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Air flow rates, air cleaners, humidity

NZEB requirements in Denmark, Estonia and Finland

COLD CLIMATE HVAC & ENERGY 2021

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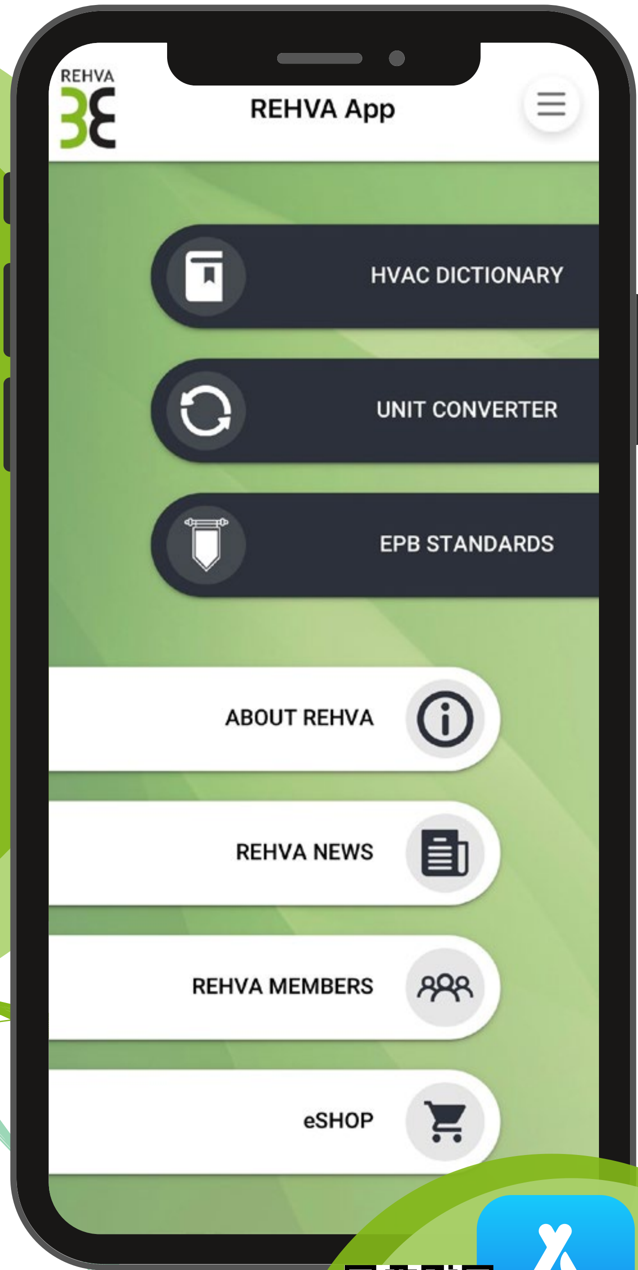

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Good indoor air quality is more than ventilation

MARTIN THALFELDT
Scientific Committee Chair,
Cold Climate HVAC & Energy
2021 Conference

OLLI SEPPÄNEN
Convenor of Nordic Ventilation
Group

Energy efficiency, in door climate and ventilation have been for years in the focus of construction sector in Nordic countries. There are good reasons for the high interest in HVAC-technology. Good heating has always been a necessity due to cold climate. Most of the energy is imported in Denmark, Finland and Sweden. As the primary energy use of buildings is about 40% of energy demand, the good energy efficiency has been on agenda for decades. The harsh climate has also made people to demand a good and comfortable indoor environment, which again has boosted the R&D work of industry. High interest on public health has been always an essential part in government policy of all Nordic countries. A specific interest has been for long time in the performance of ventilation systems for better indoor environment. The ongoing COVID-19 pandemic has brought much desired attention to indoor air quality issues, which spark investments in engineering solutions for virus control and research and development of advanced solutions for improving the living and working conditions of people. This issue contains several articles that deal with different methods for improving indoor air quality and bring attention to aspects that are often not acknowledged.

The articles in this issue are mostly from two sources – recently revived Nordic Ventilation Group, a group of scientists from Nordic counties and also selected articles from the virtual conference Cold Climate HVAC and Energy 2021.

The original Nordic Ventilation Group was established in 1980s, with focus on ventilation guidelines on air flow measurements, balancing the ductwork etc. The results were widely used in Scandinavian counties. The Group was reactivated in 2020 with focus on better understanding of indoor environment and ventilation technology. In this issue, the articles on air cleaners, indoor environment and productivity, effect of indoor humidity, illustrate the current and future voluntary work of this group. The group is integrated with Scanvac, and works in close cooperation with REHVA and its technical committees.

The articles from the conference focus on some impacts of the COVID-19 pandemic on the energy use and infection risk in University campus, describe a novel solution for air distribution at work desk. There is a study that addresses issues related with solutions required for fulfilling current NZEB requirement.

We believe that this Nordic Issue of the REHVA Journal gives you better basis for discussions on methods for controlling the spread of COVID-19 and helps you to make a better selection of appropriate solutions when needed. ■

What we know and should know about ventilation

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Ventilation is an important component of any building, even if it is achieved by opening windows or infiltration. It is without a doubt recognized as an essential means of providing good indoor air quality. Although described widely in the scientific literature, there are still a few incompletely resolved questions concerning ventilation. They include, among others: (i) How much ventilation is needed in a given building?; (ii) Which criteria should be used to determine ventilation?; (iii) What is the absolute minimum ventilation rate in a given building?; (iv) Can we use epidemiological data for setting ventilation requirements?; and (v) Can ventilation be used as an indoor air quality metric? This short article attempts to discuss some of these questions.

Introduction

Ventilation with outdoor air has always been our "ally" in reducing the concentration of air pollutants indoors and thus in mitigating discomfort and health risks, including the risk of infection from airborne pathogens. In the past, when buildings were less airtight, ventilation was obtained by infiltration through the building envelope, shafts, or operable windows (adventitious ventilation); today, it is usually achieved by specially designed systems that not always but predominantly are mechanical. The positive effect of ventilating rooms with outdoor air is only obtained if the outdoor is clean and less polluted than indoors, which is the usual assumption when designing ventilation and is frequently the case. Simulation of indoor exposures to outdoor air pollutants brought in by ventilation imply, however, that increasing ventilation without proper filtration and air cleaning will considerably increase the burden of disease caused by these pollutants [1]. These results underline the importance of ensuring that clean outdoor air is supplied indoors instead of assuming that outdoor air is clean. The few published studies showing that increasing outdoor air resulted in an increased risk of health seem to have made this flawed assumption [2].

The knowledge

Increasing building ventilation, which should be understood in this article as an increased outdoor air supply rate, has otherwise been documented and summarized in many reviews [3,4,5,6] to improve indoor air quality and benefit health, comfort, office work, and schoolwork. The positive effect of ventilation was demonstrated in the classical studies of Yaglou et al. [7], where ventilation requirements to control body odour were determined; their results were verified later in experiments performed in Denmark [8], USA [9] and Japan [10]; in each of these experiments, increasing ventilation improved indoor air quality by reducing odour intensity or the percentage dissatisfied with the air quality as estimated from subjective ratings of the acceptability of air quality. Evaluations of the air quality were made upon entering the space. Other experiments, with occupants remaining indoors until they were adapted to the indoor air quality showed no effect of increased ventilation on ratings of air quality when the air pollution source was body odour [11], but did show an improvement in perceived air quality when the air was polluted by emissions from building materials [12]. Today, these results form the basis for the ventilation requirements prescribed by ASHRAE Standard 62.1 [13] and EN 16798-1 [38]. Increased ventilation was also shown in many studies to reduce both the prevalence and intensity of non-clinical acute health symptoms known either as Sick Building Syndrome (SBS) symptoms [14] or building-related (BRS) symptoms [15] independent of the recall time of these symptoms. The risk of increased symptoms, expressed as the probability (odds) of symptoms being reported as a consequence of reduced ventilation, was estimated, i.a., by Sundell et al. [16] and Fisk et al. [17]. Finally, increased ventilation was shown to improve the performance of office work by adults [18] and of schoolwork (and hence learning) by children [19]. Other studies showed that improved ventilation could be expected to reduce short-term absence rates for both adults [20] and children [21,22]. Ventilation can also reduce the transmission of infectious diseases [23]. Although some control of the risk associated with these pathogens can be obtained by filtering the air with high-efficiency filters, by disinfection of air using, for example, UV-C, to achieve virus-free air, good ventilation with clean outdoor air is also essential. However, the epidemiological data does not provide clear evidence on the required ventilation rates that should be provided in buildings to reduce the risk of infection with airborne pathogens r [24]. Still, estimations using the Well's-Riley model document this effect [25], as well some studies analysing outbreaks related to SARS-CoV-2 [26].

In many of the above studies, carbon dioxide (CO_2) was used as a proxy for ventilation [27,28]: The ventilation rate was not measured directly but was calculated using measured concentrations of CO_2 and assuming the metabolic rate of building occupants and good mixing of air within a space. Relationships were also created between the concentration of CO_2 and different outcomes, including health [29] and cognitive performance [19]. Rudnick et al. [25] developed a CO_2-based risk equation to estimate the risk of indoor transmission of infection by the airborne route. These results do not imply that CO_2 is a causative factor, although they are sometimes interpreted this way. CO_2 is simply a marker of ventilation efficiency (when occupants are present). Some studies published recently have shown that pure CO_2 can reduce some aspects of cognitive performance; specifically, decision-making in complex and time-stressed tasks, at levels as low as 1,000 to 2,500 ppm [30,31], the performance of pilots at 1,500 ppm [32], and some have even claimed that pure CO_2 can affect office-type work such as proof-reading at levels as low as 3,000 ppm [33], although other studies were unable to confirm these results [34,35]. The comprehensive reviews by Fisk et al. [36] and Du et al. [37] show the inconsistency of the results concerning the effects of pure CO_2 on cognitive performance at levels typically occurring indoors, i.e., below its permissible occupational limit of 5,000 ppm. They concluded that it is more likely that no effects are to be expected. They also show that no effects on health or comfort are to be expected at these levels. Thus, attributing the negative effects on building occupants only to CO_2 levels is incorrect. Increasing ventilation will, of course, reduce the concentration of CO_2 that has been emitted by building occupants (if present) and also the concentrations of pollutants emitted from many other sources of pollution indoors, including humans and their activities, building, and furnishing, used filters as well as smoking (if occurring) and combustion. These emissions are mainly responsible for the effects observed in the studies described above and should be the main focus rather than CO_2.

The problem

Despite the above evidence, some central questions about ventilation are still not completely answered. Among others, which outcome shall be used to prescribe ventilation requirements in buildings, and consequently, how much ventilation is necessary? This problem is nicely exemplified in **Figure 1** showing how ventilation rates changed over time. The difficulty to set ventilation requirements was also the case when one of the first ventilation guidelines were proposed by the Chicago Commission on Ventilation in 1914 and in 1923 re-confirmed by the New York State Commission on Ventilation. No ventilation requirements were proposed back then, although setting ventilation was the main purpose of these committees. There were only general recommendations regarding the methods on how to achieve ventilation. Window-ventilated rooms with natural draft were the preferred method of ventilation proposed in these documents, but ventilation was not recommended to avoid ill health, but to avoid over-heating. Temperatures of 15–19°C in window-ventilated rooms were observed to cause the lowest prevalence of respiratory illnesses, so the resulting guidelines recommended 20°C with proper control of relative humidity for living rooms. CO_2 was not recognized as a harmful agent. Ventilation was basically required to control humidity, and this would be impossible if 100% of the air was recirculated.

Today, most of the major standards define ventilation requirements based on the resulting air quality as building occupants perceive it. They consider pollutants emitted by both humans and building materials, and stipulate the air quality and ventilation requirements based on the percentage of visitors dissatisfied with the air quality upon entering the space [38] or on the acceptability for both visitors and occupants [13]. These standards implicitly assume a connection between fulfilling comfort requirements and fulfilling the requirements for health, assuming that if the former is reached, the latter will be ensured as well. Brelih [39] and Dimitroulopoulou [40] showed that ventilation in numerous buildings does not comply with the requirements in the standards, while Asikainen et al. [41,42] showed that substandard ventilation in homes will result in an increased burden of disease, which is providing some support to the above assumption on health effects. It is still pertinent to ask whether other criteria than sensory discomfort should be used to determine ventilation requirements in buildings or whether the current requirements are sufficiently able to reduce the risks related to exposures that are not affected by air quality as perceived by building occupants.

The reasons given for the need for ventilation changed over time (**Boxes 1 and 2**). **Figure 1** shows that ventilation requirements changed too. It shows that the requirements are nearly "everywhere" on the figure, and they differ by an order of magnitude. Tredgold

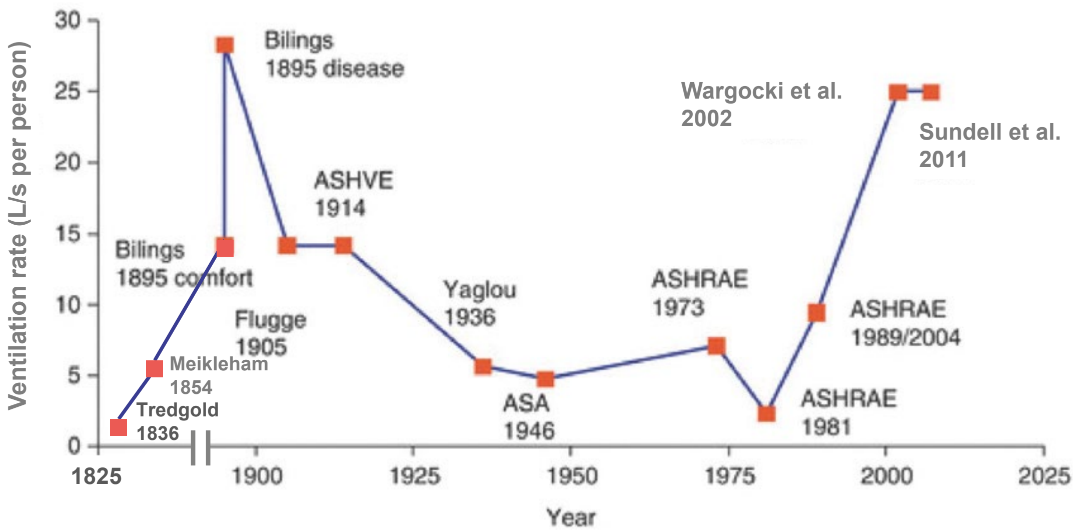

Figure 1. Ventilation requirements in buildings – historical perspective (adapted from Nielsen and Li). [64]

proposed the lowest ventilation in 1836; he suggested that the minimum ventilation rates in mines should satisfy the physiological needs of a miner. It was set at 1.7 ℓ/s per person, of which 0.2 ℓ/s was for purging CO_2 from the lungs, 1.4 ℓ/s for removing the moisture produced by the body, and 0.1 ℓ/s for keeping a candle burning. One of the highest rates was proposed 170 years later using the results of two reviews of

Box 1. Ventilation, some historical developments

In ancient Egypt ventilation was deemed essential for stone carvers, to avoid exposure to particles and dust generated during this process. Hippocrates (460-377 B.C.) described the adverse effects of polluted air in crowded cities and mines. During Roman times (1st B.C.), Sergius Orata developed hypocausts as an under-floor heating system capable of distributing heat uniformly in a house and, most importantly, avoiding combustion indoors and, subsequently, harmful exposures. In the case of open fires indoors, a minimum ratio of window to floor area was set, and parchment above the window was required to assure the supply of air due to infiltration.

In Venetian times, roof windows were developed and Leonardo da Vinci claimed that no animal could live in an atmosphere where a flame does not burn, and that dust can cause damage to health, implying a need for ventilation.

In the 17th Century, Wargentin expressed the common knowledge of this time that expired air was unfit for breathing until refreshed. In the same Century, Gauger quoting Cardinal Melchior de Polignac, remarked that it is not warmth but inequality of temperature and want of ventilation that causes maladies.

In 1756 Holwell described an accident in the Black Hole of Calcutta, a small dungeon where prisoners and soldiers were kept overnight in poor conditions, in which 125 out of 146 died due to suffocation. During the Crimean War (1853-1855), there was a faster spread of diseases among wounded soldiers in poorly ventilated hospitals. A higher morbidity and mortality were observed in overcrowded, poorly ventilated rooms. Immediately after, Florence Nightingale stated that the air the patient breathes should be as pure as the external air, without chilling him. The importance of ventilation in small room volumes, to avoid the death of the occupants, was emphasized by Beeton in 1861 and Baer in 1882.

A few years later, Reid expressed the view that along with mental anxiety and defective nutriment, defective ventilation should be considered as one of the evil enemies of the human race. Griscom expressed a similar view in 1850 and acknowledged that deficient ventilation is fatal as it leads to the spread of tuberculosis and other diseases. An effective treatment of tuberculosis using country fresh air was then achieved by Trudeau, who opened the Adirondack Cottage Sanatorium in 1873.

In the early 20th century, Winslow and Palmer suggested that poorly-ventilated rooms do not create much discomfort but do result in loss of appetite. Later, Winslow and Herrington obtained a similar result - loss of appetite for food when heating dust from a vacuum cleaner.

peer-reviewed literature on ventilation and its effect on man showing that at 25 ℓ/s per person, no negative effects on health symptoms and the performance of office work are to be expected [4,43]. Billings proposed the highest ventilation rate in buildings in 1893 to reduce the risk of spread of tuberculosis and recommended between 30 and 60 cfm/person (14–28.5 ℓ/s per person).

Box 2. Some theories underlying the need for ventilation through history

The miasma theory prevailed until XVIII–XIX Century, attributing cholera, Chlamydia, and the Black Death to a noxious form of "bad air." The germ theory of disease later displaced it after germs were discovered in the XIX Century. In the early XVII Century breathing was believed to result in a cool heart. In the same Century, Mayow attributed the effects observed to igneo–aerial particles that cause the demise of animals.

One Century later, in 1775, Lavoisier identified two gases in the air and attributed the effects of igneo-aerial particles to carbon dioxide (CO_2) and air stuffiness. The theory that CO_2 is a dominant cause of the physiological effects of bad air remained dominant for nearly 100 years, although it was acknowledged that other factors could also contribute to the effects observed. It prevailed until Pettenkofer in the 1800s, demonstrated that it is neither the deficiency of oxygen (O_2) nor excess of CO_2 but the presence or lack of biological pollutants (from humans) which are responsible for vitiation of indoor air. In 1872 Pettenkofer and Saeltzer suggested CO_2 to be a surrogate for vitiated air, an indicator of the presence of deleterious substances of unknown origin.

In 1887–1889 Brown-Sequard and d'Arsonval suggested that anthropotoxin (the toxic effluvia - toxic substances in exhaled air) was responsible for the effects reported through history when there was a lack of ventilation. Organic matter from lungs and skin had also been proposed as poisonous by many others before the anthropotoxin theory. The theory was rejected by many experiments performed later by Haldane and Smith in 1892–93, Billings in 1895, and Hill in 1913. They could not confirm that a condensate of expired air could kill animals, as Brown-Sequard claimed. The anthropotoxin theory was then superseded by an idea proposed by Billings in 1893, suggesting that the purpose of ventilation is to dilute contagions emitted by humans, thus reducing the spread of infectious diseases.

A large body of research in the early XX Century, among others by Billings, Flugge, Benedict & Millner, and Hill, showed that lack of ventilation causes discomfort exemplified by unpleasant body odours and raised temperature. At the same time, no negative physiological effects could be observed even at CO_2 levels as high as 1–1.5% (10,000 to 15,000 ppm). Lack of ventilation was consequently associated with raised temperature and discomfort. Since studies of Lemberg and Yaglou in the 1930s of the XX century, ventilation has been required to merely keep body odours at an acceptable level, defined to be at a moderate level.

In the 1980–1990s, it was also acknowledged that in addition to the body odours emitted by humans, other sources of pollution indoors determine ventilation requirements. However, the general principle of providing ventilation to reduce discomfort by achieving acceptable air quality as perceived by humans was not changed. Ventilation was merely a question of comfort, not health.

Box 3. Tentative guidelines for the design, operation, and maintenance of systems used to supply air for ventilation (from the HealthVent project)

* The systems should meet ventilation requirements from the start and throughout the entire lifetime of the building.
* Low-emitting, certified and durable materials should be used in any system used for ventilation. Emission from fibrous materials should be reduced to a minimum.
* Systems used for ventilation should be kept clean throughout the lifetime of a building. They should be cleaned at regular intervals using certified products for wet and dry cleaning that do not elevate exposures.
* The performance of mechanical ventilation systems should be verified at the commissioning phase and shall be guaranteed by the suppliers at any time for their entire service life.
* Condensation in systems used for ventilation should be minimized to avoid microbial growth. Systems should be properly drained and kept dry. Outdoor air intakes should be protected from rain and snow entrainment.
* Air cleaning that emits ozone in systems used for ventilation should be avoided.
* The ventilation rate should cope with the actual needs and demands and should be based not only on the design parameters but on the actual use and actual occupant requirements.
* If a mechanical system is used for ventilation, there should be a contingency plan for ensuring ventilation (e.g., by opening the windows or other measures) in the case of system failure, and in case of blocking and shutting down the systems by occupants or building operators.
* All outdoor air intakes, including openings for natural ventilation, should be located so that the direct entrainment of pollutants from nearby sources is minimized.
* Ventilation air should be properly distributed within the space to which it is delivered.
* The systems used for ventilation shall not become the source of nuisance and annoyance due to noise, vibration or draft at any time from commissioning and throughout its entire lifetime.
* The systems used for ventilation should be regularly maintained and inspected during normal operation. The inspections should include at a minimum the same aspects as during commissioning and additionally examination of cleanliness, loading of filters, and the need for re-balancing in case of changing demands. Those obligations shall become the exclusive responsibility of the suppliers of the systems and performed by qualified personnel.
* Systems used for ventilation should be designed, operated, and maintained by qualified personnel. The design should address the need for regular maintenance and provide the possibility of override (in case of unusual events). Continuous education programs should be implemented for designers, consultants, and facility managers, which besides technical matters, should address the connection between ventilation and exposures. Operating instructions should always be provided.

Figure 1 sends several messages. One of them is that it is difficult to define one ventilation requirement that will satisfy all demands and conditions. The reason is quite simple: different approaches were used to define ventilation requirements, different sources were controlled, and different outcomes were managed. If comfort (sensory perception of indoor air quality) is a design parameter and the target is 20% dissatisfied (80% acceptability) and humans are the major source of pollution, the ventilation rate would be about 10 ℓ/s per person as reflected in the current ventilation standards; this supports the widely accepted CO_2 concentration of 0.1% (1,000 ppm) proposed by Pettenkofer [44]. However, if health is considered, the rates required can be much higher and as high as 28.5 ℓ/s per person, as proposed by Billings. The question then is whether we can propose a ventilation rate that will satisfy all needs and criteria? In other words, can we develop a consistent framework for setting ventilation requirements instead of changing these requirements depending on the current contextual needs, assumptions made, and criteria defined? The answer seems to be affirmative, considering that an example of such a framework for ventilation requirements based on health criteria was proposed by the HealthVent project [45].

Setting ventilation requirements is only part of the problem. Scientific and technical literature shows that the design, operation, and maintenance of systems providing the air for ventilation have not always been adequate, resulting in the ventilation systems themselves becoming a strong source of pollution that can increase exposures and consequently increase health risks (e.g., [15,46,65]). The list of reported problems is long. The most common faults include insufficient air inlet size causing a loss of pressure, missing condensate drains for in-ground air heat exchangers and/or ventilation devices, no insulation of ducts conveying cold air (so condensate is formed), poor maintenance of filters, low class of filtration, inaccessible and dirty filters seldom changed for new ones, missing sound attenuators, improper cross-sections of ducts causing the air velocity to be too high or too low, inappropriate material of pipes (flexible tubes), improper location of main air intakes and exhausts, too short distances between air intakes and exhausts, supply and exhaust air openings that cause ventilation to short-circuit, partially or fully blocked (covered) air terminals. These problems have been observed irrespective of building type, and guidelines to deal with them are needed; an example of such a guideline that was developed by the HealthVent project is shown in **Box 3**.

The solution (?)

When discussing the criteria that should be used to define ventilation, we have to keep in mind the purpose and role of ventilation in buildings. This is presented in **Figure 2**. It shows that ventilation is used to reduce exposure to air pollutants, that it is exposure to pollutants that affects human response (not the ventilation), and that ventilation can only be a part of any solution to reduce the exposure. We learn that exposure can also be reduced by other means, including source control, i.e., reducing emissions from products used in buildings or capturing the pollutants at their source, filtration, and air cleaning. Ventilation can be used instead of these solutions, together with them, or once the other solutions are in place and ventilation is the last way of improving indoor air quality, to reduce the risks related to exposures that could not be reduced by other means; in each of these cases, it is, of course, assumed (as pointed out earlier) that the air supplied indoors is clean and this precondition must always be satisfied.

When ventilation is used as the primary measure to reduce exposure, different literature reviews of ventilation indicate that a ventilation rate of 10 ℓ/s per person [15], 15 ℓ/s per person [29] or 25 ℓ/s per person [4,43] would be necessary to keep indoor air quality high and ensure that health risks and the risk of reduced cognitive performance for building occupants are both kept low; a single study by Federspiel et al. [47] suggests even higher rates might be necessary.

When ventilation is used as a secondary and complementary measure for controlling exposures once other means have been exploited, we need to know the minimum (base) ventilation requirement that must be supplied in buildings when people are present. Different approaches can be used to determine the base ventilation requirement. We have already mentioned the 1.6 ℓ/s per person that Tredgold proposed for miners. Viessman [48] proposed that the minimum ventilation rate that should be ensured to provide oxygen (O_2) for breathing is about 1 cfm/person (ca. 0.5 ℓ/s per person). Following occupational hygiene standards and keeping CO_2 below 5,000 ppm, Sundell [49] proposed 4 ℓ/s per person (with a safety factor of 5); 3 ℓ/s per person was proposed to keep humidity below 45% when only moisture emitted from humans was considered, a rate similar to what was proposed by Viessman [48]. A different approach was used by Carrer et al. [45]. They reviewed the peer-reviewed epidemiological literature and reported the minimum ventilation rates at which no effects for different outcomes were seen. For example, the lowest ventilation rate at which no elevated risk of asthma and allergic symptoms was observed in the published literature was 7 ℓ/s per person [50], while 8 ℓ/s per person was the lowest in the case of acute non-clinical health symptoms in homes [51] and 9 ℓ/s per person in offices [52]. These rates can be considered as the best available tentative and empirically determined estimates of the lowest rates with no observable adverse health effects. For the sake of comparison, if the performance of office work and schoolwork are considered, these rates were higher, about 16-24 ℓ/s per person, and if short-term sick leave is considered, they were 24 ℓ/s per person. Numerous limitations of these rates were indicated by Carrer et al. [6], restricting their generalization: (i) the data were incomparable or difficult to compare; (ii) exposures were improperly characterized; (iii) there were no data on indoor pollution sources, including the maintenance of ventilation systems; (iv) it was assumed that outdoor air was clean (unpolluted); (v) health outcomes were insufficiently characterized and included mainly self-estimated acute symptoms with no data on chronic health effects;

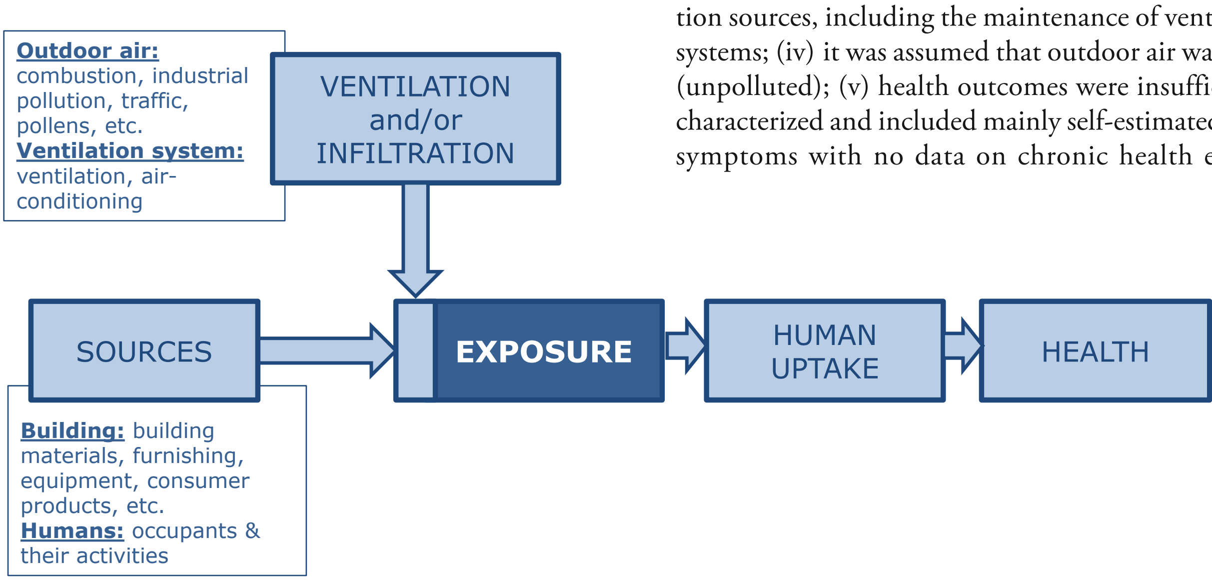

Figure 2. Ventilation is a mediating factor, not a cause.

(vi) ventilation was inadequately characterized and based often on crude measurements of the ventilation rate; (vii) exposed populations and their sensibility were poorly characterized; and (viii) experimental designs were weak. Considering these limitations, Carrer et al. [45] proposed another ventilation rate as minimum base: 4 ℓ/s person. This rate was assumed to be sufficient to keep the risk for acute health symptoms low, but only if the World Health Organization's air quality guidelines [53,54,55,56] are met, and the major source of pollution are the occupants.

The risks of infectious diseases were not considered by Carrer et al. One of the reasons was insufficient data. A single study by Sun et al. [57] performed in student dormitory rooms in China that were occupied by more than one student showed that the risk of the self-reported common cold is reduced if ventilation is increased until 5 ℓ/s per person and that any further increase in the ventilation rate will provide only a very small benefit. Generalizations of this result to other buildings and other occupant densities are difficult but a recent study of Li et al. [26] provides some support in which ventilation rates as low as 0.9 ℓ/s per person were suspected to cause the outbreak of COVID-19 in the overcrowded restaurant. Assuming that mild infections cause short-term absence rates, a study by Milton et al. [20] showed that ventilation rates of 24 ℓ/s per person would significantly reduce the risk of absence compared with 12 ℓ/s per person. However, these results were obtained in a cross-sectional study and were not confirmed in intervention studies where the levels of ventilation were about 40–45 ℓ/s per person [58]. Still, another study showed that virus might survive on a filter at ventilation rates as high as about 40 ℓ/s per person, the rate being back-calculated from the measured CO_2 above the outdoor level of 100–200 ppm [59]. With respect to the current COVID-19 pandemic, REHVA recommends ventilation rates that ensure that CO_2 is at or below 800 ppm (i.e., around 10 ℓ/s per person), while ASHRAE recommends that the rates should meet at least the minimum code requirements with improved filtration efficiency [60]. If we consider that during a pandemic, the risk of infection due to airborne pathogens in buildings will be similar to what occurs in hospital wards (patient rooms), it may be inferred that a total ventilation rate corresponding to 6 h^{-1} would be necessary with high-efficient filtration, of which 2 h^{-1} would be outdoor air; these are the rates prescribed by ASHRAE Standard 170 for health care facilities [61]. The rate of 6 h^{-1} would correspond to 17–20 ℓ/s per person in a 100 m^2 classroom with 25 students or about 5 ℓ/s per m^2 floor, of which the outdoor component should be at least 30% as in ASHRAE Standard 170 [61]. Hence, this outdoor component would be around 20 ℓ/s per person, which is close to what was found by Milton et al. [20] to reduce absenteeism in practice.

With the evidence described above we can assume that the ventilation rate in buildings can be anywhere between 4 and 25 ℓ/s per person, as also shown in **Figure 1**.

The future

There are many beliefs regarding ventilation, and many are only partly true. Among the few, it is assumed that more ventilation will always improve indoor air quality, that low ventilation rate always means poor air quality, that it is simple to measure ventilation, that ventilation can be used as a metric predicting human responses, that outdoor air and the air supplied indoors is clean, that ventilation systems are clean, and that the air indoors is fully mixed within the air volume. Irrespective of the different beliefs and opinions about ventilation, and whether or not they are true, we need ventilation in buildings and it must satisfy a number of different criteria. It must be reliable, flexible and well-functioning, adaptable, and responsive to different needs and unusual events. The urgent task of defining ventilation requirements that meet these different criteria must be solved as a high priority and may require out-of-the-box thinking and new advanced solutions for ventilation [62]. In other words, a new paradigm and a framework for defining ventilation in buildings are urgently required.

More research is also required. Current knowledge should be used and supplemented by population-representative measurement campaigns of indoor exposures in all major building types to support improved design. They will fill the gaps in knowledge on the effects of ventilation (and indoor exposures to poor air quality) on health and other relevant human responses. These measuring campaigns should include much better characterization of ventilation and exposure than was achieved earlier and should examine in detail the influence of indoor and outdoor sources of pollution on chronic health problems, and determine the environmental conditions responsible for the most severe exposures. Particular consideration should be given to people with special needs, such as patients with chronic respiratory diseases, the elderly, and children.

Epilogue

Let us conclude by quoting the 1964 version of "Basic principles of ventilation and heating" by Bedford. He wrote back then that "Great care is devoted to ensure that we have a pure water supply, and no one would suggest that in the interest of economy we should be doomed to drink polluted water. On aesthetic grounds alone, it should be one's right to be allowed to live and work in a clean atmosphere which is free of objectionable odours". Independently of Bedford, WHO [63] endorsed this opinion by publishing the document "The Right to Healthy Indoor Air". This document states that "Under the principle of the human right to health, everyone has the right to breathe healthy indoor air." Ventilation is and will continue to be one of the means to safeguard this principle. Therefore, we must agree on consistent principles and criteria for defining ventilation requirements in buildings occupied by people and follow them strictly. These criteria should consider different effects on building occupants and ensure that the systems are designed to fulfil their needs and are used efficiently. The paradigm change required should not only concern new design requirements but also new ventilation solutions and new ways to design, operate and maintain them that take account of all of the costs, not only the cost of energy but also the cost of the negative consequences of poor ventilation for health, productivity and socio-economic wellbeing. The new paradigm for ventilation in buildings should have every single building occupant at the centre of all recommendations. ■

Acknowledgements

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Please find the list of references in the html version of this article at rehva.eu

Inspection of ventilation systems

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Well-functioning ventilation is a prerequisite both for good indoor climate and for efficient use of energy in buildings, which both represent substantial economical values. Anyone who realizes the value of quality assured ventilation also realizes the importance of adequate ventilation inspections. Still there seems to be a need to promote inspection of ventilation systems by law enforcement.

Keywords: Ventilation function, air handling unit, air distribution, airflow rate, indoor climate, energy efficiency, measurement

A Swedish example of ventilation inspections

Since 1991 there is a legislative requirement for recurring ventilation inspections in Sweden. The inspections, denoted *Mandatory Ventilation Inspection* or *Obligatory Ventilation Control – OVK* (Boverket, 2021), have been extensively used as one of the tools for assuring a good built environment, which is one of the Swedish national environmental goals. The first inspection shall be carried out before any new ventilation system is taken into operation for the first time. Then, inspections shall be carried out on a regular basis. The building owner has a legislative responsibility that the inspections really are carried out according to the rules. One of the rules is that the inspections shall be carried out by personnel certified for the task.

The regular inspections shall be carried out either every 3 or 6 years, depending on the building type. Pre-schools, schools and health-care buildings shall be inspected with the shorter interval, 3 years. Multifamily buildings and office buildings with mechanical exhaust and supply ventilation shall also be inspected with the shorter interval. Buildings with natural ventilation, or mechanical exhaust ventilation only, shall be inspected every 6 years, except buildings with only one or two dwellings. Such small residential buildings shall be inspected when new, but there is no requirement for any recurring inspections.

At each inspection it shall be verified that:

- the ventilation system does not contain any pollution that may spread in the building,
- instructions and manuals are easily accessible, and
- the ventilation system works according to the intended function.

At the very first inspection it shall also be verified that the function and the properties of the ventilation system are in accordance with all relevant requirements from the authorities.

The recurring inspections shall comprise:

- verification that the function and properties mainly are in agreement with the requirements that were in effect when the system was taken into operation for the first time, and
- identification of measures that may be implemented in order to improve energy conservation without deteriorating the indoor climate.

The OVK as described above has been effective for 30 years now, and during recent years there is an ongoing debate regarding the effectiveness of the system. Recent review of the system shows that complete OVK-inspections in schools have been carried out in due time in only 30–40% of the municipalities. In every fourth municipality 25% of the schools have failed the inspection due to faults and deficiencies identified at the latest ventilation inspection. One problem in this context is claimed to be associated with lacking routines and resources at the municipal supervisory authorities.

To conclude, the system of OVK-inspections is definitely a valuable tool for the many building owners that have realized its value and, thus, are prepared to use it for quality assurance of the ventilation system function. Others appear to consider the system a burden, and when the supervisory authorities lack the strength to enforce the law, the system loses its potential. The ongoing debate can be expected to initiate reformation of the OVK-system.

Inspections to be founded already in the design-phase

Many building owners have realized that quality assured ventilation systems are a key both to good indoor climate and to efficient use of energy; conditions that represent high economical values. In this context the efforts by the Swedish National Network of Non-Residential Building Owners – BELOK are worth a closer look. Among many publications related to property management, the network has issued guidelines for both planning and conducting inspections (BELOK, 2015). Some main features of these voluntary guidelines are summarized briefly below.

A preliminary testing and inspections program should preferably be developed already in the early design-phase. The advantage is that the program will be developed with the ideas behind the selected ventilation system solution fresh in mind, which reduces the risk of misinterpretations and increases the chance that the inspections will comprise testing of all important functions. It is also a recommended practice for the design engineer to develop a check-list comprising any items that are of importance for the indoor climate control and for the energy efficiency. The intention is to provide the operating personnel with a tool that confirms correct ventilation operation, or reveals erroneous functions.

The check-list should be part of the instructions for operation, service and maintenance of the ventilation system. This documentation can be considered being a manual for the ventilation system, describing not only the overall principle, but all-important details about the intended operation. In addition to being a tool for the operation of the system, the manual will preserve information of importance when the building and/or ventilation system becomes subject to re-construction in the future. The manual would typically be developed by the ventilation design engineer, possibly assisted by the automation engineer, in case they are not one and the same. As a minimum, the manual should comprise:

- Function descriptions; of the system as a whole and of all sub-system (how the systems are intended to work).
- Instructions for operation and control of all sub-systems (how the systems shall be operated I practice).
- Principal diagrams and flow-charts (to facilitate the understanding of the two previous items in this list).
- A summary of set-points, times of operation etc.
- A list of sensors for control and for surveillance.
- Recommended procedures for calibration of sensors.

If a ventilation inspection is carried out without understanding of the information covered by the items in the list above, there is an imminent risk that the inspection will not really verify whether the ventilation system works without faults and deficiencies. This becomes increasingly important as ventilation control technology may move towards a higher degree of complexity.

The ventilation function shows the way

The basic cornerstones of ventilation inspection can be identified by considering the basic functions the ventilation is intended to provide, i.e. sufficient capacity to remove both heat surplus and airborne pollution. To ensure these functions, it is necessary that the ventilation provides:

- Appropriate airflow rates
- Proper air distribution in the occupied zones
- Adequate supply air temperature
- Clean supply air
- Ventilation operation with respect to the times of occupancy

In addition, the ventilation system must be able to function without creating disturbances like noise and draft, which both may occur if the air velocity in some parts of the system becomes too high. This may be the case if the air flow rate is unnecessarily high or if the supply air devices are of inappropriate type or size.

Given the functions indicated above, it is clear that inspection of ventilation should comprise at least measurements of airflow rates and temperature levels. Indeed, also the remaining items in the list, i.e. air distribution, supply air quality together with the time of operation, must be checked. Parts of these checks can be made as visual inspections; others may require measurements.

A systematic approach

In order to establish a systematic approach to ventilation inspection it is suitable to divide a mechanical ventilation system into the three parts illustrated in **Figure 1–3**; The air handling unit, the air distribution ductwork and the air distribution in the room. Each of these parts are built up by the sub-systems and components indicated in **Table 1**. The table gives examples of important items that should be subject to inspection. ▶

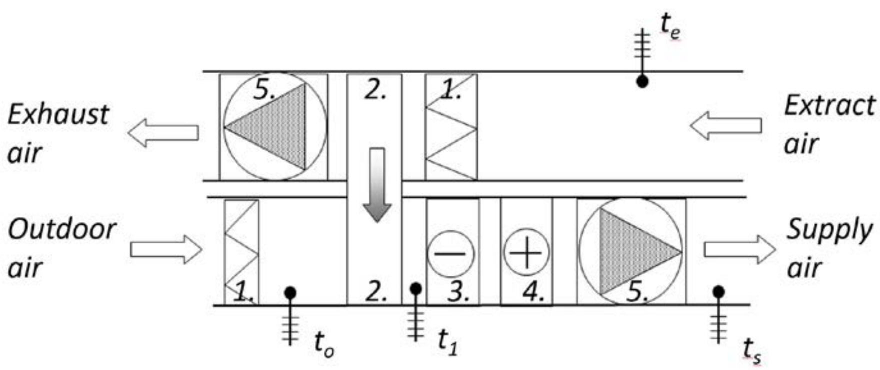

Figure 1. Sketch of an air handling unit for mechanical supply and exhaust ventilation. Components indicated: 1) air filter, 2) heat recovery unit, 3) cooling coil, 4) heating coil and 5) fan. Examples of items subject to inspection are given in Table 1.

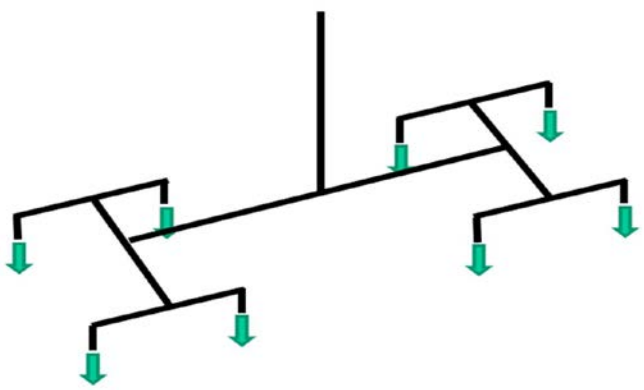

Figure 2. Sketch of supply air distribution ductwork. Components not shown: fire dampers, balancing dampers, airflow control dampers, airflow rate measurement devices, inspection hatches. Examples of items subject to inspection are given in Table 1.

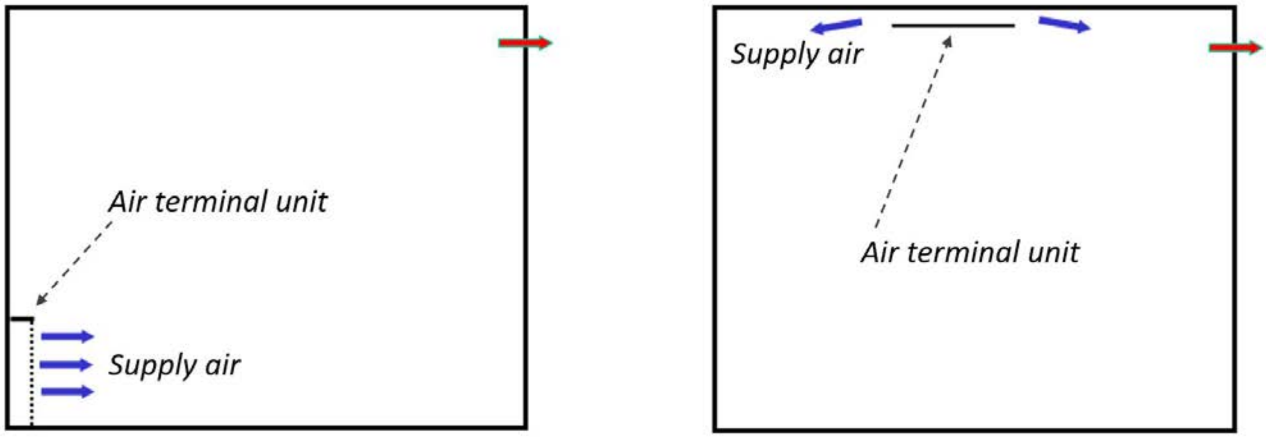

Figure 3. Sketch illustrating two different principles of room air distribution; displacement ventilation to the left and mixing ventilation to the right. Examples of items subject to inspection are given in Table 1.

Table 1. *The primary parts, sub-systems and components of mechanical ventilation systems requiring inspection.*

Primary part	Sub-system/component	Items subject to inspection
Air Handling Unit	Outdoor air intake	Cleanness, free opening, face velocity
	Air filter	Filter quality, status, pressure drop, age
	Heat recovery units	Capacity, efficiency, control functions
	Cooling and heating coils	Capacity, control-valve size and function
	Fans	Capacity, pressure vs. airflow rate, efficiency, control function
	Dampers	Air tightness, intended function (shut-off, flow control, fire-protection), control principle
Air distribution ductwork	Fire dampers	Air tightness class, automatic function
	Balancing dampers	Proper location and size
	Airflow control dampers	Proper location, size and control function
	Airflow rate measurement devices	Correctly located devices/dampers with suitable measurement range
	Possibilities for inspection of the interior surfaces	Inspection hatches, location, accessibility
	Interior cleanliness	Dust accumulation
Room air distribution	Type of air terminal units	Air-jet throw and drop (reaching across the room) Supply air velocity Low risk of draft sensation
	Locations of air terminal units	
	Supply air	Temperature according to design specification Airflow rate according to design specification and possible demand control function

Guidance regarding the practical inspection methods

The trade of carrying out ventilation inspections in practice requires thorough preparations by professionals with the right competence and experience, in order to ensure that sufficient accuracy of the results is obtained with a reasonable effort. For example, a seemingly simple task as carrying out airflow rate measurements in a ventilation system may comprise a massive amount of work if the system is big.

Obviously, the inspections must be carried out by personnel with sufficient qualifications and the assignment must be given an appropriate time-budget. Thus, the procurement of the inspection service is of great importance. The tender documents, including a clear requirement specification, must be developed by someone with good understanding of ventilation in general and the system subject to inspection in particular. Typically, a good suggestion is to give this responsibility to the ventilation design engineer.

Any inspection should preferably start by visual judgement of the status of the system and careful consideration of the required extent of any measurements. Guidance in this respect is provided by the Swedish chapter of ISIAQ, SWESIAQ (2017). Furthermore, detailed guidance for various measurement methods is provided by European and international standards, such as EN 16211:2015, EN 12599:2012 and ISO 12569:2017. Valuable method descriptions within the field of ventilation have also been published by Nordtest over the years. They are still available for download at http://www.nordtest.info. Take a look, just as an example, at Nordtest (1997) which specifies the method for measurement of indoor carbon dioxide and determination of the so-called local ventilation index.

Concluding remarks

The experience shared above indicates that enforcement of the law may not be the primary key to adequate ventilation inspections. Instead, it appears far more efficient to increase the awareness among the stake holders - in this context primarily building owners - that well-functioning ventilation is a prerequisite for good indoor climate and efficient use of energy, which both represent substantial economical values. Anyone who realizes the value of quality assured ventilation also realizes the importance of adequate ventilation inspections. ■

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Indoor climate in a simulated office room with personalized micro-environment and fully mixed ventilation systems


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One of the major challenges in modern buildings is to guarantee indoor air quality and thermal comfort in an energy-efficient manner. To fulfill both energy and indoor climate demands simultaneously, there is a need to introduce more advanced systems where users can influence their own local micro-environment.

Keywords: Personalized ventilation, Micro-environment system, Radiant panel cooling, Diffuse ceiling system, Indoor climate

In many cases, a good indoor environment and energy efficiency are seen as conflicting requirements. Therefore, novel heating, ventilating & air-conditioning (HVAC) systems are required to simultaneously achieve indoor climate and energy efficiency requirements. For that reason, more concerns have been focused on the novel solutions e.g. micro-environment of occupants to optimize energy usage and trade-off energy conservation and indoor comfort, where the main challenge is to supply clean air to the breathing zone and maintain thermal conditions.

In general, there is a need for a paradigm shift from a uniform indoor environment to a non-uniform indoor environment accommodating various individual preferences. The target should be to control local conditions when a person is at the workplace. There is also a need to introduce more advanced systems where users can influence their own local micro-environment.

Two concepts for micro-environment control

The current norm of having comfort conditioning systems that are designed for an average person, where the thermal comfort and indoor air quality conditions of individuals are deemed to be impossible to fulfill, is changing fast. The development of more advanced smart systems should be, and is being, introduced to improve indoor climate conditions for all the occupants of a space, not just the mythical average person.

Smart micro-environment systems refer to the capability of a building to sense, interpret, and respond to changing conditions, which are introduced by requirements of occupants to indoor climate, operation of technical building systems and demands of intelligent energy systems. Possibility to adapt in response to the perception of the occupants and further engage end-users makes it possible to enhance users' satisfaction to indoor climate. The main benefits of the novel system are that the controllability of indoor climate is enhanced in an energy-efficient manner, and that users' perception on the indoor climate is improved.

In literature, different personalized ventilation and micro-environment control systems are proposed. This paper introduces the results of two systems where radiant and convective cooling are utilized for micro-environment control (**Figure 1**).

In one of the studied personalized system PVRP, a PV (personalized ventilation) air terminal device (ATD) was installed on the desk at a distance of 40 cm from the dummy to supply fresh air directly to the breathing zone [1]. In the other personalized system LVRP, a low velocity unit was installed just over the radiant panels and the air was supplied through those panels [2].

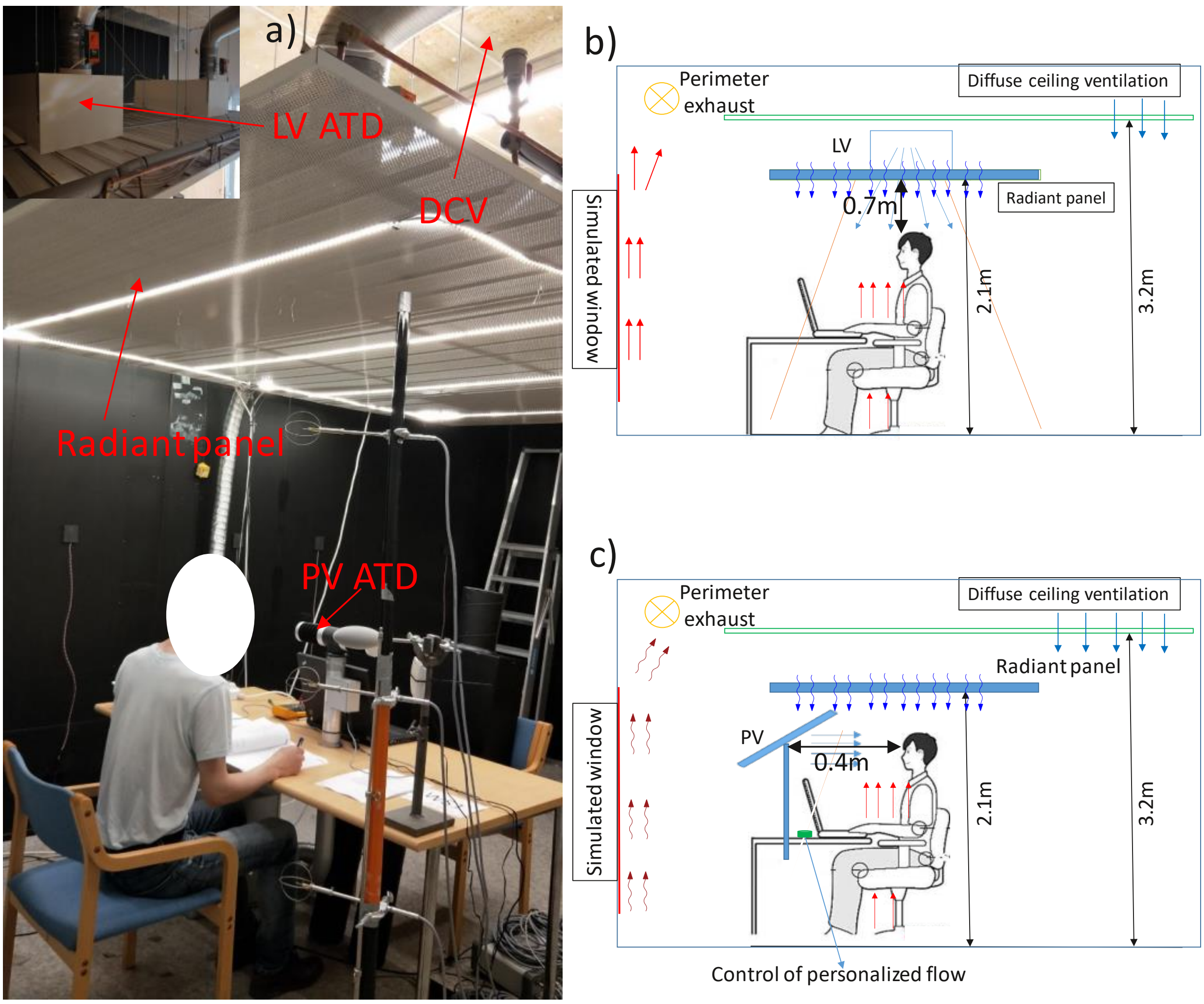

Figure 1. a) The set-up of low velocity unit and PV ATD at workstation. Two studied personalized systems b) low velocity unit and radiant panel (LVRP) and c) personalized ventilation unit and radiant panel (PVRP).

Diffuse ceiling ventilation was used to provide background ventilation outside the occupied zone. To evaluate the performance of the personalized system, it was compared with the all-air system- diffuse ceiling ventilation (DCV) in the same set-up condition.

The personalized systems were measured at 40, 60 and 80 W/m² heat gain levels. With the low velocity unit (in the LVRP system), the supply air flow rates were 10 ℓ/s and 15 ℓ/s. With the PVRP system, the supplied total airflow rate was kept the same (42 ℓ/s) with 60 W/m² and 80 W/m². The designed supply airflow rates were 7 ℓ/s, 10 ℓ/s or 15 ℓ/s from each PV air terminal device, and the rest of the required airflow is released from background ventilation (DCV system in this case). The room air temperature was kept constant at 23.5°C at the low heat gain of 40 W/m² and 26°C at high heat gains of 60 W/m² and 80 W/m². The total airflow rates used with the reference diffused ceiling system (DCV) were 78, 118 and 153 ℓ/s with 40 W/m², 60 W/m² and 80 W/m², respectively.

Smoke visualization of air distribution

Figure 2 shows the air movement with a 10 ℓ/s local air flow rate over the workstation. Smoke visualization indicates that the momentum flux of the jet was not strong enough to reach the dummy. When the local airflow rate was increased to 15 ℓ/s, the airflow from the low velocity unit was just strong enough to reach the level of the top of the dummy. This smoke visualization confirmed that the airflow rate of 15 ℓ/s could be used for local micro-environment control without significantly increasing the draught risk.

The airflow structure of the PV around the workstation was visualized by the marker smoke to assess the airflow pattern of the personalized system (**Figure 3**).

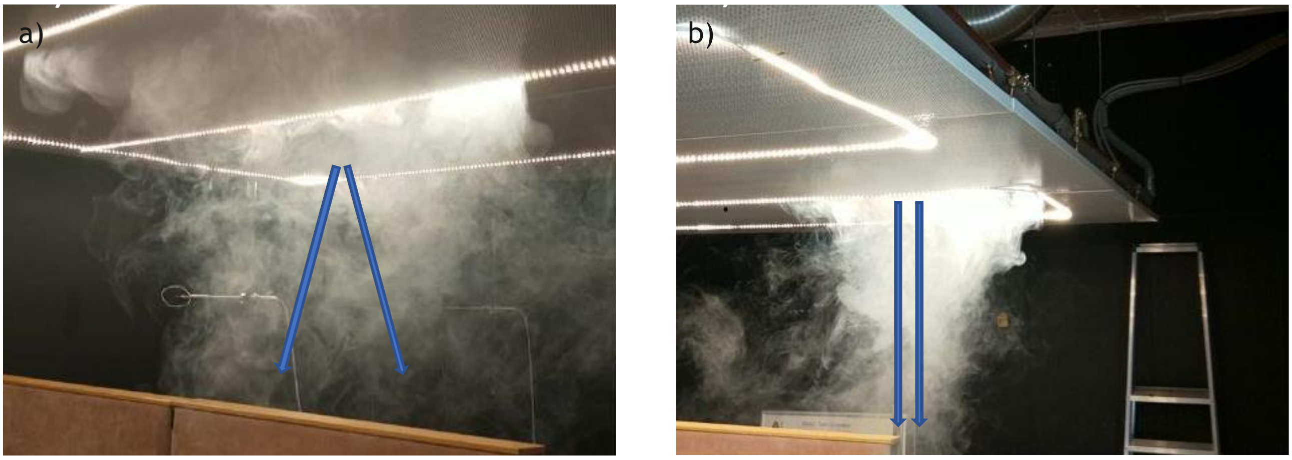

Figure 2. The smoke visualization of the low velocity system (LVRP) a) the local air distribution with the airflow rate of 10 ℓ/s and b) the local air distribution with the airflow rate of 15 ℓ/s. The blue arrows show the direction of the local airflow.

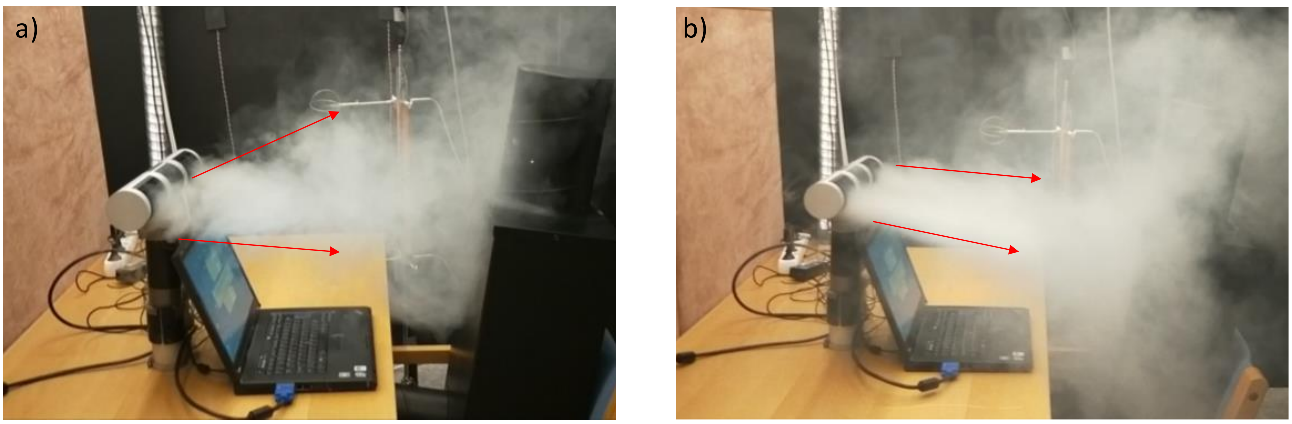

Figure 3. Smoke visualization of the personalized airflow pattern with PVRP system a) 7 ℓ/s and b) 15 ℓ/s. The red arrows show the main direction of the air jet.

When the personalized airflow rate was at the minimum setting (7 ℓ/s), the air jet turned slightly upward because of the combined buoyancy flow of the computers and dummy. However, the jet still reached the breathing zone. The momentum flux of the jet overcame the buoyancy effect, and the jet was able to reach the dummy when the personalized airflow rate was increased to 15 ℓ/s. The central axis of the jet was aligned with the level of the subject's chest, and after the jet collided with the dummy, it turned both downwards and upwards along the body. Hence, the personalized airflow entrained the convective boundary layer around the human body, and cooled down the upper body.

Air change efficiency

The air change efficiency (ACE) was between 60% and 70% with the personalized system (PVRP) depending on personalized airflow rate. ACE was higher than with the reference mixing system (DCV) system (less than 50%), as shown in **Figure 4**. With the personalized system, a higher ACE can be achieved despite supplying less outdoor air than with the DCV. Because the heat gain was distributed asymmetrically, the air was not fully mixed in the whole space. That led to an ACE of less than 50% with the DCV.

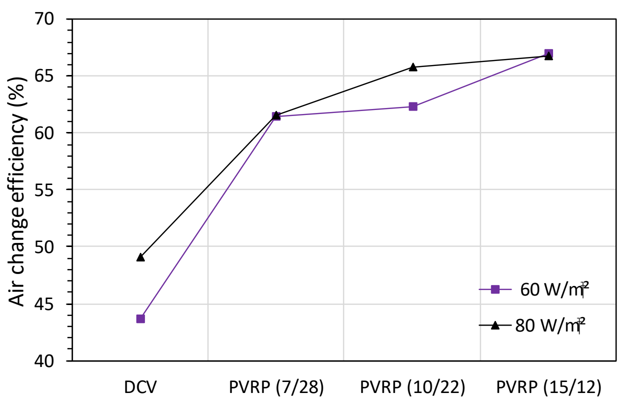

Figure 4. Air change efficiency with the personalized system (PVRP) and the reference mixing system (DCV).

The air change efficiency with LVRP was between 70% and 80%, with different conditions being higher than with the DCV (44%–49%) (**Figure 5**). Thus, the performance of the LVRP system was much better than that of the fully mixing ventilation which had an air change efficiency of 50%. This indicates that the LVRP system can achieve a higher ventilation effectiveness even with a lower airflow rate (42 ℓ/s) as compared to the DCV system (78–153 ℓ/s).

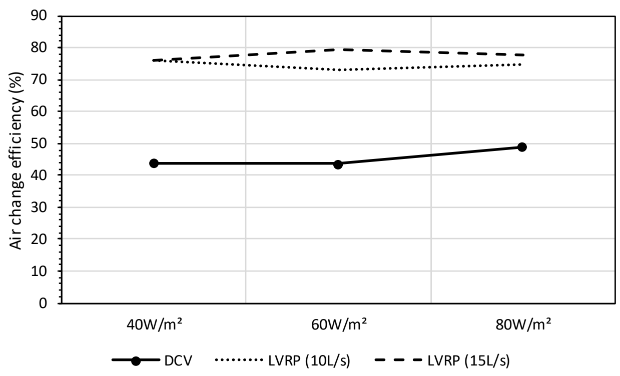

Figure 5. Air change efficiency with the personalized systems (LVRP) and the reference mixing system (DCV).

Draught risk

Figure 6 shows the vertical distribution of draught rate of LVRP system in the occupied zone with different heat gains and airflow rates. In all cases, the draught risk was quite small. Also, it shows that the average draught rates were 5.8% and 7.0% with the LVRP and DCV system from 0.1 m to 1.1 m at a heat gain of 40 W/m². The corresponding draught rate were 7% and 10% under LVRP and DCV with the heat gain of 80 W/m², respectively. With the DCV system, the draught risk at the 1.1 m height was also low (6%). However, the draught risk at ankle level (0.1 m) was much higher with the DCV (10%) than with the PVRP (less than 5%). The reason for the high draught risk of the DCV at the floor level was the return flow created from the corridor by the convection flows.

With the PVRP system, the draught risk (DR) was relatively low (**Figure 7**). The highest DR happened at the heights of 0.6–1.1 m. With the lower personalized airflow rate, DR was below 10% with PVRP system. When the personalized flow rate was increased to 15 ℓ/s, the draught risk increased to 12% and 18% at the 1.1 m level at 60 W/m² and 80 W/m², respectively.

Conclusion

The study shows that that it is possible to enhance system performance with micro-environment control systems, where users are able to control their own set points for room air temperature and indoor air quality, increasing the satisfaction on indoor climate conditions significantly.

This study compared the performance of the micro-environment control systems to that of a diffuse ceiling

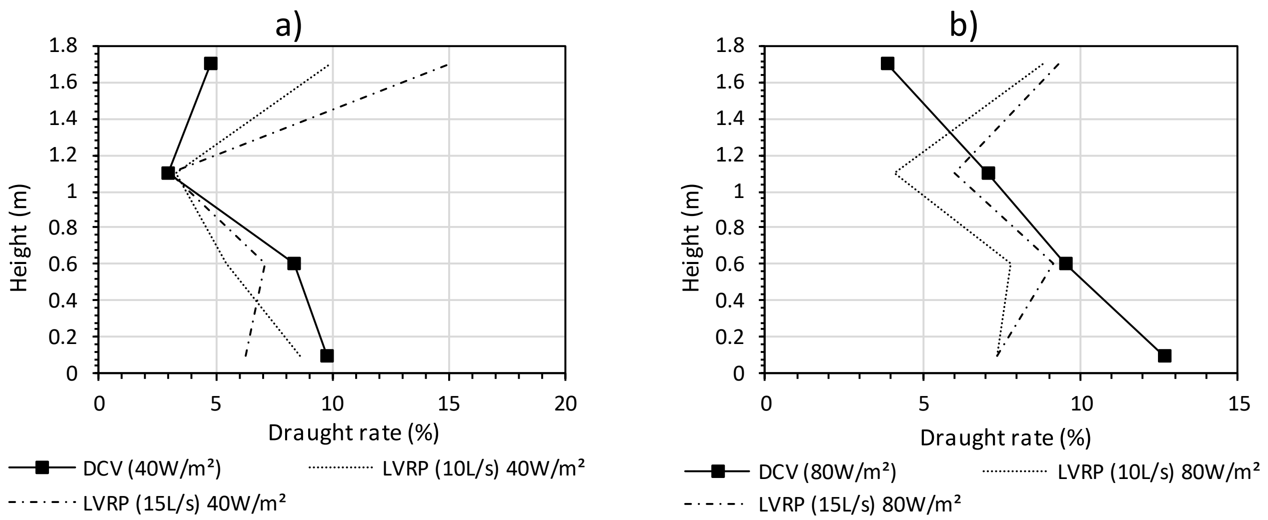

Figure 6. The vertical distribution of draught rate in the occupied zone under the DCV and LVRP system with heat gains of a) 40 W/m^2 and b) 80 W/m^2.

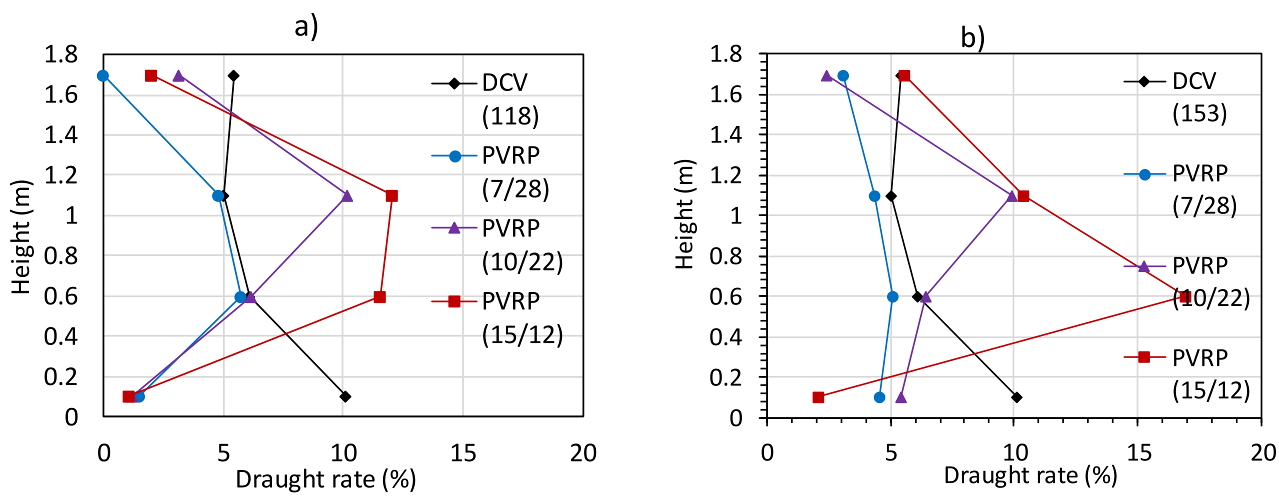

Figure 7. Draught risk under the PVRP and DCV systems at a) 60 W/m^2 and b) 80 W/m^2.

ventilation system (DCV) by experimental methods. The air change efficiency was over 60% which was better than the fully mixed flow (50%). The draught rate was between 10–15% in most of the cases. ■

Acknowledgement

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Effects of indoor air humidity

Edited by **OLLI SEPPÄNEN** with significant contribution from the members of Nordic Ventilation Group – NVG* (see www.scanvac.eu), illustrations by Lars Ekberg

This article is not intended to be a scientific review of many effects of indoor air humidity. Its purpose is to stimulate discussion and research on the effects of indoor air humidity.

Introduction

Indoor air humidity has a large variety of effects both positive and negative. These must be carefully considered when recommendations on indoor air humidity are given.

This short summary is intended for the discussion on the possible need to control the humidity indoors. More detailed overview on the effects have been published scientific papers e.g. [1], and engineering magazines e.g. [2].

*

Nordic Ventilation Group is a group of academics sharing the same interest and concerns regarding the indoor climate and ventilation. The objective of the Nordic Ventilation Group (NVG) is to develop Nordic ventilation technologies and services for good and healthy indoor environment with an energy efficient and environmentally friendly way. The work is 100% voluntary and free from commercial interest. Possible outcomes of the work can be published through various channels with the common agreement of the group. Nordic Ventilation Group was very active in 80s and 90s when mechanical ventilation became more common in Nordic counties. The group published several guidelines for measuring air flow rates and evaluating of the performance of ventilation. The group is integrated with Scanvac activities. The history and objectives of the group are described in more details at www.scanvac.eu.

The current members of the group are:

- Amar Aganovic, Associate Professor, UiT The Arctic university of Norway
- Gyangyu Cao, Professor, NTNU - Norwegian university of science and technology
- Lars Ekberg, Associate Professor, Chalmers University of Technology
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- Jarek Kurnitski, Professor, TalTech - Tallinn University of Technology
- Ivo Martinac, Professor, KTH- Royal Institute of Technology
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- Peter V. Nielsen, Professor emeritus, Aalborg University
- Bjarne W. Olesen, Professor, DTU - Technical University of Denmark
- Thomas Olofsson, Professor, Umeå University
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- Peter Schildt, Professor, OsloMet - Oslo Metropolitan University
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- Martin Thalfeldt, Professor, TalTech - Tallinn University of Technology
- Pawel Wargocki, Associate Professor, director, DTU - Technical University of Denmark
- Siru Lönnqvist, Secretary General, VVS Föreningen i Finland and SCANVAC

Conception of indoor air humidity

Relation between temperature, absolute humidity, and relative humidity (RH) is presented in the **Figure 1**. Maximum water contents in air depends on the partial pressure of water vapor in the air, which decreases rapidly with falling temperature, at the same time the absolute amount of water in the air deceases. Even if the relative humidity of outdoor air would be 100%, the absolute humidity of the air could be very low. As illustrated in **Figure 1**, when the cold air is warming up to the room temperature, its relative humidity falls, during the cold winter days towards, or even below, 10%RH. As shown in the figure, when the outdoor temperature is –10°C, the absolute humidity has to be increased by 2.5 grams of water per kg of air in order to increase the indoor relative humidity from 10%RH to 25%RH at room temperature. If the ventilation airflow rate is 1 m^3/s, just as an example, these values correspond to adding 10 kg of water per hour to the air.

Corona virus

During the pandemic of COVID-19 disease many possibilities to slow down the spreading of the corona virus have been investigated. Indoor air humidity has been one of the environmental factors which has been studied. How does the indoor air humidity influence the viability and spread of the virus and other factors of human wellbeing?

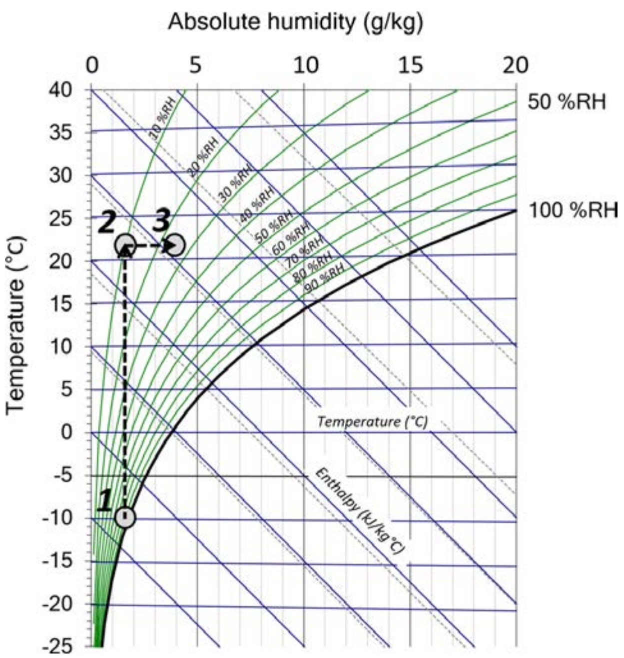

Figure 1. Psychrometric chart showing examples of three conditions of the air: 1) outdoor air (–10°C/100%RH; 2) room air heated from outdoor condition without adding any humidity (22°C/10%RH); 3) room air after adding 2.5 g of water per kg of air (22°C/25%RH).

Effect of environmental factors on the viability of corona virus has been under investigations all over the world mainly in laboratory set-ups. SARS-CoV-2 decay in aerosols has been tested at 20°C in 20 to 70% range of RH showing that decay was not dependent on relative humidity [3]. Models have been developed based on laboratory tests, one of the most comprehensive is the model developed by a group at MIT [4], published at https://indoor-covid-safety.herokuapp.com/. This model includes many environmental and behavioral variables that have influence on the potential viability of corona virus, SARS-CoV-2, including humidity, ventilation, recirculation, breathing rate, occupant density etc. It shows that many other factors have much greater influence than humidity. Humidity and temperature must be so high (80% RH and 30°C) to have meaningful effect that the values are not feasible indoors. This is also the conclusion in the REHVA COVID guidance document based on wide international consensus [5].

Corona virus seems to survive well in the cold due to protecting layers of fatty acids on its exterior surface. This feature has been suggested to be one reason of the spread of the virus in cool indoor environments like in the meat processing industry, maybe also for the frequent COVID-19 cases in ice hockey sport?

Humidity and health

Indoor air humidity affects also the infections caused by the expose to viral particles and other pathogens. Low indoor air humidity deteriorates the natural defense mechanism of the breathing tract. Mucociliary clearance** is a key mechanism for eliminating the

** Airways are lined with the gooey substance and, below that, with cilia, tiny fingerlike paddles used across the animal kingdom for movement. These two components work together like a conveyor belt: The mucus traps gunk, and the cilia beat together to move the mucus back out through the nose and mouth.

This process is called mucociliary clearance, and cold, dry air is not its friend. As low humidity dries out the mucus layers in our faces and throats, it disrupts the movement of the cilia, making it harder for the body to kick out any invaders." Citation from Fedor Kosakovski. National Georaphic."The winter surge in COVID-19 is due to more than merely spending time indoors." National Geography, Dec 15, 2020.

inhaled pathogens and irritants from the respiratory tract. The effectiveness of this self-clearing mechanism may decrease significantly with low humidity of the breathing air.

The general opinion amongst the professionals has been for years that dry air is not a health hazard if it does not contain any specific contaminants. But how often the air is 100% clean? The question is also what the definition of health hazard is. Dry air may cause discomfort. Dry air (below 15%) increases the sensation of dry eyes, skin dryness and blinking rate of the eyes. Commonly experienced eye symptoms may have increased also the number of products in the market of dry air eye drops. Prevalence of SBS-symptoms seem to increase with low humidity and decrease with high humidity. In some studies, in controlled environments, dry air (below 15%) reduced also the cognitive performance. Old studies from the 70s also showed a reduction of absenteeism due to respiratory infections at schools.

During the winter even a small increase in the humidity may be beneficial. According to the REHVA Guidance document a modest humidification of indoor air from the typical winter values of 10–20%RH to the level 20–30%RH may be beneficial. Higher humidity may not bring any additional benefits, vice versa, the risks related to the condensation of moisture will increase. The widely recommended humidity range 40–60% RH in the US may not be appropriate for the cold North European climate. More appropriate is the recommendation in the European CEN-standard EN 16798-1: "Humidification or dehumidification of room is usually not required but, if used, excess humidification and dehumidification shall be avoided." Default design value of indoor humidification is 20–30%. Dehumidification is usually not needed as the high humidity periods are so short in North Europe. One exception is dehumidification in conjunction with waterborne comfort cooling, e.g. by means of chilled beams. In such systems it may be necessary to periodically dehumidify the supply air in the central air handling unit to avoid condensation on the chilled beams in the rooms.

Absolute and relative humidity

Above, the humidity is given as relative humidity values, as this is typically the measure used in various publications on the topic. However, the driving force of the evaporation from any wet surface is the partial pressure differential of the air between the surface and the surrounding air. The partial pressure is proportional to the absolute humidity expressed as grams of water vapor per kg of dry air (g/kg). The relationship between relative and absolute humidity values is shown in **Figure 2**. During Nordic winter climate both the outdoor and indoor air typically contains just a few grams of water vapor per kg of air. For comparison, it can be noted that the air exhaled by humans contains around 35 g/kg. This difference in absolute humidity is a basic mechanism behind drying of the mucous membranes in the airways.

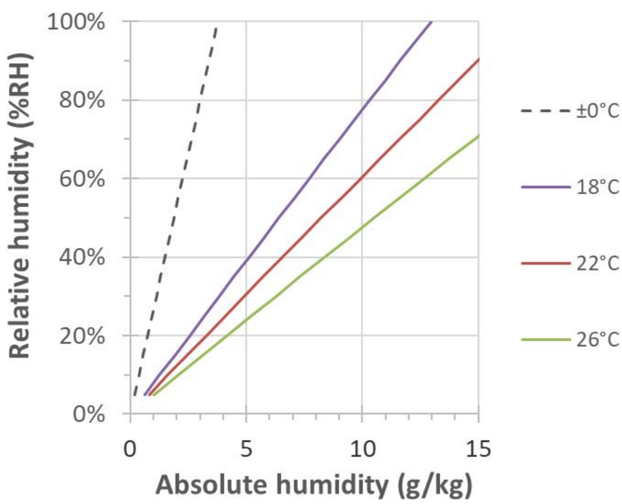

Figure 2. The relationship between relative and absolute humidity values at three typical indoor air temperatures and an example of a Nordic outdoor winter temperature (±0°C).

Droplets

During the COVID-19 pandemic the role of large droplets, airborne small droplets and droplet nuclei have been discussed, including also the effect of indoor air humidity and other environmental factors on the size and life time of droplets. Viruses do not travel in the air alone. They are carried by droplets from breathing, speaking, singing etc. The size of droplets from the respiratory tract of an infected person depends on many personal, behavioral, and environmental factors. In the close range a susceptible person is exposed to large and small droplets. All droplets will dry in seconds and become airborne and spread with air currents in the room. Only the largest droplets will be removed from the air by settling. Drying of large droplets is so fast that the effect of air humidity on drying process is negligible. The final size of the airborne droplets decreases with lower humidity of room air. The remaining potentially virus containing material will be dispersed under the influence of air movements. These particles are significantly bigger (1–50 µm) than the single virus (0.14 µm). People in the same room or space, as the infected person room, are exposed to these particles.

Microbial growth

High humidity of indoor air (over 40–50%RH) may be harmful especially during the winter. Indoor air humidity may condense on cold surfaces and increase the risk of microbial growth on surfaces, and further in structures and deteriorate indoor air quality. Condensation of moisture, particularly on windowpanes has been related to the indoor air problems linked to inadequate ventilation or wrong pressure difference over the building envelope. Moisture damages due to high indoor air humidity are, however, not so common as damages caused by other sources of water.

Critical indoor air humidity for microbial growth depends on several factors like temperature, time, species of microbes, type of surface and possible nutrients on the surface. Typically, lack of moisture restricts the growth of environmental fungi indoors. Increase of humidity on the surfaces enables microbial growth and proliferation of molds. For many of the fungal species a relative humidity of 80%RH (in equilibrium water activity 0.8) is sufficient for growth. For bacteria, the critical moisture level to promote growth is higher. High indoor air humidity is also favorable for house dust mites which may cause allergic reactions for sensitive people. Regarding the mites the indoor relative humidity indoors should not be over 50% for long periods in the winter.

Humidification

Room air can be humidified. Humidification may decrease the prevalence of typical SBS symptoms but can also increase them. In office environments even a small increase of the indoor air humidity has deceased the prevalence of symptoms. But data also shows that symptoms are more common in buildings where air conditioning system includes humidification than in buildings without. According to the REHVA COVID guidance document humidifiers have been found to increase short- and long-term sick leaves.

A humidifier is a high-risk component regarding the hygiene of air handling system. A poorly maintained humidifier can be a source of microbial contamination as the presence of water is the critical factor for microbial growth. Humidifiers have caused severe indoor air quality problems and caused humidifier fever or even legionnaire's disease. Due to these health risks and energy use humidifiers not commonly used in Nordic countries.

It is sometimes claimed that reduced air flow is a possible way to reduce the magnitude of problems with dry air indoors, during periods with winter outdoor climate. However, in many cases the feasibility of this method seems limited. For example, for typical office or school activities it shows that a 50% reduction of the outdoor air supply, from a rather high flow rate to a "nominal" flow of 10 ℓ/s per person, leads to an increase of the relative humidity by few percent-units only. A further halving down to 5 ℓ/s per person gives an additional 5 percentage points higher relative humidity indoors. Thus, the effect of ventilation rate reductions on the relative humidity of the indoor air is limited, as long as nominal ventilation rates are to be ensured. In residences the effect of the ventilation rate maybe significant with higher moisture generation due to household activities.

Energy use

Humidification of the air means in general also increase in energy use. Heat for humidification (latent heat of water) will be taken from somewhere, from the air handling unit, portable air humidifier or from the room air. In the example illustrated in **Figure 1**, the absolute humidity was increased by 2.5 grams of water vapor per kg of air. In order to achieve this, a certain amount of water has to be vaporized per unit time. If, for example, the ventilation rate is 1 m^3/s the humidification corresponds to vaporizing about 10 kg of water per hour. This requires about 7 kW of heat per m^3/s. Thus, over time, the increase of energy use may be significant.

A rough estimation for the increase of the heating energy in a 100 m^2 residential house due to humidification is 20% when the minimum relative humidity indoors is 30%RH, increase of 50% when minimum relative humidity is 40%RH, and increase of 80% when minimum humidity is 50%RH (IDA simulation for Helsinki, Stockholm, Oslo for an energy efficient house).

Humidification is often required in museums and opera houses. Energy needed for humidification at the Museum of Modern Arts in Stockholm has been estimated to 270 MWh/year if the relative humidity is required to be maintained above 40%RH and 350 MWh/year if the requirement instead is a minimum of 45%RH. Thus, in this case a slightly higher humidity setpoint (5 percentage points RH) leads to about 30% higher use of energy for humidification. The example is valid for a constant ventilation air flow rate of 10 m^3/s, heat recovery efficiency 50% and moisture recovery efficiency of 40%.

Internal moisture sources and possible moisture recovery may decrease, of course, the required humidification capacity and the energy use.

Moisture recovery

An energy efficient alternative to active humidification is moisture recovery using rotary heat exchangers or other types of regenerative heat exchangers. At very cold outdoor air temperatures then even non hygroscopic surfaces have rather high moisture recovery capacity due to condensation on cold surfaces. In combination with decreased ventilation air flow rates during periods of low internal moisture generation, normally coinciding with periods of low or no presence of persons, the number of hours with relative humidity lower than 20% can be radically reduced. However, to avoid too high relative humidity during periods of high internal moisture generation it may instead be necessary to increase the air flow rates and/or decrease the rotary speed of the recovery wheel (or lowering the switching frequency in other types of regenerative heat exchangers). Modern sorption coated rotary heat exchanger can, however, recover 60-80% of the exhaust air humidity in all conditions. One of the purposes of ventilation is often also to remove excess moisture. Sorption coated heat exchangers should therefore normally only be used in premises with very low moisture generation.

It should be noted that regenerative heat exchanger may also transfer pollutants and odor from exhaust air to supply air. Transfer of some pollutants (bi-polar) may increase with the moisture transfer.

Other effects

Air humidity has even more effects on indoor environment than dealt with above. Humidity affects the dust concentration of room air indirectly by influencing the strength of the fibers and static electricity of materials; humidity has an effect on the heat balance of the human body, odor, thermal sensation and sweating, use of voice, perceived air quality and many other human responses. Humidity may also have synergistic effects with VOCs.

Increased humidification of the spaces in the buildings, especially during the hot seasons and arid regions, will increase water consumption which could lead to increasing the stress on water resources. As the energy intensity of buildings increases (resulting from increased ventilation and humidification) the carbon inventory of buildings could increase depending on the share of fossil fuels in local sources of energy.

Summary

As a summary we can say that humidity has many positive effects but also negative. Regarding the COVID-19 transmission the current evidence shows that increasing humidity to the levels typically occurring indoors do not reduce significantly risks of COVID transmission. Other measures like limiting the occupant density indoors, keeping physical distances, wearing masks, and improving ventilation are more effective for reducing transmission risks than adding humidity to the air. However, if humidification is used, the humidifiers must always be clean and well maintained. Humidification over 35% shall be avoided and it must be realized that humidification significantly increases the energy use. ■

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Effect of Portable Air Cleaners on Indoor Air Quality: Particle Removal from Indoor Air

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The purpose of this literature review was to examine the studies, published in the last decades that analysed possibilities, applications and limitations of using portable air cleaners in order to improve indoor air quality. The article discusses the strengths and weaknesses of different air cleaning technologies by considering factors such as air quality improvement, filtering performance and energy aspect.

Keywords: particle, removal, indoor air, air cleaner, ventilation

Introduction

Measures to reduce exposure to indoor air pollutants and potential adverse health effects generally fall into three main categories: source control, ventilation control, and removal control. Source control means to eliminate individual sources of pollution or to reduce their emissions. Source control is usually the most effective way to improve indoor air quality. Another approach to diluting indoor air-pollutant concentrations to ensure adequate indoor air quality is to increase outdoor air coming indoors. Portable room air cleaners can clean the air in a polluted room when continuous and localised air cleaning is needed. For air-cleaning devices to be effective, the air-cleaner capacity must match the ventilation rate of the room. This cleaning technology is useful when there is no opportunity to clean the supply air by filtration (i.e., for buildings with a natural ventilation system or an exhaust ventilation system). Consumers should also consider possible side effects, such as noise and ozone generation when considering air-cleaning devices.

Portable air cleaners use different technologies to remove airborne particulates and gaseous pollutants. Particulate matter comprises small particles of solid or liquid droplets suspended in the air, such as airborne dust, pollen, viruses, and bacteria. Gaseous pollutants include volatile organic compounds, carbon monoxide, nitrogen oxide, and aldehydes.

Portable air cleaners use three types of technology to remove particulate matter and gaseous pollutants from the air. These technologies can be divided into three categories.

- Particle removal technology: The most commonly applied methods are fibre filtration, electrostatic precipitators (ESPs) and ionisers.
- Gas purification technology: The most commonly applied methods are adsorbent media air filters, such as activated carbon, chemisorbent media air filters, photocatalytic oxidation, plasma, ozone generators, and plants.
- Far-ultraviolet (UV-C) germicidal technology: The frequently adopted method is UV radiation.

It is crucial to understand the difference between the two parameters that influence the performance of air-cleaning devices:

- The efficiency of an air-cleaning device is a fractional measure of its ability to reduce the concentration of air pollutants that pass through the device. The fractional efficiency of a device is measured in a laboratory, where all relevant variables are controlled.
- The effectiveness of an air-cleaning device or system is a measure of its ability to remove pollutants from the spaces it serves in real-world situations.

The most helpful parameter for understanding the effectiveness of portable air cleaners is the clean air delivery rate (CADR), a measure of a portable air cleaner's delivery of relatively clean air, expressed in cubic meters per hour (m^3/h). A higher CADR relative to the room size increases the effectiveness of a portable air cleaner. A CADR can theoretically be generated for either gases or particles; however, the current test standards only rate CADRs for particle removal (AHAM, 2013).

In a review, Cheek et al. (2020) analysed the influence of air cleaners on PM2.5 concentrations in the indoor environment. The authors concluded that air cleaners reduced PM2.5 concentrations by between 22.6% and 92.0% in homes and 49% in schools. This variability can be attributed to various factors, including study design, intervention duration, CADR, and user compliance.

Air-cleaning devices are commonly marketed as benefitting air-pollutant removal and, consequently, improving the indoor air quality (Shaughnessy and Sextro, 2006). Depending on the cleaning technology, air cleaners may generate undesired and toxic by-products and contribute to secondary emissions, such as ozone and aldehyde, and their effectiveness may vary (Novoselac and Siegel, 2009; Ardkapan et al., 2014).

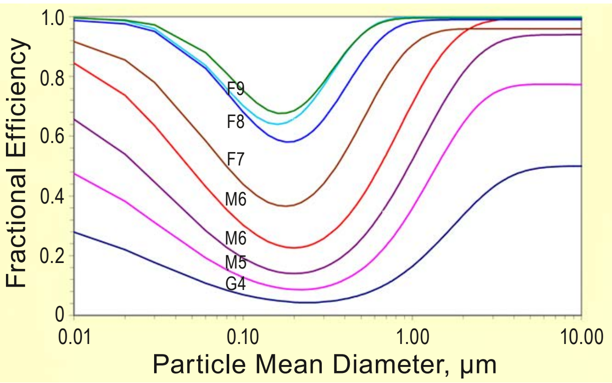


Figure 1. Composite of seven filter models based on measurements according to the standard ASHRAE 52.2-2012; adapted from Kowalski and Bahnfleth (2014).

While portable air cleaner equipped with fibre filters are designed to remove particles, they are primarily ineffective for odours. In addition, when pollutants such as bacteria and mould are trapped on the fibre filters, they may multiply over time if filters are not replaced, which can increase unpleasant smells (Kerins, 2018). To summarise, the following parameters must be considered to select a portable air cleaner for a room that can effectively remove particles.

- CADR,
- energy efficiency,
- noise,
- service and maintenance,
- placement of the air cleaner, and
- possible adverse effects of the air cleaner on the indoor air quality, such as ozone generation.

Fibre Filtration

Among various air-cleaning techniques, fibre air filtration is the most widely used and developed air-cleaning method. There are various qualities of fibre filters available in the market. The efficiency levels of the fibre filters are classified as coarse, medium, fine, efficient particulate air, high-efficiency particulate air (HEPA), and ultra-low penetration air (ULPA) filters. When an airstream containing airborne particles passes through a filter, the particles are collected using five mechanisms: interception, impaction, diffusion, electrostatic attraction, and sedimentation. The first three of these are predominantly governed filtration mechanisms. The particle collection efficiencies of these five mechanisms are determined by the filter media properties, for example, the fibre diameter, packing density, media thickness, and working conditions, such as airflow velocity (Shi, 2012; Liu et al., 2017). Fibre filtration requires the frequent need to exchange both filters to maintain the desired level of filtering efficiency.

Among the above filters, coarse, medium, and fine filters are commonly used in commercial and residential buildings. The HEPA and ULPA filters are commonly used in cleanrooms, laboratories, factories, and hospitals. The filtration efficiencies of HEPA and ULPA filters are substantially high, while the corresponding pressure drops are also high, which means that they are uneconomical for commercial and residential buildings. **Figure 1** illustrates a composite of seven filter models based on measurements according to the standard ASHRAE 52.2-2012.

The cheapest filter is not necessarily the lowest cost filter because three factors determine the filter cost: the initial investment and maintenance, energy use, and disposal. Initial investment and maintenance account for about 18.5% of the cost to operate a filter, whereas the energy use is 81% and disposal is 0.5% (National Air Filtration Association, 2021).

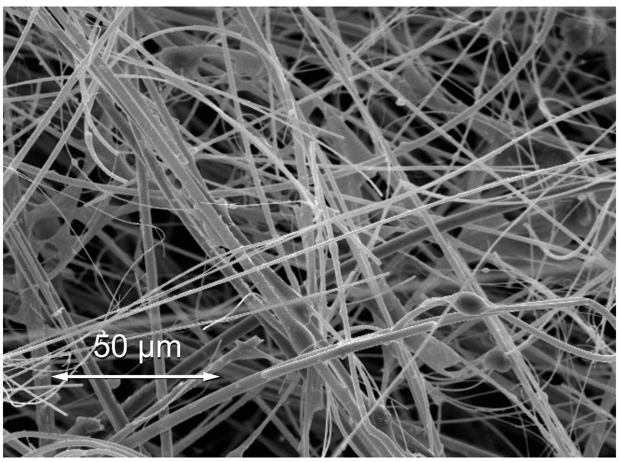
Often, HEPA filters are used in portable air cleaners. The HEPA material can remove particles, including 99.97% of particulate matter, smog, and microorganisms at a size of 0.3 µm. The filtration efficiency increases for particle diameters both less than and greater than 0.3 µm. For instance, a HEPA H13 filter can remove up to 99.95% of maximum penetration size particles. According to EN-1822, the filters must be tested with the particle of maximum penetration size. The most penetrating particle size for each filter ranges from 0.12 to 0.25 µm (EN 1822, 1998). The size of the coronavirus that causes COVID-19 is estimated to be between 0.12 and 0.16 µm, and the minimum size of a respiratory particle that can contain SARS-CoV-2 is approximately larger than 4.7 µm. In addition, the size of the particles decreases due to water evaporation on the particle surface (Lee, 2020). Therefore, portable air cleaners equipped with HEPA filters can reduce the aerosol transmission risk for SARS-CoV-2. Such devices must have a CADR that is large enough for the room size or area in which it will be used.

While higher performance air cleaners that use HEPA filters work efficiently in laboratory tests, their effectiveness in typical residential buildings is less clear. Several studies have shown that portable air cleaners equipped with a HEPA filter in residential buildings can reduce the average indoor PM2.5 by approximately 29% to 62% (Afshari et al., 2011; Allen et al., 2011).

Ward et al. (2005) evaluated the air-cleaner effectiveness in terms of the outdoor and indoor particle concentration with air cleaners relative to the indoor concentration without air cleaners. The authors found that the relative effectiveness of air cleaners for reducing occupant exposure to particles of outdoor origin depends on several factors, including the type of heating, ventilating, and air-conditioning (HVAC) filter, HVAC operation, building air exchange rate, particle size, and duration of elevated outdoor particle concentration. Maximum particle reductions of 90%, relative to no stand-alone air cleaner, are predicted when three stand-alone air cleaners are employed, and reductions of 50% are predicted when one stand-alone air cleaner is employed (Ward et al., 2005).

In the USA and Hong Kong, the Hospital Authority recommended portable HEPA cleaners in clinics and other healthcare settings when the central HVAC system cannot provide an adequate air change rate or when the system undergoes repairs (CDC, 2003).

Qian et al. (2010) studied the particle removal efficiency of the portable HEPA air cleaner in a simulated hospital ward. The results reveal that the HEPA filter can effectively decrease the particle concentration level. The effective air change rate achieved by the HEPA filter (for particle removal only) is from 2.7 to 5.6 ACH in the ward. The authors found that the tested HEPA filter produced global air circulation in the test room (The air change rate is 4.9 for a room of 6.7 m × 6 m × 2.7 m) when the airflow rate was approximately 535 m^3/h, and the airflow in the ward was nearly fully mixed. The authors concluded that the strong HEPA filter airflow completely destroyed the ward's originally designed airflow pattern. The filter efficiency was 98% for particles larger than 10 µm, 95% for particles of 5 to 10 µm, 80% for particles of 1 to 5 µm, and 53% for particles of less than 1 µm.



Fibres in a fine filter.
(© REHVA Guidebook No.11. Air filtration in HVAC systems)

Allergens cat hair with pollen.
(© REHVA Guidebook No.11. Air filtration in HVAC systems)

Electrostatic Precipitators (ESP)

Electrostatic precipitation uses electrical field forces on charged particles to separate them from a gas stream. The particles are deliberately charged and passed through an electrical field, causing the particles to migrate towards an oppositely charged electrode that acts as a collection surface (**Figure 2**). Commercial ESPs accomplish charging using a high-voltage, direct-current corona surrounding a highly charged electrode, such as a wire. The large potential gradient near the electrode causes a corona discharge comprising electrons. The gas molecules become ionised with charges of the same polarity as the wire electrode. These ions collide with and attach to the aerosol particles, charging them (Hinds, 2012; Afshari et al., 2020). This high level of voltage may cause some other reactions, such as ozone generation. Ozone can be generated from a corona discharge and the ionisation process (Boelter and Davidson, 1997). The ESPs with a fan and collection plates and the smaller ion generators, which often do not have a fan and may or may not have collection plates, are ionisers. They charge incoming particles with a corona and may produce ozone (AHAM, 2009). However, smaller particles have higher mobility and are more easily attracted by lower charge levels. In addition, the electrostatic deposition velocity of a small particle is higher than the diffusion and gravitation velocities.

Electrostatic precipitators can offer some benefits over other highly effective air filtration technologies. For example, HEPA filtration requires filters and may become 'sinks' for some harmful forms of bacteria and cause high-pressure drops. A common method of classifying ESPs is the number of stages used to charge and remove particles from a gas stream. When the same set of electrodes is used for both charging and collecting, the precipitator is called a single-stage precipitator. Single-stage ESPs use very high voltage (50 to 70 kV) to charge particles. If different sets of electrodes are used for charging and collecting, the precipitator is called a two-stage precipitator. The direct-current voltage applied to the wires is approximately 12 to 13 kV (US EPA, 2002). An experimental study shows that an ESP that uses anticorrosive materials can generate numerous unipolar ions while producing only a negligible ozone concentration and achieve a strong collection performance of more than 95% for ultrafine particles (UFPs), while only using 5 W and generating a pressure drop of 5 Pa per 1 200 m³/h (Kim et al., 2010).

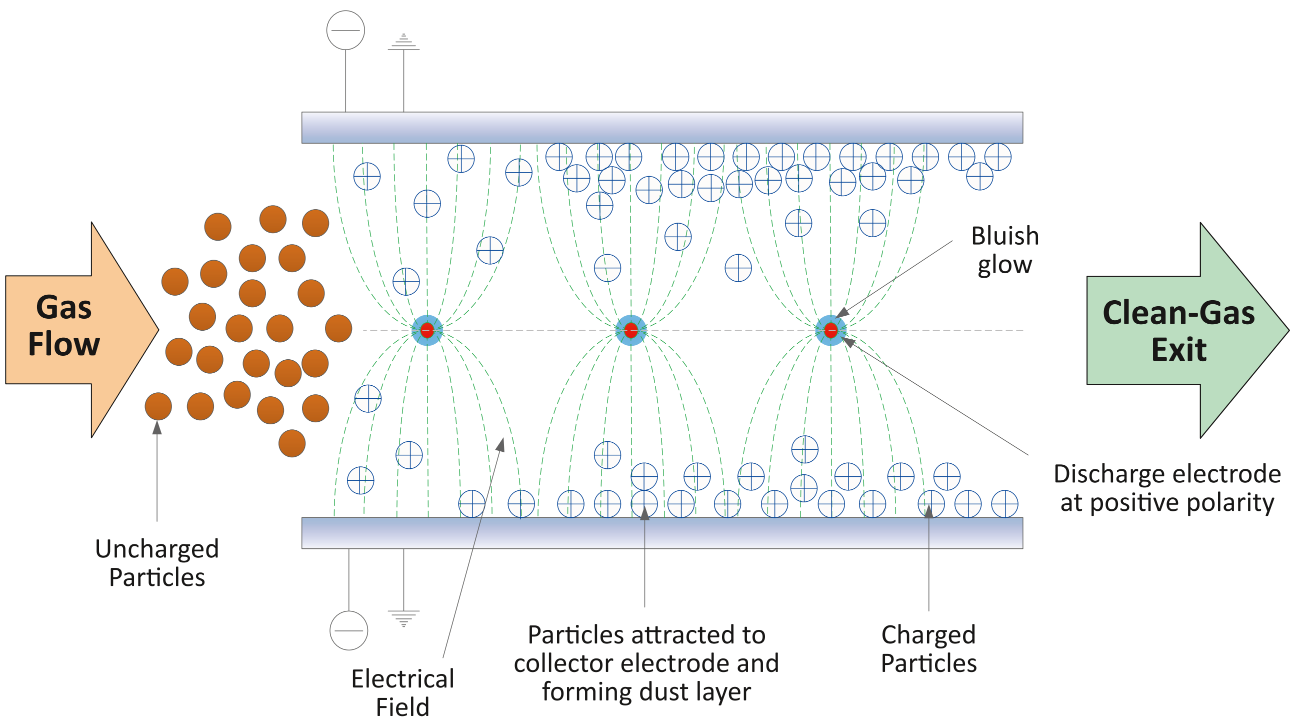


Figure 2. Schematic of the basic processes of an electrostatic precipitator (Source: modified from a guide document published by the Ohio Environmental Protection Agency, USA, accessible at www.epa.state.oh.us/portals/27/engineer/eguides/electro.pdf).

The ESPs were tested in laboratory settings to ensure that the equipment meets specific quality criteria concerning air-cleaning performance and does not produce harmful substances. However, gaps exist between the laboratory test procedures and using the equipment in 'real-life' situations. Short-term studies (less than one week) of ESPs in chambers demonstrated that ESPs could achieve more than 50% efficiency for UFPs (Kinzer and Moreno, 1997). Ardkapan et al. (2014) evaluated five portable air-cleaning technologies, including an ESP with an airflow rate of 300 m³/h to determine the cleaners' effectiveness in removing UFPs. Measurements were conducted in a test chamber. The authors reported that the effectiveness of the ESP to remove UFPs was 38%. Zuraimi et al. (2011) examined 12 different air-cleaning technologies, including an ESP with an airflow rate of 800 m³/h to determine the cleaners' effectiveness in removing UFPs. The authors found that the ESP effectively removed 95% of UFPs. Morawska et al. (2002) studied the performance of a two-stage ESP filter in an ASHRAE test rig to determine the efficiency of particles ranging from 0.018 to 1.2 µm. The authors reported single-pass efficiencies ranging from 60% to 98% for particles smaller than 0.1 µm, with lower efficiencies noted at high face velocities. Shaughnessy et al. (1993) tested an ESP in office rooms with smoking. They reported that the CADR was reduced by 38% for the ESP.

Air Ionisers

Air cleaners called 'air ionisers' work similarly to ESPs. Ionisers use high voltage to electrically charge (usually negative) particles moving through the ioniser or air molecules (**Figure 3**). Positively charged ions are called cations; negatively charged ions are anions. These charged molecules are called ions, and the ions attract oppositely charged surfaces or particles, forming them into larger particles that can fall through the air or be adsorbed into surfaces, such as carpets or curtains, that have gained a positive charge through static electricity (Tanaka and Zhang, 1996). In an electrostatic air cleaner, the negatively charged particles are attracted to a positively charged collector plate, but a regular ioniser does not have a collecting plate.

Air ionisation has been used to clean the air in an internal environment by reducing particles and gases (Daniels, 2007). However, Waring and Siegel (2011) studied an ion generator in a 27 m³ residential room. The authors concluded that the ion generator used in their investigation increased concentrations of UFPs, ozone, and, to a lesser extent, formaldehyde and nonanal. It also slightly decreased concentrations of fine particles.

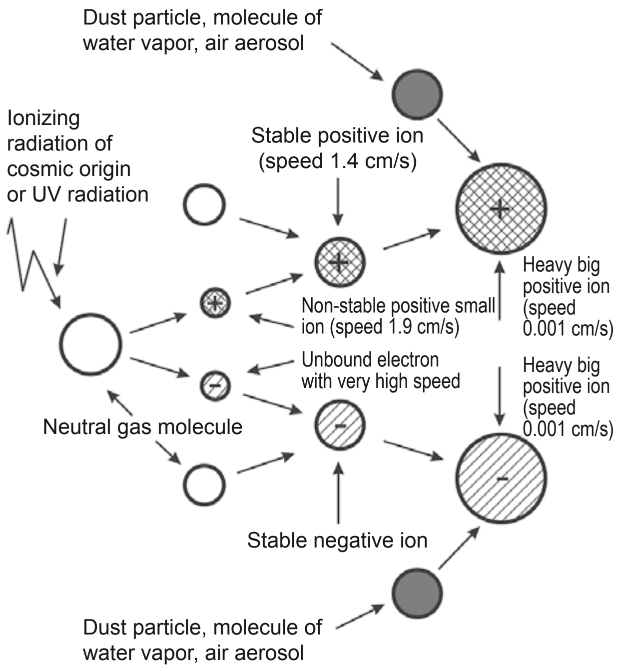


Figure 3. Principle of ion particle formation in the atmosphere (Černecky and Pivarčiová, 2015).

Ions also have antibacterial effects and may decrease the microorganisms and allergens in the air (Goodman and Hughes, 2004). The undesirable effects of air ionisation include ozone (O_3) emissions, which can react with terpenes to yield secondary organic aerosol, carbonyls, carboxylic acids, and free radicals. The authors concluded that using a corona causes ion generators to emit ozone at measured rates of 0.056 to 13.4 mg/h. The authors also reported that CADRs for portable ion generators range from 0 to 90 m³/h, at least an order of magnitude less than HEPA cleaners.

Daniels (2001) reported that recent developments in large ion generator design and operation have led to the commercial availability of energy-efficient units. These units can now produce controlled outputs of specific ions on demand, while minimising the formation of undesirable by-products, such as ozone.

Germicidal Ultraviolet

Germicidal ultraviolet (UVGI) uses ultraviolet light in the UV-C wavelength range (200 nm to 280 nm) to inactivate microorganisms. Most systems use low-pressure mercury lamps, which produce a peak emission at around 254 nm. The effectiveness of UV-C is directly related to the intensity and exposure time.

Environmental factors, such as humidity, airborne mechanical particles, and distance, can affect the performance of UV fixtures (American Air and Water, 2021). For instance, the coronavirus that causes COVID-19 is susceptible to UVGI, so if it is irradiated for a certain amount of time, it is inactivated. Three air disinfection applications are on the market. One application is upper-room germicidal systems, and the other application is UVGI cleaners used in HVAC systems and portable air cleaners. The upper-room systems can reduce the amount of active virus in the air by an amount equal to 10 or more air changes per hour of outdoor air at a much lower energy cost (Riley et al., 1976). The other application, UVGI cleaners in HVAC systems, is designed to destroy/inactivate viruses in the flowing air stream as they pass through the device. Portable air cleaners often incorporate UV-C lamps to destroy and remove viruses trapped on air-filter medium surfaces. Good evidence exists that UVGI with UV-C light is likely a viable decontamination approach against SARS-CoV-2, for instance, for unoccupied rooms (SAGE – Environmental and Modelling Group, 2020).

In addition, UV irradiation can denature microorganism DNA, causing death or inactivation (Liltved, 2000). Further, UV inactivation depends on the microorganism species and environmental conditions, such as temperature and humidity. In laboratory conditions, UVGI is effective against bacteriophages in the air against influenza, and activation reduces with increased humidity for viral aerosols (McDevitt et al., 2012).

Several portable devices are on the market, and all show good single-pass efficiency; however, their effectiveness in a room is dependent on their flow rate relative to the room size. Many devices have insufficient airflow to be effective in practice.

Several researchers have reported the efficacy of UV-C in reducing the total and viable particle counts in highly controlled operating room environments (Davies et al., 2018). Air filtration and disinfection units combining HEPA filtration and UV-C disinfection technologies may reduce the potential for patient infection.

In addition, UV-C for surface and air decontamination must consider health and safety issues. Direct exposure of the skin and eyes to UV-C radiation from some UV-C lamps may cause painful eye injury and burn-like skin reactions. Therefore, UV lamps must be located within enclosed or shielded devices or operated when no occupants are present (SAGE – Environmental and Modelling Group, 2020).

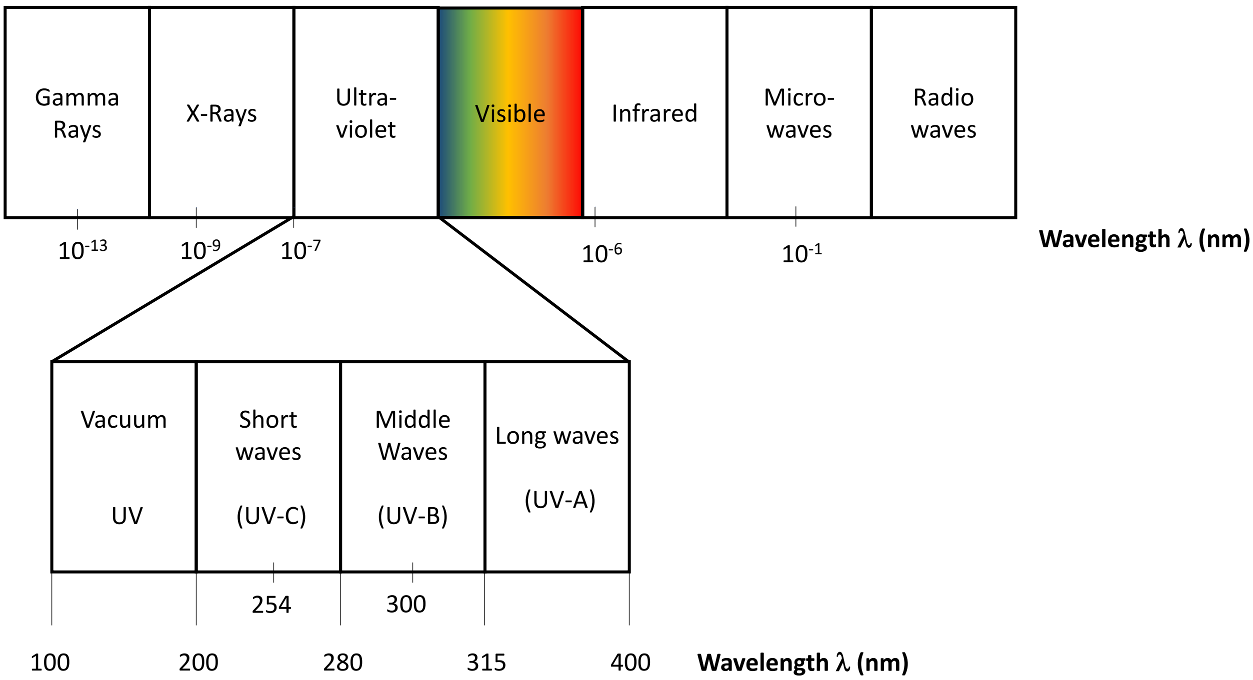


Figure 4. The electromagnetic spectrum, with the UV spectrum and the visible spectrum highlighted (Violet Defense, 2017). https://static1.squarespace.com/static/58d3f70c4402432cd581ffa9/t/59a866cacd39c3c68492094c/1504208589083/Guide+to+Understanding+UV+Light.pdf

Energy Aspect of Portable Air Cleaning

Filters increase resistance to airflow, increasing the energy use and running cost of the system, and they require regular maintenance. Following the Eurovent 4/11 guidelines, the yearly energy use of air filters can be determined as a function of the volume flow rate, fan efficiency, operation time, and average pressure drop. The related energy use during a period can be calculated from the integral average pressure drop. Among various air-cleaning techniques, fibre air filtration is the most widely used and developed air-cleaning method.

Stephens et al. (2009) presented the results for four months of detailed energy monitoring of two air-conditioning systems in a test home. The authors stated that if a high-efficiency filter increases the total system pressure by approximately 40%, the results indicate that energy use generally did not differ with high-efficiency filters compared to low-efficiency filters and that other factors should govern filter selection. These results suggest caution when assuming that high-efficiency filters require more energy than low-pressure-drop filters in residential HVAC systems. Parker et al. (1997) measured a 4% to 5% airflow rate reduction when replacing standard disposable filters with high-efficiency pleated filters. Kim et al. (2009) found that the range of airflow reductions due to filters are 5% to 10% from the recommended airflow rates.

Zuraimi et al. (2016) examined two portable air cleaners: one containing a carbon prefilter and HEPA filter and an ESP-based unit. The authors reported that energy performance implications are strongly tied to the fan design and fan speed control. The results revealed that the average initial operating power of the HEPA-carbon-based filter was 125.6 W, which reduced to 12% of its initial value after the half-life of the filter was reached. The mean airflow rate dropped to 49% of its initial value by the half-life of the filter. For the ESP-based unit, the mean operating power measured at various loading intervals was close to one another with no discernible pattern. The airflow rates were almost similar between loadings with a slight reduction in airflow rate only at the half-life. Shaughnessy et al. (1994) reported that the flow rate of an ESP unit remained constant after six months of continuous operation in a smoking office room.

Regarding air ionisers, a study was conducted regarding the effect of air anions on lettuce growth in a plant factory. Song et al. (2014) reported that energy use efficiency concerning air anion treatment was analysed based on the shoot dry weight. The total power use of the air anion treatment was 55.3 kW after four weeks of treatment. The total energy use efficiency based on the shoot dry weight was 0.59 mg/W.

The air ioniser was used in combination with intermediate class filters (M5–F9) to reduce the pressure drop of the filters while maintaining sufficient filtration efficiencies and reducing energy costs (Agranovski et al., 2006; Shi, 2012). The authors demonstrated that ionisation combined with intermediate class filters could enhance the original filtration efficiency for removing airborne particles, aeroallergens, and airborne microorganisms and has a negligible pressure drop increase. However, the reliability of the performance and the potential generation of by-products (e.g., ozone) are critical problems associated with this application.

Regarding UVGI, the energy use of UVGI system is a factor that needs to be considered. Lee et al. (2009) reported that a UVGI air disinfection system affects the energy use of a building in at least four ways: direct energy consumption for lamp operation, increased cooling energy consumption, decreased heating energy consumption, and changes in fan power consumption due to changes in supply air temperature and additional pressure drop caused by the UVGI components in the moving airstream. According to SAGE – Environmental and Modelling Group, 2020, UV carousel devices are typically deployed for between 20 and 45 minutes, depending on the room to be treated, but may also require moving and repeat treatment to overcome shadowing effects.

Foarde et al. (2006) tested in-duct UVGI equipment provided by eight manufacturers. They found that the pressure drop across most systems was less than 8 Pa. Given that this additional peak pressure loss is perhaps 1% to 2% of the total static pressure of a typical supply fan, associated differences in fan power were neglected as negligible. Notably, some of the energy used by the UVGI lamps was translated into heat generation.

Noakes et al. (2015) calculated the plane average irradiance (W/m²) and energy performance coefficient for two devices in four differently sized. **Table 1** shows the results obtained by authors. The energy performance coefficient η is calculated as follows: $\eta = E_{plane} A/W$, where E_{plane} is the plane average irradiance, A is the area of the zone and W is the supplied power use.

In all cases, it was assumed that ventilation is provided by mechanical means and that both the ventilation and UV systems operate continuously. Ventilation energy calculations follow Noakes et al. (2012); fan energy is assumed to require 2 W/ℓ/s (56.6 W/ft³/s), while ventilation heat loss is determined using the degree-day approach assuming 50% heat recovery and 2 100 degree-days per year.

The calculation shows that the energy consumption of the UV devices depends on the specific device power use, how much is converted to UV-C energy, and how well that is distributed within a room. The device 2 contains twice the lamps and uses twice the power of the device 1, but it is clearly more effective, as the average irradiance is between 2.5 and 2.9 times the irradiance in the same sized zone. It can also be seen that the relative energy performance varies within and between devices.

In addition, a potential exists for energy saving. The potential energy savings are because the fan energy required to overcome HEPA static pressure loss, for instance, is greater than the energy consumed by the UVGI lamps (Dreiling, 2008). The combination of UVGI and intermediate class filters (M5–F9) may provide performance virtually equivalent to HEPA filtration, offering the building owner the possibility of reducing energy costs.

Conclusions and Recommendations

The following conclusions can be drawn regarding the performance of portable air cleaners:

- Portable air cleaners reduce exposure to particles indoors and thus improving indoor air quality. Application of portable air cleaners may be a useful strategy to reduce particles in poorly ventilated spaces.
- Portable air cleaners only purify the air in the room in which they are placed, but have the advantage of reducing the risk due to cross contamination between rooms.
- The positioning of a portable air cleaner also affects the overall particle removal and consequently, influences occupants' exposure to particles.
- Portable air cleaner equipped with HEPA filters have high removal efficiency. However, the filters are also characterized by high pressure drop. They do not produce any ozone or harmful byproducts in the course of operation.
- Electronic air cleaners have a lower pressure drop compared to HEPA filters with comparable particle removal efficiencies and consequently, less energy use.
- Electronic air cleaners produce ozone as a by-product and work by charging particles in the air causing them to stick to surfaces. Furthermore, ozone may even react with existing chemicals in the air to create harmful by-products (e.g. formaldehyde). Exposure to ozone should be limited because of its adverse effects on human health. Inhalation of relatively small amounts of ozone can cause coughing, chest pain, throat irritation, and shortness of breath.
- Exposure to UV light may be harmful in some circumstances.
- Throughout this review, we found that there is a need of additional research for the more reliable conclusions to be made on the long-term performance of portable air cleaners, the noise level of the portable air cleaners when it is working at top capacity, the ozone emission rates, and the energy use and the cost related to it. In addition, examines would be conducted both in the laboratory and field in order to compare the performance of portable air cleaners in the well-controlled laboratory environment to that in real situation.
- Defining the performance criteria that must be met for use of the portable air cleaners and also specifying the testing criteria for room air cleaners.■

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Please find the list of references in the html version of this article at rehva.eu

Table 1. *Variation in energy performance and plane average irradiance with device and zone area (Noakes et al. (2015).*

Device	Power (W)	Coverage area (m^2)	Plane average irradiance (W/m^2)	Energy performance coefficient (–)
1	36	4	0.271	0.03
1	36	6.25	0.173	0.03
1	36	9	0.124	0.031
1	36	14	0.09	0.035
2	72	4	0.687	0.038
2	72	6.25	0.472	0.041
2	72	9	0.338	0.042
2	72	14	0.267	0.052

Recommendation from the Nordic Ventilation Group

Criteria for room air cleaners for particulate matter

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Introduction

Portable air cleaners can be used to reduce the concentration of particulate matter in room air. They may also reduce the risk of infections due to pathogens in the indoor air, as a significant amount of viral material is spread as small droplets or dried droplets which behave like small airborne particles. These viral particles can be removed from room air using portable air cleaners, by circulating the air through the unit. To be safe and effective the cleaner must fulfill certain performance criteria. If they produce ozone or hydrogen peroxide then they may pose safety concerns.

For this, the following parameters must be considered:

- Clean air delivery rate (CADR)
- Noise
- Energy efficiency
- Placement of the air cleaner
- Service and maintenance
- Generation of pollutants (the possible negative effect of the air cleaner on the indoor air quality, such as ozone generation).
- Operation
- Service

General information

The air purifier must meet all regulatory requirements and be approved from an electrical safety point of view by the European Union or national authorities.

Data which demonstrates the safe and effective performance of the unit must be obtained from third party testing and presented by a third-party certification body. An example of a certification program that operated by Eurovent Certita Certification [1] and [2].

Clean air delivery rate (CADR)

"Clean air delivery rate- CADR" is the air flow, free of specific pollutant, which is supplied to the room by the cleaner. It can be estimated as a product of air flow through the unit and the removal efficiency of the unit for a specific pollutant (usually particulate matter). Regarding the removal efficiency of the cleaner, the most critical size for particulate matter is 0.3–0.5 µm.

Particle removal efficiency is calculated by subtracting the measured average ratio of downstream-to-upstream particle concentrations from unity.

CADR can be expressed for any other pollutant as well. Eurovent Certita Certification has identified [2] the following pollutants: particles of 0.3 µm to 0.5 µm, particles of 1.0 µm to 2.0 µm, particles of 3.0 µm to 5.0 µm size, Acetone, Acetaldehyde, Heptane, Toluene, Formaldehyde, *Staphylococcus epidermidis, Aspergillus niger* and *Fel-D1* cat allergen.

The effect of CADR for the unit(s) placed in the room on the overall level of pollutants present in the room depends on the size and ventilation rate (outdoor air) of the room.

To achieve a meaningful additional reduction of viral particles in the indoor air CADR (measured for particle size of 0.3–0.5 µm) should be two times greater than the outdoor air flow by the ventilation system [2] in rooms with a ventilation rate more than 1 ACH. This CADR reduces the concentration of a pollutant by 70%. In rooms with a lower ventilation rate (lower than 1 ACH) the CADR must be at least 2 ACH.

For example: Clean air delivery rate (CADR)

If the room air volume is 200 m³ and the air change rate 3 ACH, the effective CADR must be 2 × 3 × 200 m³/h = 1 200 m³/h = 333 ℓ/s or more.

For residential use the Swedish Asthma and Allergy Association recommends CADR = 4 × (ventilation rate) [3] When the outdoor air ventilation rate is 0.5 ACH then CADR should be 4 × 0.5 ACH = 2 ACH.

In a bedroom with a floor area of 15 m² a room height of 2.7 m and design ventilation rate 0.5 ACH, the CADR should be 4 × 2.7 × 15 × 0.5 = 81 m³/h=22.5 ℓ/s.

The combined effect of the ventilation and air cleaner on the concentration of pollutants generated indoors is the sum of the CADR and the ventilation rate.

Noise

Noise generated by the cleaner is usually expressed in sound power generated by the device. The sound pressure level in the room depends on the sound power and acoustic properties of the room.

The sound power of the cleaning unit running on the effective speed shall not cause excessive sound pressure levels in the room. If the sound pressure level is too high, the user may switch the cleaner off or turn it to a lower, less effective, speed, with the consequence that pollutant levels in the space will increase. Sound pressure levels in a typical room (absorption app 10 m²-sab) are a few (1-3) decibels lower than the sound power level of the unit. The sound pressure level should not exceed nationally regulated levels, and should typically be 30dB(A) in bedrooms, 35 dB(A) in living rooms, 35 dB(A) in single offices, 40 dB(A) in landscape offices and 35 dB(A) in classrooms (Cat II in CEN 16798-1 [4]).

The sound pressure values must be tested and stated for the effective CADR of the unit, so that users know the anticipated acoustic performance of the unit at the intended CADR.

Energy efficiency

The energy efficiency of the air cleaner must be reported, based on the relevant standard test, and is defined as air flow rate per unit of electrical power, ℓ/s per W or m³/h per W. Classes used by Eurovent Certita Certification range from A class > 13 m³/h/W to class E < 2 m³/h/W.

Placement of the air cleaner

In the performance test, the air cleaner is usually placed in the middle of the test chamber. A mixing fan is used to achieve a uniform concentration in the test room. If the cleaner is placed in the room so that the air flow through it is obstructed or so that there is a short circuit from supply to return in test conditions, its cleaning effectiveness in practical applications may be reduced compared to the test result.

To avoid this the cleaner must be placed in a room so that the furniture or walls do not disturb the intended air flow pattern.

Generation of pollutants (by-product)

If the cleaner is using electricity in the cleaning process, for example for photocatalysis, electrostatic filters, UV-A or UV-C lamps and plasma/ionization units there should also be a test report on the ozone levels. Ozone levels must be below 0.05 ppm in the test room where the CADR of the air cleaner is measured. The measured results of potentially harmful byproducts should be made available on request. It should be noted that sensitive people (e.g. those who are asthmatic or have allergies) may have symptoms even at lower O_3-concentrations than 0.05 ppm. Ozone is also a driver of other indoor chemical reactions and the products of this ozone-initiated chemistry are often a greater threat to human health than their precursors.

The ASHRAE's position document on air cleaning [5] concludes that any ozone emission that is non-trivial (beyond a trivial amount that any electrical device can emit) creates a risk. Consequently, devices that use the reactivity of ozone for the purpose of air cleaning should not be used in occupied spaces and devices that emit ozone as a by-product of their operation should be used with extreme caution if emissions are non-trivial, and at best be replaced by alternatives which do not produce ozone.

The US EPA concludes that currently available scientific evidence shows that, at concentrations that do not exceed public health standards, ozone is generally ineffective in controlling indoor air pollution [6].

The UK Scientific Advisory Committee for Emergencies review of air cleaning devices [7] concludes that application of air cleaning devices may be a useful strategy to reduce airborne transmission risks in poorly ventilated spaces. It also notes that air cleaning devices have limited benefit in spaces that are already adequately ventilated, and are not necessary for adequately ventilated buildings unless there are identified specific risks.

Operation

The cleaner shall be used at a fan speed which is appropriate for the room where it is located. Most air cleaners collect dust and other pollutants in the unit. The filter media or the collecting plates may become a source of odor and pollutants if not maintained or replaced according to the manufacturer's instructions. In any case, manufacturers' instructions shall be followed by the users and when cleaning the units or filters appropriate precautions shall be taken to protect those maintaining the unit.

Service and maintenance

Spare parts like filter units must be readily available and easily replaced. Operation and maintenance information should be available, including the instructions of the replacement period of components.

The used filter units of the air cleaner must be handled as hazardous waste, along with any protective clothing and breathing masks used by the maintenance personnel. ■

Acknowledgements

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- Language checked by Hywel Davis, CIBSE

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NZEB Requirements vs European Benchmarks in Residential Buildings

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The European Commission (EC) has set benchmarks for buildings' primary energy by categorizing countries into four climate zones. Focusing on residential NZEBs in Oceanic and Nordic climate zone countries - Denmark, Estonia, and Finland – we compare the requirements and highlight the relative strictness of these benchmarks.

The EC has set recommended benchmarks for energy performance of NZEB for four EU climatic zones [1]: Mediterranean, Oceanic, Continental and Nordic. Aside from different primary energy (PE) requirements, each country has implemented its own methodology for PE calculation, which vary in terms of usage profiles, energy systems and include different aspects of building energy use as well as primary energy factors. **Table 1** presents these PE factors used in EC recommendations and national energy performance calculations in Estonia, Denmark, and Finland. The energy flows included in the national calculations and the allowed maximum PE values to comply with NZEB requirements are given in **Table 2**.

Table 1. *PE factors used in European Commission recommendations (EC) [1], Estonia (EE) [2], Denmark (DK) [3] and Finland (FI) [4].*

Energy carrier	PE factors, -			
	EC	DK	EE	FI
Electricity	2.3	1.9	2.0	1.2
District heating	1.3	0.85	0.65	0.5
Natural gas	1.1	1.0	1.0	1.0

The energy performance requirements are defined through the maximum allowed PE consumption, set in the national regulations [2, 3, 5] and is presented as Energy Performance Indicator (EPI) value in kWh/(m²·y). The EPI value incorporates so called EPBD uses, but in Estonia and Finland also lighting and appliances. Additionally, the Danish calculation includes specific "sanctions" for overheating, in which case a penalty is included as a fictive energy need, equal to the energy need (including PE factor of electricity) by an imaginary mechanical cooling system. The EPI value calculation follows in all countries the system boundaries of REHVA's definition [6], but only on-site produced energy which is used by the building systems is taken into the account and is subtracted from the delivered energy [7]. The Danish methodology allows to account max 25 kWh/(m²·y) of PE from local electricity production. Exported energy is not accounted in any country when calculating the EPI value:

$$EPI = \frac{\sum_i (Q_i \cdot f_i)}{A_{net}} \quad (1)$$

where Q_1 is the annual delivered energy use for electricity, fuel, district heating, district cooling etc, [kWh/y], f_i is the PE factor for the corresponding energy carrier, [dimensionless] and A_{net} is the net heated building area (gross area in Denmark), [m²]. The Estonian building regulation gives an additional requirement: maximum allowed PE use without accounting (subtracting) the on-site produced and used renewable energy from the building's total energy use.

The analysis of the energy performance requirements was divided into following parts:

- Comparing national requirements by the key numbers, energy performance calculation specifics and methodological differences.
- Simulating building performance as required by the national regulations of each country.
- Simulating building performance using national TRY weather and input data for standard use from EN 16798-1:2019 [8] to fulfil the EC PE recommendation for NZEB [1].
- Comparing and analysing the results to quantify the strictness of the NZEB requirements.

Reference buildings

Two residential buildings were selected for the analysis: a single storey detached house and a multi storey apartment building. Both buildings were initially designed as NZEB according to its nation of origins: the single-family house in Denmark and the apartment building in Estonia. The buildings are representative examples of new NZEBs with modern designs and technical

Table 2. *National and EC NZEB requirements and energy flows included in the PE calculations [1-4].*

	Included energy flows	PE requirement for NZEB, kWh/(m²·y)	
		Single-family house	Apartment building
EC recommendation	HVAC, DHW, auxiliary	Oceanic: 15-30 (incl. ~35 RES) Nordic: 40-65 (incl. ~25 RES)	
Estonia	HVAC, DHW, auxiliary, lighting and appliances	145 (165) (*) (A_{net} < 120 m²) 120 (140) (*) (120 ≤ A_{net} ≤ 220 m²) 100 (120) (*) (A_{net} > 220 m²)	105 (125) (*)
Denmark	HVAC, DHW, auxiliary	30 + 1000 / A_{gross}	30 + 1000 / A_{gross}
Finland	HVAC, DHW, auxiliary, lighting and appliances	200–0.6 A_{net} (50 < A_{net} ≤ 150 m²) 116–0.04 A_{net} (150 < A_{net} ≤ 600 m²) 92 (A_{net} >600 m²)	90

(*) Additional PE requirement without accounting Renewable Energy Sources (RES) solutions (**Figure 1**). The main parameters of the buildings are described in **Table 3**.

National NZEB levels comparison

Single-family house

Following the Danish requirements, installation of 12 m² of PV (**Figure 2**, case 1) sets the building on the BR 2018 voluntary "low-energy" line [PE ≤ 27 kWh/(m² y)] that is more strict than mandatory NZEB. The NZEB requirement, PE ≤ 36.1 kWh/(m² y), is achieved with 5 m² of PV panels (case 2). The initial design installation of the house with 24 m² of PV produces a surplus of 73% PV energy compared with the amount required for NZEB. However, when calculating the building with 5 m² of PV using the EU standardized input data while leaving technical systems, envelope, and other building parameters initial (case 3), the building does not achieve the recommended energy performance level (Oceanic zone) of PE ≤ 30 kWh/(m²·y), but is requiring additional 16 m² of PV panels (case 5). This means that even the amount of PV required for Danish low energy level is not sufficient to achieve EC level (case 4). In this case also the EC recommendation of PE without renewable energy production (Oceanic zone) is not fulfilled.

The PE recommendation for Nordic zone, PE ≤ 65 kWh/(m²·y), is met with 18.5 m² of PV (case 6). This amount however is not sufficient to achieve the Estonian NZEB performance level (case 7). Even the initial installation of 24 m² PV panels (case 8) is not sufficient to meet the threshold of PE ≤ 120 kWh/(m²·y). It would require 39 m² of PV panels in total (case 9) for the building to qualify in Estonia as NZEB (energy performance class A). The higher need for PV electricity production in the Estonian cases at one hand is because only the fraction of produced energy that is used in the building is accounted in energy calculation.

Table 3. *Building parameters.*

Parameter	Single-family house	Apartment building
Net heated area, m²	138	4986
Ext. walls U-value, W/(m²·K)	0.29	0.12
Roof U-value, W/(m²·K)	0.09	0.08
Slab on ground U-value, W/(m²·K)	0.12	0.12
Windows U-value, W/(m²·K)	1.3…1.5	0.9
Building leakage rate q_{50}, m³/h per m² of envelope	1.0	1.5
Ventilation heat recovery efficiency, -	0.88	0.80
Specific fan power of the ventilation system, kW/(m³/s)	1.0	1.5
Installed PV system power (max PV whole roof covered), kW	3.6	65.4
Heat generation	Heat pump, SCOP=3.58	District heating

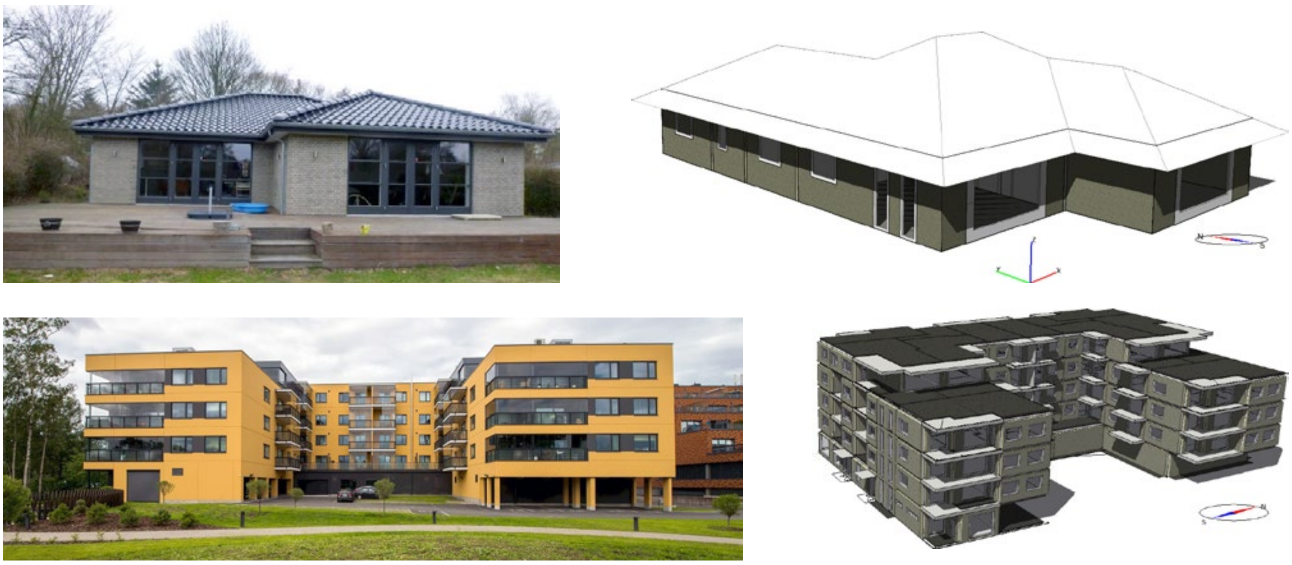

Figure 1. Photos and simulation models of the reference single-family house and apartment building.

Even with the added PV production, the building does not meet all Estonian requirements - it would need to comply with energy performance class B without accounting the on-site renewable energy production; that is PE ≤ 140 kWh/(m²·y). This requirement however is not fulfilled, meaning that, for example, the thermal or technical systems performance of the building envelope should be improved. This is also expected when moving the initial Oceanic design to a colder climate. In contrast, the Finnish NZEB requirements were met even without local renewable energy production (case 12). It must be emphasised that besides methodological and climatic differences, the PE performance results are largely influenced by the national PE factors. As the reference building utilises heat pump system for space, ventilation air, and DHW heating, the PE consist of only electricity consumption, highlighting the impact of the nationally different electricity PE factors.

Apartment building

The reference apartment building (designed for Nordic climate and including RE production to meet Estonian NZEB requirement) calculated according to the Danish building regulations met the NZEB requirement of PE ≤ 30.2 kWh/(m²·y) quite easily with total PE of 9.9 kWh/(m²·y) (**Figure 3**, case 1), which is also expected due to climatic differences. Even without PV production the building performance surpasses the required PE threshold by only 0.7 kWh/(m²·y) (case 2).

The reference apartment building without PV production (case 3) is far to meet the EC Oceanic NZEB and exceeds the EC PE limit without on-site renewable energy production PE ≤ 65 kWh/(m²·y). The reference building with PV does also not meet EC NZEB maximum value (case 4, calculated with EU standardised input data). This illustrates the relatively high performance level for EC Oceanic zone, considering the building is initially designed for Nordic climate. Basically, the results show that EC Oceanic NZEB is not achievable with district heating with EU default primary energy factor because the roof of the reference building is fully covered with PV and it is practically impossible to further improve the energy performance.

Calculation results using the EU standardised input data for Nordic climate position the building exactly to the EC recommended level for PE without accounting RE production, that is PE ≤ 90 kWh/(m²·y) (case 5). Also, the EC PE recommendation with RES is fulfilled (case 6). As the building is designed as NZEB in

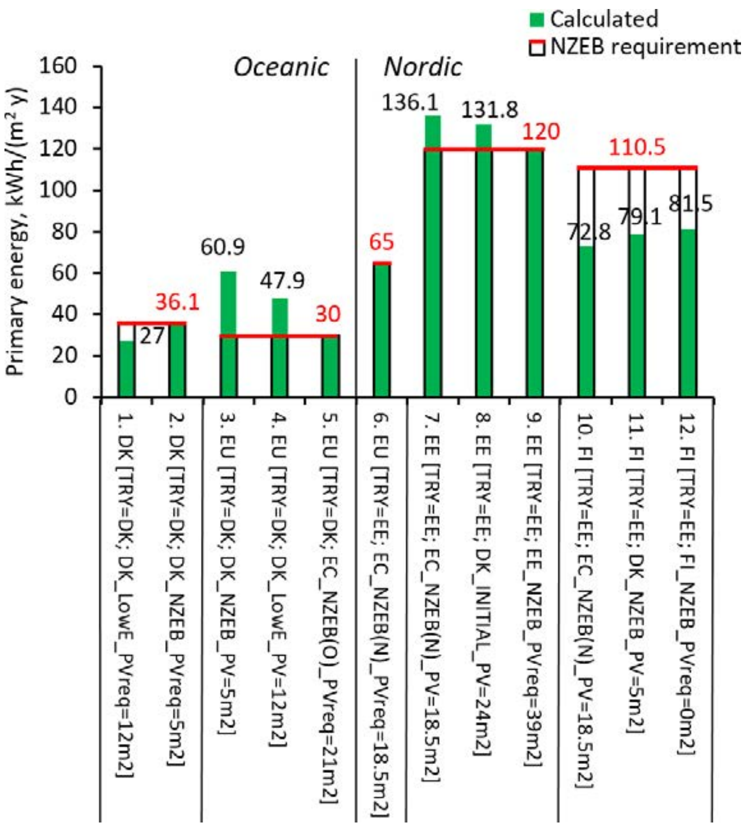

Figure 2. Annual PE consumption of the reference single-family house. PV energy production is added or removed to meet NZEB requirements. Code example: DK [TRY=DK; DK_LowE_PVreq=12 m²] – Danish methodology [Simulated with Danish TRY, meets Danish Low energy threshold with 12 m² of installed PV].

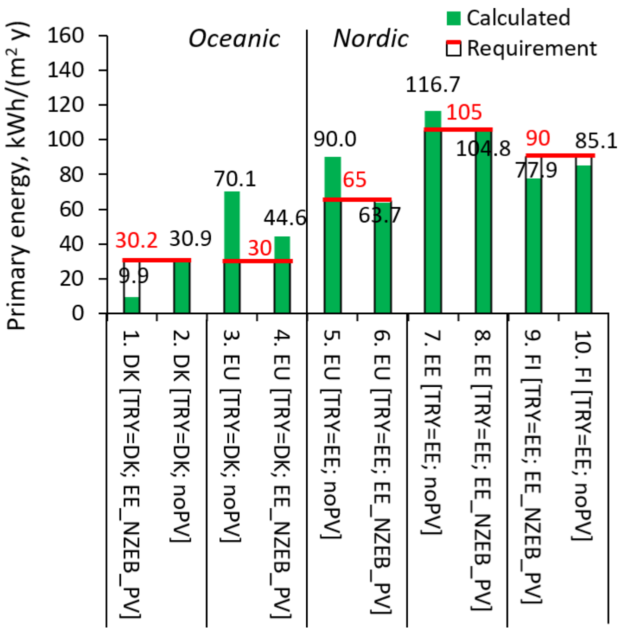

Figure 3. Annual PE consumption of the reference apartment building. PV energy production is added to meet NZEB requirements. Code example: DK [DK_LowE; TRY=DK; PV=24 m²] – Danish methodology [Danish Low energy threshold; Danish TRY and 24 m² of installed PV].

Estonia, it is also designed to meet the national NZEB requirements with initial PV production (case 8) and the required low energy (energy class B) requirements (case 7).

As was the case with Finnish requirements for detached houses, the apartment building fulfils the requirements also without on-site renewable energy production as well (cases 9 and 10). The results indicate that the Estonian requirements match the EC recommendations if the building utilises district heating energy. It can also be stated that buildings designed to comply with Finnish building regulations, would not meet the EC PE recommended levels.

Conclusions

In case of the Oceanic zone, the EC recommendations for residential NZEB PE appear to require relatively higher energy performance compared to the Nordic zone recommendations. This is illustrated with the case of Denmark, located in colder part of the Oceanic zone. A highly insulated reference apartment building with district heating and PV fulfilling EC Nordic NZEB recommendation exceeded EC Oceanic NZEB recommendation(!). At the same time, a reference detached house with ground source heat pump and extensive PV installation was capable to meet EC Oceanic NZEB recommendation. However, this performance level clearly exceeded Danish NZEB and Low Energy.

In the Nordic climate zone, Estonian NZEB requirements complied very closely to EC Nordic NZEB recommendation. Finnish NZEB requirements were less strict and did not fulfilled EC Nordic NZEB recommendation.

The study illustrates the need of having two sets of requirements: with and without renewable energy production, as is the case for Denmark and Estonia and also for EC benchmarks. Denmark has solved the issue by setting the maximum amount of RE allowed to account in the PE calculation, requiring the building to achieve a sufficient level of energy efficiency by means of thermal insulation and HVAC systems. In Estonia there are PE requirements for the building without accounting on-site RE production as well as for the building including RES. Finland with less strict requirements, however, has not followed the separation of requirements. ■

Acknowledgement

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Cost-optimal nZEB HVAC configurations with onsite storage

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Abstract

By 2021, all new buildings in the European Union must be nearly zero-energy buildings (nZEB) to contribute to the achievement of the EU-CO_2 neutrality by 2050. As the technical options to achieve highly-efficient building envelopes are available and well-known, there is no doubt that the most promising Heating Ventilation and Air Conditioning systems will include heat pumps and photovoltaic panels. However, there exist ongoing discussions on the optimal system layout and the integration of storage to achieve nZEB. In particular, there are some good arguments in favour of very low demand, while contrariwise also high flexibility is seen as an important feature to enable so-called grid-reactive operation of the building stock. Integration of onsite storage and its influence on the energy demand of the buildings and the corresponding electric load profile with focus on peak power is investigated.

Introduction - Nearly Zero Energy Buildings and flexibility

By 2021, all new buildings in the European Union must be nearly zero-energy buildings (nZEB) to contribute to the achievement of the EU-CO2 neutrality by 2050. According to EPBD, an nZEB is a nearly zero-energy building, with a very low energy demand due to efficiency measures that include efficient HVAC technology (e.g. Heat Pump-HP) and utilization of Renewables (RE) to meet the very low demand to a considerable extent. The Net zero-energy Building (NZEB) is better known outside Europe. A NZEB can be realized as a "grid-connected building that on annual basis generates the same amount of energy from on-site RE energy sources as it consumes" (IEA SHC T40 / HPT A40).

This work aims to show for the investigated virtual case in Tyrol (Austria) as an example, the potential of integrating passive and active solar technology and the role of onsite storage. A methodology was developed to analyse and compare different solutions with a special focus on HP integrated with RE in nZEB buildings.

While previous studies focused on the micro-economic aspect, this work investigates the influence of onsite storage on a macro-economic scale. It is important to determine the reduction of the grid electricity demand and the PV excess electricity depending on the sizing of the (thermal and/or electric) storage. The research question is, whether in a 100% RE-based scenario, onsite storage will play a significant role. Furthermore, it is investigated how onsite storage capacity influences the required back-up power or central storage capacity.

Energy Storage

Energy storage can be beneficial in terms of buffering short, mid-term and seasonal mismatch between energy source and energy demand. Storage can be integrated into the energy system in large central units or decentral in buildings.

Figure 1 gives an overview of the existing electric and thermal energy storage. While long-term electric and thermal storage systems are typically large-scale central units (e.g. District Heating–DH [1]), short-term electric and thermal storage can be scaled for a wide range of applications and can be applied in buildings. Latent and thermo-chemical (TC) storage are subject of research [2].

Through energy storage, energy flexibility in buildings could provide generating capacity for energy grids, and better accommodate RE sources in energy systems, possibly reducing costly upgrades of energy distribution grids.

Two types of storage on building level are possible:

- Electric: Buildings equipped with a PV can benefit from the introduction of batteries (increased self-consumption).
- Thermal: It is possible to store hot water when surplus energy is available or when electricity prices are low.

Solid sensible storage is either a massive part of the building or fillings made of gravel or rocks.

Figure 2 gives an overview of building-integrated storage systems.

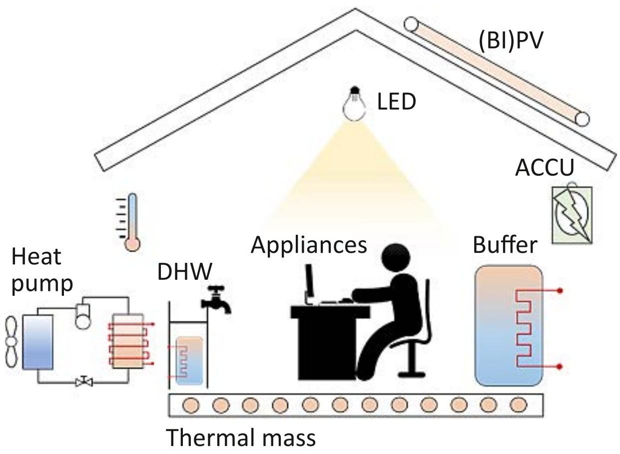


Figure 2. Schematic presentation of energy storage in buildings.

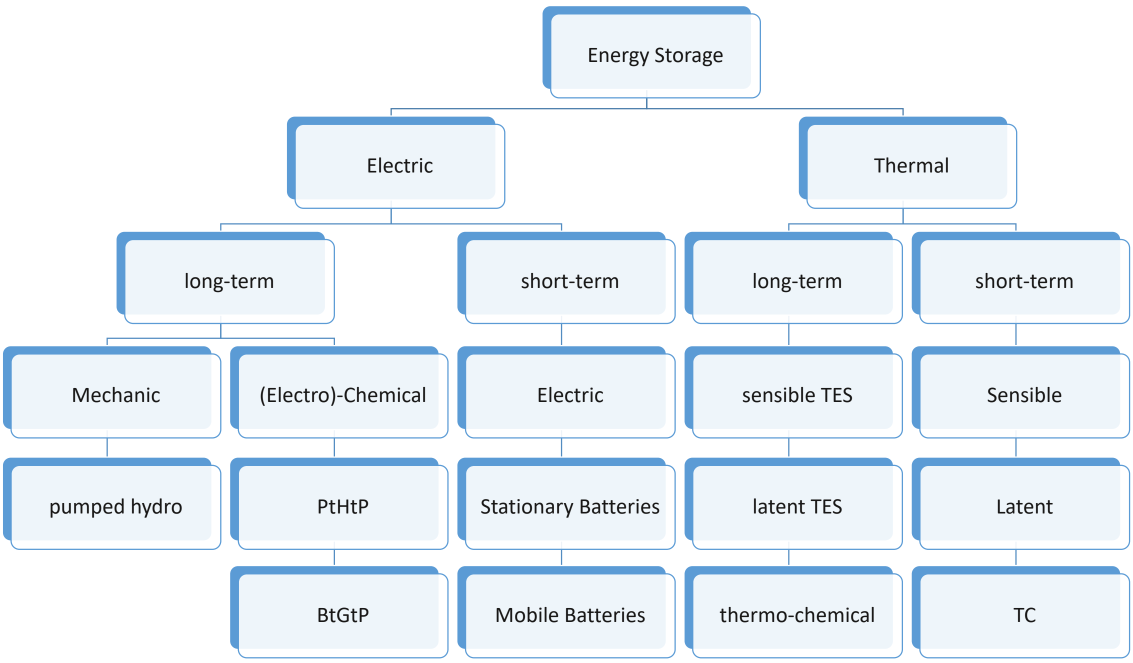


Figure 1. Overview of electric and thermal energy storage (TES); PtHtP: Power to Heat to Power BtGtP: Biomass to Gas to Power.

Building Stock Model

The building stock of Tyrol (Austria) is taken as an example (scenario Tyrol 2050 [3], total phase-out of fossil heating systems) and it is represented by 6 types of prototypical buildings i.e. SFH, small Multi-Family House (s-MFH), large MFH, office, Hotel and Industry. Each building is simulated with its individual energetic quality (representing the average status of 2050 according to [3]) and is equipped with either an HP, or a Direct Electric (DE) system, with and without PV and battery storage, representing different load patterns for the electricity grid.

The following results focus on the residential buildings (see **Table 2)** with 21% SFH, 29% s-MFH and 11% l-MFH in Tyrol.

Electric Energy Balance with onsite PV and storage

The monthly electricity consumption for the SFH is reported in **Figure 3** together with the PV yield and self-consumption for the following cases: (a) with heat pump without PV; (b) with 5 kW_p PV; (c) with

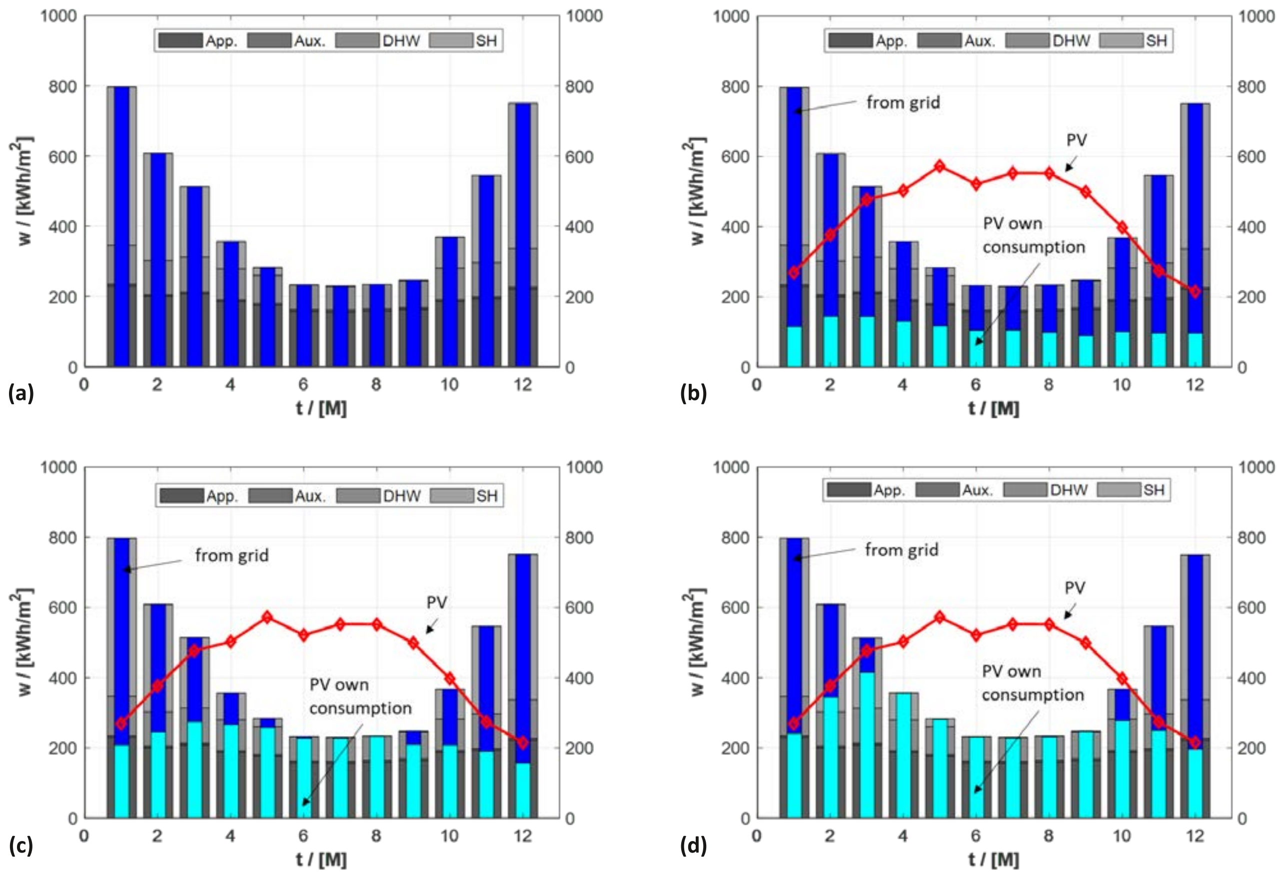


Figure 3. Monthly electricity demand, PV yield and self-consumption for the SFH with heat pump (a), with HP and PV (b), heat pump, PV and small battery (c) as well as HP, PV and large battery (d).

Table 2. Heating demand, gross floor area, available roof surface, number of buildings and installed PV peak power per building type [3].

	SFH	s-MFH	l-MFH
Heating Demand [kWh/(m²a)]	37.8	31.6	35.9
Gross floor area [m^2_{GFA}]	182.9	405.3	2 090.1
Number of floors	2	3	10
Roof surface [m²]	91.5	135.1	209.0
No of buildings	10 6579	67 592	5 063
Installed PV [kWpeak]	5	8	12
PV Yield [GWh/a]		1 200 (1 047 kWh/kW_p)	

PV combined with small battery (6.67 kWh); and (c) with PV combined with large battery (8 × 6.67 kWh).

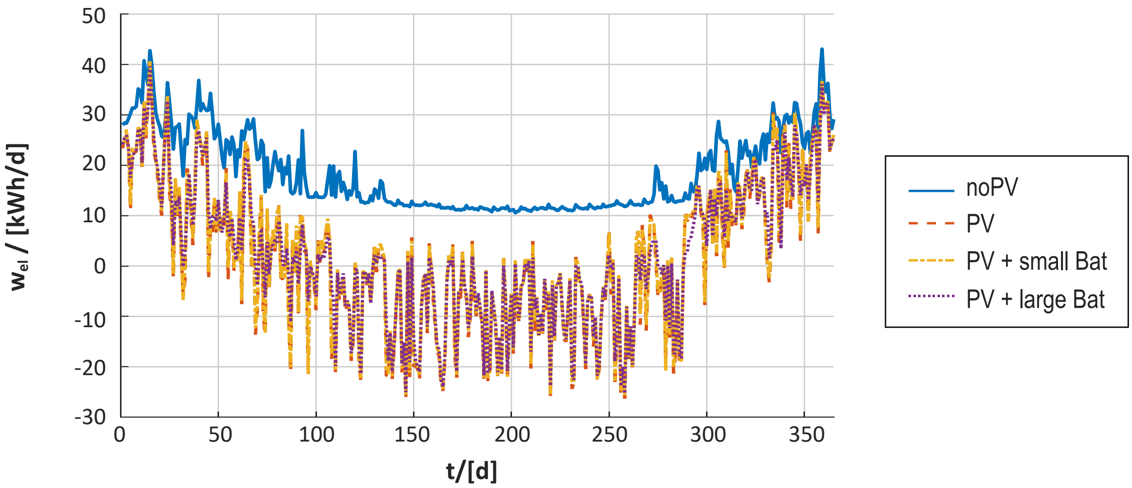
The usage of the PV without battery (case b) can cover 26% of the base electricity demand throughout the whole year exploiting 26% of the PV yield, reducing the grid electricity consumption. When additionally, a small battery is used (case c) the electricity demand covered by the solar energy is notably increased (52%) reducing the excess electricity and the electricity required from the grid. A further increase of the battery size (case d) is beneficial only in spring and autumn therefore of limited use. However, in all cases, the battery does not influence the peak power, since it is fully charged most of the time in summer and empty most of the time in winter. In consequence, there is also no relevant capacity for electricity buffer from PV of other buildings in summer, neither surplus of electricity for other buildings in winter, in case of a heating-dominated climate like Innsbruck.

Electric Energy Demand Building Stock

The total electric load of the residential building stock (acc. to the scenario Tyrol 2050 [3]) can be calculated considering the share of building types (SFH, s-MFH, l-MFH) and the corresponding share of heating systems (HP, DE and rest (biomass, DH)). In **Figure 4** the electricity demand and the load curves represent an average residential building for the case without PV, with PV, with PV plus small battery and with PV plus large battery. Again, extensive use of PV has a significant influence on the bought and sold electricity, however, the peak load is hardly reduced also with large storage capacity in the buildings. The peak power is ca. 2 200 W and the excess PV electricity supplied to the grid is ca. 5 000 W with or without onsite storage.

Discussion and Conclusions

Future nZEBs, will have a relatively low heating demand (15 to 45 kWh/(m² a)) and a DHW demand of the same order of magnitude (between 10 and 20 kWh/



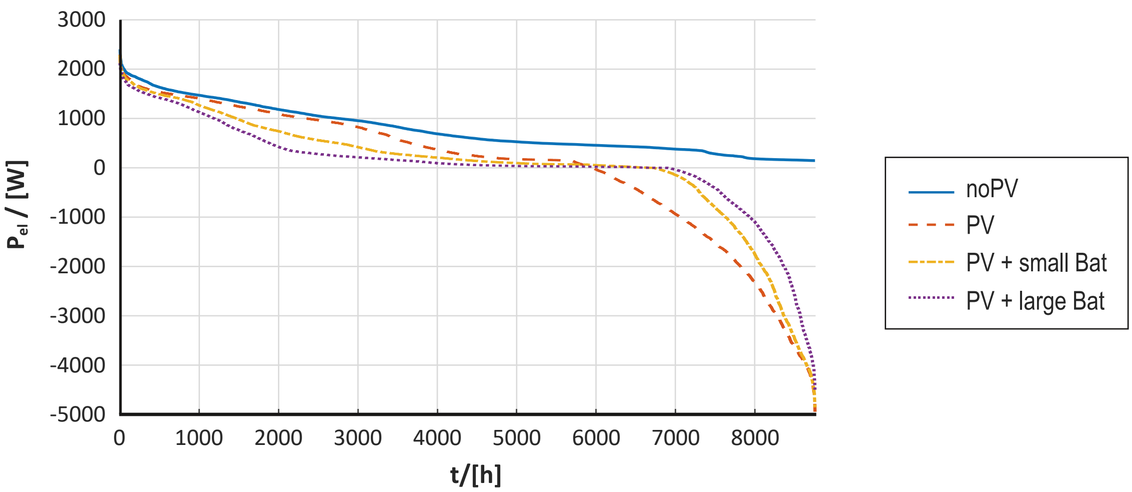


Figure 4. Total grid load of residential building with different combinations of PV and battery presented with an hourly resolution (top) and as a duration curve (bottom).

(m² a)). Assuming heat pumps being the standard heating system in the future, the total electric demand for SH and DHW is in the range of 10 and 25 kWh_{el}/(m² a) and of the same order of magnitude as the electricity demand for appliances (typically between 15 and 20 kWh_{el}/(m² a)). On an nZEB SFH with 5 kW_p PV system, the net PV yield is of the same order of magnitude as the annual total electricity demand. Hence, electric storage could cover theoretically 100% of the total demand (SH + DHW + appliances), while thermal storage could theoretically cover around 50% of the total energy demand (SH + DHW). In MFH, because of the relatively small roof area related to the GFA, the theoretical contribution of PV is significantly less.

Overall, onsite storages can be beneficial to reduce the grid electricity demand, however, they hardly influence the grid load (electricity buy and electricity sell). Hence, if at all, extensive onsite storage should be considered only on short and mid-term to promote the extended use of PV in buildings (in particular when buyback tariffs are low). On macro-economic scale, in spite of energy savings, an additional application of storage in buildings or use of existing storage will lead to higher losses without reducing the peak loads or the central storage capacity.

Based on the presented results design guidelines can be elaborated for buildings located in heating-dominated climates like Innsbruck. ■

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Infection probability of COVID-19 in a large lecture room with mechanical ventilation

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Keywords: indoor air quality, ventilation rate, mechanical ventilation, probability of infection, COVID-19, lecture room, Wells-Riley equation.

Abstract

In this field study, lecture room S2 at NTNU Gløshaugen, where a real COVID-19 infected student was present during a two-hour lecture, was investigated to calculate the probability of infection risk. The ventilation system in S2 is mechanical balanced ventilation. The results show that the probability of getting infected in S2 with one infected student is 0.098%, which is significantly lower than other studies. The result is in line with the fact that no other students were infected after attending the lecture in S2.

Introduction

Students spend a lot of time in lecture rooms, where they are closely seated and there is a great risk of infection during the COVID-19 pandemic. Viruses can be transmitted in three different ways: through direct contact, droplet transmission or airborne transmission. In the beginning of the pandemic, it was assumed that the virus could not transmit through air, however current research show there is a high possibility that this is the case [1]. It is assumed in this study that the coronavirus is in fact an airborne disease. A well-functioning ventilation system can decrease the possibility to get infected by an airborne virus, such as the coronavirus.

Previous studies have shown that too high or too low relative humidity is favourable for the survival of the coronavirus, especially for very low relative humidity. The optimal range for relative humidity and human health is 40–60% [2]. According to the University of Sydney [3], relative humidity and infected covid-19 cases have a negative correlation. They found that a 1% decrease in the relative humidity causes a 6–7% increase in infected cases. In addition, ventilation plays a key role to control the indoor air quality. Norwegian building regulation TEK17 states that ventilation rates for people with a light activity level should be minimum 26 m^3/h per person [4]. While as for ventilation for building materials, it varies in the range of 2.5–7.2 m^3/h per m^2 floor area according to the emitting materials [5].

Few studies regarding the infection risk have been done in lecture halls with mechanical ventilation. The objective of this article is to quantify the probability of infection of COVID-19 in a large lecture hall with mechanical ventilation at NTNU.

Theoretical modelling

Wells-Riley

The Wells-Riley equation can approximate the probability of infection due to human exposure to airborne infectious contaminants [6]. The equation is:

$$P = 1 - e^{\frac{-Ipqt}{Q}}$$

q – breathing rate per person $[\frac{m^3}{h}]$

I – number of infectors [-]

p – quanta per hours produced by infector $[\frac{quanta}{h}]$

t – time of exposure [h]

Q – outdoor air supply rate $[\frac{m^3}{h}]$

Ventilation rate and indoor pollutants - non-steady state equation

When non-steady state, the CO_2 concentration per time unit can be expressed as:

$$\Delta C_i = V \cdot \frac{dC}{dt}$$

This change must equal the CO_2 in the supplied air, the production of CO_2 in the room, minus the CO_2 removed by the extracted air. In this case infiltration, exfiltration and the effect of the filters in the air handling unit is neglected. The following expression for the change in CO_2 level is then obtained.

$$\Delta C_i = G + \dot{V} \cdot (C_{CO_{2,r}} - C_{CO_{2,i}})$$

Combining and rearranging the two equations give:

$$\dot{V} = \frac{V \cdot \frac{dC}{dt} - G}{(\bar{C}_{CO_{2,r}} - \bar{C}_{CO_{2,i}})}$$

$\dot{V}$ – ventilation rate $[\frac{m^3}{h}]$

$\bar{C}_{CO_{2,r}}$ – average exhaust concentration $[\frac{\mu g}{m^3}]$

$\bar{C}_{CO_{2,i}}$ – average supply air concentration $[\frac{\mu g}{m^3}]$

G – average source strength of pollutant $[\frac{\mu g}{h}]$

V – volume of room $[m^3]$

$\frac{dC}{dt}$ – change in CO_2 concentration over time $\frac{\mu g}{m^3}$

Experimental method

On September 24th, a student who was infected with the Covid-19 virus attended a lecture in S2 at NTNU Gløshaugen. There is assumed a total of 131 students present at the lecture, and no other students were infected after attending the lecture in S2 [7].

The investigated lecture room S2

S2 is a large lecture room at NTNU in Trondheim. The volume of the room is 992.1 m^3 and the area is 251.5 m^2 (see **Figure 1**). The capacity of the room is 256, but during the pandemic it is reduced to 131 due to infection control measurements. The activity level during a lecture is normally sedentary activity, according to NS-EN ISO 7730:2005.

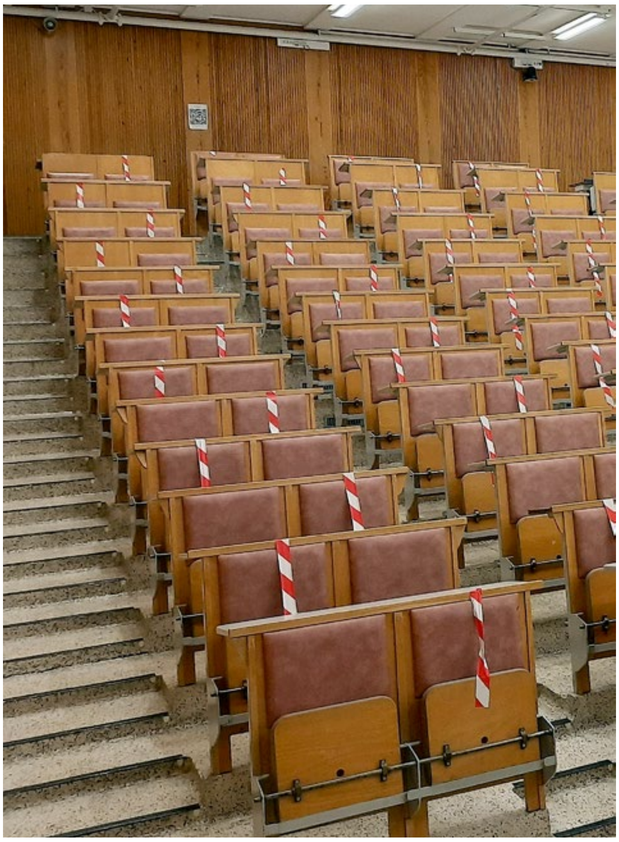

Figure 1. Lecture room S2.

Measurement setup

Measurements of CO_2, relative humidity and air temperature were carried out in S2 by the extract shown in **Figure 2**. The measurements and the occupancy level were manually recorded every minute for one hour.

Results and discussion

Measurement results

The results are presented in **Figure 3.a**, **3.b** and **3.c** that show CO_2 (ppm), temperature (°C) and relative humidity (%) in relation to the amount of people in the room.

In **Figure 3.a** the variation in CO_2 level is presented. The number of people is constant during the lecture, but at the end there is a drastic reduction. The CO_2 level varies between 600 and 650 ppm when the amount of people is constant. When the students leave the lecture, the CO_2 concentration first increase followed by a drastic decrease. In **Figure 3.b** the temperature variations are presented. It is clear that when the amount of people in the room is constant, the temperature increases. At the end of the lecture when people leave the room, the temperature decreases. **Figure 3.c** presents the variation in relative humidity. During the measurements, the relative humidity varies between 36% and 42%. The relative humidity throughout the lecture is at a moderate level, according to Ahlawat [2], and this will be favourable for a shorter survival time for the virus. With the known information that no one else got infected, the statement about moderate relative humidity throughout the lecture holds.

Probability to get infected based on Wells-Riley

The probability to get infected may be affected by the ventilation rate. To calculate the ventilation rate, the non-steady state equation and the results from the measurements are used. An individual ventilation rate is calculated for each time interval, and the average is used as the final value. The total ventilation rate is calculated to be 5 054.4 m³/h, which is equals to 5.1 h^{-1} air exchange rate. During the COVID-19 pandemic with the presence of 131 students, the airflow rate is equal to 38.6 m³/h per person or 10.7 ℓ/s per person.

If the variation of the CO_2 concentration becomes zero under steady state conditions, we may assume the room air is fully mixed with supply air. Consequently, the exhaust concentration may be equal to the room CO_2 concentration. The room CO_2 concentration is calculated to be 866.5 ppm under fully mixed steady

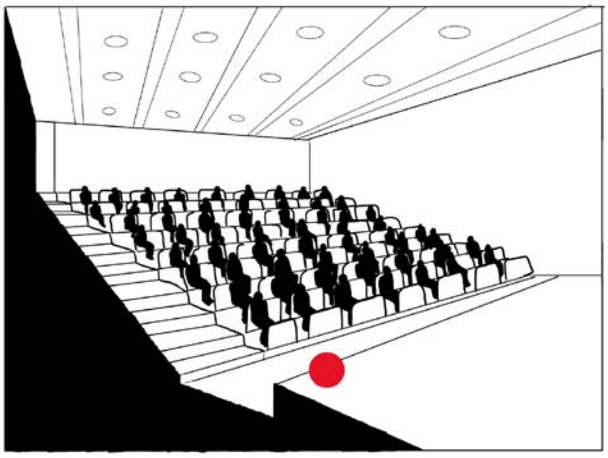

Figure 2. Measurement point in S2.

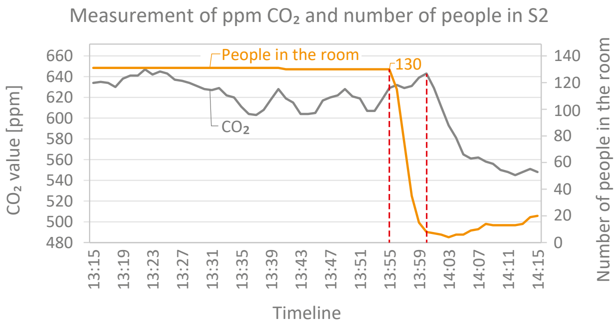

Figure 3.a. Measurements of CO_2 and number of people in the room.

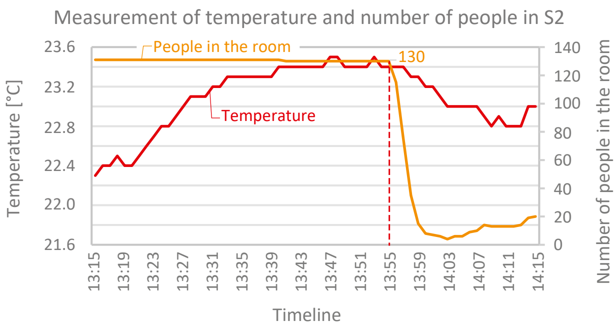

Figure 3.b. Measurements of temperature and number of people in the room.

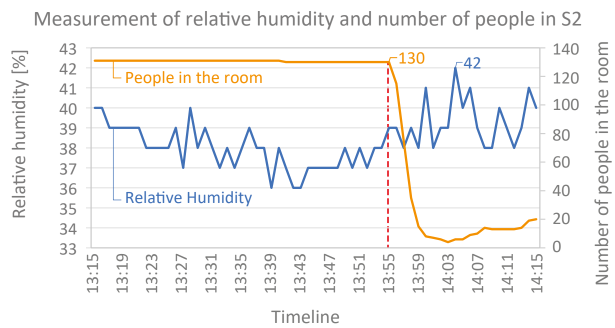

Figure 3.c. Measurements of relative humidity and number of people in the room.

state condition. The measured value was between 600 and 650 ppm, which is lower than the calculated value.

The Wells-Riley equation is used to calculate the probability of infection in S2. The input variables are gathered from [8]. The number of infected persons is set to 1, the breathing rate is normal at 0.54 m^3/h, the quanta per hour of infectious particles from the infected person is set to 4.6 for a classroom, the time of exposure is 2 hours, and the supply air rate has been calculated earlier.

From the required TEK17 value of supply rate, the probability of infection in S2 is calculated to be 0.095%. From the measured value of supply airflow rate, the probability of infection in S2 is calculated to be 0.098%. This shows that the probability to get infected is very low, which is consistent with the known information that no one else got infected after attending the lecture.

However, the Wells-Riley equation does not consider the type of ventilation system or the air flow pattern, only the ventilation rate. The air flow distribution in the room is unknown, and therefore the expected probability to get infected may be greater than the calculated value.

Conclusion

During the COVID-19 pandemic with the presence of 131 students, the supply airflow rate in S2 was equal to 38.6 m^3/h per person or 10.7 ℓ/s per person. By using the Wells Riley equation and the measured CO_2 concentration of indoor air, the probability of infection in S2 is calculated to be 0.098%. The result is in line with the fact that no other students were infected after attending the lecture in S2. In addition, this study supports the calculation by REHVA COVID 19 tool that the probability of infection is very low in a larger space with sufficient supply airflow rate.

The calculated fully mixed concentration of CO_2 is significantly higher than the measured value close to the air extraction point. This means that there are possible stagnant zones in S2, where air stays for a longer time with increased risk of occupants inhaling each other's exhaled air.

Further study may be carried out to clarify the airflow pattern and identify potential improvement of IAQ by other type of airflow distribution solutions. To make the analysis even better, an increased number of measurement points would have been ideal. ■

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Heat use profiles in Norwegian educational institutions in conditions of COVID-lockdown

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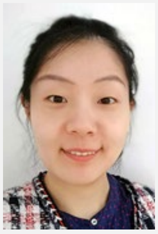

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Introduction

COVID-19 is a potentially fatal coronavirus disease that may cause severe problems with the human respiratory system [1]. Since the beginning of 2020, this disease has begun to spread rapidly around the world [2]. In March 2020, the World Health Organization (WHO) declared that COVID-19 outbreak is a global pandemic. Social distancing and personal hygiene are proved to be the primary measures that may help to prevent the spread of COVID-19 [3]. Therefore, to avoid people gatherings and crowds, most countries have imposed a partial or full lockdown of educational institutions and commercial and industrial companies. Such drastic changes in the behavior of energy users have a significant impact on energy demand and lead to substantial problems in the energy sector.

The effect of restrictions on energy demand in the EU countries is investigated in [4]. The EU countries have individually approached the restrictions associated with the COVID pandemic. The analysis of energy use showed that countries that imposed stricter restrictions experienced a higher reduction in energy demand. Currently the existing research and analysis have been focusing on the residential buildings, while research on non-residential buildings is lacking. For the educational institutions, office buildings, and other commercial buildings that experienced the lockdown, it is usually assumed that the demand profiles for weekdays during the pandemic are similar to weekends of the reference week in 2019 [4]. However, the data-based evidence for energy use profiles in these types of buildings is missing.

This paper presents heat use in buildings in Norway during the period of the COVID-19 pandemic. The study focused on the analysis of heat use in schools and kindergartens. Firstly, the study compared profiles in buildings during the COVID-lockdown and the post-lockdown period with the profiles obtained before the pandemic. Secondly, the study developed the three scenarios for heat use in buildings in conditions of the pandemic lockdown. The following scenarios were considered: 1) Scenario 1 – Modelling based on behavior in a normal year (i.e. the previous year), 2) Scenario 2 – Modelling based on heat use in night hours, 3) Scenario 3 – Modelling based on the current settings that were used in the buildings during COVID-lockdown. The proposed scenarios represented the different settings for the heating systems and might give important information for further efficient utilization of heating systems in buildings.

Methods

Three different scenarios of heat use in buildings during the lockdown were developed. A brief description for each scenario is given below.

Scenario 1 - Modelling heat use for based on behavior in a normal year

When a building is operating in a regular regime, not affected by unexpected changes in occupancy, the outdoor temperature may be treated as the main factor that explains the variation of heat use in buildings [5]. The model that expresses the relationship between the heat use in an observed building and the outdoor temperature is called the Energy Signature Curve (ESC) [6]. Usually, the ESC contains two sub-models divided by the change point temperature (CPT). Piecewise regression is a method that can be used to build the ESC model. Due to the diverse schedules of work, in working days at hours when the main activities are held, the heat use in educational buildings is much higher comparing to the rest of the time. For this reason, to plan the heat use in a regular regime, we developed the separate ESC models for each hour of the weekdays and weekends. To formulate heat use in Scenario 1, the outdoor temperature data for the typical cold and warm meteorological years (TMY) were applied as an input to the ESC models.

Scenario 2 – Modelling based on hours of night heat use

Scenario 2 considered better operation settings for the heating system during the lockdown. In this scenario, it is assumed that during the lockdown, the buildings' heat use should be kept at the level of night heat use under the normal pre-pandemic conditions. In the educational institutions, the lowest heat use can be usually observed at the night time from 1:00 o'clock to 5:00 o'clock in working days, when there are no people in buildings and the heating system is working with the minimum energy load required to maintain the lowest acceptable temperatures. To express the possible reduction of heat use in the buildings, the ESC model based only on nighttime heat use was developed.

Scenario 3 – Modelling based on current settings that were used in the buildings during COVID-lockdown

Scenario 3 explained the building heat use if the actual setting for the heating system during the COVID-lockdown in Norway would be continuously used to the typical year. Scenario 3 was developed based on the average monthly heat use that was observed before and during the COVID-19 pandemic.

Description of the observed educational buildings

Educational institutions located in Trondheim, Norway, were analyzed in this study.

The information of the heat use in eight kindergartens and 12 schools were obtained from the energy monitoring platform of the Trondheim municipality. Among these schools, nine schools are for junior pupils, two schools are secondary schools, and one is the mixed school. The areas of kindergartens are within 779–2 086 m², and the area of the schools are within 3 206–8 449 m². All the buildings in the analysis are using district heating system (DH) as the main heating supply carrier.

To compare buildings of different characteristics, the average heat use per heating area (per m²) was used as a physical indicator. Data obtained from the nearest meteorological station located in Trondheim were used [7].

Results

This section is divided into two subsections. The analyses of heat use profiles before and during the COVID-19 restrictions is given first. The three scenarios for heat use in the educational institutions are given afterwards.

Analysis of heat use profiles in educational institutions before and during the COVID-lockdown

Norway is among the countries that had imposed strict restrictions when the COVID-19 pandemic began to spread in early 2020. One of these restrictions was the temporary lockdown of educational institutions. Following the recommendations of the government, schools and kindergartens were closed from March 13th to April 23rd, 2020.

The average outdoor temperature in March 2019 was 0°C, and in March 2020 it was 1.7°C. In April 2019, the average outdoor temperature was 7.2°C, and in April 2020 it was 3.9°C. Whereas in May 2019 it was 7.9°C, and in May 2020 it was 6.4°C. Although the outdoor temperature influence heat use [8], it was decided to compare the real profiles rather than the temperature adjusted values in this work. This enables us to focus on real data without making any biased suggestions.

Since weekdays and weekends have different patterns of heat use, their profiles were considered separately. The average daily heat use profiles for kindergartens and schools of 2019 and 2020 are shown in **Figure 1** and **Figure 2**, respectively. In **Figure 1** and **Figure 2**, WD denotes working day and WE denotes weekend, and the dashed lines stand for 2019 and the solid lines for 2020. Please note that in our investigation, March and April included only days when the lockdown was imposed. From **Figure 1** and **Figure 2**, it may be observed that the shape of the heat use profiles before and during the pandemic in educational institutions remained almost the same. The profiles show that for kindergartens, this working schedule did not change during the COVID-lockdown in 2020. For schools, there was a slight change of the peak load that was shifted backwards by an hour in March and April 2020 and forward by an hour in May 2020.

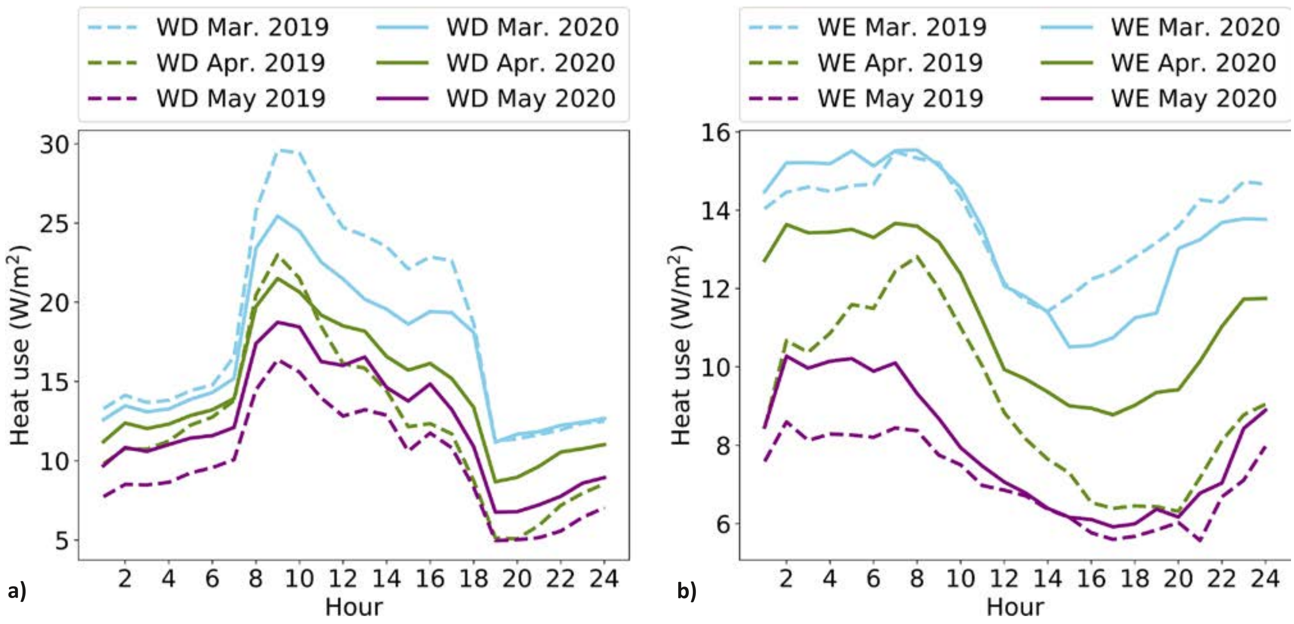

Figure 1. Heat use profiles for kindergartens, where: a) profiles for weekdays, b) profiles for weekends.

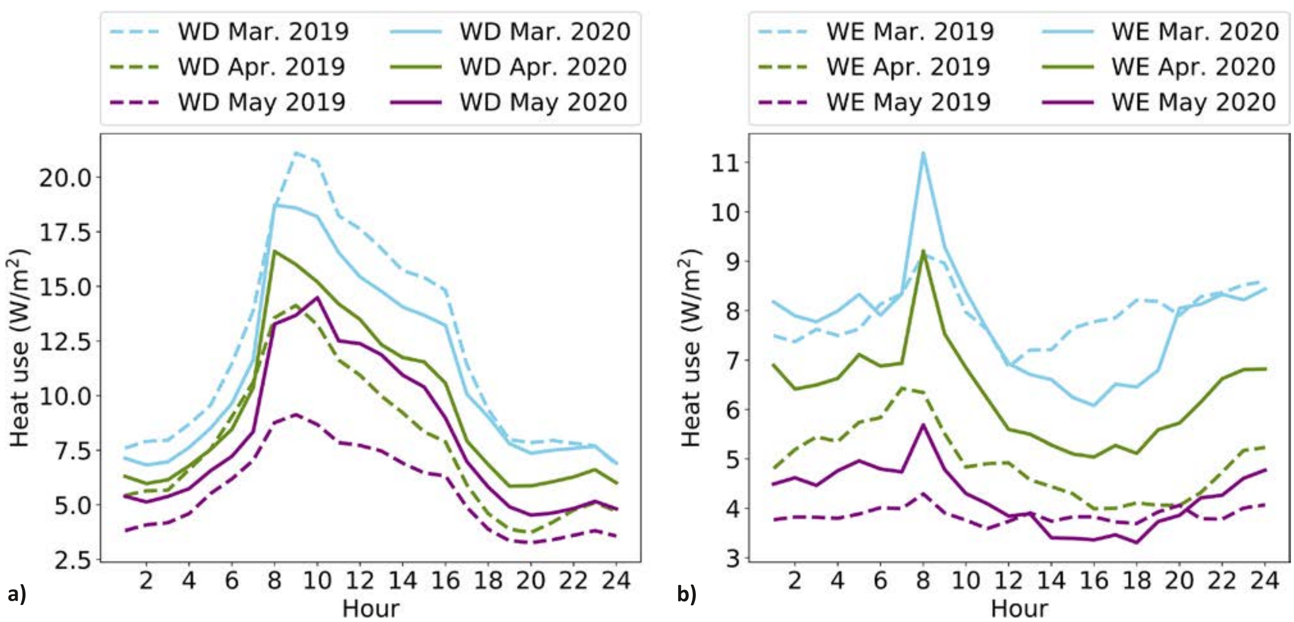

Figure 2. Heat use profiles for schools, where: a) profiles for weekdays, b) profiles for weekends.

Analysis of scenarios for heat use in educational institutions

This part presents the results for the three scenarios for the operation of the heating system in educational institutions during the pandemic. All the scenarios were developed by employing the real statistical data obtained from the schools and kindergartens. **Figure 3** and **Figure 4** show the results for the three scenarios for a typical year for the observed building types. Please note that Scenario 3 was based on a monthly model and is therefore indicating months that have the highest variation of the heat use between the typical cold and warm year. Among these months January, October, and December were the most noticeable ones.

Scenario 3 was created using the monthly average values, and therefore, it was not as accurate as Scenarios 1 and 2 with the hourly values. However, when considering the average monthly values, Scenario 3 would require higher heat use than Scenario 2, because it did not follow the advantageous energy-saving setting of the heating system.

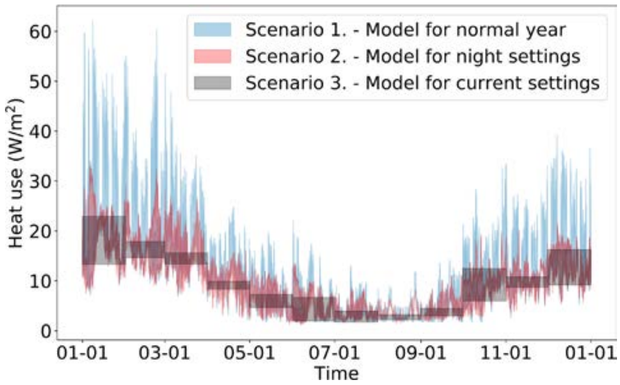

Figure 3. Three scenarios for the heat use in kindergartens.

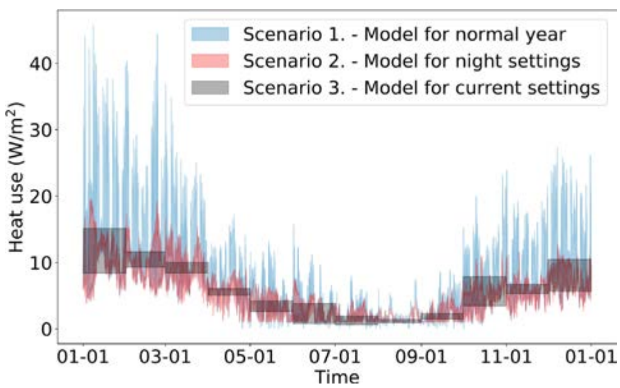

Figure 4. Three scenarios for the heat use in schools.

The above analyses showed that the application of the night setting for the whole day, see Scenario 2, might reduce the daily heat use up to 54% compared to the settings when the heating system was working in the normal conditions, see Scenario 1. For kindergartens, the daily heat use might be reduced up to 261 Wh/m² and for schools – 236 Wh/m². If the specific annual heat use is considered, for kindergartens, it might be reduced for 20.2 kWh/m² and for schools for 17.7 kWh/m². This fact indicates that there is a significant unrealized potential for energy conservation during lockdown. By applying the proper setting of the heating system during a pandemic is expected to reduce energy use and save money.

Conclusions

The COVID-lockdown in the educational institutions in Norway lasted for about two months. The comparison of the heat use profiles in this work was performed only for March, April, and May. This work focused on developing different heat use scenarios during a pandemic. These scenarios were adjusted to the outdoor temperatures of the typical cold and warm meteorological years.

Understanding the changes in energy use triggered by the pandemic is essential for further energy planning, avoiding excessive energy use, and ensuring the proper operation of buildings. This article highlights the issue of the analysis of the heat use profiles and scenario development for schools and kindergartens in Norway.

The methods and outcomes of the study may be applied to similar types of buildings when temporary lower attendance or shutdown will appear. Even though the presented results are valid for Norway, the presented results may be used for the comparison purpose. ■

Acknowledgements

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Please find the list of references in the html version of this article at rehva.eu

Improving HVAC systems energy efficiency with cloud-based control algorithms - application to a shopping mall




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Keywords: HVAC, IoT, Non-residential building, BACS, BMS, Energy efficiency, Indoor Comfort, Retrofit, Cloud, Machine learning

Abstract

The article presents the energy saving achieved thanks to the implementation of a retrofit measure applied to the Building Management System of an Estonian shopping mall. The retrofit project upgraded the HVAC-related BMS control features by exploiting IoT and ICT technologies and cloud-based machine learning algorithms. The application resulted in energy savings up to 45% with respect to heating and ventilation energy use of the whole building.

Introduction

In September 2020 the European Commission proposed to raise the 2030 greenhouse gas emission reduction target to at least 55% compared to 1990, as a stepping stone to the 2050 climate neutrality goal. To achieve this result, the EU should reduce buildings' greenhouse gas emissions by 60% (European Commission, 2020). Considering that at present roughly 97% of the EU's building stock is not energy efficient, and that only approx. 1% of the existing buildings is renovated each year (BPIE, 2020), the implementation of energy efficient retrofit measures for buildings has to accelerate significantly in the next decade.

With "energy efficiency first" and "affordability" among the guiding principles for this much longed Renovation Wave, advanced Building Automation and Control Systems (BACS) can play a major role in scoring the goal, as they can generate energy savings with rather low investment and installation burden (eu.bac, 2019).

The official definition of BACS is given by the European Standard EN 15232-1:2017 (CEN, 2017). The standard provides classification for these systems according to their energy efficiency from class D, not efficient, to class A, high performing, and quantifies the energy saving potential of high efficiency BACS (savings up to 96%). EN 15232-1 also defines the minimum functions that make high efficiency BACS capable of reaching the estimated savings: it requires the Technical Building Systems to be managed based on the monitored building status and predicted needs, optimizing occupants' comfort, maintenance and energy use. As concluded by the EPBD (European Parliament, 2018), these requirements will become mandatory for non-residential buildings with rated output for heating and ventilation of >290 kW, i.e. for the majority of the non-residential building stock, as of January 1st 2025.

The increasing implementation of Internet of Things (IoT) and Information and Communication Technologies (ICT) in buildings, which support an easier availability of a huge amount of building-related data, can hasten the adoption and further increase the impact of BACS for optimizing the energy performance of the building stock, leveraging the great opportunities provided by the current advances in applied Artificial Intelligence (AI) (Brandi et al., 2020).

This article aims at providing evidence of the energy saving potential of high performing, AI-powered BACS for the control of the Heating, Ventilation and Air Conditioning system of a tertiary building. Specifically, the following sections describe the solution implemented and the energy savings achieved in an Estonian shopping mall thanks to the implementation of the Enerbrain System - a cloud-based solution for the control of existing HVAC systems using IoT technologies and Machine Learning algorithms.

Case study

Building

The subject of this article is a three-floor, 30 000 m² shopping mall in Narva (Estonia), hosting over 50 commercial activities including a supermarket, a cinema and bowling facilities. The mall is open to the public from Monday to Sunday from 8:00 to 24:00, with opening hours varying from activity to activity.

Heat is supplied to the building by the municipality district heating, while chilled water is provided by three air cooled chillers. The main components of the HVAC system are five Full Air Handling Units, whose details are listed in **Table 1**.

The HVAC system is controlled by a Building Management System (BMS) and some independent local controllers, set up to maintain the desired indoor environmental conditions, listed below:

- Heating set-point: 22°C (heating season: October–May)
- Cooling set-point: 25°C (cooling season: June–September)
- Relative Humidity acceptability range: 30–50%
- CO_2 level acceptability threshold: 1 000 ppm

The mall's typical annual HVAC-related energy consumptions total to approximately 3 000 MWh of district heating and 1 700 MWh of electricity.

Table 1. *Features of the main HVAC components of the shopping mall.*

Building Area	HVAC component						
	Name	Year of installation	Heating Coil	Cooling coil	Supply Fan	Extract Fan	Other features
			Power [kW]	Power [kW]	Air flow [m³/h]	Air flow [m³/h]	
Shops area	AHU 1	2006	414.2 kW	340 kW	80 280	73 440	_VFD _Recirculation damper _Rotary heat exchanger
Cinema	AHU 2	2006	97 kW	61.4 kW	14 163	12 838	_VFD _Rotary heat exchanger
Shopping Center	AHU 3	2013	589.7 kW	374.5 kW	79 200	79 200	_VFD _Recirculation damper _Rotary heat exchanger
Supermarket	AHU 4	2013	62.56 kW (1) 160.68 kW (2)	118.7 kW	22 320	19 080	_VFD _Recirculation damper _Rotary heat exchanger
Shopping Center	AHU 5	2013	432.9 kW	319.1 kW	75 600	75 600	_VFD _Recirculation damper _Rotary heat exchanger

The goal of the building owner was to improve the energy efficiency of the HVAC system, thus reducing the related operational expenditures, without compromising occupants' comfort and with no major modifications to the existing set-up.

Implemented solution

The solution implemented to meet the stakeholders' expectations is made up of **IoT sensors, metering devices and controllers, and cloud-based adaptive and predictive algorithms**.

To avoid any changes to the installed components or to the existing BMS infrastructure, a "Man in the Middle" approach was proposed, i.e. the provision of a new control system to be positioned between the existing control system (the BMS) and the physical component steered by it.

Specifically, in "Man in the Middle" applications of the Enerbrain solution, IoT controllers are installed to act on selected actuators/controllers of the already in place HVAC system (e.g. to modulate fans speed by controlling VFD (Variable Frequency Drive) - see **Figure 1**. These actions on HVAC components are dictated by commands elaborated by the Enerbrain algorithm, that uses as inputs for its commands the desired settings for the building (e.g. temperature set-points and schedules), a number of external variables gathered in cloud (e.g. weather data) and the real-time conditions (e.g. indoor temperatures, CO_2, fluid temperatures) monitored by newly installed IoT wireless sensors.

Table 2 details the HVAC components and actuators object of the Enerbrain intervention in the shopping mall.

Figure 1. IoT controllers controlling the VFDs of supply and extract fans of AHU 1.

Table 2. *The Enerbrain "Man in the Middle" solution implemented.*

Building Area	HVAC component	Actuators/controllers under Enerbrain control	Indoor parameters monitored by Enerbrain
Shops area	AHU 1	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Cinema	AHU 2	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Shopping Center	AHU 3	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Supermarket	AHU 4	Pre-Heating coil valve Cooling coil valve Post-Heating coil valve	Air temperature Relative Humidity CO_2 concentration
Shopping Center	AHU 5	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration

Note that for each HVAC component under consideration, the signal from/to the existing control system is maintained, and overwritten by Enerbrain control only when the Enerbrain System is active.

Additionally, monitoring devices were installed to provide sound evidence of the energy savings generated thanks to the optimized control of the above listed AHUs' (Air Handling Units) components:

- **electricity monitoring** devices able to measure the power of individual circuits were installed **for the five AHUs (fans electricity use) and for the three chillers;**
- daily readings of the **building District Heating meter** were gathered by installing a remotized digital camera.

Energy saving

Assessment method

To offer accurate projections of the energy savings achievable thanks to the optimized control of the five Air Handling Units, **Proof of Concept (POC) periods** were scheduled before the official activation of the new advanced control system. The winter POC period lasted from October 2019 to February 2020, the summer POC from May to June 2020.

The two POCs took place in "ON/OFF" mode, alternating weeks OFF to weeks ON. Indeed, thanks to the Enerbrain "Man in the Middle" technical approach, the new system can be easily activated (Enerbrain ON) and deactivated (Enerbrain OFF) via a web application. In OFF periods the HVAC system was managed according to the existing control logics (e.g. by the BMS commands); in ON periods, the HVAC system was managed according to Enerbrain control logics (i.e. by the adaptive and predictive algorithms).

By applying the proper calculation method, the energy consumption in OFF periods can be compared to the energy consumption in ON periods, thus providing reliable results of the energy saving potential.

The savings calculation method used in this article is compliant with the guidelines given by the International Performance Measurement and Verification Protocol (IPMVP). The method involves the identification of a **calculation-based energy model** that describes the normal behaviour of a building's energy consumption, which can then be used as a **baseline** for comparison with the consumption measured after the implementation of an Energy Conservation Measure - in our case the installation of an advanced BACS. The **savings**, or rather, the "avoided consumption", is determined by the difference between the post-intervention measured consumption and the baseline energy model adjusted according to the variables.

Results and discussion

Energy

Figure 2, 3 and 4 display the recorded energy consumptions in Enerbrain OFF and ON periods for the whole building heating energy use, for the five AHUs and for the three chillers respectively.

In line with IPMVP prescriptions, the following approaches were applied to build the baseline energy models:

- **District Heating (DH) energy use**: linear regression equation using HDD_{20} as independent variable. The regression model is built by plotting the daily DH energy use monitored in days OFF with the corresponding $HDD_{20,}$ derived from the nearest weather station (Weather station ID 26058, Narva. Data source: www.degreedays.net). **Figure 5** displays the plotted data and the resulting linear regression

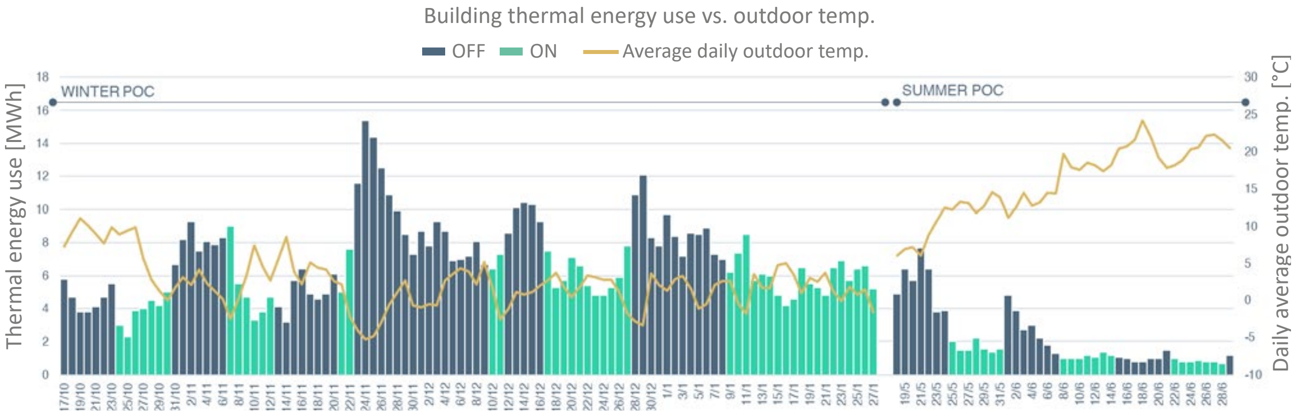

Figure 2. Recorded daily District Heating energy use of the whole building during Winter and Summer POCs.

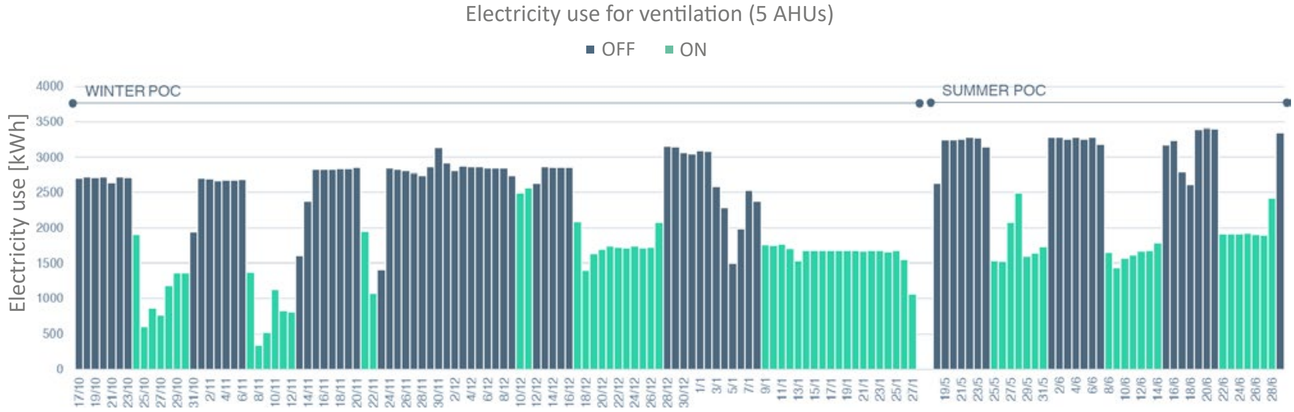

Figure 3. Recorded daily electricity use of the AHUs during Winter and Summer POCs.

equation describing the baseline District Heating energy use, i.e. the energy use without Enerbrain control in place.

- **AHUs energy use:** daily average consumption. No normalization factor applied because of the constant energy use profile detected.

Chiller's energy use: linear regression equation using outdoor temperature as independent variable. The regression line is built by plotting the daily electricity use of chillers monitored in days OFF with the corresponding daily average temperature, derived from the nearest weather station.

For each energy use, the energy savings were calculated by comparing baseline energy use calculated for the days of Enerbrain ON with the actual energy use monitored in those days. The resulting figures are summarized in **Table 3**.

Table 3. *Calculated energy savings during Winter and Summer POCs.*

Energy vector	Energy use	Energy savings	
		Winter POC	Summer POC
District Heating	Heating	29%	45%
Electricity	Ventilation (5 AHUs)	45%	43%
	Cooling	-	6%

These results are in line with the energy efficiency projections provided in EN 15232-1:2017, which estimates that in wholesale buildings a high performing BACS can improve the overall energy performance of up to 40% with respect to a standard BACS.

Comfort

The installation of IoT environmental sensors in all the areas served by the controlled AHUs allowed

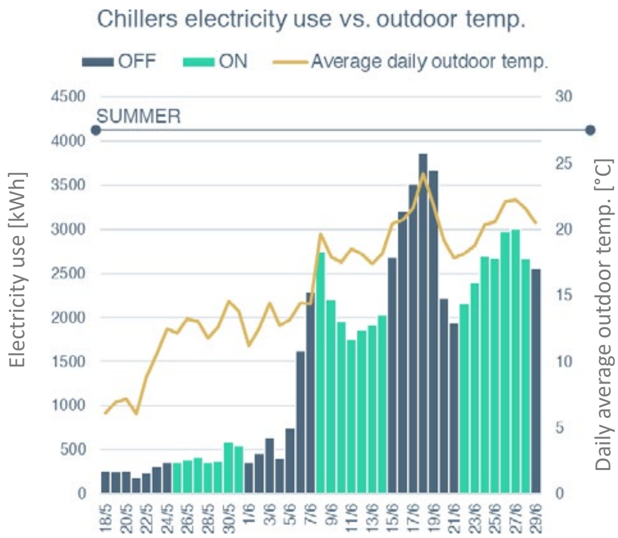

Figure 4. Recorded daily electricity use of the chillers during the Summer POC.

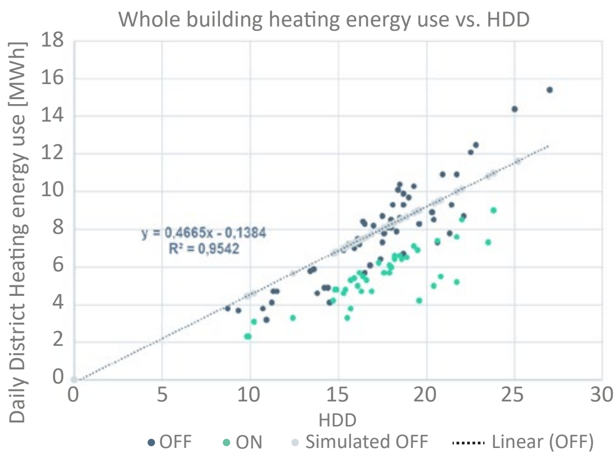

Figure 5. Daily DH energy use versus HDD, and linear regression equation resulting from the plotted data in OFF days.

building managers to verify if the achieved energy savings jeopardised the indoor comfort conditions. **Figure 6**, by displaying the hourly average temperatures recorded for each area for the whole POC duration, gives evidence that **similar comfort conditions were maintained in OFF and ON periods**.

Conclusion

This article describes the implementation of a solution to upgrade the BMS control features in a shopping mall, making it possible to have the features of an advanced BACS. Indeed, by exploiting IoT and ICT technologies and AI, the proposed solution offers the opportunity to continuously analyse the real-time conditions of the HVAC system and to modify control settings accordingly.

This retrofit measure, implemented to steer only selected components of the HVAC system via a non-invasive installation, resulted in energy savings up to 45% with respect to heating and ventilation energy use of the whole building, with no consequences on the indoor environmental quality levels.

Such results provide further evidence of the crucial role of building controls systems in supporting the transition toward an energy efficient building stock, able to meet both the long term EU carbon neutrality expectations as well as the short term building owners' financial KPIs. ■

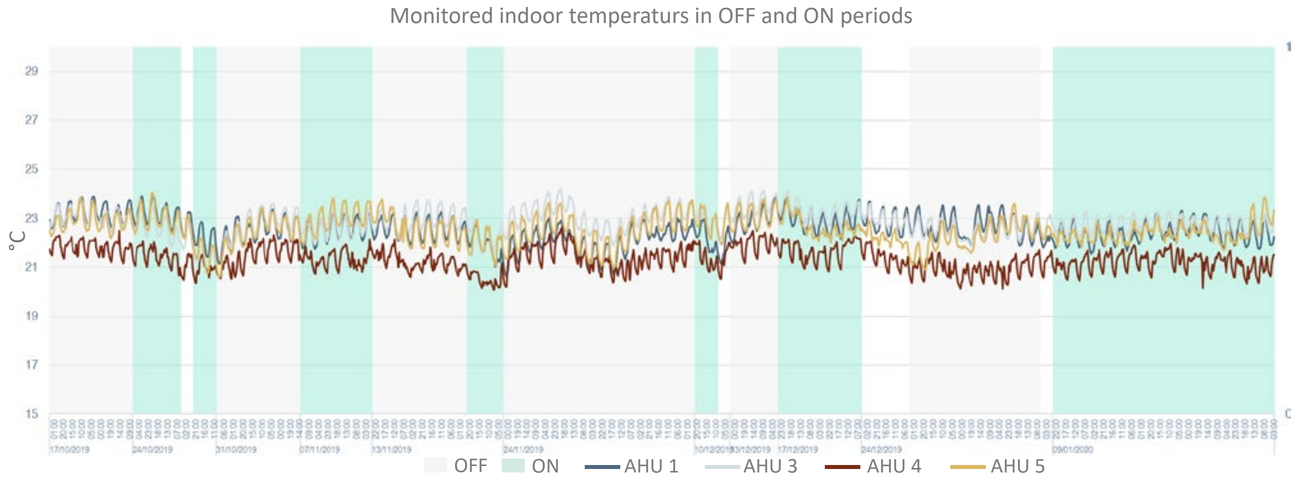

Figure 6. Hourly average indoor temperatures monitored in the areas served by the controlled AHUs.

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51st International HVAC&R Congress and Exhibition

In December 2020, Serbian REHVA Member Association, KGH organized its 51st International HVAC&R Congress and Exhibition. This online edition brought together professionals from the sector to network and share knowledge. The 52nd International HVAC&R Congress and Exhibition are to be held on December 1–3, 2021.

What an event it was...

There has never been longer correspondence, never more phone calls – without a single encounter, however. Even though everything seemed incomplete and hollow without the excitement of entering the Sava centre, exchanging greetings with our colleagues and gifts at exhibition stands, the ceremonial dinner, or putting our phones on silent mode waiting for the lecturer to address us, the 51st International Congress and Exhibition on HVAC managed to keep its position as the leading scientific and professional conference in this part of Europe.

The program comprised 59 scientific and professional papers of domestic and international authors, 18 presentations of the major sponsors, and 20 webinars and panels. In terms of topics, it was broader than ever before, which could be especially observed at webinars where notable contributions were provided by colleagues from magazine Grenef, Energy portal, and e-magazine NOVA. Among others, Professor Zoran Radojičić PhD, Mayor of Belgrade, took floor at the panel on district heating and reduction of pollution in Serbian towns.

All contributions, presentations, webinars, and stands are available at the web site of the Congress (https://bit.ly/2Hl2KTW) and on our YouTube channel (https://bit.ly/3hK4gQd), where they will be available for watching upon request.

Thanks to the sponsors, the first virtual International Congress and Exhibition on HVAC was held without a conference fee, which was appreciated by more than 1 200 registered participants, several hundred followers on social networks, while more than 1 300 presentations were downloaded from the web page of the program (https://goo.gl/c4ED7B).

Only change is continuous – that is true. We need to adapt fast and learn to use simulations, avatars, 3D technology, video-conferencing, PDF brochures, meetings through Zoom or Teams… although that will never be the genuine article. We bear witness to the fact that our children miss school! It was not so long ago when we would not miss it even at the end of a long holiday.

Despite essential differences, trade, education, healthcare, religion, travels, entertainment all implied gathering of employees, clients, students, patients, believers, travellers, and viewers. We were dependent on centralization.

Now everything is different

Even a huge tree-day conference may be prepared and implemented without a single encounter – in a decentralized manner. The archetypal need for gathering needs to retreat facing the need to preserve lives. Those who managed to suppress the need for gathering and adapt their business operations to the new conditions stands a chance of continuing development. Those who did not are doomed to failure.

On the other hand, the virtual congress on HVAC was organized with huge savings: without excessive man-hours for preparation of participation, print materials, overtime hours for hosts at stands, gifts, bills for Sava Centre heating, while the stands were virtual. The nature is grateful to us that not a single truck was moved from the beginning of preparations till the end of the calendar year.

Continuing the tradition initiated in 1908, when the Kingdom of Serbia was one of the nine states which established the Paris-based International institute for cooling, members of HVAC Association act as equal parts of scientific and professional commissions of European and global scientific and professional organizations such as REHVA, IIR, and ASHRAE. Through the competent Ministry, UN Environment selected

HVAC Association as the partner in implementation of Montreal Protocol in Serbia.

SMEITS and its associations are led by visionaries: our colleagues who look at the future. Have a look at the texts published in KGH magazine, which will celebrate half a century of existence next year. Years before the emergence of the energy crisis, the authors of this domestic journal had been warning against dangers of uncontrolled consumption of fossil fuels and proposing sustainable solutions. Back in 1984, Budva bay got a heat pump, while more than 2 000 m² of solar energy receivers were covering the car park of the Slovenska beach. The first plant of the kind in this part of Europe still operates flawlessly.

Donations of equipment and whole laboratories to schools and faculties in Serbia are countless, because engineers – members of SMEITS-affiliated associations – do not forget that they started their careers while sitting in the desks of these institutions.

We hope that the following, 52nd international Congress and Exhibition on HVAC will be a real, live event.

We wish you welcome.

More information: http://kgh-kongres.rs/index.php/en/

BRANISLAV TODOROVIĆ, President of KGH

In memoriam - Liviu Dumitrescu

REHVA is very sad to announce that Prof. Dr. Eng. D.H.C. Liviu Dumitrescu passed away in March 2021. President of the REHVA member AIIR from 1990 to 2016, a REHVA fellow since 2011 and REHVA Professional Award in Science recipient in 2012.

Liviu DUMITRESCU was President of "Association of Installations Engineers from Romania-AIIR". In 1956 graduated Bachelor of Science of The Bucharest Civil Engineering Institute the Buildings Services Faculty. In 1976 graduated Master of Science. From 1948 onwards he played an important role on building services at governmental and institutional level. To mention some of his achievements: 1979 Founder of the "Installations for Buildings" Magazine, 1979-1983 Chief Editor of the "Installations for Buildings" Magazine, 1979-1989 Vice-president and president of the Commission for the implementing of solar energy in Romania, 1983-1989 President of the Installation Department of the Building Section of the National Council of the Engineers and Technicians, 1990 Founder Member and president of "Romanian Association of Building Services Engineers - AIIR", 1993 Founding Member and Scientific Editor of the "INSTALATORUL" magazine, 1990 President of the Technical Committee – CT10 Technical Regulations for Installations and Additional Equipment, 1996 President of the Examination Commission concerning the graduation as specialists and experts for sanitary, gas and heating installations fields, 2003 President of the Ministerial Commission for Energy Auditors Certification.

REHVA and its members remember him not only for his professionalism but most importantly for his kind heart and friendliness.

We offer our condolences to family, colleagues and friends. ■

Member Associations meeting with REHVA

The continuation of a great process

REHVA started the year 2021 by continuing the rounds of discussions with its Member Associations. Those ongoing meetings are the perfect place for REHVA to exchange ideas and opinions with its Members and to pursue a stronger collaboration for the future. This process is led by REHVA Board Members Ivo Martinac, Kemal Gani Bayraktar and Catalin Lungu.

It is an opportunity for REHVA to identify, together with its Member Association, the key elements of their collaboration that have been successful until now as well as heading towards a shared future with serenity and confidence.

Multiple exchanges for a common goal

The exchanges started with Poland's PZITS and Serbia's KGH meetings before 2021. The first meetings of 2021 took place with TTMD from Turkey on the 8th and SWEDVAC from Sweden on the 21st of January.

AICVF

February meetings started when REHVA Board members met with France's association, AICVF on Monday 8 February.

Present in the AICVF meeting was Francis Allard, REHVA Past President from 2008 to 2011 as well as the full AICVF International Committee.

AICVF

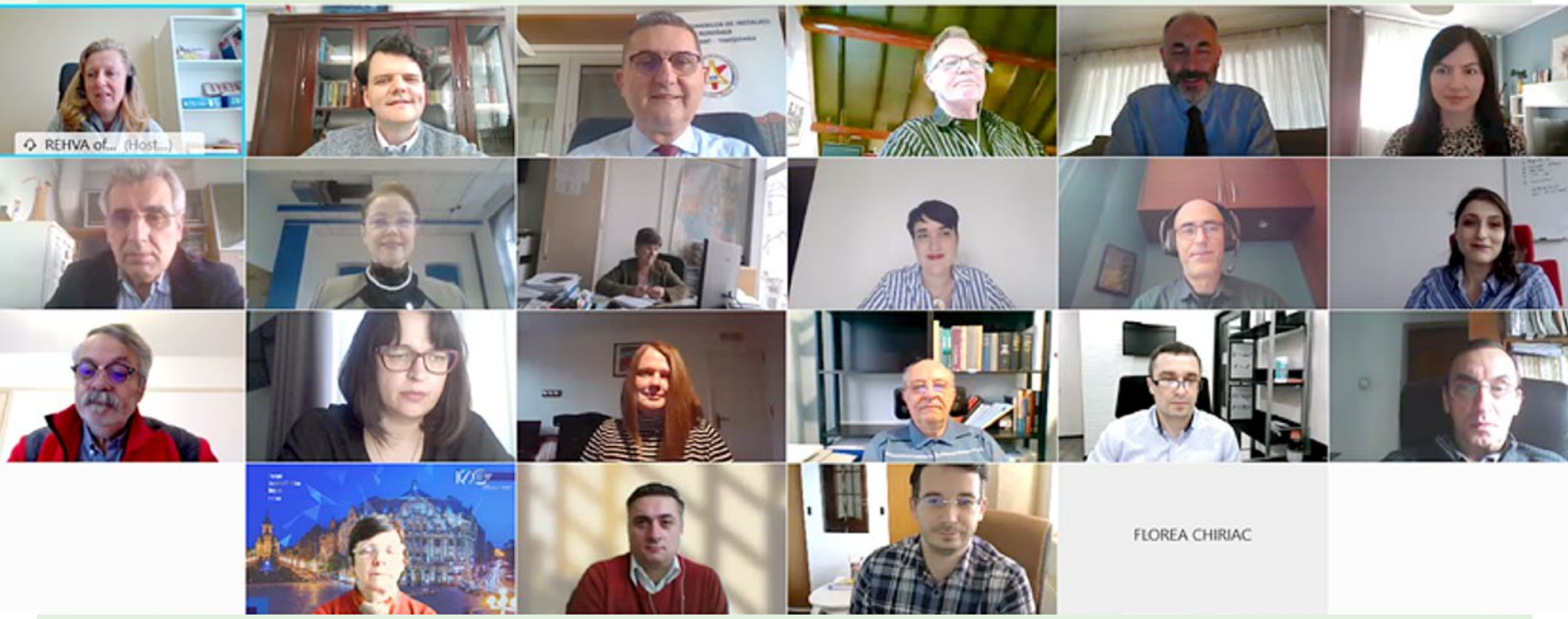
AiCARR

On Thursday February 11th it was Italy's AiCARR meeting. The AiCARR meeting participants included Stefano P. Corgnati, REHVA Past President from 2016 until 2019.

AIIR

The 18th of February was the date set for the meeting with AIIR, Romanian Member Association. REHVA is glad to have met such a participation number to this meeting where no less than 25 attendees were present including AIIR President and long term REHVA Past Board Member (2007-2016), Ioan Silviu Dobosi.

AiCARR



AIIR

STP

REHVA met with STP its Member Association from Czech Republic on the 19th of February. REHVA representatives had a deep discussion with STP representatives, among which was Karel Kabele, REHVA Past President from 2013 to 2016.

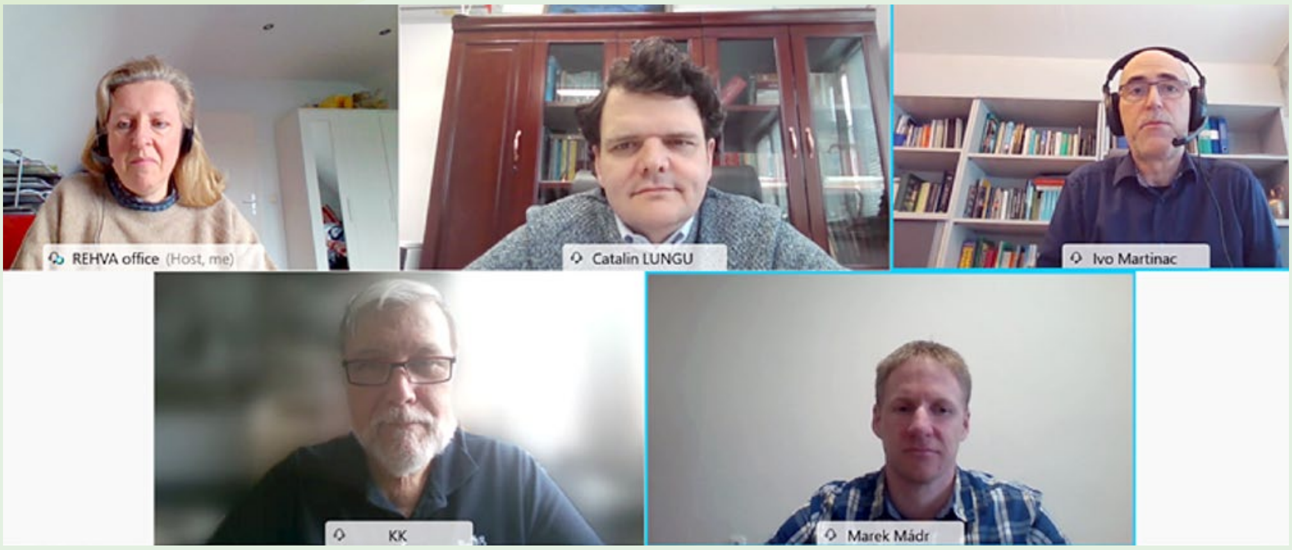
Atecyr

On the 26th of February, REHVA representatives had the pleasure to meet with Spain's Member Association, ATECYR.

The fruitful discussion led to a improved understanding of common goals and objectives between ATECYR and REHVA as well as reaffirming the intention of cooperation between the two organisations.

Next steps

Throughout the year, similar meetings will continue to take place with REHVA Member Associations to discuss, exchange, share and strengthen the collaboration between organisations. ■



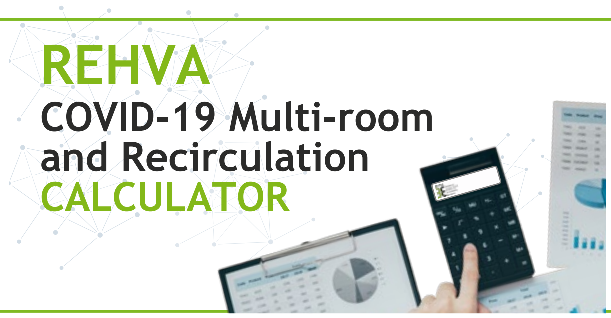
STP

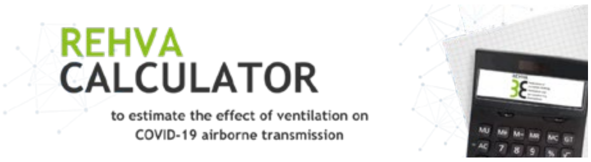
Atecyr

REHVA COVID-19 Multi-room and Recirculation Calculator

for HVAC systems operational strategy assessment for reducing infection risk in buildings

In March 2021, Professor Livio Mazzarella, in collaboration with the COVID Task Force, released the "REHVA COVID-19 Multi-room and Recirculation Calculator for HVAC systems operational strategy assessment for reducing infection risk in buildings".





This tool is recommended for specialists with a minimum understanding of ventilation and air distribution. It should be used by experts after reading the related REHVA COVID Guidance document, Technical Manual and User Guide regarding the function, limitations and use of the tool or after enrolling to the REHVA COVID-19 course.

Please, note that the tool was developed before the detection of the latest, more contagious SARS-CoV-2 variants (in the UK, South-Africa, Brazil etc.), and any subsequent research on the topic has not been considered for its development and update. Therefore, its application and calculation results should be interpreted considering this limitation.

This new tool comes after the first REHVA COVID calculator released in December 2020. The Ventilation calculation tool produced by Professor Jarek Kurnitski and the REHVA COVID Task Force that allows experts and specialists with the necessary knowledge to estimate the effect of ventilation on COVID-19 airborne transmission. ■

New WHO guideline for ventilation published in March 2021

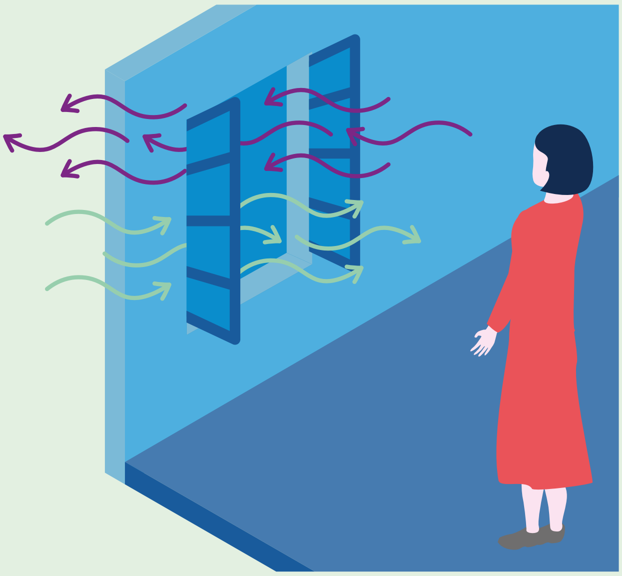
Roadmap to improve and ensure good indoor ventilation in the context of COVID-19

The risk of getting COVID-19 is higher in crowded and inadequately ventilated spaces where infected people spend long periods of time together in close proximity. These environments are where the virus appears to spread by respiratory droplets or aerosols more efficiently, so taking precautions is even more important.

Understanding and controlling building ventilation can improve the quality of the air we breathe and reduce the risk of indoor health concerns including prevent the virus that causes COVID-19 from spreading indoors.

The roadmap was developed after conducting a scoping review of the available literature and an assessment of the available guidance documents from the major internationally recognized authorities on building ventilation. The available evidence and guidance were retrieved, collated and assessed for any discrepancies by international expert members of the World Health Organization (WHO) Environment and Engineering Control Expert Advisory Panel (ECAP) for COVID-19.

The development process included two expert consultation sessions via virtual meetings, and two rounds of written submissions, to gather technical contributions and to ensure consensus building for the adaptation of recommendations. This process considered infection prevention and control (IPC) objectives, resource implications, values and preferences, ethics, and research gaps within the roadmap development. This process resulted in a roadmap on how to improve ventilation in indoor spaces.



The roadmap is divided into three settings – health care, nonresidential and residential spaces – and takes into account different ventilation systems (mechanical or natural). The roadmap is aimed at health care facility managers, building managers, as well as those members of the general public who are providing home care or home quarantine.

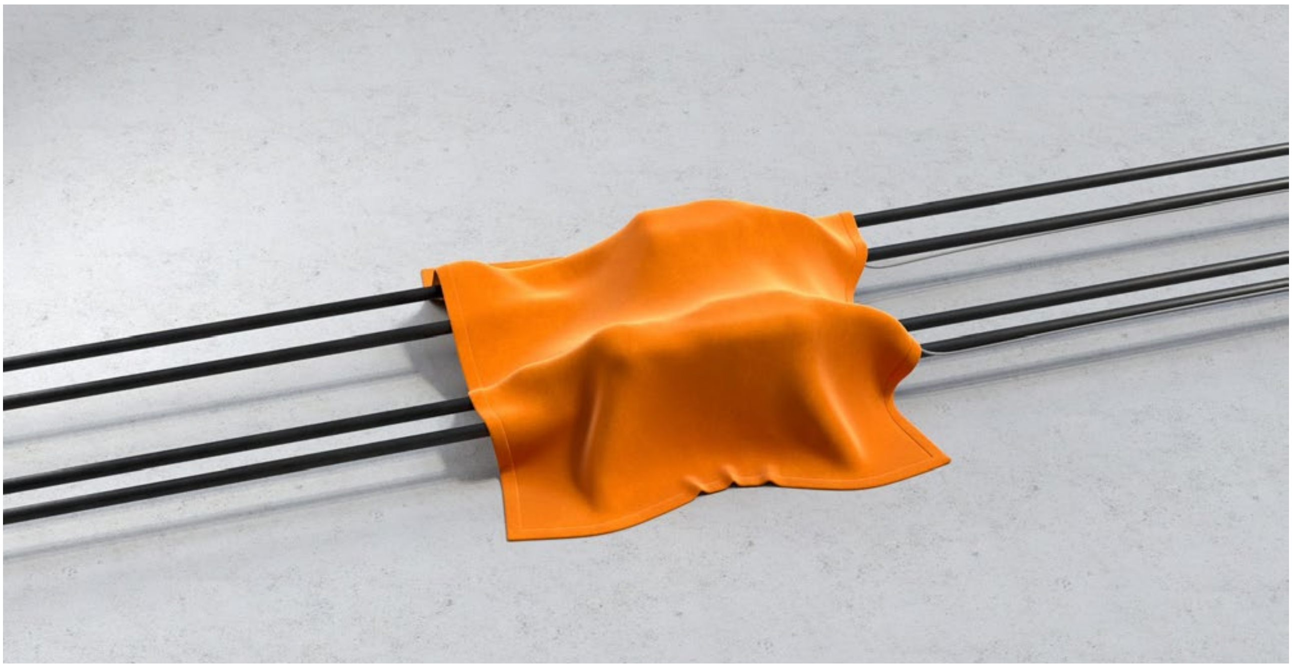
This 25-page step by step flowchart is available from WHO website: https://www.who.int/publications/i/item/9789240021280

Several experts from REHVA member societies were member of the expert panel which assisted in this work.

OLLI SEPPÄNEN

Belimo – Rethink thermal energy management

Belimo presents the new age of integrated thermal energy management to bring together what belongs together – one device for consulting engineers, system integrators, contractors and many more.



The growing demand for energy confronts all of us with huge challenges that can only be solved with new, innovative products. We present the future of integrated thermal energy management. Meet the Belimo experts who will introduce this cutting-edge device, share their insights and domain expertise in this exciting transition.

We'd love for you to join us online, 10. June, 2021, for this groundbreaking change.

Sign-up now for free, on belimo.com/change and be part of this exciting transition.

More information: www.belimo.eu ■

The Belimo Group is a leading global manufacturer of innovative electrical actuator, valve, and sensor solutions for heating, ventilation, and air-conditioning systems. The Company reported sales of CHF 661 million in 2020 and has around 1,900 employees. Information about the Company and its products is available on the internet at www.belimo.com.

The shares of BELIMO Holding AG have been traded on the SIX Swiss Exchange since 1995 (BEAN).

REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

MEMBERS

ATIC vzw–asbl – Belgium www.atic.be	STP – Czech Republic www.stpcr.cz	DANVAK – Denmark www.danvak.dk	EKVU – Estonia www.ekvy.ee	FINVAC – Finland www.finvac.org
AICVF – France www.aicvf.org	VDI–e.V. – Germany www.vdi.de	ÉTÉ – Hungary www.eptud.org	MMK – Hungary www.mmk.hu	AiCARR – Italy www.aicarr.org
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ABOK – Russia www.abok.ru	KGH c/o SMEITS – Serbia www.smeits.rs	SSTP – Slovakia www.sstp.sk	SITHOK – Slovenia https://web.fs.uni-lj.si/sithok/	ATECYR – Spain www.atecyr.org
SWEDVAC – Sweden www.energi-miljo.se	DIE PLANER – Switzerland www.die-planer.ch	TTMD – Turkey www.ttmd.org.tr	CIBSE – United Kingdom www.cibse.org	

Network of 26 European HVAC Associations joining 120 000 professionals

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REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

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Leaders in Building Services

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www.epeeglobal.org

Daikin Europe – Belgium
www.daikin.eu

Velux – Denmark
www.velux.com

Uponor – Finland
www.uponor.com

Halton – Finland
www.halton.com

Granlund – Finland
www.granlund.fi

LG Electronics – France
www.lgeaircon.com

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www.eurovent-certification.com

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www.viega.com

Rhoss – Italy
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www.royalhaskoningdhv.com

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www.systemair.com

Swegon – Sweden
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Lindab – Sweden
www.lindab.com

Fläkt Group – Sweden
www.flaktgroup.com

Camfil – Sweden
www.camfil.com

Belimo Automation – Switzerland
www.belimo.com

Eneko – Turkey
www.eneko.com.tr

Friterm Termik Cihazlar Sanayi ve Ticaret – Turkey
www.friterm.com

REHVA Associate Organisations:

Enerbrain srl – Italia
www.enerbrain.com

Enviromech – United Kingdom
www.enviromech.co.uk

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Send information of your event to Ms Nicoll Marucciova nm@rehva.eu

Exhibitions, Conferences and Seminars in 2021

Conferences and seminars 2021*

12 – 19 Apr 2021	REHVA Annual Meeting 2021	**Online**	https://www.rehva.eu/events/details/rehva – annual – meeting – 2021
20 – 21 Apr 2021	Cold Climate HVAC & Energy 2021	**Online**	https://hvac2021.org/
03 May – 05 May 2021	40th Euroheat & Power Congress	Vilnius, Lithuania & **Online**	https://www.ehpcongress.org/
12 – 14 May 2021	ISH China & CIHE	Beijing, China	https://ishc – cihe.hk.messefrankfurt.com/beijing/en.html
11 – 12 May 2021	Climamed 2021	**Online**	http://www.climamed.org/en/
31 May – 04 Jun 2021	EU Green Week 2021	Lahti, Finland & **Online**	https://www.eugreenweek.eu/
21 – 23 Jun 2021	Healthy Buildings Europe 2021	**Online**	https://www.hb2021 – europe.org/
21 Jun – 25 Jun 2021	World Sustainable Energy Days 2021	Wels, Austria & Online	https://www.wsed.at/
15 – 18 August 2021	Ventilation 2021	Toronto, Canada	https://www.ashrae.org/conferences/topical – conferences/ventilation – 2021
25 Aug – 27 Aug 2021	8th International Buildings Physics Conference	Copenhagen, Denmark	https://www.ibpc2021.org/
31 Aug – 2 Sep 2021	ISH Shanghai & CIHE	Shanghai, China	https://ishs – cihe.hk.messefrankfurt.com/shanghai/en.html
03 Sep – 04 Sep 2021	52nd AiCARR International Conference 2021	Vicenza, Italy	http://www.aicarr.org/Pages/Convegni/52%20CONV%20INTERNAZIONALE/presentaz_call_for_paper_ing.aspx
13 – 15 Sep 2021	IAQ 2020	Athens, Greece	https://www.ashrae.org/conferences/topical – conferences/indoor – environmental – quality – performance – approaches
22 Sep – 24 Sep 2021	Aquatherm Tashkent 2021	Tashkent, Uzbekistan	https://www.aquatherm – tashkent.uz/en/
29 Sept – 2 Oct 2021	ISK Sodex 2021	Istanbul, Turkey	http://www.sodex.com.tr/
29 Sep 2021	Danvak Dagen 2021	København, Denmark	https://danvak.dk/produkt/danvak – dagen – 2021/

Conferences and seminars 2022

15 – 18 May 2022	CLIMA 2022	Rotterdam, the Netherlands	https://clima2022.nl/

* Due to the COVID19 circumstances, the dates of events might change. Please follow the event's official website.

REHVA Annual Meeting 2021

REHVA Annual Meeting 2021 - Schedule

	Monday 12 April	Tuesday 13 April	Wednesday 14 April	Thursday 15 April		Friday 16 April	Monday 19 April
09:00			09:00-10:00 Awards Committee Meeting (Closed meeting)				
09:30						09:30-12:30 Board Meeting (Closed meeting)	
10:00				10:00-12:00 COP Meeting (Closed meeting)			10:00-13:00 General Assembly (for delegates of REHVA Member Associations)
10:30							
11:00					11:00-12:00 Past Presidents Meeting (Closed meeting)		
11:30							
12:00							
12:30							
13:00							
13:30							
14:00	14:00-15:30 Education and Training Committee Meeting	14:00-16:00 Supporters Committee & Expert Talk	14:00-16:30 Publishing and Marketing Committee Meeting and REHVA Journal Editorial Board Meeting	14:00-16:30 Technology and Research Committee Meeting		14:00-16:00 Plenary meeting (Closed meeting for Presidents, Directors and delegates of REHVA Member Associations)	
14:30							
15:00							
15:30							
16:00							
16:30							
17:00							

The annual meeting schedule and registration form are available on the REHVA website:
https://www.rehva.eu/events/details/rehva-annual-meeting-2021

REHVA is pleased to announce its REHVA Annual Meeting hosted online on 12–19 April 2021. Due to the Covid-19 pandemic, the REHVA Board of Directors decided to organise the REHVA Annual Meeting 2021 from April 12th till April 19th using the WebEx conference tool.

REHVA Standing Committee Meetings

The Annual Meeting will begin on Monday 12 April with the ETC Meeting. On Thursday 15 April, the joint PMC and REHVA Journal Editorial Board Meeting will be held in the morning followed by the TRC meeting in the afternoon.

REHVA Supporters Committee Meeting

Tuesday 13 April will be dedicated to REHVA Supporters during the Supporters Committee Meeting. A hybrid event will take place for the REHVA Supporters. During this years' Supporters Committee will host an 'Expert Talk: Circular Economy in the HVAC Industry', where we will have experts from the industry and policy present the context and importance of the principles of circularity within the HVAC industry. At the end of the presentations, all supporters attending will have the opportunity to ask questions to the experts.

During the last half hour of the event the remaining points on the agenda of the Supporters Committee will be addressed.

REHVA Plenary Meeting

The Plenary Meeting will take place on Friday 16 April in the early afternoon between Presidents, Directors, and delegates of REHVA Member Associations.

REHVA General Assembly

To close the 2021 Annual Meeting, on Monday 19 April, the General Assembly will be held for delegates of REHVA Member Associations.

For any questions or additional information, please contact info@rehva.eu ■

The World Sustainable Energy Days 2021

Climate neutrality ↔ Economic recovery

A special edition of the World Sustainable Energy Days (WSED), one of Europe's largest annual conferences on climate neutrality, takes place from 21–25 June 2021 in Wels/Austria and online.

Europe has the ambitious goal of becoming the first climate neutral continent by 2050. The current economic challenges and related investment programmes are an opportunity to accelerate decarbonisation and to create a fairer society and a more competitive economy. It is crucial that the investment decisions made in the next few years put us on the path to climate neutrality!

In 2021, the conference - which attracts over 600 participants from over 60 countries each year - shows how we can make a green recovery happen in practice and how the energy transition can contribute as an investment engine to this deep transformation.

The WSED will be held as a hybrid event: you can join in Wels/Austria (conference days 22–24 June) or connect digitally from anywhere in the world!

Upper Austria – a leader in the clean energy transition

The WSED are organised by the *OÖ Energiesparverband*, the energy agency of Upper Austria. Upper Austria, one of Austria's 9 regions, is well on its way in the clean energy transition. Through significant increases in energy efficiency and renewables, greenhouse gas emissions from buildings were reduced by 32% in 10 years. 75% of the electricity, 60% of all space heating and 31% of the primary energy already come from renewables. Over 2 billion Euro are invested each year in the energy transition.

Mark your calendar for 21-25 June 2021 and join REHVA and the worldwide energy efficiency community at the World Sustainable Energy Days!

World Sustainable Energy Days 2021

21 - 25 June 2021, Wels/Austria

Conferences and events:

- European Energy Efficiency Conference
- European Pellet Conference
- Young Energy Researchers Conference
- Energy Efficiency Policy Conference
- Industrial Energy Efficiency Conference