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Review

A Review of Heat Recovery in Ventilation

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Abstract: The purpose of the article was to present information on heat recovery in ventilation systems and to highlight what has not been sufficiently researched in this regard. A lot of information can be found on methods and exchangers for heat recovery in centralized systems. Decentralized, façade systems for cyclical supply and exhaust air have not been sufficiently researched. It is known that these devices are sensitive to the influence of wind and temperature, hence heat recovery may be ineffective in their case. The literature describes the aspect of heat recovery depending on the location in climatic zones, depending on the number of degree days (HDD). Attention was also paid to the risk of freezing of heat recovery exchangers. The literature review also showed the lack of a universal method for assessing heat recovery exchangers and the method of their selection depending on the climate.

Keywords: heat recovery; ventilation systems; recovery efficiency; energy-consumption

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1. Introduction

Buildings are a key sector in terms of energy users. Their exploitation and maintenance currently consumes up to 40% of the total energy demand in the world [1–6]. Heating, ventilation and air conditioning (HVAC) systems account for 40–60% of a building's energy needs [7–10], and the ventilation systems themselves account for 20–30% [11]. The heat demand can be reduced by reducing the building's heat loss by insulating and sealing the building envelope. However, such actions have consequences in the form of reduced air exchange, and deterioration of indoor air quality (IAQ). This in turn has a negative impact on the performance and health of people staying in the room [12–15]. In order to improve the air quality in rooms, mechanical ventilation is used, where a large amount of heat is lost with the exhaust air. In order to reduce energy consumption, the heat energy contained in the exhaust air stream is recovered. Its efficiency varies depending on the airflow (more airflow means less efficiency) and the temperature difference between outside and inside (higher gradient means better efficiency). Likewise, the way the air is distributed in the room is important. In the process of designing an installation, it is assumed that fresh air and indoor air are ideally mixed if the flows specified in the regulations are adopted. In fact, with different locations of air inlets and outlets, the air may not be renewed, and this results in an increase in the amount of air to achieve a minimum IAQ. This obviously increases the amount of energy consumed. A further increase in energy consumption results from the use of highly efficient filters that remove dust particles, which are currently the main public problem [16,17].

At the same time, it should be noted that the energy consumption of the building sector will continue to grow. New buildings start using energy, while the energy consumption of existing buildings never falls but remains constant or rises. In order to globally reduce energy consumption and CO_2 emissions, old buildings should be modernised [18–21]. Installation of centralised ventilation systems may not be possible in this case [22–25], but there are options to reduce energy consumption. For this purpose, hybrid ventilation systems or decentralised facade ventilation can be used [26–29]. The latter make it possible to adjust the capacity to the current needs of the amount of fresh air. Because of the lack of

ventilation ducts, they are equipped with small fans, which translates into low pressure losses [30].

Heat occurs in sensible and latent form. The sensible form of heat is that where temperature change is visible during the flow of heat. In turn, latent heat is the heat recovered from the moisture contained in the air stream. Commonly-used devices enable the recovery of sensible or total heat, i.e., the sum of sensible and latent heat [31–36].

The ventilation systems with heat recovery as a way to reduce the consumption of heat and cooling energy have been known since the 1970s [37]. The use of heat recovery in airtight buildings can reduce the annual energy consumption for heating and cooling by up to one-third [38–40]. The Energy for Buildings Directive (EPBD) even imposes an obligation to use heat recovery in mechanical ventilation systems [41]. The "Ecodesign" Directive [42] imposes requirements in the European Union on the efficiency of heat recovery. In the case of intermediate systems it is 68% and for the remainder is it 73%. Each investment in the heat recovery depends on profitability, building regulations and the scope of the renovation. Carlsson et al. [43] found on the basis of the conducted research that the combination of modernisation consisting in sealing the building envelope and the use of the ventilation with the heat recovery allows for a 78% reduction in total energy for space heating and 83% reduction in greenhouse gas emissions.

The ventilation heat recovery devices include rotating thermal wheels, plate exchangers, heat pipes, run-around systems and heat pumps. Each type of heat recovery device has its own advantages, disadvantages and respective applications. The building attributes define the type of heat recovery equipment to be installed [25]. Air handling units with heat recovery can bring significant final and primary energy savings. However, the profitability of the analysed units with heat recovery differs significantly depending on the energy efficiency level of the building and the heat supply, the frost level, the energy price development and the real discount rate used for the analysis [44].

In the literature there are a review of types of the heat recovery exchangers and the review of the physical and performance parameters of heat exchangers. There is no review that indicates the types of ventilation systems where heat recovery has not been sufficiently investigated. The review described in the literature do not include the influence of climate on the heat recovery. The article reviews the available heat recovery technologies, the parameters that affect the amount of heat recovery, and the methods of assessing its effectiveness. The aim of the article was to show the gaps in research on heat recovery, to show what else should be investigated and what is not described in the literature.

2. Methods

This systematic review identified all studies which investigated heat recovery in ventilation systems. So, for the current review a heat recovery was defined as exchangers using in the ventilation systems.

Studies that investigated various types of exchangers, various methods of efficiency assessment and influence of various factors on efficiency were included. The main focus was on the heat recovery in the façade decentralized ventilation and passive ventilation systems. This action was due to the least available test results for the heat recovery in these systems. All included studies were published in the English language and we placed no country, date or publication restriction to the search.

Although some studies provide additional details (e.g., methods of efficiency assessment or impact of HDD or external temperature on heat recovery), these are not universally provided and there is great variety in the way are categorized making them hard to use in a systematic review.

The search strategy used was developed to find peer reviewed full journal articles and abstracts (subject to enough information), grey literature including conference proceedings.

Electronic searches included Web of Science (1900–2021), Scopus (1900–2021) and ResearchGate (1900–2021) Database. These databases were chosen as they are key heat recovery databases, and it was unlikely that new studies could have been found elsewhere.

A search strategy was developed to include all relevant keywords relating to heat recovery, ventilation, and visual search in each resource. In order for a record to be included in the initial search, the study must have included at least one word or phrase from among those entered.

3. Heat Recovery Exchangers (HR) in Heating-Ventilation-Air Conditioning (HVAC) Systems

3.1. Storage Heat Exchangers

Storage heat exchangers work alternately, in the first phase heating up from the warm air stream, in the second phase giving up heat to the cold stream. They found their application in decentralised facade ventilation systems [45]. In this case, pay attention to the risk of condensation and to allow the condensation to run off by leading the duct for the installation of wall elements with a slope to the outside of the building. At the same time, the authors state a negligible risk of fungus and mould growth due to constant contact with alternating air flow, large temperature fluctuations, constant air movement and no possibility of stagnation.

The spherical packed beds (SPD) as a method of heat accumulation are widely used in chemical reactors, grain dryers, nuclear reactors, and in heat storage in buildings and solar power plants. These systems operate under constant flow conditions, unlike decentralised heat recovery ventilation (HRV) systems which are designed to operate cyclically. Genc et al. [46] investigated the heat recovery efficiency of a packed bed spherical heat exchanger for a decentralised HRV system (Figure 1). The authors developed a one-dimensional mathematical model for the SPD and their own computer code. They investigated a number of bed and ball diameters as well as different flow times and number of cycles.

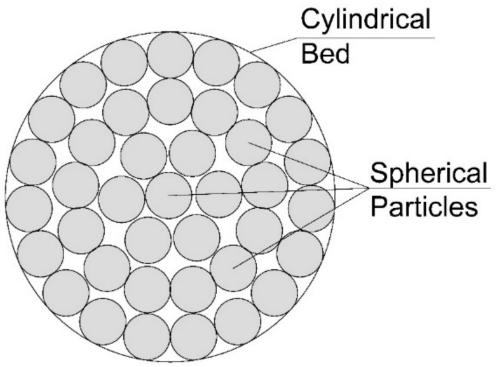


Figure 1. A Spherical packed bed (SPD) [46].

The changes in the void in the SPD are proportional to the bed diameter and the balls used. Proper void selection is essential to calculate pressure drop, cost and fan size. The authors found that as the number of cycles increases, the efficiency of PBHE first increases, and over time, stable periodic working conditions are created and the performance is constant. In addition, as hot and cold flow times increase, the system becomes stable with fewer cycles. For shorter flow times, more cycles are required for the system to reach a steady state.

Chang et al. [47] investigated experimentally the effect of various energy storage materials on the performance of a periodic total heat exchanger. They found better heat recovery properties of a heat exchanger after using an energy storage material. Among the blends of activated carbon, aluminium and aluminium/activated carbon that are chosen as storage materials, the best performance gains were obtained with activated carbon.

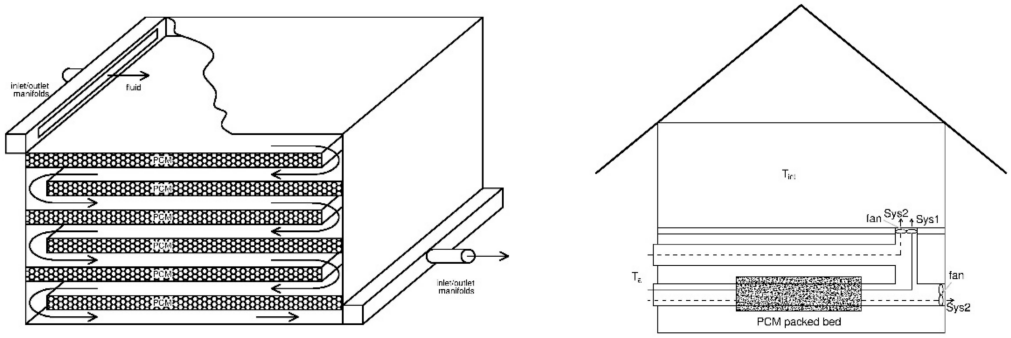
Koç et al. [48] designed a hollow heat exchanger that was filled with an organic substance (working fluid) with a low boiling point and high heat of vaporisation. The exchanger was placed in a facade-mounted device for ventilating a single room, which alternately supplied and exhausted air. The authors examined several fluids, and the

obtained results allowed them to conclude that the best properties have n-Pentane, which showed the best heat recovery efficiency, and is safe for indoor ambient conditions and is environmentally sound. Fluids with a higher latent heat of vaporisation have a greater capacity to store thermal energy, which means that the amount of energy recovered is also large.

Phase Change Materials (PCMs)

Phase change materials (PCMs) are used for the storage of sensible and latent heat in the building structure. Their action is based on the accumulation and release of thermal energy through the cyclic change of state between solid and liquid. The melting and freezing points of PCMs must be precisely matched to local climate conditions to ensure maximum system efficiency [49]. According to Kelly [50], phase change materials can be divided into organic compounds, inorganic compounds and inorganic eutectics. The most popular PCM is inexpensive paraffin wax, with a wide range of melting points (20–70 °C). The disadvantage of paraffin waxes is low thermal conductivity and large volume change, which limits their use.

Latent heat thermal energy storage is an attractive technique because it has a high energy storage density, which can be 5 to 14 times greater than that of a conventional sensible heat storage material [51]. However, the use of PCMs has an important disadvantage of low thermal conductivity, which means a low energy charge and discharge rate. Other important disadvantages of PCMs include density changes, poor stability with extended cycles, phase segregation, and cost. Morales-Ruiz et al. [52] analysed the PCM heat storage (Figure 2a), which they described mathematically. They based their formulations for PCM on the conservation equations of mass, the linear momentum and the energy. The thermal behaviour of PCMs was solved on a stationary grid using the enthalpy method. In turn, they based the mathematical formulation of the plate on the heat conduction equation. In an experimental study, they showed that the proposed solution can be used to store heat from the water drainage. Further research is needed to determine the possibility of using stored heat for heating the ventilation air.



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

Figure 2. PCM heat storage unit: (**a**) schematic representation of plate heat storage unit [52], (**b**) scheme of storage heat exchanger with PCM packed bed [53].

There are known uses of PCM in walls to increase the heat capacity 12 times [54]. Lessing rings can be used in storage tanks for improving the solidification [55]. Various PCM can be used (Table 1); paraffin waxes, fatty acids or hydrated salts [56]. The PCM are difficult to integrate into existing structure, their thermal conductivity is low, and they are expensive. But to improve their properties the storage tank can be modified and equipped with fins [57]. Determining the optimal working conditions of PCM is difficult due to the changing conditions outside the building. However, it is known that the distance between the fins is the most influencing factor on the amount of storage heat, not fins' thickness.

The greater the distance, the greater the amount of paraffin, and in turn, the greater the amount of heat.

Table 1. Advantages and disadvantages of PCM.

PCM	Advantages	Disadvantages
commercial paraffin waxes [58–60]	cheap moderate thermal storage densities (200 kJ·m^{-3}) wide range of moulting temperature chemically inert and stable	low thermal conductivity (0.2 W·m^{-1}·K^{-1}) /to improve the metallic filters, tubes etc. are used/
pure paraffin waxes [61–63]	latent heat of moulting (210 kJ·m^{-3})	very expensive
fatty acids (capric, lauric, palmitic, stearic) [64–66]	moulting range 30–65 °C latent heat of transition 153–182 kJ·kg^{-1}	subcooling
hydrated salts [67,68]	high volumetric storage density (350 MJ·m^{-3}) high thermal conductivity (0.5 W·m^{-1}·K^{-1}) moderate costs	problem with the phase segregation subcooling

3.2. Heat Pipes

Heat pipes uses a multiphase process to transfer heat from one air stream to another [69]. A hermetic tube filled with a fluid which, undergoing continuous phase change in the evaporator and condenser, transfers heat (Figures 3–5) [70]. There is no risk of cross-contamination and there are no moving parts. Heat pipes are a reliable and low-cost solution. The use of heat pipes in HVAC systems has been dealt with, inter alia, [71–76]. According to El-Baky and Mohamed [71], heat pipes achieve optimal efficiency when the fresh air temperature is close to the working temperature of the fluid filling the heat pipe. Moreover, in winter and summer conditions, when the difference in temperature inside and outside is greater, both the efficiency of heat recovery and the coefficient of performance (COP) are higher [77].

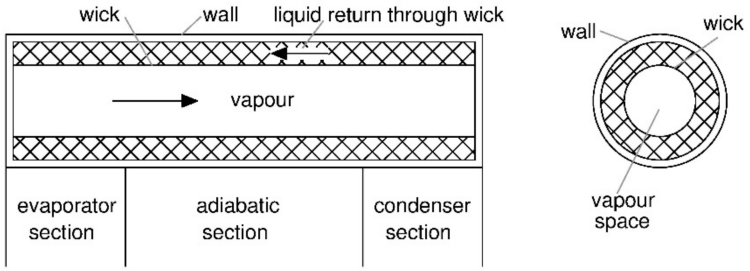


Figure 3. The main regions of heat pipe [70].

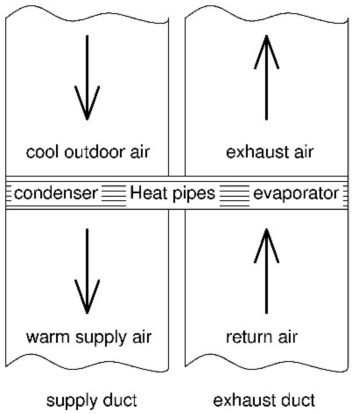


Figure 4. The use of heat pipe in heat recovery from air exhaust.

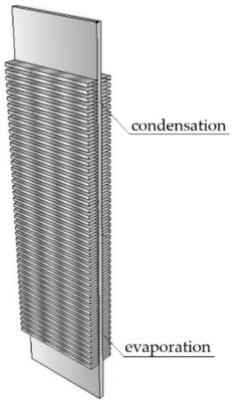


Figure 5. The heat pipe with fins. According to the reports of Mardiana-Idayu and Riffat [78], heat pipes are the most effective solution for heat recovery for passive ventilation.

Heat pipes include traditional heat pipes (CHP) and oscillating heat pipes (OHP). A characteristic feature of CHP tubes is the moisture-wicking structure (coaxial grooves, sintered particles) along the inner circumference [78,79]. With OHP, there is no need for an internal wicking structure. It usually consists of a closed-loop capillary structure forming multiple 'turns' [80].

Mahajan et al. [81] proposed an OHP system cooperating with the HRV system, which consisted of 15 rows of 20-turn OHPs with rectangular blade-type fins 8 mm apart and a tube-to-tube, transverse pitch of 2.18 cm. Such features ensure minimal pressure drop at high heat transfer rates. The authors found that the heat recovery from the proposed system is higher during winter operation than in summer. OHP-HRV is able to reduce the total average annual energy consumption by 16%. Although its efficiency is lower than that of e.g., an enthalpy wheel, it does not need energy to operate and the energy lost due to pressure drop is lower.

3.3. Rotary Heat Exchanger

The principle of the rotary wheel heat exchanger is based on the periodic accumulation of heat in the rotating storage mass. A rotating porous wheel transfers heat from one air stream to the other (Figure 6). The limitation for the use of this type of exchanger is the occurring cross-contamination, as well as high pressure losses. For overcoming pressure losses, additional fans are used, which maintain the air flow rate. There may be a situation where the fan power demand will be higher than the recovered power.

According to reports by Mardian-Idayu and Riffat [78], in mechanical ventilation systems, the most common use for rotating enthalpy wheels was to dry the air. The heat wheel, used only for the heat recovery without dehumidifying the air, rotates faster because it does not need prolonged contact to adsorb water molecules [82]. Rotary heat exchangers are characterised by relatively high efficiency and compact structure [83,84]. In addition, they have the ability to regulate the amount of heat transported.

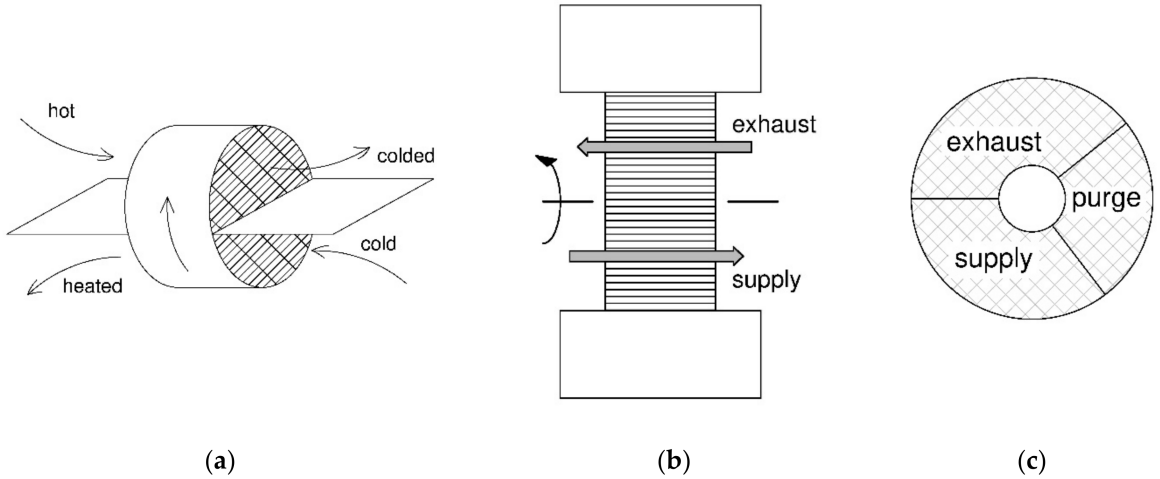


Figure 6. Operation principle of heat wheel (rotary heat exchanger): (**a**) view of rotary exchanger [85], (**b**) side view, (**c**) cross-section view.

The efficiency of heat recovery in the rotary heat exchanger is measured mainly in terms of the heat efficiency of the exchanger and the total pressure loss on the rotating core, which determines the required pumping power [86]. The authors point to the possibility of improving the regenerator's efficiency by manipulating the design factors. However, the potential for an increase in pressure drop brings with it the likelihood of needless extra expense, the risk of which should be avoided.

Smith and Svendsen [87] developed a short, rotating heat exchanger for single-room ventilation. The use of counter-current flow resulted in 80% efficiency. The length of the exchanger must be adapted to the wall thickness, at the same time it should be taken into account that heat conduction along the length may reduce the effectiveness of the short regenerators.

3.4. Cross Flow Fan

Speer and Pfluger [88] described a cross flow fan (Figure 7) that has two functions, generates two flows as efficiently as possible and works as an efficient counter-current heat exchanger. The cross flow fan can be installed in the wall as a decentralised device. In this case, the external pressure drop can be reduced to a minimum. The device allows large air flows, which allows a wide application of the solution.

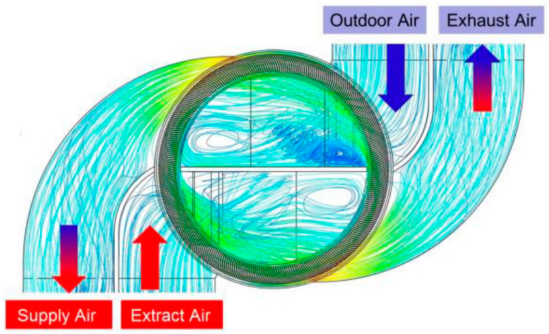
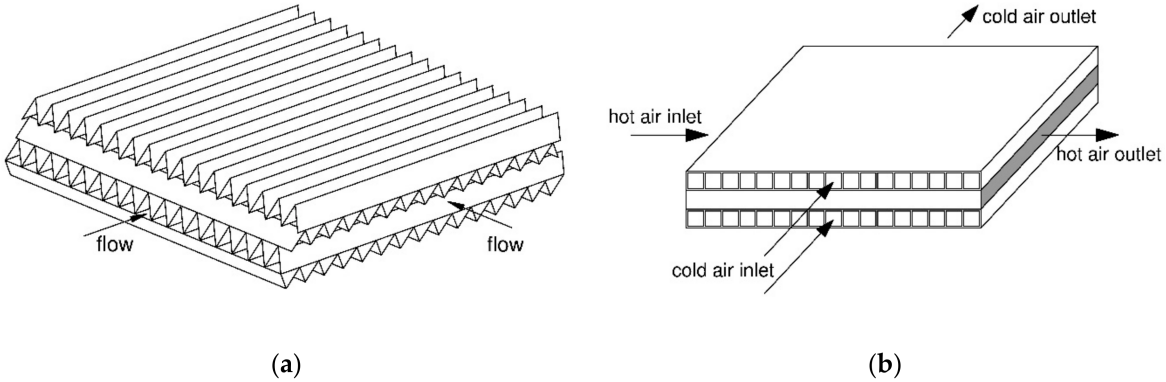


Figure 7. Concept of the Counter flow Heat Recovery Fan. Cross section of the flow conduction [88].

3.5. Plate Heat Exchanger

Plate heat exchangers are exchangers known from the 1940s. They can be used for sensible heat recovery or energy recovery, and their efficiency is extremely high [89]. Among the plate heat exchangers there are: cross-flow, concurrent and counter-flow exchangers. Out of these three systems, the manufacturing process of the cross-flow exchanger is the least complicated and the counter-flow exchanger has the best efficiency [90]. They are

usually made of aluminium and consist of a series of plates placed at equal distances from each other and joined by welding or gluing [91]. The heat exchanger can have differential the shape of plates (Figure 8).



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

Figure 8. The fixed plate heat exchangers: (**a**) corrugated plates with triangular ducts [92], (**b**) rectangular plain fin shape [93].

The problem of these heat recovery exchangers is the risk of condensate build-up in the structure, which can significantly reduce the efficiency of the exchanger [94]. In addition, installation in areas with low outside air temperatures involves freezing of the condensate. The initial freezing point occurs at the supply air flow temperature, which ranges from −3 °C to −7 °C for the cross heat exchanger and −8 °C to −12 °C for the cross energy exchanger [95]. Freezing inside the heat exchanger impedes the air flow, which results in lower heat recovery efficiency and an increase in the pressure difference in the rooms [96–98]. At the same time, Zhang and Fung [99] confirmed that the energy recovery units are more frost-resistant than the heat recovery units. Their research shows that energy recovery units are able to withstand temperatures as low as −16 °C without compromising performance. Gendebien et al. [30] developed a model of an exchanger to define the air flow control strategy to be used to avoid the freezing of the heat exchanger. The exchanger analysed by them was made of several corrugated plates in synthetic material. The central (main) area of the heat exchanger was a counter-current arrangement consisting of parallel triangular ducts (Figure 9). The inlet and outlet areas of the heat exchanger were arranged in a cross-flow and they consisted of channels with rectangular cross-sections.

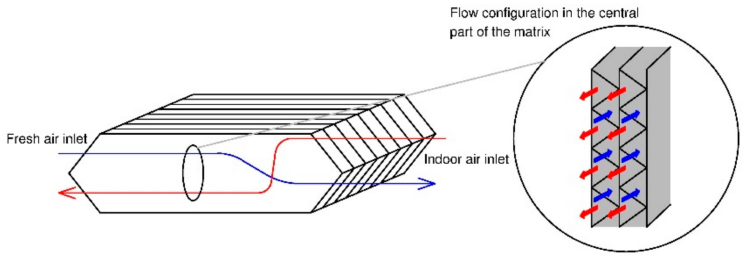
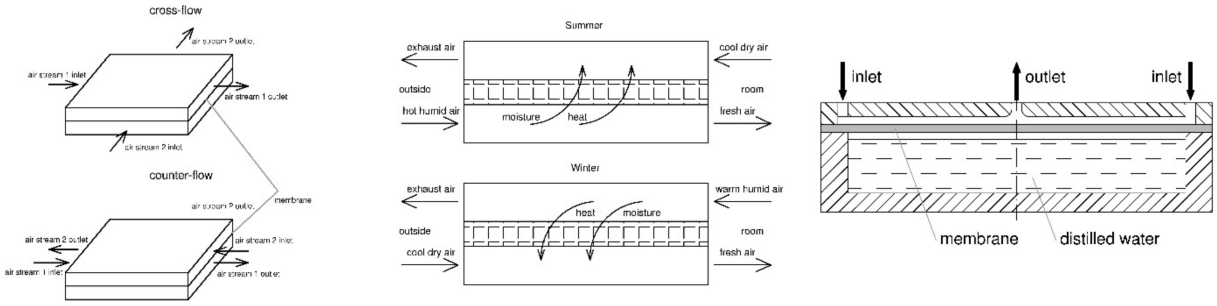


Figure 9. The exchanger of several corrugated plates in synthetic material [31].

Based on the conducted analyses, Vera and Quintero [100] found that increasing the heat exchange surface and improvement of air distribution on the plate surface can be achieved by changing the surface geometry in order to increase the heat transfer rate and the system efficiency. However, severe turbulence can increase pressure drop and reduce overall system efficiency. Therefore, in order to optimise the operation of the exchanger, the pressure drop should be taken into account.

3.6. Heat Exchanger with Membrane

Heat exchangers with a solid membrane are stationary heat exchangers that transfer heat and moisture by convection and conduction (Figure 10). Membrane materials generally have lower thermal conductivity than metallic materials used in plate heat exchangers, e.g., Yaici et al. [35] used porous membranes. The materials used in membrane exchangers are permeable to water vapour, but impermeable to undesirable gases, such as CO_2 [35]. Min [101–104] investigated the influence of the outdoor air condition, the properties of the membrane, and membrane spacing and thickness on the performance of the membrane-based enthalpy exchanger. Feng [105] discovered thin membranes with moisture transport faster than paper. Zhang [106] used composite membranes with a liquid membrane to recover moisture from the air.



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

Figure 10. The heat exchangers with membrane: (**a**) solid membrane [107], (**b**) thin membrane to heat and moisture transfer [108], (**c**) liquid membrane [36].

Currently, there are two types of materials used as total heat exchanger membranes, synthetic polymers with ionic groups and cellulose-based paper with hydrophilic additives. Due to its high heat capacity, water vapour plays an important role in the enthalpy exchange process [107,109]. Based on their research on the use of smectite clay (Na^+-MMT) and PVC, Liu et al. [108] found that the content of Na^+-MMT played a large role in controlling the structure and properties of hybrid PVC/Na^+-MMT membranes. The energy recovery membranes with high Na^+-MMT typically had high surface roughness, high water vapour transmission rates, as well as good temperature, enthalpy and moisture exchange efficiency, although the mechanical properties of the membranes deteriorated with less polymer content. When the Na^+-MMT content was 60% or less, a dense membrane was formed with openings no larger than 25 nm in which the transmission of bacteria and viruses could be effectively inhibited. When the Na^+-MMT content was in the range of 60–70%, they tended to fuse in the PVC phase, creating through-holes of about 20–200 nm, facilitating faster diffusion of CO_2 or water vapour. There was a strong correlation between the water penetration coefficient and the enthalpy exchange efficiency. As the Na^+-MMT content increased, the rate of water vapour transmission through the membranes increased exponentially, which resulted in improved enthalpy exchange and properties of overall heat recovery [108].

Another important feature is the surface of the membrane. Using a wavy membrane instead of a flat membrane allowed scientists to achieve an efficiency of 82% [92]. The other way to increase the efficiency of heat recovery is to use film with induced vibrations [110]. Various thicknesses of the films were tested. The best results were obtained for thickness equals to 0.06 mm and 0.175 mm, and the worst one for thickness equals to 0.15 mm. The scientists have shown that vibrations increase the efficiency of heat exchange.

3.7. Run-Around

Vali et al. [111] developed two exchangers placed in two separate air streams, connected by a closed loop containing the fluid constantly pumped between the exchangers. The heat is transferred from the hot side (exhaust air) to the cold side (supply air) via the heat transfer medium [112]. The principle of the run-around heat exchanger's operation has been shown in the Figure 11. These systems require energy to drive the pumps, but are less energy intensive than circulating air fans.

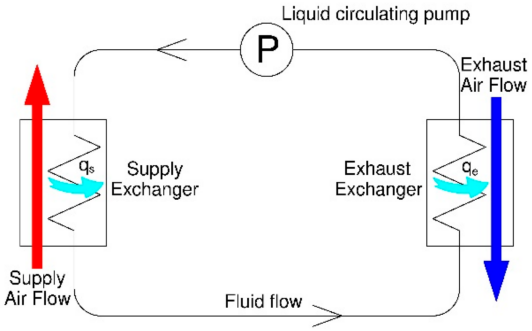


Figure 11. The scheme of ru-around heat exchanger.

In Table 2 the comparison of the heat exchangers properties has been shown. The heat recovery efficiency and the way to regulation of heat recovery amount has been presented.

Table 2. Advantages and disadvantages of PCMs.

Type of Heat Exchanger	Efficiency (%)	Heat Recovery		Performance Regulation	Risk of Frosting	Cross Contamination
		Sensible	Latent			
storage heat exchanger [27,28,53,113]	75	+	+/−	contact time	yes	yes
PCM [59,63]	low	+	+	contact time	-	yes
heat pipes [15,16]	80	+	-	air velocity	no	no
heat wheel [20–23]	>80	+	+/−	rotational speed	no	yes
fixed plate [17–19]	70–90	+	+/−	air velocity	yes	no
Membrane [3,4]	70–80	+	+/−	air velocity	yes	no
run-around [114–116]	50–80	+	−	contact time	no	no

4. Use of HR in Selected Ventilation Systems

The use of heat recovery in centralised systems is widespread and well researched. Virtually all of the described methods of heat recovery can be used in this type of system (Table 3). The attributes of buildings determine the type of heat recovery devices to be installed. In the passive and the decentralised ventilation systems, it is not possible to use all available technologies due to the specificity of these ventilation devices. As they are coming into ever-greater use, they are considered in this article.

Table 3. The use of the heat recovery in various ventilation systems.

Type of Heat Exchanger	Exhaust Ventilation	Supply-Exhaust Ventilation	Passive Ventilation	Decentralised Ventilation	
				Single Fan	Mini AHU
storage heat exchanger		✓		✓	✓
PCM		✓		✓	✓
heat pipes	✓	✓	✓		✓
heat wheel		✓	✓		✓
cross fan				✓	
fixed plate		✓			✓
membrane		✓			✓
run-around	✓	✓	✓		✓

4.1. The Use of HR in Passive Ventilation

The combination of heat recovery and passive ventilation requires keeping the pressure drop low. The devices showing the greatest potential in this respect are rotary heat wheels and heat pipes [7]. These two solutions ensure the highest temperature efficiency, while counter-flow heat exchangers result in insufficient air flow when used in passive buildings [117].

One of the passive ventilation solutions are windcatchers. According to Shao et al. [118], when windcatchers operate, a large amount of heat is lost with the exhaust air, hence heat recovery is justified. It can be realised with the use of a rotary heat exchanger [119]. In this case, special care should be taken not to reduce the air flow rate to a level below which ventilation is ineffective.

4.2. The Use of HR in Single Room Ventilation

Buildings can be equipped with a central ventilation system that prepares the air for the entire building, but in older buildings undergoing modernization it is increasingly common that single room are fitted with individualized ventilation systems. They can be made as mini-Air Handling Units (AHU) equipped with two fans and a heat recovery exchanger [120], or as facade mounted units with one fan and with or without a heat recovery exchanger. In the second case, we have systems with a reversible fan that alternately in one cycle supplies the air and in the next cycle exhausts the air to the outside [121]. Another solution are devices, where the cyclical supply and exhaust are realised by changing the damper system [122]. The authors, examining solutions without a heat recovery exchanger [122], indicated the need to heat the air due to the risk of drafts. The commonly used exchanger in devices mounted in the facade are storage tanks made of aluminium or ceramics [27,123]. Choi et al. [124] analysed aluminium oxide (AL_2O_3) as a heat storage factor in facade-mounted decentralised ventilation systems. They found that when the bidirectional mode is changed, the demand for heating and cooling energy is lower by approximately 20% compared to the simulation of the simultaneous supply and exhaust mode. At the same time, it should be noted that facade-mounted systems have lower pressure losses, are easy to install and are maintenance-free. However, they generate higher noise levels and are more sensitive to wind pressure and stack effects [125]. Merzkirch et al. [27] have shown that a large imbalance of the supply and exhaust flows in decentralised devices leads to reduced heat exchange efficiency. Moreover, due to the change in the direction of rotation, decentralised wall devices have a time-varying efficiency of heat exchange resulting from the process of charging and removing heat [126].

For single-room ventilation, rotary heat and mass wheels could be used. Smith and Svendsen [127] found that devices of this type are suitable for use in dry rooms, but are not suitable for ventilating wet rooms. For this application the moisture recovery is too high. The authors also showed that rotary heat wheels show a low to moderate risk of mould when ventilating individual rooms in dry conditions.

When comparing the energy consumption of the decentralised units with a central ventilation system, it should be remembered that an average of eight single units is needed to sufficiently ventilate a house [123].

Moreover, the efficiency of heat recovery in decentralized façade units is dependent of cycle time supply/exhaust (Figure 12). During the cycle time the heat efficiency is increasing and the greatest it is for the shortest cycle time [46].

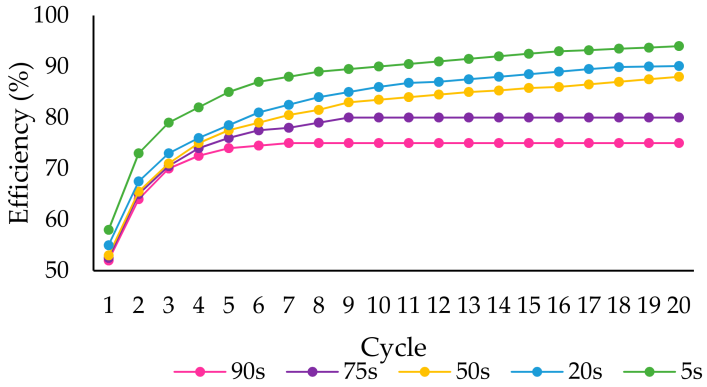


Figure 12. The efficiency values according to the number of cycles for spherical packed bed in decentralized heat recovery ventilation units [46].

5. Factors Influencing HR

Many factors can have a negative effect on the actual heat recovery, such as flow imbalance, leakage, insulation defects, contamination etc. [128,129]. Depending on the quality of the installed windows, air tightness, architectural design and climate zone, ventilation with heat recovery can save up to 30% of energy [33,125]. In practice, the difference in heat transfer between primary and secondary flow can be as high as 20% [130]. Pecceu and Caillou [131] calculated that the lack of insulation of 3 to 4 m of ventilation ducts in residential building results in a reduction of the heat recovery potential by 10%. On the other hand, Roulet et al. [128] drew attention to short circuits and leaks which, apart from worsening IAQ, dramatically reduce the efficiency of heat recovery.

The potential for energy savings may in some cases be very low or cannot be guaranteed. Roulet et al. [129] found in studies of thirteen ventilation systems that the energy savings in several cases were small or even negative. Other authors [37,132–137] suggest taking the following into account when estimating energy savings: local climate, thermal properties of buildings, air flow rate and the characteristics of the heat recovery system itself. Real energy savings in a cold climate can be much greater than in a hot summer and cold winter climate. Moreover, the internal temperature also influences the amount of recovered heat [128]. Another factor influencing the efficiency of heat recovery is cross-flow and leakage. As reported by Roulet et al. [129] the efficiency of heat recovery due to the air leakage in the ducts drops from nominal values between 50% and 90% to values in the range 5% to 68%.

The amount of energy consumed by the system is influenced by the speed of the flowing air, the higher the which the greater the fan power consumption. According to the analysis by Yaïci et al. [34] if the device works in the winter season, as a result of increasing the flow speed from 0.5 to 2.5 m/s, the fan power consumption may increase as much as 32 times.

6. Climate, Air Parameters and HR

The scope of energy savings resulting from the use of ventilation with heat recovery depends on the type of solution used, but also on the terrain conditions, local climate, outside temperature and the ventilation air flow rate [1,117,128,138]. In cold climates, the use of heat recovery is more effective, as was already mentioned, although buildings use more energy on cold days [1,138–140]. Fouih et al. [112] carried out studies on various types

of low-energy buildings located in different climate zones. The results obtained led the researchers to the conclusion that in cities with a low level of heating degree days (HDD) during the heating period, the total primary energy consumption in an office building using heat recovery ventilation (HRV) is up to 30% higher than in a facility with mechanical exhaust ventilation (MEV). At higher HDD values, this difference narrows, and from a HDD of 2630, HRV becomes more efficient than MEV. In residential buildings, energy consumption for HRV installations is lower than MEV with a HDD higher than 1400. This is due to the longer occupancy of buildings by users in residential buildings than in office buildings. Similar conclusions were reached by other researchers [3,141] who found that the payback time for heat recovery ventilation in places where a HDD is 2500–3000 is too long. At the same time, it is worth noting that climate change will cause an increase in the cooling load, and hence a greater energy demand for air conditioning systems. This is confirmed by studies carried out by Al-Zubaydi and Hong [142], who described an increase in cooling capacity and a decrease in efficiency with an increase in inlet air temperature in both of the tested exchangers (see Figures 13 and 14).

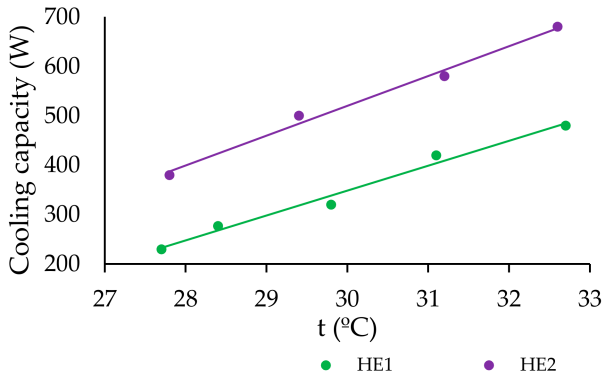


Figure 13. Effect of the inlet temperature of the primary airflow on cooling capacity [142].

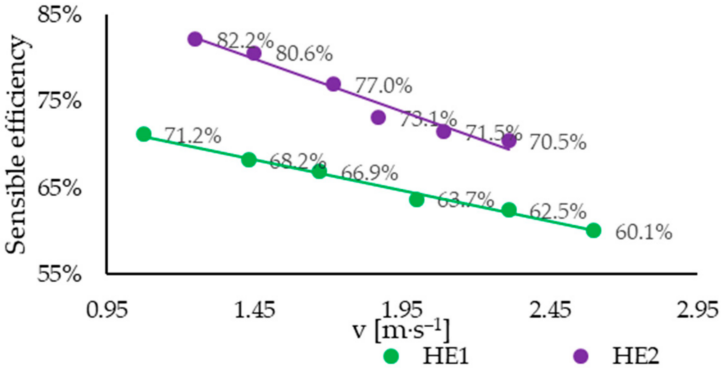


Figure 14. The inlet velocity of the primary air impact on the sensible efficiency [142].

Moreover, the authors found that in the case of energy recovery during the cooling period, the relationship between efficiency and speed is opposite to that in the heating period. In this case—in the cooling mode—the higher the speed of the flowing air, the higher the efficiency of heat recovery.

In periods of low temperatures, frost is an additional problem. The frost layer reduces the cross-sectional area, which results in a pressure drop and thus an increase in the electric power of the fans. If the electric power remains constant, the air flow rate through the heat exchanger decreases, which can lead to uneven flow rates and, in extreme cases, complete blockage of the flow. In addition, the frost layer provides additional thermal resistance, which affects the heat transfer rate [95,143–145]. Gendebien et al. [146] investigated the effect of the frost layer on the hydraulic and thermal parameters of an air-to-air heat exchanger dedicated to ventilation of single rooms. The authors added a third zone to the

commonly used "two-zone" model, the so-called frost zone. The model was verified by means of experimental tests. On the basis of their research, they concluded that the choice of strategies to deal with frost conditions should be made on the basis of a trade-off between energy considerations, air exchange, negative pressure/overpressure in the building and practical implementation.

In the case of the use of decentralised facade units with heat recovery, an important issue is raised by Mikola et al. [147], where they showed in their research that the pressure difference caused by the difference in the temperature of indoor and outdoor air and dynamic wind load may result in asymmetry of the supply and exhaust air streams, which reduces the efficiency of heat recovery. Decentralised ventilation units (DVU) were analysed in terms of their applicability in various climates [129,148–152], too. The authors showed that they are not suitable for use in temperate climates.

A factor worth to consider, especially when the seasons change, is the bypass control mode. This is a strategy to introduce outdoor air into the fan unit, without passing the air through the heat recovery exchanger. This allows the reduction of pressure losses in the period when heat recovery is ineffective due to the value of the outside air temperature close to the required temperature of the supplied air (there is no need to heat it) [153]. The authors showed that when the bypass for ACH = 0.5 was used, 57–62% of the fan power was used, for ACH = 1.0 45–58%, and for ACH = 1.5 45–64%. Hence, the bypass mode allows energy savings of up to 8–39%, compared to ventilating the entire room under extreme conditions.

Laverge and Jansses [154], while assessing energy consumption and heat recovery, judged that in the moderate climate of middle Europe, if low specific fan power is not achieved, neither natural ventilation, simple mechanical exhaust ventilation nor heat recovery ventilation have a clear advantage over the others. On the other hand, in the Mediterranean basin, heat recovery ventilation can only be used profitably in systems with low pressure drop and low fan power. Meanwhile, in Scandinavia heat recovery ventilation is beneficial in virtually all tested conditions. The possibility of using heat recovery in various climate conditions is confirmed by the studies of Lazzarin and Gassparella [132], who in their research concluded that heat recovery allows the reduction of the energy used for heating, cooling and installed power, and that economic profitability is possible even with higher efficiency, lower ventilation flows and a mild climate.

7. Efficiency of the Heat Recovery Exchanger and Energy Consumption

The heat exchanger efficiency (ε) is the ratio of actual heat transferred to the theoretical heat transferred. Theoretically, the heat recovery efficiencies on the supply and exhaust side are perfectly equal, but in practice this is not the case. This is due to the heat recovery unit itself, the flow balance, the heat released by the fans, etc. The energy recovered in the heat exchanger is limited by the smallest flow rate. The flow imbalance is compensated for by additional infiltration or exfiltration, which in both cases leads to additional energy loss [131]. Higher efficiency of the exchanger means more heat recovered and consequently a reduction in total energy consumption. In a climate with low HDD, increasing the efficiency of the exchanger hardly affects the total energy consumption. Keep in mind that as the pressure drop increases, this increases the fan's electricity consumption, which is also part of the total energy consumption. However, in areas with high HDD, increasing the efficiency of heat transfer has a significant impact on reducing energy consumption. (see Figure 15 taken from [136]).

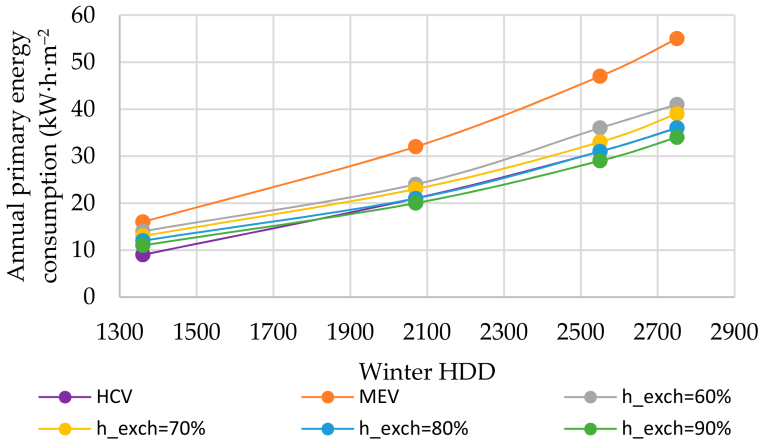


Figure 15. Heat exchanger efficiency effect on the annual primary energy consumption of the house building [136].

8. Assessment of the Efficiency of Heat Recovery

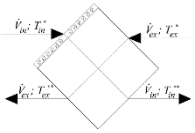
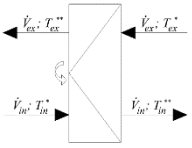
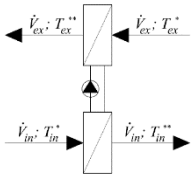
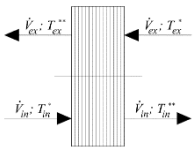
Predicting energy performance at the planning stage of a building or renovation project is complex. It is also important with risk management in innovative projects [155,156]. Fleur et al. [157] showed that the efficiency of heat recovery during the use of the facility was significantly lower than assumed. The assessment of the heat recovery systems and devices is most often based on energy efficiency and investment cost analysis [85]. However, the last criterion is also not always taken into account. Some authors [158] propose an exergy approach based on the application of the first and second laws of thermodynamics. However, applying exergy alone may be economically ineffective [159]. Combined exergy and economic analysis was performed [159–163]. For example, Mróz and Dutka [159] conducted four case studies which they assessed using the weighted sum method, with a set of decision criteria consisting of: driving exergy, simple payback time and investment cost, and four preference models. The results of the investigators' exergo-economic evaluation showed that the rotary heat regenerator and the counter-current plate heat exchanger are the best compromise solutions for the heat recovery. A water loop exchanger and a heat pipe exchanger, on the other hand, should not be taken into consideration.

Kilkis [164] drew attention to the fact that CO_2 emission is proportional to the destruction of the exergy. He proposed an alternative COPEX coefficient of performance that describes the performance and environmental impact of HRV units. The commonly used COP indicates efficiency only in the light of the first law of thermodynamics, and the new approach also embraces the second law. The author stated that without reference to the term COPEX, design, evaluation and operation would not be rational and HRV units would still be responsible for avoidable CO_2 emissions due to exergy destruction. While HRV systems with fast economic returns are recommended for IAQ applications because of their first law efficiency, they do not bring returns in terms of exergy and CO_2 emissions, while more exergy is destroyed than recovered from waste heat, unless electricity is supplied by renewable energy sources on-site or nearby.

Mróz and Dutka [159] have made the exergy-economic analysis (Table 4) where they have compared fixed plate, rotary, run-around and heat pipe heat exchangers. Their analysis included not only thermal efficiency but exergy criterion and investment costs.

The method of selecting a heat recovery system depends on many factors. Decision-makers are also guided by different criteria. Figure 16 shows the preferences of decision makers for four indicators of the selection of heat recovery ventilation devices. Residential house decision-makers take into account the initial investment and operating costs of the device. Small-store decision-makers focus on system performance and believe that high efficiency will have a good energy-saving effect. Public service centres decision-makers focus on the balance between system performance and operating costs [25].

Table 4. Comparison of heat recovery efficiency and SPBT for four types of heat recovery exchangers.

Type of Heat Exchanger	Efficiency (%)	SPBT (a)
	50 [95,110,131]	2.55
	75 [87,165–167]	2.57
	40 [114–116]	4.19
	45 [71,168]	3.60

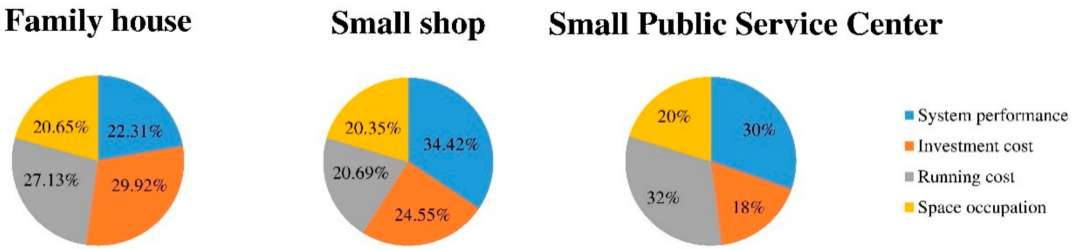


Figure 16. Preference results of different decision makers for evaluation indexes [25].

The comparison of the various systems is not straightforward, especially when one recovers only sensible heat and the other recovers sensible and total heat. The use of exergy analysis and non-equilibrium thermodynamics [169] enables the quantification, evaluation and comparison of different devices using the effectiveness of exergy. This parameter describes the loss of work potential and may take into account different sources of work loss as well as differences in energy quality. When the efficiency of the exergy is negative, the recovered heat and moisture are not enough to compensate for the fan power necessary to drive the air flow in the recovery unit.

Various methods of assessing the efficiency of heat recovery were compared by Coydon et al. [170]. According to Figure 17, in their article, a large disparity between all evaluation methods can be seen. The second conclusion is that conventional methods actually overestimate the efficiency of heat recovery, and the efficiency of heat recovery in the work environment is much lower than that declared by the manufacturer.

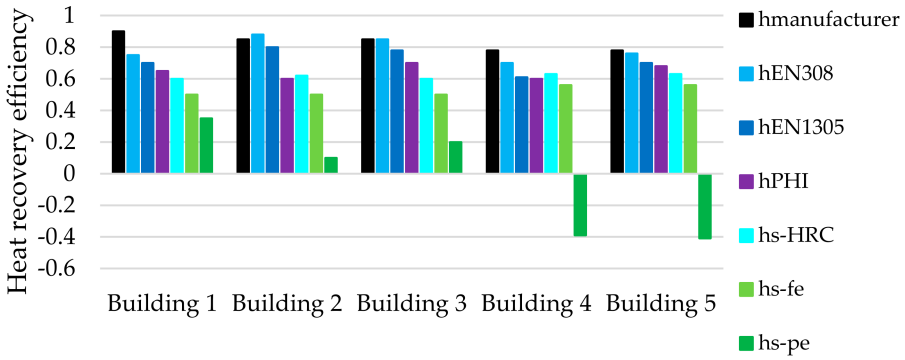


Figure 17. Preference results of different decision makers for evaluation indexes [170]; where: $\eta_{manufacturer}$—efficiency given by the manufacturer; η_{EN308}—efficiency calculated in accordance with EN-308 [171]; η_{EN1305}—efficiency calculated in accordance with EN-13053 [172]; η_{PHI}—efficiency calculated according to the Passivhaus test procedure; $\eta_{s\text{-}HRC}$—efficiency as a ratio of the reduction of heat demand to the reference heat demand; $\eta_{s\text{-}fe}$—final energy seasonal yield; $\eta_{s\text{-}fe}$—seasonal primary energy yield.

9. Conclusions

Heat recovery offers a wide range of energy savings. However, it is not always profitable. There are many solutions available on the market, but it is impossible to clearly indicate which might be the best one. The complexity of the process allows manufacturers to adapt the method of assessing the efficiency of heat recovery in such a way as to show the highest efficiency. Therefore, they most often show it as temperature or enthalpy efficiency or COP. Failure to take into account the energy consumption of devices and the impact on CO_2 emissions results in overestimation of the parameters provided by them.

Heat recovery in decentralised devices with one fan is the one that raises the most doubts due to the sensitivity of devices located in the building facade to the effects of wind and temperature. In the case of this type of device, energy storage works best and here you should look for a substance that has good accumulation properties, but at the same time has low thermal conductivity allowing for the quick charging and discharging of the storage.

It is important to continue searching for an objective method of assessing heat recovery devices and the method of their selection, taking into account the climate in which the ventilation system with heat recovery is to operate. However, it must take into account the needs of decision-makers and allow them easy use of the tool.

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