1 year	Elecrochemical
	0-0.17 ppm			1 ppb	$1,000-$2,000		Metal oxides
TVOC	0.02-20 ppm		±25%		$5,000 (w/ T & RH)	Not required or every 6 months or 3 years	PID
Formaldehyde	0-2/10 ppm		±5%	0.01 ppm	$2,000 - $4,000	Not required, every 1 year	Elecrochemical
A set of VOCs	low ppb - low ppm	low ppb			$20,000 - $35,000		An array of QCM, QMB, MOS, &/or SAW
Particle	0.3 - 25 µm	37-74 ppb*			$4,000-4,500 (hand-held) > $10,000 (portable)		Light scattering
	0.3 - 5 µm	5-55 ppb*			$2,000-4,000		
Radon	0-1,000 pCi/L			1 pCi/L	$150 - $4,000	Once every 6 months or 1 year	Various

* The number concentration in Table 17 was converted to the mass concentration, assuming all particles have a size of 1 µm and a density of 1 g/cm^3

Concerning occupancy detection, Chenari, et al. (2016) mention that occupancy schedules have today been replaced by more sophisticated occupancy-detection strategies such as motion sensors, infrared, video, or camera occupant counters. In this report, only motion sensors are investigated because they are more often used in residential buildings than occupant counters. Occupant counting has been tested for DCV applications in non-residential buildings with mixed results in regards to accuracy (Fisk and Sullivan 2010).

Infrared technology is used most often, detecting occupants' heat signatures. Another technology functions by emitting a beam of ultrasound waves and detecting any moving objects or people. Some sensors use a combination of these two types of technologies in order to give more reliable detection (Fisk and De Almeida 1998).

A motion sensor should cover the entire space during the entire period of use. They are, for instance, very well-adapted to bathrooms. An alternative solution for bathrooms might be to combine the light and fan switches (Caillou, et al. 2014b), but this strategy would be relevant only for rooms without sufficient light from a window.

The adequacy of the precision of such infrared sensors for DCV applications was investigated by Bernard, et al. (2003), who developed a laboratory method to test reliability of detection using a set of predetermined movements by a robot. They tested some sensors for their ability to detect forced entry into the house and found them unreliable. Even the best sensors failed to detect some small movements, even at very close range (0.6 m). Large and small movements could be detected only sporadically up to a 2-meter sensor-occupant distance. Moffat, et al. (1991) considered passive infrared activity sensors reliable in their field testing. Infra-red detector costs were estimated by De Almeida and Fisk (1997) in the range \$50 USD—\$200 USD and by Mortensen (2011) in the range 400 DKK—800 DKK (~\$60 USD—\$120 USD, ~55 EUR—110 EUR).

Other types of occupancy sensing have been suggested and studied. Walker, et al. (2014) proposed the use of personal electronic devices (PEDs) for determining occupant presence in homes. Schild (2007) looked at the ability to quantify occupancy by sensing the locking of doors in a reference building in Stockholm.

An alternative strategy developed by Federspiel (1996); Ke and Mumma (1997); and Wang and Jin (1998) involved detecting occupancy quickly by analyzing the indoor CO_2 generation rateEven under transient conditions, using a well-mixed single zone model allows them to estimate this parameter, even if the inadequacies of this strong assumption are not discussed elsewhere in the literature. Lu, et al. (2010) have further investigated this type of approach with a modeling and experimental study in a sports training center in Finland. Their results show that this new strategy could save between 26% and 34% more energy than strategies with airflows proportionally controlled by CO_2-concentrations.

Data transmission is also a subject of interest. Kumar, et al. (2016) mention in their review that a number of sensors with incorporated communication protocols are available, allowing the transmission of data via Bluetooth or Wi-Fi to a remote platform such as a PC or smartphone for viewing. Such technologies may be extended to smart ventilation applications. Other devices, such as alarms detecting outdoor pollution, are available on the market, with applications such as detection of chemical hazards on industrial platforms, even if applications in residential buildings are rare (Walker and Sherman 2013).

The type of control, either centralized or per-zone, is also worth discussing. Central control always gives lower performance than local control since airflows in rooms of interest are less sensitive to measured parameters in these rooms. For CO_2-based DCV systems, local detection and corresponding control in living rooms and bedrooms can save 20% more energy than centralized regulation (Caillou, et al. 2014b).

Location and number of sensors can strongly impact performance. For obvious reasons, a smart ventilation strategy based on only one sensor in one room, or one location within a network of ductwork, is not likely to perform well from either an energy or an IAQ perspective. Some authors have quantified variation in performance with location and number of sensors. Caillou, et al. (2014b) estimated the energy demand of a CO_2-DCV system based only on a single sensor in the living room. They found a 15% increase in energy demand with poor IAQ results. These authors also showed that systems with a small number of strategically placed CO_2 sensors (e.g., only in the bedrooms, or only in the main bedroom and in the living room) could be interesting, even if they do not perform as well ass those with sensors in every dry room (Table 9).

Another recent study of 62 homes in the Netherlands (van Holsteijn and Li 2014) showed that if CO_2 measurements are not made at the mechanical supply and/or exhaust serving the room of interest and linked to the measurement made in that room, or if the room sensor is located outside the room of interest in a connected space, resulting IAQ is the same or worse than that of common systems which have no CO_2-sensors. Nevertheless, Rackes and Waring (2016) conclude that one accurate sensor in the return duct can give results better than several less-accurate sensors throughout a room.

In a room, the best location for pollutant sensors is in the pre-defined breathing zone. As it is not always possible to do this in practice. Correlation factors may be used which relate concentrations at this ideal place to a more practical place: either on the wall, in a duct, or in a grille. Chao, et al. (2004) compensated for CO_2 and ozone levels measured at the air return duct using such correction factors in their DCV system.

Schell and Inthout (2002) suggest that the best solution is locating a sensor in each room and passing the greatest measured concentration to the air handler. Feedback on the use of such a strategy in residential buildings is still missing.

Control strategy algorithms

Sherman, et al. (2012) points out that, in a smart ventilation strategy, the controller must know the target airflow and the current airflow, and be able to adjust a piece of ventilation equipment every 10 minutes. De Almeida and Fisk (1997) identified the following three mechanisms available for control:

- Cycling fans on and off
- Modulating inlet and outlet dampers
- Continuously varying fan speed.

Such control strategies are already used in hybrid ventilation systems. Such systems sense outdoor and indoor parameters in order to determine if natural ventilation is sufficient, or if a fan must be activated (Jreijiry, et al. 2007; Buonomano and Sherman 2009; Turner and Walker 2013; Chenari, et al. 2016).

A common control strategy used in CO_2-based DCV systems is to fix a set point, 1,000 ppm for instance, and to minimize ventilation as long as this threshold is not reached. A purge before occupancy periods can improve this control strategy (Emmerich, et al. 1994; Knoespel, et al. 1991). In those strategies, CO_2 sensors have often been placed in the return air duct.

More advanced controlled strategies have been developed and are largely used in European countries such as Belgium. Air outlets generally have associated minimum and maximum airflows, and intermediate airflows follow either a linear function of demand, a step change, or a more complex relationship. In these systems, the setpoint can be fixed at 500 ppm, 800 ppm, 1000 ppm, or 1200 ppm (Caillou, et al. 2014b).

As discussed previously in this report, common humidity-based DCV systems use mechanically variable cross-sections in inlets and outlets. Such sensors are widely used in France, and also in other countries such as Poland and Germany. These air outlets generally have a minimum airflow of around 10 m^3/h, a maximum airflow between 50 m^3/h and 75 m^3/h depending on the type of room considered, and a modulation of airflow between these extremes which follows a linear function of relative humidity in the range 30%—35% to 70%—80%, as shown in Figure 4.

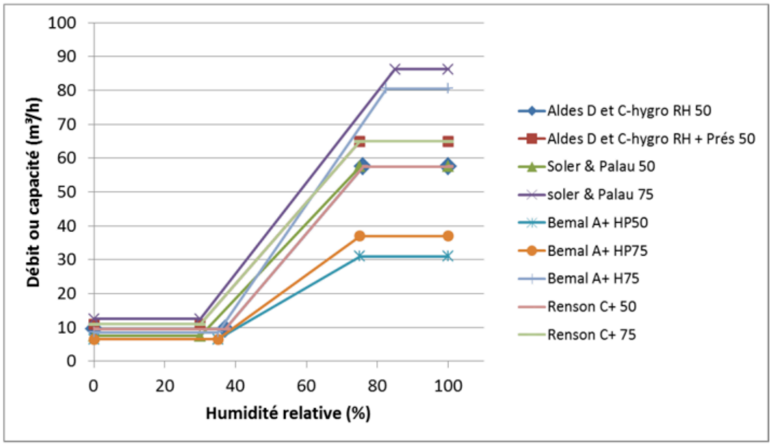


Figure 4: Relationship between airflow and relative humidity for air outlets used in nine current humidity DCV systems in Belgium (Caillou, et al. 2014b)

Some other systems such as Renso C+ evo, Duco Comfort, and Thermelec GLC use such outlets but with hysteresis (Caillou, et al. 2014b). Yet other systems such as Zehnder Comfo plan, Renson C++ EVO II, and Renson C+ Cube use more complex algorithms to control airflows in response to not only the measured relative humidity in the room but also the rate of change in humidity (Caillou, et al. 2014b).

Only a function of both humidity and time spent at a high humidity can quantify the condensation risk. The literature review for this research did not reveal such a control strategy in the market.

Other strategies based on a limited number of preset airflows can also be used to control ventilation. One example includes setting three airflow rates: a minimum, used to dilute pollutants emitted by materials and furnishings during unoccupied periods q_{min}, a basic rate to dilute pollutants emitted constantly by occupants q_{base}, and a high rate to dilute or remove pollutants during peak activities such as cooking, showering, or house cleaning q_{forced}. In multi-family homes, the airflow ratios q_{forced}/q_{base} and q_{base}/q_{min} should be identical in order to limit the number of the predefined positions of the dampers, and to simplify the whole control strategy (Mortensen and Nielsen 2011).

In a passive house context, Szkarłat and Mróz (2014) studied variable air volume controls as a function of sensible heat balance calculated via temperature sensors, latent heat balance calculated via RH sensors, and CO_2 balance. They looked at defining control parameters and algorithms for high heat gains in passive houses. They studied classical controllers and fuzzy controllers, concluding that continuous PID[2] control must be used together with parameters that are precisely controlled with the use of, for example, fuzzy logical controllers. Fuzzy logical controllers give more stable results; however, they sometimes respond more slowly.

Parameters can be selected that have the greatest influence on DCV performance. Caillou, et al. (2014b) highlighted that the most influential parameters for DCV controls are:

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[2] A PID controller is a proportional–integral–derivative controller. It continuously calculates the difference between a setpoint and a measured variable and its control signal is a function of the difference, integral and derivative.

- A high maximum airflow for a high concentration (e.g., 100% of airflow for CO_2 > 950 ppm or RH>70%)
- A minimum airflow low enough when concentration is low (e.g., <40% of airflow for CO_2 <400 ppm or RH<35%) but not less than 10% of the airflow
- A high enough minimum airflow in given conditions (e.g., 30% of airflow if CO_2 or RH is the only control parameter, or 25% of airflow when RH>50%).

Other control strategies are at least as important as sensor-based control strategies from a smart ventilation perspective. For instance, as discussed in this report, Sherman and Walker (2011) demonstrated 1000 kWh energy savings during the course of a year in a California house using a constant air change rate strategy. This was accomplished by taking into account known times of greatest energy requirements to condition ventilation air and exogenous air transfers via the use of an advanced control strategy, but included no additional sensors.

Fisk and De Almeida (1998) first mentioned the use of energy management systems to control loads in response to real-time prices, and such systems have made a great deal of progress the last few years, even in residential buildings. Eventually consumers could participate in programs to decrease the peak electricity load. This could be accomplished via an email, or through phone or Internet systems. Some of these systems have been developed to directly turn off devices such as air-conditioning appliances, washing machines, and dryers.

For such applications, controllers are available on the market such as those sold by Honeywell and Aprilaire (predominantly used for central-fan integrated supply systems), Tamarack (for controlling exhaust fans), or Davis Energy group with Nightbreeze (ventilative cooling and/or evaporative cooling) (Walker, et al. 2011). Such a smart ventilation strategy can be used to avoid outdoor peak pollutant concentrations when outdoor concentrations are the main source of indoor pollutants, as is the case with ozone (Walker and Sherman 2013).

4. ENERGY AND IAQ PERFORMANCE-BASED METHODS IN STANDARDS AND REGULATIONS AS OPPORTUNITIES FOR SMART VENTILATION SYSTEMS

Overview of standards and regulations for residential buildings integrating smart ventilation

A number of ventilation standards and national regulations have progressively integrated an allowance for smart ventilation strategies and/or DCV systems in residential buildings. Simultaneously, an increasing number of energy performance regulations include the opportunity to claim credit in energy calculations for savings from such systems. A 2004 federal technology alert circulated by the U.S. government suggested that the HVAC systems in buildings should use DCV to tailor the amount of ventilation air to the occupancy level for both energy and IAQ reasons (Federal Technology Alert 2004). Some years later, ASHRAE 62.2 (ANSI/ASHRAE 2016) added a section to allow the use of smart ventilation technologies using real-time controls. Research for this paper did not reveal evidence that smart ventilation systems receive credit in state energy codes in the United States or in energy rating systems. In Europe, ventilation codes in several countries enable the use of DCV systems, including Belgium, France, Spain, Poland, Switzerland, Denmark, Sweden, the Netherlands, and Germany (Savin and Laverge 2011; Kunkel, et al. 2015; Borsboom 2015). More recently, energy regulations in some European countries have also begun to include DCV.

In those countries, smart ventilation and/or DCV systems must generally prove their equivalence to constant rate ventilation systems in maintaining the IAQ, in order to comply with the ventilation regulation and get a credit in the energy-performance regulatory calculation.

In Europe, two recently published directives (n°1253/2014 regarding the ecodesign requirements for ventilation units and n°1254/2014 regarding the energy labeling of residential ventilation units) (European Parliament and the Council 2014) are moving toward a generalization of low-pressure systems, DCV systems, and balanced heat recovery systems on the 2018 horizon. Central and local DCV systems will be labeled according to these directives. Such labeled systems will be allowed to use a 15% and 35% reduction (for central and local systems, respectively) in ventilation energy consumption calculations.

State-of-the-art of existing equivalence principles or performance-based approaches for smart ventilation used in residential buildings

The motivation behind the ventilation equivalence concept is the requirement that, compared to constant-rate systems prescribed in current regulations and standards, an innovative smart ventilation system should save energy without degrading IAQ. In practice, this equivalence concept can be used in many ways, and is often combined with a minimum airflow rate for unoccupied periods. The common thread in all of these methods is that they are more performance based than analogous prescribed constant rate approaches, and they use, at a minimum, the exposure to a pollutant generated indoors (very often the CO_2) and condensation risk to determine the necessary ventilation.

In the United States and Canada, the equivalence principles in ventilation and IAQ described by Sherman (2004) and Sherman, et al. (2012) have been partially integrated into the current version of the ventilation standard ASHRAE 62.2 2016. Some state building regulations, such as Title 24 energy-performance regulations in California, require compliance with this ASHRAE standard. The standard gives a method to calculate the minimum constant airflows for residential buildings. It also allows the use of variable volume mechanical ventilation, which could be:

1. Ventilation averaged over short periods
2. Scheduled ventilation
3. Ventilation continuously controlled in real time.

In the first strategy, total airflow rate equivalence is required over any three-hour period. This allows for switching off the ventilation system during short periods if high airflow rates can be provided later. In any of the three cases, the equivalent ventilation principle is required: the annual exposure must not be higher than that produced by constant airflow systems. In other words, the annual average relative exposure must be less than one. The calculation must use single-zone modeling, with a constant pollutant emission rate, and a time-step no longer than one hour. At each time step *i*, the relative exposure R_i is calculated from Equation 15 and Equation 16, and shall not exceed a value of 5 in order to avoid peak exposure. The manufacturer, specifier, or designer should certify that the calculation meets the requirements.

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_i \Delta t / V_{space}} < 5 \qquad if\ Q_i \neq 0$$

Equation 15

$$R_i = R_{i-1} + \frac{Q_{tot} \Delta t}{V_{space}} < 5 \qquad if\ Q_i = 0$$

Equation 16

$$R_0 = 1$$

Equation 17

Where Q_{tot} is the minimum constant ventilation rate calculated according to section 4.1 of the ASHRAE 62.2,
Q_i is the real-time airflow in the variable mechanical ventilation system at time step i,
Δt is the time-step used in the calculation,
V_{space} is the volume of the space.

In France, manufacturers must follow a compliance procedure for DCV to ensure adequate ventilation. Once a system receives certification of compliance via this procedure, called "Avis technique," it can be used in homes according to its specifications. The agreement is a document of at least 30—60 pages that specifies how the system must be designed, how all the components of the system (including inlets, outlets, and ducts) must be installed, and precisely how the system must be commissioned and maintained. For each type and size of home, the agreement gives references that must be used for selecting air inlets and outlets and the input data for energy calculations. The procedure (CCFAT 2015) describes the common scenarios used to evaluate the DCV systems through a multi-zone software, MATHIS (Demouge, et al. 2011). Notably, each room of the home is modeled as single zone, with a time-step of 15 minutes. This procedure is based on the evaluation of humidity-based DCV systems that have been used for more than 30 years, and thus must be adapted for other innovative types of DCV systems. Typical input data, which are given in the procedure, include:

- External data: calculation period (October 1st-May 20th), outdoor CO_2 concentration, meteorological data and wind effects parameters
- The homes: geometry of the representative homes (14 houses and 10 apartments), airtightness of the homes, and its distribution on the different facades
- The occupancy scenario: metabolic emission rates of CO_2 and humidity, number of occupants, occupancy schedules, activity level, and associated moisture emission rates
- The ventilation components: trickle ventilator positioning, aerodynamic characteristics of hygrovariable air inlets and outlets (effects of external and internal temperatures on the inlets and outlets are taken into account as well), schedules for bathroom (toilet and shower), and toilet exhausts and kitchen exhausts.

As part of the compliance procedure, an “IAQ calculation” and an “Energy calculation” must be performed. First, the cumulative CO_2 exposure indicator E_{2000} (Equation 18) must be calculated and must be under 400,000 ppm-h in each room. This threshold is supposed to represent the mean cumulative exposure under a constant ventilation strategy, although the exact source of this number is not readily available in the literature.

$$E_{2000} = \sum_{t=0}^{T} C_{CO_2>2000}(t) * t < 400\,000\ ppm.h$$

Equation 18

Where $C_{CO_2>2000}(t)$ is the absolute concentration in the room at t time-step, if it is higher than 2000 ppm.

Second, the number of hours when relative humidity is higher than 75%, $T_{RH>75\%}$, must be calculated. This value is representative of the condensation risk (Equation 19).

$$T_{RH>75\%} = \sum_{t=0}^{T} t < 600\ h\ in\ kitchen, 1000\ h\ in\ bathrooms, 100\ h\ in\ other\ rooms$$

Equation 19

Once the IAQ calculation has been performed and both IAQ requirements are fulfilled, the energy calculation must be performed. The procedure specifies the input data to be used in the energy performance (EP) calculation, which is a set of single-zone modeling calculations specific to each new home design. For each home, the mean equivalent exhausted airflow (m^3/h) and the total air inlet mean area (m^2) are calculated. This detailed performance-based approach is performed once for each new DCV system, and then averaged to be later taken into account in each home EP-calculation as average values. Typical energy savings are about 40% compared to a constant airflow. In France, switching off the ventilation system during unoccupied periods is not permitted and trickle ventilators cannot be closed. The minimum airflow is set between 10 m^3/h and 35 m^3/h depending on the number of rooms in the building. The DCV system is generally certified for a three-year period, in order to take into account possible updates in regulations, agreement procedure, and available knowledge and technologies.

Spain has a similar approach to France's procedure: a performance-based approach that will be implemented in the future IAQ regulations. Because current regulations are expressed as constant ventilation flows, DCV systems must pass through a compliance procedure. Once a system receives a certificate of compliance, called a *Documento de Idoneidad Técnica* (DIT), it can be used in homes according to its specifications.

The DIT is a document of about 30 pages that specifies how the system must be designed, how components of the system such as air intakes, exhausts, and ducts must be selected and installed, and precisely how the system must be commissioned and maintained. For each type of home and climate, the DIT gives input data for energy calculations in the form of an equivalent reduction of constant ventilation flow rates that is specified in the current regulations. The DIT is adopted for a five-year period and subject to yearly reviews. The compliance assessment involves analysis of reference scenarios. In these scenarios, each room of the home is modeled as single-zone with the multi-zone software CONTAM (Walton and Emmerich 1994), with a time-step of 40 seconds (for hygro ventilation systems; other systems may have a different time-step). Standardized input data are given, which include:

- External data: calculation period (all year), outdoor CO_2 concentration, meteorological data
- The homes: geometry of the standard homes (14), air infiltration is not considered
- The occupancy scenario: metabolic emission rates of CO_2 and humidity, number of occupants, occupancy schedules, a schedule of their activities and associated moisture emission rates
- The ventilation components: trickle ventilator positioning, aerodynamic characteristics of hygrovariable inlets and exhausts, schedules for toilet exhausts.

As a result, if the following IAQ indicators can be achieved, the annually averaged equivalent ventilation airflow can be implemented in the EP-calculation:

- Annually averaged CO_2 concentration must be lower than 900 ppm
- Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} (see Equation 18) must be lower than 500,000 ppm-h in each room.

Future changes to the building code are being reviewed (Linares, et al. 2014; Garcia and Linares 2015; Linares, et al. 2015). The changes aim to implement a performance-based approach with respect to IAQ requirements at the design stage of a building, which shall be used for all sorts of ventilation systems, including DCV systems. The proposed IAQ requirements are the same ones that are used in the current procedure for DCV. They would also be calculated using a multi-zone code like CONTAM, with prescribed input data concerning human CO_2 generation, proposed occupancy schedules, and occupancy rate selected according to the national population and 2011 housing census. The minimum airflow during unoccupied periods will be set to 1.5 l/s in each room.

In Belgium, the procedure for residential buildings was similar to the French and the Spanish approach until 2015. Before 2015, to get a credit in the energy calculation, each new system had to pass through an IAQ equivalence procedure before receiving an agreement, called "ATG-E," delivered by a national organization (UBATC), and then consolidated through a ministerial order in each region. The equivalence procedure was described in ATG and BCCA (2012) and was based on multi-zone modeling with CONTAM (Walton and Emmerich 1994), using a time-step of five minutes. The standardized input data were both deterministic (geometry of the typical house, air leakage, moisture buffering parameters, indoor temperature, exterior climate file, calculation period (October to April) and stochastic (building orientation, wind shielding and terrain roughness, occupancy scenario, and contaminant generation). Contaminants that were considered were CO_2, relative humidity, and a tracer gas emitted for 5 minutes in toilets each time these rooms are occupied. One hundred datasets were used per level of envelope air-leakage. The reviewed system was then compared to the three reference systems defined in the regulation (A=natural, C=exhaust, D=balanced). The IAQ performance was evaluated through three indicators:

1. The per-person cumulative CO_2 exposure indicator E'_{950} (Equation 20)
2. The average time per month critical thermal bridges were exposed to relative humidity over 80% from December 1st to March 1st
3. The exposure to a tracer gas emitted from the bathrooms.

$$E'_{950} = \sum_{t=0}^{T} \left(C_{CO_2>950}(t) - 950 \right) * t$$

Equation 20

Where $C_{CO_2>950}(t)$ is the absolute concentration to which an occupant is exposed at time-step *t*, if it is higher than 950 ppm.

Unlike the other two, the second requirement is an absolute requirement (Caillou, et al. 2014b). Owing to its inherent uncertainty, it was given an associated tolerance that is somewhat greater.

Once the three IAQ indicators have been calculated and are shown to be equal or better than the worst-performing reference system, the energy savings coefficient f_{reduc} is determined by an extrapolation explained in Figure 5 and Equation 21, based on the heating-season integrated ventilation heat loss E (MWh/year), excluding infiltration heat losses which are treated separately in the energy calculation method.

$$f_{reduc} = \frac{E_X}{E_{ref}}$$

Equation 21

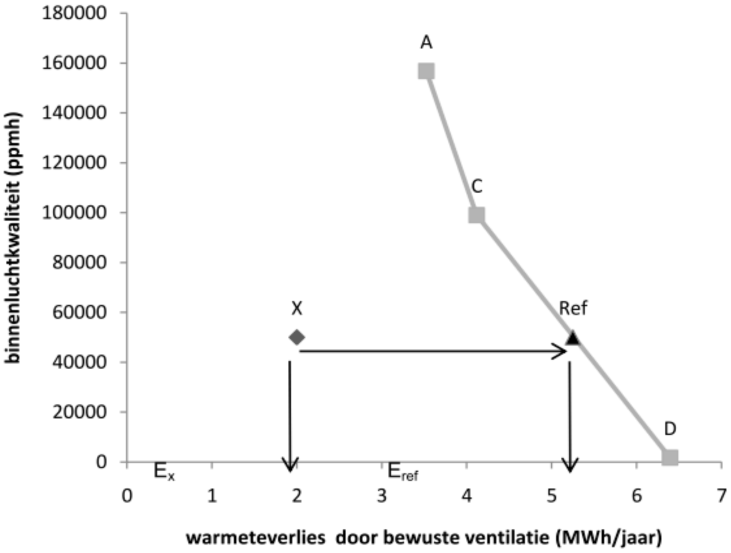


Figure 5: Energy saving coefficient calculation for a DCV system X (ATG and BCCA 2012)

In 2014, Belgian regions considered DCV systems mature enough to be directly integrated into the EP-calculation method, without requiring the equivalence method. A study conducted by UGent and BBRI (Caillou, et al. 2014b) evaluated the 35 systems gaining the ATG-E through an advanced equivalence method. They improved the initial method by taking into account some of its limitations, such as the fact that the three reference systems defined in the regulation (A=natural, C=exhaust, D=balanced) are not equivalent (illustrated in Figure 5).

Moreover, Figure 5 illustrates that cumulative CO_2 exposure under system A (natural ventilation) is very high (thus not a strong requirement). Also, that energy gains in systems with very good IAQ are over-estimated because of the over-estimation of the system D (balanced) ventilation heat loss—notable because it doesn't take into account the possibility of manual control. Calillou, et al. added generation of a VOC pollutant emitted proportionally to the surface area of each room to the evaluation method and calculation of the cumulative exposure to this pollutant. They proposed classifying DCV systems according to the sensing type: type of sensor (CO_2, RH, occupancy), type of spaces (humid and/or dry), and regulation type: exhaust only, supply only, balanced, and local sensing vs. centralized. For each class of DCV systems, they proposed standard values for the energy saving coefficient f_{reduc}.

As a result, as of January 1st 2016, only the energy saving coefficient f_{reduc} given in the tables (Table 9) of a ministerial order (Moniteur Belge 2015) can be used directly in the EP-calculation, and the equivalence procedure no longer exists. This order requires sensors to conform to the accuracy requirements discussed above. In the case of DCV systems, minimum airflows greater than 10% of the minimum constant airflow for each room are also required. Intermittent ventilation is allowed if the 15-minute average airflow is equal to this 10% requirement.

Table 9 : Energy saving coefficient f_{reduc} in Belgium for natural, exhaust-only, supply-only, balanced DCV systems with a regulation of air inlets based on needs in dry spaces and/or with a regulation of air outlets based on needs in humid rooms (another table is available for exhaust-only systems with a regulation of air outlets based on needs in dry spaces)

Type of detection in dry spaces	Type of regulation of air inlets in dry spaces	Local detection in humid spaces with regulation of air outlet *Local regulation*	Local detection in humid spaces with regulation of air outlet *No local regulation*	Other or no detection in humid spaces
CO_2-local : at least a sensor in each dry space	Local	0.35	0.38	0.42
	2 zones (night/day) or more	0.41	0.45	0.49
	Central	0.51	0.56	0.61
CO_2- partially local: at least a sensor in each bedroom	Central	0.60	0.65	0.70
CO_2- partially local: at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.43	0.48	0.53
	Central	0.75	0.81	0.87
CO_2-central: at least a sensor in the exhaust duct(s)	Central	0.81	0.87	0.93
Occupancy-local: at least a sensor in each dry space	Local	0.54	0.60	0.64
	2 zones (night/day) or more	0.63	0.67	0.72
	Central	0.76	0.82	0.88
Occupancy-partially local: at least a sensor in each bedroom	Central	0.87	0.93	1.00
Occupancy-partially local: at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.66	0.72	0.78
	Central	0.87	0.93	1.00
Other or no detection in dry spaces	No, local, per zone, or central	0.90	0.95	1.00

In the Netherlands, for DCV systems used in residential buildings, it is possible to use correction factors for the ventilation airflow in the EP-calculation, based on the standard NEN 8088 (NEN 2011). The standard provides standard energy reduction factors for quite a few DCV systems, ranging from 0.52 to 0.95. A complementary equivalence approach can be performed (VLA 2013), using COMIS simulation software, in a semi-probabilistic approach (seven home types, different occupant types, different airtightness levels, different wind exposure). The IAQ metric employed is the cumulative CO_2 exposure index requirement per person, LKI_{1200}, calculated for the period September 29th-April 25th with Equation 22.

For a new product type, manufacturers should submit their report to one of three predefined research institutes or consulting companies for review. At the end of the process, an agreement is published on the Dutch Association of Air Handling Equipment Manufacturers (VLA) website, and shortly thereafter a declaration of equivalence is published in the database of the Bureau of Control and Registration (Borsboom 2015). A minimum airflow is prescribed according to the number and the type of occupants.

$$LKI_{1200} = \sum_{t=0}^{T} \left(\frac{C_{CO_2>1200}(t) - 1200}{1000} \right) * t < 30\ kppm.h$$

Equation 22

Where $C_{CO_2>1200}(t)$ is the absolute concentration at which an occupant is exposed at *t* time-step, if it is higher than 1200 ppm, or 800 ppm above the outdoor concentration.

In Germany, a methodology for assigning an energy credit for the use of DCV systems in the EP-calculation was investigated (Krus, et al. 2009), in order to update the existing credit of 10% over constant exhaust ventilation.

Table 10: Overview of equivalence principles for smart ventilation and/or DCV in some residential building regulations

Country	Person in charge	Ventilation Equivalence method	Calculated IAQ indicators	Credit in EP-calculation	Minimum airflow
USA and Canada (ASHRAE 62.2 2016)	The manufacturer or designer is supposed to certify that the calculation meets the requirements.	Single zone modeling, $\Delta t<1h$, constant pollutant emission rate	No specifically defined pollutant Yearly average relative exposure $R<1$ At each time-step $R_i<5$	No	Can be null if the total airflow rate equivalence is required over any 3-hour periods
France	The manufacturer for each (humidity) DCV system shall pass through an agreement procedure	Multi-zone modeling with MATHIS, Δt =15 min, Conventional entry data	Per room, over heating period only: 1/CO_2 cumulative exposure indicator E_{2000} < 400.000 ppmh 2/Number of hours $T_{RH>75\%}$ <600 h in kitchen, 1000 h in bathrooms, 100 h in other rooms	Average equivalent exhausted airflow (m^3/h) can be implemented in the EP-calculation	Switch off not allowed, minimum airflow is 10-35 m^3/h according to the number of rooms in the building
Spain (<2017)	The manufacturer for each DCV system shall pass through an agreement procedure	Multi-zone modeling with CONTAM, Δt =40 s, Conventional entry data	Per room, over entire year: 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500.000 ppmh	Yearly average ventilation airflow could be implemented in the EP-calculation	
Spain (future)	The designer of the building, of the base of information given by the manufacturer	A performance-based approach for all ventilation systems is going to be implemented, using a software and conventional data at the design stage of each building	Per room, over entire year: 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500.000 ppmh	Yearly average ventilation airflow could be implemented in the EP-calculation	The minimum airflow during unoccupied periods is set to 1.5 l/s in each room.
Belgium (< 2015)	The manufacturer for each DCV system shall pass through an agreement procedure	Multi-zone modeling with CONTAM, Δt =5 min, conventional entry data both deterministic and stochastic	Per room, over heating period only: 1/CO_2 cumulative exposure indicator E'_{950} 2/Monthly average RH> 80% on critic thermal bridges from December 1st to March 1st 3/Exposure to a tracer gas emitted in toilets and in bathrooms They must be at least equal that the worst performing reference system.	An energy saving coefficient f_{reduc} is extrapolated and can be implemented in the EP-calculation	
Belgium	The person involved	No longer existing.	No longer exists	Published	Minimum airflows over

Country	Person in charge	Ventilation Equivalence method	Calculated IAQ indicators	Credit in EP-calculation	Minimum airflow
(since 2015)	in EP-calculation and manufacturer for each DCV system	An advanced equivalence method has been performed by (Caillou, et al. 2014) on all the systems having an agreement.		conventional energy saving coefficients can be used directly in the EP-calculation. They depend on the sensing type, type of spaces and the regulation type	10% of the minimum constant airflow for each room. Intermittent ventilation is allowed if the average on 15 minutes enables to comply with this 10%.
The Netherlands	The person involved in EP-calculation (standard approach) OR the manufacturer for each DCV system (equivalence approach)	Even if correction factors are given in the standard, a complementary equivalence approach can be performed, using the multi-zone pressure code COMIS, in a semi-probabilistic approach	Per person, over the heating period only: Cumulative CO_2 exposure over 1200 ppm: $LKI_{1200} <$ 30.000 ppm.h	Either, correction factors given in the standard for quite a few DCV systems, are used directly in the EP-calculation, Or, Correction factors from the equivalence procedure can be used.	A function of the number of type of occupants
Germany	/	/	/	Conventional ventilation gain of 10%	/

Only one study was found in the literature (Sherman, et al. 2012) that proposes the consideration of not only ventilation equivalence but also IAQ equivalence, based on health-related metrics. The authors propose a method taking advantage of available data in previous work (Logue, et al. 2011b, 2011a) and using the disability-adjusted life years (DALYs) metric. Based on disease incidence models, (Logue, et al. 2011b) calculated the DALYs lost as a result of long-term exposure to indoor pollutants in residences and published values of the DALYs lost per incidence of disease. In this calculation, they used the unit damage estimate (UDE) value for each pollutant of interest. The IAQ equivalence principle also proposed the use of these UDE_i values to set a DALY limit value (Equation 24) and then proposes checking that the combination of contaminant concentrations according to Equation 23 stays below this limit. Sherman, et al. (2012) established this limit as 8200 μDALY per person per year for the pollutants in Table 11. It can be seen that $PM_{2.5}$ dominates this list. If radon, ozone, and $PM_{2.5}$ can be handled through prescriptive measures, then the DALY limit decreases to 90 μDALY/p/year.

This approach is obviously limited, since it assumes that indoor contaminants of concern are clearly identified and prioritized. This equivalent methodology also needs to include acute exposure issues. Nevertheless, it could eventually be integrated into evaluation methods for innovative smart ventilation systems, and even directly into the control of such systems with real-time sensors. This background will serve the development of a smart IAQ approach that goes beyind just ventilation.

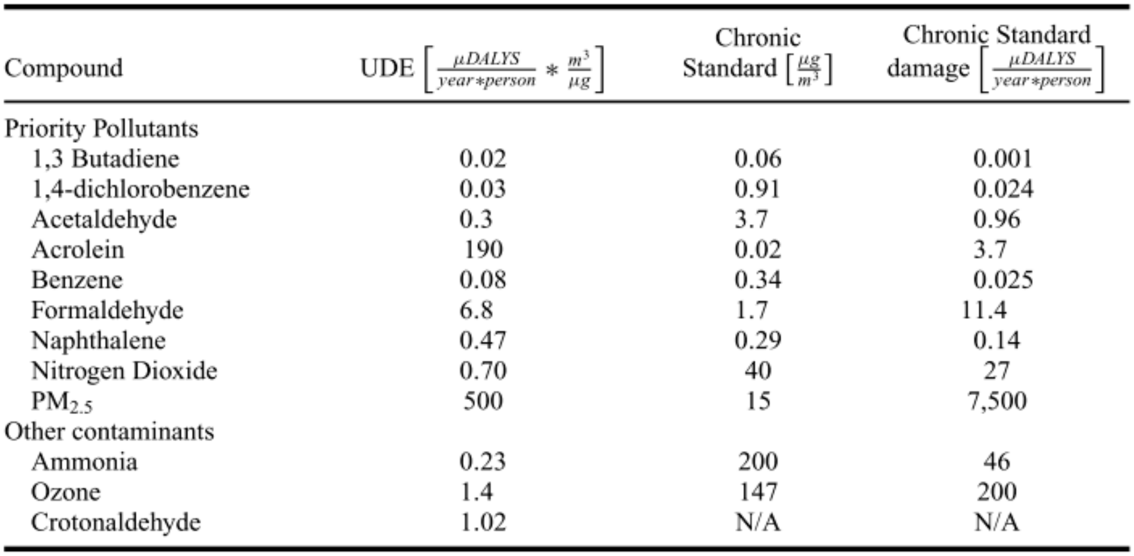
$$DALY = \sum_i Concentration_i * UDE_i$$

Equation 23

$$DALY_{limit} = \sum_i Standard_i * UDE_i$$

Equation 24

Table 11: Indoor air contaminants – UDE_i and $Standard_i$ values to implement IAQ equivalence according to Equation 23 and Equation 24 (Sherman, et al. 2012)



Compound	UDE $\left[\frac{\mu DALYS}{year*person} * \frac{m^3}{\mu g}\right]$	Chronic Standard $\left[\frac{\mu g}{m^3}\right]$	Chronic Standard damage $\left[\frac{\mu DALYS}{year*person}\right]$
Priority Pollutants			
1,3 Butadiene	0.02	0.06	0.001
1,4-dichlorobenzene	0.03	0.91	0.024
Acetaldehyde	0.3	3.7	0.96
Acrolein	190	0.02	3.7
Benzene	0.08	0.34	0.025
Formaldehyde	6.8	1.7	11.4
Naphthalene	0.47	0.29	0.14
Nitrogen Dioxide	0.70	40	27
$PM_{2.5}$	500	15	7,500
Other contaminants			
Ammonia	0.23	200	46
Ozone	1.4	147	200
Crotonaldehyde	1.02	N/A	N/A

Current availability of smart ventilation systems

Given the opportunity offered by standards and regulations in Europe, the use of DCV systems are quite developed in several European countries. As of August 1st 2016, there were 23 DCV systems in France, 34 in Belgium, 37 in the Netherlands, and three in Spain that have received certification. In the USA, some DCV systems are available, though not strictly based on the ASHRAE 62.2 equivalence principle (Less, et al. 2014). Most of these systems are CO_2- or humidity-controlled systems.

Manufacturers have to adapt their systems to the regulations or standards with which they have to comply. As a result, a DCV system produced by a certain manufacturer is not necessarily identical from country to country.

Table 12: Overview of certified DCV systems on some European countries

Country	Number of total DCV systems	Source
France	23	http://evaluation.cstb.fr/rechercher/produits-evalues
Belgium	34	http://energie.wallonie.be/fr/concepts-novateurs-liste-des-equivalences-peb.html?IDC=8825&IDD=52265
The Netherlands	37	http://www.vla.nu/gelijkwaardigheidsverklaringen/ soon on: www.dcrg.nl
Spain	3	http://www.ietcc.csic.es/index.php/es/?option=com_chronoforms&chronoform=RespuestaDIT

5. LITERATURE REVIEW: SMART VENTILATION PERFORMANCE IN RESIDENTIAL BUILDINGS

Smart ventilation is often considered a strategy specific to buildings with large changes in occupancy over the course of a day, such as office buildings (Mysen, et al. 2010), commercial buildings (Apte 2006), and more generally non-residential buildings (Emmerich and Persily 2001). However, the literature in this field shows that interest in residential smart ventilation systems has existed since the early 1980s.

The literature review for this research attempts to put into perspective the advantages of smart ventilation strategies. Studies analyzed also include:

1. Studies on energy and/or IAQ benefits of residential smart ventilation systems
2. Studies on occupant behavior and occupants' ability to perceive IAQ and operate ventilation systems
3. Experimental studies highlighting the multi-zone aspect of residential ventilation.

IAQ and energy performance of residential smart ventilation

We analyzed field and modeling studies on energy and/or IAQ benefits of residential smart ventilation systems from 1979 to 2016. The International Energy Agency Annex 18 (Raatschen 1990) reviewed 31 papers from 1979 to 1989, including four studies on the implementation of DCV systems in homes (Anon 1983; Barthez and Soupault 1984; Nicolas 1985; Sheltair Scientific, Ltd. 1988). Then, Fisk and De Almeida (1998) proposed a review of sensor-based demand-controlled ventilation, including the aforementioned review (Raatschen 1990), 13 other papers of this Annex (including six case studies on the implementation of DCV systems in homes) (Mansson 1993), and 15 additional papers published before 1997, including only one on a residence (Kesselring, et al. 1993). Until then, the vast majority of the studies had considered only relative humidity-based control, and in some rare cases CO_2-based control. Last, in a recent review on sustainable, energy-efficient and healthy ventilation strategies in buildings (Chenari, et al. 2016), the authors devote a large section to DCV systems, including 15 additional papers from 2004 to 2013. Four of these concern smart ventilation in residential buildings (Jreijiry, et al. 2007; Laverge, et al. 2011; Nielsen and Drivsholm 2010; Pavlovas 2004). As a result, these three available reviews include 15 papers on smart ventilation, all DCV, in residential buildings.

The review for this research analyzed 23 additional studies of interest on residential smart ventilation. Thirteen of the studies report on various smart ventilation systems using either CO_2 control or humidity control; one presents a combined CO_2- and TVOC-controlled ventilation system; three study occupancy-based smart ventilation systems; three study outdoor temperature-controlled smart ventilation; and three LBNL studies look at other smart ventilation strategies including the development and use of the RIVEC prototype.

Results of these 38 studies are compiled in **Table 13**. Performance results in the analyzed studies are very difficult to compare for at least four reasons:

1- Difference in the types of smart ventilation systems used: there is often a lack of precise data on the type and location of sensors, the type of control and the type of ventilation system.
2- A lack of information on the conditions of the studies (climate, occupancy, energy performance level, range of ventilation rates, building materials emission, and absorption characteristics). A study can give bad results for given conditions but this does not necessarily mean that the system is bad.
3- Calculation of indicators: there is neither a universal indicator, nor a universal method to calculate the indicators, and there is often a lack of uniformity in the way the indicators are calculated. For instance, the average CO_2 concentration is often given without information on either the location of the measurement (which room), or the averaging time used (one day, one week, one year).
4- Differences in reference cases: Reference cases, including reference airflow rates, are different in each standard or code to which each building regulation refers. Comparisons of IAQ and energy performance must also be carefully analyzed.

The performance of humidity- and/or CO_2- controlled smart ventilation systems has been considered in several modeling and field studies.

Until the early 1990s, researchers published primarily case studies in the literature, reporting a large range of energy savings (0% to 60%) with small to moderate IAQ improvements (Anon 1983; Barthez and Soupault 1984; Nicolas 1985; Sheltair Scientific, Ltd. 1988; Wouters, et al. 1991; Moffat, et al. 1991; Mansson 1993; Kesselring, et al. 1993). Though all the data required to account for these large differences is rarely available, a few explanations are likely: type of DCV system, improvement over time for these technologies, and outdoor climate (for humidity-controlled DCV).

Parekh and Riley (1991) studied the implementation of an RH-based DCV system in two houses. The whole-house ventilation system had inlet exhaust grilles with a cross-section size that modulated in response to the RH level in the room. They observed only 6% energy savings (calculated over a short time period, which could reduce calculated savings) and concluded that IAQ was poor, especially in the bedrooms where CO_2-concentration was greater than 1200 ppm. They highlighted the fact that a high level of air leakage in their setup would reduce the potential impact of the ventilation system.

Nielsen (1992) monitored the performance of a humidity-based DCV system installed in a new single-family house in Denmark, occupied by two retired people, 21 hours a day for a period of one month. The system injects air into each room, including the kitchen and bathroom, with exhausts in the bathroom and in a laundry room connected to the kitchen. A regulating damper in the inlet duct of each room regulates the air volume in response to temperature and relative humidity measurements. Sensors are located in each room and in the inlet duct. Two criteria control the operation of the ventilation system: first, the relative humidity must stay under 45% to avoid house dust mite growth; second, condensation on double-pane glass windows must be avoided. Additionally, the authors fixed the minimum airflow rate at 10 l/s, and the maximum airflow rate at 35 l/s. The control operates continuously and makes a control change every 1 minute. As a result, the total airflow rate was able to be reduced 39% below the

Danish code requirement, with a relative humidity of 45% exceeded about 10% of the time, and 47% exceeded only 1%—5% of the time. No condensation was observed, nor estimated, over the time of monitoring. CO_2 concentrations were lower than 1200 ppm 98% of the time.

Nielsen and Ambrose (1995) monitored the performance of humidity-controlled ventilation systems in 16 apartments for three months and compared results with a group of 16 identical apartments equipped with constant airflow ventilation. In most of the apartments, the balanced DCV system consists of on-off supplies controlled by capillary hygrostats in each bedroom, and exhausts in the bathroom and kitchen automatically regulated by a motor-driven exhaust air valve. The ventilation need is automatically accounted for by the pressure difference between the space and the fan inlet. The opening of inlet valves has no impact on total exhaust airflow but changes the distribution of where air enters the home: typically the air is supplied to the bedrooms. RH set points are fixed at 40% in bedrooms and 45% in other rooms. For outdoor air temperatures less than 1°C, a constraint, which is a function of indoor RH and outdoor temperature measurements, is added to avoid condensation on windows. The resulting maximum reduction in total airflow rate was 35%, obtained at an outdoor temperature of 1.5°C. For outdoor temperatures greater than 9°C, the airflow was constant because the outdoor air had no dehumidification potential compared to the indoor air. The mean relative humidity did not exceed 43% and was slightly lower in bedrooms equipped with DCV. No condensation on windows was recorded.

Afshari and Bergsøe (2003) present a five-year project on the evaluation and development of innovative energy and ventilation strategies. They calculated energy savings of 20%—30% for an RH-controlled ventilation system that they confirmed by measurements on a test apartment. In this apartment, they simulated two-person occupancy and emissions from materials and furnishings (using an N_2O tracer) in the living room. They first installed a standard exhaust-only ventilation system delivering a constant rate of 35 L/s (20 L/s in the kitchen and 15 L/s in bathroom). Next, they installed RH-controlled exhausts and passive RH-controlled inlets. The base flow rates were 10 L/s[1] in humid rooms. A relative humidity of 45% activated a high rate of 50 L/s in the kitchen and 20 L/s in the bathroom. As a result, even with a higher exhaust rate in the kitchen, the home ventilation rate is reduced to 2/3 that of the reference case. The CO_2 concentration is reduced by 10% and the concentration of pollutants emitted by materials and furnishings is reduced by 50% in the living room.

Pavlovas (2004) modeled a typical Swedish apartment equipped with four types of exhaust-only ventilation with the IDA Climate and Energy software. The four types of ventilation were:

1) A reference system providing a constant airflow rate
2) A CO_2-based DCV system with sensors in humid rooms
3) A humidity-based DCV system with sensors in humid rooms
4) An occupancy-based DCV system.

In all systems, the exhaust airflow rate varies from a base flow of 10 l/s up to 30 l/s when needed. Different setpoints were tested: 800 ppm, 1000 ppm, and 1200 ppm for CO_2-based control, and 60%, 70%, and 80% for the maximum humidity threshold. Position of interior doors (closed or open) was also tested. Both CO_2- and occupancy-based DCV resulted in similar CO_2 concentrations but increased the risk for high humidity levels. The RH-based DCV increased CO_2 concentrations. Both CO_2 and RH strategies resulted in more than 50% annual heating demand savings, and the occupancy-based system resulted in approximately 20% energy savings. Optimal setpoints were found to be 1200 ppm for the CO_2 concentration and 80% for the high relative humidity threshold.

Jreijiry et al. (2007) developed and tested a demand-controlled hybrid ventilation system for residential buildings as a part of the RESHYVENT European project. Yearly simulations were performed in houses located in four climates equipped with two different DCV systems: one based on CO_2, the other on occupancy in the dry rooms. In each system, occupancy is detected in the toilets, humidity is detected in the bathroom and kitchen, and temperatures of exhaust and outdoor air are used. Air inlets and exhaust grilles can be modulated to eight different positions. Every 10 minutes, a control algorithm adjusts the fan speed in response to the measured data and the available natural ventilation. In the CO_2-based DCV strategy, inlets and grilles open based on humidity and CO_2 concentration. Both strategies have economizer and night-cooling functionality in their algorithms. Results were compared to a single-exhaust ventilation system. They showed better performance under colder climates because of the greater stack effect. In all the climates, the CO_2 exposure in occupied dry rooms is reduced at least by a factor of two: the summer thermal comfort is nearly always better, the energy for heating is reduced 2%—5%, and the electrical consumption of the fan is reduced 91%—96%. IAQ was better with the strategy based on CO_2.

Van den Bossche, et al. (2007) modeled an exhaust-only RH-based DCV system in a typical Belgian house equipped with self-regulating trickle ventilators with CONTAM and compared results with an exhaust-only constant airflow ventilation system. They simulated four-person occupancy and used outdoor data from a reference year in Uccle, Belgium. The nominal ventilation exhaust rates were 50 m^3/h in the kitchen and 25 m^3/h in the bathroom. In the DCV strategy, humidity sensors in the humid rooms controlled airflow to 20%—100% of the nominal airflow for a relative humidity range of 30%—100%, with a linear relationship between the two setpoints. Also, motion sensors in humid rooms ensured nominal airflows for a 20- to 30-minute period after the last detection of occupancy.

Van den Bossche showed that IAQ, estimated either by the time spent in each CO_2-IDA class of the EN 13779 standard, or by the LKI index of the Dutch standard (Equation 22), was slightly lower for the studied DCV system. The other indicator used was the percentage of time when relative humidity failed to stay in the 30%—70% range. This indicator was found to be very sensitive to envelope airtightness. In the bathroom and bedroom of an airtight house (n_{50}=0.6 h^{-1}), the studied DCV system maintained the space in this range only for 67% of the time, while the reference system succeeded 90% of the time. For a house with average airtightness (n_{50}=11.2 h^{-1}), they observed no difference in performance. The energy savings potential was calculated at around 1,100 kWh—1,200 kWh, which is about 27% of the ventilation-related energy for very airtight houses, and 14% of the energy for houses with an average airtightness. They also studied the moisture-buffering effect and showed that it did not affect DCV performance, with only 0.75% extra energy demand.

Woloszyn, et al. (2009) studied the performance of humidity-based DCV systems for residential buildings, comparing four different heat, air, and moisture simulation software packages and taking into account the moisture-buffering effect. For a whole-house exhaust-only ventilation system with exhaust airflow depending on RH, Woloszyn showed a mean ventilation rate reduction of 30%—40%, generating 12%—17% energy savings during the cold season. They highlight that these gains were achieved while keeping the peak RH values the same. As CO_2 concentrations were estimated to be greater than 1,200 ppm around 33% of the time during the cold period, they conclude that an optimization of combined RH- and CO_2-based strategies should result in better IAQ performance.

During the Performance Project (Air H 2010; Bernard 2009), measurements during two complete heating seasons were performed in 31 new occupied apartments equipped with humidity-based inlet and outlet DCV systems. Measured variables included outdoor and indoor CO_2, temperature and humidity, and ventilation parameters (pressure, inlet cross-sections, airflows through the trickle ventilators, and exhaust air outlets). The measured values were recorded every minute. The measurements validated the theoretical IAQ performance modeled by the software used in the French agreements for DCV systems (Avis techniques). Cumulative CO_2 exposure, even in high-occupancy bedrooms (four adults), and condensation risk were very low in the vast majority of homes. IAQ was better in bedrooms during nights than it was with fixed air inlets. Total average ventilation airflow was measured at approximately 30% lower than with fixed ventilation rates. Energy savings on ventilation motor consumption was estimated at between 35% and 50%. The authors extrapolate this result to homes with greater occupancy and arrive at ventilation energy savings of approximately 55%.

Nielsen and Drivsholm (2010) studied a simple DCV approach for homes measured the concentration in the air-handling unit and modulated the fan speed between two levels. This strategy was implemented in a new Danish single-family house occupied by two adults and two children and equipped with a single ventilation system. Measurements were performed with and without the new control strategy. The high speed is fixed to 100% of fan capacity and is based on the flow rate required by the Danish building code (216 m^3/h or 0.43 $l.s^{-1}.m^{-2}$ for the tested house); the low speed is 40% of the speed at high-flow rate. A difference of 100 ppm, 150 ppm or 200 ppm between CO_2-concentrations measured in the exhaust or outdoor air signals that the building is occupied and activates operation at the high speed. A difference of 2g/kg in absolute humidity also activates high-speed operation, which takes into account the fact that in the Danish climate the outdoor temperature is below 5°C over 3000h per year. Results show an optimum at a CO_2 concentration difference setpoint of 150 ppm. At this setting, the ventilation rate can be set to “low” 37% of the time without significant change in the CO_2 concentrations compared to the fixed rate ventilation strategy, but with energy savings estimated at 35% of the fan’s electricity consumption and 37% of its heating needs. Measurements of the fan speed throughout the week show that the control strategy followed the unoccupied schedules during daytime well.

Laverge, et al. (2011) tested the performance of four approaches for DCV in a typical Belgian house: 1) humidity-controlled in the humid rooms with an “on-off” strategy on the size of the exhaust grille based on an RH setpoint of 70%, 2) occupancy-controlled, with an “on-off” strategy on the fan running once 20 minutes of occupancy is detected, 3) CO_2-controlled in the dry rooms with air inlets reduced to 10% opening if CO_2 concentration is lower than 1000 ppm in the room, 4) the three approaches combined. Multi-zone modeling was performed with CONTAM and results were compared to a reference exhaust-only constant flow rate ventilation. Two IAQ indicators were used: 1) The mean excess CO_2 concentration over 1000 ppm to which an occupant is exposed during the heating season, 2) the exposure to a tracer gas emitted in toilet rooms (efficiency of the exhaust in removing at source). The total, heating season ventilation energy savings were in the range of 25% (only one control parameter) to 60% (three combined). CO_2 detection in dry rooms was found to be more robust than than the other strategies. Reducing inlet size effectively moves responsibility for aerodynamic management to the fan, rather than wind or stack effect. Complementary analyses with different levels of envelope airtightness confirmed this analysis. The CO_2 indicator results were better with CO_2 and occupancy control. Exposure to the toilet room tracer gas under all strategies was similar.

In a recent study evaluating different control algorithms mainly based on the 35 DCV systems available on the Belgian market, Caillou, et al. (2014b) calculated the energy savings to be between 0% and 40%, varying by type of system, for only the systems fulfilling the IAQ requirements. The most IAQ-friendly and energy-efficient systems are locally regulated and combine an exhaust controlled by relative humidity in each humid room and a supply (through air supply inlets in a balanced system or through trickle ventilators in an exhaust only system) controlled by CO_2 in each dry room. The less IAQ-friendly and energy-efficient systems are those with only RH-regulated exhaust in humid rooms and no control on the air inlets. Most energy saving coefficients are given later in Table 9.

Another recent study was based on one year of measurements in 62 homes in the Netherlands (van Holsteijn and Li 2014), some of which were equipped with CO_2-based DCV systems. They used cumulative CO_2 exposure index requirement, LKI_{1200}, as an IAQ indicator (Equation 22). Depending on the location of the sensors, they showed a range of performance for the DCV systems. If RH and CO_2 sensors were all linked to a mechanical supply and/or exhaust air component in the rooms where the sensors were located, good performance was observed. In the other cases, energy performance and IAQ can be worse than in constant airflow reference systems. Reference systems for single-exhaust ventilation had a mean performance of 119 MJ/m²/heating season and 244 kppm/person. Systems with only CO_2 sensors in the living room decreased the performance of the two systems by 21% and 11%, respectively. Systems with RH and CO_2 sensors in all the rooms increased performance by 31% and 70%, respectively. The reference system for balanced ventilation had a mean performance of 24 MJ/m²/heating season and 68 kppm/person. Systems with only CO_2 sensors in two zones increased energy performance by 24% and decreased IAQ by 54%; systems with RH and CO_2 sensors in all the rooms decreased performance by 325% and 169%, respectively. Systems with RH and CO_2 sensors in all the rooms and supply in the connecting spaces increased energy performance by 45% and decreased IAQ by 11%.

The performance of other pollutant-based smart ventilation systems for residential buildings has been studied by Seong (2010). A standard Korean multi-zone apartment has been modeled with CONTAM and EnergyPlus at a 1 hour time-step, equipped with a whole-house balanced DCV system either based on CO_2 demand or on TVOC demand. The investigated control strategy is an “on-off” strategy, with a base airflow rate fixed at the reference in the Korean regulation, 0.7 h^{-1}. The location of the sensors is not given. TVOC generation rates were modeled based on data measured by the Korean Ministry of Environment. They differ for each room, and include an emission rate per floor area, then finishing and product emissions (furniture, bed mattress, chest of drawers, desk, personal computer, chair, kitchen unit, shoe rack, TV). The TVOC exposure is not calculated and thus it is difficult to compare the performance results. The CO_2-based DCV strategy allows the home to stay under 1000 ppm at low TVOC concentrations most of the time, with some peaks, staying in the range 150 $\mu g\text{-}m^3$—800 $\mu g\text{-}m^3$. The energy savings are estimated at 17%. The TVOC-based DCV strategy maintains CO_2 concentrations under 2200 ppm, and TVOC concentrations of 400 $\mu g\text{-}m^3$—800 $\mu g.m^3$. It showed energy savings estimated at 26%.

The performance of occupancy-based smart ventilation systems has been demonstrated in some modeling and field studies.

Through a preliminary TRNSYS-modeling study, Römer and van Ginkel (2003) demonstrated energy savings of about 15% for a low-energy house equipped with a ventilation system with a night-time strategy. In this strategy, base airflows during nights are multiplied by a factor of two in bedrooms and reduced by the same factor in the other rooms. Another strategy consisted of dividing base airflows by a factor of two when rooms were unoccupied. Based on a typical schedule for a four-person family, they calculated 20% energy savings. Such a balanced occupancy-based ventilation system was installed in a low-energy test house. If the relative humidity in a room exceeded 70% or the indoor temperature exceeded the comfort temperature, the high airflow rate was also activated. Movement detection in a room manages ventilation system control dampers directing flows to individual rooms until the prescribed levels of temperature and RH are reached. Römer and van Ginkel measured a reduction of 50% to 80% in the kitchen air change rate, no change in bedroom air change rate, and an increase of 160% in the living room, compared to the constant air change rate. No information is given in the paper about the total airflow reduction or IAQ effects.

Several studies from LBNL have demonstrated the applicability of an intermittent ventilation strategy for residential buildings based on occupancy. The concept of equivalence in exposure was primarily developed considering such strategies (Sherman 2004) and has been integrated into previous updates of the ASHRAE 62.2 standard (2016). Later, Sherman, et al. (2011) further developed this concept to apply under a variety of ventilation rates, emission rates, and the evaluation periods for the dose.

Based on this background for chronic and acute exposure evaluation, D. K. Mortensen, et al. (2011) studied the optimization of the performance of a whole-house ventilation strategy with two fan speeds. They studied variations in the emission ratio (the ratio between all pollutant source strengths and background pollutant source strength), the low ventilation factor (the ratio between the low ventilation rate and the ventilation rate of the equivalent constant rate system), and this equivalent constant rate. They show that the performance can always be optimized given the occupancy time and emission characteristics. The low-ventilation factors were 0.13—0.4 at peak effectiveness, and all the systems had a high-to-low airflow ratio of 2.5-5. Mortensen also calculated the ratio of the acute to the chronic exposure and showed that it was always less than three, which means that such DCV systems also provide for acceptable peak exposures. Their research shows that, for a home occupied for 16 consecutive hours, the total ventilation rate reduction is about 12% compared for equivalence to a target constant rate of 0.5 h^{-1} and an emission ratio of 1.5. At the extreme case when occupant pollutant emissions are dominant, the reduction can be approximately 18%. At the other extreme, where there is no contribution to contaminant emissions from occupants, reduction is minimal at 9%.

In a recent modeling study of a new three-level house in Sweden, Hesaraki and Holmberg (2015) studied the IAQ and energy impact of a whole-house exhaust-only DCV system based on occupancy, considering unoccupied periods of 4, 6, 8, and 10 hours. The whole-building airflow rate is 60 l/s (0.75 $l/s\text{-}m^{-2}$) and is switched to 16 l/s(0.1 $l/s\text{-}m^{-2}$) during unoccupied periods. Compared to the reference constant airflow system at 60 l/s, the mean age of air at 6 pm (when occupants return) decreases to 94.7%, 82.8%, 66.7%, or 48.7%, respectively. The VOC concentration increases to 3%, 4%, 7%, or 15%, respectively—in the last case going over the threshold value to 0.1 ppm while the CO_2 concentration stays below the considered 1000 ppm threshold value. For the acceptable IAQ system with 8 hours unoccupied (e.g., the ventilation is turned on two hours before the occupants come back) the heating energy savings was estimated at 20% and fan consumption 30%. As a result, the total building energy consumption was reduced by 10%, from 52 kWh.m^{-2} to 47 kWh.m^{-2}. Similar savings were also observed by Laverge, et al. (2011).

The performance of outdoor temperature-controlled smart ventilation systems has been demonstrated in some recent modeling studies, sometimes in conjunction with hybrid ventilation systems.

The use of RIVEC, presented in detail in the following section, was studied to optimize hybrid and passive ventilation strategies in single-family homes (Turner and Walker 2013). In this study, RIVEC first determines the available airflow rate in a designed passive stack (the signal could be given from a pressure probe or other airflow meter). This passive stack airflow is limited to 100% of the ASHRAE 62.2 minimum requirement. If the airflow is not sufficient to meet the IAQ equivalence requirements, RIVEC turns on the whole-house exhaust fan. As a result, Turner and Walker showed that there was room to optimize hybrid ventilation systems with good sizing of the passive stack and smart ventilation strategies.

Less, et al. (2014) recently used RIVEC to study an outdoor temperature-controlled ventilation strategy allowing ventilation to be switched off when the stack effect alone was sufficient to provide ventilation. Simulations were performed in all U.S. climate zones, for two house geometries and under envelope airtightness levels in the range of 0.6—10 air changes at 50 Pascal (ACH_{50}). Four control strategies were studied to optimize the solution:

1. Infiltration dependent: the fan is turned off if stack effect provides the target airflow
2. Infiltration dependent2: the fan is turned to half-flow if stack effect provides 50% of the target airflow
3. Infiltration-independent-25th: the fan is turned off each time the outdoor temperature drops below 5°C
4. Infiltration-independent-25th: the fan is turned-off each time outdoor temperature drops below the 25th percentile of coldest hours determined from TMY data files.

The simplest strategy, with the cutoff set to 5°C, was the most efficient across a variety of climate zones. However, this approach of accounting for natural infiltration is limited in tighter homes. Houses tighter than 3 ACH_{50} were never able to reach natural infiltration air change rates equivalent to ASHRAE 62.2 (note that the natural infiltration airflows were still accounted for in the controls). For leakier houses in severe climates, such strategies can become effective and reach annual HVAC energy savings in the range of 100 kWh—4000 kWh. Fans should be oversized by 5%—150%, with an average of 34%.

Lubliner, et al. (2016) further investigated such a low-cost, temperature-based smart ventilation control system (less than $80) on two houses, using REGCAP and EnergyGauge USA energy software and a field-testing campaign lasting several months in two climates. Weekly testing in these houses allowed them to fix the outdoor temperature setpoint for each house. As a result, they obtained energy savings between 73 kWh/year and 230 kWh/year. They also demonstrated the importance of the location of the temperature sensors. They observed no significant effects on CO_2 or humidty using this strategy. Occupancy, window opening and wind effects were found to have significant effects on CO_2 and humidity.

Other control strategies for smart ventilation systems have also been studied by LBNL during the development of the smart ventilation concept based on equivalence in exposure (Sherman 2004). Sherman and Walker (2011) developed RIVEC, the smart ventilation prototype. This update to their previous work consisted of an intermittent ventilation strategy controlled by the operation of other air devices in the house and with a switch-off during the 4-hour period of peak energy demand. The theoretical background supposes a continuously occupied home with a constant emission rate. The authors propose controller logic with a set of actions at each time step, fixed primarily at 10 minutes. The controller:

1. Determines the current ventilation rate, taking into account exogenous ventilation airflows and separating exhaust, supply, and balanced flows
2. Estimates the current IAQ from relative exposure and the relative dose calculated with the constant emission rate assumption
3. Turns on or off the whole-house ventilation system, according to a detailed control algorithm dividing the day into four periods: a 12h-base period, a 4h-pre-peak shoulder period, a 4h-peak period (off), and a 4h- post-peak period.

Simulations were performed with a 1-minute time-step with the simulation tool REGCAP (Walker and Sherman 2006) on a typical new Californian home in three climate conditions (mild, warm, and cold mountain). This smart ventilation strategy was modeled with four ventilation types: continuous exhaust, heat recovery ventilator, continuous exhaust with a central fan integrated supply, and continuous supply. They observe a decrease in the annual average relative dose of up to 14% and a peak relative exposure no more than 11% above the target limit, even with a 4-hour shutoff period. Energy savings, including heating gas savings and electricity savings (cooling and fans), were estimated between 11% and 61%. Energy savings recalculated considering equivalent IAQ (and not better IAQ as originally observed) were between 20% and 64%. The fractional run time of the ventilation fans was about 25% of what it would be without dynamic control.

Next, Walker and Sherman present the RIVEC prototype (Walker, et al. 2011). After being built and bench tested it was field tested in an occupied house in Moraga, California, and equipped with an economizer. The field test was divided into three periods: three weeks of operation of the RIVEC system, six days with the whole-house ventilation system turned off, and two days with the whole-house system operating without RIVEC. From measurements, simulations were performed over the year and energy savings were estimated at 1000 kWh. RIVEC reduced the run time of the fans by up to 71% for a home with an econmizer. The whole-house fan must be oversized by 25% to allow it to provide sufficient off-peak ventilation rates.

The RIVEC was then further developed to be more robust, with only two periods in the day (eliminating the pre and post-peak periods), and to take into account varying occupancy in the control algorithm (Turner and Walker 2012, 2013). These further modeling investigations with REGCAP (Walker and Sherman 2006) looked at diverse climates (16 Californian climate zones), various home geometries, four mechanical ventilation systems, and two passive or hybrid systems and envelope airtightness levels to give a good representation of the majority of the California housing stock. The authors concluded that ventilation energy savings are typically 40% while maintaining, or even going beyond the IAQ equivalence of ASHRAE 62.2, and without allowing unacceptable acute exposure to constantly emitted pollutants. This results in absolute energy savings from 500 kWh/year to 7000 kWh/year per household. Those energy savings are robust across climate, house geometry, and airtightness level. The peak power is also significantly reduced up to 2 kW for a typical house.

Another aspect of smart ventilation is to control exposure to outdoor pollutants—typically particles and ozone. RIVEC was used to simulate a smart ventilation strategy that switched off the ventilation fan during outdoor ozone level peaks in a typical single-family house located in two places in California (Walker and Sherman 2013). They demonstrated reductions of 10%—40% in indoor-to-outdoor ozone ratios compared to continuously operating ventilation systems for a typical new California home (Specific Leakage Area = 4).

Much less work has been done with the goal of employing residential ventilation as a resource for the electric grid. This is likely the case for several reasons, including the lack of dedicated residential ventilation systems in the United States, the need for active control of ventilation systems rather than some of the passive systems discussed above which are used in Europe, the need for infrastructure that can inform smart residential systems of grid needs, and the barriers to smart ventilation in general mentioned above.

Notable exceptions are the 2016 studies by Rotger-Griful, et al. (Rotger-Griful, Jacobsen, Nguyen, and Sorensen, 2016; Rotger-Griful, et al. 2016). These studies looked at the demand-response potential of ventilation systems in Nordic countries where heating and cooling are not needed and reduced load from curtailed ventilation would be in the form of fan power only. They found that, for short-term modulation, ventilation in a 12-story residential building with 159 apartments could provide 1 kW of reduction and 4.5 kW of power increase in 30 seconds. For peak demand reduction, they showed that ventilation could be curtailed to reduce power by 1.5 kW without increasing the CO_2 concentration beyond 900 ppm. The authors conclude that many such buildings would need to be aggregated in order to provide a substantial service to the grid.

Table 13 : Summary of surveyed studies on energy and IAQ performance of smart ventilation strategies in residential buildings.

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Anon 1983) ***France*** **Original paper not found, information from the review in Raatschen 1990**			Balanced + whole house + short term supplementary airflows in kitchen	RH-controlled exhaust grilles + RH-controlled supply	The measured average relative humidity controls the supply and exhaust airflow rates	Cost of 230€ for a 3 BR-apartment Humidity sensors, air inlets and exhaust have been tested for several years in two independent laboratories (EDF+CETIAT)	Fewer condensation problems	50%-60%
(Barthez and Soupault 1984) ***France*** **Original paper not found, information from the review in Raatschen 1990**	Apartment	Modeling + experimental	Single Exhaust + Whole house + Short term supplementary airflows in kitchen	CO_2 + no sensor in other rooms	Control a two-speed fan	Good relationship between CO_2 and occupancy but difficult to conclude relationship between CO_2 and relative humidity	CO_2 between 400 and 750 ppm Relative humidity around 60%	60% of the total airflow modeled and measured
(Nicolas 1985) ***France***	Residential	Modeling	Single exhaust + whole house + Short term supplementary airflows in kitchen	Mechanical RH + Mechanical RH	The cross-section of the air inlets and outlets is a mechanical function of RH	Performance varies according to air leakage level, climate, occupancy, and activity level scenarios		30% of the total exhaust airflow (takes into account compensation by air leakage) 10% heating energy savings
(Sheltair Scientific, Ltd. 1988) ***Vancouver, Canada***	1 house	Monitoring for 1 week	Single exhaust + whole house	Mechanical RH	The section of the air inlets and outlets is a mechanical function of the RH	The tested system shall be more effective in a drier climate Some accuracy measurement problems were underlined by the authors	The relative humidity levels stayed constant, without responding to the occupancy,	0 %, explained after further investigations by leaks on the boiler heater
(Parekh and Riley 1991) ***Ottawa, Canada***	2 houses	Monitoring campaign over 6 months	Single exhaust + whole house	Mechanical RH + Mechanical RH	Cross-section of grilles is mechanically controlled function of RH	Impact of air leakage underlined	Poor IAQ, especially in the bedrooms with CO-concentration > 1200 ppm	6 % energy saving
(Mansson 1993) **(Wouters, et al. 1991)** ***Namur, Belgium***	9 reference flats + 9 equipped with RH DCV in a 9-story building	Monitoring campaign 3 days in 3 periods	Natural + whole house (Shunt ductworks in humid rooms)	RH-controlled exhaust grilles + RH-controlled grilles	Cross-section of grilles is mechanically controlled function of RH	Same CEC project as the two following studies No measure in the bedrooms and living rooms	% of time CO_2 under 1000 ppm and 1500 Is lower with DCV	**improvement

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Mansson 1993) **(Wouters, et al. 1991)** ***Schiedam, The Netherlands***	7 reference flats + 7 equipped with RH DCV in a 10-story building	Monitoring campaign 72 days in 3 periods	Natural + whole house (Shunt ductworks in humid rooms)	RH-controlled exhaust grilles + RH-controlled grilles	Cross section of grilles is mechanically controlled function of RH	No measure in the bed- and living-rooms The poor results are explained by the small size of the existing ducts	No improvement	**no improvement
(Mansson 1993) **(Wouters, et al. 1991)** ***Les Ulis, France***	10 reference flats + 10 equipped with RH DCV in a 5-story building	Monitoring campaign 143 days in 3 periods	Natural + whole house (Shunt ductworks in humid rooms)	RH-controlled exhaust grilles (except in kitchen) + RH-controlled grilles	Cross-section of grilles is mechanically controlled function of RH	No measurement in the bedrooms and living rooms Airtight building with appropriate size of existing ducts explains the good results	CO_2 and RH are well correlated	** 30% on a heating season
(Mansson 1993) ***Torino, Italy (2700 HDD)***	9 rooms of 3 flats in a 6-story building	2-month monitoring campaign heating period	Simple exhaust + whole house	RH-controlled exhausts + RH-controlled grilles	Cross-section of grilles is mechanically controlled function of RH		Surface condensation risk on windows metal frames related to meal preparation	40% of the total airflow
(Mansson 1993) ***Maasbree, The Netherlands***	1 attached energy-efficient house	Monitoring 2 weeks	Balanced + whole house	1)RH sensor in living room 2) RH sensor in exhaust air 3) RH sensor and mixed gas sensor in exhaust air	Setpoints- RH: adjusted as a function of outdoor air temperature: control three fan speeds (35-155-220 m^3/h)		Average bedroom CO_2 concentration: Ref) 900 ppm 1) 1050 ppm 2) 890 ppm 3) 575 – 790 ppm No condensation risk	*** Fan level in % low/middle/high Ref) 73/3/24 1) 100/0/0 2) 100/0/0 3) 29/16/55
(Mansson 1993) **(Moffat, et al. 1991)** ***Ottawa & Vancouver, Canada***	5 energy efficient houses	Monitoring before and after DCV installation from 189h to 1385h	3 Balanced, two simple exhaust + whole house	CO_2, pressure differences, temperatures, RH, absolute humidity, activity, operating of air equipment.	Smart ventilation strategy	The study also included the test of air cleaners	Slight reduction in average CO_2 but significant reduction in peak CO_2 levels.	-6 to 21% of total airflow - 23 to 34% of fan electrical energy demand
(Nielsen 1992) ***Denmark***	A new single family house	Monitoring over 1 month	Air supply in all the rooms, with exhausts in the bathroom and in a laundry room + local regulation	RH	A damper in the inlet duct of each room modulates air volume every minute, RH < 45%		RH>45% 10% of the time, RH>47% only 1%-5% of the time. No condensation. CO_2 <1200 ppm 98% of the time	Total airflow rate could be reduced at least 39% below the Danish code

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Kesselring, et al. 1993) ***Florida, USA***	1 energy efficient home	5 days monitoring	Balanced + whole house	1 indoor CO_2 sensor, no location information	On-off-controlled Dt=15 min based on a 600 ppm setpoint		CO_2 concentrations in master bedroom 600-900 ppm	The ventilation system was on 1/3 of time
(Nielsen and Ambrose 1995) ***Denmark***	16 apartments	Monitoring during 3 months	Balanced + whole house + centralized and local regulation	RH air supplies and exhausts controlled by capillary hygrostats in each room	Set points fixed to RH=40%-45%. If outdoor air < 1°C, a condensation criterion is added	Results were compared with a group of 16 identical apartments equipped with constant airflow ventilation	Mean RH< 43% No condensation on windows was registered.	Maximum reduction in total airflow rate: 35% For outdoor temperatures > 9°C, 0%
(Römer and van Ginkel 2003) ***Petten, the Netherlands***	1 test low-energy house	Preliminary modeling (TRNYS) + experimental results	Balanced + whole house + local regulation	Occupancy + RH + indoor temperature	1a) night time strategy 1b) occupancy strategy 2) occupancy, RH> 70% or indoor temperature > comfort		1) not studied 2) no significant risk from biological agents, temperatures>25°C often occur during the winter, low radon levels	Modeled energy savings : 1a) 15% 1b) 20% 2) No information
(Afshari and Bergsøe 2003) ***Denmark***	1 test 1BR apartment 74m², a 2-person occupancy simulated	3 days monitoring	Exhaust-only, whole house + local regulation	RH + passively controlled RH air inlets	Minimum rate fixed at 10 L.s^{-1}, RH=45% activate a forced rate in humid rooms	2-person occupancy simulated with CO_2 and RH emissions, constant NO_2 emission simulated emission from material and furnishings	CO_2 concentration – 10% Pollutant emitted by materials and furnishings – 50%	Total airflow rate – 30%
(Pavlovas 2004) ***Sweden***	A typical Swedish apartment	Modeling (IDA Indoor climate and energy)	Exhaust only, whole house + global regulation	1) CO_2-based DCV with sensors in humid rooms, 2) humidity-based DCV with sensors in humid rooms, 3) occupancy-based DCV	Exhaust airflow 10 l.s^{-1} or 30 l.s^{-1}.	Indoor doors closed or open have been also tested. Optimums were found at setpoints at 1200 ppm CO_2 and 80% high RH.	CO_2- and occupancy-based DCV: similar CO_2 concentrations but increase in risk of high humidity levels RH-based DCV : increases CO_2 concentration	Annual heat demand savings: >50% (CO_2 and RH) 20% (occupancy control)
(Jreijiry, et al. 2007) ***Athens, Greece*** ***Nice, Trappes, France*** ***Stockholm, Sweden***	Single family house	Modeling (MATLAB/Simulink and Simbad)	Whole-house assisted (hybrid) natural ventilation	Toilets: occupancy kitchen and bath: RH dry rooms:	Air inlets and grilles over 8 positions. A 10-min control algorithm		CO_2 exposure in occupied dry rooms is at least reduced by a factor of 2, the	Heating needs reduced: 2%-5% Fan electrical consumption reduced: 91%-96%

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
				1)occupancy detection 2)CO_2	regulates the fan speed		summer thermal comfort is nearly always improved	
(Van den Bossche, et al. 2007) ***Uccle, Belgium***	1 house with different airtightness	Modeling with CONTAM	Whole-house exhaust only	RH-controlled exhausts in humid rooms, self-regulating trickle ventilators in dry rooms, motion sensors in kitchen and bathroom	Linear relationship between RH in range 30%-100% and nominal airflow rate in range 20%-100%. Motion sensors in humid rooms activates nominal airflows for 20-30 minutes	Simulated 4-person occupancy	IAQ, estimated either by the time spent in each CO_2-IDA class, or by cumulative exposure, is slightly lower for the studied DCV system. In bathroom and bedroom of an airtight house (n_{50}=0.6 h^{-1}), DCV system in the range only for 67% of the time	Energy savings around 1100 kWh-1200 kWh, 27% for very airtight houses, 14% for houses with average airtightness. The moisture buffering effect adds only a 0.75% extra energy demand.
(Krus, et al. 2009) ***Three climates in Germany***	1 test apartment 75m², 3-person occupancy simulated	Modeling (Wufi-Plus)	Exhaust-only, whole house + local regulation	RH + RH	Fan at constant pressure 100 Pa, RH controls the opening of valves in exhaust ducts	Goal of this study was to compare an exhaust-only DCV system with a balanced system with heat recovery	CO_2 stayed lower than 1200 ppm	Not investigated
(Woloszyn, et al. 2009)	1 test room	Modeling (TRNSYS, IDA-ICE, Clim2000, HAM-Tools)	Exhaust only, whole house + local regulation	RH-controlled exhausts in humid rooms	Linear relationship between measured RH and nominal airflow rate	They stress that these gains are obtained while keeping the peak RH values the same	RH in the range [40%-50%] 80% of the time and CO_2 concentrations higher than 1200 ppm 33% of the time during the cold period	Mean ventilation rate reduced 30%-40% and energy savings 12%-17% in the cold period
(Air H 2010; Bernard 2009) ***Paris and Lyon, France***	31 new apartments	Monitoring over two heating seasons	Exhaust-only + whole house + local regulation	RH-controlled exhaust grilles + RH-controlled inlets + occupancy in toilets	Cross-section of grilles is mechanically controlled function of RH	Measured parameters included pressure, air inlet opening cross-sections, airflows through the trickle ventilators and the exhaust air outlets	Cumulative CO_2 exposure and condensation risk very low IAQ better in bedrooms (nights) than with fixed air inlets	-30% measured total average airflow - 35%-50% energy savings on fan consumption -55% total energy saving due to ventilation

Reference (classified by date) *Country*	Type of residential building	Method	Type of system + regulation	Type & location of sensors	Control strategy	Main findings / comments	IAQ performance	Energy savings compared to constant rate reference*
(Nielsen and Drivsholm 2010) ***Denmark***	A new single-family house	Measurements with and without the DCV system	Exhaust-only + whole house + centralized regulation	Difference in CO_2 and absolute humidity between measurements in the air handling unit and outdoors	High and low flow rates with setpoints fixed to a difference of 150 ppm in CO_2 and to 2g/kg in absolute humidity	Measurements of the fan speed along the week show that the control strategy succeeded in identifying periods that building was unoccupied	No significant change in IAQ	Low ventilation rate: 37% of the time Energy savings estimated to 35% on fan electricity consumption and to 37% on heating needs
(Seong, 2010) ***Seoul, South Korean***	A standard Korean multi-zone apartment	Multi-zone modeling CONTAM + Energy plus Dt=1 hp	Whole-house balanced DCV system	1)CO_2 demand 2)TVOC demand. Location of the sensors is not given.		"On-off" control strategy with a base airflow rate fixed at the reference in the Korean regulation 0.7 h^{-1}.	1) CO_2<1000ppm, TVOC in 150-800 mg.m^3 with peaks 2) CO_2<2200ppm, TVOC in 400-800 mg.m^3	1) 17%. 2) 26%.
(Laverge, et al. 2011) ***Belgium***	Typical Belgian single-family house	Modeling (CONTAM)	Exhaust-only Whole house + local regulation	1) RH in humid rooms 2) occupancy 3)CO_2 in dry rooms 4) the three combined	1)"On-off" size grille setpoint RH=70%, 2) "On-off" on fan - 20 min 3)Inlets reduced to 10% if CO_2 < 1000 ppm	Results were compared to a reference exhaust-only constant flow rate ventilation CO_2 detection in dry rooms was found to be more robust than other rooms	CO_2 exposure better in 2) and 3) Same exposure to the toilet tracer gas	Total mean convective heat ventilation loss in the range 25% (1 control parameter) to 60% (3 combined).
(D. K. Mortensen, et al. 2011)	Single-family house	Calculation approach	Whole-house ventilation	Occupancy schedules (of 4-8 or 16h)	Two fan speeds based on the chronic exposure equivalence calculation	Performance curve plots allow definition of optimum points given the occupancy time, the reference rate, the high to low ratio, the emission characterization	Equivalence in 24h-chronic exposure, acceptable peak exposure	For a home occupied during 16 consecutive hours Total ventilation rate - 12% Can achieve >-18% if occupant emissions are dominant
(Mortensen and Nielsen 2011)	Multi-family home	Modeling study	Whole house + balanced with heat recovery + centralized	N/A	Several control strategies on the air handling unit	The authors propose a simple cost-effective (+500$ compared to a heat-recovery balanced ventilation system) solution for the system design of a centralized balanced DCV system	Compared static pressure reset at part load conditions fixed static pressure	Yearly electricity consumption: -20% to 30%

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Sherman and Walker 2011) ***Three climates, California, USA***	Single-family house	a) Modeling (REGCAP) b) Field study of a prototype (RIVEC)	a) Whole house + centralized + 4 ventilation types b) exhaust-only with economizer	Control by the operation of other air devices and with a switch-off during a 4h-peak electricity demand period	Controller logic with a set of actions at each time step, set primarily to 10 minutes. Four periods in the day	The theoretical background supposes a continuously occupied home with a constant emission rate.	Decrease of the annual average relative dose can reach 14% peak relative exposure no more than 11% above the target limit, even with 4h-off period	a) Energy savings: -11 to 61%, run time of the ventilation fans: - 25% b) Annual energy savings estimated to 1000 kWh, run time of the fans: - 71%
(Turner and Walker 2012) ***16 climate zones, California, USA***	Single-family houses (3 geometries)	Modeling (REGCAP)	Whole house + centralized + 6 ventilation types	Same + occupancy	The controller logic was updated with 2 periods in the day based on occupancy	Energy savings are robust across climate, house geometry and airtightness.	Maintaining IAQ equivalence of ASHRAE 62.2, and without acute exposures to constantly emitted pollutants	Ventilation energy savings > 40%. Absolute energy saving 500 to 7000 kWh/year. Peak power reduction up to 2 kW
(Turner and Walker 2013) ***Sixteen climate zones, California, USA***	Single-family houses (3 geometries)	Modeling (REGCAP)	Whole house + centralized + hybrid exhaust-only system	Same	If the available airflow rate in a designed passive stack is not sufficient, RIVEC turns on the whole-house exhaust fan	The authors show that there was room to optimize hybrid ventilation systems with good sizing of the passive stack and smart ventilation strategies	IAQ clearly improved	Ventilation energy savings about 25%
(Walker and Sherman 2013) ***Livermore and Riverside, California, USA***	A typical Californian single-family house	Modeling (REGCAP)	Whole house + centralized + 7 types of ventilation	Same The 4h switch-off period for peak electricity demand coincides with peak ozone concentrations			A reduction of 10%-40% in ratios of indoor-to-outdoor ozone, while continuous exhaust ventilation systems gave ratios around 20%	
(Less, et al. 2014) ***All USA climate zones***	Single-family houses (2 geometries)	Modeling (REGCAP)	Whole house + centralized + exhaust only	Outdoor temperature	4 control strategies were studied to optimize the solution	The simplest strategy with a cut-off set to an outdoor temperature of 5°C was the most efficient one across a variety of climate zones	Equivalent IAQ	For houses >3 ACH_{50} in severe climates, HVAC energy savings of 100-4000 kWh Fan should be oversized by an average of 34%

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Szkarłat and Mróz 2014) ***Poznan, Poland***	1 passive house	Monitoring one year + Modeling	Whole HVAC system decentralized regulation	Temperature, RH, CO_2 sensors in every room	Variable air volume control as a function of sensible heat balance for temp control, latent heat balance for RH control, CO_2 balance	Challenge was in how to define control parameters and algorithms to deal with high internal gains in passive houses	1000 ppm was often exceeded, sometimes reached 1500 ppm or more	Not studied
(Caillou, et al. 2014b) ***Belgium***	1-level house	Modeling (CONTAM)	Natural, exhaust only, balanced + whole house + regulation Centralized or local	1)RH exhaust only 2) CO_2 supply only 3)RH exhaust+ CO_2 supply 4) RH exhaust only + central regulation 5) CO_2 supply only + central or zonal regulation 6) CO_2 sensor in dry room controlling exhausts (in dry room)	Multiple control strategies described in § *Availability, reliability and accuracy of pollutant-and occupancy-sensors*	Study evaluating different control algorithms based mainly on the 35 DCV systems available on the Belgian market	1) reference 2) better than ref 3) clearly better 4) lightly better 5) better 6) better	1) 0% 2) 26-37% 3) 38-39 % 4) -21 to -28% 5) -15% to +36 % 6) 4-35 %
(van Holsteijn and Li 2014) ***The Netherlands***	Occupied single-family house and apartments	1 year of experi-mental measure-ments	Natural, exhaust only, balanced + whole house + regulation centralized or local	13 types of ventilation systems including 7 CO_2 or CO_2+RH DCV		IAQ-indicator, LKI_{1200}, Equation 22. Depending on the location of the sensors, they showed varying performance in DCV systems	Reference for single-exhaust: mean of 244 kppm/person DCV : +11% to -70% Reference for balanced: mean of 68 kppm/person. DCV : +11% to -169%	Reference for single-exhaust: mean of 119 MJ/m^2/year DCV : -31% to +21% Reference for balanced: mean of 24 MJ/m^2/year DCV : -25% to +325%

Reference (classified by date) ***Country***	**Type of residential building**	**Method**	**Type of system + regulation**	**Type & location of sensors**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings compared to constant rate reference***
(Hesaraki and Holmberg 2015) ***Sweden***	3-level low-energy house	Modeling (IDA ICE 4)	Exhaust only, whole house, centralized	Unoccupied periods of 4, 6, 8, and 10 hours	Base airflow rate 60 $l.s^{-1}$ is switched to 16 $l.s^{-1}$ during unoccupied periods	For acceptable IAQ, the ventilation shall be turned on 2 hours before the occupants come back The reference constant airflow system delivers 60 $l.s^{-1}$	Mean age of air decreases resp. to 94.7,82.8,66.7,-48.7%, VOC concentration increases to resp. 3,4,7,15%, in the last case over the threshold value, CO_2 staid below 1000 ppm	20% on heating needs 30% on fan consumption, 10% on total building energy consumption
(Lubliner, et al. 2016) ***Washington and Illinois, USA***	2 houses	Modeling (REGCAP and EnergyGauge USA) + Test fields	Exhaust-only, whole house, centralized	Outdoor temperature	On-off strategy according to a predefined setpoint	Investigation of a low-cost temperature-based smart ventilation control (less than $80)	No significant impact on CO2 and humidity	Energy savings between 73 and 230 kWh/year

*: the reference is the constant flow rate of the required standard. The reference is also different in each country.

**: the reference case is a classic natural ventilation system

***: the reference case is a balanced ventilation system manually controlled with three speeds

Occupant behavior and suitability of automatically controlled ventilation systems

Several studies revealed that home occupants are not necessarily sensitive to the quality of their indoor air, and that they do not necessarily operate ventilation systems when they are needed. From this perspective, smart ventilation strategies including automatically controlled ventilation systems appear to be particularly relevant.

A review on the health of occupants in energy-efficient new homes (Leech, et al. 2004) reveals that 10% of the occupants don't use their ventilation system. In a field study measuring airflows and surveying occupants in 139 apartments in the southern part of the Seoul metropolitan area, Park and Kim (2012) observed that almost 70% of the dwellers did not use their mechanical ventilation system, and that 60% did so in order to save energy. In a recent study of 62 homes in the Netherlands (van Holsteijn and Li 2014), it was also revealed that occupants almost never control their ventilation systems, so that manually controlled ventilation systems stay at low speed most of the time. In the Performance Project (Bernard 2009), occupants did not realize that their ventilation systems were off during a one-month period, and also didn't try to compensate for it by, for instance, opening windows more often. Also in this project, through the two-year study, occupants almost never used the high-speed ventilation in the kitchen. This issue was confirmed by (Klug, et al. 2011; Mullen, et al. 2013) with only about a quarter of people regularly using kitchen exhaust fans. In a field survey in 300 recently built Dutch homes, (Balvers, et al. 2012) observed that almost all occupants (96%) do not use their ventilation system as prescribed by manufacturers.

We must also mention that some studies showed that occupants need to feel in control of some of the parameters in their environment, and that they could be bothered by the lack of personal control caused by an automated ventilation system (Balvers, et al. 2012; Boerstra 2013).

Faced with these considerations, a smart ventilation strategy is able to offer a compromise: the ventilation system doesn't need any input from the occupant to be efficient, but can allow for occupant control under some circumstance, such as a brief period of high occupancy (party) or high emissions (hobby activity, cleaning, etc…). Such systems with occupant-override capability should have an automatic reset, for instance every 24h (Walker, et al. 2014).

Suitability of a multi-zone–based approach

Exhaust-only and balanced ventilation systems, the predominant type in new homes in Europe, are very often based on a whole-house ventilation strategy, where fresh air enters the dry rooms, and moves to the humid rooms to be exhausted there. In such a strategy, a multi-zone approach in the design and the performance evaluation is more applicable than a whole-house one, as pointed out by (Laverge, et al. 2011). In the United States, most of the houses are equipped with air conditioning systems and do not have trickle ventilators, since fresh air is supposed to come from envelope air leakage. In such homes, the principle of a "well-mixed" zone can be considered applicable and therefore multi-zone approaches for ventilation were have not been used. New high-performance houses need much less heating and cooling and therefore have much less mixing from central systems as well as the reduction in mixing provided by natural infiltration though envelope leakage. In addition, it is becoming more common to not have a central forced air system in these homes—instead using local heating and cooling with mini-split systems. For these reasons, multi-zone approaches will become more relevant and could easily become integrated into smart ventilation, because such a system offers the ability to treat each room according to its needs. This section relates evidence from the literature demonstrating the disparity in pollutant or CO_2 concentrations in the different rooms of a home, and examines the differences between single-zone and multi-zone IAQ and airflow modeling in residential buildings.

The literature shows how CO_2, humidity, and/or pollutant concentrations can vary from room to room. Measured concentrations and corresponding room-specific ventilation rates are influenced by many parameters, including differences in emission and ventilation rates, presence of a DCV strategy, presence of an air recirculating system, and also the position of the indoor doors (Rudd and Lstiburek 2000; Björling, et al. 2007; Sherman 2008; Sherman and Walker 2008). To evaluate differences between well-mixed and zonal approaches this study used the metric proposed by Hodgson, et al. (2004): the absolute average fractional differences, defined as the difference between two values (one in a room, one in another room) divided by the average of the two.

Hodgson, et al. (2004) measured VOC concentrations during one year in a new manufactured house. Depending on the particular VOC compound (of 22 studied), the absolute average fractional difference between living room and master bedroom was in the range of 1%—48%, with a standard deviation in the range 5%—58%. Hodgson observed a statistically significant difference between the two rooms for phenol, toluene, styrene, m/p-Xylene, and 1,2,4-Trimethylbenzene through 2-tailed Student's t test with $p>0.95$.

Nielsen and Drivsholm (2010) monitored CO_2 concentrations for a week in all the rooms of an existing house equipped with a constant airflow ventilation system. From their data, the standard deviation of concentration in each of the rooms, during nights when steady-state is reached, is calculated to be in the range of 178 ppm—285 ppm, with a median value of 221 ppm and a mean value of 224 ppm. The absolute average fractional differences between living room and master bedroom can be calculated in the range of 29%—56%, with a median value of 44% and a mean value of 42%. The absolute average fractional differences between the master bedroom and the boy's room can be calculated in the range of 67%—79%, with a median value of 67% and a mean value of 70%.

Alessi and Sollaris (2011) measured the concentration of several VOC compounds with passive samplers throughout a week in all 12 rooms of two two-story laboratory passive houses equipped with a balanced ventilation system. They observed strong differences in some pollutants, such as benzene, between the kitchen and living room on one side and the bedrooms on the other side. Other pollutants such as toluene and formaldehyde were more evenly distributed among the rooms.

In the MONICAIR project, van Holsteijn and Li (2014) monitored the ventilation and IAQ of all individual rooms in 62 homes every five minutes for a whole year. They calculated the CO_2-excess dose according to Equation 22, but per room and not per person, for each type of ventilation system. From their data, the standard deviation of this indicator for the heating season per type of ventilation system can be calculated. Depending on the type of ventilation, this standard deviation is in the range 17 kppm—259 kppm-h, with a median value of 95 kppm-h. The lowest standard deviations occur for constant airflow balanced ventilation systems and for DCV exhaust-only ventilation systems with RH and CO_2 sensors in every room. The absolute average fractional differences between living room (or open kitchen) and master bedroom can be calculated in the range 1%—171%, with a median value of 97% and a mean value of 91%. The absolute average fractional differences between the two bedrooms can be calculated in the range 42%—192%, with a median value of 151% and a mean value of 142%.

Derbez, et al. (2014) monitored the IAQ in seven new energy-efficient houses before and during the first year of occupancy. The absolute average fractional differences in the measured radon concentrations between living room and master bedroom can be calculated in the range 20%—100%, with a median and a mean value of 50%.

Eklund, et al. (2015) studied ventilation effectiveness by monitoring 29 houses with five types of ventilation systems in Washington State. For the 11 houses with data available, a comparison of the percentage of time when the measured CO_2-concentrations at night were lower than 1000 ppm can e made. This indicator varies by a factor of between zero and 8.5 in the master bedroom and the second bedroom, respectively, with a median value of 1 and a mean value of 2. Depending on the ventilation system, they also observed that the relative humidity was never higher than 70% in the living room even as it exceeded its threshold in the master bedroom and in some cases also in the second bedroom around 5% of the time. These homes were very tight and did not have central forced air systems, so when bedroom doors were closed, CO_2 concentrations became high—resulting in the large ratios reported above.

Guyot, et al. (2016) monitored IAQ in 10 new energy-efficient houses during a winter week, two of which were equipped with a humidity-based DCV system. They calculated the average value of the 60 highest CO_2 concentrations in the main bedroom and in the living room. The ratio between the master bedroom and second bedroom varies between 1 and 2.1, with a median value of 1.7 and a mean value of 1.6.

Ribéron, et al. (2016) calculated an air stuffiness index in the main bedroom and the living room of 10 homes based on measurements during two weeks. This index is a logarithm function of the percentage of time when the measured CO_2-concentration at night is higher than 1000 ppm and 1700 ppm. They showed that only 60% of the homes could be considered uniform.

Data from controlled experiments also exists, but was artificially obtained by tracer gas injections. These data have been used for the validation of multi-zone IAQ modeling software such as CONTAM or COMIS (Lansari, et al. 1996; Sextro, et al. 1999; Zhao, et al. 1998, 1998).

Another issue considered here is the discrepancy between single-zone and multi-zone IAQ and airflow modeling in residential buildings demonstrated in the literature.

D'Ottavio and Dietz (1985) studied the errors resulting from the use of a single -zone ventilation model on a ranch house with a basement. They demonstrated that, with a single-zone model, errors on peak concentration could be ±35%, depending on the definition of the zone perimeter, with a variable emission source such as a gas stove compared to a two-zone model. With a constant emission source, errors are in a larger range (-19%; +60%). Errors in the calculated energy required to heat infiltration air were less than 15% over a large range of outdoor temperatures for a single-zone case, and much higher (35%—45%) for another single-zone case. They also demonstrated that these errors do not depend linearly on errors in the air exchange rate, so that they conclude that an accurate air change rate measurement combined with a zone model should be considered only as a first approximation.

Du, et al. (2012) characterized air change rates and interzonal airflows in 126 residences and evaluated their effects on IAQ. Then, a two-zone model (the bedroom and the rest of the house) calibrated with the field study was conducted for the IAQ study. Air change rate measurements were made using the constant multi-zone injection method, using two tracer gases, over a week, in different seasons. They were 0.73±0.76 h^{-1} (median value = 0.57 h^{-1} ; n=263) in the living room, and higher in the bedrooms: 1.66±1.5 h^{-1} (median value= 1.23 h^{-1} ; n=263). They showed that 26±20% of the air entering the living room comes from the bedrooms, 50±18% from the rest of the house, with slight variations over the seasons. In the IAQ modeling study, they considered either a source in living room or in the bedroom. They also showed strong differences between the average PM concentrations in the living room and in the bedroom. Concentrations in the bedroom are 43%—47% lower than those in the living room. For strong sources in the bedroom, the concentrations are 65 to 74% higher than those in the living room. A sensitivity analysis using the two-zone model demonstrated that the key factors influencing pollutant concentrations are the emission source strength and location, the air change rates, and the inter-zonal air flows. They concluded that single-zone models should apply only in the case of uniform emission sources for tight homes, with closed bedroom doors and no central forced air system.

6. FURTHER DEVELOPMENTS

Towards an optimal solution in the IAQ metrics for smart ventilation

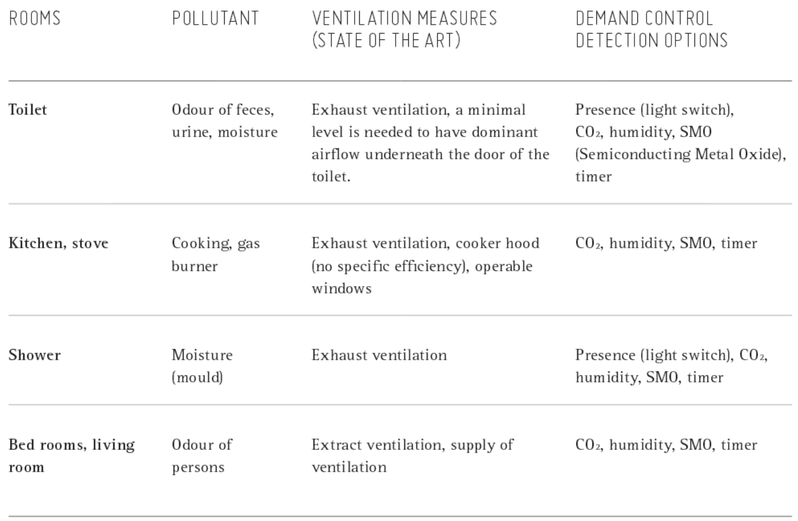
IAQ metrics is an active research area and this review serves as a background for future research. As described in Table 1 the advanced smart ventilation concept is composed of a list of control strategies, including pollutant-based strategies. This section of the report deals specifically with such control issues, which is a subset of the smart ventilation concept.

A function of home location and pollutant sources is suggested by several authors in the literature (Raatschen and Trepte 1987; Caillou, et al. 2014; Borsboom, et al. 2016) and combined with the use of multiple parameters in control algorithms (Won and Yang 2005). This could be a promising solution for smart ventilation strategies.

Raatschen and Trepte (1987) showed that, in an unoccupied bathroom, the hourly air change rate needed to remove moisture was higher than the one to remove formaldehyde, but the opposite was observed in the living room. They concluded that, in occupied rooms, moisture control was important, but that formaldehyde could become dominant in unoccupied rooms and must be considered in adjusting minimum airflows in residential buildings.

Ribéron, et al. (2016) proposed an air stuffiness index for homes. In France, more than 50% of the time spent in the house is spent in a bedroom (Zeghnoun, et al. 2010), so the authors conclude that it is relevant to study the nocturnal bedroom occupancy in order to define an air stuffiness index for homes. Borsboom, et al. (2016) proposed pollutants of concern depending on the type of room and corresponding demand control detection options in their recent AIVC Technical Note on "Residential Ventilation and Health" (Table 3).

Table 14: Rooms and state-of-the art ventilation measures in residential buildings (Borsboom, et al. 2016)



ROOMS	POLLUTANT	VENTILATION MEASURES (STATE OF THE ART)	DEMAND CONTROL DETECTION OPTIONS
Toilet	Odour of feces, urine, moisture	Exhaust ventilation, a minimal level is needed to have dominant airflow underneath the door of the toilet.	Presence (light switch), CO_2, humidity, SMO (Semiconducting Metal Oxide), timer
Kitchen, stove	Cooking, gas burner	Exhaust ventilation, cooker hood (no specific efficiency), operable windows	CO_2, humidity, SMO, timer
Shower	Moisture (mould)	Exhaust ventilation	Presence (light switch), CO_2, humidity, SMO, timer
Bed rooms, living room	Odour of persons	Extract ventilation, supply of ventilation	CO_2, humidity, SMO, timer

From their experience in multi-zone modeling of homes for several years in the Belgian equivalence procedure, and through a comprehensive complementary modeling study, Caillou, et al. (2014b) proposed a list of relevant sensors according to the type of space. For bedrooms and living rooms, CO_2 and VOC sensors would be the most relevant. For humid rooms other than toilets, relative humidity sensors would be the most relevant. CO_2 sensors could be used to complement relative humidity sensors in open kitchens, which could see high occupancies. For the toilet, the occupancy sensor is considered the best solution to avoid the transmission of odors to the rest of the home. Such good results in toilets could also have been obtained under given conditions by the coupling of light and ventilation switches, or with VOC sensors.

An update of the table published by Borsboom, et al. (2016) is presented in Table 15. The use of multiple pollutant metrics in control algorithms is proposed by several authors, including Brinke, et al. (1998); Sekhar, et al. (1999); Mendell (2003); Oakes, et al. (2014); and Teichman, et al. (2016), which can then allow control of the airflow rates in smart ventilation strategies.

Table 15: A synthesis of optimal solutions for smart ventilation

Rooms	Pollutants and comfort parameters of concern **also an acute issue*	Sensors	Complementary control strategy for peak control
Closed kitchen	Humidity, $PM_{2.5}$*, formaldehyde*, acrolein*, NO_2*	RH, PM-counter, gas sensors, timer	High air flow during 30 min
Open kitchen	Idem + CO_2	RH, CO_2, PM-counter, gas sensors, timer	High air flow during 30 min
Bathroom	Humidity, Chloroform*	RH, gas sensors, timer	High air flow during 30 min
Toilets	Odor	Presence, timer, RH, CO_2, gas sensors	High air flow during 20 min
Bathroom with toilets	Humidity, Chloroform*, odor	Presence, RH, gas sensors, timer	High air flow during 30 min
Other humid room	Humidity	Presence, RH, timer	High air flow during 20 min
Dry rooms	Odor of persons, $PM_{2.5}$*, formaldehyde*, acrolein*, CO_2	CO_2, RH, PM-counter, gas sensors	

Combining ventilation for health and ventilation for comfort. The European collaborative action leading to the "Guidelines for ventilation requirements in buildings" (Bienfait, et al. 1992) proposed separate calculation of ventilation requirements to satisfy health concerns from that for comfort, and the use of the highest value at the design stage. This concept could be implemented in a smart ventilation strategy, in order to control the ventilation rate at each control time-step, according to comfort parameters and pollutant measurements. However, ventilation requirements for comfort are not well defned (and may be undefineable beyond delivered air temperature and velocity requirements), so smart ventilation strategies, such as those developed by LBNL, have been based on health and not on comfort.

Feedback from real-world applications and recommendations for implementation

General feedback on poor-quality ventilation installations must be taken into account in the future implementation of smart ventilation. In Europe (Dimitroulopoulou 2012), Canada (Hill, et al. 1998), and the United States (Stratton, et al. 2012 and Sonne, et al. 2015), ventilation installations have failed to meet prescribed requirements. A roughly 50% non-compliance rate has been observed in the Netherlands (Balvers, et al. 2012; Borsboom 2015), in Belgium (Caillou, et al. 2012), and in France (Jobert and Guyot 2013). Compliance can be the lowest for single-family homes, with non-compliance rates of 68% to 100% in a recent study of 20 low-energy homes (Guyot, et al. 2016). One possible reason for this noncompliance is that neither the United States nor European standards, and rarely regulations, require commissioning of ventilation installations. But other issues must also be considered to improve future ventilation and smart ventilation installations. These include the lack of proper fan sizing during design, lack of systems maintenance, the lack of continuity in the chain of actors involved in the ventilation installation, the lack of awareness of occupants, and the lack of professional training.

IEA Annex 18 Mansson, et al. (1997) gives guidelines for DCV system development and recommendations concerning the applicability of DCV systems, including issues such as:

- Airtightness of the building: airflows must be controlled by the ventilation system and not dominated by infiltration.
- Building emissions: if strong sources are known to be in the building and cannot be reduced, the DCV system is not appropriate, or should be able to increase the rate for particular periods in the building’s life. This can be the case in new buildings when painting, materials and furnishing have just been completed or installed.
- Outdoor climate: its impact on indoor climate, infiltration rates, and humidity-controlled ventilation systems must be clearly evaluated to be sure that a DCV strategy is applicable to this outdoor climate.

7. SUMMARY AND CONCLUSIONS

This research is a part of the project called *Smart Ventilation Advanced for Californian Homes* (SVACH). Smart ventilation is made possible through the use of the three complementary components of smart ventilation:

- First, ventilation is provided in response to demand for ventilation rather than only a prescribed, conservative prescription on ventilation airflow rate. This example of a smart ventilation strategy has been studied and implemented fairly widely under the banner of DCV. Most often demand has been quantified in terms of occupancy, or some other measureable quantity that is usually intended to indirectly estimate occupancy, such as RH or CO_2 concentrations. Less often studied is the quantification of demand in terms of individual pollutant loads, through sensing of individual pollutants, and the allowance for reduction in demand based on these measurements. The newest and least studied and implemented approach is the reduction in calculated in demand based on other mechanisms of air entry or exhaust into a space, such as infiltration and mechanical equipment used for source removal such as kitchen hoods and bathroom fans.
- The second aspect of smart ventilation strategy is that it can employ the principle of equivalent ventilation to satisfy demand at times of the day that are not necessarily coincident with the demand itself. Through the equivalent ventilation principle, proper IAQ and acceptable levels of exposure to pollutants can be maintained even if ventilation quantity is not proportional to demand at any point in time. This approach allows for benefits such as shifting ventilation from times when thermal loads associated with ventilation are high to those when it will be lower.
- Lastly, Smart Ventilation is smart in that decisions made by a controller used in smart ventilation applications will integrate information from many sources to make an informed decision about how best to ventilate. These sources of information may include outdoor conditions such as temperature, humidity, pollutant concentration, wind speed and wind direction; indoor conditions such as occupancy, humidity, pollutant concentrations, and static pressure; whole-house conditions such as predefined schedules and the operation of other mechanical equipment; and global inputs such as community- or regional-scale demand for electricity or the prince of electricity. With this information, a smart ventilation controller can them make decisions based not just on current conditions but, conceivably, also prediction of future conditions and weighing of the appropriateness of various control strategies based on financial, energy, and air quality considerations in the future.

This report also discusses the appropriateness of several environmental variables for use as inputs in a smart ventilation strategy. There is no consensus in the literature as to the “right” variables to use in a smart ventilation strategy. The most commonly used variables include humidity and CO_2 concentrations because of the ease of measurement and their assumed correlation with occupancy, which is seen as a driver of IAQ concerns. Non-occupancy related emissions, such as those from furnishings, may drive ventilation needs as well. While directly measuring some pollutants of concern, such as particulate matter and individual gaseous pollutants, may offer advantages, this is less often done for several reasons. These include the fact that sensors used to measure these pollutants are relatively expensive and may require calibration more often than is desired, and knowledge of concentrations of some pollutants may not be sufficient information for controlling ventilation systems, even if this information were readily available. Outdoor temperature and TVOCs have also been used to control ventilation with varying levels of success.

The state of the art in sensor technology used to measure these variables is also reviewed. Devices for sensing humidity directly or indirectly are the cheapest and most commonly used, followed by those for sensing CO_2 concentrations. CO_2 sensors are also often utilized because of the ease with which they can be calibrated. Particle sensors capable of providing estimates of concentration with the level of precision and accuracy needed are still expensive, but quickly becoming more competitive. Sensors for measuring individual gases are nearing maturity.

There are various strategies for controlling residences to ensure that adequate ventilation is provided in the least expensive and most energy efficient manner possible. The most obvious means is to control ventilation to match demand posed by occupancy. This has been done widely and is incorporated into some building codes. Occupancy-based ventilation control is often coupled with a constant baseline ventilation rate designed to dilute pollutants emitted by home furnishings and the home itself. Less understood are the benefits and consequences of controlling ventilation by other means, such as modulating controllers in response to outdoor conditions or electric power grid singals, directly controlling based on measured potentially harmful pollutant concentrations, and model-predictive control based on multiple input signals.

A multi-zone approach to smart ventilation control has pros and cons in terms of desirability and feasibility. Studies in the literature demonstrate the disparity between pollutants and CO_2 concentrations in different rooms of a home, and also discrepancies between single-zone and multi-zone IAQ and airflow modeling results in residential buildings. Different control strategies and even different control variables may be appropriate for different rooms within a home. This is a subject suitable for further investigation.

A favorable context exists in many countries for development of such strategies. As a result, DCV systems are readily available on the market; more than 30 compliant DCV systems are available in countries such as Belgium, France, and the Netherlands.

A review of 38 studies of various smart ventilation systems included CO_2, humidity, combined CO_2 and TVOC, occupancy, outdoor temperature-controlled ventilation and smart ventilation strategies. The studies show that ventilation energy savings up to 60% can conceivably be achieved without compromising, and even sometimes improving, IAQ. However, cases also exist in which negative effects on performance were observed. Ventilation energy savings come in many forms, including a decrease in the total airflow supplied to the space through a simple global reduction in rates of a demand-specific continuous control made possible by sensing, reduction of heating and cooling loads through shifting of ventilation times, and reduction of required whole-house ventilation rates by accounting for other means of air introduction into the space. Much less understood is the ability of smart ventilation systems to contribute to demand response for utility grids.

Several studies also revealed that home occupants are not necessarily sensitive to the quality of their indoor air, and that they do not necessarily operate the ventilation systems when they are needed. From this perspective, smart ventilation strategies, including automatically controlled ventilation systems, are particularly appealing.

Continued research in fields with immediate applicability to smart ventilation strategies is recommended. This includes research into determination of appropriate IAQ metrics, addressing the lack of quality of ventilation installations, and filtration and air cleaning issues.

This review provides the groundwork for a path forward for future smart ventilation research. This path includes extensive validated modeling, which will take into account the state of the art and priorities for smart ventilation research including determination of appropriate control strategies and recommendations for best practices. The results of this modeling can then be validated through field demonstrations in real homes. Through these efforts, the state of the art of smart ventilation will be advanced to the benefit of homeowners, energy providers, and many other stakeholders.

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