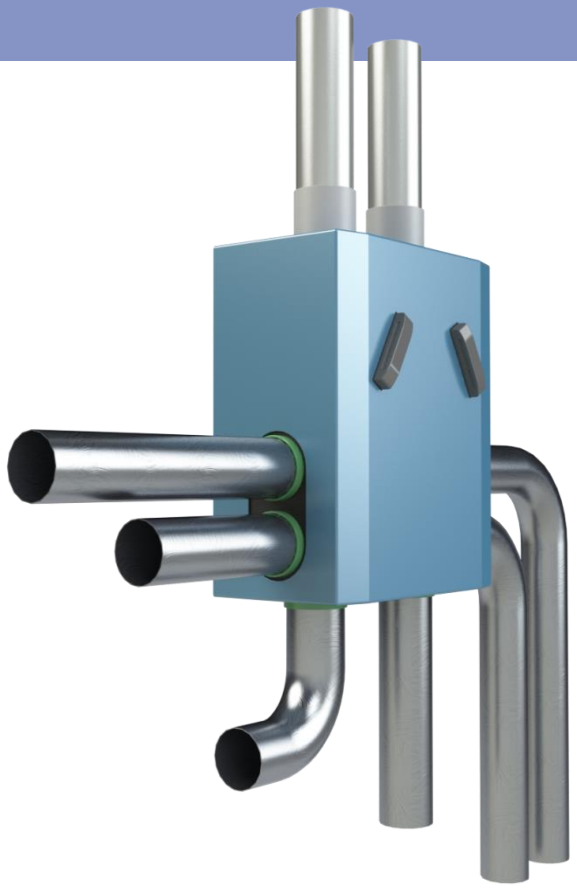
European Commission

Ventilation Units

Ecodesign and Energy Labelling



Review Study

Phase 1.1 and phase 1.2
Technical Analysis and update
Preparatory Studies

Draft Interim Report

TASK 4. Technologies

Review study on Regulations EU 1253/2014 (Ecodesign requirements for ventilation units) and EU 1254/2014 (energy labelling of residential ventilation units)

Prepared by
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The information and views set out in this study are those of the author(s) and do not necessarily reflect the official opinion of the European Commission.

Grow

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Executive summary Technologies

This is the draft Task 4 report of the preparatory review study on the Ecodesign Commission Regulation (EU) No. 1253/2014 and Energy Label Commission Delegated Regulation (EU) No. 1254/2014 for Ventilation Units.

This Task 4 report deals with the new technological developments that are considered relevant for the review of the current Ventilation Unit Regulations.
Technologies that were already discussed in the previous LOT 10 (2009) and LOT6 (2012) studies (i.e. fan types, fan efficiency, motor controls (VSD) and motor types) are not repeated here.

Since smart ventilation control is considered one of the key technologies with which the energy consumption for ventilation can be further reduced, while simultaneously improving the ventilation performance, Chapter 1 covers the Best Available Technology (BAT) for occupancy- and IAQ-sensors and for monitoring devices. Not all sensors are equally suited for all room types however, which requires that their suitability for the different room types is further discussed.
Local demand-controlled ventilation cannot be achieved by only using the right sensors in the right locations. It also requires the technical ability of the ventilation system to vary the airflow rates per individual room. Chapter 2 therefore highlights the technical developments for ducted systems in this area and describes the best available technology regarding flowrate control per individual room. In view of a possible inclusion of ventilation units with an electric power consumption below 30 watts and their intrinsic characteristic of enabling local flowrate control, non-ducted local UVUs and BVUs with power consumption below 30 watts per airstream and their best available technologies are discussed in the last paragraph of this chapter 2.
Chapter 3 covers the non-ducted alternating BVUs, which is a relatively new product group in the ventilation sector gaining increased attention from several member states. Several scientific studies have recently been performed which facilitates a proper evaluating of this product. The chapter describes the best available technology and discusses the research that has been done.
Because it is proposed to include humidity recovery (through enthalpy heat exchangers) in the revised Regulations (see also Task 3 report section 1.7), the product types and their humidity recovery technologies are further discussed in Chapter 4. Apart from rotary wheels, enthalpy plate heat exchangers and regenerative heat exchangers with alternating airflows are further discussed. The fact that some of the materials used for regenerative heat exchangers are also used in the field of air cleaning (abatement of gaseous pollutants) raises the question regarding the risk of a possible transfer of gaseous pollutants.
In Chapter 5 the topics on filter technology are further addressed. Depending on the required indoor air quality and the available outdoor air quality, filtration may be needed. The additional pressure drop and related energy consumption can be further reduced by developments in filter technology. The chapter also addresses the topic of indoor air cleaning and recirculation, which can potentially reduce the amount of air that needs to be replaced by outdoor air, thus reducing the heating/cooling energy that is lost due to this air exchange.

Introduction

This draft Task 4 report covers the current status of the work that has been done for Phase 1.1 and phase 1.2 of the Review Study, comprising the Technical Analysis and the update of the Preparatory studies. According to the Terms of Reference (T.o.R.) Phase 1.1 shall assess the items listed in Article 8 of Regulation 1253/2014 (Ecodesign of Ventilation Units) and Article 7 of Regulation 1254/2014 (Energy Labelling of Residential Ventilation Units), being:

a) the need to set requirements on air leakage rates in the light of technological progress
b) the possible extension of the scope of Regulation 1253/2014 to cover unidirectional units with an electric power input of less than 30 W, and bidirectional units, with a total electric power input for the fans of less than 30 W per air stream
c) the verification tolerances set out in Annex VI to Regulation 1253/2014
d) the appropriateness of taking into account the effects of low-energy consuming filters on the energy efficiency
e) the need to set a further tier with tightened Ecodesign requirements
f) the possible inclusion of other ventilation units, notably of non-residential units and of units with a total electric power input smaller than 30 W under Regulation 1254/2014,
g) the specific energy consumption calculation and classes for demand controlled unidirectional and bidirectional ventilation unit (in this respect, it would be very relevant to provide, if possible, an estimate of the efficiency and energy labelling levels of the installed base of residential and non-residential ventilation units in the European Union (EU).

According to the Terms of Reference the following additional items need to be analysed:

h) the influence of the ambient conditions and the climatic zones in the EU on the quantitative requirements for heat recovery;
i) the need of specific provisions (and related formulation) on historic or listed buildings where the lack of space available can make it challenging to fit in ventilation units compliant with the two Regulations;
j) the need for (further) clarification on the nature of ‘box fans’ and ‘roof fans’, in particular concerning their compliance with the two Regulations, and the fans Ecodesign regulation 327/2011;
k) the need/feasibility to impose quantitative requirements on the maximum internal leakage for bidirectional ventilation units, as well as the need/feasibility of correction factors for the declared thermal efficiency of a residential ventilation units, based on the internal leakage rate;
l) Introduction, in the text of the two Regulations (e.g. in the definitions of unidirectional and bidirectional ventilation units), of the clarifications contained in the ‘Question on a combination of a supply UVU and an exhaust UVU being considered as a BVU (11-2016)2’;
m) improvement/increased description of the definition of ‘nominal flow rate’ of non-residential ventilation units;
n) improvements/changes in the definition of ‘ventilation unit’, with particular regard of the inclusion/exclusion of ventilation units for industrial applications (on the basis of FAQ 10 of the ‘Guidelines accompanying Regulation (EU) No 1254/2014

with regard to the energy labelling of residential ventilation units and Regulation (EU) No 1253/2014 with regard to Ecodesign requirements for ventilation units'.

o) the application and potential improvement of the requirement on the provision of instructions for the effective material recycling of the ventilation units (as in Annex IV - point 3 - of the Regulation 1253/2014);
p) other clarification requests from stakeholder in the context of the stakeholder consultation process.

And finally, if needed, the existing 'Guidelines accompanying Regulation (EU) No. 1254/2014 with regard to the energy labelling of residential ventilation units and Regulation (EU) No 1253/2014 with regard to Ecodesign requirements for ventilation units' will be updated.

In the subsequent phase 1.2 the Preparatory Studies are updated, where according to the T.o.R. at least the following additional items need to be addressed:

1) the identification of potential new functional parameters at product level, in particular concerning the indoor air quality when relevant and feasible;
2) resource efficiency aspects3 - most likely disassembly, recyclability, reparability, durability and content of Critical Raw Materials (CRM), following the adoption of the Circular Economy Package in December 2015 and the new Ecodesign Working Plan 2016-2019. This includes the analysis of requirement already set (on the instruction for material recycling), their effectiveness in promoting the resource efficiency of ventilation unit, and the identification of additional and/or more ambitious requirements, when relevant (e.g. on the content of CRM in magnets);
3) the potential inclusion in the analysis of smart controls and demand control options (such as, but not limited to, solutions for building/home energy management system based on the European standards SAREF/SAREF4ENER).

The study is performed as a supplement to already existing preparatory studies for Lot 6 and Lot 10, indicating that topics that have already been addresses will not be addressed again, unless there are new elements to be reported.

This sub-report on Task 4, specifically deals with updates on topics regarding Technologies.

Acronyms and units

Acronyms

AC/DC	Alternating/Direct Current
ADCO	Administrative Co-operation
AHRI	American Air Conditioning, Heating and Refrigeration Institute
AMCA	Air Movement and Control Association
ATEX	ATmosphères EXplosibles
BC	Backward Curved
BVU	Bidirectional Ventilation Unit
CECED	European Committee of Domestic Equipment Manufacturers
CEN	European Committee for Standardization
CFD	Computer Fluid Dynamics
CIRCA	Communication and Information Resource Centre
CLP	Classification, Labelling and Packaging (Regulation)
DigitalEurope	Association representing the digital technology industry in Europe
DoC	Document of Conformity
DoE	US Department of Energy
EC	Electronically Commutating
EN	European Norm
EPEE	European Partnership for Energy and the Environment
Eurovent	Association of European refrigeration, air conditioning, air handling, heating and ventilation industry
EVIA	European Ventilation Industry Association
FC	Forward Curved
GWh	Giga Watt hour 109 Wh
HNL	Howden Netherlands
HRS	Heat Recovery System
ICSMS	Information and Communication System on Market Surveillance
ISO	International Standardisation Organisation
JBCE	Japan Business Council in Europe
JRAIA	Japan Refrigeration and Air Conditioning Industry Association
N	Efficiency grade
NRVU	Non-Residential Ventilation Unit
RAC	Run Around Coil
RAPEX	EU Rapid Alert System
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (Regulation)
RoHS	Restriction of Hazardous Substances (directive)
RVU	Residential Ventilation Unit
rpm	rounds per minute (unit for fan rotation speed)
TC	Technical Committee (in ISO, CEN, etc.)
TWh	Tera Watt hour 1012 Wh
UVU	Unidirectional Ventilation Unit
VU	Ventilation Unit
WEEE	Waste of electrical and electronic equipment (directive)
WG	Working Group (of a TC)
yr	year

Parameters

A	floor surface area building [m²]
cair	specific heat air [Wh/ m³.K]
Q	heat/energy [kWh]
q	hourly air exchange [$m^3.h^{-1}$/ m³]
rec	ventilation recovery rate [-]
S	shell surface area building [m²]
SV	shell surface/volume ratio building
t	heating season hours [h]
T_{in}	Indoor temperature [°C]
T_{out}	outdoor temperature [°C]
U	insulation value in [W/K. m²]
V	heated building volume [m³]
ΔT	Indoor-outdoor temperature difference [°C]
η	efficiency [-]

Units

€	Euro
°C	degree Celsius
a	annum (year)
bn	billion (1000 million)
CO_2	carbon-dioxide (equivalent)
h	hours
K	degree Kelvin
kWh	kilo Watt hour
m	metre or million
m²	square metre
m³	cubic metre
Pa	Pascal
W	Watt

Table of Contents

1. Monitoring and Local Detection Ventilation Demand

1.1. Introduction

Local *sensors* and *monitoring* systems are making a cautious start with filling the void in the human sensory system to assess the ventilation performance. Where the occupants do not have the ability to correctly assess the ventilation performance and related IAQ-levels, local sensors and monitoring systems can. *Local ventilation control* refers to the ability of ventilation systems to adjust the ventilation rates in each individual room or space separately (opposite to central ventilation rate control).
This combined approach of local sensors, local ventilation control and monitoring, can ultimately have a huge impact on both the energy- and ventilation performance and as such may elegantly solve the conflicting requirements concerning energy consumption (aiming at lowering the ventilation rates) and indoor air quality (preferring higher ventilation rates). Local sensors that detect presence and number of people in a confined space, as well as local sensors that detect actual pollutants concentrations can be used to determine the required ventilation rates in order to minimise exposure. During absence and low pollutant concentration levels, the minimum required ventilations rates can be applied in order to minimise energy consumption for ventilation.

This chapter 1 will further discuss the technical developments as regards to the sensors for detected local ventilation demand and the monitoring systems. The following three chapters (chapter 2, 3 and 4) address the technical options that have been developed over the last decade for controlling the airflow rates per individual room or space with ducted- and non-ducted ventilation units.

To further indicate the type of controls that are meant in this context, the table below summarises the control types and their classification according to the EN 16798-3. IDA-C5 and IDA-C6 are the control classes that are referred to in this context of local demand control.

Table 1. Possible types of control of the airflow rate (Table 12 in EN 16798-3)

Category	Description
IDA – C 1	The system runs constantly.
IDA – C 2	Manual control The system runs according to a manually controlled switch.
IDA – C 3	Time control The system runs staged according to a given time schedule.
IDA – C4	Presence control The system runs dependent on the presence (light switch, infrared sensors etc.)
IDA – C5	Demand control (based on the number of occupants) The system runs staged dependent on the number of people in the space.
IDA – C 6	Demand control (based on air quality indicator) The system is controlled by sensors measuring indoor air parameters or adapted criteria, which shall be specified (e.g. CO_2, mixed gas, humidity or VOC sensors). The used parameters shall be adapted to the kind of activity in the space.

Complementary to the descriptions presented in table 1 for IDA-C5 and IDA-C6, a more detailed assessment is needed to determine when what type of IAQ /Demand Control – sensors are preferred for what situations. Surely, not all sensors are equally suitable for all room types. Without such an assessment, the efficacy of the various sensor types cannot be determined. Typical room types that can be discriminated with regards to ventilation systems intended to"
'replace air that is utilised/polluted due to presence of human beings and their use of the building including emissions from building materials, decorative and interior product equipment' are the following:

1.
<u>Habitable and otherwise occupied spaces</u>
Spaces that are typically occupied for longer periods and need ventilation (air exchanges) '*due to presence of human beings and their use of the building including emissions from building materials, decorative and interior product equipment'.* They typically produce category ETA1 (ETA2) extract air (see also EN 16798-3 and -4).
Examples (for residential and non-residential sector):

- Bedrooms
- Living rooms
- Living kitchens (opposite to separate kitchen)
- Study rooms
- Recreation rooms
- Dining rooms
- Offices
- Meeting rooms
- Classrooms
- Other workspaces used for activities not producing other emissions than the ones stated in the definition above.

Pollutant load for these spaces are strongly related to the number of occupants; in case there are no occupants, the required basic ventilation levels are applicable in order to dilute the emissions coming from building materials, decorative and interior product equipment.

2.
<u>Exhaust spaces</u>
Spaces that are occupied for short periods and in which emissions (humidity, odours, cooking fumes, etc.) are actively produced, and therefore preferably apply the air exchanges by means of direct exhaust of the polluted air. They typically produce category EHA3 (EHA4) exhaust air (see also EN 16798-3 and -4).
Examples (for residential and non-residential sector):

- Bathrooms
- Kitchens
- Toilets and washrooms
- Laundry rooms
- Utilities
- Other

Pollutant loads for these exhaust spaces are not only related to people entering the room (and causing the emissions), but mainly to the amount of the pollutants that are produced. Related pollutant concentrations can remain too high for a certain period of time, even after the occupant has left the specific room or space.
In case of no occupants, the required basic ventilation levels are applicable in order to dilute the emissions coming from building materials, decorative and interior product equipment.

1.2. Occupancy sensors

Occupancy sensors are defined here as sensing devices that are capable of counting the number of occupants in a room. In that sense, they are different from *presence sensors*, which are only capable of determining whether or not the room is occupied, regardless the number of occupants.
The combined use of occupancy sensors and local ventilation controls will lead to more accurately measured ventilation rates. This optimises both the IAQ- and the energy performance of the ventilation system.

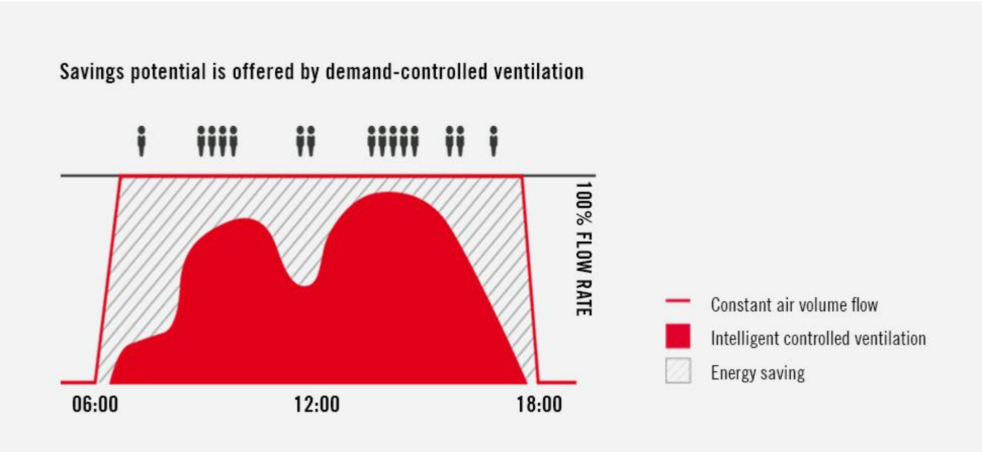


Figure 1. Saving potential occupancy-controlled ventilation

Various technologies can be used to determine the number of people in a room.

1.2.2. Infrared counters

Density (https://www.density.io/)

Density is an IR Depth Sensor, that counts people as they walk beneath the unit, in and out of a space. The Density DPU and Bracket need to be centred and installed directly above the entryway to ensure people are detected.


Figure 2. Density IR Depth Sensor

In the first mass market sensor, they have combined a powerful people counter, a modern Application Programming Interface, a dedication to privacy, and a sensor-as-a-service business model. The hardware is free. Users pay a monthly fee for access to the data. Prices start at USD 45 / sensor / month.

Density uses depth technology, computer vision, and an on-board quad-core processor to anonymously measure and manage entrances and exits through a door. The sensor attaches above a doorway, and tracks movement frame-by-frame with two infrared beams that bounce off from the floor. Algorithms filter out signal noise — boxes, strollers, pushcarts, plates, and other items being carried or pushed — to measure the direction, collision, and speed of people walking into and out of view. The data is funnelled via Wi-Fi to Density's cloud-hosted backend, where it is processed and analysed. A basic web dashboard provides insights like the real-time capacity of a room and historical crowd sizes, and an API allows third-party apps, services, and websites to make use of the data in novel ways.

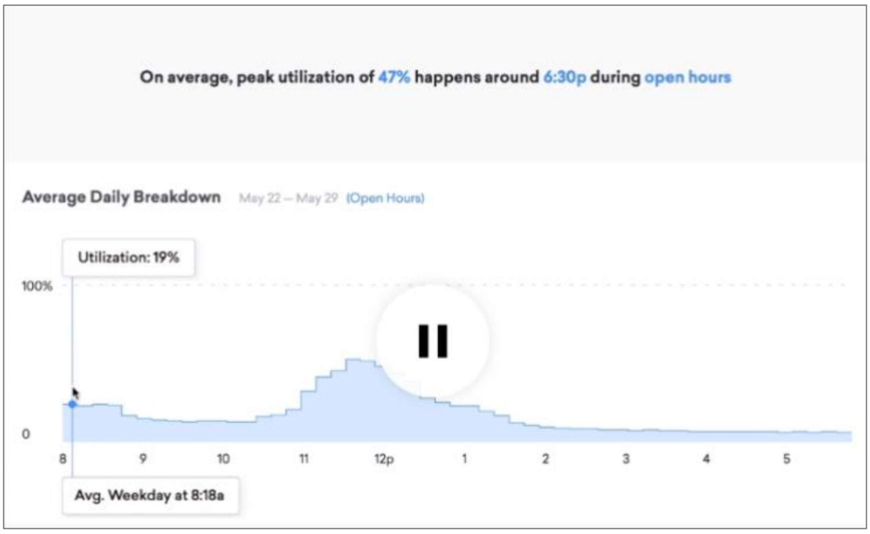


Figure 3. Example of Density dashboard

IEE People Counter

IEE has developed a 3D sensor that uses MLI (Modulated Light Intensity) technology. This technology is based on the optical time of flight (TOF) principle, where an active, non-scanning light source emits modulated near-infrared light. The phase shift between the light emitted by the source and the light reflected by the people and objects in the field of view is measured to create a real-time topographic image of the monitored area. The overhead-located 3D MLI Sensor™ processes 3D data in order to detect and count the number of people in a specific area and track the direction of their movements.

Figure 4. IEE People Counter

Device Properties	PC96M4.0	PC64M4.0
Mounting height	2.5 to 3 m	3.0 to 5.0 m
Detection area	1.5 m x 0.9 m to 2.5 m x 1.5 m	1.5 m x 0.8 m to 3.2 m x 1.6 m
Field of view/illumination	90° x 60°	60° x 40°
Type of illumination	Modulated near infrared light (NIR)	
Weight	0.8 kg (Core Housing) + 0.16 kg (Design Housing)	
Dimensions of the Core Housing	Ø 138 mm x H 60 mm	
Dimensions of the Design Housing	Ø 147 mm (integration cutout diameter), Ø 181 mm (outside rim diameter), 70 mm (height)	
Operational temperature range	–20°C to +50°C	
Core housing ingress protection	IP 30	
Supply voltage	24 V DC ± 15%	
Power consumption	max. 1.0 A at 24 V DC	
Housing material	Polymer	
Technology	3D MLI Sensor™	

Figure 5. Technical properties IEE PC

Test scenarios have demonstrated that IEE's People Counter's sophisticated algorithms ensure reliable segmentation, tracking and counting of people. With high accuracy levels around 99%, IEE's People Counter provides reliable data for demand-controlled ventilation.

<u>Bi-directional IR people counter</u>

Bi-directional wireless infrared-based people counters are so called 'break-beam sensors, having both an emitter and a receiver. The sensors are typically placed on one or two sides of a doorway, depending on the type used. The more intelligent versions can detect bidirectional movement. The data can be transmitted wirelessly to a bridge device.

Figure 6. Examples of break-beam IR sensors

These sensors may be adequate to determine the total number of people that visited a particular room over a certain period (visitors per day), but they have limitations as regards to their ability to determine the instantaneous number of occupants in the room, due to:

- Blindness: Break beam sensors are inaccurate. The sensor becomes blind when two people enter at the same time (side-by-side) or enter and exit at the same time.
- Human movement is complex: Break beam sensors rely on signal processing to sort out when a person has entered. The signal is hard to make sense of when lines form or people bring boxes and bags with them.

PIR: Passive Infra-Red sensor

Passive infrared sensors have widespread use in many applications, including motion detectors for alarms, lighting systems and hand dryers. Combinations of multiple PIR sensors have also been used to count the number of humans passing through doorways. In a practical research[1] it was demonstrated that a single PIR sensor can be used as a tool for occupancy estimation inside of a monitored environment. Using flexible nonparametric machine learning algorithms useful information about the occupancy could be extracted from a single PIR sensor. This approach makes use of the motion patterns generated by people within the monitored environment. The proposed counting system uses information about those patterns to provide an accurate estimate of room occupancy which can be updated every 30 seconds. The system was successfully tested on data from more than 50 real office meetings consisting of at most 14 room occupants.

While the accuracy of the proposed system does not yet reach the current state of the art obtainable with stereo cameras and computationally demanding image processing algorithms (or multi-sensor devices), the research project shows the ability to count the number of room occupants to within ±1 individual while substantially reducing the hardware costs, computational power and the need for specialist installation. Applications where accuracy is not critical, for instance, optimizing energy usage in buildings, can benefit from this cost-effective and easy to deploy approach.

1.2.3. Cameras / Optical Sensors

Modern video-based people counting uses IP cameras with embedded video analytics for maximum accuracy and reliability. The cameras are typically placed above the area where you want to count the people that enter. Authorized users can then view real-time and historical statistics from any device and location. The system is easy to add to your existing network as it is based on IP cameras.

Example: AXIS People Counter (https://www.axis.com/products/axis-people-counter)

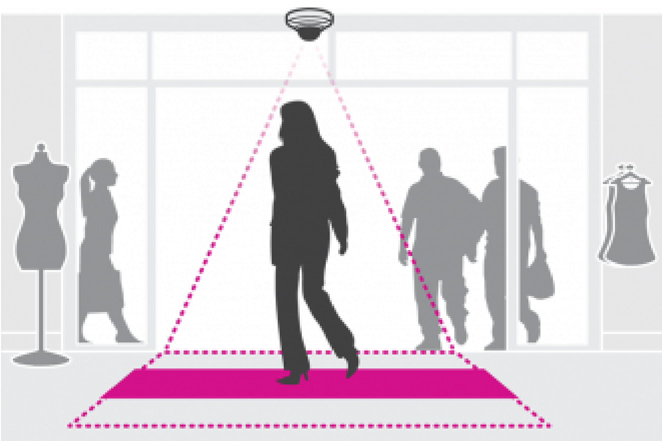


Figure 7. Illustration from AXIS

The AXIS People Counter automatically counts in real time the number of people passing under a camera and in which direction. AXIS People Counter is an automated system that enables simultaneous two-way counting of people moving in and out of a passageway. It disregards baby carriages and shopping carts. The software is built on advanced and proven algorithms from Cognimatics, whose programs have led in retail analytics for more than a

[1] Raykov, Y.P, Ozer, E., Dasika, G., Boukouvales, A., Little, M.A., Predicting room occupancy with a single beam passive infrared (PIR) sensor through behaviour extraction, UBICOMP '16, September 12-16, Heidelberg, Germany.

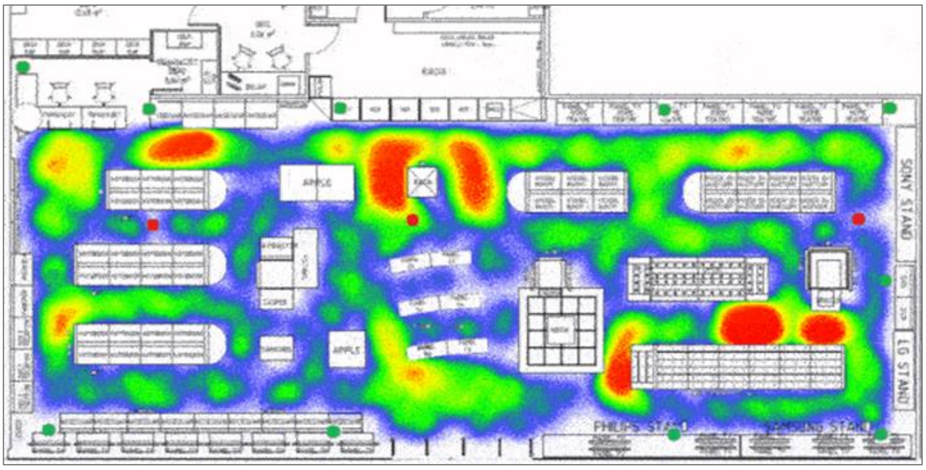
decade. Offering high-speed execution and low memory requirements, the software has been installed in thousands of cameras worldwide.

Camera-based occupancy detection unfortunately has various limitations, of which privacy is is the most important. Security and privacy of innocent people are seriously compromised during camera-based occupancy. Unauthorized persons or intruders can access people flow information. In order to secure occupancy information from attackers, image data should be in an encrypted format.

1.2.4. WLAN/Wi-Fi and Bluetooth tracking

WLAN/Wi-Fi tracking works as follows:

- Mobile phones are always looking for known Wi-Fi networks. It does this out of convenience so you can automatically connect to a known network without manually selecting it.
- The way your phone finds a Wi-Fi network is by sending out what is called a “probe request” (Bluetooth does similar).
- All Wi-Fi routers can track your phone. All you need is to have your Wi-Fi turned on.
- Multiple routers are listening and triangulating. They compare the relative strength of that signal to one another and can approximate where you are in the building.
- The routers roll up this data and send it to an analytics platform that may looks like the picture below:



Average costs for such a system varies widely by platform. Depending on the analytics, it can vary from ten 10 euros a month to thousands of euros per month. Existing enterprise Wi-Fi system need to be upgraded and extended with additional software.
Depending on the environment the technology is deployed, this can be considered an invasive technology. It is not “opt-in” meaning, the users the system tracks haven’t given their permission. Main drawback of Wi-Fi tracking, though, is inaccuracy. The system usually isn’t granular enough to determine the use of a specific room. So you end up with heat maps and approximation like graphic above.

1.3. IAQ-sensors

IAQ sensors are defined here as sensing devices that can measure certain pollutant concentrations in the air. Four types of IAQ-sensors are predominantly used in the ventilation sector:

1. CO2 sensors
2. RH-sensors
3. TVOC sensors
4. PM-sensors

1.3.1. CO_2 sensors

Carbon dioxide (CO_2) is not only a by-product of combustion, it is also a result of the metabolic process in living organisms. Because carbon dioxide is a result of human metabolism, concentrations within a building often are used to indicate whether adequate fresh air is being supplied to the space. Moderate to high levels of carbon dioxide can cause headaches and fatigue, and very high concentrations can produce nausea, dizziness, and vomiting. Loss of consciousness can occur at extremely high concentrations. To prevent or reduce high concentrations of carbon dioxide in a building or room, fresh air should be supplied to the area. CO_2 cannot be detected with your senses alone. Carbon dioxide does not have a colour or smell. The only way you can know the level of carbon dioxide in your home for sure is through a carbon dioxide monitor.

Carbon dioxide levels and potential health problems are indicated below:

- 250-350 ppm: background (normal) outdoor air level
- 350-1000 ppm: typical level found in occupied spaces with good air exchange
- 1000-2000 ppm: level associated with complaints of drowsiness and poor air
- 2000-5000 ppm: level associated with headaches, sleepiness, and stagnant, stale, stuffy air; poor concentration, loss of attention, increased heart rate and slight nausea may also be present.
- > 5,000 ppm: This indicates unusual air conditions where high levels of other gases also could be present. Toxicity or oxygen deprivation could occur. This is the permissible exposure limit for daily workplace exposures.

The main types of CO_2 sensors on the market fall into three categories:

I) Non-dispersive infrared sensors
II) Electrochemical sensors
III) Metal oxide semiconductor sensors

<u>Non-Dispersive Infrared (NDIR) CO_2 Sensors</u>

A NDIR CO_2 sensor works as follows: Air will enter the sensor; the sensor then activates a light set at one of the specific wavelengths for CO_2, usually around four microns, at one end of the sensor. The other side will hold a receptacle that will measure how much light makes it to the other side. Once the light is activated, any CO_2 in the air sample will absorb some of the beams. In doing so, the amount of light that makes it to the other side of the sensor decreases. The amount of light that gets absorbed depends on how much carbon dioxide is present. The more CO_2 is present, the more light will be absorbed.
Main advantages of this sensor type are 1) they are very long-lasting (> 10 years), 2) other substances will not interfere with readings, and 3) they work well at common CO_2 ranges (around 1000ppm). Main drawback is the fact that they can be affected by humidity and temperature.

Figure 8. NDIR CO2 sensors from2 different manufacturers

OEM prices are estimated at between 10 – 70 euro, depending on batch size. For this study, an OEM-price (VAT excluded) of 20 euro will be used for lifecycle cost calculations.

Technical Specifications Telaire T6713 EP

Method	: Non-Dispersive Infrared (NDIR), gold plated optics, diffusion sampling (with Telaire's Patented ABC Logic Self Calibrated Algorithm)
Meas. Range	: Output bounded 400 to 5000 ppm
Dimensions	: 1.18 in X 0.787 in X 0.34 in (30 mm X 15.6 mm X 8.6 mm)
Accuracy	: Accuracy @ 25°C: ±6% of the reading Accuracy @ -10°C to +40°C: ±10% of the reading
Start Up Accur.	: +/- 150ppm - ABC logic first corrects after 24 hrs
Temp. Dep.	: 5 ppm per °C or 0.5% of the reading per °C, whichever is greater
Stability	: < 2% of FS over life of sensor (15 years typical)
Press. Dep.	: 0.13% of reading per mm Hg
Calibr. Interval	: Not required
Response Time	: < 3 minutes for 90% step change typical
Signal Update	: Every 5 seconds
Warm Up Time	: < 2 minutes (operational), 10 minutes (maximum accuracy)
Operat. Cond.	: -10°C to +40°C (14°F to 104°F), 0 to 95% RH, non-condensing
Storage Cond.	: -30°C to 70°C (-22°F to 158°F)

Operating Temperature Range -10°C – 40°C (14°F to 104°F)

Electrochemical CO_2 sensor

Electrochemical carbon dioxide sensors measure electrical current or conductivity to determine how much CO_2 is present in the air.
When CO_2 enters the sensor, it chemically reacts within the sensor. As this reaction occurs, the sensor experiences an electrical change. Depending on the specific type of sensor, the reaction can make the sensor pick up an electrical current, change an existing current, or change how well the sensor would carry a current. The sensor will then use the type and amount of electrical change to determine how much CO_2 is present.
The chemical material itself has the highest sensitivity of CO_2, but the chemical material is also sensitive to other gas like CO, Alcohol and other gas. To get the real level of CO_2 in the air, it needs to work with other gas sensors to calibrate the data. Another disadvantage relates to the fact that the sensor material is consumable. It means that the accuracy of the sensor will go down as time goes on.

In summary: Advantage of this sensor type is the fact that it is less susceptible to humidity and temperature changes than NDIR or MOS sensors. Disadvantages relate to the fact that other substances can throw off readings, that the sensor does not last as long as NDIR sensors and that the sensor can "drift," and lose accuracy.

OEM prices are estimated around 5 - 50 euro, depending on type and batch size. For this study, an OEM-price (VAT excl.) of 15 euro will be used for lifecycle cost calculations.

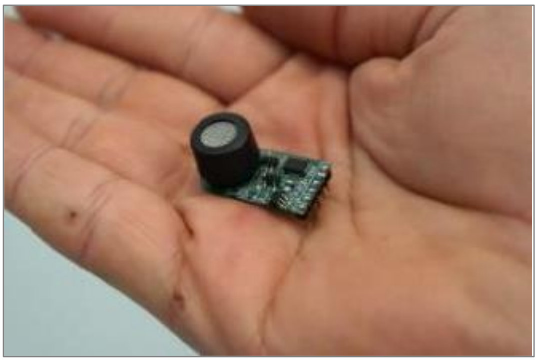


Figure 9. AR-5000 CO2 sensor from PSS Korea

AR-5000 CO_2 sensor module is a compact electrochemical type gas sensor using solid electrolytes where the EMFs are measured proportional to the logarithm of the CO_2 concentration in the ambient (Nernst equation). The circuit measures the EMF of the sensor and automatically converts it into CO_2 concentration. It provides I2C output (slave up to 50 kHz) for digital interface. Since the sensing element is made of dense ceramics, it is quite durable and is generally resistant to hostile environments

Table 2. AR-5000 CO_2 sensor characteristics

Item		Contents			
		Min.	Typ.	Max.	Units
Detection Range		0		5000	ppm
Operating Temperature		0		60	°C
Operating Humidity		5		90	%RH
Storage Temperature		-10		70	°C
Life Expectation			5		year
Response Time			3	10(diffusion)	seconds
Size		13x25x11			mm
Weight		2			g
Temperature Coefficient		5 ppm/°C (or <0.5%/°C)			
Accuracy		±5% (or ±50 ppm)			
Packaging Type		Glass Polyvinyle Plastic Custom			

<u>Metal Oxide Semiconductor CO_2 sensors</u>

MOS carbon dioxide sensors use the resistivity of metal compounds to test the amounts of gas in the air. Resistivity is how easily electricity flows through something. So, something like copper, which is used a lot in wiring, would be less resistant than rubber, which is used to stop electric currents.

A MOS sensor has a metal strip or film that is exposed to the air you want to test. This strip has a constant electric current running through it. As the target gas comes into contact with the piece, it will interact with the metal and change the chemical composition either through a reduction or oxidation reaction. When this happens, the resistivity, or conductivity, or the metal will be altered. The kind of resistance change, whether increasing or decreasing, and the magnitude of this change determines the concentration of the target gas. Based on what kind of metal it is, different gases will react to the strip.

Advantages: their very simple design makes them easy to use. Disadvantages: Readings can be affected by temperature and humidity; More suited for higher, less common CO_2 concentrations (>2000 ppm); Other substances in the air can throw off readings.
OEM prices are estimated around 5 - 50 euro, depending on type and batch size.

For this study, an OEM-price (VAT excl.) of 15 euro will be used for lifecycle cost calculations.

1.3.2. Humidity sensors

Humidity sensors are used to detect when moisture is produced in e.g. bathroom, kitchens and laundry room, etc. and subsequently increase ventilations rates in order to directly remove this surplus of moisture production.
Humidity sensors are sometimes also used to detect occupancy and adjust ventilation rates accordingly. A person could perspire and exhale 40 g of water vapour per hour when sleeping, 70 g/h when seated and 90 g/h when standing or doing housework. This person related humidity production changes the RH-values in a room. Detection of such changes may be used to control the ventilation rates. Unfortunately, there are more parameters that influence the real-time humidity values which makes it difficult to accurately relate humidity changes to occupancy. Temperature, outdoor humidity levels, indoor activities and ventilation rate itself all influence the actual occurring RH-levels. RH-sensors are therefore less accurate in occupancy detection than e.g. CO_2 sensors.

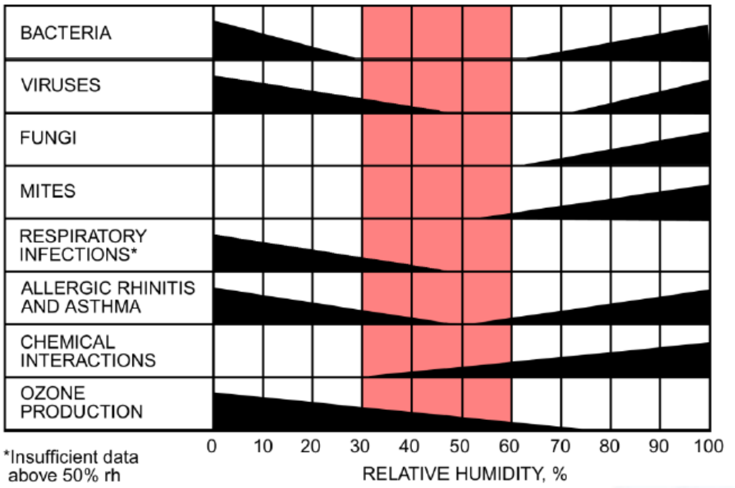


Figure 10. Optimal relative humidity ranges for health[2]

RH-values that are generally considered optimal for human occupancy are the values in the mid-range, between 30-60% relative humidity.

There are various types of humidity sensors; they come in different sizes, operate in different temperatures, and they detect different levels of accuracy. There are three main types of humidity sensors:

Capacitive

These sensors measure moisture levels using a humidity-dependent condenser; they are suitable for wide RH ranges and condensation tolerance. These sensors are commonly used in industrial and commercial environments.

Resistive

These sensors can measure the electrical change in devices such as conductive polymers and treated substrates. They are suitable for use in residential and commercial environments.

[2] E.M. Sterling, A. Arundel, and T.D. Sterling, Criteria for Human Exposure to Humidity in Occupied Buildings (ASHRAE Transactions, 1985), Vol. 91, Part 1

Thermal Conductivity

These sensors are suitable for use in environments that have high temperatures. They measure humidity by calibrating the difference between the thermal conductivity of dry air and that of moist air.

Depending on sensor accuracy, type and batch size, OEM prices may vary between 1-30 euro. For this study, an OEM-price (VAT excl.) of 5 euro will be used for lifecycle cost calculations.

1.3.3. TVOC sensors

TVOC sensors are sensing devices that are capable of measuring VOC and/or TVOC concentrations in the air.

Volatile organic compounds (VOCs) are emitted as gases from certain solids or liquids. VOCs are numerous, varied, and ubiquitous. They include both human-made and naturally occurring chemical compounds. Most scents or odours are of VOCs. Long-term exposure to VOCs in the indoor environment can contribute to sick building syndrome. In offices, VOC results from new furnishings, wall coverings, and office equipment such as photocopy machines, which can off-gas VOCs into the air. Organic chemicals are widely used as ingredients in household products. Paints, varnishes and wax all contain organic solvents, as do many cleaning, disinfecting, cosmetic, degreasing and hobby products. Fuels are made up of organic chemicals. All these products can release organic compounds while you are using them, and, to some degree, when they are stored. During certain activities indoor levels of VOCs may reach 1,000 times that of the outside air. Studies have shown that individual VOC emissions by themselves are not that high in an indoor environment, but the indoor total VOC (TVOC) concentrations can be up to five times higher than the VOC outdoor levels. New buildings especially, contribute to the highest level of VOC off-gassing in an indoor environment because of the abundant new materials generating VOC particles at the same time in such a short time period. In addition to new buildings, many consumer products emit VOCs, therefore the total concentration of VOC levels is much greater within the indoor environment.
VOC concentration in an indoor environment during winter is three to four times higher than the VOC concentrations during the summer. High indoor VOC levels are attributed to the low rates of air exchange between the indoor and outdoor environment as a result of tight-shut windows. Good ventilation and air-conditioning systems are helpful at reducing VOCs in the indoor environment.

Health effects due to exposure to higher VOC-concentrations may include: Eye, nose and throat irritation, headaches, loss of coordination and nausea, damage to liver, kidney and central nervous system. Some organics can cause cancer in animals, some are suspected or known to cause cancer in humans. Key signs or symptoms associated with exposure to VOCs include: conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnoea, declines in serum cholinesterase levels, nausea, emesis, epistaxis, fatigue and dizziness.

Key strategy for reducing indoor VOC-concentrations is avoiding or limiting the use of products that emit VOCs, i.e. by selecting the right building materials, decorative- and interior products, and choosing the right home and personal care products (cleaners, disinfectants, air fresheners, cosmetics, etc.). As a second stage strategy, increased ventilation rates are used to reduce TVOC concentrations.

Types of VOC-sensors

Nearly all small commercial VOC sensors are based on one of the six principles of operations summarized below:

- Photo-ionization detectors (PID), both portable handheld instrument and Original Equipment Manufacturers (OEMs)
- OEM electrochemical sensors either of amperemetric or potentiometric type,
- OEM metal oxide sensors (MOx) with change of conductivity instead of chemical reaction,
- Optical sensors including UV portable spectrometers,
- Portable or micro-gas chromatograph (μGC) that combines micro column with MOx or PID OEM as detectors.
- Electronic noses and sensor-arrays.

Main question related to (T)VOC sensors regards its suitability as main indicator for ventilation control for human occupancy. As already indicated, there are thousands of VOCs and their concentrations may incidentally change due to certain activities that may occur both indoors and outdoors. Basing ventilation rates on incidentally occurring (T)VOC emission may be difficult.
Several case studies were done to assess the suitability of TVOS-sensor for ventilation control for human occupied buildings.
1.
DTI[3] tested six different TVOC sensors and found that they were good at detecting changes in the IAQ. Other conclusions were that there are differences between sensor models as regards to their sensitivity, differences in types of VOCs that are measured, differences in response to changes in RH and temperature. Furthermore, there were variations between sensors of the same model, and last but not least there are differences in de way ventilation rates are controlled. Overall conclusion is that, although they are not plug and play yet, it considered possible to make them suitable for ventilation control.
2.
Together with the Aarhus University and the Danish Technological Institute, the Technical University of Denmark[4] also performed laboratory measurements on MOS VOC sensors. MOS VOCD sensors are advertised as smaller, cheaper and less energy consuming sensors, that do not only indicate CO2-concentrations but also measure various VOCs (odours), making them suitable for usage in all rooms of a building and for IoT (Internet of Things) applications. Issues that were found relate to:

- Information is missing regarding the sensor properties
- Different response for multiple samples of same sensor type and same manufacture
- Auto-calibration function (to background pollutant levels) can have adverse effect
- Definition of set-point value is problematic due to the broad range of sensitivities and the relative nature of the response
- It is not known, which pollutant is driving the response

It is concluded that additional future work is necessary with regards to accuracy, pollutants driving the response and the auto-calibrating functions, before they can be used for DCV-control.
3.
University of Gent[5] did a monitoring study, comparing values coming from dedicated NDIR CO_2 sensors with emulated CO_2 concentration values coming from MOS TVOC-sensors. The hypothesis that both CO_2 and VOC can be used as indicator for changing IAQ caused by occupancy and activities of people was further investigated in this study.

[3] Lyng, N.L., Can TVOC-sensors be used for ventilation control?, Danish Technological Institute. AIVC Webinar 'Using MOS sensors to measure VOC for ventilation controls, September 2018.

[4] Kolarik, J., MOS VOC sensors' properties and suitability for DCV-control, Technical University of Denmark, AIVC Webinar, September 2018.

[5] De Sutter, R., Laverge, J., Janssens, A., Performance of demand controlled ventilation systems controlled by VOC- and CO2- sensors, juni 2016, University of Gent.

As can be seen from Figure 11, the moments that VOC-signals increase and decline run synchronously to the CO_2 signals. As regards to the dynamics and unpredictability, there are huge differences between the two signals.
Figure 12 shows the general average correlation between the VOC and the CO_2 concentrations. They not only show strong variations between dwellings, but also between user profiles. It was also identified, that when ventilation systems is controlled by the CO2 signal, these correlations were much higher compared to a situation where ventilation is controlled by the VOC signal.

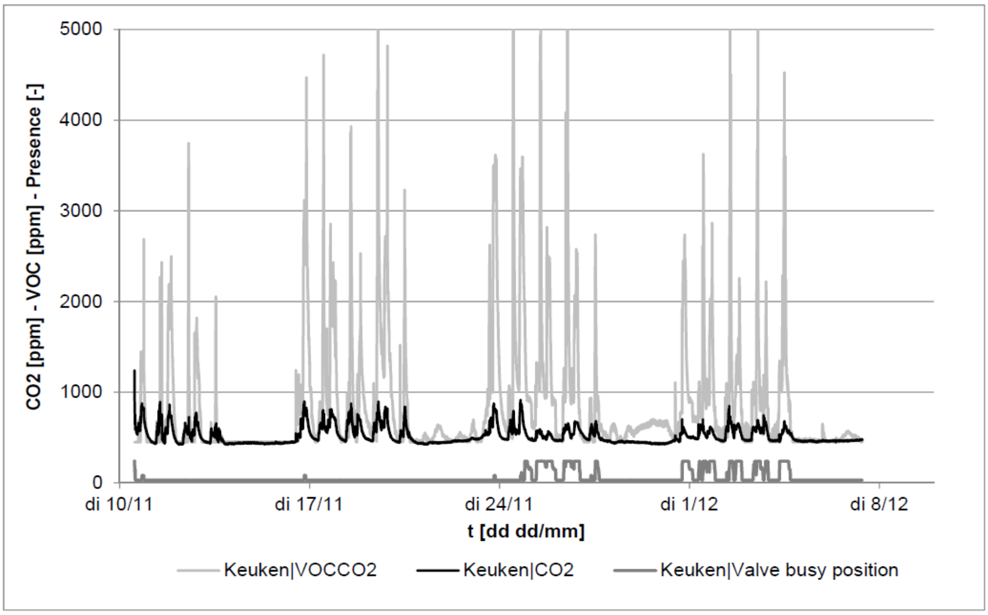


Figure 11. Comparison measured values for CO2- and VOC concentrations

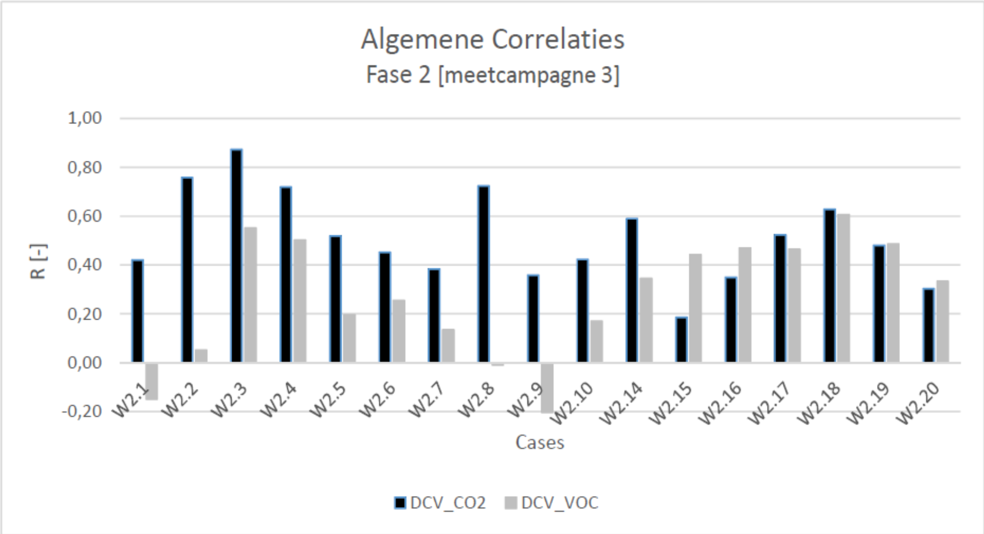


Figure 12. Correlation between NDIR CO2 and MOS TVOC values

Main conclusions of the study are that raw TVOC-signals may be used for event detection (and occupancy), but that the equivalent TVOC-concentration in general is more than 50% higher than the CO2-conentration. TVOC-controls increased the total ventilation rates significantly (with around +70% in bedrooms and +175% in kitchens). TVOC-concentrations peaks much more with occupant behaviour, so transforming TVOC-signals to a usable input for ventilation control still requires some work.

OEM prices for TVOC sensors are comparable to the electrochemical CO_2-sensors and are estimated around 5 to 50 euro, depending on type and batch size. For this study, an OEM-price (VAT excl.) of 10 euro will be used for lifecycle cost calculations.

1.3.4. PM-sensors

Particulate Matter (PM) is a mixture of airborne solid particles and liquid droplets that - when inhaled - and may cause serious health problems. PM includes particles with different characteristics – i.e. shape, optical properties, size and composition – but it is most commonly divided into sub-categories based on the particle size information.
Different PM categories are usually reported under the common nomenclature of PMx, where ‘x’ defines the maximum particle diameter in the airborne particle mixture or ‘aerosol’. For example, PM2.5 defines inhalable particles with a diameter of generally 2.5 micrometres and smaller, PM10 particles with a diameter of 10 micrometres and smaller, and so forth.

The PM10 and PM2.5 categories have been historically identified by national governments as important monitoring levels to assess the quality of the air we breathe, because PM10 particles irritate exposed mucous such as the eyes and throat and PM2.5 particles travel all the way through the lungs into the alveoli. New categories like PM1.0 and PM4.0 are also finding their way into air quality monitoring devices as these new outputs provide additional information to the traditional PM10 and PM2.5 levels, enabling a better particle pollution analysis and the development of new device-specific actions based on the detected aerosol type (e.g. house dust vs. smoke).

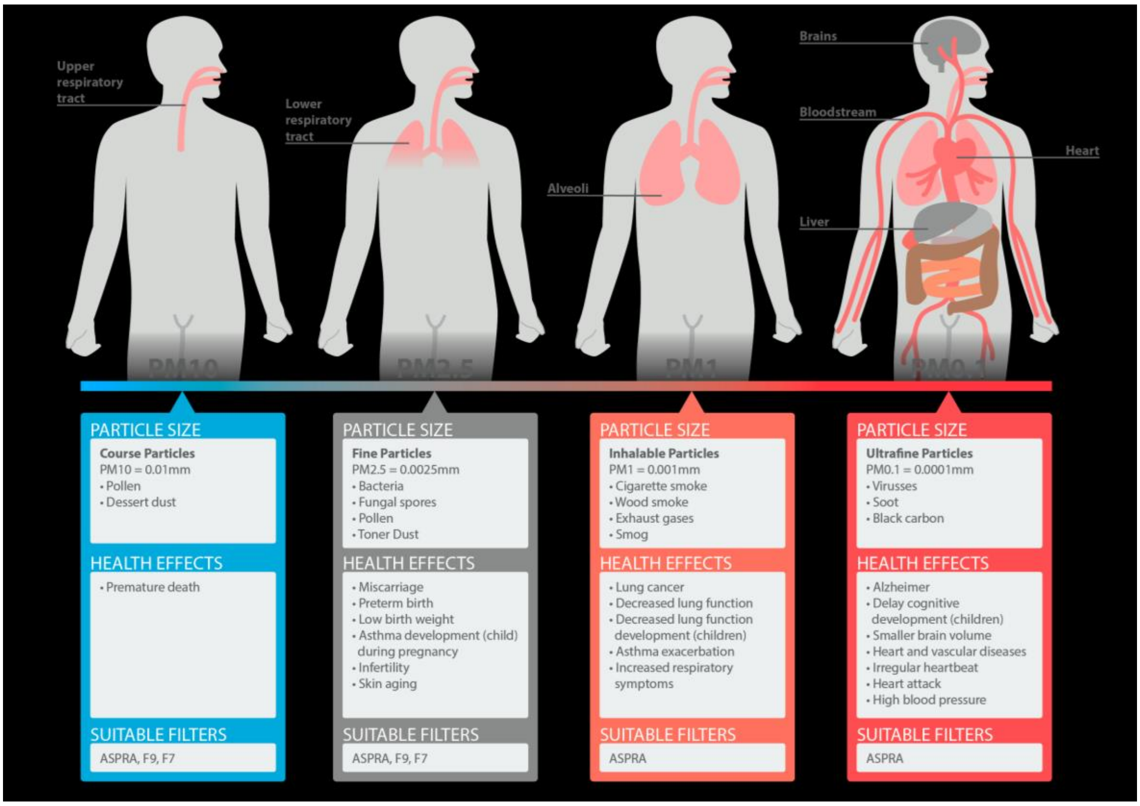


Figure 13. PM and their effect in the body (source: VFA-Solutions)

Indoor PM can be generated through cooking, combustion activities (including burning of candles, use of fireplaces, use of unvented space heaters or kerosene heaters, cigarette smoking) and some hobbies. Indoor PM can also be of biological origin.

Indoor PM levels are also dependent on several other factors including outdoor PM levels, infiltration, types of ventilation and filtration systems used. In homes without smoking or other strong particle sources, indoor PM would be expected to be the same as, or lower than, outdoor levels.

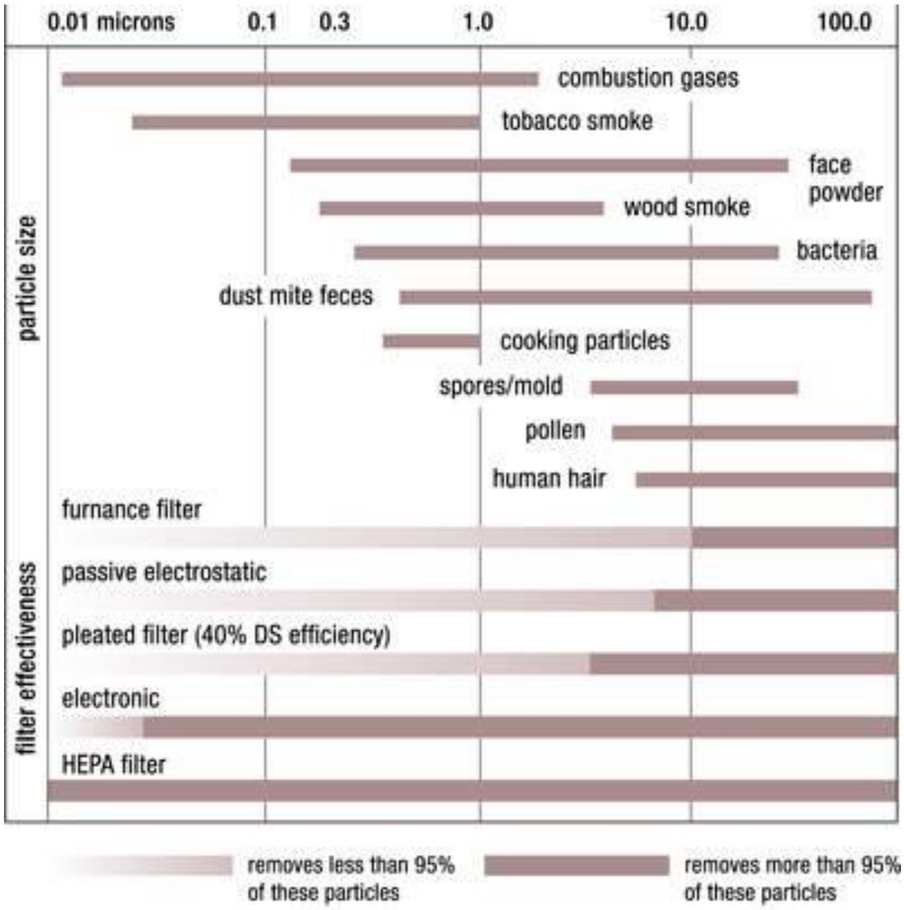


Figure 14. Size range of common pollutant sources
(source: John Wiley & Sons, Best practices guide residential construction 2006)

Cooking without proper extraction of the cooking fumes, can be an important source for high indoor PM-concentrations. In a field study performed by TNO[6] in the Netherlands, it was found that PM-peaks due to cooking can be very high (up to 1900 µg/m^3). The table below provides information on type of dwellings, kitchen hoods, ventilation types and family composition of the location where the field trials were performed.

[6] Jacobs, P., Borsboom, W., Kemp, R., PM2.5 in Dutch Dwellings due to cooking, TNO The Netherlands, September 2016, 37th AIVC Conference Alexandria.

Table 3. Dwelling and kitchen characteristics of the field study locations

Measurement	Cooker	Hood type	Capacity [m³/hour]	Vent. system	Ventilation [m³/hour]	Volume living room/kitchen [m³]	# persons	Dwelling type
Ettenleur	Gas	motorised	700[1]	C	700 + 75[1]	240	4	detached
Delft 2	Gas	motorised	166/212/238	C	166 + 13	120	2	row
Leiden	Induction	recirculation	500[1]	D	> 100	350	4	row
Amsterdam 2	Induction	recirculation	400[1]	D	60	110	2	apartment
Bilthoven	Gas	motorless	155	D	155 + 21	85	2	apartment
Delft 1	gas	motorless	123	D	123	128	4	row
Voorschoten	gas	motorless	35[1]	C	35 +15[1]	125	4	row
Den Haag	induction	motorless	38	C	69	120	4	semidetached
Amsterdam 1	gas	no hood-	-	A	40[1]	15	2	apartment
Ettenleur	gas	motorised[2]	-	C	75	240	4	detached

[1]Estimated from supplier information. [2]During half the week the motorised hood was intentionally not used.

Main results of the field trials are presented in Table 4. The last column in this table gives the averaged PM-increase over the period 18.00 – 23.00 hours due to cooking. Peaks that were not related to cooking in this period are not included in these averages. These averages can be considered indicative for the additional exposure to PM2.5 caused by cooking. From the table it may be concluded that the kitchen hood, its ventilation capacity and its efficacy play an important role in this PM-increase and related exposure. Another influencing factor on the PM-exposure related to cooking that is identified is the kitchen hood airflow rate in relation to the volume and ventilation of the kitchen itself.

Table 4. Results of the field measurements

Measurement	Cooker	Hood type	Capacity [m³/hour]	Air exchange rate[1] [ACH]	Max. PM due to cooking [ug/m³]	PM increase 18.00 – 23.00 hour [ug/m³]
Ettenleur	gas	motorised	700[4]	3.2	16 - 25[2]	0
Delft 2	gas	motorised	166/212/238	1.5	10 - 25[2]	0.5
Leiden	induction	recirculation	500[4]	0.3	70 - 110[2]	8
Amsterdam 2	induction	recirculation	400[4]	0.5	57	0 - 8
Bilthoven	gas	motorless	155	2.1	174	3
Delft 1	gas	motorless	123	1.0	40 - 94[2]	10
Voorschoten	gas	motorless	35[4]	0.4	242 - 1919[2]	16
Den Haag	induction	motorless	38	0.3	20	-[3]
Amsterdam 1	gas	no hood	-	2.7	651	5
Ettenleur	gas	no hood[1]	-	0.3	121 - 350[2]	44

[1]Air exchange rate with hood in operation. [2]Pancakes with bacon. [3]Ambient too high. [4]Supplier information.

<u>Type of PM-sensors</u>

The real-time optical particle counters (OPCs) have progressively found their way into the air quality monitoring market. These instruments are based on different optical principles, typically scattering or absorption, with light scattering being the most commonly used. In these OPCs, the particle passes through the light source (usually a laser beam) and causes scattering (or absorption) of the incoming light, which is then detected by a photodiode and converted into real-time particle count and mass concentration values.
Currently, optical detection is the most widespread technique due to its ease of use and unbeatable cost-performance ratio. In recent years, OPCs have become small enough to be integrated into air conditioners, air quality monitors and air purifiers, and are used to regulate and control air quality in households, cars and outdoor environments.

Prices for low cost PM sensors may vary between €5 and around €60, depending on accuracy and batch size.

Not all OPCs perform in the same way and the quality of their measurement depends greatly on the design and engineering of the device. The optical principle works very well in terms of particle counting, but as these devices are used mainly for the estimation of the PM mass concentration, they will be susceptible to estimation errors due to the different optical properties of the particles (e.g. shape and colour) and different mass densities. The quality of the mass estimation will thus vary highly depending on the manufacturer algorithm used to convert the measured optical signal into PM mass concentration. But also, the internal airflow engineering has a high impact on the accuracy and drift of these sensors as particles can accumulate easily on their optical elements (laser, photodiode, beam-dump) and degrade their output over time if they are not properly engineered.

Example Sensirion SPS30[7]

The working principle of the Sensirion SPS30 is based on laser scattering. A controlled airflow is created inside the sensor by means of a fan. As shown in Figure 15, an internal feedback loop between the microprocessor and fan stabilizes the fan speed and therefore the airflow through the sensor.

Environmental PM travels inside the sensor from inlet to outlet, carried by the airflow. In correspondence with the photodiode, particles in the airstream pass through a focused laser beam, causing light scattering. The scattered light is then detected by the photodiode and converted to a mass/number concentration output through Sensirion’s proprietary algorithms, which run on the SPS30 internal microcontroller.

Figure 15. Sensirion SPS30
(source https://www.sensirion.com/en)

1.4. Occupancy measurement via sensors fusion

Relying on single sensor data may cause significant errors. Due to different applications and targeting higher accuracy, a fusion of multiple sensors is more and more being used in occupancy detection and estimation. In a recent study[8] a literature review was done on this topic, looking at the integration of multiple sensors such as light, acoustic, temperature, motion, CO_2, humidity and PIR sensors for accurate occupancy detection.

A short summary of the findings of this literature review (see study paper, page 4 to 6):

– A new method introduced as SUN (sensor-utility-network) utilises a number of sensor measured data which reduced error from 70 to 11% as compared to such method which uses solely one sensor output. The occupancy was measured via distributed sensor measures such as CO_2, PIR, video, sound and badge counters.

[7] Lattanzio, L., Particulate Matter Sensing for Air Quality Measurements, Sensor Insights, December 2018.

[8] Ahmad, J., Larijani, H., Emmanuel, R., Mannion, M., Javed, A., Occupancy detection in non-residential buildings – A survey and novel privacy preserved occupancy monitoring solution, Applied Computing and Informatics, December 2018, https://doi.org/10.1016/j.aci.2018.12.001

- Ebaddat et al., used three different sensors data i.e., CO_2, ventilation actuation signals and temperature to build a dynamic model for occupancy. However, it has been pointed out in a research that temperature parameter contains less information gain for occupancy modelling.
- Zhang et al. concluded in their research that the correlation between the number of occupants and each individual environmental variable temperature, relative humidity, CO_2 and acoustic ranks approximately 11.98%, 32.49%, 35.70% and 48.05%, respectively.
- For the demand-driven application such as HVAC, Yang et al. presented a multi-sensor-based occupancy estimation model, which can estimate the number of people using the combination of indoor temperature, humidity, CO_2 concentration, light, sound and motion.
- Another implicit method for occupancy was proposed via the data obtained from (1) physical sensors: temperature sensor, relative humidity sensor, light levels sensor; and (2) software sensors: computer power consumption.
- In experiments with a Random Neural Network (RNN), occupancy was estimated from four sensors: (1) environmental CO_2 sensor (2) Air inlet CO_2 sensor (3) room temperature sensor and (4) Air inlet temperature. The occupancy information is further utilized in the HVAC system and the accuracy of the smart controller was 94.87%, 98.39%, and 99.27% for heating, cooling, and ventilation, respectively. Occupancy estimation time in was slower due to CO_2 sensor which is improved via a Hybrid RNN based occupancy estimation and PIR and magnetic reed switches.
- With data obtained from room temperature, inlet air temperature, inlet CO_2 concentration, indoor CO_2 levels, detection of a single occupant was tested. The accuracy of the estimation proposed in was around 92%.
- Another multiple sensor-based technique for correct occupancy estimation was proposed, based on sensors motion detection, power consumption, CO_2 concentration sensors, microphone and door/window positions. This research used feature selection via information gain strategy and concluded that indoor environment temperature has a very low role in occupancy detection. Acoustic sensors were the main feature in the proposed occupancy detection algorithm.
- Candanedo et al. proposed a model for occupancy detection via light, humidity, CO_2, and temperature measurements using Classification and Regression Trees (CART), Random Forest (RF) and Linear Discriminant Analysis (LDA). However, this work is limited to occupancy detection only and cannot estimate the number of occupants. The reported accuracy of Candanedo et al. model was surprisingly 95 to 99%. Using only the temperature data, the accuracy was 83 to 85%.
- Instead of utilizing multiple wireless sensors, Jiang et al. measured carbon dioxide concentration via CO_2 sensor for real-time indoor occupancy. The authors utilized Feature Scaled Extreme Learning Machine (FS-ELM) algorithm, which is a variation of the standard Extreme Learning Machine (ELM). The performance of FS-ELM is better than ELM in occupancy estimation problem. The measured CO_2 concentration had some serious spikes which was resolved with pre-smoothing filtering. Authors found out that pre-smoothing the CO_2 data can greatly improve the estimation accuracy up to 94%.

1.5. Suitability sensors for different room types

Depending on the type of rooms and the activities that are performed in the rooms, the sensors discussed in the previous sections can be more suitable or less suitable for DCV in specific room types. The table below attempts to make an initial evaluation/classification of the suitability of sensors for various room types in buildings primarily intended for human occupancy. Proposed classification is partly based on the definition with regards to the purpose of the ventilation that is meant in this context.
Text used in VU Regulation to describe the ventilation function: *'replacement of the air that is utilised/polluted due to the presence of human beings and their use of the building, including emissions from building materials, decorative and interior product and equipment'*

Table 5. Initial assessment suitability sensor types for DCV in various room types

Room types	**Habitable spaces**	**Exhaust spaces**			**Storage spaces**	**Connecting spaces**
Description	Rooms occupied by people for non- or low emitting activities such as: – Leisure – Sleeping – Eating – Hobbies – Waiting – Studying – Working	Rooms where people's activities produce pollutants that are preferably directly expelled, amongst which: 1) Odours 2) Moisture 3) Cooking fumes 4) High VOCs emissions			Rooms where items are kept or stored that have no to limited pollutant emissions	Rooms/spaces that need to be crossed before reaching a specific room
Examples	Living room Bedroom Diner Study Waiting room Office	Toilet	Bathroom Utility room	Kitchen Printer room	Pantry Storage room	Corridor Hall Stairway
Typical occupation	Long periods of occupation (> 1 hour)	Short visits (5 min.)	Visits of up to 0.5 hour	Visits of up to 1 hour	Short visits (< 5 min.)	Short visits (< 5 min.)
Preferred ventilation strategy	*During presence:* Predefined vent. rates per person to dilute bio-effluents and building/room emissions *During absence:* Basic vent. rates per m^2 to dilute building & room emissions	*Presence:* Predefined high extract rates + after run time *Absence:* Predefined basic extract rates	*Presence:* Predefined high extract rates + after run time *Absence:* Predefined basic extract rates	*Presence:* Predefined high extract rates+ after run time *Absence:* Predefined basic extract rates	*Continuous*: basic ventilation rates to dilute/ extract building, room- & storage emissions	*Continuous*: basic ventilation rates to dilute/ extract building & room emissions
People counters (all types)	+	+	+	+	No DCV needed therefore no sensors needed	
Bi-directional IR-laser	+/–	+/–	+/–	+/–		
PIR presence detection	–	+	+/–	+/–		
NDIR CO_2	+	+/–	+/–	+/–		
Electrochem. CO_2	+/–	?	–	–		
MOS CO_2	+/–	?	–	–		
TVOC	+/–	+	+/–	+		
Humidity sensors	+/–	–	+	+		
PM sensors[1)]	–	–	+/–	+		

1) PM is primarily generated in the kitchen; PM sensors are mainly used to assess the outdoor air quality and the need for filtration.

Because occupancy- and related exposure time are the longest in habitable spaces, these rooms are the most important where human exposure to pollutants concentrations is concerned. The exhaust spaces are important because – depending on ventilation strategy – the pollutants produced may spread to the rest of the building when not adequately removed; in case of excess moisture is not sufficiently removed, this may also bring damage to the building.

This initial evaluation of the applicability of sensors can be used for assessing the controls factor in residential ventilation systems (see Task 3 report, section 1.2 Ventilation Performance).

1.6. Monitoring and feedback systems

1.6.1 Introduction

Monitoring is the regular observation and recording of IAQ-levels in the various rooms of a dwelling. It is the process of routinely gathering information and making this information real-time available to the inhabitants. Purpose of the feedback can be twofold:

1) To influence the behaviour of the inhabitants where the operation of the ventilation provisions is concerned
2) To check or monitor the performance of demand-controlled ventilation (DCV) systems

As regards the first objective, there are many handheld sensor devices than can assist inhabitant to check IAQ-levels and operate ventilation provisions accordingly. Although this approach can be very helpful in creating awareness regarding worsening IAQ levels and indeed may improve the way ventilation provisions are operated, they do not - according to the study team - represent the ultimate solutions for achieving continuously good IAQ-levels with low energy use. Since the human sensory system is not reliable for sensing IAQ-levels, this approach requires continuous vigilant control of the handheld IAQ-devices as well as continuous adjustments to the ventilation provisions. This is not considered a viable long-term solution for the IAQ-problem.

The second objective of the monitoring and feedback systems (see under 2 above) is therefore considered a more feasible solution for improving IAQ-levels while minimising energy consumption. Using real-time data regarding IAQ-levels as direct input data for the demand-controlled ventilation systems is regarded as the future way to go for buildings with varying human occupancy rates.

1.6.2. Example of cloud connected smart DCV systems

A first large scale study into the effects of sensor-controlled cloud connected residential DCV-systems is described in the paper 'Large-scale performance analysis of a smart residential MEV system based on cloud data' presented at the 40th AIVC Conference in Ghent, October 2019[9].

Since IoT (Internet of Things) devices also become available in the residential ventilation industry, investigation of the real performance of these ventilation units during their lifetime becomes possible. The paper represents the first study into the real-life performance of a demand controlled central mechanical extract ventilation (DC-MEV) unit. The study compares the performance of units without air extraction in the bedrooms (no-smartzone)

[9] De Maré, B., Germonpré, S., Laverge, J., Losfeld, F., Pollet, I., Vandekerckhove, S., Large-scale performance analysis of a smart residential MEV system based on cloud data, 40th AIVC Conference, Ghent, Belgium.

with units that do apply direct extraction in the bedrooms (smartzone). About 350 units were analysed over a period of 4 months from December 2018 up to March 2019, corresponding with the main winter period in Belgium. Half of the units were installed as a smartzone system which means there is mechanical extraction from habitable rooms (bedrooms) as well. The air extraction was controlled on different parameters (humidity, CO_2 and VOC) depending on the room type. Indoor climate and IAQ were analysed with respect to design criteria set out in standards as well as fan characteristics and energy consumptions.

<u>DC-MEV-System</u>

Passive vents (ventilation grids), placed on top of the windows, supply the outdoor air in the habitable rooms. These passive vents are pressure controlled and can gradually be adjusted by the inhabitants between fully open and closed. By means of valves directly attached to the central unit at the end of the extract duct, the air extraction was locally controlled on different parameters depending on the room type: in bathroom and utility room on absolute and relative humidity (AH and RH); in kitchen and bedroom (if extraction available) on CO2 and in toilets on volatile organic compounds (VOC). Sensors were located at the valves and not within the rooms, which means that sensor values could - to a certain extent - deviate somewhat from the room conditions.
The following standard control algorithms were implemented in the system to regulate the extract airflow rate between a minimum and the required airflow capacity of the room according to the Belgian regulations. The nominal flow rates are for open kitchen: 75 m^3/h; bathroom, closed kitchen and laundry: 50 m^3/h; toilet: 25 m^3/h; bedroom: 30m^3/h).

- CO2: proportional between 800 – 950 ppm CO_2
- Humidity: step function as a function of a gradient $\Delta AH/\Delta t$ and a RH threshold
- VOC: step function as a function of a gradient $\Delta VOC/\Delta t$

<u>Main results</u>

Since the ventilation systems are also controlled on humidity, periods of RH levels >80% were limited. The typical RH ranges (between 30 and 70% or 25 and 60%) set out in standards for habitable spaces were fulfilled during at least 80% of the time, without causing complaints from the users.

As regards the CO_2 concentration in bedrooms, overall average values were below 950 ppm during at least 90% of the night-time. When considering only active ventilation (i.e. during occupancy) this percentage varied between 70 and 80%, with a dominant group in category 800-950 ppm and only about 20% in the category < 800 ppm. During 95% of the occupied time the values remain below 1200 ppm (see also figure 16). The average daily exposure over the dwellings was 245 ppmh/day which is only 33% of the 773 ppmh/day by van Holsteijn and Li (2014). This big difference can be explained by the lower control setpoint of 950 ppm instead of 1200 ppm.

These CO_2 concentrations during occupancy in the habitable spaces (bedrooms) are the ones that really matter because they are directly related to human exposure. These measured CO2-concentrations related to smartzone VUs can most probably be further improved (reduced) when the control algorithms for habitable spaces are adjusted, allowing a higher maximal airflow rate (higher than the value prescribed by the Belgian building codes (30 m^3/h)) for the parent bedrooms.

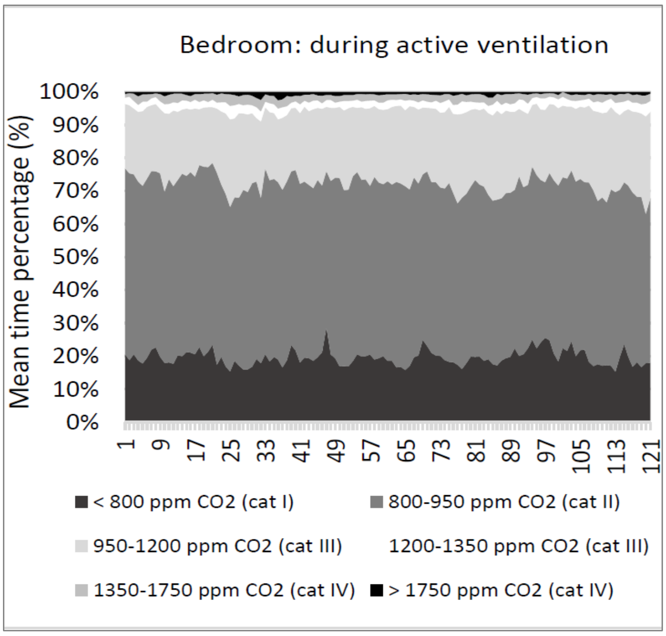


Figure 16. Average CO_2 concentrations in bedrooms for smartzone DC-MEV-units, during active ventilation

The dwellings without smartzone VU (i.e. no mechanical extraction from habitable rooms) were monitored separately. It was found that in such cases many elements have an impact on the IAQ in the bedrooms, such as size of the supply opening, position of the door, occupancy level and wind direction. As a consequence, CO_2 levels may vary between very good (< 1000 ppm) and very bad (> 2000 ppm). In general, omitting direct extraction from the bedroom gave rise to CO2 concentration levels to above 1350 ppm (category IV and V) in the parent bedroom.

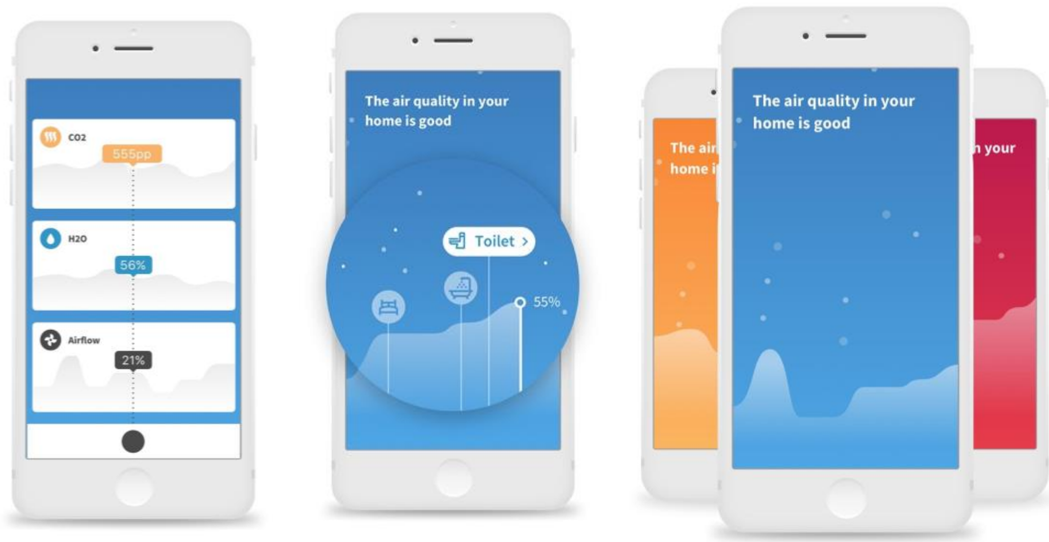


Figure 17. Screenshots of the app that can be used by the inhabitants when cloud connected components are used

Source: https://www.renson.eu/en-gb/producten-zoeken/ventilatie/mechanische-ventilatie/units/healthbox-3-0

This study clearly demonstrates that whether or not having a mechanical ventilation component in the habitable spaces, strongly influences the IAQ-levels in these rooms. The study also reflects the fact that, using cloud connected devices in combination with the proper sensors and control algorithms, the ventilation performance can be made visible to the user and – more importantly- largely be improved.

2. Flowrate control per room

2.1 Introduction

Local demand-controlled ventilation cannot be achieved solely by placing the correct sensors in the right locations (see previous chapter). Local DCV also requires the technical ability of the system to vary the ventilation flowrate in each and every room individually.
Where flowrate control per individual room is already common practice in the large majority of the ventilation systems for non-residential buildings, the residential sector is only recently moving away from systems where exclusively one central fan (or two in case of HR) is being controlled. Main reason for this transition, is the fact that monitoring studies indicate that flowrate control per individual room can improve both the ventilation performance and the energy performance of the overall system. Different technical principles can be used to achieve better flowrate control per individual room. The principles that are discussed in this chapter, refer to solutions that imply actual changes in the infrastructure (i.e. ductwork).

2.2 Ducted mechanical extraction with valves in all rooms for MEV

In the traditional MEV-systems, natural supply provisions in habitable spaces are combined with ducted mechanical exhaust in wet spaces, using one central extract fan. These systems have limited control over the ventilation airflows per individual room.
Several manufacturers have solved this, by extending the ducted mechanical extraction to all the rooms in a dwelling, including the habitable spaces, and by adding a controllable valve in all the individual extract ducts. This enables the variation of the extract flow rates for each room individually. With the correct sensors for the various rooms and proper control software for both fan and valves, the right air exchange rates can be achieved in each and every room independently of each other. This system is referred to as 'VST4' (see table 3 Task3 report).

The Demand-Flow system from Itho Daalderop achieves this by applying an additional manifold or plenum box, containing enough spigots for all the rooms in a dwelling. All spigot are equipped with control valves. The control valves related to the wet rooms are controlled by a humidity sensor, and the control valves for the habitable rooms by a CO_2-sensor. The plenum box is connected to a basic unidirectional VU. A separate control unit (type DF2-R) controls all the valves and the central extract fan.

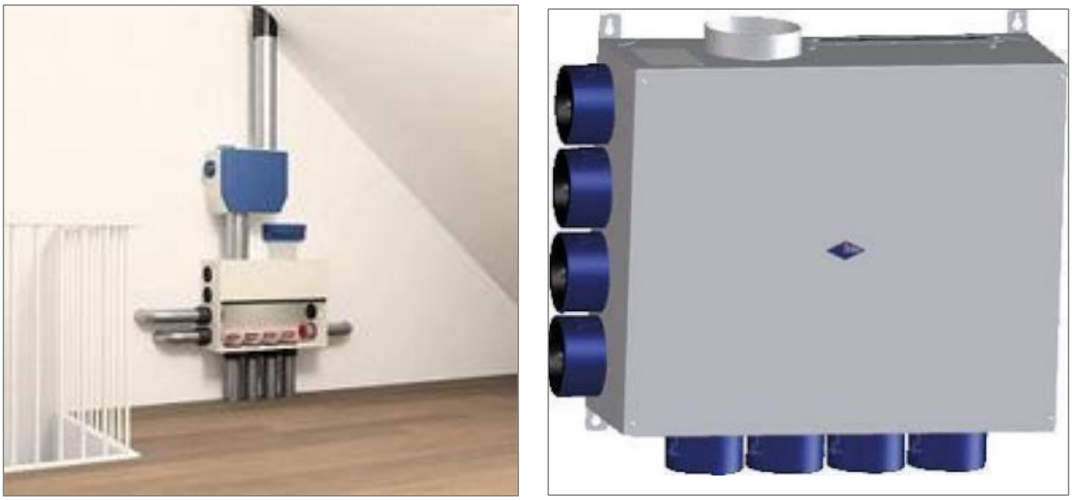


Figure 18. Itho Daalderop DemandFlow system

Source: https://test.ithodaalderop.nl/producten/ventilatie-hele-huis/vraaggestuurde-ventilatie/demandflow

Another, similar solution is offered by Renson. Main difference is that all the spigots and control valves that are needed are directly connected to the unidirectional extract VU. Each spigot may contain one or more sensors, depending on the room type that is connected.

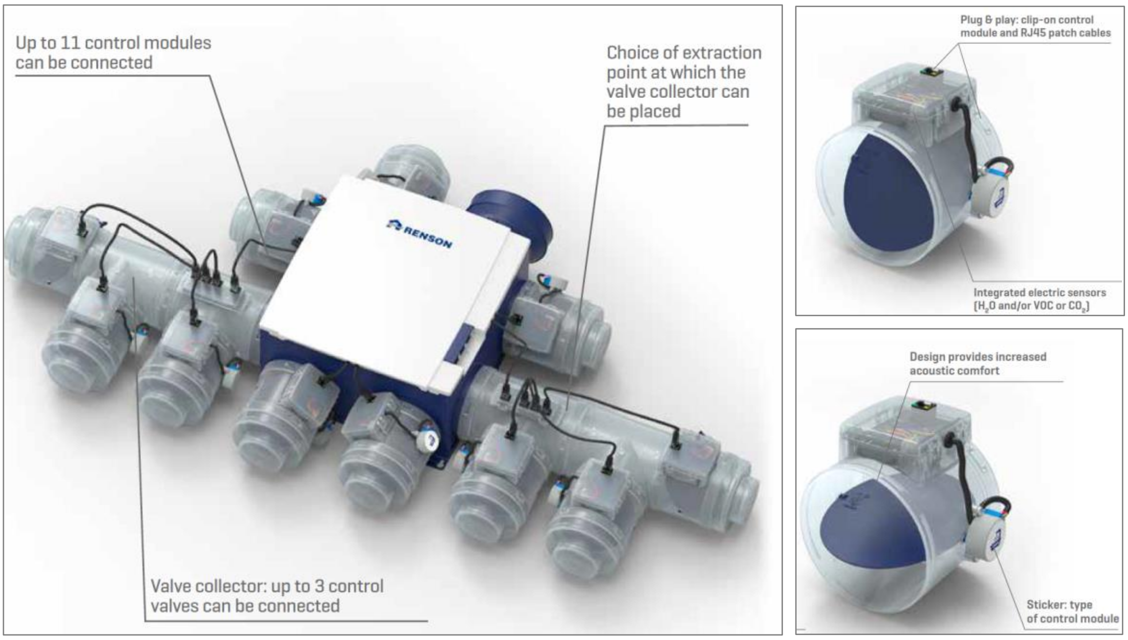


Figure 19. Renson Healthbox 3.0

Source: https://www.renson.eu/en-gb/producten-zoeken/ventilatie/mechanische-ventilatie/units/healthbox-3-0

The unit can be used in combination with a Wi-Fi connected installer app, that allows for testing and calibrating the airflows (flow resistance may be different for each room and each dwelling) and commissioning of the ventilation system. Maximum flowrates may be different per room type, depending on the country of installation and its specific buildings codes. If desired, the maximum airflow rates can be adjusted. Renson also provides a web portal with which installers can manage and monitor their installations.

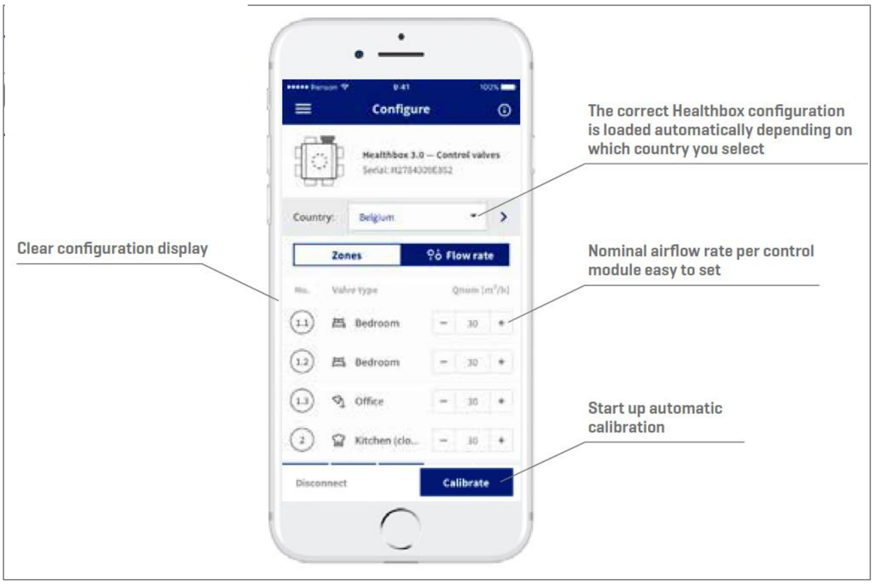


Figure 20. Renson installation app

Source: https://www.renson.eu/en-gb/producten-zoeken/ventilatie/mechanische-ventilatie/units/healthbox-3-0

2.3 Ducted mechanical extraction with valves in all rooms for MVHR

The same approach as described in paragraph 2.2 can be used for a central mechanical ventilation system with heat recovery (MVHR). The only difference is that now, the ducted mechanical extraction with controllable valves in all rooms are combined with a mechanical central supply provision in the connecting spaces (corridor, hallway, staircase) which replaces the natural supply provisions in the habitable spaces. The fresh and preheated outdoor air is now provided by a BVU and indirectly supplied to all the wet and habitable rooms. The total mechanical extract airflow is balanced with the total mechanical supply airflow and energy is recovered using a heat exchanger. This system is referred to as 'VST6' (see table 3 Task3 report).

The same components are used as illustrated in Figure 18, only the extract unidirectional VU is replaced by a bidirectional ventilation unit with heat recovery. Also, the appropriate software and control algorithms for steering the two fans and (if necessary) any additional valves, are installed.

2.4 Ducted mechanical supply/exhaust in HS/ES with valves (MVHR)

The standard ducted BVU-system in the residential sector (referred to as VST5 in table 3 of the Task 3 report) is a system were only the two central fans are controlled. The system consists of supply ducts with fixed valves to all habitable spaces, and exhaust ducts with fixed supply valves to all wet spaces. Varying the flowrate of both fans is done simultaneously, keeping both airflows in balance. This ducted BVU system with fixed valves only allows for changes in the overall airflow over the dwelling. If the airflow in one room is increased, it also increases in all the other rooms.

The principle that some manufacturers currently apply for the exhaust ducts only (see paragraph 2.2 and 2.3), can obviously also be applied for both the supply ducts and the exhaust ducts. By doing so, the standard ducted BVU system can be transformed into a system that allows flowrate control for all rooms individually. This can further improve the ventilation performance and energy efficiency of the standard BVU.

As far as the study team was able to determine, no BVU type VST5 systems could be found on the market that apply controllable valves in all wet spaces and in all habitable spaces with related actuators and control algorithms. In this respect it appears that there is room for further improvement of this standard ducted BVU-type.

2.5 Non-ducted local VUs and/or BVUs in ES/HS

Another way to achieve flowrate control in each room individually, is to apply non-ducted mechanical local ventilation units instead of central ducted mechanical VU having only one central fan, in which case the individual fans in each room can be controlled separately. Various products are placed on the market for this purpose:

a) Non-ducted local exhaust VUs

b) Non-ducted local supply VUs

c) Non-ducted local BVUs with recuperative heat exchanger

d) Non ducted local alternating BVU with regenerative heat exchanger

Advantage of this non-ducted local approach is the fact that the ductwork needed for centralized fans no longer is required. For retrofit, this is a big advantage and saves drilling and channelling activities. A second advantage relates to the fact that the airflow resistance due to the ductwork no longer applies, indicating that the power consumption needed for achieving similar airflows can be reduced.

2.5.1 Non-ducted local exhaust VUs

The ventilation units that are referred to here, are the non-ducted local extract fans that continuously extract air in baseload airflow rates (e.g. according EN 16798-1) and are in addition capable of achieving the flowrates following the minimum to-be-installed capacity according to applicable building codes or EN 16798-1 guidelines.

In that sense, bathroom- and kitchen extractor fans that can only manually be switched between on and off, do not qualify as a non-ducted local exhaust ventilation unit. There must be a continuous base load extract airflow than cannot be switched off. And the unit must be capable of achieving the minimum requested extract rates according to building codes and/or European guidelines. The units can be switched from basic continuous to higher extract flowrates by practically any type of control. Manufacturers often have the complete range of control options available: manual, timer, humidity, presence, VOC, CO_2 etc. See pictures below for some examples of these fans.

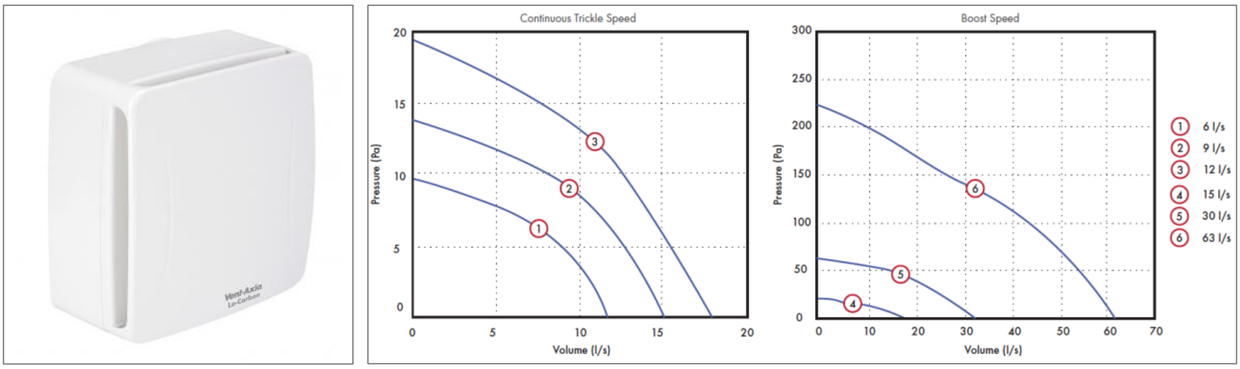


Figure 21. VentAxia Low-Carbon Quadra

Source: https://www.vent-axia.com/range/lo-carbon-quadraselv

The VentAxia Low-Carbon Quadra is a rectangular extract unit (230x260 mm) with a centrifugal fan and continuous basic flowrates varying from 6 to 12 l/s and high flowrates varying from 15 to 63 l/s. List price excl. VAT around 250 euro.

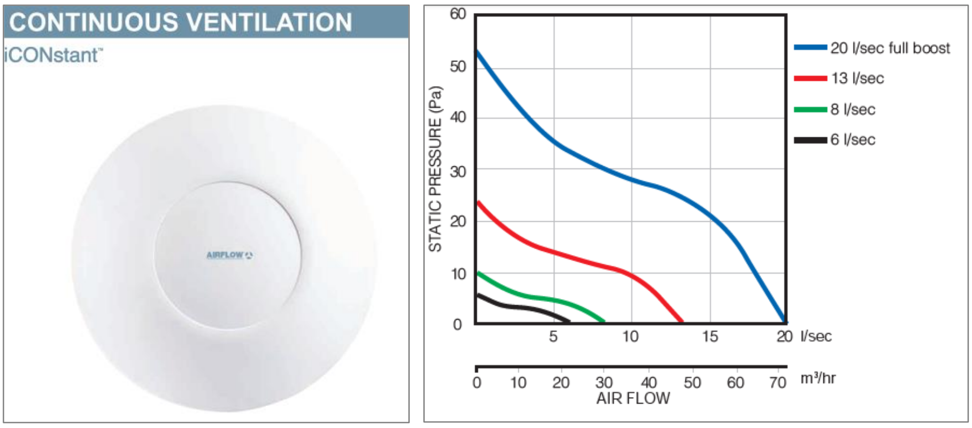


Figure 22. iCONstant by Airflow

Source: https://www.airflow.com/products/pg_iCONstant1/iCONstant-Fan-Range

The iCONstant from Airflow is a round (d= 197 mm) extract unit with an axial fan and continuous basic flowrates varying from 6 to 12 l/s and high flowrates varying from 22 to 72 l/s. List price excl. VAT around 170 euro.

Important to note here is the difference in the QH-curves of these two example fans. The axial fan is much more pressure sensitive than the centrifugal fan. With higher counteracting elevated pressure differences over the façade, the axial fan may achieve no basic extract rates at all. In case of negative pressure differences, the basic extract rates may be doubled. These differences in sensitivity will have an effect on the ventilation performance and thus also on the IAQ-levels.

2.5.2 Non-ducted local supply VUs

In principle, a similar description/explanation as for local exhaust UVUs could be given for local supply UVUs. The fact is, however, that only a very limited number of local non-ducted supply fans are offered on the market. The dominant supply provisions in the market are in fact passive natural supply grids, a.k.a. trickle vents or air inlets. These passive supply provisions are cheap and do not use electrical energy. The downside however is that they also suffer from pressure sensitivity, indicating that depending on the wind pressure and wind direction, the air supply may not always correspond to the actually needed supply rates in the various rooms. Furthermore, natural passive supply grids are generally manually operated of not operated at all, implying that correct control is more the exception than the rule. These two downsides will influence the ventilation performance, the energy performance and related IAQ-levels. With supply fans, these two drawbacks can be avoided.

Figure 23. S-fan, example of local supply fan
(source: https://www.climarad.nl/producten/actueel/climarad-s-fan/)

Technical specs S-fan:

Fan type	: 1x centrifugal
Nominal airflow	: 50 m^3/h
Maximum airflow	: 300 m^3/h
Controls	: CO_2, RH, T_{inside} $T_{outside}$
Communication	: RF
Specific Power Input SPI	: 0.07 $W/m^3/h$
Standby consumption	: < 1 Watt
Filtration	: G4 / F7 optional
List price (VAT excl.)	: around 600 euro

2.5.3 Non-ducted local BVUs with recuperative heat exchanger

Non-ducted local BVUs with recuperative heat exchanger have been on the market since end of the previous century (around 1990-2000). They consist of a recuperative heat exchanger, two fans, controls, one or two wall ducts and an outlet- and inlet opening on both the indoor- and outdoor side of the unit. Many manufactures nowadays have such units in their product portfolio.
Their benefits include the ease-of installation (no ductwork through the building is needed) and with it their total acquisition costs and the fact that – with the right sensors - flowrates can be controlled per individual room.
The issues of this type of solution mainly relate to noise production at elevated flowrates, its susceptibility to recirculation of air (in- and outlet are very close to each other) and, not least, the compromises that are needed in terms of product specs to keep the units small and less obtrusive. Heat exchangers, fans, filters, supply and exhaust surfaces are mostly smaller than preferred.
Finally, depending on the type of fan and overall technical design of the product, their flowrates may be susceptible to pressure differences / wind load over the façade, which can seriously affect the overall heat recovery efficiency and ventilation performance. For that reason, the *indoor/outdoor airtightness* and *airflow sensitivity* are important parameters and their values need to be determined according to the related standard (FprEN13141-8). With these values, corrections are to be made on the overall average temperature efficiency of the unit and on its ventilation performance.

Some examples of non-ducted local BVUs with recuperative HEs:

Figure 24. Example local BVU: Lunos Nexxt

Source: https://www.lunos.de/en/product/nexxt-en/

Fan type	: 2x centrifugal
Wall ducts	: 1x D=160 mm
Max flowrate	: 110 [m^3/h]
SPI	: 0.29 [$W/m^3/h$]

Heat exchanger type	: recuperative enthalpy (i.e. moisture is transferred)
Temperature efficiency	: counterflow :73% and crossflow 62% @75 [m^3/h]
Size	: w x h x d = 480 x 480 x 170 mm
Sound power level	: 49 dB(A) @ reference flowrate of 75 [m^3/h]
Internal & external leakage	: 2%
Mixing rate	: 2%
Airflow sensitivity	: 0%
Indoor/outdoor airtightness	: 1 m3/h
Filters	: M5, F7 or F9
List price excl. VAT	: around 1000 euro

Measurements according EU 1254/2014

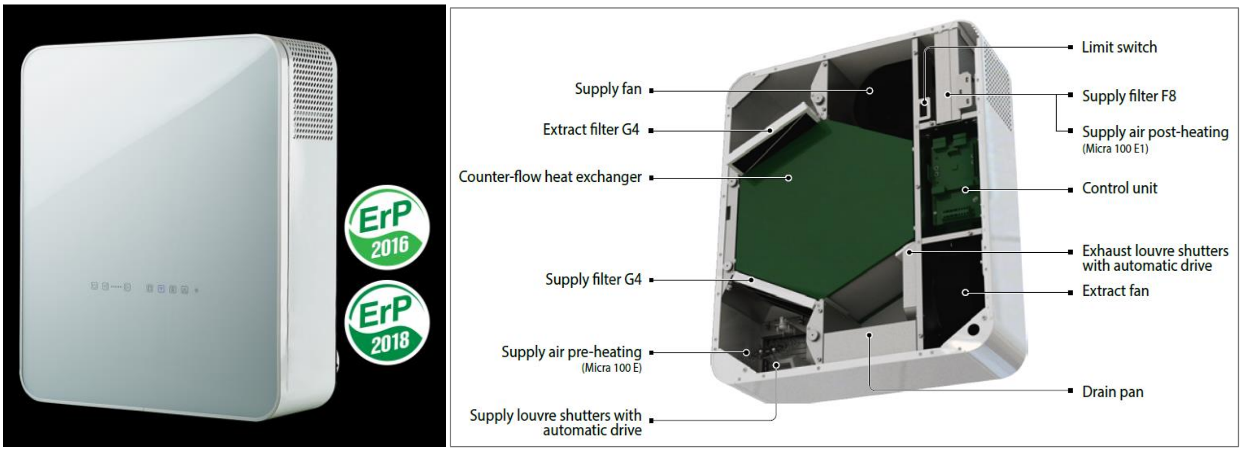


Figure 25. Example local BVU: VENTS Micra 1000

Source: https://ventilation-system.com/de/series/micra-100

Fan type	: 2x centrifugal
Motor type	: EC (electronically commutated)
Wall ducts	: 2x D=100 mm
Max flowrate	: 100 [m^3/h]
SPI	: 0.483 [$W/m^3/h$]
Heat exchanger type	: recuperative, optional enthalpy
Temperature efficiency	: counterflow recuperative :92% @ …[m^3/h]?
Dimensions	: w x h x d = 550 x 650 x 200 mm :
Sound power level	: 47 dB(A) @ reference flowrate
Internal & external leakage	: 1%
Mixing rate	: 20%
Airflow sensitivity	: 7%
Indoor/outdoor airtightness	: 7 m3/h
Filters	: G4 or F8
List price excl. VAT	: around 1000 euro? (no internet supplier found)

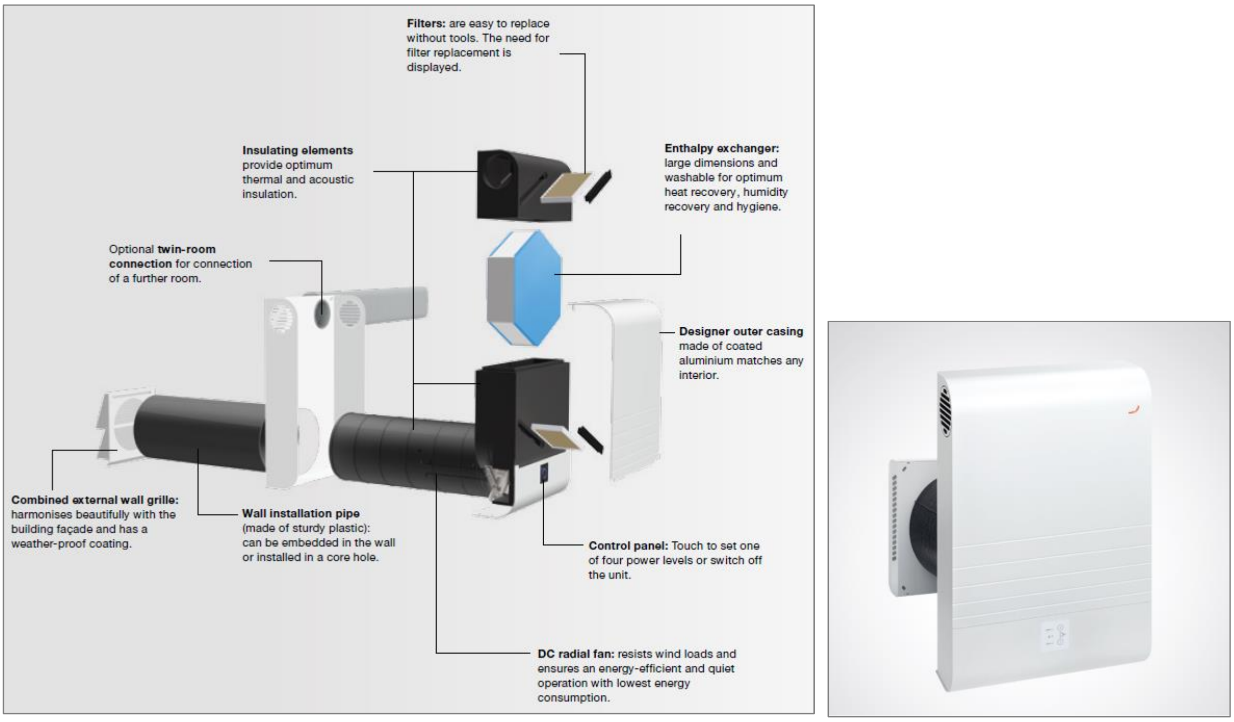


Figure 26. Example local BVU: Zehnder ComfoAir 70

Source: https://www.international.zehnder-systems.com/products-and-systems/comfosystems/zehnder-comfoair-70

Fan type	: 2x radial
Motor type	: EC
Wall ducts	: 1x D=250 mm
Max flowrate	: 60 [m^3/h]
SPI	: 0.21 [W/m^3/h]
Heat exchanger type	: enthalpy
Temperature efficiency	: counterflow recuperative :76% @ 42[m^3/h]?
Dimensions	: w x h x d = 660 x 440 x 141 mm :
Sound power level	: 47 dB(A) @ reference flowrate
Internal & external leakage	: 1%
Mixing rate	: Class U1
Airflow sensitivity	: <10%
Indoor/outdoor airtightness	: 5 and 7 m3/h
Filters	: G4 or F7
List price excl. VAT	: around 1200 euro

2.5.4 Non-ducted local BVUs with regenerative heat exchanger

The non-ducted local BVU with a regenerative heat exchanger is a relatively new type of product. Because of that and because this product is becoming quite popular in certain countries, a separate chapter (Chapter 3) is dedicated to this this product type.

3. Non-ducted alternating local BVUs

Another version of the non-ducted local BVU concerns the alternating BVU using a single fan and a regenerative heat exchanger. These products are on the market since the beginning of this century, and - when looking at their sales development in certain countries – are becoming quite favourable.
As indicated, they consist of a regenerative heat exchanger, one fans, controls, one wall ducts and an opening on both the indoor- and outdoor side, which is alternately used as air inlet or outlet. Several manufactures nowadays have such units in their product portfolio.

Alternating local BVUs are used to provide ventilation for living rooms and bedrooms. An integrated thermal accumulator in combination with and reversible fan are used for heat recovery purposes. The integrated thermal accumulator charges itself with heat energy from the room's air as it flows to the exterior (extract air). After 70 seconds, the fan changes direction and the stored heat energy is transferred to the incoming outside air (supply air). For this principle to work correctly and to ensure the room’s pressure stability the incoming air and extract air volumes must match, indicating that two units are required operating in sync: one ventilation unit works in supply air mode while the other works in extract air mode at the same time. These decentralized ventilation systems are based on the free movement of air between individual pairs of ventilation units. Therefore, internal doors must not have air-tight seals. Adequate air transfer measures are required (an air gap of about 10 mm below the door, a ventilation grille or similar, etc.)

The benefits of these units mainly include the ease-of installation (no ductwork through the building is needed) and - compared to the recuperative BVUs - even lower total acquisition costs due to the fact that the product is even smaller and uses less components (one fan, one flow path). Also, for this product type there is the benefit that – with the right sensors - flowrates can be controlled per individual room.
These products also have some noteworthy disadvantages, however. These issues again, mainly relate to noise production at elevated flowrates and the compromises that are needed in terms of product specs to keep the units small and less obtrusive. Heat exchangers, fan, filters and airflow openings are mostly smaller than preferred.
Another issue relates to the possible recirculation of air, not only between the two units of a pair of alternating BVUs, but also in a single unit: i.e. a part of the used air that is exhausted could be pulled in again, and alternatively a part of the fresh supplied air can be pulled out again. This recirculation affects the ventilation effectiveness.
Finally, because many of these products use small axial fans, their flowrates are susceptible to pressure differences / wind load over the façade, which can seriously affect the overall heat recovery efficiency and ventilation performance. For these reasons, the *indoor/outdoor airtightness*, the *airflow sensitivity* and the *exhaust- and supply air transfer ratios* are important parameters and their values need to be determined according to the related standard (FprEN13141-8). With these values, corrections are to be made on the overall average temperature efficiency of the unit and on its ventilation performance.

The followings section gives some examples of these alternating BVUs together with their technical specifications. The subsequent paragraph discusses some of the tests and monitoring studies that were performed on these units. For many of these products test data regarding *indoor/outdoor airtightness*, *airflow sensitivity* and the *exhaust- and supply air transfer ratios* are not available. Main reason for this probably is that the related standard FprEN13141-8 is not approved and applicable yet.

3.1 Examples of alternating non-ducted BVUs

Some examples of non-ducted local alternating BVUs with regenerative heat exchangers and their technical specifications are presented in this section.

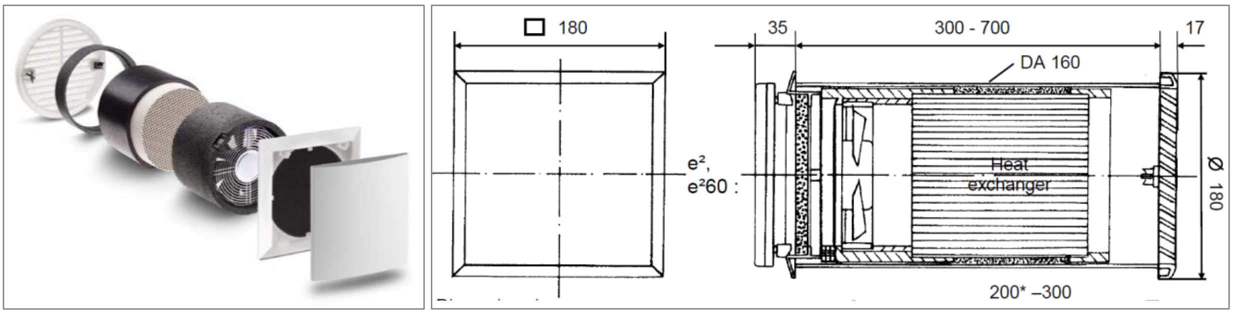


Figure 27. Example local alternating BVU: Lunos e^2

Source: https://www.lunos.de/en/product/

Decentralised ventilation devices with heat recovery of the type e^2 only function in pairs. One device operates 70 s (50s for e^2 short) in supply air operation, the other 70 s (50 s for e^2short) in exhaust air operation at the corresponding airflow level as set. Then the air direction is changed. It is thus ensured that the total of the airflow volume supplied is equal to the total exhaust airflow volume. If a device pair operating in alternating (or push-pull) mode is installed and operated in two different rooms of an apartment, a sufficiently dimensioned interconnection between the air movement must be provided by excess flow air vent. If a pair of devices is installed in one room, the minimum distances as indicated below are recommended.

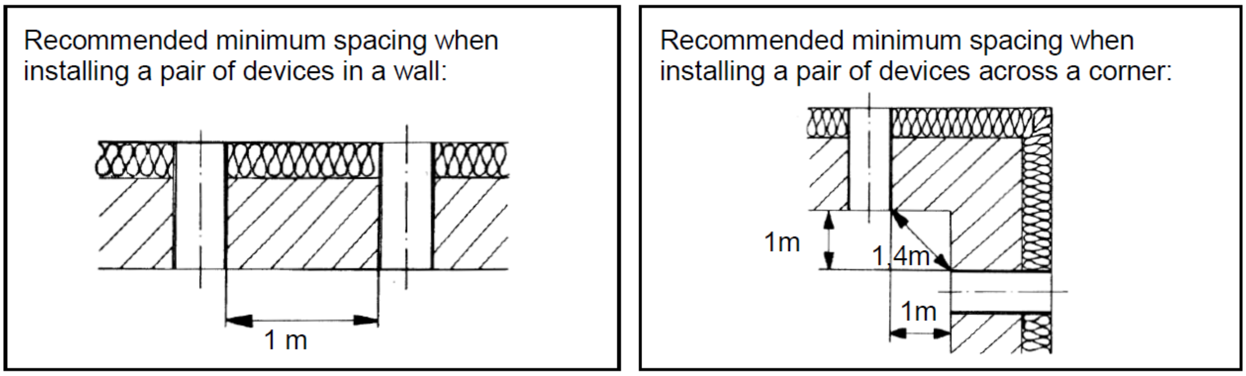


Figure 28. Recommended spacing between a pair of Lunos e^2 units

<u>Produktdatenblatt Lunos e^2 (gem.VO 1254/2014 vom 11 juli 2014, ref. E222 12.19)</u>

Fan type	: 1x axial (ebm-papst)
Motor type	: 12 V DC
Wall ducts	: 1x D=160 mm
Max flowrate	: 38 [m^3/h] (figure relates to a pair of devices)
SPI	: 0.21 [W/m^3/h]
Heat exchanger type	: regenerative with humidity recovery
Temperature efficiency	: 85% @ 26.6 [m^3/h]
Dimensions	: inner cover w x h x d = 180 x 180 x 35 mm
Sound power level	: 40 dB(A) @ reference flowrate (@26.6 [m^3/h])
Internal & external leakage	: 0%
Mixing rate	: 0%
Airflow sensitivity	: 53%
Indoor/outdoor airtightness	: 3.9 m3/h
Filters	: G3
List price per pair	: around 1000 euro (excl. VAT and excl. installation cost)

Figure 29. Example local alternating BVU: Korasmart Tube 2400

Source: https://www.korado.com/products/local-ventilation-units/korasmart-tube-2400-and-2400e.html

Fan type	: 1x axial
Motor type	: ?
Wall ducts	: 1x D= 160 mm
Max flowrate	: 45 [m^3/h] (figure relates to a pair of devices)
SPI	: 0.18 [W/m^3/h]
Heat exchanger type	: regenerative
Temperature efficiency	: 81% @ 32[m^3/h]
Dimensions	: inner cover w x h x d = 279 x 279 x 63 mm
Sound power level	: 46 dB(A) @ reference flowrate (@32 [m^3/h])
Internal & external leakage	: -
Mixing rate	: -
Airflow sensitivity	: +32% / -42%
Indoor/outdoor airtightness	: +2.7 / -1.2 m3/h
Filters	: G3
List price per pair	: around 900 euro (excl. VAT and excl. installation cost)

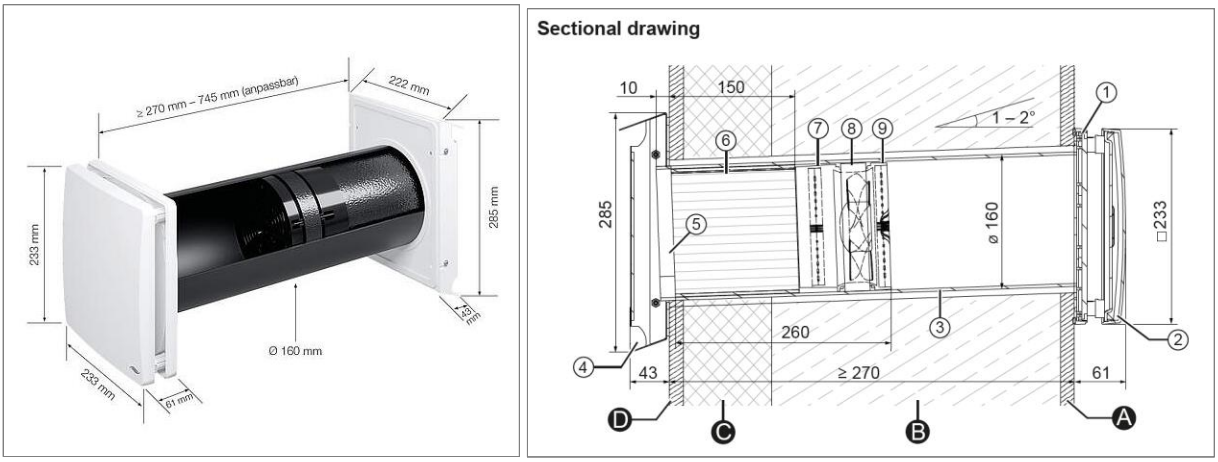


Figure 30. Example local alternating BVU: inVENTer iV-Smart+

Source: https://www.inventer.eu/products/ventilation-units/inventer-iv-smart/

Fan type	: 1x axial
Motor type	: 24V DC
Wall ducts	: 1x D= 160 mm
Max flowrate	: 58 [m^3/h] (figure relates to a pair of devices)
SPI	: 0.15 [W/m^3/h]
Heat exchanger type	: regenerative
Temperature efficiency	: 87% @ 42[m^3/h]
Dimensions	: inner cover w x h x d = 233 x 215 x 61 mm

Sound power level	: 46 dB(A) @ reference flowrate (@32 [m^3/h])
Internal & external leakage	: -
Mixing rate	: -
Airflow sensitivity	: 29.4%
Indoor/outdoor airtightness	: 6.3 m3/h
Filters	: G3
List price per pair	: around 1000 euro (excl. VAT and excl. installation cost)

3.2 Monitoring & simulation studies alternating BVU

Various studies have been carried in the last couple of year to gain more knowledge and information regarding the actual performance of these alternating BVUs. The important studies are summarized below.

3.2.1 Impact of pressure conditions on performance alternating BVU

A recent paper in *Energies* (https://www.mdpi.com/1996-1073/12/13/2633/htm), describes the result of a study into 'The impact of air pressure conditions on the performance of single room ventilation units in multi-story buildings'[10] .

In Estonia, multi-story apartment buildings constitute about 60% of the whole dwelling stock, and the majority (75%) of the buildings were built primarily in 1961–1990. Part of the building stock built before the 1990s has already been renovated but for many apartment buildings this process is yet to start.
Typical multi-story apartment buildings have been built with natural ventilation, where fresh outdoor air enters through leaks or openings of the windows and doors, mixes with the warm room air, and leaves the building through shafts in the bathroom and kitchen. With retrofitting the building envelope, in order to achieve necessary thermal insulation for reducing the energy consumption for space heating, the air tightness of the building increases and the air flow through cracks and leaks is reduced. As a result, the air changes through natural ventilation decrease and the required air ventilation rates are no longer achieved. Several analyses on the performance of ventilation in old Estonian dwellings show that the average indoor air CO_2-concentrations in occupied periods is above 1200 ppm which means the air change rate is too low to ensure good indoor air quality. With the renovation of old apartment buildings, the improvement of ventilation is therefore unavoidable in order to provide healthy indoor environment for the occupants.

Single room ventilation units with heat recovery is one of the ventilation solutions that have been used in renovated residential buildings in Estonia. In multi-story buildings, especially in a cold climate, the performance of units is affected by the stack effect and wind-induced pressure differences between the indoor and the outdoor air. Renovation of the building envelope improves air tightness and the impact of the pressure conditions is amplified. The aim of this study was to predict the air pressure conditions in typical renovated multi-story apartment buildings and to analyse the performance of room-based ventilation units. The field measurements of air pressure differences in a renovated 5-story apartment building during the winter season were conducted and the results were used to simulate whole-year pressure conditions with IDA-ICE software. Performance of two types of single room ventilation units were measured in the laboratory and their suitability as ventilation renovation solutions was assessed with simulations.

[10] Mikola, A., Simson, R., Kurnitski, J., The impact of air pressure conditions on the performance of single room ventilation units in multi-story buildings, Energies 2019, 12, 2633, July 2019.

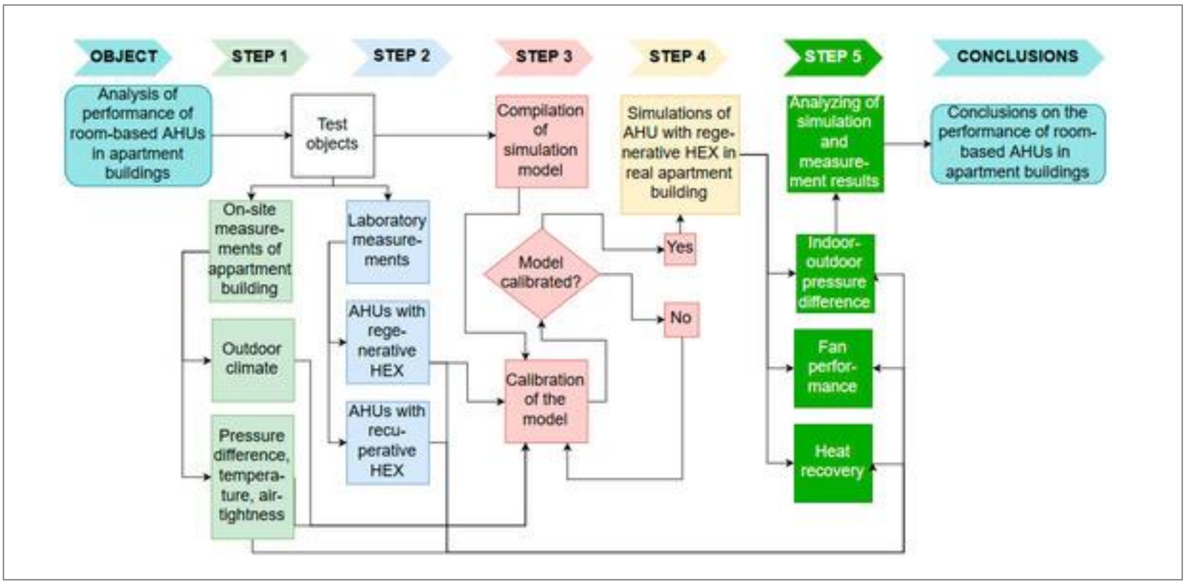


Figure 31. Flow chart of the studies that were performed

Source: Mikola, A., Simson, R., Kurnitski, J. (see footnote)

<u>Results field measurements</u>

The results of field measurements showed that the pressure difference across the building envelope was negative during the entire measurement period in the first-floor apartment and mostly negative in the fifth-floor apartment (see Figure 33 left).

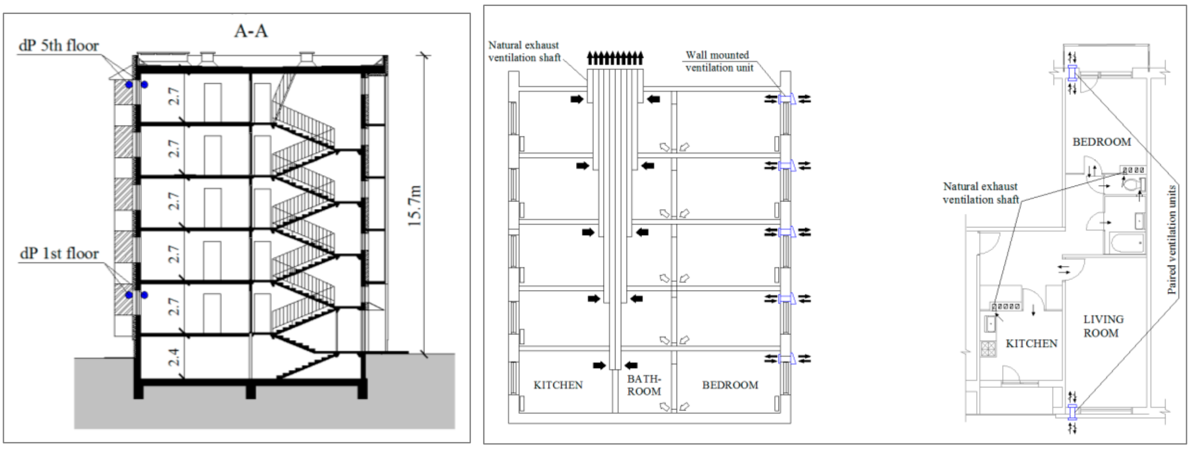


Figure 32. Cross section & measurement points (left); principle of ventilation system (right)

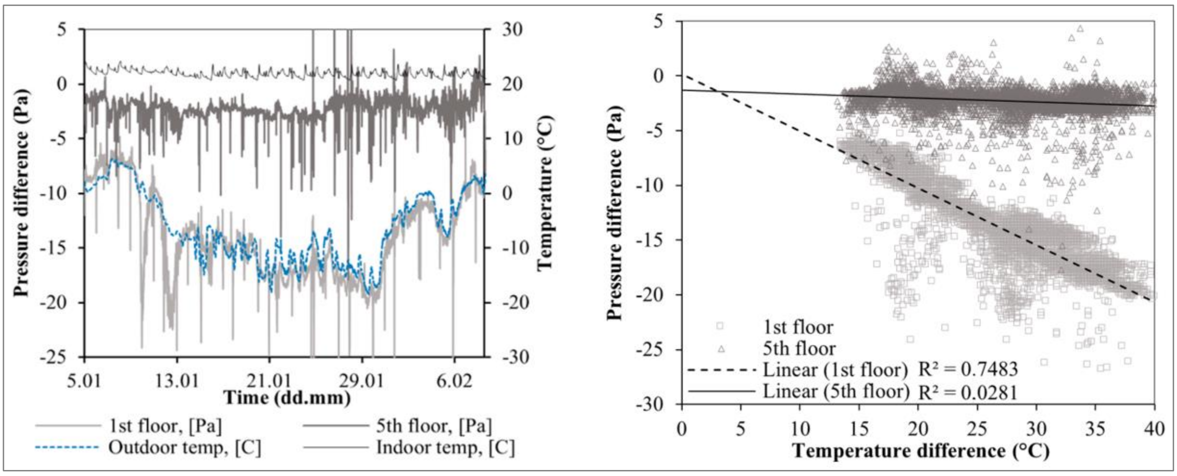


Figure 33. Left: measured indoor & outdoor pressure differences and indoor/outdoor temperature. Right: Relation pressure conditions and indoor/outdoor Temp-difference.
Source: Mikola, A., Simson, R., Kurnitski, J. (see footnote)

Occasional peaks toward zero-pressure difference are most likely caused by using the cooker hood, opening the windows or external doors to the balcony or staircase, the peaks and periods toward greater difference indicate the wind-induced effect. Pressure difference caused by wind can be dominant also for longer periods. The results indicate that the pressure difference is mostly caused by the stack effect being strongly dependent on the outdoor temperature in the bottom floor apartment, whereas on the top floor the dependence is weak due to the reduced height of the shaft (see Figure 32 right). The measured indoor temperature during the measurement period in both apartments was roughly between 20 and 22 °C. The dependence between the indoor and outdoor pressure and temperature is shown in Figure 33 on the right.

<u>Results Laboratory Measurements</u>
Based on the results of laboratory measurements the fan performance and HEX temperature efficiency of the alternating BVUs were studied. The measurement results of the performance of the unit are shown in Figure 34. In the beginning of the tests the value of under pressure in the room was −2 Pa which means that supply and extract airflows were more or less equal. After the pressure difference increased the extract air flow decreased and supply airflow increased at the same time. As results indicate, the supply and extract airflows are equal only at very low pressure differences. The greater the difference, the more the air flows differ. It can be seen that in case of 75% fan power, with differential pressure over −20 Pa the extract airflow is close to zero and the supply airflow around 60 m3/h (Figure 34 left). The supply–exhaust cycles, which are presented in Figure 34 on the right, show a quick drop of the supply air temperature after the cycle change. During the tests, the outdoor air temperature was close to −5 °C. If the supply and extract airflows are equal, the supply air temperature was about 7 °C but if the pressure difference was increased from 0 Pa–20 Pa in test room, the supply air temperature at the end of the supply working cycle was about −2 °C.

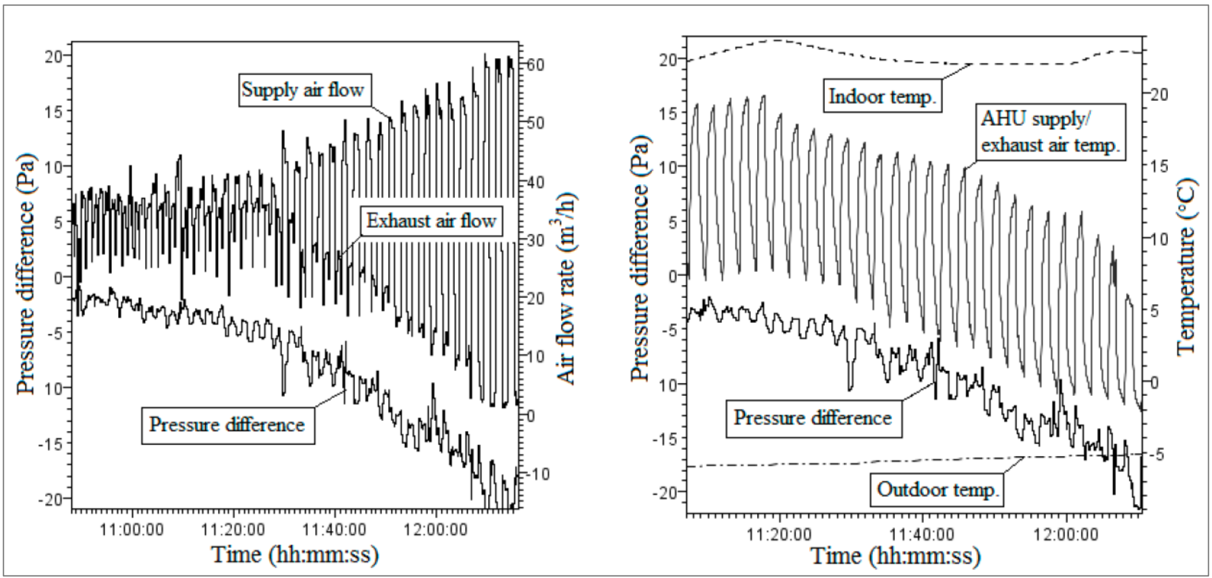


Figure 34. Measured airflows and temperatures of alternating BVU

Source: Mikola, A., Simson, R., Kurnitski, J. (see footnote)

The fan performance curves were constructed for the fan speed levels of 25%, 50%, 75%, and 100% (see Figure 35 left). The fan performance curves show how the supply and extract airflows of the ventilation units are related to the in-and outdoor pressure difference. It is also possible to present how the pressure difference is related to the temperature efficiency of studied ventilation units (see Figure 35 right). The results indicate that if the pressure difference rises, the temperature efficiency decreases. The same trend appears for all tested fan speeds. For example, in case the 50% speed level, the temperature efficiency is over 0.5 if the pressure difference is smaller than 4 Pa.

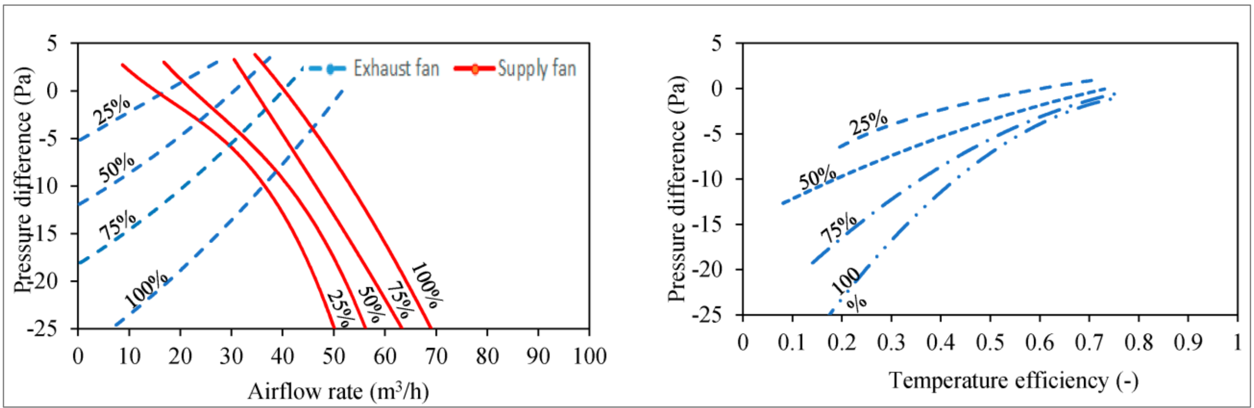


Figure 35. measured performance curves and temperature efficiencies of alternating BVU with axial fan and regenerative heat exchanger

Source: Mikola, A., Simson, R., Kurnitski, J. (see footnote)

To compare these results with the other type local BVUs (the ones with two centrifugal fans and a recuperative HEX), fan performance curves and temperature efficiency graphs were also constructed for this type of unit.
Again, the fan performance curves were established for the fan speed levels 25%, 50%, 75%, and 100%. Compared to the ventilation units with regenerative HEX, the units with recuperative heat exchanger perform adequately in case of higher pressure differences between indoor and outdoor air. However, if the pressure difference is −20 Pa at fan speed level 50%, the airflow balance is also compromised (supply airflow is about 15% higher than exhaust airflow). The temperature efficiency of ventilation units with recuperative HEX is presented in Figure 36 on the right-hand side. Compared to units with regenerative HEX,

the temperature efficiency of studied ventilation units is significantly better at higher pressure difference conditions. The pressure difference influences the temperature efficiency the most in lower fan speed levels.

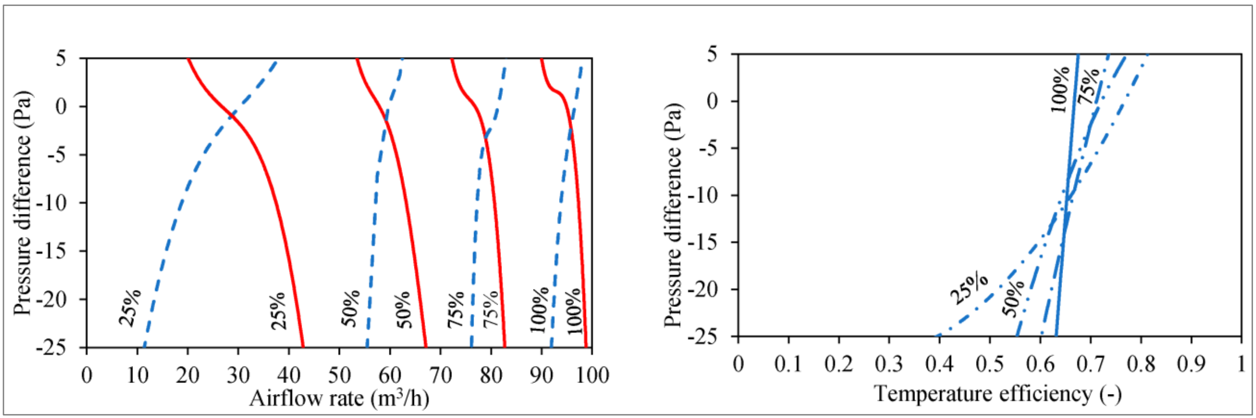


Figure 36. measured performance curves and temperature efficiencies of BVU with two centrifugal fans and recuperative heat exchanger

Source: Mikola, A., Simson, R., Kurnitski, J. (see footnote)

The performance curves of both BVU-types illustrate that – even at 0 pascal pressure difference - the airflow balance differs for each fan speed. With higher delta P, the airflow balance progressively deteriorates particularly for the alternating units, leading to considerable reductions of the heat recovery efficiency and thermal comfort.

The paper finally concludes that test results show, that in cold periods, apartments in the first floor can be under negative pressure as high as −20 Pa for longer periods of time. In ventilation system planning, values of −10 Pa in fifth floor, −15 Pa in third floor and −20 Pa in first floor apartments can be recommended to be used as design values for ventilation units. The simulation results of single room units with regenerative HEX show that during heating season, supply air temperature was close to the outdoor temperature and that supply airflow rate was much higher than exhaust airflow rate, showing that the unit operated as air intake. Due to the differences in supply and exhaust airflows, there is a risk for freezing the heat exchanger, which excludes using studied ventilation units in rooms with high humidity.
The laboratory measurement results confirmed, that the axial fan used in the ventilation unit was not capable to work in typical pressure conditions occurring in multi-story building in cold periods, in order to achieve sufficient air change rate, heat recovery and supply air temperature, with noise levels under acceptable limits. In the case of the unit with recuperative HEX and centrifugal fans, under the same circumstances, the temperature efficiency of the unit remained higher than 0.5 even under negative pressure as high as−25 Pa, making it possible to use the device in first floor apartments.

3.2.2 Project EwWalt

In the project 'EwWalt'[11] (Energetische Bewertung dezentraler Einrichtungen für die kontrollierte Wohnraumlüftung mit alternierender Betriebsweise), some of the gaps in knowledge concerning the performance of these alternating units are further addressed. Topics like system design, sensitivity to pressure differences, characteristic heat recovery

[11] Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C., EwWalt - Energetische Bewertung dezentraler Einrichtungen für die kontrollierte Wohnraumlüftung mit alternierender Betriebsweise, TGA-Report Nr. 6, Veröffentlicht: 03/2019, Bestell-Nr.: 335

performance, ventilation effectiveness and appropriate test standards, are further investigated in this study that is performed under the supervision of RWTH Aachen, with contributions from HLK Stuttgart and ITG Dresden.

System designs
Various system designs were simulated using CFD-calculations. For both apartment buildings and single-family dwellings, different system designs were evaluated, all within the preconditions stipulated in the DIN 1946-6:2009.

Building:

- New built (insulation values according to DIN 1946)
- Airtightness: n50 = 1
- Wind conditions: weak winds
- Wind shielding correction factor: ε_A = 1.00
- Correction factor for height: ε_H = 1.00

Ventilation units

- Basis is 'Nennlüftung'
- Max. airflow for a pair of alternating BVUs is 45 m3/h
- Alternating BVUs may only be applied in pairs (electronically connected)
- In kitchens and bathrooms on external facade, twin-units are applied (= a pair of alternating BVUs)
- In internal bathrooms, extraction UVUs are applied with max. airflow of 60 m3/h
- Overflow components in internal doors to allow airflow between rooms
- Alternating BVUs are placed at the height of the window lintel, 30 cm distance from a window, opposite of the internal door

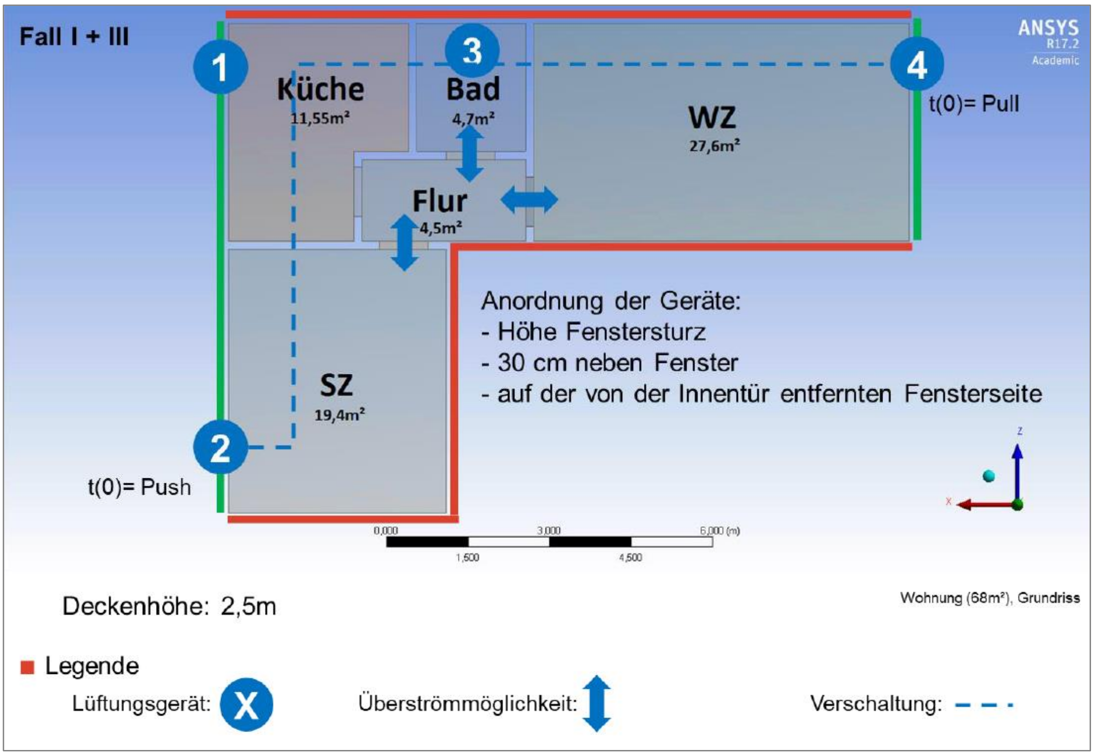


Figure 37. System design Case I and III for an apartment: Alternating BVU No. 2 and 4 are connected (a pair) and require an overflow between SZ (bedroom) and WZ (living room), No. 1 is a twin-unit and No.3 is an extract UVU which also requires an overflow.

Source: Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C.: EwWalt Study

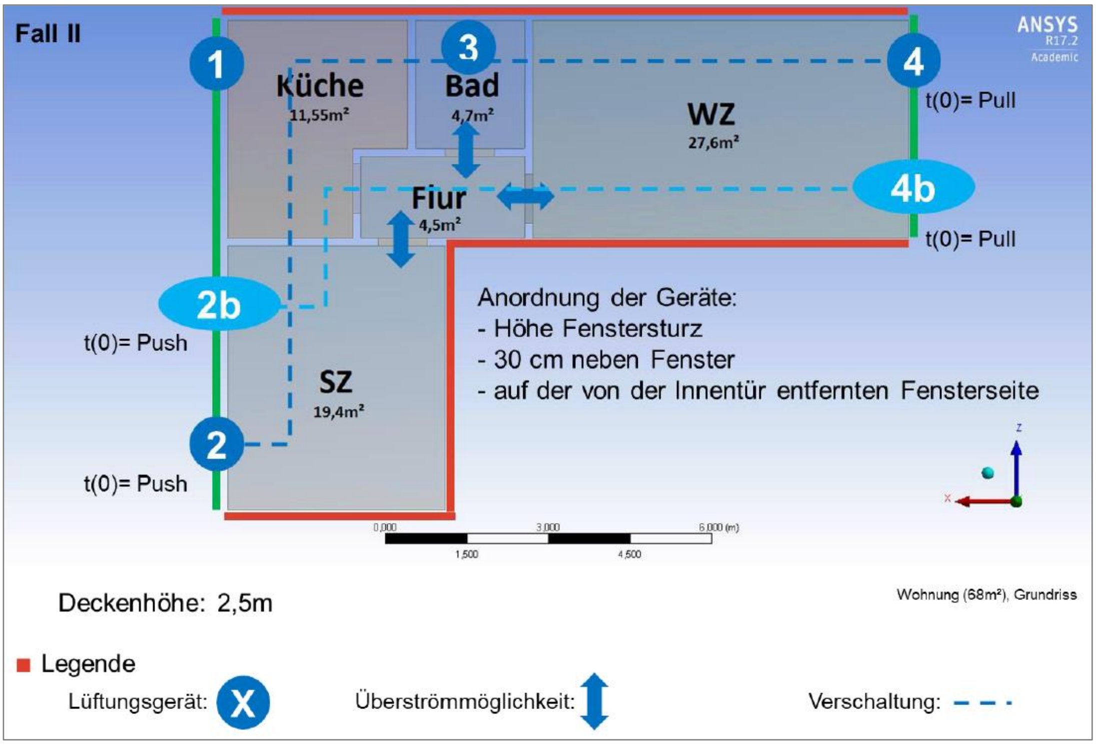


Figure 38. System design Case II for an apartment: Alternating BVUs No. 2 & 2b and 4 and 4b are connected (a pair in both habitable spaces), No. 1 is a twin-unit and No.3 is an extract UVU which requires an overflow.

Source: Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C.: EwWalt Study

Ventilation effectiveness

Comprehensive CFD-calculations were performed for the various system designs under various conditions (varying indoor/outdoor temperatures, wind pressures, bathroom extraction flowrates, and cycle-times) to simulate the airflows and related *air exchange effectiveness* in the various rooms.

This air exchange effectiveness (ε^a) represents the ratio between shortest possible time needed for replacing the air in the room (τ_n) and the average time actually needed for the air in the room to be exchanged (τ_{exe}):

The average time for air exchange can be calculated as $\tau_{exe} = 2 \cdot \langle \tau \rangle$, where $\langle \tau \rangle$ represents the average of local values of age of air. The shortest possible time needed for replacing the air in the room (τ_n) is a reciprocal value of the number of air changes in the room ($\tau_n = 1/n_{AC}$). Table 6 presents the air exchange efficiency values for characteristic flow types.

Table 6. Air Exchange Effectiveness for characteristic room ventilation flow types

Flow pattern	Air exchange efficiency	Comparison with the average time of exchange
Unidirectional flow	0.5 - 1.0	$\tau_n < \tau_{exc} < 2\tau_n$
Perfect mixing	0.5	$\tau_{exc} = 2\tau_n$
Short Circuiting	0 - 0.5	$\tau_{exc} > 2\tau_n$

The CFD-calculations indicate that, irrespective of the various conditions, the air exchange effectiveness of the various system designs with alternating BVUs is on average predominantly around 0.5. Due to the an-isothermal airflow coming from the alternating BVUs, the mixing of the supply airflow is enhanced (similar to recuperative BVUs). The spread around this mean is somewhat bigger though for alternating units.

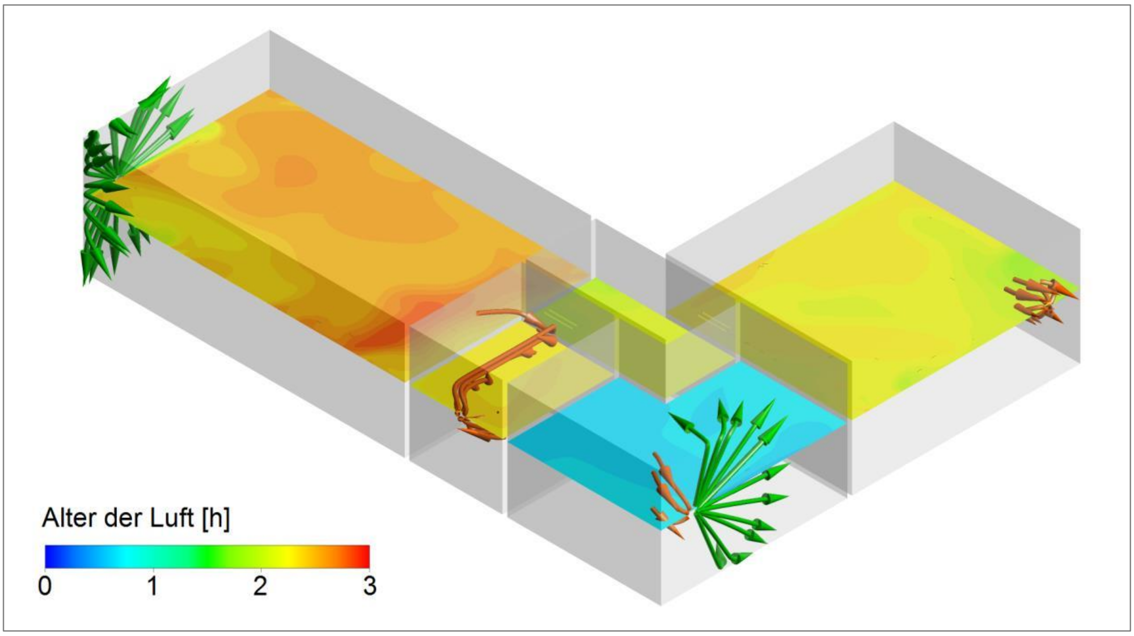


Figure 39. Example plot of a simulation of the age of the air in the various rooms with active extract ventilation according 'Nennlüftung'

Source: Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C.: EwWalt Study

Conditions that have the strongest influence on the magnitude of these variations are wind pressure and airtightness of the dwelling.

Sensitivity to pressure differences

In the EwWalt project the airflow characteristics of three different alternating BVUs (appliance A, B and C) were measured according FprEN 13141-8. The maximum flowrates measured were 28 m3/h for appliance A, 23 m3/h for B and 30 m3/h for appliance C. Their respective airflow sensitivity (to pressure differences) are given in the graphs below.

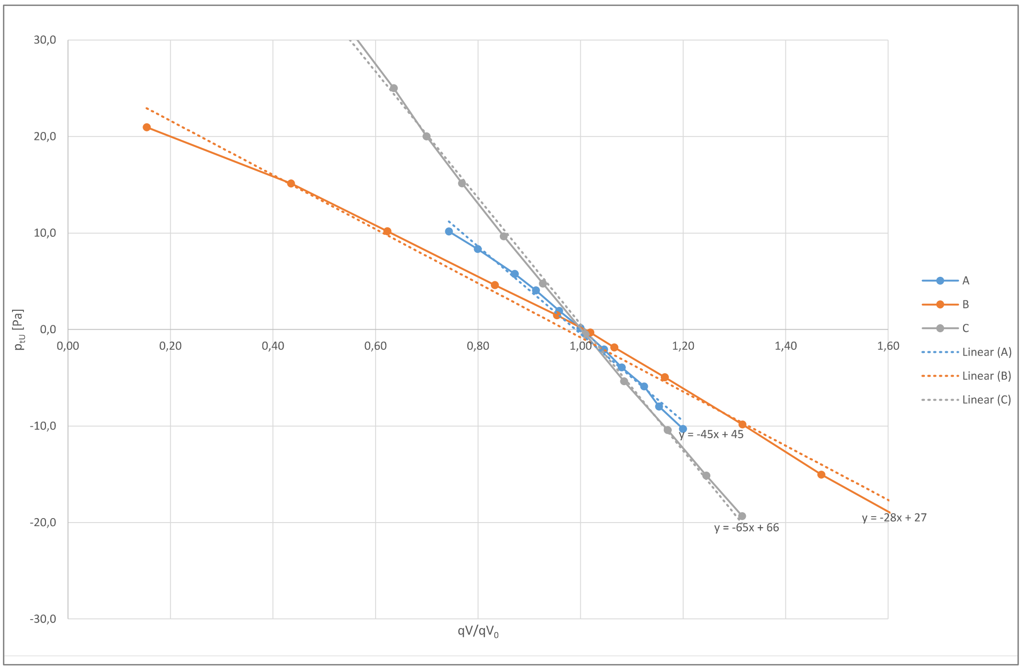


Figure 40. Maximum airflow characteristics (qv,max) of alternating BVUs A, B and C

Source: Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C.: EwWalt Study

Appliance B (red line) is the most sensitive to pressure differences. At 10 Pa the maximum airflow against the pressure is reduced with 38% and with pressure increased with around 32%. Appliance C is the less pressure sensitive: at +10 Pa the maximum airflow against the pressure is reduced with 15% and with the pressure, increased Pa with around 17%.

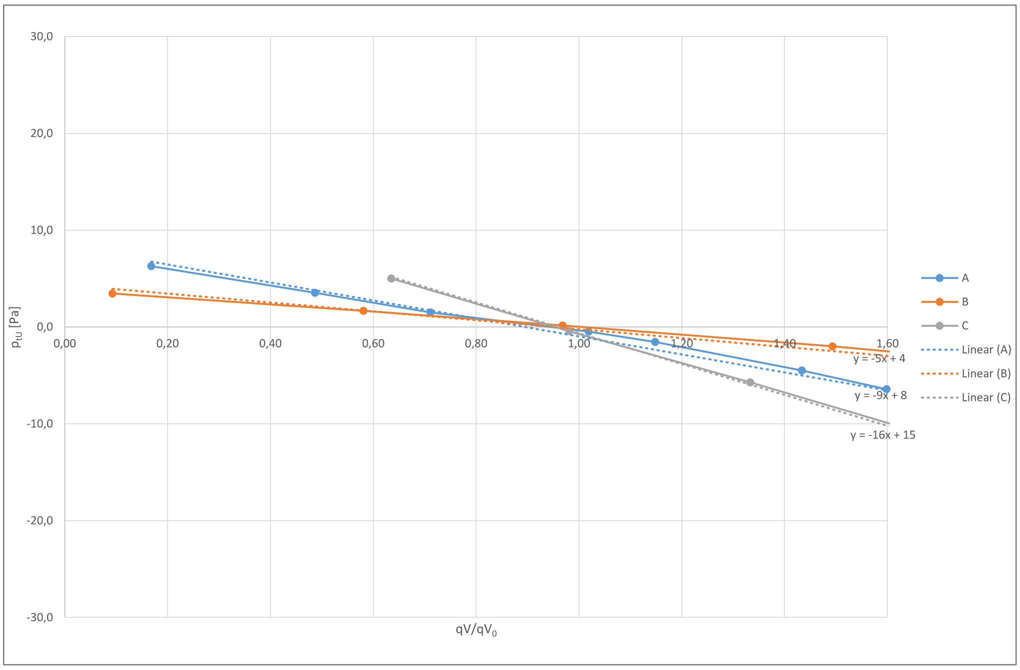


Figure 41. Minimum airflow characteristics (qv,min) of alternating BVUs A, B and C

Source: Mathis, P., Röder, T., Klein, B., Hartmann, T., Knaus, C.: EwWalt Study

Also, at minimum airflow appliance B (red line) is the most sensitive to pressure differences. At +5 Pa the minimum airflow is reduced with 90% and at -5 Pa with around 80%. Appliance C is the less pressure sensitive: at +5 Pa the minimum airflow is reduced with 35% and at -5 Pa with around 30%.

This means that the sensitivity to pressure differences is high, especially at lower flowrates, indicating that the heat recovery function is severely compromised. For dwellings with alternating BVUs on opposite sides of the dwelling, a high airflow sensitivity will have only limited effects on the total air exchange airflows, due to cross ventilation. But for dwellings with alternating BVUs on only one pressure side of the dwelling, the consequences will be considerably bigger because cross ventilation is not applicable.

Heat recovery & test standards

In the EwWalt project, heat recovery measurements according to the direct method (following an older version of the EN 13141-8) were compared to HR measurements according to the indirect (or purge-air) method (following the DIBt). There are also differences in the applicability of both methods (see table below).

Table 7. Applicability of test methods

	Direct method (EN13141-8:2018)	Indirect method (DIBt)
Independent of appliance properties	-	+
Exhaust air temperature efficiency	+	+
Temperature efficiency humid air	+	+
Humidity transfer efficiency	-	+
Applicable to recuperative BVUs	O	+

The comparative measurement results show that that the temperature efficiency figures are higher (too high?) and less accurate (due to inhomogeneous supply airflow) when the direct method is used. The differences between the two methods are around 6% for the supply air temperature ratio and around 10% for the exhaust air temperature ratio.
In the new prEN 13141-8 adjustments will be made regarding the testing of heat recovery for alternating units and the purge air method (indirect method) will be used.

3.2.3 Overall valuation alternating BVUs

As regards the air exchange effectiveness, alternating BVUs can successfully deployed, as long as they are installed in pairs and - in case buildings suffer from prevailing increased pressure differences over the building -, the units can be installed on both pressure sides of the building.
In case only one pressure side of a building can be used for installing alternating BVUs, an increased pressure difference over this facade will influence the air exchange effectiveness, especially in cases where the supply airflow is compromised (i.e. ε^a will become lower than 0.5). In addition, requested ventilation rates may not always be achieved.

In a way, alternating BVUs can be considered a hybrid solution, combining properties of passive pressure-controlled ventilation grids with characteristics of fans driven recuperative BVUs. When there is no or minimal pressure difference over the façade holding the alternating BVUs, they will function as intended both in terms of air exchange effectiveness and heat recovery.
When the pressure difference over the façade increases, the units on one pressure side of the building will have higher supply airflow and lower exhaust airflows, while the units on the other pressure side of the building have the opposite. Due to cross ventilation the air exchange effectiveness remains, but the heat recovery function is compromised. Under such conditions, alternating BVUs show similarities with passive pressure-controlled ventilation grids that also rely on cross ventilation when pressure differences over the facades of the building increases.

As regards basic ventilation (Feuchteschutzlüftung) and Nennlüfting (when considered over the whole building and when related to airtight buildings), the use of sensor controlled alternating BVUs represent a considerable improvement compared to window ventilation (Fensterlüftung), mainly because manual operation (of windows) is no longer requested and comfort issues are reduced. And in addition, some heat is also recovered.

But when targeted room-based ventilation airflow rates are pursued, following EN16798-1 and related airflow rates belonging to IAQ-category I or II during *presence* and basic ventilation rates during *absence*, alternating BVUs will find difficulties meeting these requirements for the following reasons:

- Pressure differences can strongly influence the supply airflow rate. Many factors can disturb the preferred zero pressure difference between inside and outside and with it, the requested supply airflow, amongst which: wind load building/facade, temperature gradient of the air, temperature difference (between inside and outside), use of a chimney (open fire, passive stack), etc.
- In the case alternating BVUs are installed on both pressure sides of the building, the supply air in a room may result from cross ventilation, in which case the position of the internal doors, the airtightness of the building, and the operating modes of the other BVUs will have an influence.
- In the case alternating units are only installed on one pressure side, supply airflows will either be too big or too small.
- To achieve IAQ class I or II airflow rates during presence, a pair of BVUs needs to be installed in each and every habitable room. Following EN16798-1, a parent bedroom for instance requires 70 to 50 m3/h of airflow respectively during presence (to keep CO_2-levels below limit values), implying that the bedroom requires a pair of alternating BVUs operating at maximum airflow rates, producing around 46 dB(A) of noise. Provided that pressure differences are limited and the supply airflow rates are actually achieved, noise production could become an obstacle for achieving class I or II airflow rates.
- The airflow sensitivity of the alternating BVU is an even greater problem for achieving basic ventilation rates during absence. Because its sensitivity increases at lower flowrates, it will be even harder to achieve these low flowrates during absence, in which case cross ventilation is practically indispensable to achieve requested basic ventilation rates. Dwellings that do not have two opposite facades will have difficulties achieving basic ventilation rates in all rooms using alternating BVUs.

An additional topic that needs further investigation and clarifications concerns the products hygiene. Do the humidity recovery function combined with alternating airflows pose any risk in the hygiene and health area? It is unknown whether sufficient research has already been done here.

Summary

Sensor controlled alternating BVUs represent a considerable improvement compared to window ventilation commonly applied in Germany and some other member states. Compared to this convectional way of window ventilating, alternating BVUs improve both the air exchange (ventilation) performance and the energy performance.
When judged against to the objective of achieving optimal ventilation performance (*'targeted ventilation during presence with category I or II IAQ-related airflow rates and maximized heat recovery and basic ventilation during absence'*) alternating BVUs will have

difficulties meeting these performance goals, mainly due to their airflow sensitivity, related reduced heat recovery and noise production. Due to this, the occurring airflow rates coming from alternating BVUs cannot be tailored to the actual airflow needs in the various individual rooms. This reduces both the ventilation performance and energy performance of alternating BVUs. Values resulting from the airflow sensitivity tests (FprEN 13141-8) will need to be used to correct the temperature and humidity efficiency figures and to correct the ventilation performance figure.
As proposed in the Task 3 report, the temperature efficiency figure is to be corrected according to Table 2 of the FprEN 13142: instead of η_0 the corrected η_5 will be used, with holds (amongst others) a correction for the airflow sensitivity. In addition, it is proposed in Task 3 to apply a correction factor when determining CTRL-factor, based on the airflow sensitivity figure (*v*) and the indoor/outdoor airtightness q_{vio} of the unit.

4. Enthalpy heat exchangers

Enthalpy heat exchangers are air to air exchangers that are also capable of transferring the humidity content from one airflow to the other airflow. For the indoor relative humidity during winter times this is generally an advantage because it helps maintaining indoor RH-values within the comfort zones (see Figure 42). Without humidity transfer the indoor air can become very dry (< 30% RH).
In summertime, humidity transfer is convenient in the warmer climates, because the it reduces the thermal capacity of the humid supply air, which reduces the energy consumption for cooling.

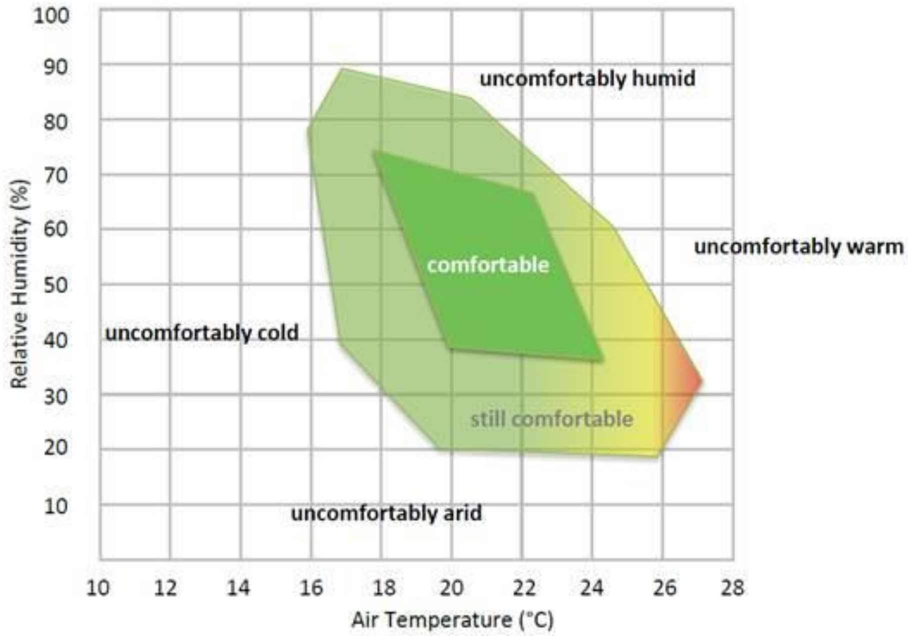


Figure 42. Indoor climate comfort zones

In other words, humidity transfer additional to the transfer or sensible heat clearly represents an added value which is currently not valued in the Ecodesign and Energy labelling Regulations for VUs.

Three different technical principles for enthalpy heat exchangers are offered on the market:
1) Rotary heat exchangers or rotary wheels
2) Enthalpy plate heat exchangers, using a water vapour permeable sheet or membrane
3) Regenerative alternating air flow heat exchangers

4.1 Rotary wheels

At the moment, these types or enthalpy heat exchangers are probably most popular in the non-residential sector. The concept of a rotary wheel is simple. At the point in a building's ventilation system where fresh air and exhaust air run counter currently, but adjacent to each other, a rotary wheel can be placed in the ventilation system such that half of the wheel will be exposed to fresh, incurrent air, and the other half to contaminated, excurrent air. This allows the rotary wheel to absorb the desired temperature and humidity properties of the excurrent air (which has been conditioned to be suitable for within the building) and transfer them to the incurrent air. In this way, the incurrent air is preconditioned to be close to a desired temperature and humidity. This process is passive and can significantly reduce the energetic and monetary cost of using new energy and moisture to treat incurrent air. Depending on the conditions, energy recovery wheels can reduce the energetic demand of conditioning incurrent air by up to 90%.

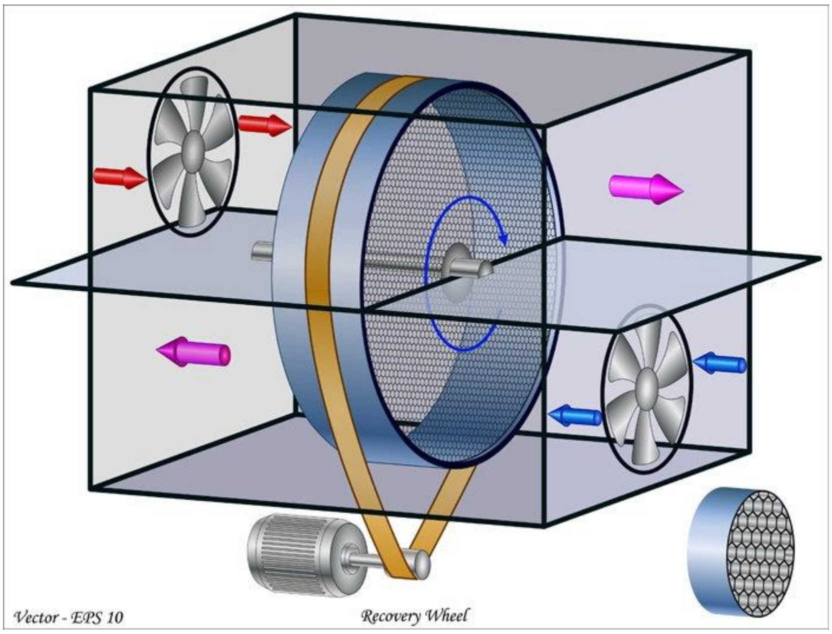


Figure 43. Principle of the energy recovery wheel (ERW)

Source: https://web.uponor.hk/radiant-cooling-blog/understanding-energy-recovery-wheels/

The energy recovery wheel (ERW) is made of a complex lattice of sensible energy absorbing metal alloy, which is usually coated with a moisture absorbing substance such as silica gel or a molecular sieve. The honeycomb matrix of metal and moisture absorbing material maximizes the surface area the air passes over, to optimize the area for energy transfer. As the excurrent air passes through the ERW, the half of the wheel exposed will absorb sensible and latent energy from the air, and then carry that energy as it slowly rotates, to be exposed and transferred to the incurrent air to be released. The physical properties of the ERW allow it to be adjusted to either warm up or cool down, to humidify or desiccate, incurrent air into a building. This adjustment capability is critical for the functionality of the ERW in different seasons. In a hot, humid summer the ERW can be used to passively cool down and desiccate the incurrent air into a building, and in winter then ERW can be used to warm up and humidify the incurrent air into the building. In both cases, the ERW recycles the desirable properties of the air already inside the building, transferring that energy, rather than forcing the use of new energy.

<u>Cross contamination</u>

It is not very well known that there can be issues regarding the materials used for humidity transfer in regenerative heat exchangers like rotary wheels.
There are several materials that can be used for coating the aluminium or fibre matrix of the energy recovery component. Commonly used sorption materials are *silica gel*, *molecular sieves*, *ion exchangers*, *zeolites* etc. Possible transfer of other gases besides water vapor is very probable with some of these materials. It is claimed that up to 20-40% of exhaust air VOC gases can be carried over in the matrix material (MBCO= matrix borne carry over) to supply air, if wrong type of sorption material is used. When limit values are of 5% on EATR are used for obvious reasons, it is also justifiable to discuss and consider this matrix borne carry over (MBCO).

Silica gel and zeolite e.g. are also used in some applications for removing organic solvents and other VOC types, i.e. proving the obvious risk of VOC carry over in the matrix (MBCO).

Together with the suppliers of these materials, one has to discuss how the VOC gas transfer can be minimized e.g. by using the correct materials and how find other ways to limit the possible VOC carry over to values of maximal 5-10% (to be discussed).

Some examples of Rotary wheels

Figure 44. Non-residential BVU/NRVU: CASA R15 Smart

Source: https://www.swegon.com/globalassets/_product-documents/home-ventilation/air-handling-units/swegon-casa-r-series/_en/r15_smart_en_p.pdf

Manufacturer	: Swegon
Drive type	: Variable speed drive
HR-system	: Regenerative / rotary
Temperature eff.	: Up to 86% (EN308), compliant with Ecodesign limit value
Casing sound power	: 50 dB(A)
Flowrate	: 360 - 1710 m3/h
Controls	: Demand-controlled humidity function (standard)
	: Automatic summer function and passive cooling
Anti-frost protection	: yes
SFP	: ?
External leakage	: ?
EATR	: ?
AOCF	: ?
Energy Label	: n.a.
Dimensions	: WxHxD = 1080 x 788 x 1100 mm

Figure 45. BVU: Domekt-R-300-V-R1-M5

Source: https://www.komfovent.com/en/product/domekt-r-300-v-2/

Manufacturer : Komfovent
Drive type : Variable speed drive
HR-system : Regenerative
Thermal efficiency : 85%
Casing sound power : 40 dB(A)
Reference flowrate : 220 m3/h
Reference ΔP : 50 Pa
SPI : 0.28 $W/m^3/h$]
CTRL factor : 0.65
External leakage : < 1%
Carry over : <0.5%
Energy Label : A+
Dimensions : WxHxD = 502x610x598

4.2 Enthalpy plate heat exchangers

Recently, enthalpy plate heat exchangers are gaining momentum, especially in the residential sector. They save heating- and cooling energy and control the humidity of the air supplied. They humidify the air in wintertime and dry the air in the summertime. Another important advantage relates to the fact that enthalpy plate heat exchangers are not easily covered by ice during low outdoor temperatures (unlike the conventional counter- or cross flow plate heat exchangers).
Enthalpy plate heat exchangers are made from a special membrane that allows the return of moisture back onto the premises (which cannot be done with conventional plate heat exchangers).

Polymer membrane enthalpy he

Amongst others, the company dPoint Technologies produces a polymer membrane that is frequently used in enthalpy plate heat exchangers. This membrane consists of a dense continuous selective film layer (<5 microns) on a porous substrate, having the following properties:

- High transport of water vapour
- High selectivity
- Excellent dimensional stability, durability
- Wash-able, freeze tolerant
- Antimicrobial resistance

The membrane is tested on VOC and contaminant cross over. Furthermore, fungal tests according to ISO 846A and AATCC 30 are performed on the material, as are bacterial tests according to ISO 846C and AATCC 147.
The hygiene is ensured at any time due to the anti-microbial properties of the membrane using Microban®. Only heat and water vapour are transferred.

In a study[12], performed by the Department of Building Service Engineering, Faculty of Mechanical Engineering of the Budapest University of Technology, the performance of two counterflow heat exchangers were tested and compared: a sensible heat exchanger using polystyrene as he-material, and an enthalpy plate heat exchanger using polymer membrane and he-material. The energy exchange performance were experimentally tested under different operating conditions by selecting three European cities with three different climate zones (cold climate Reykjavik, average climate Budapest and warm climate Rome). The results show that the energy recovery from ventilation air using the polymer membrane (indication PEE) counterflow heat exchanger performs better that polystyrene based (indication PHE) counterflow heat recovery unit.

Figure 46 and Figure 47 give the calculated energy savings for the two heat exchanger types during the winter period and summer period. The additional savings related to the humidity transfer of the enthalpy heat exchanger are significant and may be sufficient to account for the additional investment cost related to this type of heat exchanger.

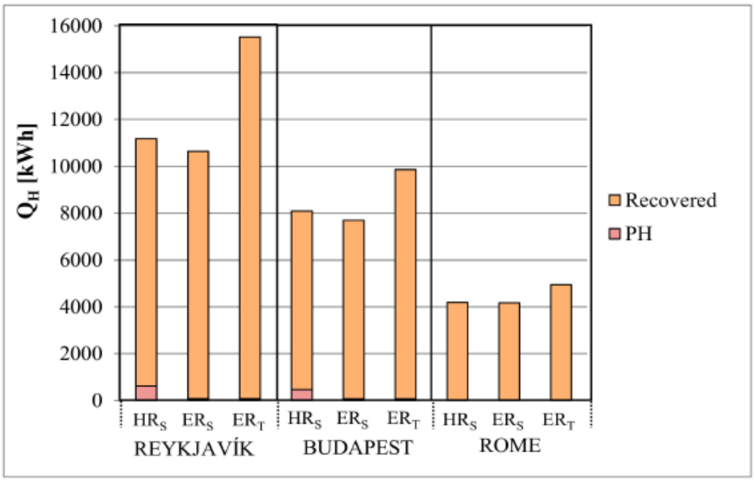


Figure 46. Energy recovered during heating period (HR_S = recovered sensible heat in PHE; ER_T = total recovered energy in PEE)

Source: Kassai, M., Al-Hyari, L. (see footnote)

[12] Kassai, M., Al-Hyari, L., Investigation of Ventilation Energy Recovery with Polymer Membrane Material-Based Counterflow Energy Exchanger for Nearly Zero Energy Buildings, Energies 2019, 12, 1727; doi:10.3390/ en12091727.

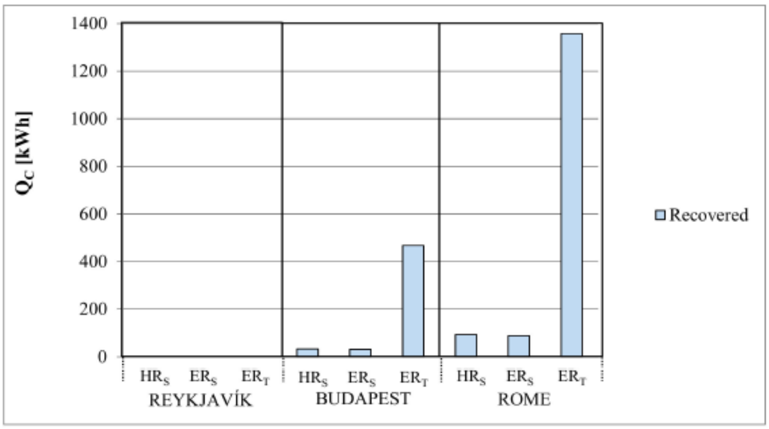


Figure 47. Energy recovered during cooling period (HR_S = recovered sensible heat in PHE; ER_T = total recovered energy in PEE)

Source: Kassai, M., Al-Hyari, L. (see footnote)

Example of polymer membrane Enthalpy plate heat exchangers

Figure 48. residential BVU: Zehnder ComfoAir Q350 ERV

Source: https://www.international.zehnder-systems.com/products-and-systems/comfosystems/

Manufacturer	: Zehnder
Drive type	: Variable speed drive
HR-system	: Recuperative/enthalpy
Thermal efficiency	: 85%
Casing sound power	: 40 dB(A)
Maximum flowrate	: 350 m^3/h
Reference flowrate	: 245 m3/h
Reference ΔP	: 40 Pa
SPI	: 0.15 W/m^3/h]
CTRL factor	: 0.65 (2 sensors)
External leakage	: < 1,2 %
Internal leakage	: < 1.8 %
Energy Label	: A+
Dimensions	: WxHxD = 725x850x570

Paper enthalpy he

Another material that is used to create enthalpy plate heat exchangers is treated paper. The Lossnay core is an example of such a product.
The Lossnay core is a crossflow energy recovery unit constructed from specially treated paper with a corrugated structure. The fresh air and exhaust air passages are totally separated allowing the fresh air to be introduced without mixing with the exhaust air.
The Lossnay Core uses the heat transfer properties and moisture permeability of the treated paper. Total heat (sensible heat plus latent heat) is transferred from the stale exhaust air to the ventilation air being introduced into the system when they pass through the Lossnay.

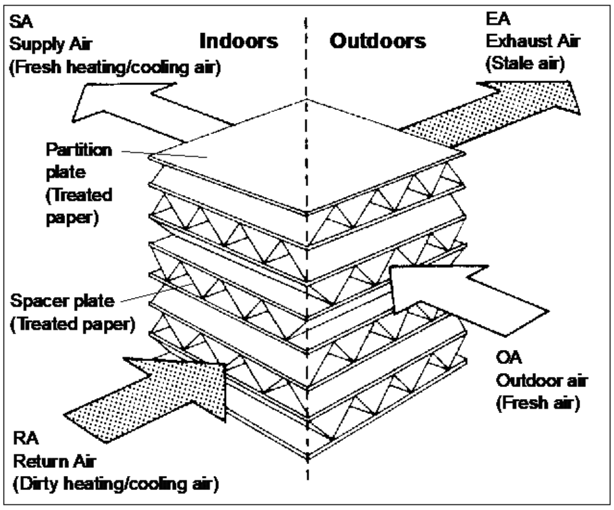


Figure 49. Lossnay core construction

Source: http://www.mitsubishielectric.com.au

The paper partition plates are treated with special chemicals so that the Lossnay Core becomes an appropriate energy recovery unit for ventilation purposes. The he-membrane itself has the appropriate qualities, amongst which:

- Incombustible and strong.
- Selective hygroscopicity and moisture permeability that permits the passage of only water vapor (including some water-soluble gases).
- Gas barrier properties that do not permit gases such as CO_2 from entering the conditioned space.

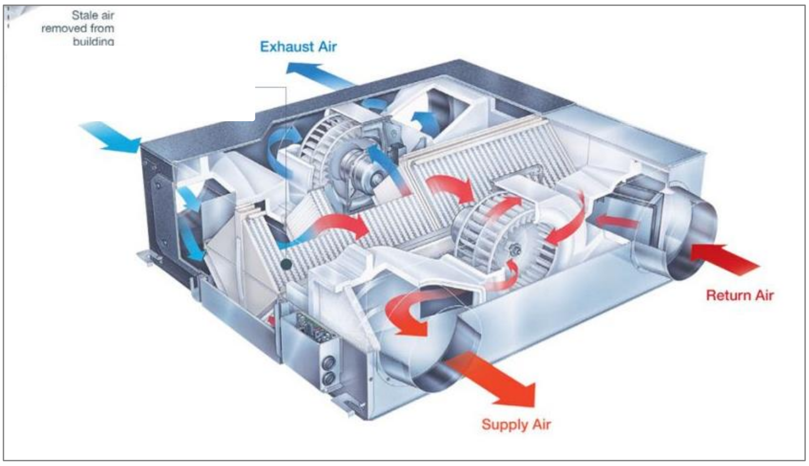


Figure 50. Losnay residential BVU

Source: http://www.mitsubishielectric.com.au/2096.htm

4.3 Regenerative heat exchangers with alternating airflows

This type of enthalpy heat exchanger also uses the regenerative heat exchanger type like in rotary wheels, but now the airflow is redirected, instead of moving (rotating) the heat exchanger itself.

The heat recovery ventilation system consists of two static accumulation masses that alternately are heated by the exhausted warm air. The damper system serves to direct the flow of air in and out in the relevant areas of accumulation. The sector loaded with warm exhaust air is used in the next cycle for the incoming air. This is heated almost to the temperature of the indoor environment and is introduced into the building through the air entrance. At the same time after that the sector with the air inlet has been discharged, it is automatically converted on the flow of exhausted air, in this way the sector is again heated in the next cycle.

Adjustments to the energy-recovery performance can be made through the variation on the time interval of the frequency deviation of the dampers, which can be adjusted from 100% to 0%. With 0% value, the dampers are no longer changed and it enables a free cooling of the building through the air entrance. The gradual adjustment of the system can be regulated with any desired control algorithms.

Like with rotary systems, the alternation of exhaust and supply airflows in the heat exchanger sections, ensure that the heat recovery system is frost resistant. Therefore, it does not need expensive bypass systems or preheating.

The paragraph on cross contamination in section 4.1 is also applicable for the types of enthalpy exchangers.

<u>Some examples</u>

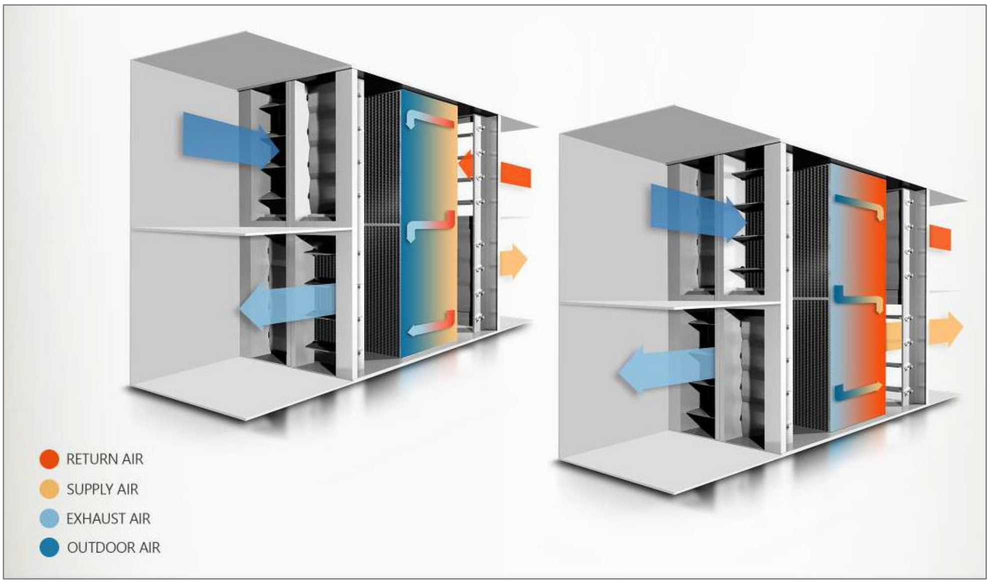


Figure 51. Enthalpy exchanger in non-residential BVU/NRVU: Accuair Enthalpy System

Source: https://ericorporation.com/products/enthalpy-exchanger-accuair/

Manufacturer	: ERI Corporation
Maximum airflow	: various sizes means various q_{max} values
Temp. efficiency	: up to 90%
Hum. Recovery	: up to 70%
Dimensions	: depends on selected size; from H*W*L = 1135*600*1510 mm to 2505*2400*1819 mm

A BVU-unit similar to the one described in Figure 51 was tested at the Galway-Mayo Institute of Technology in Galway Ireland. A paper[13] that was presented during the CLIMA 2019 on this topic describes the main results:

The aim of the study was to investigate the thermal performance characteristics of a reverse-flow energy recovery ventilator (RF-ERV) designed for domestic indoor climate control applications. The principle of operation of the RF-ERV in cold climates is described. A total of eight steady state tests were conducted in a controlled test environment under various operating conditions. Ventilation rates ranged from 144.2 to 330.8 m^3/h, the enthalpy ratio ranged from 72.8% to 88.6%, temperature ratio ranged from 86.0% to 92.9% and humidity ratio ranged from 9.8% to 77.1%, respectively. Maximum recovered energy of 2218.7 W, 1794.5 W and 424.2 W for total, sensible and latent heat was calculated under Test 8 conditions, respectively, corresponding with a total electrical power input of 111.1 W. During the sub-zero Celsius ODA Tests 7 and 8, the RF-EVR flap switching interval of 300 seconds was sufficient to avoid ice formation and therefore negates the need for frost protection unit. Subsequently, the highest recovery efficiency ratio (RER = total recovered thermal energy – total electrical power input) of 19.97 was recorded under these conditions.

The regenerative heat exchangers that are used in non-ducted alternating BVUs (see section 3.1) are also capable of transferring the humidity from one airflow to the other airflow. These regenerative he-cores generally have a honeycomb-like shape. The biggest hole number is around 40 per square centimeter and its density around 4~6 grams per cubic centimeter. The water absorption rate is above 20%.
Materials used here are e.g. Cordierite, Corundum Mullite, Mullite or Silicon Oxide.

Figure 52. Enthalpy regenerative exchanger in residential non-ducted alternating BVU

Source: https://www.ventilation-alnor.co.uk/index/products-en/heat-recovery-%E2%80%93-air-handling-units/heat-recovery-units-hru-wall/

These materials however are also used in abatement of Volatile organic compounds (VOC) , hazardous air pollutants (HAP), carbon monoxide (CO), nitrogen oxides (NOx), organic particulate matter (OPM), HC nytron, SO_2, odours, and other air toxics in oil and chemical industry through a regenerative thermal oxidizer (RTO) device.

[13] Hunt, D., Mac Suibhne, N., Dimanche, L., McHugh, D., Lohan, J., Thermal performance characterization of a reverse-flow energy recovery ventilator for residential building application, CLIMA 2019, http://doi.org/10.1051/e3sconf/201911101010

Possible transfer of other gases besides water vapor is therefore very probable with some of these materials. Together with the suppliers of these materials, limit values for the matrix borne carry over to the supply air (MBCO) need to be discussed to minimize this risk.

5. Filter technology

5.1 Introduction

Although ventilation plays a crucial role in maintaining a clean indoor environment, in some cases ventilation systems can also be a source for airborne pollutants as a result of polluted outdoor air, inadequate system design, internal leakage and cross-contamination, etc. Thus, air filtration technology plays a key role in protecting human health by removing indoor and outdoor air pollutions.

Mechanical ventilation (exchanging indoor air with outdoor air using one or more fans), consumes both heating energy and electricity. The use of filters will increase the electricity consumption for ventilation because filters increase the resistance in the flow path of the supply and exhaust air. It is therefore important to try to reduce the additional pressure induced by filters. To give a rough indication: an increase of 50 pascal for filter purposes in the ventilation supply airstream of on average 110 m^3/h in all EU28 dwellings would results in an additional total annual power consumption of around 6.5 TWh[14] (26 kWh/an/hh).

And if parts of the indoor air can also be cleaned by filtration and recirculation (i.e. without exchanging indoor air with outdoor air) this could also contribute to further energy savings without compromising on IAQ, because heating energy is no longer necessary to reheat the fresh outdoor air.

Technical developments related to these two topics will be further discussed here.

5.2 Filtration and pressure drop

Filters may be used for the filtering of both particulate matter (PM) and gas-phase pollutants (VOCs, odours, etc.) that are present in the outdoor- or indoor air. This section 'on filters and pressure drop' only refers to filters that are used for removing PM, because there are no test standards (yet) for gas-phase pollutants and their application for indoor air in buildings still is limited (see further explanation under section 5.3.2).

With around 80%, energy consumption represents the largest share in the total lifecycle cost for filters. Remaining 20% relates to initial investments and disposal (source : https://filterservices.com/pressure-drop-considerations-in-air-filtration/). The pressure drop of the filter is the precursor for the energy consumption.

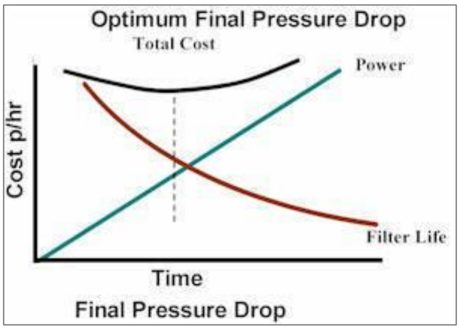


Figure 53. Optimum filter costs

[14] TWh_{deltaP} = (qv*deltaP*hours*No EU28 dwellings)/(eta_{fan}*1000) = 0,03*50*8760*250*10^6/(0.5*1000)=6.57 TWh

Source: R.H. Avery, Optimum Final Pressure Drop, *NAFA Guide to Air Filtration* 3rd Edition, Chapter 13

Figure 53 illustrates the optimal change-out point of an air filter – that point where the pressure drop increases electrical consumption and overtakes the initial cost of the filter.

Obviously, filter pressure drop is not the same for all the existing filter types and filter brands. The same goes for filter pressure drop at end of life. To manifest the differences between filters, Eurovent further developed their Guideline 4/21-2019 regarding the Energy Efficiency Evaluation of Air Filters for General Ventilation Purposes (see also Task 3 report section 1.8.1).

5.2.1 EUROVENT Guideline on Energy Efficiency of Filters

This Eurovent Guideline that was updated in November 2019:

- Implements the EN ISO 16890 classification and testing methods
- Defines energy efficiency evaluation methods
- Defines the energy efficiency of air filters for general ventilation purposes

The aim of this guideline is to assess the yearly energy consumption based on a laboratory test procedure which can be the basis for an energy efficiency classification, to give the user of air filters guidance for the filter selection.

Two important notes to this:

- In order to actually reduce the energy consumption by using more energy efficient filters, it is also required that the speed of the fan can be adjusted accordingly to supply the requested air (if the fan is operated at a fixed speed, lowering the (average) pressure drop of the air filters will result in an increased air volume flow rate; in the worst case scenario, this may even result in a situation where the fan is operated in a region with lower efficiency resulting in an increased overall)
- The method provided in this document is based on laboratory test data with standardized test conditions, which may differ significantly from the individual application in a building ventilation unit. Hence, the yearly energy consumption calculated following this guideline, can only be used as an indicator for the classification system and relates only to the contribution of the air filters involved. The yearly energy consumption in an individual, actual application may differ from this significantly.

The calculation principle used is as follows:

The energy consumption of a fan in an air handling unit can be evaluated as a function of the volume flow rate supplied by the fan, the fan efficiency, the operation time, and the difference of the total pressure (static plus dynamic pressure) after the fan and the static pressure of the ambient air (assuming that the fan sucks in air from a static reservoir). Typically, the volume flow rate supplied by the fan and the pressure difference the fan has to overcome are related to each other by the characteristic fan curve. The efficiency of the fan is a function of the fan speed. The actual fan efficiency also strongly depends on the design and the layout of the fan and can be in the best case as high as 0.80 or even higher, and in the worst case as low as 0.25 or even lower.

The portion of the total yearly energy consumption which is related to the filters' pressure drop can be calculated using the following equation:

$$W = \frac{q_V \cdot \overline{\Delta p} \cdot t}{\eta \cdot 1000}$$

Where we define: q_V = 0.944 m³/s, t = 6000 h/a and η = 0.5

For a detailed description of the test- and rating method, see the latest version of the Eurovent Guideline 4/21-2019 regarding the Energy Efficiency Evaluation of Air Filters for General Ventilation Purposes.

The certification program applies to air filter elements rated as ISO PM1, PM2.5 and PM10 (according to EN ISO 16890) referring to a front size of 592 x 592 mm and nominal airflow rates between 0.24 and 1.5 m^3/s. The filters shall be declared according to one of the following filter groups (see following tables).

Table 8. Energy classes Eurovent Filter Groups (with Mx = max. dust load, AEC = ann. electricity consumption)

M_X = 200 g (AC Fine)	AEC in kWh/y FOR ePM1					
	ePM_1 and $ePM_{1,\ min} \geq 50\%$					
	A+	A	B	C	D	E
50% & 55%	800	900	1050	1400	2000	>2000
60% & 65%	850	950	1100	1450	2050	>2050
70% & 75%	950	1100	1250	1550	2150	>2150
80% & 85%	1050	1250	1450	1800	2400	>2400
> 90%	1200	1400	1550	1900	2500	>2500

M_X = 250 g (AC Fine)	AEC in kWh/y FOR ePM2.5					
	$ePM_{2.5}$ and $ePM_{2.5,\ min} \geq 50\%$					
	A+	A	B	C	D	E
50% & 55%	700	800	950	1300	1900	>1900
60% & 65%	750	850	1000	1350	1950	>1950
70% & 75%	800	900	1050	1400	2000	>2000
80% & 85%	900	1000	1200	1500	2100	>2100
> 90%	1000	1100	1300	1600	2200	>2200

M_X = 400 g (AC Fine)	AEC in kWh/y FOR ePM10					
	$ePM_{10} \geq 50\%$					
	A+	A	B	C	D	E
50% & 55%	450	550	650	750	1100	>1100
60% & 65%	500	600	700	850	1200	>1200
70% & 75%	600	700	800	900	1300	>1300
80% & 85%	700	800	900	1000	1400	>1400
> 90%	800	900	1050	1400	1500	>1500

Compared to the previous edition, the November 2019-version now includes an Annex 1 in which a method is given for recalculation of energy consumption at air flow rate different that the nominal one (tested). This simple formula was developed based on several tests performed be various manufactures. The formula works well within the Eurovent classification range. The lower deviation of the actual air flow rate from the nominal one, the higher its accuracy.

In their study[15] 'Status on Air Filter Characteristics and Energy Efficiency', the authors analysed a sample of 1800 certified filter test results. The results (see figure below) prove that only a minor portion of certified air filters have proper energy performance and the rest are certified as Classes C, D and E. The authors conclude that the topic filters need more efforts and attention from manufactures to further improve on their filter products.

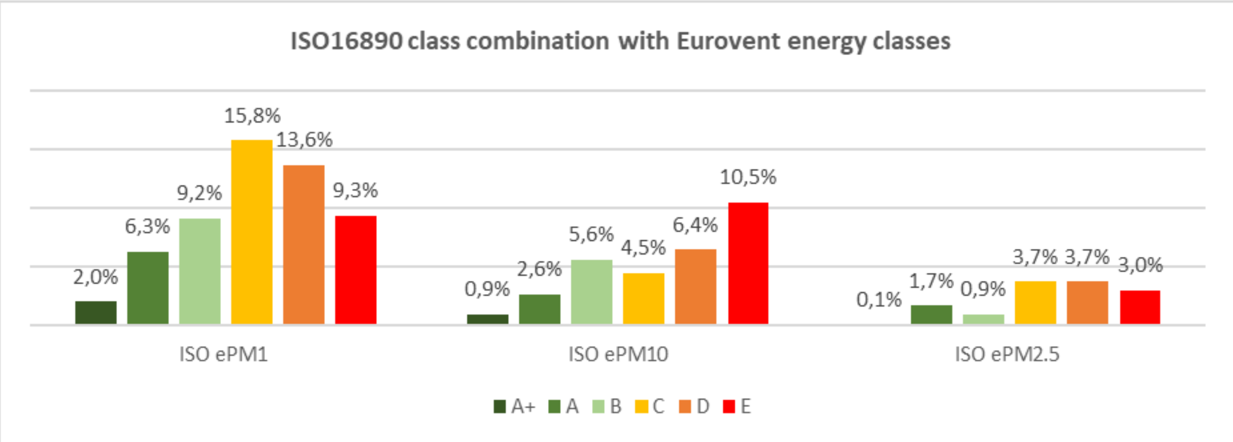


Figure 54. ISO Class rating (ISO 16890) and Eurovent Energy Efficiency Class percentages Source: Vadoudi, K., Kelijian, G., Marinhas, S. (see footnote)

5.2.2 Developments PM-filters and pressure drop

As can be deducted from the previous section, there is still a lot to be gained where the energy performance of filters is concerned. A labelling scheme as developed by Eurovent and its members, can become an important instrument in the pursuit for reduced pressure drops in filter technology.

A technology that is worth mentioning in this context, is the use of electrostatic filters. The EN ISO 16890 allows for the test and assessment of electrostatic filters. The advantage of electrostatic filters over traditional fibre-based filters can be that:

- Due to the working principle the pressure drop can in principle be low (lower) compared to fibre-based filters.
- Pressure drop remains constant or only increases only a little bit with increased dust loading, implying that flow control for the purpose of compensating increased pressure drops are not necessary.
- As a result, the energy consumption due to the filter is constant and does not increase during use.

[15] Vadoudi, K., Kelijian, G., Marinhas, S., Status on Air Filter Characteristics and Energy Efficiency, 40th AIVC Conference, October 2019, Ghent, Belgium.

Figure 55. Example active electronic filter

Source: Expansion Electric

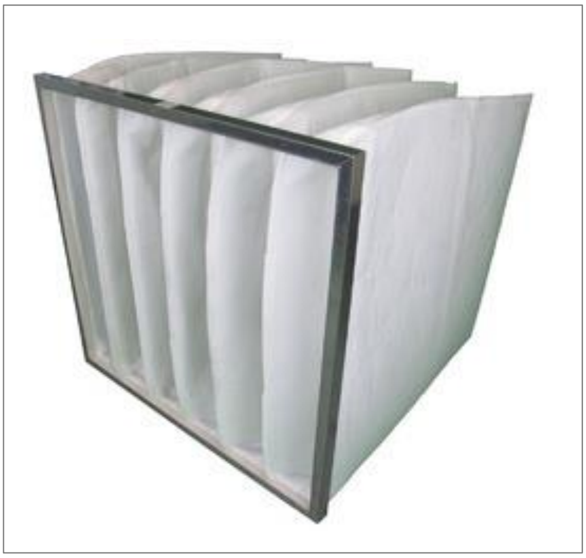


Figure 56. Example pocket filter

Random picture of pocket filter

For comparison, a calculation is made of the annual electricity consumption for an ePM1:70% electrostatic filter with an averaged ΔP of 62 Pa and an ePM1:70% pocket filter with an averaged ΔP of 215 Pa.

Electrostatic filter FE600 ePM1:70%

E = 0.944*62*6000 / (0.5*1000) = 351168/500 = 702 kWh/year

Average Pocket filter ePM1:70%

E = 0.944*215*6000 / (0.5*1000) = 1217760/500 = 2435 kWh/year

Types of electrostatic filters

Two types of electrostatic filters can be distinguished: passive and active electrostatic filters.

The general principle in in the electrostatic filtering systems technology relates to the electrostatic effect that occurs when a polluting particle (dust, smoke, fibres, etc ...) has, on its surface an electric charges (positive and/or negative) that makes it adhere to another surface (filter fibres, walls, curtains, TV and laptop screens, etc..) with equal but opposite charge. If the particle mass is sufficiently small, the electric charge presents on its surface makes it adhere to another opposite electric charge, present on the surface of the mattress filter. By applying this electrostatic effect, high filter efficiencies can be achieved, also for smaller particle sizes.

Passive electrostatic filters

When this phenomenon is enhanced artificially, by electrostatically charging the fibres of a filter, a so-called "passive electrostatic filter" is obtained, which in order to work well must be made with very high electrical resistivity fibres, as for example the rectangular plastic fibres. Its negative aspect is that just the deposit of polluting particles on the filter fibres makes it immediately decrease the ability of pollution's abatement.
Moreover, if the environment is particularly damp, the water contained in the air condenses

on the surface of the fibres and eliminates in a very short time each electric charge, transforming the product into a simple mechanical sieve filter. To overcome this problem the so-called 'buffer' filtering systems were created, in which the filtering means are submerged in an electric field which maintains the attraction power and the pollutants retention. The negative side is in the operation, starting from the fact that it depends on a filter mattress (the so-called buffer) that, even if electrostatically charged, presents the same disadvantages of the mechanical filters.

Active electrostatic filters

Filtration with an active electrostatic system consists of a two-phase system thanks to which it is possible to obtain the precipitation of solid or liquid particles contained in the air flow through the action of an electric field.

The company 'Expansion Electronic' uses the following illustration and accompanying text for explaining the principle of active electrostatic filters:

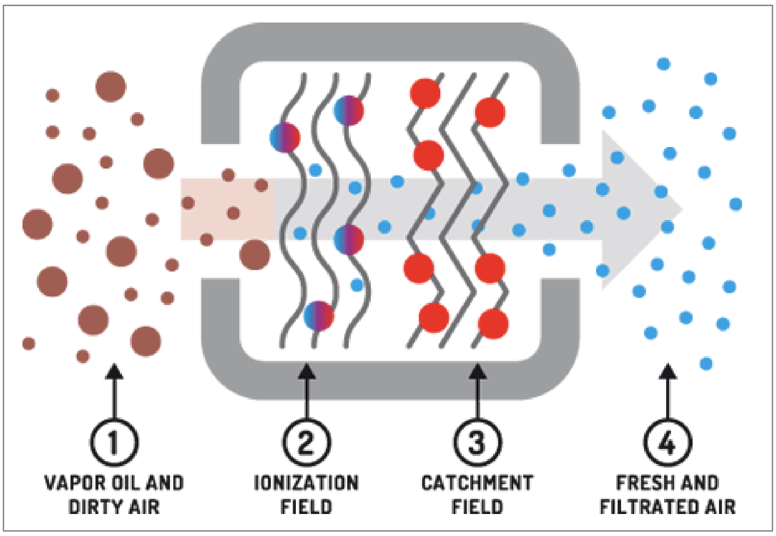


Figure 57. Principle of active electrostatic filter

Source: https://www.expansion-electronic.eu/index.php/en/what-we-do/operating-principle

In a first phase, the air that passes through the FE System electrostatic filter is subjected to the action of an electric field with positive ionization, generated by a powered wire with high electrical voltage placed between two plates connected to ground: that field causes the liberation of positive ions, generating a phenomenon known as "crown discharge". The electrical charges that migrate between the electrode and the grounded surfaces collide with the air particles present in the air flow, giving to them part of their positive electric charge.

In the second phase, the previously loaded gaseous flow crosses the electric field of catchment: this is constituted by positively charged plates and by plates connected to ground, alternately arranged.

Thanks to that shape of the FE System electrostatic filter and to the participation of the electrostatic force, the solid particles contained in the air are attracted to the positively charged catchment plates, since they are negatively charged.

Periodically, depending on the concentration of the pollutants, it is necessary to wash the filter with a particular detergent, in order to guarantee a better performance and a longer life cycle of the product.

In that sense the application of active electrostatic filters, can also help reducing the waste flows of traditional fibre-based filters which need to be replaces regularly and cannot always be cleaned.

5.3 Cleaning and recirculation of indoor air

The requirements for ventilation in most standards and guidelines are based on the assumption that the quality of (clean) outdoor air is acceptable. In various location around the world however, outdoor air quality can be very poor. In such cases, an alternative strategy may be to substitute ventilation-with-outdoor -air, at least in part, with air-cleaning and recirculation. By doing this the energy for heating or cooling the ventilation air and for transporting the air (fan energy) may be saved. For locations where the outdoor air is sufficiently clean, this air-cleaning strategy may also be an alternative additional strategy, provided it can increase the IAQ-performance without impairing the energy performance.

5.3.1 Cleaning indoor air from particulate matter

Indoor PM levels are dependent on several factors amongst which:

- outdoor PM levels,
- infiltration,
- types of ventilation and filtration systems used,
- indoor sources,
- personal activities of occupants.

Main indoor sources of PM are cooking, combustion activities (including burning of candles, use of fireplaces, use of unvented space heaters or kerosene heaters), cigarette smoking and some hobbies.

In homes without smoking or other strong particle sources, indoor PM would be expected to be the same as, or lower than, outdoor levels (source: https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter).

Primary and preferential strategy for reducing indoor generated PM obviously is source control: use efficient cooking hoods, avoid unvented fireplaces or heaters, prohibit smoking indoors.

This strategy always prevails any use of air circulation combined with PM-filters.

5.3.2 Cleaning indoor air from gaseous pollutants

The previous section basically indicates that recirculating and cleaning of indoor air is more about removing or reducing gaseous pollutants (coming from building materials, furniture and decorative products, office equipment, combustion equipment, occupants and their activities) than reducing PM-concentrations.

Opposite to the filtration of particulate matter (PM) however, (for which standards and test methods are already available), the technology of gas-phase air-cleaning is not supported by any standards on how to evaluate its efficiency and effectiveness in removing gaseous pollutants.

To fill this gap in knowledge, the Energy in Buildings and Communities Programme (EBC) of the IEA started a new EBC Annex 78, titled 'Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications'. The duration of this research-project is from 2018 – 2020, and the operating agents are Prof. Bjarne Olesen and Dr. Pawel Wargocki, both from the Technical University of Denmark. Participating countries are Canada, Czech Republic, P.R. China, Denmark, Finland, Italy, Japan, Singapore, USA.

Main objectives of this project are:

- quantify the energy performance of using air cleaning as part of the ventilation requirements,
- analyse how air cleaning can partially substitute for ventilation,
- advance standard testing procedures for air cleaners,
- carry out field studies of the energy performance and indoor air quality in buildings using gas phase air cleaning

(See also https://iea-ebc.org/projects/project?AnnexID=78)

Technical principles for removal of gaseous pollutants

Technology	Mechanism	Advantages	Disadvantages
Ionization	A discharge wire charges incoming particles and VOCs, that collect on oppositely charged plates	– Quiet – Low maintenance – Low pressure drop	– Generates ozone
Adsorption	The gases physically adsorb onto high-surface area medio (activated carbon)	– Potential for high removal efficiency for many gaseous pollutants – No by product formation	– Regular replacement needed – Effectiveness unknown – High pressure drop – Different removal efficiency for different gasses – Test methods limited or lacking
Chemisorption	Gases chemically adsorb onto media coated or impregnated with reactive compounds	– Potential for high removal efficiency for many gaseous pollutants – Chemisorption is an irreversible process (pollutants are permanently captured)	– Regular replacement needed – Effectiveness unknown – High pressure drop – Different removal efficiency for different gasses – Test methods limited or lacking
Catalytic oxidation	(Photo)catalytic oxidation (PCO) in which a high-surface-area medium is coated with titanium dioxide as a catalyst; gases adsorb onto the media and UV lamps activate the titanium oxide which reacts with the adsorbed gases and transforms them	– Can degrade a wide array of gaseous pollutants (e.g. aldehydes, aromatics, alkanes, olefins, halogenated hydrocarbons) – Can be combined with adsorbent media to improve effectiveness	– Can generate harmful by-product (formaldehyde, acetaldehyde, ozone) – No test methods – Relatively low removal efficiency – Lack of studies to validate performance – Catalyst has finite lifespan
Plasma	Electric current is applied to create an electric arc; incoming gases are ionized	– Can have high removal efficiency	– Wide variety of plasma generation types yields

	and bonds are broken to chemically transform the gaseous pollutants	– Can be combined with other air cleaning technologies to improve performance	confusion on how a product actually works – By-products are formed (included particles and gaseous pollutants)
Ozone	Intentional generation of ozone using corona discharge, UV or other method to oxidize odorous compounds and other gases	– Reacts with many indoor gases – Can be combined with adsorbent media to improve effectiveness	– High ozone generation rates – High amounts of by-product formation – Can cause degradation to indoor materials
Ultraviolet	UV-light kills or inactivates airborne microbes	– Can be effective at high intensity and sufficient contact time – Can be used to inactivate microbes on cooling coils and other surfaces	– Can generate ozone – May cause eye injury – High electrical power draw requirements – Inactivates but does not remove microbes

Source: www.epa.gov/iaq