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

Gaëlle Guyot[1], Max H. Sherman[2], Iain S. Walker[2]

[1] Cerema & Savoie Mont Blanc University
[2] Building Technologies and Urban Systems Division

December 2017

DOI : 10.1016/j.enbuild.2017.12.051

Funding was provided by the U.S. Dept. of Energy under Contract No. DE-AC02-05CH11231, the CEC under the Califoarnia Energy Commission contract No. EPC-15-037 and Aereco SA under Contract No. FP00003428. The contribution of Cerema is funded by the French Ministries in charge of sustainable development, transports and urban planning, and by the Région Auvergne Rhône-Alpes.

Disclaimer

Acknowledgements

The authors would like to thank Samuel Caillou (BBRI, Belgium), Pilar Linares, and Sonia García Ortega (CSIC, Spain), and Wouter Borsboom (TNO, the Netherlands) for their help in the description of the past and current equivalence procedures for demand-controlled ventilation systems in their countries.

Keywords: Ventilation, indoor air quality, performance, residential buildings, demand-controlled ventilation, review

ABSTRACT

To better address energy and indoor air quality issues, ventilation needs to become smarter. A key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or indoor air quality (IAQ) advantage (or both) and less when it provides a disadvantage. A favorable context exists in many countries to include some of the existing smart ventilation strategies in codes and standards. As a result, demand-controlled ventilation (DCV) systems are widely and easily available on the market, with more than 20 DCV systems approved and available in countries such as Belgium, France and the Netherlands. This paper provides a literature review on smart ventilation used in residential buildings, based on energy and indoor air quality performance. This meta-analysis includes 38 studies of various smart ventilation systems with control based on CO_2, humidity, combined CO_2 and total volatile organic compounds (TVOC), occupancy, or outdoor temperature. These studies show that ventilation energy savings up to 60% can be obtained without compromising IAQ, even sometimes improving it. However, the meta-analysis included some less than favorable results, with 26% energy overconsumption in some cases.

BACKGROUND

The present review paper is a part of the project called “Smart Ventilation Advanced for Californian Homes” (SVACH) further developed in the Lawrence Berkeley National Laboratory (LBNL) report (Guyot et al., 2017). This report addresses several aspects of smart ventilation: 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, the available systems on the market in different countries, and a summary of ongoing developments in research areas related to ventilation, including IAQ metrics and feedback from on-site implementations.

Through updates to California building codes, California is leading the way in reducing energy use in residential buildings, and is even on the way to mandating zero net energy homes. This is also the case in other municipalities, in Europe, for example, which has issued the energy performance building directive (European Parliament, 2010). Such energy-efficient homes require rethinking their ventilation strategies, because of ventilation’s substantial impact on the heat balance and associated conditioning energy in homes. For these high-performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies.

Indoor air quality is another major area of concern in buildings and is influenced by ventilation. Because people spend 60–90% of their life in indoor environments (homes, offices, schools, etc.), indoor air quality is a major factor affecting public health (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 the current damage to public health in disability-adjusted life years (µDALY) per person per year from all sources attributable to IAQ, excluding second-hand smoke and radon, was in the range between the health effects of road traffic accidents (4,000 µDALY/p/yr) and heart disease from all causes (11,000 µDALY/p/yr). By way of comparison, this means that, according to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

As a result, interest in a new generation of ventilation systems has been growing. “Smart ventilation” strategies, including demand-controlled ventilation (DCV), usually denote the use of controls to ventilate more when doing so provides an energy or IAQ advantage (or both) and less when it provides a disadvantage, relative to a “dumb” base case. DCV strategies have been considered in the literature (Laverge et al., 2011) as a cost/energy and IAQ measure, including in existing buildings. DCV strategies have the potential for energy reductions for all ventilation systems.

A favorable regulatory context exists in many countries to develop such strategies (Guyot et al., 2017). Consequently, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

Ventilation should not be seen as a panacea: to achieve good indoor air quality, source control and reduction must be considered as the starting point (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 policies that push the development of low emitting building materials and furnishings is another example: Composite wood product airborne toxic control measure (California Environmental Protection Agency, 2011) and compulsory labeling of VOC emission of all construction products and decorative products installed indoors (French Ministry for Ecology, 2011). While source reduction is key in reducing pollutant levels, this paper limits its scope to ventilation system design.

As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom et al., 2016). Instead, prescribed ventilation rates have been used. The trouble with this approach is that it assumes that in addition to displacing human bio-effluents including odors, ventilation is a sufficient means of controlling other contaminants (Matson and Sherman, 2004 and Persily, 2006). The committee chair of ASHRAE Standard 62-1989 noted that the minimum ventilation requirement of 7.5 $L.s^{-1}$ per person was based on body odor control (Janssen, 1989), and that this minimum was increased to 10 $L.s^{-1}$ per person in many building types to account for contaminants other than human bio-effluents, such as building materials and furnishings. However, no specific methodology articulating the justification of this increase was 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 and et. al., 2012; Wargocki, 2012).

SMART VENTILATION

The key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy use and cost while maintaining or improving IAQ relative to a continuously operating system.

Demand-controlled ventilation (DCV)

The DCV concept is a specific subset of smart ventilation. DCV systems generally use indicators of demand for ventilation, such as excess CO_2 or humidity, to control a ventilation system. Such strategies have been widely used in the scientific literature and in materials associated with the technologies available over the past 30 years. DCV has been defined in a variety of ways. According to the IEA Annex 18, DCV denotes continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson et al., 1997). (Limb M.J, 1992, p. 36) 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."

Several types of DCV are currently available in the literature and on the market depending on the type of building regulation, the type of sensing combinations, and the types of control algorithms. For instance in Belgium (Caillou et al., 2014b; Moniteur Belge, 2015), DCV systems have been classified according to measured IAQ-related parameters such as CO_2, relative humidity, 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). Here we disaggregate by airflow direction because this is key for the system installation and evaluation at the design stage.

Balanced DCV systems

Balanced DCV system control can be centralized or zoned and 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 the ventilation system must be able to balance the exhaust and supply continuously.

Exhaust-only DCV systems

Exhaust-only DCV system controls can also be centralized or decentralized. In a tight home the distribution of air intakes could be controlled for zonal ventilation with either central or multiple exhausts. In leaky homes this strategy is less effective (infiltration would counteract decreased airflow through air inlets). These 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 that compensate for under-ventilation due to airtightness (Caillou et al., 2014b).

Residential Integrated Ventilation-Energy Controller (RIVEC)

With the Residential Integrated Ventilation-Energy Controller (RIVEC), the LBNL has more recently been developing another subset of smart ventilation. It was developed in order to control fans to minimize energy use (Sherman and Walker, 2011; Walker et al., 2011; Turner and Walker, 2012; Walker et al., 2014). This smart ventilation concept uses the equivalent ventilation principle (Sherman, 2004) to allow for modulation of ventilation airflows in response to several factors, including outdoor conditions, utility peak loads, occupancy, and operation of other air systems. Equivalent exposure compares the exposure for the system being evaluated to that from a continuous ventilation system (assuming a continuously generated pollutant). This generic approach allows for any smart ventilation strategy to have real-time control by targeting a relative exposure of unity. This has been integrated into ASHRAE Standard 62.2 (ANSI/ASHRAE, 2013,2016) as an optional compliance path. This concept was further developed (Sherman et al., 2011) to be applied under a variety of ventilation rates, emission rates, and the evaluation periods for the dose of pollutants.

One current update of the RIVEC (Sherman and Walker, 2011; Walker et al., 2011) is a real-time whole-house ventilation system. Figure 1 is an illustrative example showing the operation of a RIVEC-controlled fan that combines forced fan off times with the response to the operation of other fans. RIVEC works 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 and reduces costs if time-of-use energy rates are in effect.
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.
5. Account for natural infiltration contributions to total ventilation.
6. Respond to peak demand signals from utilities.
7. Change ventilation times to reduce entry of outdoor pollutants when their levels are high.

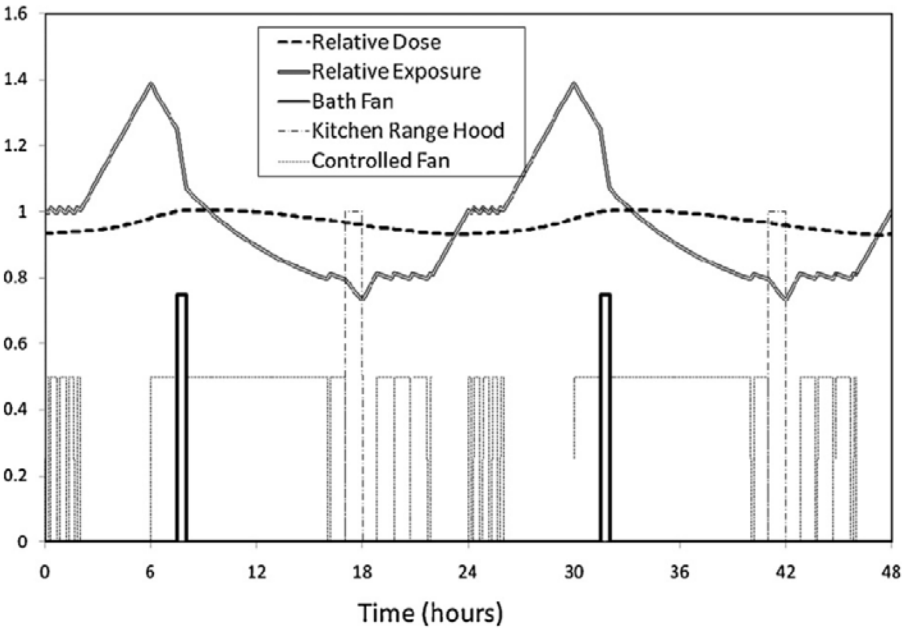

Figure 1: Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter; source: (Sherman and Walker, 2011)

In smart ventilation strategies, 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-sectional area, 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) is also an important topic that can have a substantial impact on IAQ and energy performance.

REVIEW PROCEDURE

In this paper, we analyzed field and modeling studies on energy and/or IAQ benefits of residential smart ventilation from 1979 to 2016. The summaries presented above are instructive and provide a valuable resource to initiate the current work even though many of the summarized studies are for non-residential buildings.

As part of the International Energy Agency Annex 18, (Raatschen, 1990) reviewed 31 papers from 1979 to 1989, including four studies on implementation of DCV systems in homes (Anon, 1983; Barthez and Soupault, 1984; Nicolas, 1985; Sheltair scientific Ltd., 1988). A further review (Fisk and De Almeida, 1998) on sensor-based demand-controlled ventilation combined 13 other papers from Annex 18 including six case studies on implementation of DCV systems in homes (Mansson, 1993), together with 15 additional papers published before 1997, including only one on a residence (Kesselring et al., 1993). The vast majority of these studies considered only relative humidity-based control, and in some rare cases CO_2-based control. A recent review of sustainable, energy-efficient and healthy ventilation strategies in buildings (Chenari et al., 2016) devoted 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). Between these three existing reviews there are 15 papers on smart ventilation, all DCV, in residential buildings.

In the present review, we analyzed 23 additional studies of interest on residential smart ventilation: 13 cover various smart ventilation systems based either on CO_2 control or on 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 concern other smart ventilation strategies based on the RIVEC.

The results of these 38 studies are summarized in a table at the end of the article. We must stress that it is very difficult to compare performance results between different studies, for at least four reasons:

1- Differences in the types of smart ventilation strategies used: there is often a lack of precise data on the type and location of sensors, the method of air flow regulation 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 poor results for given conditions, but this does not necessarily mean that the ventilation system is bad.
3- Differences in measuring IAQ-related parameters: there is neither a single parameter or set of parameters common in these studies, nor a universal method to calculate the indicators. There are often differences on the metrics used to evaluate the IAQ parameters. 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 (1 day, 1 week, 1 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.

Despite these differences it was possible to find commonalities and derive general guidance from the reviewed papers. Table 2 contains a summary of all the studies reviewed in this paper.

PERFORMANCE OF HUMIDITY- AND/OR CO_2-CONTROLLED SMART VENTILATION SYSTEMS

Historically, humidity and CO_2 have been used as indictors of IAQ and therefore used to control DCV systems. Humidity is one of the prioritized pollutants of concern (Borsboom et al., 2016). 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 (Zhang et al., 2016) or ventilation rates. The only health threshold on which several studies converge is an exposure of 10,000 ppm for 30 min, corresponding to respiratory acidosis for a healthy adult with a modest amount of physical load (ANSES 2013), far from concentrations observed in indoor environments. Nevertheless, CO_2 exposure has often been used in the literature, describing a time-integrated concentration.

The following reviews focus on these control strategies. Note that these studies did not measure any pollutants such as particles, formaldehyde, NO_2, etc.; however, the control strategies were used also because sensors for humidity and CO_2 are easily available at an affordable price.

Until the beginning of the 1990s, the literature we reviewed (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) contained mainly case studies, reporting a wide range of energy savings (0%–60%), with small to moderate IAQ improvements. Although all the data required to account for these large differences are rarely available, several explanations for the differences can be identified, including type of DCV system, the advancement of these technologies, and outdoor climate (for humidity-controlled DCV).

(Parekh and Riley, 1991) studied the implementation of a relative humidity (RH)-based DCV system in two houses. The whole-house ventilation system had inlet and exhaust grilles with a cross-sectional area modulating in response to the RH level in the room. They observed only 6% energy savings (calculated over a short time period, which could reduce the savings calculated) and concluded that the IAQ was poor, especially in the bedrooms, which had a CO_2 concentration greater than 1200 ppm. They highlighted the fact that a high level of air leakage in their setup would reduce the influence of the ventilation system on total building air flow rates and IAQ. As a result, DCV system performance may be underestimated.

(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 for around 21 h a day over 1 month. The system is described as injecting air in 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, relative humidity must remain under 45% in order to avoid house dust mite growth; and second condensation on double-pane glass windows must be avoided. Additionally, the authors set the minimum airflow rate at 10 $L.s^{-1}$, and the maximum airflow rate at 35 $L.s^{-1}$. The controller makes a decision about changing air flow to maintain these criteria every 1 min. As a result, the total airflow rate could be reduced to 39% below the Danish code requirement, with a RH of 45% exceeded about 10% of the time, and 47% exceeded only 1–5% of the time. No condensation was observed, or predicted based on RH results, over the monitoring time. CO_2 concentrations were lower than 1200 ppm 98% of the time.

(Nielsen and Ambrose, 1995) monitored the performance of a humidity-controlled ventilation system in 16 apartments for 3 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 damper. The opening of inlet valves has no impact on total exhaust airflow but distributes the air supply between the bedrooms. RH set points are set at 40% in bedrooms and 45% in the other rooms. For outdoor air temperatures less than 1°C, a constraint that is a function of indoor RH and outdoor temperature measurements is added to avoid condensation on windows. The resulting maximum reduction in the 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 RH 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 5-year project on the evaluation and development of innovative energy and ventilation strategies. They calculated energy savings of 20–30% of ventilation-related energy, for a RH-controlled ventilation system confirmed by measurements on a test apartment. In this apartment, they simulated two-person occupancy and emissions of materials and furnishings (N_2O tracer) in the living room. They first installed a standard exhaust-only ventilation system delivering a constant rate of 35 $L.s^{-1}$ (20 $L.s^{-1}$ in the kitchen and 15 $L.s^{-1}$ in the 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 $L.s^{-1}$ in the kitchen and 20 $L.s^{-1}$in the bathroom. As a result, even with a higher exhaust rate in the kitchen some of the time, the home ventilation rate was reduced to 20–30% of the reference case. The maximum CO_2 concentration in the living room is reduced by 10% and the concentration in the living room of pollutants emitted by materials and furnishings stays at the same level when the building is occupied and can be reduced by 50% the rest of the time. The maximum CO_2 concentration in the bedroom is doubled from 600 to 1200 ppm.

(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 (kitchens and bathrooms),
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 $L.s^{-1}$ up to 30 $L.s^{-1}$ when needed. Different set points were tested: 800, 1000, and 1200 ppm for CO_2-based control, and 60, 70, and 80% for the maximum humidity threshold. The position of interior doors (closed or open) was also tested. Authors judged air quality through both CO_2 concentrations and high humidity levels. 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 about 20% energy savings. The greatest energy savings, without compromising indoor air quality, were obtained with the following set-points: 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 (combined passive stack and mechanical) ventilation system for residential buildings as a part of the European RESHYVENT project. Yearly simulations were performed in a house located in four climates equipped with two different DCV systems, based on CO_2 or on occupancy in the dry rooms. The air flow in the passive stack is calculated based on the indoor-outdoor temperature difference and an air flow resistance model of the stack. 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 min, a control algorithm adjusts the fan speed in response to the calculated passive stack air flow. In the CO_2-based DCV strategy, inlets and grilles open, based on humidity and CO_2 concentrations. Both strategies have economizer and night-cooling functionality in their algorithms. The results were compared to a single-exhaust ventilation system, considered as the reference system. In all the climates, when compared to the reference system, authors noted no significant difference on the summer thermal comfort and the energy consumption for heating. Nevertheless, they highlighted strong impacts on CO_2 exposure in occupied dry rooms and on electrical consumption of the fan. The hybrid smart system reduced the exposure to CO_2 at least by a factor of 2 and the electrical consumption of the fan by 90%.

(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 the 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 $m^3.h^{-1}$ in the kitchen and 25 $m^3.h^{-1}$ 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 set-points. Also, motion sensors in humid rooms ensured minimum airflows for a 20- to 30-min period after the last detection of occupancy.

They showed that IAQ, estimated either by the time spent in each CO_2-IDA class of the EN 13779 standard (CEN, 2007) or by the LKI_{1200} index of the Dutch standard NEN 8088 (NEN, 2011), was slightly lower for the DCV system studied. This IAQ metric is the cumulative CO_2 exposure index requirement per person calculated with Equation 1 for the heating period considered, September 29th to April 25th. 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 DCV system studied maintained the space in this range only for 67% of the time, while the reference system succeeded 90% of the time. For a leaky house with average airtightness (n_{50}=11.2 h^{-1}), they observed no difference in performance. The energy savings potential was calculated at around 1100–1200 kWh, which is 27% for the airtight houses and 14% for average airtightness. They also studied the moisture-buffering effect and showed that it did not affect DCV energy performance, with only 0.75% extra energy demand.

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

Equation 1

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.

(Woloszyn et al., 2009) studied the performance of a humidity-based DCV system for residential buildings, comparing four heat, air, and moisture simulation software, and taking into account the moisture buffering effect. For a whole-house exhaust-only ventilation system with exhaust airflow depending on RH, they showed a mean ventilation rate reduction of 30–40% with 12–17% energy savings in the cold period, compared to a constant airflow exhaust-only ventilation system. They highlight that these gains were achieved while keeping the peak RH values the same. CO_2 concentrations were estimated to be greater than 1200 ppm around 33% of the time during the cold period. They also conclude that it should be suitable to optimize such systems, combining RH- and CO_2-based strategies, in order to reduce CO_2 concentrations as well.

Measurements over two complete heating seasons were taken in 31 new occupied apartments equipped with humidity-based inlet and outlet DCV systems (Air H, 2010; Bernard, 2009). For more than 30 years the market in France has largely been dominated by such humidity-based DCV systems with a mechanically variable inlet and outlet cross-sectional area (Savin et al., 2014). They use advanced materials such as polyamide fiber, which varies in length with the relative humidity. They are not classical sensors but could be described as sensor-actuators: the dimensional changes are used directly to adjust vent opening. The variables measured included outdoor and indoor variables (CO_2, temperature, and humidity), and ventilation parameters (pressure, inlet cross-sectional area, airflows through the trickle ventilators, and exhaust air outlets). They were captured every minute. The measurements validated the theoretical IAQ performance modeled by the software used in the French certification of compliance for DCV systems (CCFAT, 2015). Manufacturers must follow this compliance procedure for DCV to ensure adequate ventilation. 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 the night than it was with fixed air inlets, even if IAQ indicators were acceptable in both cases. Average ventilation airflow was measured at around 30% lower than with the fixed ventilation rates required by the airing regulations, accounting for an approximately 0.5 air change rate per hour. The authors extrapolate this result to homes with more standard occupancy patterns and obtained a reduction of average ventilation airflow of around 50–55%. Energy savings on ventilation motor consumption were estimated between 35 and 50%.

(Nielsen and Drivsholm, 2010) studied a simple DCV approach for homes with control based on measurements in the air-handling unit that 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 taken with and without the new control strategy. The high-speed fan is set at 100% of fan capacity and is based on the flow rate required by the Danish building code (216 $m^3.h^{-1}$ or 0.43 $l.s^{-1}.m^{-2}$ for the house tested); the low speed is 40% of the speed at the high-flow rate. A difference of 100–150 or 200 ppm between CO_2 concentrations measured between the exhaust and outdoor air indicates that the building is occupied and activates operation at high speed. A difference of 2 g/kg in absolute humidity also activates the high-speed fan, which takes into account the fact that in the Danish climate the outdoor temperature is below 5°C over 3000 h per year. The results show an optimum at a CO_2 concentration difference set-point of 150 ppm. At this setting, the ventilation rate can be set to ”low” 37% of the time, mostly during unoccupied periods, without significant change in the IAQ performance, based on CO_2 and humidity, compared to the fixed rate ventilation strategy. The corresponding energy savings have been estimated at 35% of the fan’s electricity consumption and 23% of the heating needs. Measurements of the fan speed throughout the week show that the control strategy closely followed the unoccupied schedules during the daytime.

(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 based on the RH measured in the exhaust air with a set point of 70%, 2) occupancy-controlled, with an “on-off” strategy on the fan running once 20 min of occupancy is detected, 3) CO_2-controlled in the dry rooms with air inlets reduced to 10% opening if the CO_2 concentration is lower than 1000 ppm in the room, 4) the three approaches combined. Multi-zone modeling was performed with CONTAM and the results were compared to 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 and 2) the exposure to a tracer gas emitted in rooms with a toilet (efficiency of the exhaust in removing humidity at the source). The total heating-season-averaged heat loss through ventilation 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 in the other rooms. Reducing inlet size effectively moves the responsibility for aeraulic management to the fan, more than wind or the 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 energy savings between 0 and 40%, varying by type of system, only for the systems fulfilling the IAQ requirements. The most IAQ-friendly and energy-efficient systems are locally regulated and combine 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 in Table 1. These results are published in a Ministerial Order (Moniteur Belge, 2015) to be used directly in the energy performance calculations. The energy savings coefficient f_{reduc} is calculated from Equation 2, based on the heating season integrated ventilation heat loss E (MWh/year), excluding infiltration heat losses, which are treated separately in the EP calculation method. E_X is calculated for the smart system X studied. E_{ref} is the energy use of a system that has the same CO_2 exposure indicator as the system being rated and is determined as shown in Figure 2. The per-person cumulative CO_2 exposure indicator E'_{950} (Equation 3) is calculated starting from the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 950 ppm.

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

Equation 2

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

Equation 3

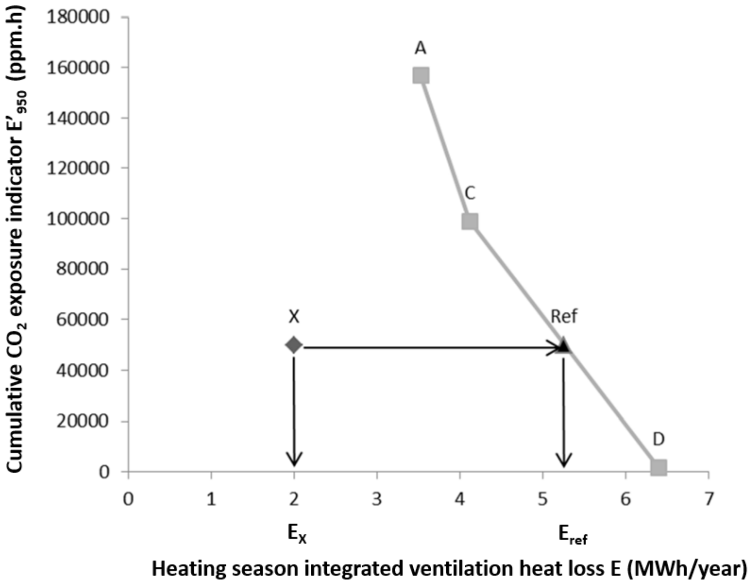

Figure 2: Energy saving coefficient calculation for a DCV system X (ATG and BCCA, 2012)

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 1 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 1 sensor in the main bedroom + at least 1 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 1 sensor in the exhaust duct(s)	Central	0.81	0.87	0.93
Occupancy-local: at least 1 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 1 sensor in each bedroom	Central	0.87	0.93	1.00
Occupancy-partially local: at least 1 sensor in the main bedroom + at least 1 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

Table 1: 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)

Another recent study was based on 1 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 as an IAQ indicator the cumulative CO_2 exposure index requirement, LKI_{1200}, Equation 1. 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 performed measurements, 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 energy performance of 119 MJ/m²/heating season and an IAQ performance of 244 kppm/person. Systems with only CO_2 sensors in the living room decreased the performance based on these two indicators by 21% and 11%, respectively. Systems with RH and CO_2 sensors in all the rooms increased performance based on these two indicators by 31% and 70%, respectively. The reference system for balanced ventilation had a mean energy performance of 24 MJ/m²/heating season and an IAQ performance of 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 and supply in the connecting spaces increased energy performance by 45% and decreased IAQ by 11%. Much higher performance was observed for systems with RH and CO_2 sensors in all the rooms.

PERFORMANCE OF OTHER SYSTEMS: BEYOND CO_2 AND HUMIDITY

Some other smart ventilation strategies are based on other pollutants, occupancy, or outdoor temperature. More recently concerns about constantly emitted pollutants (e.g., VOCs including formaldehyde) mean that occupant-only-related indicators may be considered inadequate to control smart ventilation strategies.

(Fisk and De Almeida, 1998) recommended using VOC sensors in conjunction with CO_2 sensors. They highlighted 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. As more than 300 VOCs have been measured in indoor air, the total VOC (TVOC) concentration is often used in the literature and sensor technologies to simply characterize the total concentration with a single parameter. It is calculated from the measurement of one or several VOCs. 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).

In an example of VOC-based system design, a standard Korean multi-zone apartment has been modeled with CONTAM and EnergyPlus at a 1-h time step, equipped with a whole-house balanced DCV system either based on CO_2 demand or on TVOC demand (Seong, 2010). The control strategy investigated 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 the Environment. They differ for each room and include first an emission rate per floor area, then finishing and product (furniture, bed mattress, chest of drawers, desk, personal computer, chair, kitchen unit, shoe rack, TV) emissions. The TVOC exposure is not calculated and thus it is difficult to compare the performance results. The CO_2-based DCV strategy keeps the home under 1000 ppm and at low TVOC concentrations most of the time, albeit with some peaks, remaining in the 150–800 $\mu g.m^{-3}$ range. The authors compare this range to the initial concentration set to 1000 $\mu g.m^{-3}$, the concentration obtained without any ventilation system 4000 $\mu g.m^{-3}$, and the one obtained when ventilated by the Korean standard, 600 $\mu g.m^{-3}$. The energy savings are estimated at 17%. The TVOC-based DCV strategy maintains CO_2 concentrations under 2200 ppm, and TVOC concentrations of 400–800 $\mu g.m^{-3}$. 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 based on a night-time strategy. In this strategy, base airflows during the night are multiplied by a factor of two in bedrooms and reduced by the same factor in the other rooms. Another strategy consisted in dividing the 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 the opening of ventilation valves until the prescribed levels of temperature and RH are reached. The authors measured a 50–80% reduction in the kitchen air change rate, no change in the bedroom air change rate, and an increase of 160% of the living room, compared to the constant air change rate. No information is given in the paper about the total airflow reduction.

Based on the LBNL smart ventilation studies background for chronic and acute exposure evaluation, (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 – defined as the ratio between all pollutant source strengths and background pollutant source strength, the low ventilation factor – defined as the ratio between the low ventilation rate and the ventilation rate of the equivalent constant rate system; and this equivalent constant rate. The results 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 flow airflow ratio of 2.5–5. They also calculated the ratio of acute to chronic exposure and showed that it was always less than 3, which means such DCV systems provide acceptable peak exposure. They showed that for a home occupied for 16 consecutive hours, the total ventilation rate is reduced by about 12% for a constant rate of 0.5 h^{-1} and an emission ratio of 1.5. When occupant pollutant emissions are dominant, the airflow reductions can be more than 18% and would be reduced to 9% when there is no contribution from occupants.

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 schedules. The whole-building airflow rate is 60 $L.s^{-1}$ ($0.75\ L.s^{-1}m^{-2}$) and is switched to 16 $L.s^{-1}$ ($0.1\ L.s^{-1}m^{-2}$) during unoccupied periods (8 am to 6 pm). The authors studied the impact of using the low rate for 4,6, 8, or 10 h, starting from 8 am. Compared to the reference constant airflow system at 60 $L.s^{-1}$, the mean age of air at 6 pm (when the occupants return) increases by 5.5, 22.2, 50, or 105.5%, respectively; the VOC concentration at 6 pm increases by 4, 20, 65, or 211%, respectively, in the last case going over the threshold value to 0.1 ppm, while the CO_2 concentration stays below the 1000 ppm threshold value considered. For the acceptable IAQ system with 8 h unoccupied, 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 to 47 $kWh.m^{-2}$. Similar good savings were also observed in (Laverge et al., 2011).

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

The use of the RIVEC 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 to prevent excess energy use in extreme weather. If the airflow is not sufficient to meet the IAQ equivalence requirements, RIVEC turns on the whole-house exhaust fan. As a result, the authors showed that there was room to optimize hybrid ventilation systems with accurate 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 equivalent air change rates. Simulations were performed in all climate zones in the United States, 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 the stack effect provides the target airflow;
2. Infiltration-dependent2: the fan is turned to half-flow if the stack effect provides 50% of the target airflow;
3. Infiltration-independent: 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 the outdoor temperature drops below the 25th percentile of the coldest hours determined from TMY data files.

The simplest strategy, with the cut-off set to 5°C, was the most efficient one 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 100–4000 kWh. Fans should be oversized by 5–150%, with an average of 34%.

(Lubliner et al., 2016) further investigated this type of 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 set the outdoor temperature set-point for each house. As a result, they obtained energy savings between 73 and 230 kWh/year. They also demonstrated the importance of the location of the temperature sensors. They observed no significant impact on CO_2 and humidity. Occupancy, window opening, and wind effects were found to have significant effects on CO_2 and humidity.

IMPACT OF DIFFERENT CONTROL STRATEGIES FOR SMART VENTILATION PERFORMANCE

Other control strategies for smart ventilation systems were also studied during the development of the RIVEC (Sherman and Walker, 2011). 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-h period of peak energy demand. The theoretical background still assumes 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 min. 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 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 12-h base period, a 4-h pre-peak shoulder period, a 4-h peak period (off), a 4-h post-peak period.

Simulations were performed with a 1-min time step with the REGCAP simulation tool (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 an up to 14% decrease in the annual average relative dose and a peak relative exposure no more than 11% above the target limit, even with a 4-h shutoff period. Energy savings, including heating gas savings and electricity savings (cooling + 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%.

A RIVEC prototype was field-tested in an occupied house in Moraga, California, equipped with an economizer (Walker et al., 2011). The field test was divided into three periods: 3 weeks of operation of the RIVEC system, 6 days with the whole-house ventilation system turned off, and 2 days with the whole-house system operating without RIVEC. Experimental data were combined with a modeling approach to estimate the energy savings over the year, in three California climate zones (temperate, Oakland; warm, Fresno; cold mountain, Mount Shasta). Modeling showed a potential of 13–44% (1000 kWh) annual ventilation energy savings, while preserving IAQ and eliminating 100% of the peak power associated with ventilation. RIVEC reduced the run time of the fans by up to 71% for a home with an economizer. 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 looked at diverse climates (16 California climate zones), various home geometries, four mechanical ventilation systems, and two passive or hybrid systems and envelope airtightness levels to give an accurate representation of the majority of the California housing stock. The authors concluded that ventilation energy savings were 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 to 7000 kWh/year per household. These energy savings are robust across climates as well as house geometric and airtightness levels. The peak power is also significantly reduced up to 2 kW for a typical house.

Another aspect of smart ventilation is that it is designed 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 Californian home (with a specific leakage area of 4).

CONCLUSIONS AND OBSERVATIONS

With smart ventilation strategies, including demand-controlled ventilation (DCV) strategies, the concept consists in using controls to ventilate more at times when it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This can be done in a manner that provides improved home energy and IAQ performance. A favorable regulatory context exists in many countries to develop such strategies. As a result, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

This article begins to address the fact that under the umbrella of "CO_2-based DCV systems" or "humidity-based DCV systems" or "smart ventilation systems," there can be a wide variety of systems and strategies, with differences in the type of sensors, type of regulations, type of control algorithms, etc. To correctly analyze the performance of such systems, it is also very important to clearly define them and give a precise description of how they work.

Through this meta-analysis of 38 studies of various smart ventilation systems with control based on CO_2, humidity, combined CO_2 and TVOCs, occupancy, outdoor temperature, or other control strategies, we learned that:

- demand-controlled ventilation based on CO_2 or humidity is well established in some countries with standardized performance calculation procedures and readily available controls and ventilation systems;
- there is clearly a potential for improved indoor air quality using smart ventilation strategies;
- significant energy savings up to 60% can be obtained, with less favorable results including 26% overconsumption in some cases.

The low number of studies reviewed, 38 since 1983, suggests that smart ventilation is still an emerging technology. In this review highlighting the lack of data on ventilation strategies controlled by other parameters than humidity or CO_2, we identified issues that require greater understanding:

- What are the relevant pollutants to sense for residential ventilation control and can we sense them with sufficient accuracy and reliability for control?

- Can we ignore building and materials pollutants when homes are unoccupied? Can we ignore outdoor pollutants? Current regulations and the demand-controlled ventilation systems reviewed do not account for these effects.
- Can we reliably detect occupancy so as to realize the potential savings?

As a perspective for the future for real-time controllers like RIVEC compared with current DCV approaches, we would also suggest research in those areas, in order to:

- develop better indoor air quality metrics for residential ventilation control including the use of accurate and reliable sensing devices;
- better understand the differences between contaminant sources between occupied and unoccupied dwellings;
- include air cleaning in ventilation controls.

ACKNOWLEDGEMENTS

Funding was provided by the U.S. Dept. of Energy under Contract No. DE-AC02-05CH11231 and the CEC under the contract No. EPC-15-037 and Aereco SA by the Contrat No. FP00003428. The contribution of Cerema is funded by the French Ministries in charge of sustainable development, transport and urban planning, and by the Région Auvergne-Rhône-Alpes. The sole responsibility for the content of this publication lies with the authors.

REFERENCES

Afshari, A., Bergsøe, N.C., 2003. Humidity as a Control Parameter for Ventilation. Indoor Built Environ. 12, 215–216. doi:10.1177/1420326X03035163

Air H, 2010. Deux années de mesure de la VMC hygroréglable de type B dans 31 logements occupés répartis sur deux sites en France - Dossier de presse du projet Performance (Projet PREBAT ADEME).

Anon, 1983. Humidity-controlled ventilation. Un nouveau principe de ventilation mecanique - la ventilation hygroreglable. Chaud Froid Plomb. 37, p.107-109.

ANSES, 2013. Concentrations de CO2 dans l’air intérieur et effets sur la santé - Avis de l’Anses - Rapport d’expertise collective, Édition scientifique.

ANSI/ASHRAE, 2013. ASHRAE Standard 62.2 « Ventilation and acceptable indoor air quality in residential buildings ».

ATG, BCCA, 2012. Goedkeuringsleiddraad voor de energetische karakterisatie van vraaggestuurde residentiele ventilatiesystemen.

Barthez, M., Soupault, O., 1984. Control of Ventilation Rate in Building Using H2O or CO2 Content, in: Ehringer, H., Zito, U. (Eds.), Energy Saving in Buildings. Springer Netherlands, pp. 490–494. doi:10.1007/978-94-009-6409-9_61

Bernard, A.-M., 2009. Performance de la ventilation et du bâti - Phase 3 - Performance énergétique et QAI des systèmes hygroréglables (Projet PREBAT ADEME).

Borsboom, W., 2015. Quality and compliance on building ventilation and airtightness in the Dutch context.

Borsboom, W., De Gids, W., Logue, J., Sherman, M., Wargocki, P., 2016. TN 68: Residential Ventilation and Health, AIVC Technical Note 68.

Brasche, S., Bischof, W., 2005. Daily time spent indoors in German homes--baseline data for the assessment of indoor exposure of German occupants. Int. J. Hyg. Environ. Health 208, 247–253. doi:10.1016/j.ijheh.2005.03.003

Caillou, S., Heijmans, N., Laverge, J., Janssens, A., 2014b. Méthode de calcul PER: Facteurs de réduction pour la ventilation à la demande.

California Environmental Protection Agency, 2011. Composite wood product airborne toxic control measure.

CCFAT, 2015. VMC Simple Flux hygroréglable - Règles de calculs pour l'instruction d'une demande d'avis techniques - GS14.5 - Equipements / Ventilation et systèmes par vecteur air.

CEN, 2007. NF EN 13779. Ventilation des bâtiments non résidentiels – exigences de performances pour les systèmes de ventilation et de conditionnement d'air.

Communiqué de presse - Indoor air pollution: new EU research reveals higher risks than previously thought [WWW Document], 2003. URL http://europa.eu/rapid/press-release_IP-03-1278_en.htm (accessed 11.28.16).

Erhorn, H., Erhorn - Kluttig, H., Carrié, F.., 2008. Airtightness requirements for high performance buildings, in: 29th AIVC Conference. Presented at the Advanced building ventilation and environmental technology for addressing climate change issues, Kyoto, Japan.

European Parliament, 2010. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast).

Fisk, W.J., De Almeida, A.T., 1998. Sensor-based demand-controlled ventilation: a review. Energy Build. 29, 35–45. doi:10.1016/S0378-7788(98)00029-2

French Ministry for Ecology, 2011. Compulsory labeling of VOC emission of all construction products and decorative products installed indoors.

Guyot, G., Sherman, M., Walker, I.S., 2017. Residential smart ventilation: a review. LBNL Report.

Hesaraki, A., Holmberg, S., 2015. Demand-controlled ventilation in new residential buildings: Consequences on indoor air quality and energy savings. Indoor Built Environ. 24, 162–173. doi:10.1177/1420326X13508565

Homod, R.Z., Sahari, K.S.M., 2013. Energy savings by smart utilization of mechanical and natural ventilation for hybrid residential building model in passive climate. Energy Build. 60, 310–329. doi:10.1016/j.enbuild.2012.10.034

janssen, 1989. Ventilation for acceptable indoor air quality. Ashrae J.

Jantunen, M., Oliveira Fernandes, E., Carrer, P., Kephalopoulos, S., European Commission, Directorate General for Health & Consumers, 2011. Promoting actions for healthy indoor air (IAIAQ). European Commission, Luxembourg.

Jreijiry, D., Husaunndee, A., Inard, C., 2007. Numerical study of a hybrid ventilation system for single family houses. Sol. Energy 81, 227–239. doi:10.1016/j.solener.2006.03.013

Kesselring, J.P., Koontz, M.D., Cade, D.R., Nagda, N.L., 1993. Evaluation of residential ventilation controller technology, in: Proceedings of 'Indoor Air '93', The 6th International Conference on Indoor Air Quality and Climate". Finland, Helsinki, p. pp 73-78.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Anal. Environ. Epidemiol. 11, 231–252. doi:10.1038/sj.jea.7500165

Krus, M., Rösler, D., Holm, A., 2009. Calculation of the primary energy consumption of a supply and exhaust ventilation system with heat recovery in comparison to a demand-based (moisture-controlled) exhaust ventilation system, in: 30th AIVC Conference " Trends in High Performance Buildings and the Role of Ventilation." Berlin, Germany.

Laverge, J., Van Den Bossche, N., Heijmans, N., Janssens, A., 2011. Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. Build. Environ. 46, 1497–1503. doi:10.1016/j.buildenv.2011.01.023

Less, B., Walker, I., Tang, Y., 2014. Development of an Outdoor Temperature-Based Control Algorithm for Residential Mechanical Ventilation Control. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Limb M.J, 1992. TN 36: Air Infiltration and Ventilation Glossary. AIVC Technical Note.

Logue, J.M., Price, P.N., Sherman, M.H., Singer, B.C., 2011b. A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. Environ. Health Perspect. 120, 216–222. doi:10.1289/ehp.1104035

Lubliner, Francisco, Martin, Walker, I., Less, B., Viera, Kuckle, Merrin, 2016. Practical Applications and Case Study of Temperature Smart Ventilation Controls, in: Thermal Performance of the Exterior Envelopes of Buildings XIII, ASHRAE/DOE/BTECC.

Mansson, L.G., 1993. IEA Annex 18. Demand Controlled Ventilation Systems: Case Studies, Document. Swedish Council for Building Research, Stockholm, Sweden.

Mansson, L.G., Svennberg, L.A., Liddament, M.., 1997. Technical Synthesis Report. A Summary of IEA Annex 18. Demand Controlled Ventilating Systems, AIVC.

Matson, N.E., Sherman, M.H., 2004. Why we ventilate our houses-An historical look. Lawrence Berkeley Natl. Lab.

Moffat, P., Moffat, S., Cooper, K., 1991. Demand-controlled ventilation - final report. canadian Mortgage and Housing corporation, Ottawa, Canada.

Moniteur Belge, 2015. Arrêté ministériel déterminant les valeurs du facteur de réduction pour la ventilation visé à l'annexe A1 de l' arrêté du Gouvernement wallon du 15 mai 2014 portant exécution du décret du 28 novembre 2013 relatif à la performance énergétique des bâtiments.

Mortensen, D.K., Nielsen, T.R., 2011. System Design for Demand Controlled Ventilation in Multi-Family Dwellings. Int. J. Vent. 10, 205–216. doi:10.1080/14733315.2011.11683949

Mortensen, D.K., Walker, I.S., Sherman, M.H., 2011. Optimization of occupancy based demand controlled ventilation in residences. Int. J. Vent. 10, 49–60.

NEN, 2011. NEN 8088-1:2011 nl Ventilatie en luchtdoorlatendheid van Gebouwen - Bepalingsmethode voor de toevoerluchttemperatuur gecorrigeerde ventilatie- en infiltratieluchtvolumestromen voor energieprestatieberekeningen - Deel 1: Rekenmethode (Ventilation and infiltration for buildings - Calculation method for the supply air temperature corrected Ventilation and infiltration air volume rates for calculating energy performance - Part 1: Calculation method).

Nicolas, C., 1985. Analysis of a humidity-controlled ventilation system. Evaluation des performances d'une ventilation hygromodulante., in: Proceedings of the CLIMA 2000

World Congress on Heating, Ventilating and Air-Conditioning, Indoor Climate. P O Fanger, Copenhagen, p. p339–343.

Nielsen, J., 1992. A new ventilation strategy for humidity control in dwellings., in: 13th AIVC Conference “Ventilation for Energy Efficiency and Optimum Indoor Air Quality”,. Nice, France,.

Nielsen, J., Ambrose, I., 1995. A new ventilation strategy for humidity control in dwellings - a demonstration project., in: 16th AIVC Conference “Implementing the Results of Ventilation Research”,. Palm Springs, USA,.

Nielsen, T.R., Drivsholm, C., 2010. Energy efficient demand controlled ventilation in single family houses. Energy Build. 42, 1995–1998. doi:10.1016/j.enbuild.2010.06.006

Parekh, A., Riley, M., 1991. Performance analysis of demand controlled ventilation system using relative humidity as sensing element., in: 12th AIVC Conference “Air Movement and Ventilation Control within Buildings.” Ottawa, Canada.

Pavlovas, V., 2004. Demand controlled ventilation: A case study for existing Swedish multifamily buildings. Energy Build., REHVA Scientific 36, 1029–1034. doi:10.1016/j.enbuild.2004.06.009

Persily, A., 2006. What we Think we Know about Ventilation. Int. J. Vent. 5, 275–290. doi:10.1080/14733315.2006.11683745

Raatschen, W., 1990. IEA Annex 18. Demand controlled ventilating system: state of the art review, Document. Swedish Council for Building Research, Stockholm, Sweden.

Römer, J.C., van Ginkel, J.T., 2003. Demand controlled ventilation in a low-energy house: Preliminary results on energy conservation and health effects, in: The 4th International Conference on Cold Climate - Heating, Ventilating and Air-Conditioning.

Savin, J.-L., Berthin, S., Jardinier, M., 2014. Demand-controlled ventilation. 20 years of in-situ monitoring in the residential field, in: 35th AIVC Conference “ Ventilation and Airtightness in Transforming the Building Stock to High Performance.” Poznań, Poland.

Seong, N.C., 2010. Energy Requirements of a Multi-Sensor Based Demand Control Ventilation System In Residential Buildings, in: 31st AIVC Conference “ Low Energy and Sustainable Ventilation Technologies for Green Buildings”,. Seoul, Korea,.

Seppanen, O., et. al., 2012. HealthVent Project Report WP5 – Existing buildings, buildings codes, ventilation standards and ventilation in Europe.

Sheltair scientific Ltd., 1988. Preliminary Results of “Evaluation of the Aereco ventilation system in the VIS Residence.” For Canadian Home Builders association, Vancouver, Canada.

Sherman, M.H., 2004. Efficacy of intermittent ventilation for providing acceptable indoor air quality (No. LBNL--56292, 834643).

Sherman, M.H., Hodgson, A.T., 2002. Formaldehyde as a basis for residential ventilation rates. Lawrence Berkeley Natl. Lab.

Sherman, M.H., Mortensen, D.K., Walker, I.S., 2011. Derivation of equivalent continuous dilution for cyclic, unsteady driving forces. Int. J. Heat Mass Transf. 54, 2696–2702. doi:10.1016/j.ijheatmasstransfer.2010.12.018

Sherman, M.H., Walker, I.S., 2011. Meeting residential ventilation standards through dynamic control of ventilation systems. Energy Build. 43, 1904–1912. doi:10.1016/j.enbuild.2011.03.037

Szkarłat, K., Mróz, T., 2014. System for controlling variable amount of air ensuring appropriate indoor air quality in low-energy and passive buildings, in: 35th AIVC Conference “

Ventilation and Airtightness in Transforming the Building Stock to High Performance." AIVC, Poznań, Poland.

Turner, W., Walker, I., 2012. Advanced Controls and Sustainable Systems for Residential Ventilation.

Turner, W.J.N., Walker, I.S., 2013. Using a ventilation controller to optimise residential passive ventilation for energy and indoor air quality. Build. Environ. 70, 20–30. doi:10.1016/j.buildenv.2013.08.004

Turner, W.J.N., Walker, I.S., Roux, J., 2015. Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass. Energy 82, 1057–1067. doi:10.1016/j.energy.2015.02.011

Van den Bossche, Janssens, A., Heijmans, N., Wouters, P., 2007. Performance evaluation of humidity controlled ventilation strategies in residential buildings., in: Thermal Performance of the Exterior Envelopes of Whole Buildings X. ASHRAE, Clearwater Beach, FL, USA, p. 7p.

van Holsteijn, R., Li, W., 2014. MONItoring & Control of Air quality in Individual Room - Results of a monitoring study into the indoor air quality and energy efficiency of residential ventilation systems.

Walker, I., Sherman, M., 2006. Evaluation of existing technologies for meeting residential ventilation requirements. (No. LBNL-59998).

Walker, I., Sherman, M., Dickerhoff, D., 2011. Development of a Residential Integrated Ventilation Controller (No. LBNL-5401E). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Walker, I., Sherman, M.H., Less, B., 2014. Houses are Dumb without Smart Ventilation. eScholarship.

Walker, I.S., Sherman, M.H., 2013. Effect of ventilation strategies on residential ozone levels. Build. Environ. 59, 456–465. doi:10.1016/j.buildenv.2012.09.013

Wargocki, P., 2012. The effects of ventilation in homes on health, in: Ventilation 2012. INRS, Paris, France, p. 21 p.

WHO, 2014. Burden of disease from Household Air Pollution for 2012. World Health Organization.

Woloszyn, M., Kalamees, T., Olivier Abadie, M., Steeman, M., Sasic Kalagasidis, A., 2009. The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. Build. Environ. 44, 515–524. doi:10.1016/j.buildenv.2008.04.017

Wouters, P., L'Heureux, D., Geerinckx, B., Vandaele, L., 1991. Performance evaluation of humidity controlled natural ventilation in apartments., in: 12th AIVC Conference "Air Movement and Ventilation Control within Buildings." Ottawa, Canada.

Zeghnoun, A., Dor, F., Grégoire, A., 2010. Description du budget espace-temps et estimation de l'exposition de la population française dans son logement. Inst. Veille Sanit. Qual. L'air Intér. Dispon. Sur Www Air-Interieur Org.

Zhang, X., Wargocki, P., Lian, Z., 2016. Physiological Responses during Exposure to Carbon Dioxide and Bioeffluents at Levels Typically Occurring Indoors. Indoor Air n/a-n/a. doi:10.1111/ina.12286

Table 2: Summary of the studies surveyed on energy and IAQ performance of smart ventilation strategies in residential buildings. For supplementary material.

Reference *Country*	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
(Anon, 1983) ***France***			Balanced + whole house + short-term supplementary airflows in kitchen	RH-controlled extraction grills + RH-controlled supply	Average RH controls supply and extract airflow rates	Cost of 230€ for a 3 BR-flat Sensors, air inlets, and exhaust tested for several years in two independent laboratories	Less condensation	50–60%
(Barthez and Soupault, 1984) ***France***	Apartment	Modeling + experimental	Single exhaust + whole house + short-term in kitchen	CO_2 + no sensor in other rooms	Control a 2-speed fan	Good relationship between CO_2 and occupancy but no conclusion between CO_2 and RH	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	Sections = mechanical function of RH	Performance varies according to air leakage level, climate, occupancy scenarios	/	- 30% of the total exhaust airflow, 10% heating energy savings
(Sheltair Scientific Ltd., 1988) ***Vancouver, Canada***	1 House	Monitoring campaign for 1 week	Single exhaust + whole house	Mechanical RH	Sections = mechanical function of RH	Could be more effective in a drier climate. Accuracy measurement problems	RH constant, contrary to the CO_2	0%, Explained by leaks on the boiler heater
(Parekh and Riley, 1991) ***Ottawa, Canada***	2 Houses	Monitoring campaign 6-month duration	Single exhaust + whole house	Mechanical RH Mechanical RH	Sections = mechanical function of RH	Impact of air leakage highlighted	Poor IAQ, especially in the bedrooms	6% Energy savings
(Mansson, 1993) **(Wouters et al., 1991)** ***Namur, Belgium***	9 Reference flats + 9 with RH DCV in a 9-storey building	Monitoring campaign 110 days in 3 periods	Natural + whole house (shunt ductworks in humid rooms)	RH-controlled extraction grills + RH-controlled grills	Sections = mechanical function of RH	**Same "CEC" project as the following 2 studies** No measure in the bed- and living-rooms	% Of time CO_2 under 1000 ppm and 1500 Is lower with DCV	**Improvement
(Mansson, 1993)	7 Ref flats +	Monitoring	Natural + whole	RH-controlled	Sections =	No measure in the bed-	No improvement	**No

Reference ***Country***	**Type of home**	**Method**	**Type of system and regulation**	**Type of sensor (Humid rooms + Dry rooms)**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings**
(Wouters et al., 1991) ***Schiedam, The Netherlands***	7 with RH DCV in a 10-storey building	campaign 72 days in 3 periods	house (shunt ductworks in humid rooms)	extraction grills + RH-controlled grills	mechanical function of RH	and living-rooms Poor results explained by the excessively small existing ducts		improvement
(Mansson, 1993) **(Wouters et al., 1991)** ***Les Ulis, France***	10 Ref flats + 10 with RH DCV in a 5-Storey building	Monitoring campaign 143 days in 3 periods	Natural + whole house (shunt ductworks in humid rooms)	RH-controlled extraction grills (except in kitchen) + RH-controlled grills	Sections = mechanical function of RH	No measure in the bed- and living-rooms Airtight building with appropriate size of existing ducts explains the good results	CO_2 and RH correlate well	** 30% duringa heating season
(Mansson, 1993) ***Torino, Italy (2700 HDD)***	9 Rooms of 3 flats in a 6-storey building	Monitoring campaign, 2 months heating period	Simple exhaust + whole house	RH-controlled extractions + RH-controlled grills	Sections = mechanical function of RH		Surface condensation risk on windows metal frames	- 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 3) RH and mixed gas sensor in exhaust	Set-points, RH as a function of outdoor temperature, controls 3 fan speeds (35, 155, 220 $m^3.h^{-1}$)		Avg BR CO_2 : 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 189 h to 1385 h	3 Balanced, 2 simple exhaust + whole house	CO_2, pressure differences, temperatures, RH, absolute humidity, activity, operating air equipment	Smart ventilation strategy		Slight reduction in average CO_2 but significant reduction in peak CO_2 levels	- 6–21% Of total airflow - 23–34% Of fan electrical energy demand
(Nielsen, 1992)	A new	Monitoring for 1	Air supply in all the	RH	A damper in		RH>45% 10% Of	Total airflow

Reference *Country*	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
Denmark	single-family house	month	rooms, with exhausts in the bathroom and in a scullery + local regulation		the inlet duct of each room regulates air volume every min, RH < 45%		the time No condensation CO$_2$ <1200 ppm 98% of the time	reduced from 39% compared to the Danish code
(Kesselring et al., 1993) ***Florida, USA***	1 Energy-efficient home	5 Days monitoring	Balanced + whole house	One indoor CO$_2$ sensor	"On-off" controlled Δt=15 min set-point at 600 ppm		CO$_2$ in master bedroom 600–900 ppm	Ventilation system turned on 1/3 of time
(Nielsen and Ambrose, 1995) ***Denmark***	16 Apartments	Monitoring for 3 months	Balanced + whole house + centralized + local regulation	RH air supplies and exhausts controlled by capillary hygrostats in each room	Set-points at RH=40–45%.	Results compared to a group of 16 identical apartments equipped with constant airflow ventilation	Mean RH< 43% No condensation on windows	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	1) Preliminary modeling (TRNYS) + 2) 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 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 1-BR apartment 74 m², 2-person occupancy	Monitoring for 3 days	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	2-Person occupancy simulated with CO$_2$ and RH emissions, a constant N$_2$O emission simulated from material and	CO$_2$ concentration, 10% in living room *2 in the BR	Total airflow rate reduced to 20–30%

Reference *Country*	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
	simulated				humid rooms	furnishings	Pollutant emitted by materials and furnishings, 50%	
(Pavlovas, 2004) ***Sweden***	A typical Swedish apartment	Modeling (IDA Indoor Climate and Energy)	Exhaust-only, whole house + global regulation	1) CO_2 DCV with sensors in humid rooms, 2) RH DCV with sensors in humid rooms, 3) occupancy DCV	Exhaust airflow 10 $L.s^{-1}$ or 30 $L.s^{-1}$	Indoor doors closed or open were also tested	CO_2 and occupancy DCV: similar CO_2 concentrations but increase the risk for high humidity levels RH DCV: increases CO_2 concentrations	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: 1) occupancy detection 2) CO_2	Air inlets and grills over 8 positions. A 10-min control algorithm regulates fan speed		CO_2 exposure in occupied dry rooms at least reduced by a factor of 2, summer thermal comfort is nearly always bettered	Heating needs reduced: 2–5% Fan electrical consumption reduced: 91–96%
(Van den Bossche et al., 2007) ***Uccle, Belgium***	1 House with different airtightness levels	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	RH sensor control [20–100%] of nominal airflow for a RH range of [30–100%]. Motion sensors activate nominal	They simulated a 4-person occupation	IAQ slightly lower for the DCV system studied. 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 1100–1200 kWh, 27% for very airtight houses, 14% for houses with an average airtightness. The moisture buffering effect adds only a

Reference *Country*	**Type of home**	**Method**	**Type of system and regulation**	**Type of sensor (Humid rooms + Dry rooms)**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings**
					airflows for 20–30 min			0.75% extra energy demand
(Krus et al., 2009) ***3 climates in Germany***	1 Test apartment 75m², 3 occupants	Modeling (Wufi-Plus)	Exhaust-only, whole house + local regulation	RH + RH	RH controls opening of valves in exhaust ducts	Comparison of an exhaust-only DCV system with a balanced-heat recovery system	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 extractions in humid rooms	RH sensors control nominal airflow for a RH range	Gains while keeping the peak RH values at the same level	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 by 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 2 heating seasons	Exhaust-only + whole house + local regulation	RH-controlled exhausts + RH inlets + occupancy in toilets	Sections = mechanical function of RH	Parameters measured included ventilation parameters (pressure, air inlets opening cross-sectional area, airflows through the trickle ventilators and the extraction air outlets)	CO_2 cumulative 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 ventilation energy savings
(Nielsen and Drivsholm, 2010) ***Denmark***	A new single-family house	Measurements with and without the DCV system	Exhaust-only + whole house + centralized regulation	Difference CO_2 and absolute humidity between measurements in air-handling unit and outdoors	High- and low-flow rates with set-points set at a difference of 150 ppm in CO_2 and to 2 g/kg in absolute	Measurements of the fan speed throughout the week showed that the control strategy succeeds in tracing the non-occupancy schedules	No significant change in IAQ	Low ventilation rate: 37% of the time energy savings estimated at 35% on fan electricity consumption and 23% on

Reference *Country*	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
					humidity			heating needs
(Seong, 2010) ***Seoul, South Korean***	A standard Korean multizone apartment	Multizone modeling CONTAM + Energy plus $\Delta t=1$ hp	Whole-house balanced DCV system	1) CO_2 demand 2) TVOC demand Location of the sensors unknown		"On-off" control strategy, with a base airflow rate set at the reference in the Korean regulation, 0.7 h^{-1}	1) CO_2<1000 ppm, TVOC in 150–800 $\mu g.m^3$ with peaks 2) CO_2<2200 ppm, TVOC in 400–800 $\mu g.m^3$	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 3 combined	1) "On-off" size grille set point 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 the other ones	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)
(Mortensen et al., 2011)	Single-family house	Calculation approach	Whole-house ventilation	Occupancy schedules (of 4–8 or 16 h)	Two fan speeds based on the chronic exposure equivalence calculation	Performance curve plots can define optimized points given the occupancy time, the reference rate, the high to low ratio, the emission characterization	Equivalence in 24-h chronic exposure, acceptable peak exposure	Total ventilation rate, 12% Can achieve ≥18% if occupant emissions are dominant
(Mortensen and Nielsen, 2011)	Multi-family dwelling	Modeling study	Whole house + balanced with heat recovery + centralized		Several control strategies on air handling unit		Strategy based on the resetting of the static pressure at part load conditions	Yearly electricity consumption: −20 to 30%
(Sherman and Walker, 2011) ***3 climates,***	Single-family house	a) Modeling (REGCAP) b) Field study of a	a) Whole house + centralized + 4 ventilation types	Control by the operation of other air	A controller logic with a set of actions	The theoretical background assumes a continuously occupied	Decrease of the annual average relative dose can	a) Energy savings: −11 to 61%. Run time of

Reference ***Country***	**Type of home**	**Method**	**Type of system and regulation**	**Type of sensor (Humid rooms + Dry rooms)**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings**
California, USA		prototype (RIVEC)	b) exhaust-only with economizer	devices and with a switch-off during a 4-h peak electricity demand period	at each time step, set primarily at 10 min; 4 periods in the day	home with a constant emission rate	reach 14% Peak relative exposure no more than 11% above the target limit, even with 4- h off period	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	Controller logic was updated with 2 periods in the day depending on occupancy	Energy savings are robust across climates, house geometries and airtightness levels	Maintaining the IAQ equivalence of ASHRAE 62.2, and without acute exposures to constantly-emitted pollutants	Ventilation energy savings > 40%. Absolute energy saving 500–7000 kWh/year. Peak power reduction up to 2 kW
(Turner and Walker, 2013) ***16 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 insufficient, RIVEC turns on the whole-house exhaust fan	The authors show that there was a place to optimize hybrid ventilation systems with good sizing of the passive stack and smart ventilation strategies	IAQ clearly bettered	Ventilation energy savings about 25%
(Walker and Sherman, 2013) ***Livermore and Riverside, California, USA***	A typical California single-family house	Modeling (REGCAP)	Whole house + centralized + 7 types of ventilation	Same. The 4-h switch-off period for peak electricity demand is the same as that			A reduction of 10–40% in ratios of indoor-to-outdoor ozone, while continuous exhaust ventilation	

Reference *Country*	Type of home	Method	Type of system and regulation	Type of sensor (Humid rooms + Dry rooms)	Control strategy	Main findings / comments	IAQ performance	Energy savings
				for ozone peak			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 solution	The simplest strategy with a cut-off set at an outdoor temperature of 5°C was the most efficient one across a variety of climate zones	Equivalent IAQ	For leakier than 3 ACH_{50} houses in severe climate, HVAC energy savings in the range 100–4000 kWh. Fan should be oversized by an average of 34%
(Szkarłat and Mróz, 2014) ***Poznan, Poland***	1 Passive house	Monitoring 1 year + Modeling	Whole HVC system decentralized regulation	Temperature, RH, CO_2 sensors in every room	VAV control as a function of sensible heat balance of temp control, latent heat balance of RH control, CO_2 balance	The issue was how to define control parameter 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	Multiple control strategies	Study evaluating different control algorithms mainly based on the 35 DCV systems available on the Belgian market	1) ~Reference 2) better than ref 3) clearly better 4) slightly better 5) better 6) better	1) 0% 2) 26–37% 3) 38–39% 4) −21 to −28% 5) −15% to +36% 6) 4–35%

Reference ***Country***	**Type of home**	**Method**	**Type of system and regulation**	**Type of sensor (Humid rooms + Dry rooms)**	**Control strategy**	**Main findings / comments**	**IAQ performance**	**Energy savings**
				only + central or zonal regulation 6) CO_2 sensor in dry room controlling exhausts (in dry room)				
(van Holsteijn and Li, 2014) ***The Netherlands***	Occupied single-family house and apartments	Experimental 1-year measurement	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 1. Depending on the location of sensors, they showed poor and good performance of DCV systems	Mean annually CO_2 exposure +11% to −70% for a single-exhaust system	MJ/m²/year −31% to +21% for a single-exhaust system
(Hesaraki and Holmberg, 2015) ***Sweden***	3-Level low-energy house	Modeling (IDA ICE 4)	Exhaust-only, whole house, centralized	Occupancy, non-occupancy periods = 8 am-6 pm Low rate used for 4,6, 8, or 10 h, starting from 8 am	Base airflow rate 60 $L.s^{-1}$ is switched to 16 $L.s\ s^{-1}$ during nonoccupancy periods	For an acceptable IAQ, ventilation turned on 2 h before occupants return; reference constant airflow system delivers 60 $L.s^{-1}$	Mean age of air increases resp. by 5.5, 22.2, 50, 105.5%, VOC concentration at 6 pm increases by resp. 4, 20, 65, 211%, CO_2 stayed 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 set point	Investigation of a low-cost temperature-based smart ventilation control (less than $80)	No significant impact on CO_2 and humidity	Energy savings between 73 to 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 3 speeds