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Review

Recent Advancements in Ventilation Systems Used to Decrease Energy Consumption in Buildings—Literature Review

Łukasz Amanowicz [1,*], Katarzyna Ratajczak [1] and Edyta Dudkiewicz [2]

[1] Institute of Environmental Engineering and Building Installations, Poznan University of Technology, ul. Berdychowo 4, 61-131 Poznan, Poland
[2] Faculty of Environmental Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
* Correspondence: lukasz.amanowicz@put.poznan.pl

Abstract: The need for healthy indoor conditions, the energy crisis, and environmental concerns make building ventilation systems very important today. The elements of ventilation systems to reduce energy intensity are constantly the subject of much scientific research. The most recent articles published in the last three years are analyzed in this paper. Publications focused on the topic of reducing energy consumption in ventilation systems were selected and divided into five key research areas: (1) the aspect of the airtightness of buildings and its importance for the energy consumption, (2) the methods and effects of implementing the concept of demand-controlled ventilation in buildings with different functions, (3) the possibilities of the technical application of decentralized ventilation systems, (4) the use of earth-to-air heat exchangers, (5) the efficiency of exchangers in exhaust air heat-recovery systems. The multitude of innovative technologies and rapid technological advances are reflected in articles that appear constantly and prompt a constant updating of knowledge. This review constitutes a relevant contribution to recognizing current advancements in ventilation systems and may be helpful to many scientists in the field.

Keywords: ventilation; energy efficiency; airtightness; DCV; thermal performance of buildings; heat recovery; earth-to-air heat exchangers; decentralized ventilation; solar chimney

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1. Introduction

1.1. Ventilation System Requirements

The thermal and humidity conditions in the room must meet the user's expectations and meet legal and technological requirements. Technical equipment systems, in particular HVAC (heating, ventilation, and air conditioning), are responsible for shaping the microclimate in buildings. To maintain appropriate thermal conditions, ventilation and heating systems are used. If, in addition, the humidity of the air in the room is also regulated, this is called a full air-conditioning system.

Although the design of ventilation in energy-efficient buildings is a key issue, searching the Scopus database for the phrase "designing of ventilation systems" leads to finding many papers from not only the last 3, but even the last 5 years, that present useful tips for designing ventilation systems in such buildings. Therefore, information from articles in local (Polish) journals [1,2] was used to outline the general requirements. Their results present requirements that seem to be universal and, in principle, coincide with the content presented in the article [3], which describes ventilation systems that meet the requirements of "ASHRAE Standard 62.2-2004":

- the building envelope should be airtight to achieve energy efficiency in the building,
- ventilation should be controlled: demand-controlled ventilation (DCV) systems should be used,
- the selection of the ventilation airflow should be based on hygienic or technological reasons,

- the heat from the exhaust air should be possible to be recovered,
- Renewable energy sources (RES), such as, e.g., earth-to-air heat exchangers, heat-pumps, etc. are recommended to be used,
- decentralized systems are recommended.

The general division of the systems used to shape the proper parameters of the air in the room is shown in Figure 1 [4].

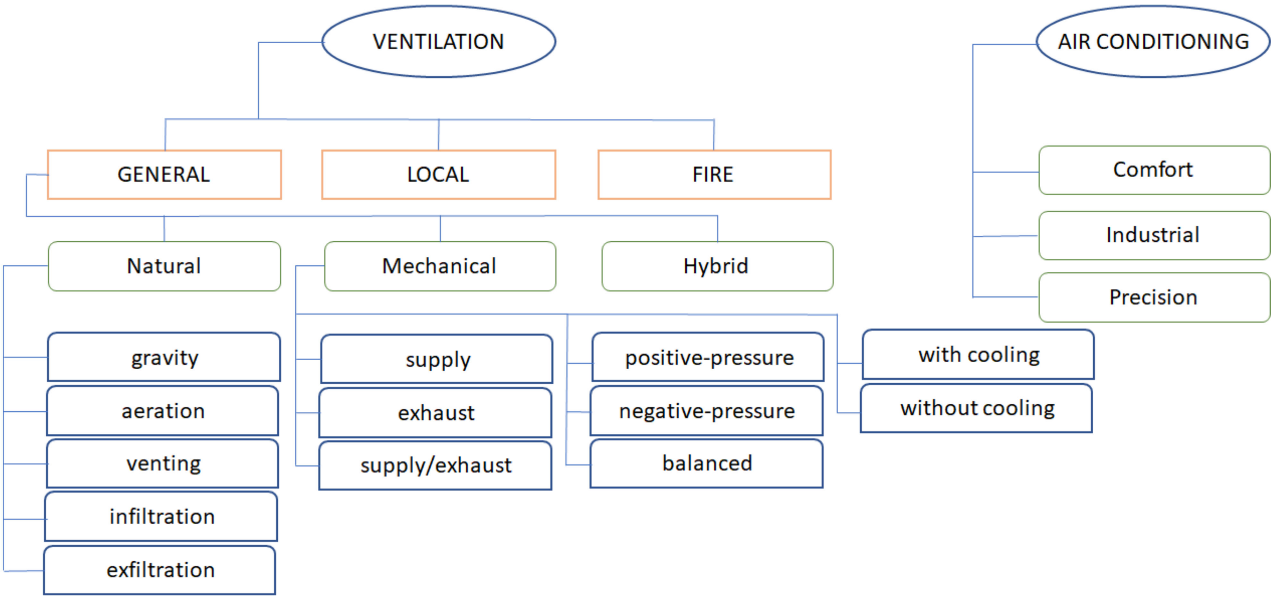


Figure 1. General division of ventilation and air-conditioning systems [4].

The main purpose of ventilation is to exchange air and ensure proper indoor air quality [5]. An appropriate ventilation intensity allows the removal of pathogens from the indoor air and at the same time increase the air quality. The use of appropriate filtration and possibly air sterilization contributes to high indoor air quality [6]. A higher intensity of ventilation also reduces the probability of transmission of airborne infections [7–9]. Although much research and analysis on ventilation has already been carried out, the multitude of innovative technologies and rapid progress in civilization is reflected in articles that appear constantly and encourage a constant updating of knowledge. This is due to the new challenges for ventilation systems, especially in energy-efficient and intelligent buildings [10].

The energy demand for ventilation results from the need to heat the supply air stream and the stream that infiltrates from the outside through leaks in the building envelope. It has been proven that the heat losses resulting from these air flows depend in particular on the type of ventilation system and the airtightness of its partitions [11,12]. In existing buildings, which generate more than 40% of the global energy demand, modernization is necessary, including the introduction of modern solutions that aim to reduce energy demand while ensuring the quality of the internal environment [5,13,14]. A reply to the frequently increasing share of heat demand for ventilation in the total heat demand of a building is the utilisation of advancements in ventilation systems such as demand-controlled ventilation as a ventilation-control strategy, elements of decentralized ventilation, earth-to-air heat exchangers, and heat recovery from exhaust air.

1.2. The Aim of the Paper

The aim of this article is to present the results of a review of the latest research from the last three years on ventilation systems that help reduce energy consumption in buildings. This objective is achieved with a literature review of five key issues concerning the airtightness of buildings, demand-controlled ventilation strategies, decentralized ventilation, ground heat exchangers, and heat recovery from the air removed from rooms.

1.3. Literature Review—Materials and Methods

As part of the literature review, scientific articles that were included in the Scopus and Web of Science databases were analyzed, assuming as search criteria: research article, full text, and conference papers published in 2020–2022. There were also publications from other years that had to be mentioned as key in a given topic. Selected keywords, appropriate for individual chapters, allowed us to select 98 articles for the narrative review. Based on the best knowledge of the authors, the most effective technologies with the highest potential were selected. To make it easier for the reader to recognize the issues discussed in individual chapters, the publications are summarized in five tables. They also provide the number of citations for these publications and the keywords provided by their authors.

2. Airtightness of the Building's Envelope as a Basic Requirement for Decreasing Energy Consumption

The energy efficiency of a building could be improved by improving its airtightness, measurement of which by different methods can have different errors [15]. In energy-efficient buildings with good thermal insulation, airtightness, expressed in air changes per hour by the n_{50} factor, is particularly important for annual energy demand. An increase in airtightness results in significant energy savings [16]. They are greater the better the thermal insulation of the building. Minimum thermal insulation requirements for buildings' partitions force the use of solutions with heat transfer coefficients appropriate for the country, and those in Poland are much stricter than the requirements in other European countries [17]. The reduction in energy consumption in well-insulated buildings is due to a lower infiltration airflow, which, coming through leaks as uncontrolled air, nullifies assumptions about energy efficiency. The percentage differences are greater the lower the energy demand for other building purposes. Therefore, energy-efficient buildings should be airtight, as can be demonstrated using 52 buildings in cities in the United States using a simplified calculator available online [16]. The apparent effect of increased airtightness on the building's thermal performance supports the decision-making process involved in renovating a building envelope with an emphasis on taking care of its airtightness.

Analysis [2] confirms that the energy demand of a building depends, among other factors, on the airtightness of the building. In the case of a building with a low value of the average heat transfer coefficient U (Variant II: U = 0.2 W/(m^2·K)), airtightness affects the energy demand to a greater extent compared to variant I, i.e., a building with a much worse thermal insulation parameter of partitions (U = 0.4 W/(m^2·K)). This is presented in Figures 2 and 3, which show, respectively, calculated heat losses through transmission and ventilation, assuming different classes of airtightness (Figure 2), and savings of usable energy for heating and natural ventilation due to better tightness—lower value of the airtightness coefficient n_{50} (Figure 3).

The airtightness of the building (expressed in L/s/m^2 at a pressure difference between the interior of the building and the environment of 75 Pa) was tested in six commercial buildings in Canada [18]. The authors diagnosed the location of the leakages using an infrared camera. Calculations have shown that the additional energy consumption due to detected leaks ranges from 47 to 64 kWh/m^2/year in these buildings. The diagnosed places of leakage include wall-to-roof connections, window and door assembly processing, and technical passages of pipes and channels through various elements of the building envelope.

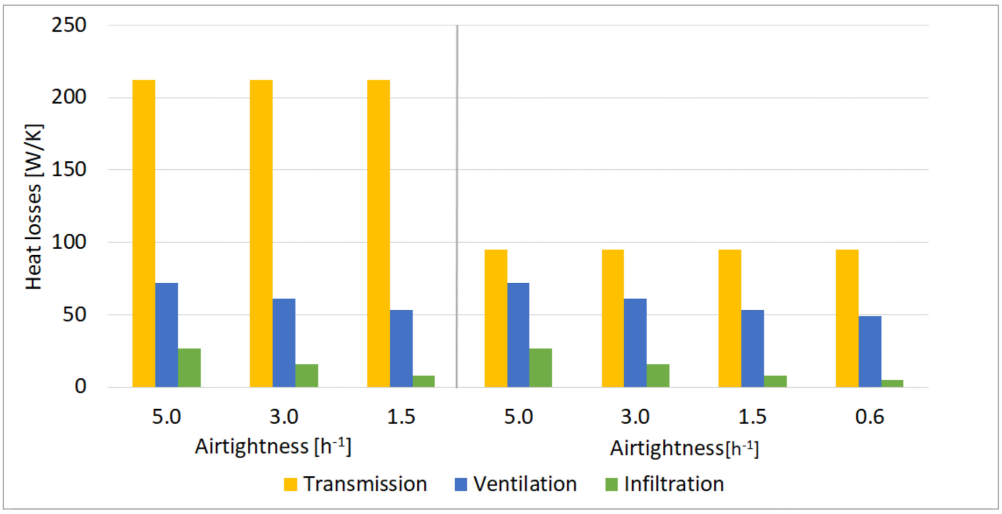


Figure 2. Transmission, ventilation, and infiltration heat losses for exemplary single-family building in the climate of Poland, assuming different airtightness, prepared based on data from [2].

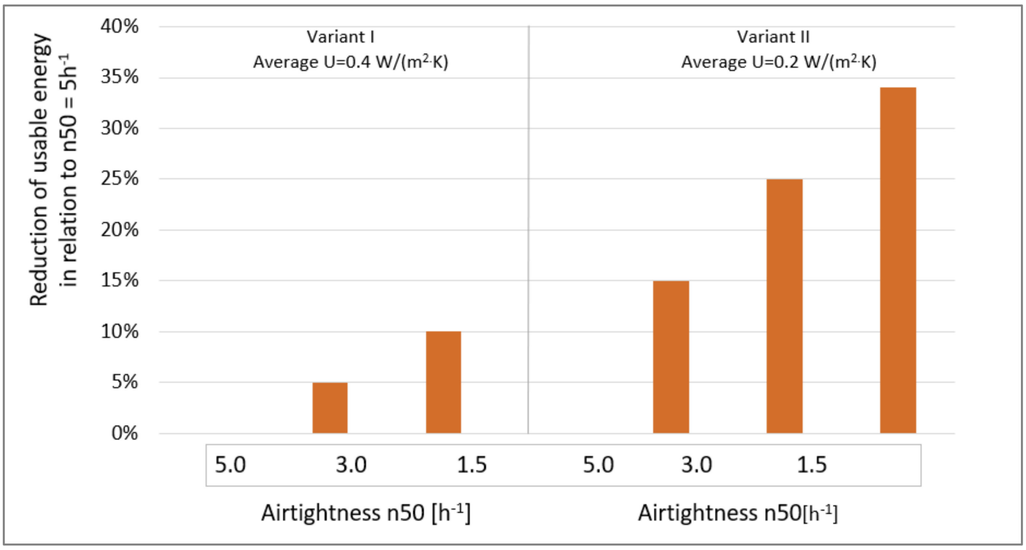


Figure 3. Reduction in usable energy for heating and ventilation in relation to the case n_{50} = 5.0, prepared based on data from [2].

In another paper [19], the significant importance of air leakage and infiltration on the energy consumption of an airport in China was demonstrated. The authors found that air infiltration is almost the most relevant factor influencing space heating and is equal to 18% to 71% of the total heat loss. In addition, they showed that by reducing leaks and using underfloor heating in airport terminals, the annual demand for heating can be reduced by as much as 84%.

The theme of "air leakage" was the leading topic during one of the sections of the 12th Nordic Symposium on Building Physics in 2020. Among the many interesting papers (E3S Web of Conferences Volume 172), attention is drawn to [20], in which the variability of airtightness was analyzed in the case of 41 energy-saving buildings in the period of use from 0.5 to 12 years. Interestingly, the air permeability increased in 29 buildings and decreased in four buildings. On average, at a pressure difference of 50 Pa during the tests, the leakage of the buildings increased by 38%, while at the same time causing an increase in the specific infiltration by 0.15 $m^3/(h{\cdot}m^2)$.

A similar analysis was presented by the authors of the publication [21]. They described the results of research on changes in the n_{50} coefficient in the short (1–3 years) and long

(3–10) period of time. Leakage rates increased by 18% and 20% respectively. The results of the research allowed the authors to conclude on the influence of the type of building structure on the deterioration of airtightness over time ("the number of levels, the type of roof and the type of building material and air-barrier").

In another report [22] on the example of simulations carried out for single- and two-family residential buildings, it was shown that air leakages significantly affect the value of the peak demand for thermal power for heating purposes. Underestimating it may result in an incorrectly sized and functioning heating system. What should be emphasized is that the authors showed that due to the lack of airtightness of buildings, the peak demand for thermal power for heating purposes was recorded with the strongest wind. It increases infiltration and causes an additional load for the building's heating system, which is more than in case of the lowest outdoor air temperatures. This is confirmed by the results of the numerical simulations presented in [23]. For different locations of the same building in Poland characterized by the coefficient n_{50} = 0.63 h^{-1}, the values of infiltration heat losses differed significantly due to different wind distribution, as shown in Figure 4.

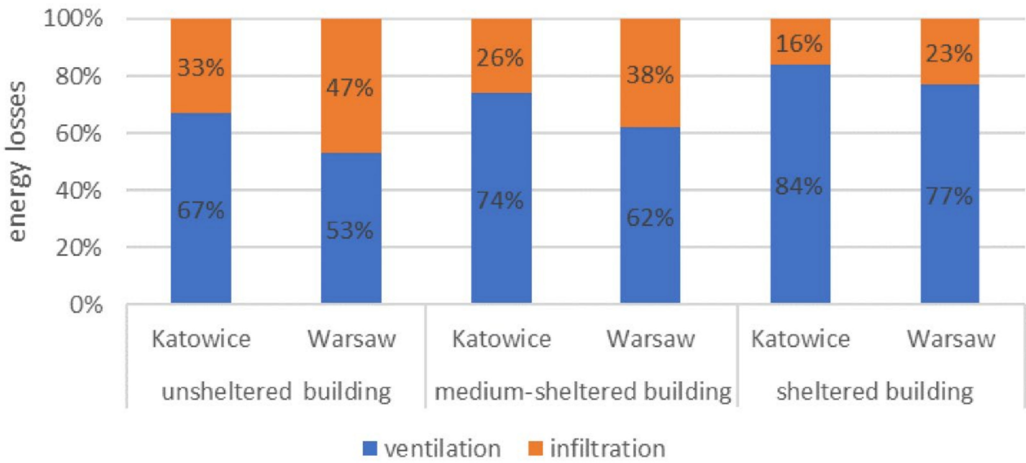


Figure 4. Percentage share of ventilation and infiltration heat losses in total heat losses for ventilation of a building with n_{50} = 0.63 located in two cities of Poland for different sheltering conditions [23].

The authors of [23] highlight the importance of location and related climate as well as the building's cover on the intensity of infiltration and energy consumption. Simulations show that the difference in annual energy consumption for a building in the same location, but with different airtightness standards, can be as much as 90%. Additionally, taking into account the different degrees of building sheltering, these differences can reach up to 200%. The authors emphasized that this is the reason why the legal requirements concerning, e.g., airtightness should be differentiated depending on the building's exposure to undesirable factors resulting from the climatic zone (wind, temperature) and/or the building's surroundings in a given location. In support of their appeal, the authors also cited other scientific works.

The authors of another conference paper [24] on airtightness measurements in middle-size stores and distribution centres showed that the proper infiltration flow at a pressure difference of 50 Pa is 1.04 $m^3/m^2/h$ and 1.35 $m^3/m^2/h$, respectively. In their conclusions, they proposed an increase in legal requirements and establishment of new standards for these types of buildings. By increasing airtightness, they could significantly improve their energy performance.

The airtightness of more than 400 single- and multi-family dwellings located in different regions of Spain and built in different years was investigated in a paper [25]. The energy impact of measured leakages on heating demand was in the range 2.43–19.07 $kWh/m^2/year$, showing a great challenge and potential for energy efficiency of buildings not only in Spain. However, the authors did not note the significant importance of airtightness for the energy demand for cooling purposes.

The results of dynamic simulations in the TRNSYS program are presented in the article [26] also confirm the lack of influence of airtightness on energy demand for cooling purposes. The authors simulated a dwelling equipped with a mechanical ventilation system for different locations in Europe (Spain, France, Italy, Germany, UK). In northern and colder locations, the energy impact of infiltration was +13% in energy demand for heating and cooling, in Mediterranean areas from +4 to +7% and in southern locations only +3%. Although the authors highlighted that the passivhaus standard requires the same value of n_{50} regardless of location, their research shows that it should be differentiated. It should be higher in locations with frequent low temperatures (0.6 h^{-1}) and lower where outside air temperatures are high (even 1–2 h^{-1}).

In [27] the importance of airtightness on the energy consumption of social buildings built in the years 1950–1979 in Spain (different variants of the Mediterranean climate) was analysed. The impulse for the research for the authors was, among others, the quote of almost the highest value in Europe of the number of mortalities associated with winter weather. The authors link it with the low quality of social housing in Spain, which was in force before the changes in the legal requirements regarding the quality of the building envelope. Their research results showed that in regions with more severe climates, air leaks are responsible for an additional consumption of more than 10 kWh/m^2/year. It was calculated that an increase in airtightness by 0.1 h^{-1} would reduce annual heat demand by 5% in warmer zones and by 7.2% in the colder regions of Spain. Their results are presented in Figure 5.

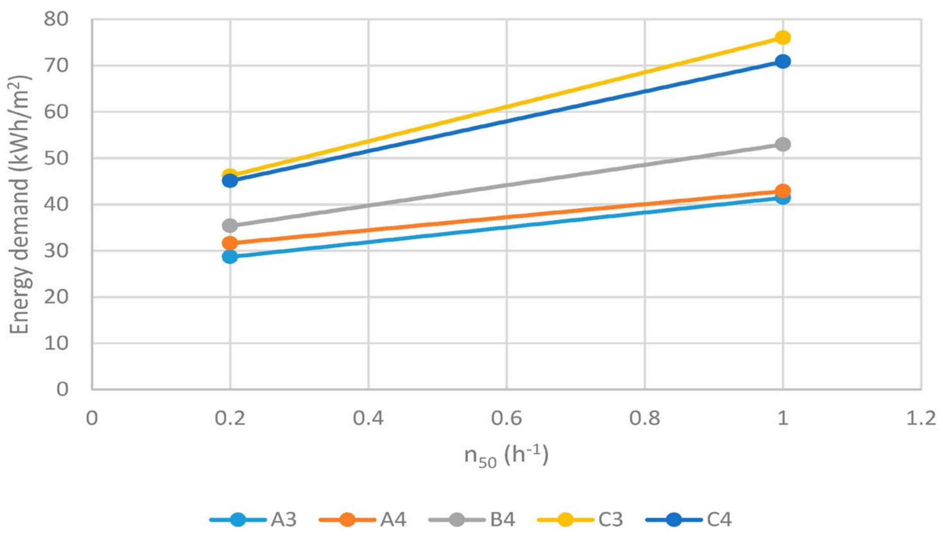
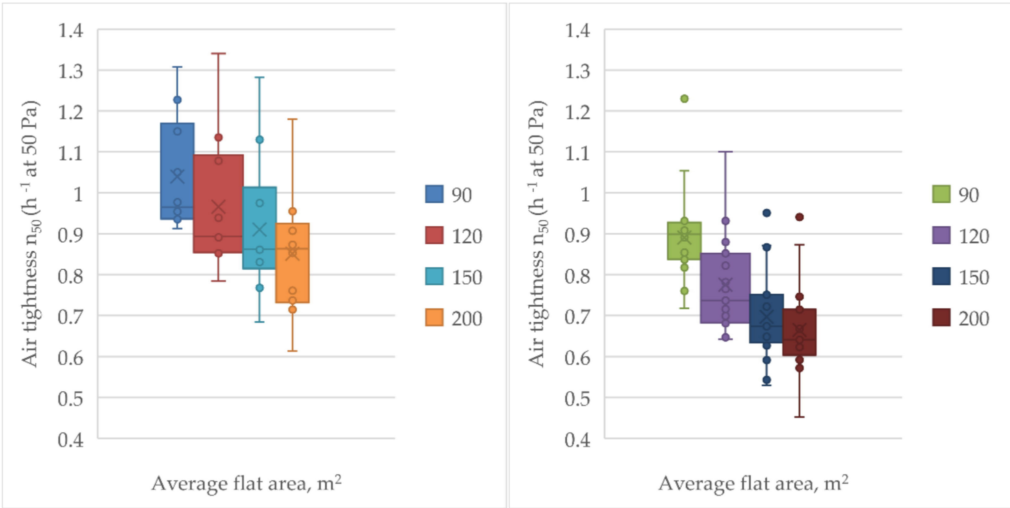


Figure 5. Dependence of the value of the annual infiltration heat loss index for an example building with different degrees of airtightness (n_{50} from 0.2 to 1.0) located in different climates of Spain "most representative of Andalusia, ranging from very mild (zone A) to cold (zone C) winters and warm (zone 3) to hot (zone 4) summers" [27].

Another interesting work is [28], which presents the range of variability of the n_{50} coefficient value for flats of similar area, but located in different parts of the building and on different floors of a multi-family building. As shown in Figure 6, the values differed by up to 25% between apartments with extreme values of area, because, as the authors conclude: "local air leakages or minor construction defects of larger flats statistically had less influence on the general airtightness". The flats located in the end parts of the building had up to 20% higher n_{50} than those in the middle, which "can be explained by a longer length of structural joints in the end units" [28] (Figure 6).



(**a**) (**b**)

Figure 6. Airtightness of buildings: (**a**)—end units (flats), (**b**)—inside units [28].

The authors of [12] presented interesting results of tightness tests of two single-family buildings in the post-conference paper. The tests were carried out in two variants: (1) for the entire building and (2) separately for the residential part and the garage. The results showed that the airtightness of the residential part (n_{50} = 2.65 h^{-1} or 1.47 h^{-1}) is several times higher than that of the garage (n_{50} = 8.91 h^{-1} or 8.11 h^{-1}, respectively). Assuming the average value of n_{50} in the calculations of energy for heating resulted in a 12% higher energy demand than the value resulting from the assumption of a more realistic (measured) n_{50} for both zones separately. It is interesting that the result depends on the direction of airflow; if infiltration air flows from the garage to the occupant area, the difference in energy usage can be lower or even negligible. This confirms the need for dynamic simulations of air flows between building zones.

Such simulations are presented in [29]. The article describes an accurate method for the dynamic simulation of infiltration that can be used to assess its effect on building energy demand more accurately than in comparison to steady-state methods with an accuracy of 2.5% in comparison to field tests.

Airtightness measurement methods are a separate issue. An interesting overview of the reasons for the uncertainty in conducting leak tests is described in [30]. In the paper, various sources of error are presented and the research perspectives are described for better understanding the problem. The methods to measure the airtightness of buildings, including two nontypical—in transient conditions and acoustic—are presented in [31]. The methods of predicting airtightness performance are worth mentioning; they are being developed all over the world and can be useful for conducting energy simulations of buildings. One of those approaches is described in [32], where a statistical predictive model was developed based on data from real facilities in Spain. The model takes into account variables such as "the age of the building, typology, building state, construction system, and dimensions".

Summarising the review of research on the importance of the airtightness of the building envelope on thermal performance, it can be said that the topic is important, which is confirmed by the number of publications and citations listed in Table 1. Undoubtedly, energy-efficient buildings with various functions should be characterized by high airtightness; otherwise, its absence causes an increase in the demand for thermal power for heating and ventilation purposes (from 2.4 to even 64 kWh/m^2/year), while it practically does not affect the demand for cooling. It should be noted that the location of the building and the resulting climatic conditions are important, as well as the degree of its shielding, which increases the energy demand. The most important is the type of building partition construction and the introduction of more restrictive requirements in various countries is indicated. Also important is the flow of air between zones inside the building, the use of dynamic methods to predict heat losses as a result of leaks, and paying attention to the methods of measuring airtightness.

Table 1. Reviewed papers on airtightness.

Authors, Year	Title	Journal	Citations	Keywords
Amanowicz Ł., Ratajczak K. 2021, [2]	Practical aspects of designing energy-saving ventilation systems (in Polish)	Rynek Instalacyjny	2	Ventilation, energy-efficient buildings, energy performance, PE indicator, technical conditions
Verbeke S., Audenaert A. 2020, [20]	A prospective Study on the Evolution of Airtightness in 41 low energy Dwellings	E3S Web of Conferences	2	-
Simson R. 2020, [22]	The impact of infiltration on heating systems dimensioning in Estonian climate	E3S Web of Conferences	4	-
Miszczuk A., Heim D. 2020, [23]	Parametric Study of Air Infiltration in Residential Buildings—The Effect of Local Conditions on Energy Demand	Energies	6	Airtightness, climate data, building exposure, airflow network, performance simulation
Nitijevskis A. et al., 2020, [24]	Overview of large building testing in Baltic countries	E3S Web of Conferences	0	-
Heim D. et al., 2020, [29]	Modelling building infiltration using the airflow network model approach calibrated by air-tightness test results and leak detection	Building Services Engineering Research & Technology	2	Airtightness, building energy conservation, building simulation
Zheng X. et al., 2020, [31]	A practical review of alternatives to the steady pressurisation method for determining building airtightness	Renewable and Sustainable Energy Reviews	19	Building airtightness, steady pressurisation, blower door, unsteady technique, pulse technique, acoustic method
Liu X. et al., 2021, [19]	Energy saving potential for space heating in Chinese airport terminals: The impact of air infiltration	Energy	21	Airport terminal, space heating, field investigation, air infiltration, indoor thermal environment, energy saving
Moujalled B. et al., 2021, [21]	Mid-term and long-term changes in building airtightness: A field study on low-energy houses	Energy and Buildings	5	Airtightness durability, field measurements, building envelope, low-energy house
Poza-Casado I. et al., 2021, [25]	Airtightness and energy impact of air infiltration in residential buildings in Spain	International Journal of Ventilation	6	Air leakage, blower door, energy impact, residential buildings, fan pressurisation test
Paukštys V. 2021, [28]	Airtightness and Heat Energy Loss of Mid-Size Terraced Houses Built of Different Construction Materials	Energies	1	Airtightness, blower door, heat energy loss, thermographic photo research, building energy performance
Banister C. et al., 2022, [18]	Energy and emissions effects of airtightness for six non-residential buildings in Canada with comparison to contemporary limits and assumptions	Journal of Building Engineering	0	Airtightness, air leakage, infiltration, energy effects, building codes, building emissions
Mélois A. et al., 2022, [30]	Uncertainty in building fan pressurization tests: Review and gaps in research	Journal of Building Engineering	1	-
Poza-Casado I. et al., 2022, [32]	An envelope airtightness predictive model for residential buildings in Spain	Building and Environment	1	Predictive model, airtightness, blower door, dwellings, database, statistical analysis

The authors of this article are of the opinion that the design of the ventilation system in an energy-efficient building should be associated with ensuring the high airtightness of the building. In the case of air leakage, the effectiveness of even a very advanced energy-saving ventilation system will be destroyed by the influence of air infiltration through leaks in the building envelope, and heat losses will be noticeable as a result of increased operating costs. According to the authors' experience, the impact of leakage will be negligible when the value of n_{50} is lower by about one order of magnitude than the value of the base flow rate for ventilation. Also of interest are the research results cited, which show that airtightness changes over the life of a building, which is currently not taken into account in multi-year energy analyses.

3. DCV as a Ventilation Control Strategy

To obtain the highest energy efficiency and low energy consumption, ventilation systems should be adjusted to the actual needs of the occupants. This type of ventilation is called DCV (demand-controlled ventilation). These systems should be highly energy-efficient, as during periods of reduced air demand, lower costs are incurred in pumping air through the duct network, while at the same time the cost of thermal treatment is significantly reduced. Maintaining a constant nominal (design) air flow causes unnecessary costs to be incurred for heating/cooling the air, but also for pumping it through the system (overcoming flow resistance). Fans are commonly powered by electricity, and this, in many countries, still comes from burning nonrenewable fossil fuel resources. Matching the performance of the ventilation system to current needs is therefore justified by concerns in terms of energy, economics, and the environment. The DCV concept is mostly implemented by:

- the use of indoor sensors for CO_2, occupancy, humidity, etc.
- use of variable air volume (VAV) controllers for central systems,
- dividing a building into zones (zoning) with similar usage characteristics with separate ventilation units responsible for air quality in a given zone, such as in several rooms.

The authors of [33] reviewed the latest literature in the field of DCV systems controlled on the basis of carbon dioxide (CO_2) measurements. The three main types of CO_2 control strategies in DCV systems are presented—rule-based (i.e., controlling the CO_2 set-point), model-based (i.e., predictive control), and learning-based—along with their pros and cons. The meaning of sensor performance, sensor placement, and their errors on the effectiveness of the CO_2-based DCV system is extensively discussed. Moreover, many simulation and field test case studies are described and compared.

A review of articles on the impact of demand-controlled ventilation on energy use led to the article [34]. Although published in 2018, it not only shows potential energy savings (ranging from 64% to 84%) compared to the constant air volume (CAV) system, but also presents an innovative approach to the problem of maintaining constant pressure in the main duct. The authors indicate that reducing the pressure setting together with the decreasing demand for air can bring additional energy savings for driving fans at the level of 10% to even 50% in the case of heavily used and lightly used rooms, respectively. To complete this task, throttle position sensors in VAV controllers were used. The savings are greater the more diverse the room use profiles are, especially in the case of rooms that are rarely or not fully used (e.g., lecture halls, where the variability of users may range from 1 to 120 people).

The energy effects of using the DCV system were also analyzed in [35–37]. The simulations carried out in [35] show that in multi-family buildings the DCV system allows for higher indoor air quality, that is, a lower concentration of CO_2 and appropriate humidity in relation to the CAV system. Furthermore, it allows one to save 22% energy for heating when comparing both systems equipped with heat recovery or even 86% when comparing both systems without the possibility of heat recovery from the exhaust air. In [35] a wide variety of humidity loads and occupants in different dwellings was evaluated. These are the elements that are confirmed by users of DCV systems. The authors of the article suggest the use of a two-way control, DCV control according to the moisture load and volatile organic compounds, to better match the real needs of each apartment. In [36] it was shown that a DCV system used in an office building allowed for approximately 30% energy savings. In [37] energy savings of about 25% for ventilation needs due to the use of DCV were shown in school buildings located in the hot climate of Saudi Arabia.

An interesting analysis showing that DCV systems are not always more energy-efficient than CAV is presented in [38]. The influence of longitudinal heat conduction (LHC) on the efficiency of heat recovery using heat-wheel-type heat exchangers was analyzed. It turns out that the effect of lowering the efficiency of heat recovery is significantly greater in the case of low air flow, i.e., when the DCV system reduces its efficiency to match the reduced needs of the user. In some cases, it may turn out that the energy loss resulting from the LHC is greater than the energy savings due to the reduced airflow. However, it should be emphasized that the situation may occur in specific weather conditions (i.e., for several hours a year). Nevertheless, it is also worth taking into account the possibility of this problem when analyzing the potential causes of the so-called "performance gap"—i.e., the difference between the computational and real characteristics of a building. This issue is described, among others, in [39,40].

Experimental studies [41] of indoor air quality were carried out in school classrooms in Australia supplied with fresh air using DCV and traditional constant-flow systems. The concentration of CO_2 and VOCs (volatile organic compounds) were measured. The maximum concentration of CO_2 in the classroom without DCV was equal to 2981 ppm, while in the classroom with DCV it was 1335 ppm. The VOC measurements also showed a better quality of air in the DCV-supplied classroom. An additional interesting element of the research was the survey of students, which showed that not only CO_2 concentration but a combination of these two parameters at once affects the feeling of fatigue and distraction during classes.

The challenges posed by the operation of DCV systems are discussed in the example of eight public buildings in Finland in [42]. The following were measured: air streams, temperature, and CO_2 concentration in individual zones of the building. It was discovered that only in one of the eight buildings did the system work under the designed parameters. Although the users did not complain of poor air quality or uncomfortable temperatures, it turned out that air flows were not as intended in the design. This sheds light on problems with DCV systems that go undetected in many buildings until they affect occupant comfort. However, the purpose of DCV is also to save energy. If these systems do not work according to the designed strategy, they will be more energy-consuming in reality than they could be theoretically.

When CO_2 sensors are used to control the efficiency of the ventilation system, there is always a doubt as to where they should be installed. In [43], the results of the CFD analysis simulating airflow and CO_2 distribution in the lecture hall are presented to select a representative location of the sensors. The results of the analysis showed an uneven distribution of CO_2 in the room and led to the conclusion that in the analyzed room, the places near the ceiling represent the best average CO_2 concentration.

Not only is the location of sensors in the room important, but for air quality management strategy, it is also important because of the sensitivity to influences and recognizing when, how often, and for how long these influences are active [44]. It is also important to indicate the type of pollutant whose concentration is to be measured as a signal for DCV regulation. In [45] the methodology is presented to select the measured parameter in order to obtain a good indoor air quality. The authors noted that the current state of the external air (e.g., $PM_{2.5}$) also affects the indoor air quality. Based on measurements of five parameters, the concentration of CO_2, concentration of particulate matter $PM_{2.5}$, temperature, relative humidity, and formaldehyde in the office, gym, and kitchen, they conclude that the absolute humidity and temperature are correlated, and formaldehyde is correlated to temperature and CO_2; however, CO_2 and temperature did not capture most of the peaks in $PM_{2.5}$.

In Oslo, Norway, experimental research was carried out on the thermal comfort of young people in rooms with the DCV system [46]. The results showed that depending on the age range of theroom occupants, DCV systems should use different CO_2 set-points. The assessment of air quality, especially in the case of younger children, is highly dependent on their age. The authors of another article [47] also came to similar conclusions. They showed that the feeling of warmth is affected by the concentration of CO_2, but ensuring proper ventilation is also necessary in terms of energy efficiency.

Three articles [48–50] refer to the failure of CO_2 sensors used in DCV systems. In [49], based on failure models, a method is presented to assess the impact of sensor failures, while in [50] the automatic 4S3F fault-detection system for DCV systems was presented, based on four generic types of symptoms of faults (4S) and three generic types of fault (3F). In [48] a model for simulating sensor failures was presented, in which the fault injection framework was used to simulate potential failure scenarios (Figure 7). This model can be used to realistically simulate the energy consequences of CO_2 sensor failures in DCV systems.

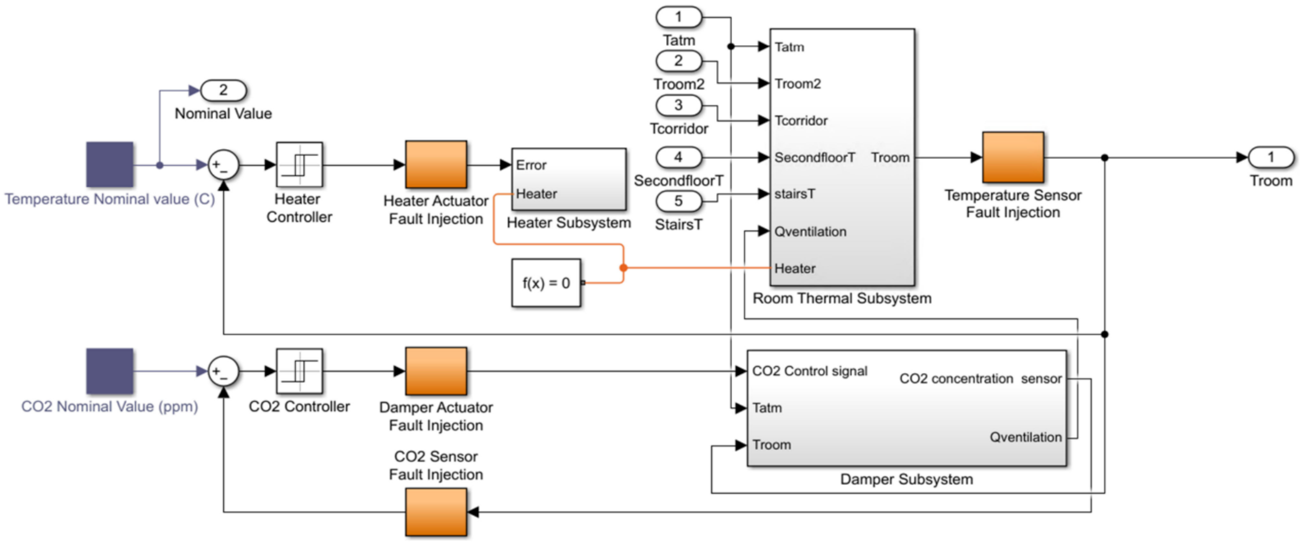


Figure 7. Model of HVAC system with DCV ventilation including fault injector blocks [48].

In summary, it can be seen that adjusting the efficiency of the ventilation stream to the current needs in the room is a result of energy and environmental benefits. Due to the air quality management strategy, the sensitivity of air to impacting factors resulting from human activity and the recognition by the ventilation system of when, how often, and for how long these factors are active are important. Additionally, the correct selection of sensors due to the correct measurement and their placement in the room are key issues for properly operating energy-saving DCV ventilation, which is confirmed by 18 selected recent publications collected in Table 2.

Table 2. Reviewed papers in DCV.

Authors, Year	**Title**	**Journal**	**Citations**	**Keywords**
Hamid A.A. et al., 2020, [35]	The impact of a DCV-system on the IAQ, energy use, and moisture safety in apartments—a case study	International Journal of Ventilation	1	-
Lu X. et al., 2020, [49]	A novel simulation-based framework for sensor error impact analysis in smart building systems: A case study for a demand-controlled ventilation system	Applied Energy	27	Demand-controlled ventilation (DCV), error impact analysis, sensors, simulation, sensitivity analysis
Taal A. et al., 2020, [50]	Fault detection and diagnosis for indoor air quality in DCV systems: Application of 4S3F method and effects of DBN probabilities	Building and Environment	18	4S3F framework, fault detection and diagnosis (FDD), demand-controlled ventilation (DCV), diagnostic Bayesian networks (DBN), building management systems (BMS), energy performance, indoor air quality (IAQ)
Abuimara T. et al., 2021,[36]	Exploring the adequacy of mechanical ventilation for acceptable indoor air quality in office buildings	Science and Technology for the Built Environment	1	-
Bandurski K. et al., 2021, [39]	Difference Between Calculated and Measured Energy Consumption for Heating in Multi-Family Buildings in Poland (in Polish)	Ciepłownictwo, Ogrzewnictwo, Wentylacja	1	Performance gap, multi-family residential building, multi-unit residential building, energy certification, building energy performance, occupant behavior, building energy modelling, monthly method, energy-efficient buildings
Haddad S. et al., 2021, [41]	On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms	Energy and Buildings	25	Indoor environmental quality, air quality, thermal comfort, school buildings, ventilation
Shin H. et al., 2021, [47]	A study on changes in occupants' thermal sensation owing to CO_2 concentration using PMV and TSV	Building and Environment	8	Indoor environmental quality, indoor air quality, CO_2 concentration, predicted mean vote (PMV), thermal sensation vote (TSV), discrepancy between TSV and PMV (DV)
Lu X. 2022, [33]	Advances in research and applications of CO2-based demand-controlled ventilation in commercial buildings: A critical review of control strategies and performance evaluation	Building and Environment	2	CO_2 control strategies, demand-controlled ventilation, energy efficiency, performance evaluation, CO_2 sensor
Alaidroos A. et al., 2022, [37]	Evaluation of the performance of demand control ventilation system for school buildings located in the hot climate of Saudi Arabia	Building Simulation	3	Mechanical ventilation, Demand-controlled ventilation (DCV), indoor air quality (IAQ), CO_2 concentration, energy efficiency, school buildings
Liu P. 2022, [38]	Heat recovery ventilation design limitations due to LHC for different ventilation strategies in ZEB	Building and Environment	2	Energy-efficient ventilation, rotary heat exchanger, zero-emission buildings, longitudinal heat conduction
Ratajczak K. et al., 2022, [40]	Differences Between Calculated and Measured Energy Use For Heating and Domestic Hot Water Preparation on the Example of Single-Family Buildings (in Polish)	Ciepłownictwo, Ogrzewnictwo, Wentylacja	0	Performance gap, single-family buildings, energy certification, energy efficiency calculation, final energy, occupant behaviour, building energy modelling, monthly method, energy-efficient buildings, domestic hot water

Table 2. *Cont.*

Authors, Year	Title	Journal	Citations	Keywords
Zhao W. et al., 2022, [42]	Operational Challenges of Modern Demand-Control Ventilation Systems: A Field Study	Buildings	0	demand-controlled ventilation, performance of ventilation system, public buildings, field study
Mou J. et al., 2022, [43]	Computational fluid dynamics modelling of airflow and carbon dioxide distribution inside a seminar room for sensor placement	Measurement: Sensors	1	Carbon dioxide (CO_2) distribution, computational fluid dynamics (CFD), sensor placement, demand-controlled ventilation (DCV)
Szczurek A. et al., 2022, [44]	The Detection of Activities Occurring Inside Quick Service Restaurants That Influence Air Quality	Sensors	1	Indoor air quality, aensing, pattern recognition
Kiamanesh B. et al., 2022, [48]	Realistic Simulation of Sensor/Actuator Faults for a Dependability Evaluation of Demand-Controlled Ventilation and Heating Systems	Energies	1	HVAC systems, fault injection, fault scenario generation, fault model, finite-state machine, stateflow
Alonso M.A. et al., 2022, [45]	A methodology for the selection of pollutants for ensuring good indoor air quality using the de-trended cross-correlation function	Building and Environment	6	IAQ, DCV, CO_2, air temperature, RH, $PM_{2.5}$, formaldehyde

4. Decentralized Ventilation Systems

Maintaining the appropriate parameters and pumping air from the intake to the rooms and on to the exhaust requires the supply of a large amount of energy. Removing the costs associated with air transport is made possible with decentralized ventilation. Decentralized ventilation is a system that uses several smaller ventilation units that are dispersed throughout the facility. In other words, decentralization involves the use of multiple small-capacity units that can be applied to individual rooms [51–54], and, as a result, form a system or systems in which the division of rooms into zones served by separate units has been made [55]. In addition, unlike central systems, most often decentralized, wall-mounted, distributed systems do not take up as much space. This is important because the space taken up by the system is considered an argument that keeps investors and users from considering the introduction of a mechanical ventilation system. When used in many different types of buildings, such as residential, swimming pools, schools, and offices, it enables tangible energy and financial benefits. This is also confirmed by previous studies [56]. Heat recovery, balance of flow, and low specific fan power enabled energy savings in each of the analyzed 20 decentralized systems and 60 central systems in residential buildings [56]. Compared to the variant of natural ventilation without heat recovery, simulations showed that a decentralized ventilation system provided annual primary energy savings of 4.75 Wh/m^3, and the central system 2.93 Wh/m^3.

A significant part of the energy in a building is used for air heating and its circulation, so it is worth considering the possibility of reducing the energy consumption in the building through the use of decentralized ventilation.

The authors of [57] studied the energy effects as a result of the use of a ventilation unit with a capacity of 300 m^3/h with a heat-recovery exchanger for an office building. Using TRNSYS software, the cooperation of ventilation with the heating and cooling system was assessed for buildings located in different climates in Sweden, Germany, and Italy. The solution made it possible to obtain lower electricity consumption thanks to the introduction of the DCV strategy.

The authors of [58] compared three ventilation systems: central mixing, displacement with the air-handling unit located in the basement, and decentralized with wall units. The results showed that the decentralized system ensures lower power consumption while ensuring adequate air quality. This issue was the subject of another study [52] describing the use of reversible fans in the rooms of an apartment in a multi-family building. The analyzed system is shown in Figure 8.

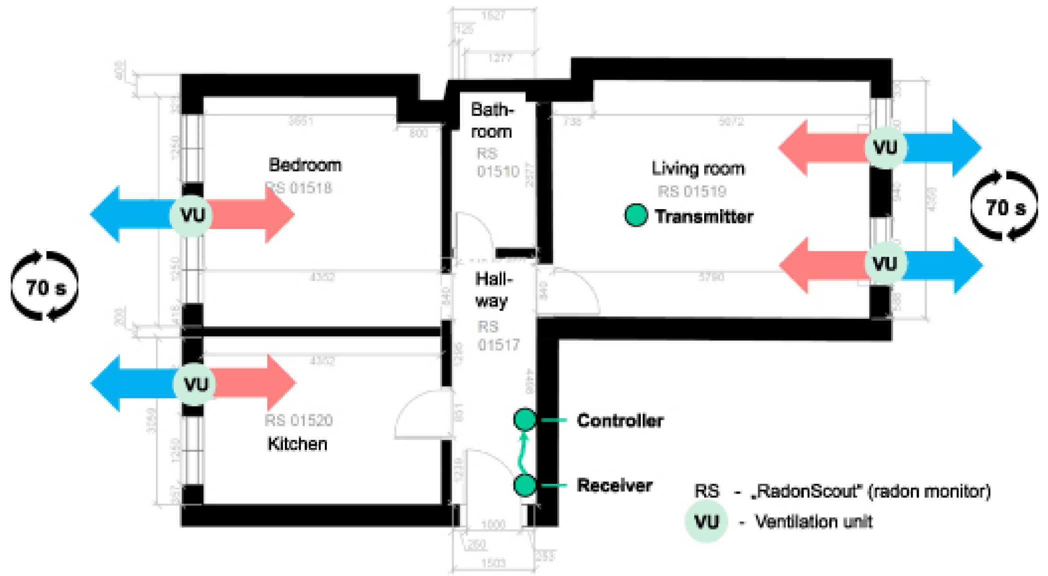


Figure 8. Decentralized ventilation system for an apartment analyzed in [52].

The authors of [52] conducted research on the assessment of the impact of open and closed doors in an apartment on the radon concentration. In rooms without mechanical ventilation, the radon concentration reached 7000 Bq/m^3 and increased when the door was open. The installation of four ventilation units, operating at full capacity in the heat recovery, made it possible to reduce the radon concentration to 300–800 Bq/m^3, that is, to the value recommended by the World Health Organization.

Subsequent research by these authors [51] showed more favorable air conditions in summer and allowed them to conclude that the operation of decentralized ventilation units may depend more on weather conditions than in the case of traditional central systems. The dependence between the operation of decentralized ventilation units and weather conditions was also studied by the authors of [59]. They found that there is a strong relationship between the wind and the efficiency of air supply to a home equipped with two-room ventilation units. The negative influence of the wind can be reduced using dampers controlled as a function of relative humidity. In other studies [60], the influence of wind on the operation of units with axial fans was assessed to be significant. The solution to the problem, according to the authors' suggestions, might be to change the type of fans to radial ones.

Another group of studies related to decentralized ventilation shows the specific use of ventilation units to improve indoor air quality. They focus on the fact that decentralized ventilation in the form of wall devices does not require a large amount of space for its installation. In [53], a strategy for ventilating rooms used as a nursery was proposed by installing wall units with reversible fans equipped with a ceramic exchanger for heat recovery. This has brought the benefits of ensuring a CO_2 concentration of 1000 ppm. The savings resulting from changing the ventilation method from ventilation by opening windows to forced ventilation were also calculated, which can be up to as much as 75% of the annual costs of heating the supplied air. Previous analyses [54] have also shown that a ventilation solution with reversible fans in the nursery will not increase the cost of electricity to supply the ventilation. Good air quality was also obtained through the use of façade devices in studies conducted in office buildings [61].

Due to the need to make openings in the outer partition, it is not always possible to use reversible fans. An example would be a historic school building where there was a problem of high CO_2 concentration during lessons [62]. The authors proposed masking channels in the window opening (Figure 9), which made it possible to maintain not only the CO_2

concentration at the assumed level of 1200 ppm, but also the proper radon concentration. In addition, the use of a heat-recovery exchanger allowed the authors to obtain the desired air temperature in winter, which was impossible when ventilating classrooms during breaks.

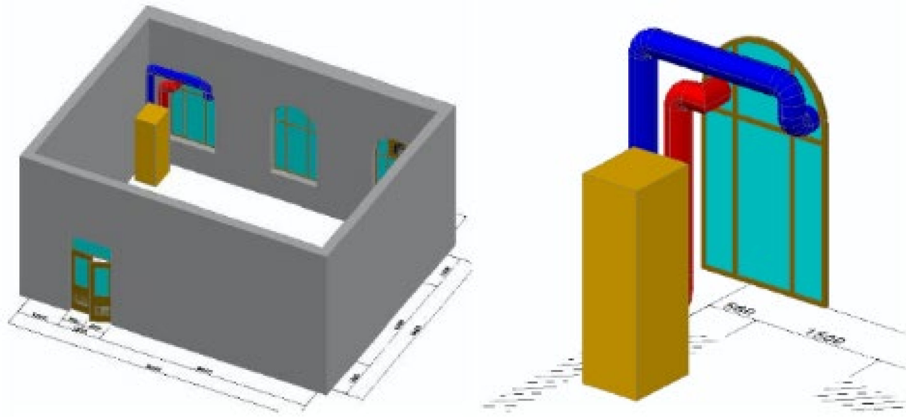


Figure 9. Model of HVAC system with DCV ventilation including fault injector analyzed in [62].

In the case of decentralized wall (façade) units, where the intake and exhaust are located in the same place and the air is removed and taken in through the same channel, there may be doubts as to the hygienic safety of such a solution. Laboratory tests described in [63] have shown that these units are safe from a hygienic point of view and there is no risk of mixing the intake and exhaust streams. In the same research, the authors carried out calculations showing that thanks to the use of a decentralized ventilation system in thermally modernized buildings, it is possible to reduce primary energy by up to 70%.

The authors of [64] tested a new algorithm for controlling decentralized units located in an apartment. The algorithm takes into account the preferences of users in terms of room ventilation, CO_2 concentration, and thermal comfort. Based on the research, energy savings of 20% were obtained while meeting the expectations of users. It should be noted that sometimes taking into account all user suggestions can increase energy consumption, so a compromise should be found between the needs of users and a reasonable level of energy consumption [65].

In the case of the assessment of decentralized ventilation units, the concentration of particulate matter PM is an important parameter. The comparative assessment of the central and decentralized systems [58] showed the correct air parameters for both systems in which air filters were used (MERV 8, MERV 10, MERV 14, MERV 16). Although the central system provided better air purification efficiency, the decentralized system was able to ensure adequate and sufficient air purity.

The decentralization of the ventilation system to divide the space into smaller ones with different needs was considered in the example of a swimming pool facility [55]. Figure 10 shows the two air distribution systems: the traditional central system that prepares the air for the entire swimming pool hall and the decentralized system that takes into account the division of the facility into zones with different needs: pool basins, external partitions, and the auditorium.

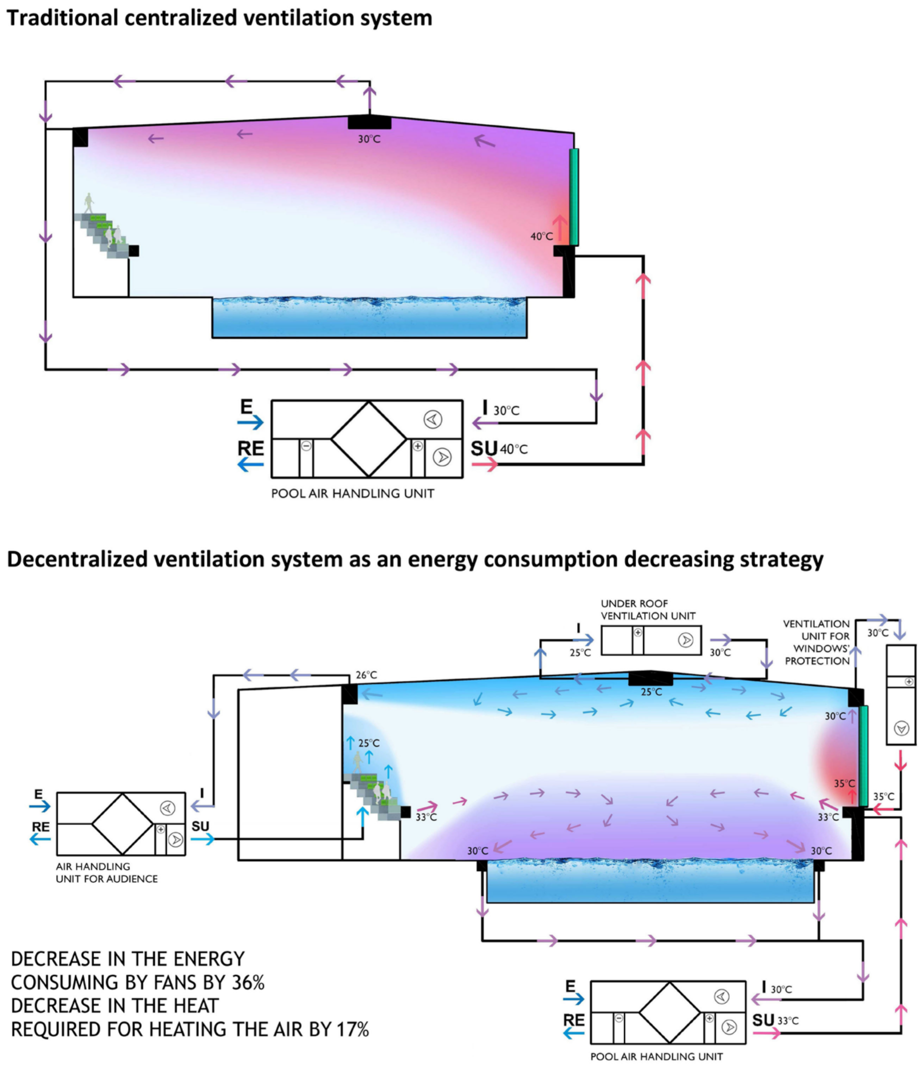


Figure 10. Traditional and decentralized ventilation systems for swimming pool analyzed in [55].

The demand for energy to heat the ventilation air was lower by 30–36% (depending on the method of air heating), and the electricity consumption needed to supply air in the decentralized system was lower by 42%. In addition, it is possible to maintain appropriate conditions in various zones of the facility as required.

Another topic of research is the assessment of the thermal comfort of users of rooms equipped with ventilation units [66]. The authors found that in such rooms people feel discomfort, which is associated with the supply of low-temperature air, because the façade devices are not equipped with air heaters. The author has come to similar conclusions before [67] while testing the created external façade unit (Figure 11), thanks to the application that good air quality was obtained in the tested room.

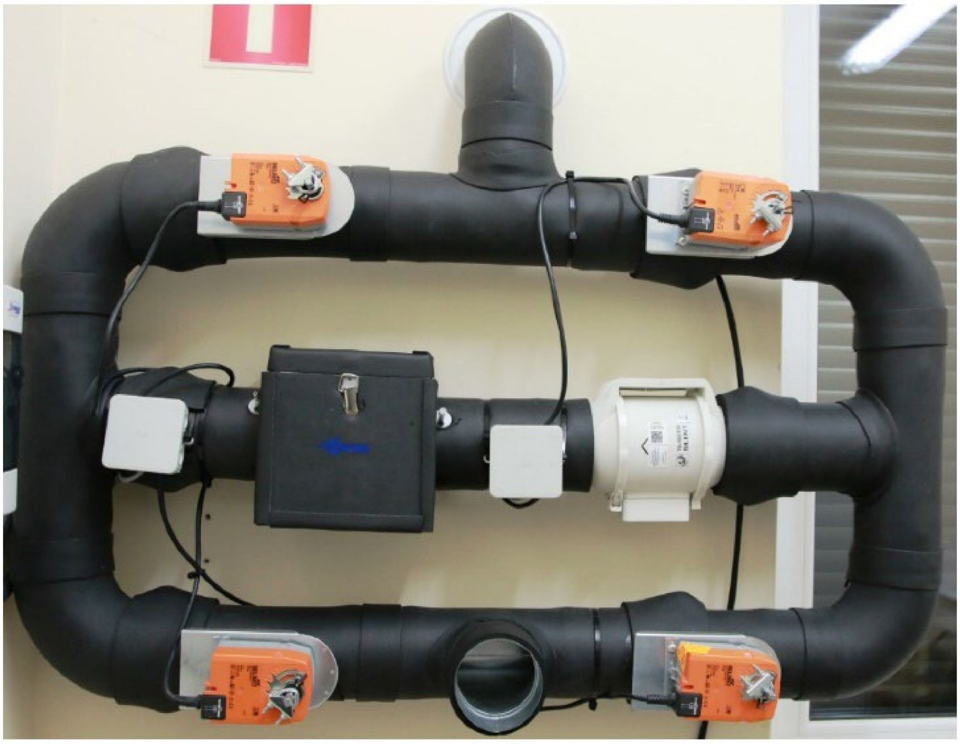


Figure 11. Façade ventilation unit analyzed in [67].

Recently, solutions have also been sought to improve the work of products on the market. The authors of [68] evaluated the length of the work cycle throughout the year. For the commonly used work cycle lasting 70 s, they obtained a heat-recovery efficiency of 67%, and increasing the time to 120 s, the efficiency was as much as 82%. Furthermore, the authors pointed out, similarly to [51,52], that taking into account the seasonal change in the parameters of the outside air will improve the operation of the system. Another element of wall (façade) systems that is used as elements of decentralized ventilation systems is a heat-recovery exchanger. The authors of [69] tested the efficiency of heat recovery in devices available on the market (Figure 12).

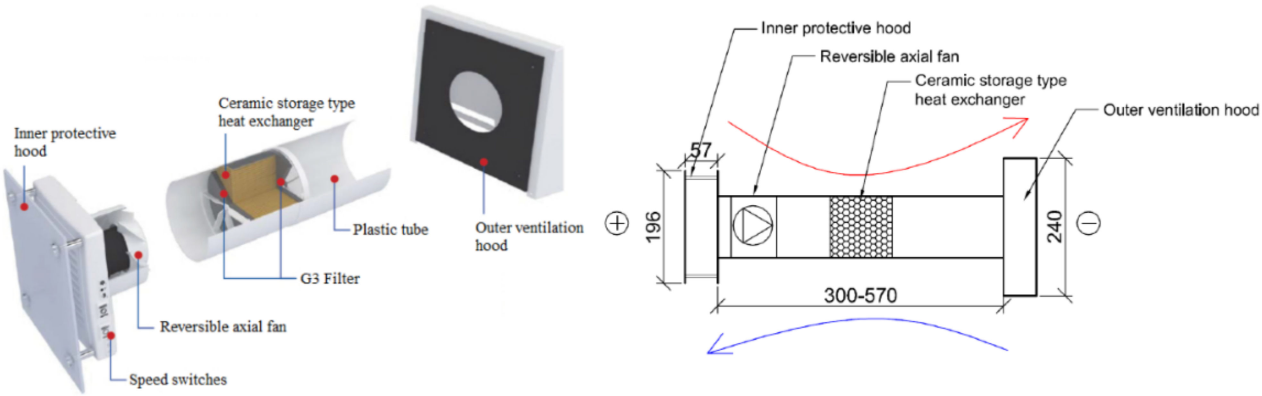


Figure 12. Decentralized ventilation unit with reversible fan and ceramic heat exchanger [69].

As a result of their research, they found that the efficiency of heat recovery provided by manufacturers may differ significantly from what will occur when working in real conditions. This may affect the results of the building's energy performance calculations. In the case of the tested unit, the manufacturer gave an efficiency of 85%, while the tests obtained a range of 20–50%, which was related to the pressure difference. High efficiency

(73%) occurred at a pressure difference of 0 Pa, and a high efficiency of 85% only in the initial period of the fans' work cycle.

A novelty in wall-mounted units may be the replacement of the ceramic heat exchanger with phase-changed material (PCM) filling [70], creating a latent heat-recovery ventilation system (HRV). The combination of ventilation systems and PCM as a solution enabling energy savings is the use of PCM façades as the first stage of heat recovery for decentralized ventilation units [71]. Due to the fact that outside air is introduced into the space behind the glass façade, the air temperature is 3 °C higher in winter and 5 °C lower in summer. The proposed solution can be used in new and existing buildings.

Research on decentralized ventilation systems is carried out in various scopes: efficiency; reduction in the demand for heat, cold, or electricity; the technical possibilities of use in buildings; and the effects measurable with parameters of indoor air, e.g., CO_2, radon, or dust. Modern PCM and façade solutions are being developed. All the articles collected in Table 3 present analyses that indicate that the decentralization of the ventilation system has many benefits in terms of its application, improvement of air quality, and reduction in energy demand, and encourage further research. At the same time, it was shown that there are premises for further research on decentralized systems, e.g., in terms of providing greater comfort to users or further improving the operation of small units that could be used in modernized buildings.

Table 3. Reviewed papers on decentralized ventilation systems.

Authors, Year	Title	Journal	Citations	Keywords
Ratajczak K. et al., 2020, [55]	Energy consumption decreasing strategy for indoor swimming pools—Decentralized Ventilation system with a heat pump	Energy and Buildings	15	-
Bonato, P. 2020, [57]	Modelling and simulation-based analysis of a façade-integrated decentralized ventilation unit	Journal of Building Engineering	14	-
Carbonare N. et al., 2020, [60]	Simulation and Measurement of Energetic Performance in Decentralized Regenerative Ventilation Systems	Energies	0	Decentralized ventilation, heat recovery, honeycomb heat exchanger, computational fluid dynamics, Modelica
Zender-Świercz E. 2020, [61]	Improvement of indoor air quality by way of using decentralised ventilation	Journal of Building Engineering	15	Decentralised façade, ventilation systems
Ratajczak K. et al., 2020, [63]	Assessment of the air streams mixing in wall-type heat recovery units for ventilation of existing and refurbishing buildings toward low energy buildings	Energy and Buildings	20	Integrated wall-type air intake-outtake unit, air streams mixing assessment, indoor air quality, heat recovery ventilation unit, energy efficiency in buildings, thermomodernization
Zemitis J. Bogdanovics R. 2020, [69]	Heat-recovery efficiency of local decentralized ventilation devices	Magazine of Civil Engineering	0	Decentralized ventilation, heat recovery, efficiency, pressure difference
Dehnert J. 2021, [52]	Radon protection in apartments using a ventilation system wireless-controlled by radon activity concentration	Journal of Radiological Protection	2	-
Ratajczak K. Basińska M. 2021, [54]	The well-being of children in nurseries does not have to be expensive: The real costs of maintaining low carbon dioxide concentrations in nurseries	Energies	4	Decentralized ventilation, façade ventilation
Fu N. 2021, [58]	Comparative Modelling Analysis of Air Pollutants, $PM_{2.5}$ and Energy Efficiency Using Three Ventilation Strategies in a High-Rise Building: A Case Study in Suzhou, China	Sustainability	2	Decentralized ventilation system, centralized ventilation, indoor air quality, high-rise building, infiltration, air filter efficiency

Table 3. *Cont.*

Authors, Year	Title	Journal	Citations	Keywords
Filis V. et al., 2021, [59]	The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery	Energy and Buildings	6	Decentralized ventilation, room ventilation units, façade ventilation, heat recovery, rotary heat exchanger, stack effect, centrifugal fans, axial fans, humidity-controlled damper
Carbonare N. 2021, [64]	Design and implementation of an occupant-centered self-learning controller for decentralized residential ventilation systems	Building and Environment	3	Mechanical ventilation, occupant-centered control, adaptive control, building simulation, residential buildings, occupant behavior
Dudkiewicz E. et al., 2021, [65]	Users' Sensations in the Context of Energy Efficiency Maintenance in Public Utility Buildings	Energies	1	CO_2 concentration, lecture room, students' preferences, sultriness, thermal comfort; willingness to work
Zednre-Świercz E. 2021, [67]	Assessment of Indoor Air Parameters in Building Equipped with Decentralised Façade Ventilation Device	Energies	4	Air quality, CFD simulation, decentralised façade ventilation systems
Pekdogan T. 2021, [68]	Experimental investigation of a decentralized heat recovery ventilation system	Journal of Building Engineering	6	Indoor air quality, ventilation, decentralized heat recovery, sensible energy storage
Pekdogan T. 2021, [70]	Experimental investigation on heat transfer and air flow behaviour of latent heat storage unit in a I integrated ventilation system	Journal of Energy Storage	2	-
Altendorf D. 2022, [51]	Decentralised ventilation efficiency for indoor radon reduction considering different environmental parameters	Isotopes in Environmental and Health Studies	0	Decentralised ventilation
Ratajczak K. 2022, [53]	Ventilation Strategy for Proper IAQ in Existing Nurseries Buildings—Lesson Learned from the Research during COVID-19 Pandemic	Aerosols and Air Quality Research	3	Ventilation strategy, nurseries, indoor air quality, COVID-19 pandemic, decentralized ventilation
Zender-Świercz E. et al., 2022, [66]	Assessment of Thermal Comfort in Rooms Equipped with a Decentralised Façade Ventilation Unit	Energies	0	Thermal comfort, decentralised façade ventilation units, storage heat exchangers for heat recovery
Shahrzad S. 2022, [71]	Parametric optimization of multifunctional integrated climate-responsive opaque and ventilated façades using CFD simulations	Applied Thermal Engineering	7	Decentralized ventilation

5. Preheating/Cooling of Outdoor Air in Earth-to-Air Heat Exchanger (EAHE)

Fresh ventilation air can be preheated (in winter) or cooled (in summer), achieving a partial air-conditioning effect through the use of earth-to-air heat exchangers (EAHEs), a kind of ground heat exchanger. EAHEs can take the form of pipes buried in the ground, be made as gravel-type, i.e., with an accumulation layer of supporting stones, or be plate-type, i.e., with plates of various shapes buried in the ground under which air flows. In recent years, multi-pipe earth-to-air heat exchangers have attracted the interest of researchers. These are heat exchangers built of multiple parallel pipes, which are used, for example, for facilities with high air ventilation demand. They allow a reduction in flow resistance and the use of smaller-diameter pipes, which are easier to place under the ground surface. A schema of single-pipe and multi-pipe EAHE is presented in Figure 13.

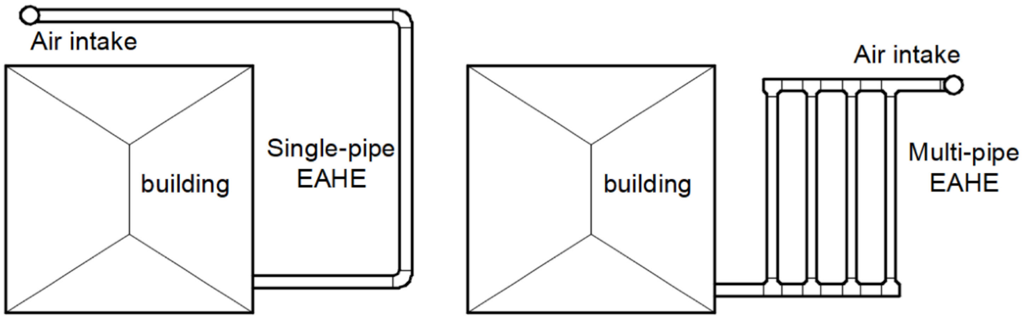


Figure 13. Schema of single-pipe and multi-pipe EAHE [72].

Another idea, the ISOMAX system, allows the use of solar energy stored in a ground buffer or in a foundation plate [73–76]. The system is based on a co-axial pipe in a pipe counter recuperator for ventilation purposes and was investigated in Slovakia [77,78]. The system is still being developed and allows for an improvement in the energy efficiency of heating and cooling sources [79].

Earth-to-air heat exchangers make it possible to preheat air in the ground in winter and thus protect heat-recovery systems from frost. This is a more efficient solution than bypass [80] and is based on the high thermal inertia of the ground, the temperature of which at a certain depth, depending on the type of soil and climatic zone, is always higher than 0 °C. In summer conditions, on the other hand, the air flowing through the heat exchanger can be cooled and also dehumidified by condensation on the cool surface of the exchanger. In energy terms, the profit of EAHE operation is the use of renewable energy from the ground, while the cost is the electricity required to overcome the resistance of the airflow through the exchanger and ducts. To ensure efficient heat exchange in the exchanger, devices are used to increase its intensity, and at the same time the flow resistance. These solutions always require a comparative analysis to judge which variant will be a compromise or optimal, e.g., in terms of energy or finance. Also important is the issue of unequal distribution of airflows in EAHE pipes, which has a bearing on energy requirements for heating and cooling. This issue is illustrated from the company's own CFD simulation results in Figure 14, where the distribution of velocities in individual pipes is shown for multi-pipe EAHE where blue colour means the lowest velocity and yellow to red colour, the highest values.

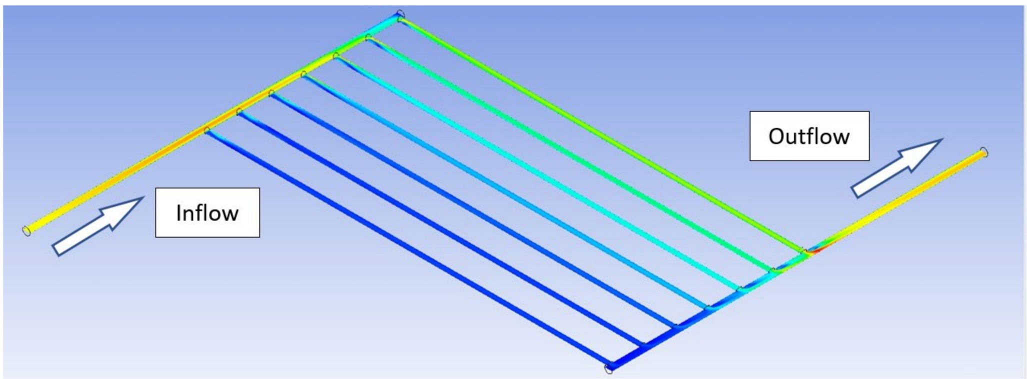


Figure 14. Distribution of air velocity in the axis of individual pipes of a multi-pipe EAHE: blue color—the lowest velocity, yellow to red—the highest; results of own simulation.

Earth-to-air heat exchangers are used around the world and in virtually every climate. The vast majority of the research work is on tubular heat exchangers, although gravel-type EAHEs have also recently been published [81]. The transfer of the recovered heat to cold and dry outside air results in a significant reduction in primary energy requirements for other purposes [82].

The number of research papers on earth-to-air heat exchangers is huge. Among them, there are well-known works dealing with mathematical modelling issues without any proof of the practical application of these devices in building ventilation systems. In this review, we focus on selected works that address the energy aspects of the exchanger's operation in the context of its use in ventilation systems.

The most recent review article on the subject of EAHE is [83], which summarizes the results of experimental studies, numerical simulations, and case-study analyses from around the world. The chapters discuss the methods used to model the performance, conduct experimental studies, and then describe parametric studies, hybrid systems with other renewable energy sources, and economic assessments. This is a very comprehensive work that leads to the conclusion that EAHEs can be successfully applied worldwide, bringing benefits in reducing energy demand and decarbonizing the building sector, as well as lowering the operating costs of HVAC systems. In an overview article [84] the authors analyzed the results of various publications that show the cooperation of EAHE with other systems: air conditioners, air-source heat pumps, heat-recovery units, evaporative cooling or air humidity control devices, photovoltaic (PV) systems, solar air heaters, solar chimneys (SC), wind towers, phase-change materials, roofs, and floors. This is a valuable overview that confirms the advantages of using EAHEs in various applications.

For proper operation of EAHE heat exchangers, an intensification of heat transfer is required, which is achieved using flow disturbances that increase the airflow turbulence. They usually increase pressure losses, but there are also solutions that intensify the heat transfer without increasing the flow resistance. An example is the research results presented in [85]. The study analyzed the impact of using different configurations and shapes of high-heat-transfer-coefficient fins mounted on EAHE ducts. An improvement in the heat exchanger's thermal efficiency by 33% over the baseline variant of the duct with a rectangular cross-section without fins was obtained. Another example of a way to intensify exchanger performance is to use backfilling material with a high value of the conduction coefficient, as analyzed in [86]. Based on the study, it was concluded that the thermal conductivity of backfilling materials should be no higher than 2.5 W/(m·K) to ensure the improved thermal performance of the analyzed system.

In recent years, solar chimneys (SC) coupled with EAHEs (SC + EAHE = SCEAHE) have become very popular in international journals. The use of a solar chimney creates a sufficient pressure differential to induce air flow through the exchanger without the need for electricity. The schematic diagram of an SCEAHE is presented in Figure 15.

In [87] the influence of various parameters of the solar chimney and EAHE was analyzed using numerical simulations. It has been shown that the diameter of the EAHE pipes and their length are much more crucial than the height of the chimney and the length of the solar collector. An analysis of the use of solar energy as a driving force showed that during the day airflows of 260–280 m^3/h were achieved, while at night only 50–100 m^3/h were achieved. Thanks to the solar chimney, EAHE obtains renewable energy from the ground in a passive way and has allowed the indoor air temperature to be reduced by 4.4 °C in summer and increased by 6.4 °C in winter. In another article [88] experimental studies of the solar chimney natural ventilation system operating with EAHE were carried out. The flow rate was 209 m^3/h during the day and 139 m^3/h at night. The indoor air temperature for the transitional season was 19.7–22.7 °C with the outdoor air temperature in the range of 12.5–25.0 °C. Experimental studies of natural ventilation in a system with an earth-to-air heat exchanger and a solar chimney are also presented in [89]. In summer, the air flow was at the level of 56.5 m^3/h at night and 291.5 m^3/h during the day, while in winter it was 90.9 and 388.8 m^3/h, respectively. The results confirm the phenomenon of a decrease in ventilation intensity in the absence of solar radiation at night. At the same time, it was shown that the ventilation air streams were higher in winter than in summer—thermal efficiency in winter and summer was 61% and 86%, respectively. Further experimental studies for SCEAHE with diameters of 0.3 m and 0.2 m are described in the article [90]. The paper notes that the "daily natural ventilation cycle" consists of the following stages: "thermal mass driven ventilation, coupling ventilation, solar chimney driven ventilation, coupling ventilation, and thermal mass driven ventilation". The maximum air flows achieved for the exchanger diameters are 252 m^3/h and 166 m^3/h during the day and 50–70 m^3/h and 45–50 m^3/h at night, respectively. The peak cooling capacity of the EAHE with SC was calculated to be 1179 W with a 0.3 m pipe diameter and 629 W with a 0.2 m pipe diameter. This is explained by the higher air flow, as the maximum temperature drop in both cases was similar: at approx. 12.5–13 K, similar capacities, i.e., 252 m^3/h during the day and 50–70 m^3/h at night, were obtained as a result of experimental tests presented in [91]. In [92] numerical simulations were presented to determine the cooling potential of SCEAHE, in which SC is filled with a phase-change material (PCM). With this modification, the airflow during the night was increased by 50%, while the internal air temperature was 0.8 K lower than the SCEAHE system without PCM. The maximum airflow during the day in the system with PCM was 17.8% lower than without PCM and amounted to 209.5 m^3/h. The use of phase-change material resulted in a reduction in the difference between the extreme values of airflow observed during the day and at night. In addition, as expected, the percentage increase in the stream at night was greater than the decrease in the stream during the day, which eliminated too-low air flow during the night due to the lack of solar radiation. The results of the discussed tests of the natural ventilation system with SCEAHE are summarized in Table 4.

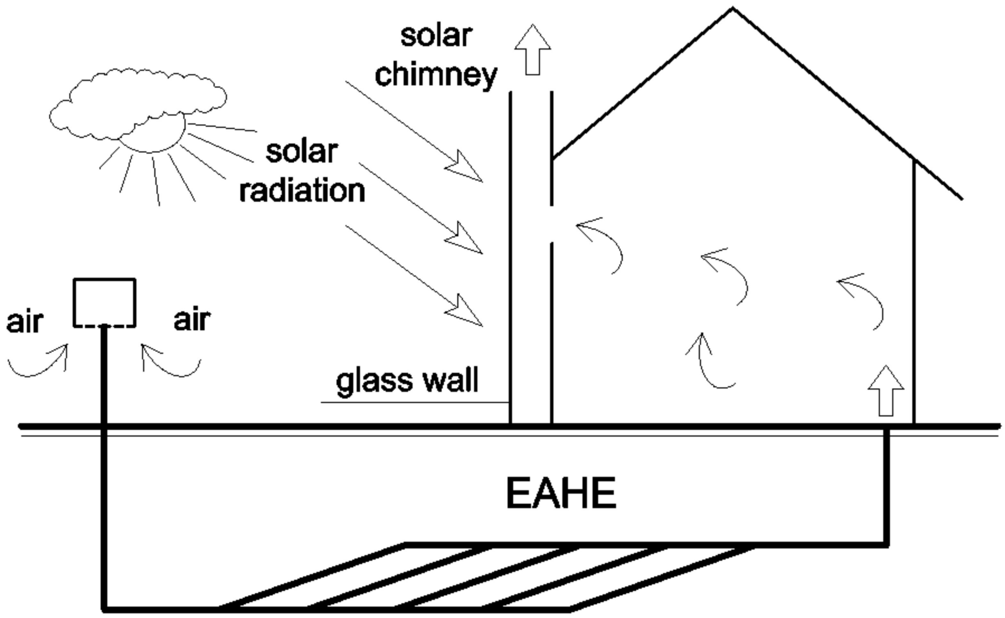


Figure 15. Schematic diagram of solar chimney (SC) coupled with earth-to-air heat exchanger (EAHE) = SCEAHE.

Table 4. A summary of SCEAHE research results.

Paper	Day-Time Airflow	Night-Time Airflow	Thermal Effect
[87]	260–280 m^3/h	50–100 m^3/h	Reduction in indoor air temperature by 4.4 °C in summer and increase by 6.4 °C in winter
[88]	209 m^3/h	139 m^3/h	Indoor air temperature 19.7–22.7 °C with outdoor air temperature 12.5–25.0 °C
[89]	291.5 m^3/h (summer) 388.8 m^3/h (winter)	56.5 m^3/h (summer), 90.9 m^3/h (winter)	The efficiency of obtaining energy from the ground was 86% in summer and 61% in winter
[90]	252 m^3/h (pipes diameter 0.3 m) 166 m^3/h (pipes diameter 0.2 m)	50–70 m^3/h (pipes diameter 0.3 m) 45–50 m^3/h (pipes diameter 0.2 m)	Reduction in the temperature of the supply air to the room by 12.5–13 K, translating into a cooling power of 1179 W for 0.3 m pipe diameter and 629 W for 0.2 m pipe diameter
[91]	252 m^3/h	50–70 m^3/h	Reduction in room supply air temperature by 12.5 K, maximum total cooling capacity (latent + sensible): 1398 W
[92]	209.5 m^3/h with PCM 255 m^3/h without PCM	95 m^3/h with PCM 50 m^3/h without PCM	Air temperatures at the outlet of EAHE with and without PCM of 24.8–26.5 °C and 24.4–27.2 °C, respectively; more stable indoor thermal comfort with PCM

A sensitivity analysis of the SCEAHE performance to changes in selected parameters affecting flow through the system is presented in [93]. It can be read that "increasing the solar collector length or the chimney height can both increase the system performance. However, the effect of chimney height is not as significant as that of solar collector length. The higher the solar intensity, the higher the buoyancy force, the airflow rate, the outlet air temperature, and the cooling capacity. The cooling capacity is increased by 101.4% by increasing the solar intensity from 100 W/m^2 to 600 W/m^2". While researching the optimal geometry of EAHE it was found that a pipe of 0.6 m diameter and 60 m long provides the highest performance. Further increasing the length of the pipe reduces the airflow rate.

The application of SCEAHE for ventilation of a swimming pool located in a hot, arid climate is presented in [94] using the CFD simulation tool. The results demonstrated that on the most critical design day, most date of temperature, velocity, relative humidity and CHCl3 mass fraction lay in the standard ranges. The system met the expectations of ventilation systems and is energy-efficient because of the use of passive technique.

In a warm, dry climate EAHEs can harvest a desirable coolness from the ground. If it is humid, they can additionally dry the air thanks to the condensation phenomenon on the pipe walls. Experimental studies of cooling capacity in hot and humid climates are presented in [95], where increasing the depth and decreasing the diameter decrease the air temperature/moisture content. The results of the study showed that increasing the depth of the EAHE location is conducive to achieving greater cooling and dehumidification of ventilation air (which is desirable in the climate studied). However, the limit value that would be economically viable was not analyzed, and the cost of making a deeper excavation was not considered.

In [96] an experimental study of the effect of EAHE on indoor humidity was conducted in buildings located in arid regions. The study involved a 66 m long, 0.11 m diameter pipe exchanger located in Algeria 1.5 m below the ground surface. An increase in relative humidity (RH) of 19% during the period requiring humidification of the air and a decrease in RH of 27% during the period requiring a decrease in humidity were observed. It was concluded that "the EAHE technique has excellent potential for the enhancement of building hygrometry in arid regions". Another experimental set-up was built in Algeria to study the transient thermal performance of EAHE [97]. Investigations revealed a temperature drop of ventilation air at a level of 19 K. The decrease in the air cooling capacity was 0.85 K after 95 h of continuous operation of the exchanger with a constant maximum air flow velocity of 3.5 m/s.

The application of EAHE in subtropical climates (warm and humid) is presented in [98]: "EAHE system reduced the temperature in a single room building by a maximum of 2.18 °C, saving 415.92 kWh energy (on average 59.91 kWh) during a 3-months summer".

The application of EAHE in the temperate climate of Poland (Central Europe) has been analyzed in recent years, including in [99], where experimental studies showed that EAHE "reduces the demand for energy in the ventilation system by around 45%, and it can reduce the energy load of the entire building by around 20%".

In [100] calculations of the hourly energy demand for a building cooperating with EAHE were carried out. The EN ISO 13790 standard was used to model the building (describing the so-called "5R1C" model) and the EN 16798-5-1 standard to calculate the outlet air temperature after EAHE. The results of calculating the temperature change due to air flow through a ground exchanger installed in Poland are shown in Figure 16. It is shown that the use of a "bypass and switching between the EAHE and ambient air as the source of ventilation for the building resulted in annual energy savings of 123 kWh".

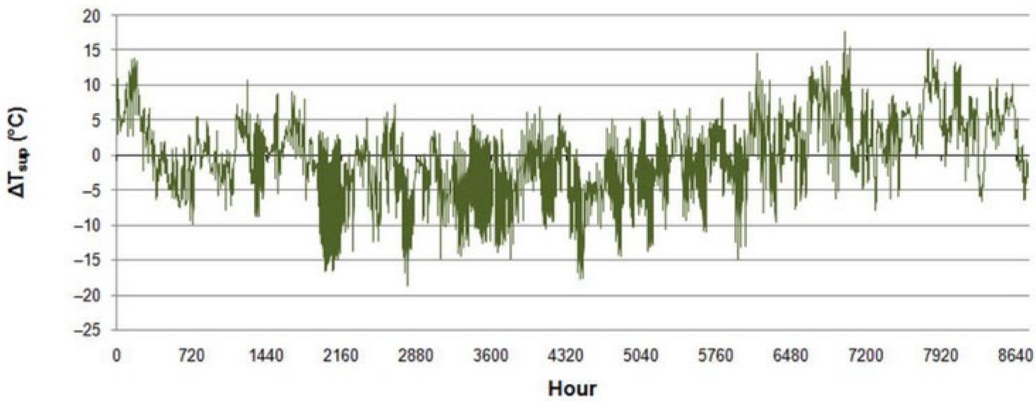


Figure 16. The change in the temperature of the air flowing through the exchanger over a year (0 h = 1 January, 8760 h = 31 December) [100].

In [101], which is a continuation of the previous paper, the authors analyzed the effect of changes in air density in Poland's climate on simulated EAHE performance. It was noted that the comparison of density variation with temperature for the typical meteorological year (at constant pressure) and the method of EN 16798-5-1 causes an hourly difference of unit gain of up to 4.3 W/m^2 and 2.0 W/m^2 for heating and cooling, respectively. In the case of International Weather for Energy Calculation files the differences were from 5.5 W/m^2 to 1.1 W/m^2. Differences in the values of the volumetric heat capacity of air, used in the next step of the EAHE thermal performance calculations, resulting from different calculation methods are shown in Figure 17.

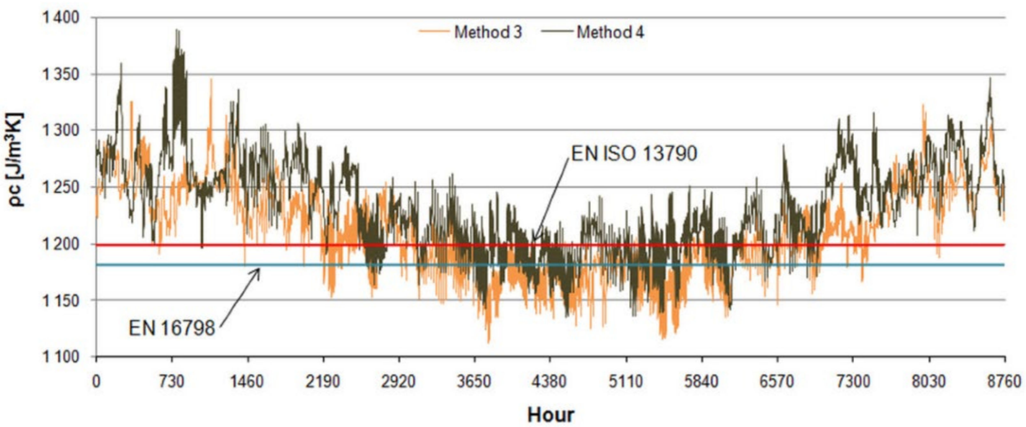


Figure 17. Volumetric specific heat of air according to various methods [101].

In [72] calculations were performed of the amount of energy saved by the operation of single-pipe and multi-pipe earth-to-air heat exchangers in the climate of Central Europe. Based on the study of their structure, it was proven that the appropriate selection of single-pipe EAHE is able to provide an equivalent energy yield to the multi-pipe structure with similar or lower pressure losses. The yearly energy usage for driving the fans for multi-pipe structures of length L = 55.4 m and single-pipe structures of equivalent length in the context of heating capacity with different pipe diameters (d = DN200, DN250 or DN315, V = 600 m^3/h) is presented in Figure 18. The paper presents a methodology for the simple and quick comparison of different EAHE structures and geometric and environmental parameters affecting the energy yield. The method takes into account the correction factor resulting from the analyses presented in [102].

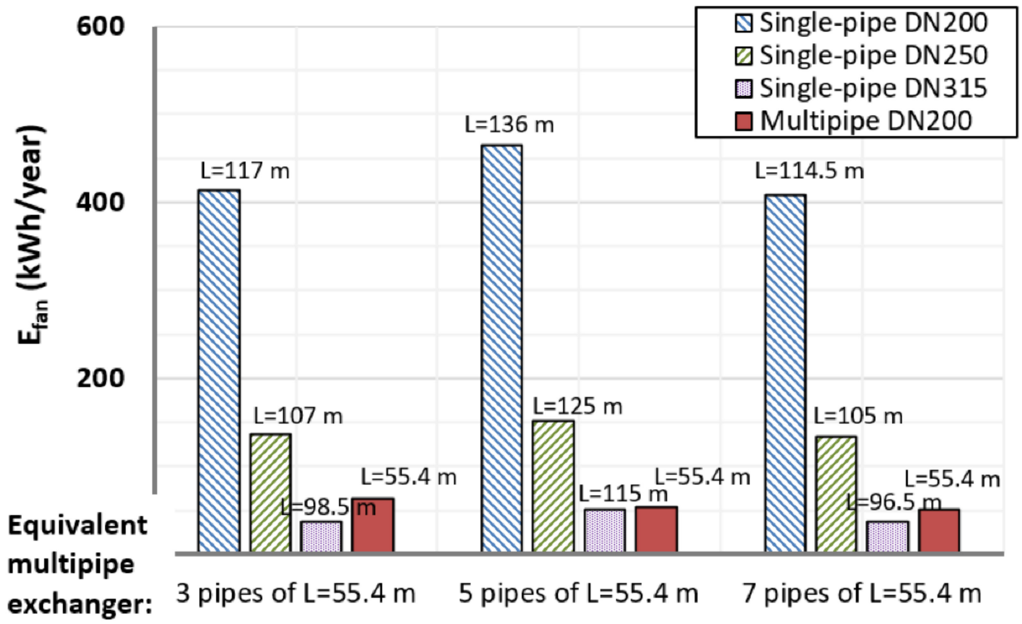


Figure 18. The yearly energy usage for driving the fans in the case of multi-pipe and single-pipe structures [72].

In [102] the relationship between the airflow distribution in the EAHE tubes and the heating and cooling yield is presented. It is shown that as a result of an uneven distribution of airflows, the energy gained can be up to 28% less than that determined for ideal conditions, i.e., assuming an even distribution of air in the exchanger tubes. Airflows in individual branches of multi-pipe EAHEs were determined in experimental studies and published in [103]. The given approximations make it possible to calculate the instantaneous values of the airflow in each branch of the multi-tube exchanger under varying ventilation system loads (different total airflow through the exchanger).

The topic of the effect of exchanger geometry on the uniformity of air distribution and on the reduction in energy consumption was continued by the research team in experimental studies [104] and numerical simulations [105]. These were also used to determine the effect of geometric parameters on pressure loss and heat capacity [106]. The results of the study confirmed the conclusions of [104], in which lower pressure losses, better uniformity of air distribution in the exchanger branches, and higher efficiency of exchangers with a U-type structure than exchangers with a Z-type structure were demonstrated. These studies were also confirmed in [107], where a case study of the use of multi-pipe EAHE for greenhouse ventilation was presented.

A not-very-popular type of EAHE is the gravel-type heat exchanger. The possibility of its use in the ventilation system of a single-family house in various configurations is described in [81] and demonstrated in Figure 19. Due to the direct contact of the ventilation air with the ground layer and the accumulation mass (gravel), it is heated and humidified in winter, and cooled and dried in summer. The estimated simple payback time (SPBT) was 3.65 years.

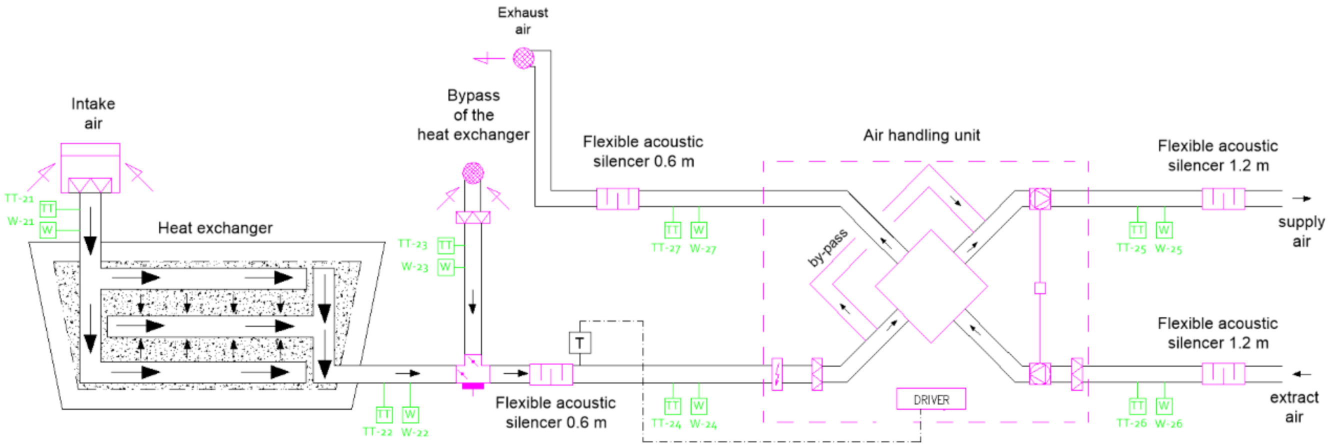


Figure 19. Diagram of integration of gravel-type EAHE into the mechanical ventilation system of a single-family building [81].

Currently, various efficiency-modeling methods are being used and experimental research is being conducted to develop an exchanger that works in the most efficient system with other renewable energy sources. Efforts are being made to reduce pressure losses and achieve the highest possible efficiency per day and per year. The interest in the topic of EAHEs is huge, which confirms many scientific publications and their citations (Table 5). Numerous studies by many authors confirm that different configurations of EAHEs can be used all over the world in different climatic conditions. Their installation allows a reduction in the energy demand for ventilation and decarbonization in the building sector.

Table 5. Reviewed papers on earth-to-air heat exchangers.

Authors, Year	Title	Journal	Citations	Keywords
Kalus D. et al., 2022 [79]	Experience in Researching and Designing an Innovative Way of Operating Combined Building–Energy Systems Using Renewable Energy Sources	Applied Sciences	0	Combined building–energy systems, RES, energy roof, ground-source heat storage; peak heat source, ground-heat recovery, air–heat exchanger, cooling circuits
Wei H, et al., 2020, [95]	Field experiments on the cooling capability of earth-to-air heat exchangers in hot and humid climate	Applied Energy	35	Earth-to-air heat exchanger, renewable energy, cooling capacity, configuration parameter, hot and humid climate
Sakhri N. et al., 2020, [96]	Experimental investigation of the performance of earth-to-air heat exchangers in arid environments	Journal of Arid Environments	27	Earth-to-air heat exchanger, soil temperature, arid region, hygrometry regime, natural ventilation
Amanowicz Ł. Wojtkowiak J. 2020, [102]	Thermal performance of multi-pipe earth-to-air heat exchangers considering the non-uniform distribution of air between parallel pipes	Geothermics	16	Multi-pipe earth-to-air heat exchanger, airflow distribution, thermal performance, tnergy efficiency, multi-tube
Amanowicz Ł. Wojtkowiak J. 2020, [103]	Approximated flow characteristics of multi-pipe earth-to-air heat exchangers for thermal analysis under variable airflow conditions	Renewable Energy	21	Earth-to-air heat exchanger, multi-pipe, flow characteristics, airflow distribution, thermal analysis
Soares N. et al., 2021, [84]	Advances in standalone and hybrid earth-air heat exchanger (EAHE) systems for buildings: A review	Energy and Buildings	12	Earth-air heat exchanger (EAHE) hybrid system, geothermal energy, design parameters, operation conditions, thermal performance

Table 5. *Cont.*

Authors, Year	Title	Journal	Citations	Keywords
Li Y. et al., 2021, [91]	An experimental investigation on the passive ventilation and cooling performance of an integrated solar chimney and earth–air heat exchanger	Renewable Energy	20	Earth–air heat exchanger, solar chimney, natural ventilation, cooling capacity, full-scale experimental study
Long T. et al., 2021, [93]	Numerical investigation of the working mechanisms of solar chimney coupled with earth-to-air heat exchanger (SCEAHE)	Solar Energy	8	Solar chimney, earth-to-air heat exchanger, passive cooling, natural ventilation, numerical simulation
Pouranian F. et al., 2021, [94]	Performance assessment of solar chimney coupled with earth-to-air heat exchanger: A passive alternative for an indoor swimming pool ventilation in hot-arid climate	Applied Energy	7	Indoor swimming pool, renewable energies, solar chimney, passive ventilation, thermal comfort, computational fluid dynamics
Skotnicka-Siepsiak A. 2021, [99]	An Evaluation of the Performance of a Ground-to-Air Heat Exchanger in Different Ventilation Scenarios in a Single-Family Home in a Climate Characterized by Cold Winters and Hot Summers	Energies	4	Ground-to-air heat exchanger, sustainable indoor ventilation system, energy-efficient ventilation
Amanowicz Ł. Wojtkowiak J. 2021, [72]	Comparison of Single- and Multipipe Earth-to-Air Heat Exchangers in Terms of Energy Gains and Electricity Consumption: A Case Study for the Temperate Climate of Central Europe	Energies	8	Earth-to-air heat exchangers, pressure losses, multipipe, renewable energy, geothermal energy, building energy performance, ventilation
Qi D. et al., 2021, [106]	Comparative analysis of earth to air heat exchanger configurations based on uniformity and thermal performance	Applied Thermal Engineering	15	Multi-pipe earth to air heat exchanger (MEAHE), uniformity, thermal performance, pressure drop
Mihalakakou G. et al., 2022, [83]	Applications of earth-to-air heat exchangers: A holistic review	Renewable and Sustainable Energy Reviews	11	Earth-to-air heat exchangers, studies of EAHE Systems, experimental studies, hybrid EAHE Systems, economic assessment
Radomski B. et al., 2022, [81]	The Direct-Contact Gravel, Ground, Air Heat Exchanger—Application in Single-Family Residential Passive Buildings	Energies	0	Air direct-contact; gravel; ground heat exchanger; heating and cooling support; passive buildings
Ramalho J. et al., 2022, [85]	Accessing the thermal performance of Earth–air heat exchangers surrounded by galvanized structures	Sustainable Energy Technologies and Assessments	0	Earth–air heat exchangers, (EAHE), fins, galvanized structures, thermal conductivity, thermal performance, numerical simulations
Gao X. et al., 2022, [86]	Thermal potential improvement of an earth-air heat exchanger (EAHE) by employing backfilling for deep underground emergency ventilation	Energy	3	Geothermal, EAHE system backfilling, energy-efficiency ventilation, deep underground buildings
Long T. et al., 2022, [87]	Numerical simulation of diurnal and annual performance of coupled solar chimney with earth-to-air heat exchanger system	Applied Thermal Engineering	2	Solar chimney, earth-to-air heat exchanger, diurnal and annual performance, dynamic simulation
Long T. et al., 2022, [88]	Natural ventilation performance of solar chimney with and without earth-air heat exchanger during transition seasons	Energy	7	Earth–air heat exchanger, solar chimney, buoyancy force, natural ventilation, indoor thermal environment
Bai Y. et al., 2022, [89]	Experimental investigation of natural ventilation characteristics of a solar chimney coupled with earth-air heat exchanger (SCEAHE) system in summer and winter	Renewable Energy	2	Solar chimney, earth-air heat exchanger, natural ventilation, summer and winter, experimental study

Table 5. *Cont.*

Authors, Year	Title	Journal	Citations	Keywords
Long T. et al., 2022, [90]	Investigation on the cooling performance of a buoyancy driven earth-air heat exchanger system and the impact on indoor thermal environment	Applied Thermal Engineering	3	Earth-air heat exchanger, solar chimney, thermal mass, buoyancy force, indoor thermal environment
Long T. et al., 2022, [92]	Benefits of integrating phase-change material with solar chimney and earth-to-air heat exchanger system for passive ventilation and cooling in summer	Journal of Energy Storage	3	Solar chimney, earth-to-air heat exchanger, phase-change material, passive ventilation passive cooling
Belloufi Y. et al., 2022, [97]	Transient assessment of an earth air heat exchanger in warm climatic conditions	Geothermics	2	Earth air heat exchanger, transient thermal performance, continuous operation, derating factor, summer cooling
Ahmed SF. et al., 2022, [98]	Thermal performance of building-integrated horizontal earth-air heat exchanger in a subtropical hot humid climate	Geothermics	2	Building energy consumption, ground heat exchanger, thermal modelling, thermal performance, renewable energy, cnergy savings
Michalak P. 2022, [100]	Hourly Simulation of an Earth-to-Air Heat Exchanger in a Low-Energy Residential Building	Energies	4	Earth-to-air heat exchanger; EAHE, EAHX, outlet air temperature, ground temperature, EN 16798-5, EN ISO 13790, 5R1C model, bypass
Michalak P. 2022, [101]	Impact of Air Density Variation on a Simulated Earth-to-Air Heat Exchanger's Performance	Energies	1	Earth-to-air heat exchanger, air density, specific heat of air, barometric formula, EAHE, outlet temperature, ground temperature, EN ISO 13790, 5R1C model, hourly simulation
Qi D. et al., 2022, [107]	Structural optimization of multi-pipe earth to air heat exchanger in greenhouse	Geothermics	5	Multi-pipe parallel earth-to-air heat exchanger, air distribution, heat exchanger performance, greenhouse

6. Heat Recovery from Exhaust Air

The drive toward near-zero-energy buildings is driving interest in a variety of energy harvesting methods. For ventilation systems, great potential exists in the use of heat from exhaust air. The use of heat-recovery exchangers to recover heat from moist exhaust air at low outdoor temperatures makes it possible to recover both sensible heat and latent heat. The recovered heat can be used to heat the supply air to the rooms, but also for heating or hot water preparation, as long as heat pumps are used for the purpose of providing sufficiently high temperatures. Striving for the highest possible heat-recovery efficiency is most often associated with a simultaneous increase in flow resistance through heat-recovery exchangers. It is therefore necessary to find a compromise. Due to the possibility of water vapor freezing, which can condense on the surface of heat-recovery exchangers, there is a need to defrost them, which consumes additional energy. New exchanger designs are still being sought and control strategies are being developed for air-handling units that will minimize the energy consumed in defrosting.

A very popular solution for heat recovery is the use of a plate heat exchanger, the energy effects of which are analyzed, for example, in [108] (Figure 20). The problem of water vapour condensation in such a heat exchanger was investigated experimentally in [96]. An increase in the heat capacity of the exchanger was observed, with a simultaneous increase in the flow resistance on the side where condensation occurred.

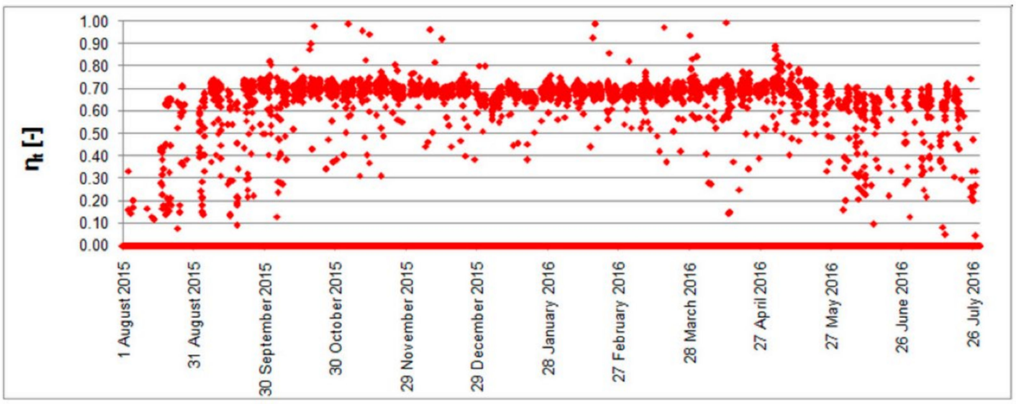


Figure 20. Efficiency of heat recovery between 1 August and 31 July [108].

However, in air-handling units, typical plate heat exchangers are sometimes replaced by membrane heat exchangers, in which the membrane used allows not only heat transfer by penetration through their wall, but also diffusion of water vapor (moisture recovery) based on the concentration difference between air streams separated by the membrane. In [109] the authors reviewed membrane heat exchangers, their design and operating efficiency under various conditions, and the mathematical models used to simulate their operating efficiency. In [110] one can read about assisting the heat-transfer process in a membrane heat exchanger with ultrasound.

Another way of recovering heat from the exhaust air is the use of an accumulating rotary heat-wheel heat exchanger, for which the authors of [111] note that its efficiency is reduced by longitudinal heat conduction. They proposed a wheel made of plastic offering high effectiveness of about 90% at acceptable pressure losses and low cost of material. A similar concept in principle of an exchanger for heat and moisture recovery was proposed in [112]. The hollow fiber membrane heat exchanger was developed and its latent and sensible heat-recovery effectiveness was examined (also experimentally for validation of simulation mode) resulting in an effectiveness of 80% and 62%, respectively, for latent and sensible heat. A similar problem was also observed and analyzed in [46], where it was shown that the average annual temperature recovery efficiency can be 10% lower if the effect of longitudinal heat conduction is taken into account.

A very interesting and comprehensive way to recover heat from exhaust air is the system presented in [113]. The technology is based on the use of an air-handling unit with a high-efficiency heat-recovery exchanger, a cooling system for PV panels and preheating of fresh air using ventilation air. The added effect is an increase in the efficiency of the PV panels and greater electricity production. Similarly, a complex system that is used to recover heat and at the same time dehumidify the air in a building is described in [114]. Exhaust air is directed to a module on the roof of the building, where heat and water vapor exchange takes place. Depending on the mode of operation (day/night), the exhaust air is superheated and/or humidified, and then directed to the heat exchanger in the air-handling unit. There it causes a significant increase in the temperature of the fresh air supplied to the building, also due to the enthalpy of the water vapor in it. In turn, in summer conditions, the system allows one to reduce the moisture load, and thus reduce the energy consumed by the air conditioner. On the contrary, a similar system, but using double glazing of the building, is described in [115]. The removed air is routed between the glazing, causing a reduction in the intensity of heat transfer through the partition, thus reducing heat gain in summer and heat loss in winter, generating the lower energy demand shown in Figure 21 depending on the recovery systems. The systems also have a positive effect on thermal comfort as a result of the elimination of the asymmetric thermal field. The authors note the problem of condensation on the glazing and the formation of fog that obscures the view through the window.

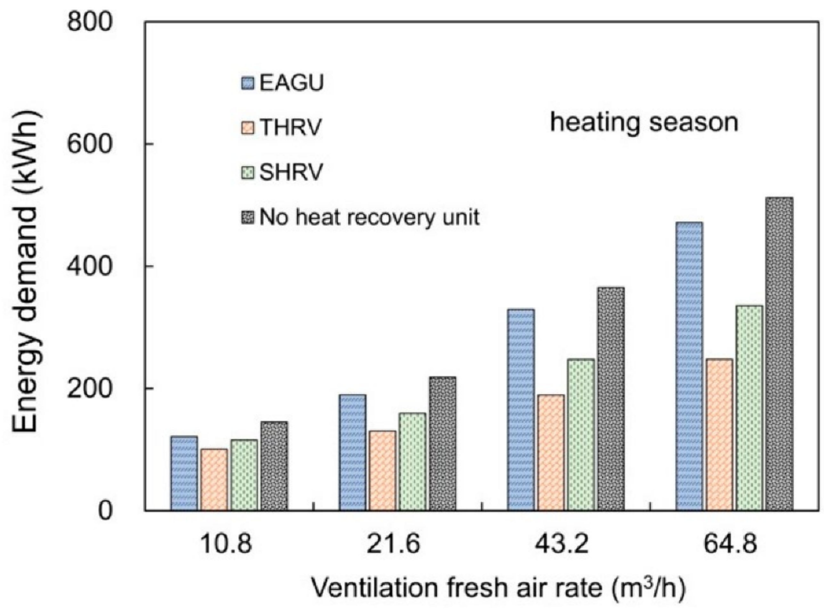


Figure 21. Yearly energy demand for ventilation using different heat-recovery systems: EAGU = exhaust air glass unit, THRV = conventional total heat recovery ventilator, SHRV = sensible heat recovery ventilator [115].

Ventilation systems with a so-called “warm air intake,” where fresh air is drawn through a glazed element that acquires radiant heat from the sun, are described in the paper [116]. “Sunspaces” were investigated in the climate of Spain, where reductions in energy savings ranging from 2.51 kWh/m^2/year in areas of the country with milder climates to as much as 39.54 kWh/m^2/year in areas with colder climates were obtained. In contrast, [117] tested a system for heat recovery and fresh air supply integrated into a window frame in which heat pipes were installed. The CFD simulations showed a heat-recovery efficiency of 65–95% depending on the size of the airflow.

A comprehensive review of various types of technologies for heat recovery from exhaust air was published in [118]. The authors pay special attention to the problem of frosting of appliances in cold climates. This is a phenomenon associated with condensation of water vapor and its subsequent freezing on cold components. The solution to this problem still requires various strategies of protection against frosting or defrosting, which, however, are associated with additional energy consumption, a temporary reduction in air quality in the building, maintenance of the continuity of air supply, and a lack of stable pressure distribution in the building. The economic energy aspect, which is not always beneficial, of heat recovery in various ventilation systems is also presented by the author of a review publication [119].

In [120,121] a heat-recovery system integrated with a pump-driven loop heat pipe and a heat pump is presented. The proposed combination of compressor and pump circuits, as well as the principle of the heat pipe, allows the operation mode to be adjusted to current conditions, ensuring energy savings. The system requires four properly interconnected heat exchangers and is particularly effective in cold climates.

In [122] a typical indoor air heat-recovery system based on a compressor heat pump installed inside a ventilation unit is presented. Innovative in this solution is the dual-cylinder compressor, and complementing the study of the heat-recovery system itself are simulations of the annual operation of this device in the ventilation system of a building.

The results of a study, rarely used in the ventilation of a thermoelectric heat pump, are presented in [123]. The system, although less efficient than the compressor heat pump in the proposed solution, can be competitive for buildings with low heating power requirements of <10 W/m^2. A wide and smooth performance control range and high control accuracy are presented as advantages of this solution. The results of system optimization were presented by the same team of authors in the article [124].

The authors of [125] investigated the feasibility of using a thermoelectric heat pump mounted on a window frame as aheat-recovery element from exhaust air. Pilot studies were conducted in the UK. The conclusions emphasized that the system would be most environmentally friendly if it worked in conjunction with PV panels.

Heat recovered from exhaust air can also be used for heating purposes in a multi-family building. This solution, taking into account the location of the building as well as the different operating parameters of the heating system, was analyzed in [11] and is presented in Figure 22. The highest average coefficient of performance (COP) of the system was found in Koszalin (mild climate on the Baltic Sea in Poland) for the lowest operating parameters of the heating system (35/28 °C). The article highlights that CO_2 emissions for heating the analyzed buildings can be further reduced if the electricity to power the heat pump comes from PV panels. The authors' team also performed an analysis of the efficiency of air heat recovery to heat domestic hot water [126]. For the case analyzed and the Polish energy production conditions, the final energy demand for hot water preparation was 35.1% lower compared to the use of a condensing gas boiler only.

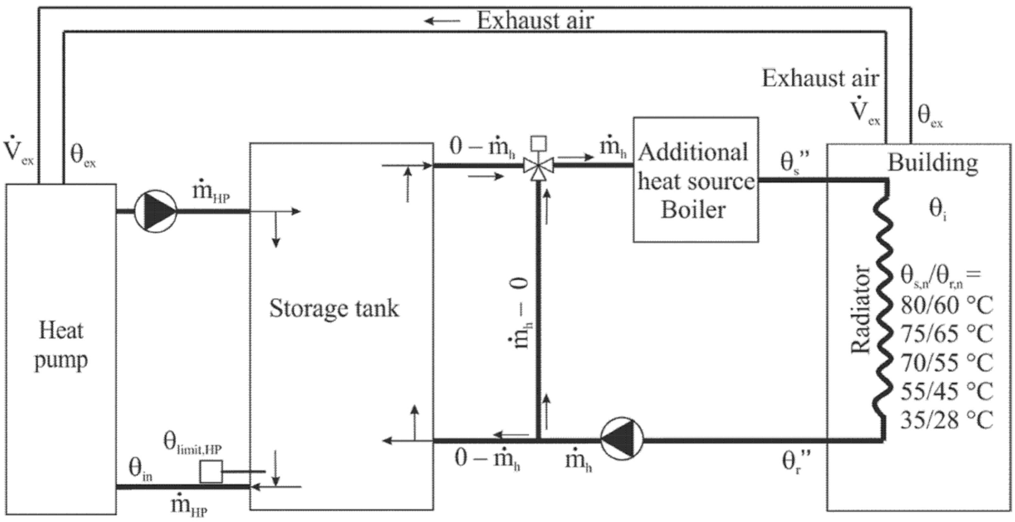


Figure 22. Schema of the system of heat recovery from exhausted air, presented in [11].

A system of two recovery exchangers as an idea to increase heat-recovery efficiency is analyzed in [127]. In summer, exhaust air is directed to the secondary heat exchanger to heat the air behind the cooler and then goes to the primary unit to pre-cool the fresh air. Compared to the baseline solution, with a single heat-recovery exchanger, the solution reduced the energy consumption of the cooler by more than 20% and that of the heater by 80%.

The test results in [128] especially should move those responsible for maintaining mechanical ventilation systems. The study showed that the pressure loss of a dirty exchanger was 12% higher and the thermal efficiency 8% lower compared to a clean exchanger. Attention is paid to the need for cleanliness and periodic inspection of system components.

In recent years, there have been many publications on innovations in the field of heat-recovery technology from exhaust air. The 23 most interesting articles, in the opinion of the authors, have been selected to show trends and developments (Table 6). It is possible to create a heat-recovery system from exhausted air owing to numerous configurations of heat exchangers, i.e., plate, membrane, heat wheels, and using heat pumps. Composite systems with several exchangers are being developed, allowing multi-stage heat recovery. To ensure the high efficiency of heat exchangers, it is necessary to protect them from freezing and keep them clean.

Table 6. Reviewed papers on heat recovery from exhausted air.

Authors Year	Title	Journal	Citations	Keywords
Cepiński W. et al., 2020, [126]	Waste heat recovery by electric heat pump from exhausted ventilating air for domestic hot water in multi-family residential buildings	Annual Set The Environment Protection	2	Air-to-water electric heat pump, waste heat recovery, heat recovery in ventilation, domestic hot water, TRNSYS
Zender–Świercz E. 2021, [119]	A Review of Heat Recovery in Ventilation	Energies	15	Heat recovery, ventilation systems, recovery efficiency, energy-consumption
Michalak, P. 2021, [108]	Annual Energy Performance of an Air Handling Unit with a Cross-Flow Heat Exchanger	Energies	3	Air-handling unit, cross-flow heat exchanger, heat recovery, temperature effectiveness, temperature efficiency, EN 308, ventilation loss
Kowalski P. et al., 2021, [11]	Waste Heat Recovery by Air-to-Water Heat Pump from Exhausted Ventilating Air for Heating of Multi-Family Residential Buildings	Energies	1	TRNSYS, air-to-water electric heat pump, AWHP, hybrid heat source, waste heat, building energy performance, primary energy, exhaust ventilation, energy efficiency
Bai H.Y. 2022, [118]	A review of heat recovery technologies and their frost control for residential building ventilation in cold climate regions	Renewable and Sustainable Energy Reviews	9	Heat recovery, cold climate, indoor air quality, frosting control, energy-efficient ventilation
Li J. et al., 2022, [109]	A review of air-to-air membrane energy recovery technology for building ventilation	Energy and Buildings	3	Energy recovery, air-to-air membrane, moisture transfer effectiveness, ventilation
Gurubalan A., et al., 2022, [110]	Performance Improvement of Membrane Energy Exchanger Using Ultrasound for Heating, Ventilation, and Air Conditioning Application	Journal of Thermal Science and Engineering Applications	0	Ultrasound, energy exchanger, membrane dehumidifier, membrane humidifier, membrane energy recovery ventilator, energy efficiency, energy systems, heat and mass transfer, thermal systems
Liu P. et al., 2022, [111]	Development and optimization of highly efficient heat recoveries for low carbon residential buildings	Energy and Buildings	4	Energy-efficient ventilation heat recovery, heat wheel, low-carbon buildings
Cho H.J., 2022, [112]	Development of empirical models to predict latent heat exchange performance for hollow fiber membrane-based ventilation system	Applied Thermal Engineering	0	Air-to-air hollow fiber, membrane, energy recovery ventilation, latent heat exchanger, experimental analysis, empirical models
Tang Y et al., 2022, [113]	Performance prediction of a novel double-glazing PV curtain wall system combined with an air handling unit using exhaust cooling and heat recovery technology	Energy Conversion and Management	3	Solar energy, AHU, double-skin PV façade, exhaust air, heat recovery
Chen Y, et al., 2022, [114]	Energy saving potential of passive dehumidification system combined with energy recovery ventilation using renewable energy	Energy and Buildings,	1	Passive dehumidification, moisture adsorption, moisture desorption, energy recovery ventilation, renewable energy, latent heat-load reduction
Guo J. et al., 2022, [115]	Utilization of Window System as Exhaust Air Heat Recovery Device and Its Energy Performance Evaluation: A Comparative Study	Energies	1	Exhaust air heat recovery, exhaust air glass unit, low-energy building, window system; comparative study
Gainza-Barrencua J, et al., 2022, [116]	Use of sunspaces to obtain energy savings by preheating the intake air of the ventilation system: Analysis of its main characteristics in the different Spanish climate zones	Journal of Building Engineering	1	Sunspace, solar heating, mechanical ventilation, heat recovery, heat storage

Table 6. *Cont.*

Authors Year	Title	Journal	Citations	Keywords
Barreto G. 2022, [117]	An innovative window heat recovery (WHR) system with heat pipe technology: Analytical, CFD, experimental analysis and building retrofit performance	Energy Reports	3	Building ventilation, heat recovery, window heat recovery, heat pipe, energy performance, thermal comfort
Liu S. et al., 2022, [120]	Experimental study of ventilation system with heat recovery integrated by pump-driven loop heat pipe and heat pump	Journal of Building Engineering	3	Ventilation heat recovery, integrated heat pump, pump-driven loop heat pipe, switch temperature
Shuailing L. et al., 2022, [121]	Performance of a mechanically-driven loop heat pipe heat recovery system	Applied Thermal Engineering	3	Heat recovery, ventilation, heat pipe, refrigerant pump, booster
Jia X. et al., 2022, [122]	The applicability and energy consumption of a parallel-loop exhaust air heat pump for environment control in ultra-low energy building	Applied Thermal Engineering	2	Exhaust air heat pump, heat recovery, ultra-low energy building, energy consumption, COP
Diaz de Garayo S. et al., 2022, [123]	Annual energy performance of a thermoelectric heat pump combined with a heat recovery unit to HVAC one passive house dwelling	Applied Thermal Engineering	5	Thermoelectricity, heat pump, passive house, HVAC, heat recovery
Diaz de Garayo S. et al., 2022, [124]	Optimal combination of an air-to-air thermoelectric heat pump with a heat recovery system to HVAC a passive house dwelling	Applied Energy	6	Hermoelectricity, Heat pump, Heat-recovery unit, Passive house, HVAC
Xu Q. et al., 2022, [125]	Ecopump: a novel thermoelectric heat pump/heat recovery ventilator system for domestic building applications	International Journal of Low-Carbon	0	-
Goldanlou A.S. et al., 2020 [127]	Energy usage reduction in an air handling unit by incorporating two heat recovery units	Journal of Building Engineering,	72	Air-handling unit, energy demand, exergy, building
Abdul Hamid A. et al., 2020, [128]	Determining the impact of air-side cleaning for heat exchangers in ventilation systems	Building Services Engineering Research and Technology	4	-
Abadi I.R. et al., 2022, [129]	Experimental investigation of condensation in energy recovery ventilators	Energy and Buildings	5	Energy-recovery ventilator, total heat exchanger, energy exchanger, heat and moisture exchanger, condensation, membrane

7. Conclusions

The literature review was performed to leverage the current knowledge base to present the advances in ventilation systems that reduce energy consumption. This issue is still a challenge, as evidenced by the many studies conducted and analyses performed during the last three years. As many as 98 papers were subjectively chosen based on the high value of compelling evidence within. The results of the publications reviewing advancement in ventilation systems may be useful to many scientists—young and experienced—as in the case of other similar reviews, e.g., [130]. They can adopt these as an initial step to write articles, as well as to provide a guide pointing out cutting-edge technologies and strategies in ventilation systems. Although this review does not define a stance, there is a relevant contribution to recognizing the issues of the requirements for ventilation systems, the airtightness of the building's envelope, the demand-controlled ventilation strategy, decentralized ventilation systems, earth-to-air heat exchangers, and the recovery of exhaust air heat. Summaries of these aspects are presented in the particular paragraphs.

- This literature review reinforces the belief that:

- airtightness of the building's envelope is as a basic requirement for efficiency of buildings; in many countries, regulations need to be introduced or revised to suit the current global energy situation,
- lower demand for ventilation airflow and the associated lower amount of energy to drive fans are the main advantages of the ventilation control strategy known as DCV,
- decentralized systems, which do not require the use of long ducts, are an interesting alternative used to save energy, as it is known that the use of a central ventilation system requires more power consumption,
- due to the multitude of solutions and operating conditions, there is no simple answer to the question: which type of ground exchanger is better in terms of energy—multi-pipe or single-pipe? In order to answer this question, a detailed analysis of a given case should be carried out, taking into account the financial and/or energy aspect, or a SWOT analysis (strengths and weaknesses, opportunities and threats),
- the use of mechanical ventilation with heat recovery is actually a necessity regardless of the purpose of the building; such solutions are advantageous for enabling the maintenance of adequate indoor air quality, while improving the thermal performance of buildings.

We hope that, together with the discoveries of other scientists, this paper will be helpful for further developments in ventilation systems because the application of the advancements of technology in ventilation systems is an effective way to reduce the energy consumption in buildings currently and in the future.

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Abbreviations

CAV	constant air volume
CO_2	carbon dioxide
DCV	demand-controlled ventilation
EAHE	earth-to-air heat exchanger
HRV	heat-recovery ventilation
HVAC	heating, ventilation, and air conditioning
LHC	longitudinal heat conduction
MERV	minimum efficiency reporting value
n_{50}	airtightness coefficient
PCM	phase-changed materials
PM	particulate matter
PV	photovoltaic
RES	renewable energy sources
RH	relative humidity
SC	solar chimney
U	heat transfer coefficient
VAV	variable air volume
VOCs	volatile organic compounds

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