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An Environmental Evaluation of Ventilation Systems Aimed at Reducing Indoor Radon Concentration

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Abstract: The primary measures against radon in buildings are a tight contact structure or venting the subsoil beneath the building. In many cases, ventilation systems used in buildings to ensure good indoor air quality can also be used to reduce the radon concentration. This study aims to evaluate the environmental impacts of residential ventilation systems for their ability to lower the concentration of this gas. The life cycle assessment methodology was used to assess two kinds of ventilation systems. The results indicate that 95% of environmental impacts are associated with operational emissions, while 5% are associated with embodied ones. Moreover, an increase in radon supply rates resulted in an increase in energy consumption and related emissions, for example, the operational energy of an exhaust ventilation system aimed for a reduction to 200 Bq/m^3 in a 9/15 cyclic mode range from 9.69 for a radon supply rate of 50 Bq/m^{3}h to 32.27 for 200 Bq/m^{3}h. These simulations show that ventilation systems cannot be considered universally suitable measures to reduce the radon concentration because they may become very energy demanding, and their environmental impact may be significant even considering the type of energy source. Based on this study, we can determine whether it makes sense for a given radon supply rate and energy source to use a ventilation system to reduce the radon concentration in residential buildings.

Keywords: LCA; indoor environment; ventilation systems; environmental impact; operational impacts; residential buildings; radon control technologies; radon indoor concentration; radon; HVAC energy consumption

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1. Introduction

There has been considerable interest in indoor air quality (IAQ) and energy consumption in the building sector for several decades. It has been estimated that 40% of all European energy consumption is used for construction, resulting in 36% of all CO_2 emissions [1,2]. In residential buildings, various mechanical ventilation systems are used to ensure high-quality indoor air. The use of these systems is also considered to be a way to prevent an unhealthy amount of indoor radon concentration [3,4]. Ventilation systems can affect the pressure differences between indoor and outdoor air, and thus they can influence the transport of radon from the subsoil in a building. For this reason, all contact structures should be as tight as possible to minimize the amount of radon entering the building [5]. Once it is inside the building, it accumulates in spaces directly in contact with the ground (ground floors, underground floors, and cellars). This makes these locations especially prone to the dangers posed by high levels of radon [6–8]; the European Union Directive 2013/59/Euratom [9] states that measures should be taken to reduce its concentrations in dwellings if the average concentration exceeds 300 Bq/m^3. Examples of possible measures are radon-proof insulation, ventilation of the subsoil, ventilation of interior spaces, etc. [10]. The choice of an appropriate measure depends in each specific case on the type of house, the level of radon concentration, etc. [11,12].

The materials used and the energy consumed during the production, construction, and maintenance of buildings or products have significant environmental implications. As described by Felicioni et al. [8,13], the environmental impacts of radon control technologies have not yet been sufficiently investigated. The study presented here is an important contribution to the growing body of research on the sustainability of ventilation systems by enabling a comprehensive assessment of their environmental impacts using the life cycle assessment (LCA) methodology [14]. In the literature, different studies (e.g., [15–17]) have explored the environmental impacts of ventilation systems; however, none of them have specifically focused on diluting the radon concentration. However, there are studies focusing on ventilation systems aimed at reducing the radon concentration (e.g., [18–20]), but without providing an environmental assessment of the related impacts. By providing an in-depth analysis of the impacts of residential ventilation systems, our study further amplifies the need to consider their long-term sustainability before installation.

This work contributes to the evaluation of the potential environmental impacts of two types of active ventilation measures with respect to their ability to lower the indoor radon concentration C (Bq/m^3). Various forms of active ventilation systems are a common part of modern and low-energy buildings. There is a widespread belief among construction professionals that these systems are the perfect protection against radon and that no other type of protection is needed. Such an opinion is based on the experience with common pollutants, such as water vapor and CO_2. This research therefore aims to find out whether the considered ventilation systems really constitute universal protection against this gas and what impact they have on the environment.

Thus, this work aims to highlight environmental categories [21,22], such as acidification potential (AP; kg—SO_2 eq.), ozone depletion potential (ODP; kg CFC-11 eq.), global warming potential (GWP; kg—CO_2 eq.), eutrophication potential (EP; kg—$PO4^{3-}$ eq.), abiotic depletion potential elements (ADPf; kg—Sb eq.), and abiotic fossil fuel depletion (ADP; MJ) resulting from the embodied and operational impacts (i.e., electricity consumption) of two kinds of residential ventilation systems—mechanical exhaust ventilation and balanced ventilation—considering two operation modes for each system with the main objective of reducing the indoor radon concentration. Moreover, the Environmental Footprint 3.0 Method (EF 3.0) [23], an impact assessment method developed by the European Commission—Joint Research Centre for the Environmental Footprint (EF) initiative [24], was used to normalize and weigh the environmental parameters through a single-score indicator.

The motivations and objectives of the work are to perform a theoretical evaluation of the environmental impacts of two kinds of residential ventilation systems used to reduce the radon concentration in houses below the required value and to determine the conditions under which ventilation systems are acceptable as an effective and environmentally friendly measure.

It is not the purpose of the work to design a ventilation system for a specific house in detail, because greatly limits the practical applicability of the knowledge gained. Indeed, a key priority of Directive 2013/59/Euratom [9] is to reduce exposure to radon in buildings. Moreover, this directive has raised awareness of the radon risk indoors by implementing rules in every European country since 2018, with consequent monitoring and risk-mitigating actions [25]. The design and size of ventilation systems play a significant role in influencing the use of energy in residential buildings, as well as the costs and environmental impacts.

This paper forms part of the RadoNorm project [26] under the umbrella of the EU Horizon 2020 funding program (H2020), and it is a first attempt to connect radon control technologies with their environmental impacts. The project's scope aims for effective radiation protection based on improved scientific evidence and social considerations. The task of the authors is to investigate the environmental impacts of various types of building radon control technologies.

2. Materials and Methods

The whole study is based on different phases that are illustrated in Figure 1 and described in the subsequent sections. Phase 1 involved the definition of the ventilation system and operating modes to be considered in the study. During Phase 2, data, such as the number of operating hours, the radon supply rate, etc., were used to calculate the operational energy of such systems. In Phase 3, the outputs of Phases 1 and 2 were used as inputs, respectively, the bill of quantities of materials and the operational energy demand to perform the LCA. This phase resulted in the environmental assessment of the ventilation systems and the results are categorized as embodied impacts (strictly related to the bill of quantities), operational impacts (strictly related to the operational energy), and overall impacts (considering both operational and embodied impacts).

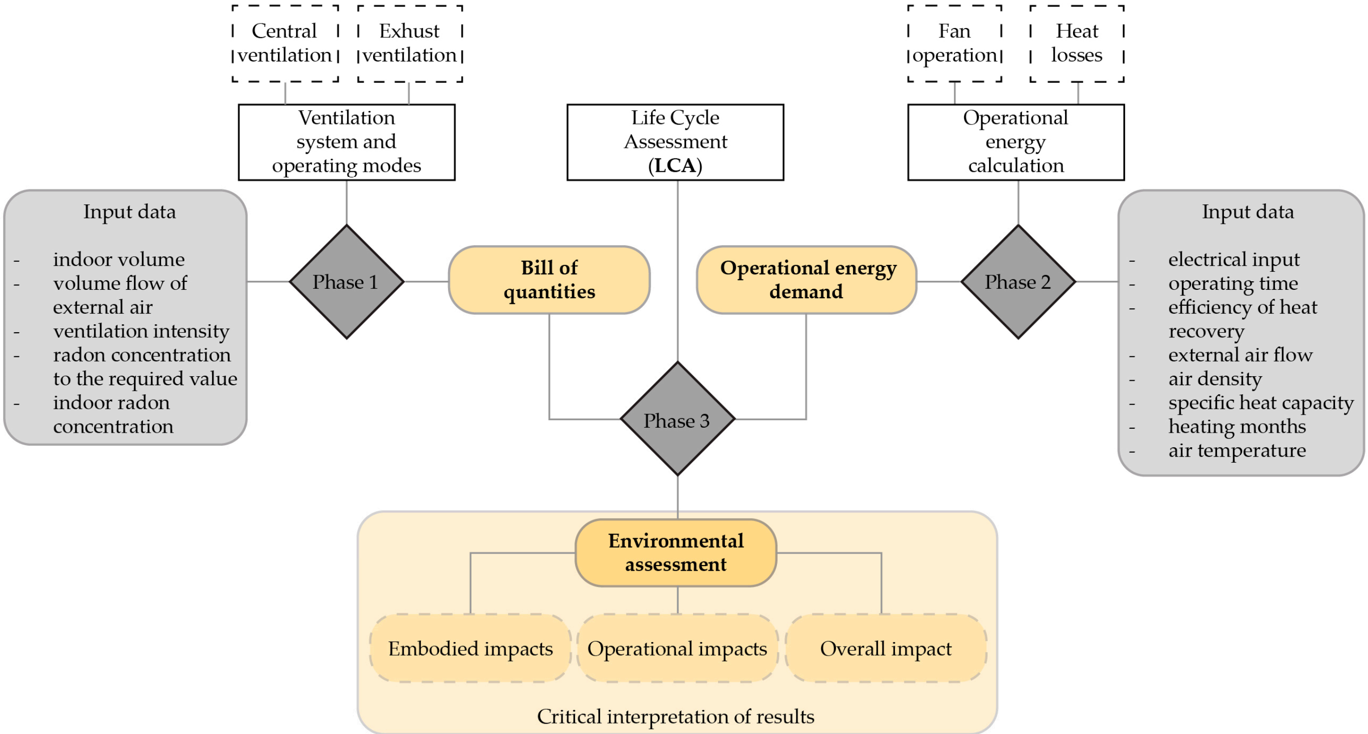

Figure 1. Overview of workflow.

2.1. Ventilation Systems and Operating Modes

The effect of ventilation on the indoor radon concentration is illustrated in Figure 2. The indoor radon concentration C (Bq/m^3) is directly proportional to the radon supply rate J_s (Bq/m^{3}h) and is inversely proportional to the intensity of the ventilation n (h^{-1}). Four values of J_s (50, 100, 150, and 200 Bq/m^{3}h) were considered in this study. These values were chosen so that, for normal ventilation intensities from 0.1 to 1.0 h^{-1} [27], they produced indoor radon concentrations [28,29] that could normally occur in new non-basement buildings.

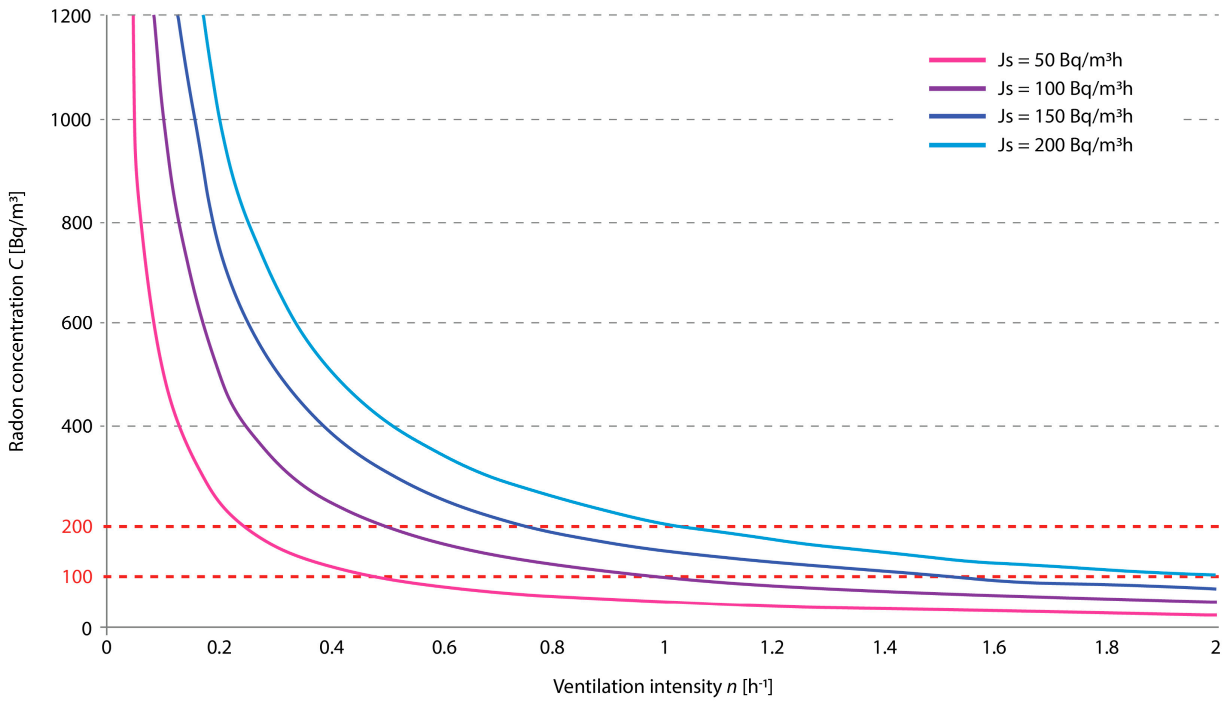

Figure 2. Indoor radon concentration in dependence on the radon supply rate Js and intensity of ventilation n. Two different C_{req} values of 100 Bq/m^3 and 200 Bq/m^3 are marked with a red dotted line.

In Figure 2, two red dashed lines indicate two levels of internal radon concentrations C_{req} (100 Bq/m^3 and 200 Bq/m^3), which should not be exceeded in the habitable space of a building. The choice of a specific value depends on the requirements of the national legislation or the wishes of the owner of the building.

The ventilation systems used to reduce the radon concentration must be capable of providing an intensity of ventilation n_{req} that ensures that the concentration falls below the required value C_{req}. Equation (1) can be used to determine the required ventilation intensity:

$$n_{req} = \frac{J_s}{C_{req}} \tag{1}$$

where n_{req} is the ventilation intensity to be provided by the ventilation system in order to decrease the radon concentration to the required value C_{req} [h^{-1}], C_{req} is the indoor radon concentration value [Bq/m^3] required by the owner of the building (usually below the reference level of 300 Bq/m^3 [9]), and J_s is the radon supply rate [Bq/m^{3}h].

The required volume flow of external air Q_v [m^3/h] that must be supplied by the ventilation unit can be calculated as follows:

$$Q_v = V \times n_{req} \tag{2}$$

where V is the volume of the ventilated space [m^3].

The simulation of the environmental impact was conducted on an example of a typical family house located in Prague (Czechia), with an interior air volume V = 400 m^3 and a service life of 50 years.

The impacts of two different ventilation systems were investigated.

- The first system was a centrally controlled mechanical ventilation with heat recovery (CV). A balanced system was considered, where the amount of air supplied was equal to the amount of air removed (Figure 3a). CV systems suffer from significant pressure losses due to their comparatively long air ducts, filters, and heat exchangers. They typically utilize two fans: one for the supply air and the other for the exhaust air. As a result, they consume more electricity to operate the fans.

- The second system was mechanical exhaust ventilation (EV) with the air intake through ventilation registers in the window frames. This system does not include heat regeneration and therefore results in high heat losses (Figure 3b). Exhaust ventilation is the most appropriate for colder climates since, in warmer climates, depressurization can draw moist air into the wall cavities, where it may condense and cause moisture damage. In the case of EVs, the air ducts are short, which means that the pressure losses in the ducts are low, and therefore fans with less power are sufficient.

It was assumed that none of the ventilation systems changed the pressure difference between the subsoil and the interior; therefore, they did not affect the radon supply rate.

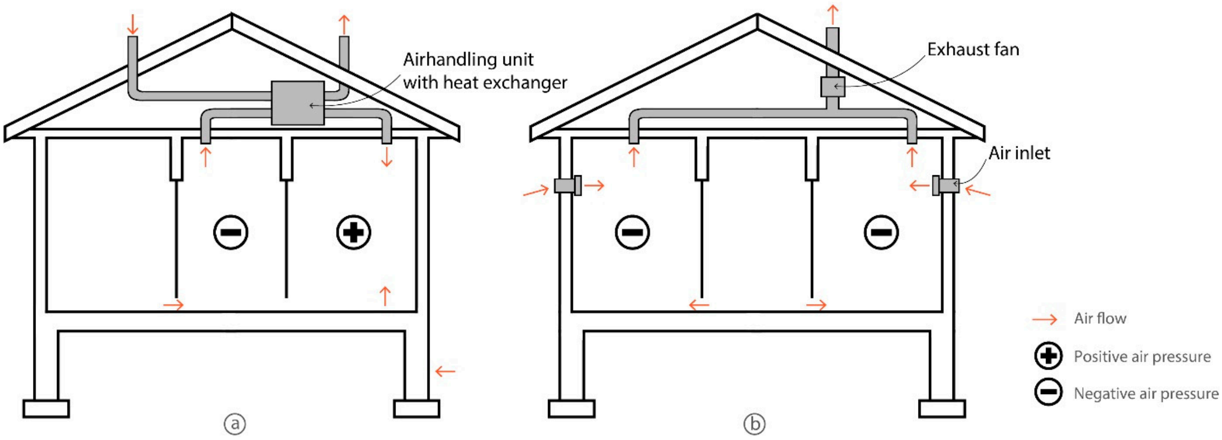

Figure 3. Schematic representation of the two ventilation systems: (**a**) central balanced ventilation; (**b**) exhaust ventilation.

Both ventilation systems under consideration here consumed energy to operate the fans and to cover the heat losses caused by increased ventilation. The annual energy consumption of the fans E_f [kWh/y] was calculated based on the electrical input and operating time. On the subject of the operating times, two scenarios were considered:

- Continuous operation ensuring n_{req} for 24 h a day, 365 days a year;
- Cyclic operation ensuring n_{req} for 15 h every day of the year, while for the remaining 9 h n = 0, 1 h^{-1} (the minimum ventilation intensity required by EN 15665 [30] for the period when the building was not occupied; this value corresponded to the ventilation intensity, which was measured in new buildings with the mechanical ventilation switched off). The ratio of work and rest periods (15/9 h) was based on the following model situation—the user of the house works outside the home for 8 h, the journey to work takes him/her 1 h and it takes him/her the same time to arrive home, and the ventilation system must be switched on 1 h before he/she arrives home so that the radon concentration drops to the required level.

The annual energy needs for eliminating the heat losses E_h [kWh/y] were calculated according to the relationship published in [4] by Jiránek and Kačmaříková and shown by Equation (3), considering that the reference single-family house was located in Prague (CZ). The efficiency of heat recovery was evaluated in relation to the airflow rate and the type of ventilation unit.

$$E_h = 2.778 \times 10^{-7} \times (1 - \eta) \times Q_v \times \rho_a \times c_a \times \sum_{m=1}^{9} h_d \times d_m(\theta_i - \theta_{me}) \quad (3)$$

where 2.778 × 10^{-7} is the conversion factor from Joule to kWh, η is the efficiency of the heat recovery [-], Q_v is the external air flow [m^3/h], ρ_a is the air density [1.230 kg/m^3], ca is the air specific heat capacity [1005 J/kg·K], m is the number of heating months (from

September to May), h_d is the number of operating hours per day, dm is the number of days per each heating month, θ_i is the indoor air temperature of 21 °C, and θ_{me} is the average outdoor temperature for each heating month—the outdoor air temperatures were assumed to be those of Prague.

2.2. Environmental Assessment of the Ventilation Units

A study was performed on the environmental impacts of ventilation units using the LCA methodology. The methodology is based on four main steps, illustrated in Figure 4: (1) goal and scope (2) inventory analysis, (3) impact assessment, and (4) interpretation of results.

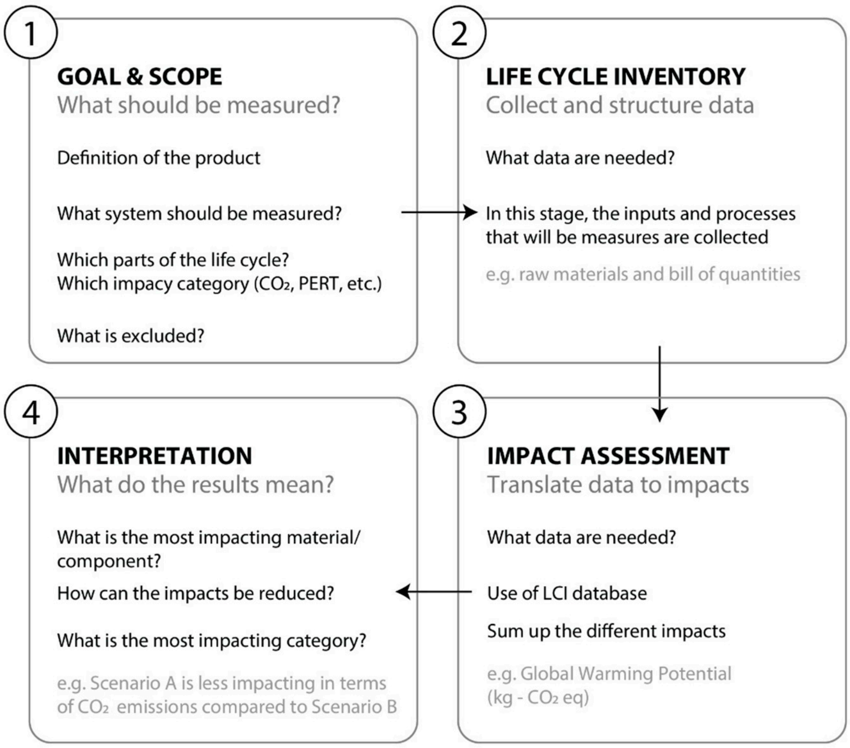

Figure 4. Life cycle assessment methodology: an overview of the four stages.

In the part of the methodology that deals with the goal and scope, the objectives of the study are identified, including the intended application, the purpose, and the intended audience [31]. In this case, the goal was to evaluate the impacts on the environment of two residential ventilation systems that used different operating modes to reduce the concentration of radon indoors. This study may help designers decide whether to choose one ventilating system or another, taking into consideration both indoor radon reduction and the impacts on the environment.

The functional unit of the assessment was a ventilation system for a typical single-family house in Czechia with an internal ventilated volume of 400 m^3 considering a service life of 50 years.

A number of methodological choices were also made in this step, such as defining the boundaries of the system and selecting the impact categories to be studied. In particular, this study assessed the production stages (modules A1–A3) [32], i.e., module A1 corresponded to the raw material supply, A2 corresponded to the transportation of the material to the manufacturer, and A3 corresponded to the manufacturing process, and the operational stage (module B6), i.e., B6, corresponded to the operational energy. These were the stages considered in the assessment (Figure 5). The study did not consider A4–A5 (the construction process stages), B1 to B5 (the building fabric stages), B7 (operational water use), and the end-of-life and benefit stages (C and D)—this division of the LC of construction products into individual stages was presented in the EN 15804 + A2 standard [33].

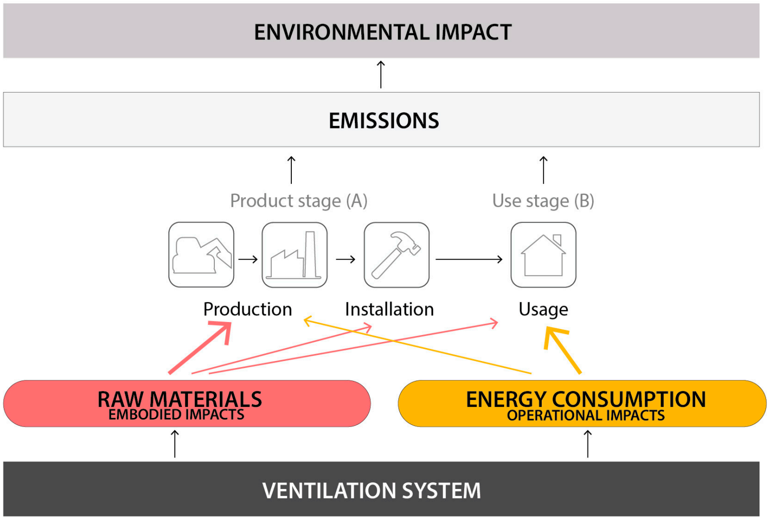

Figure 5. Overview of impacts from ventilation units, taking into consideration the building life cycle.

The life cycle inventory (LCI) step involved the data collection and calculation of the inputs and outputs for the system under study. The inputs and outputs included those related to energy, raw materials, and other environmental aspects. In this study, the two mechanical ventilation systems were designed with the following components:

- Mechanical centrally balanced ventilation (CV):
- One air handling unit—average service life of 25 years, so a replacement occurred 2 times, considering a reference study period of 50 years;
- Non-woven polypropylene air filters (PPs)—average service life of 0.5 years, so a replacement occurred 2 times per year, resulting in 100 units in a 50-year reference study period;
- A total of 55 m-long steel air ducts for a single-family house; 50-year service life;
- Mechanical exhaust ventilation system (EV):
- One exhaust fan—average 17-year service life, so a replacement occurred 3 times, considering a reference study period of 50 years;
- A total of 12 m-long steel air ducts for a single-family house; 50-year service life;
- Eight polyvinyl chloride (PVC) window inlets, 50-year service life.

The ventilation systems were described in terms of material, quantity, and size of individual components. The individual components of the ventilation systems and their energy consumption levels were the input data for determining their embodied (calculated from the amount of material) and operational (calculated from the amount of energy consumed) environmental impacts. A detailed design of the ventilation systems was not performed because, for the purpose of our study, it was not important to know where and how the individual components were located in the house. The placement of the components had no effect on the environmental impact. Indeed, the data for the air-handling unit, the exhaust fan, and the steel air ducts were taken from Environmental Product Declarations (EPDs) in accordance with EN 15804 + A2:2019 [33] or from the ISO 14025:2006 [34] standards, which were freely available online on the LCI open source databases [35]. The use of the method presented here may have been limited by the fact that these databases provided a limited number of construction materials/components. In fact, if other databases had been considered, other options might have appeared. The other components were modeled in SimaPro v9.4.0.2 [36], one of the most widely-known software for conducting LCA assessments based on the Ecoinvent v3.9.1 LCI database [37].

In this study, three residential building air handling units for CVs were considered, because they could support different airflow ranges: the R3 smart model (dimensions: 599 × 361 × 700 mm, Ø125 mm) could handle a maximum of 288 m^3/h, while the R7V smart model (dimensions: 855 × 571 × 932 mm, Ø200 mm) could handle a maximum of 677 m^3/h, and the R9 smart model (dimensions: 1080 × 788 × 1100 mm, Ø250 mm) could handle 871 m^3/h. For the operational energy environmental assessment, all the calculations were performed in SimaPro. Additionally, it was essential to note that the origin of electrical energy used in the buildings varied from location to location. The ventilation units in this study were assumed to be powered by a medium-voltage electricity mix from Czechia (the Simapro data were from 2017). At that time, the Czech energy mix was composed of 54.03% fossil fuels (43.89% lignite, 9.89% natural gas, etc.), 40.41% nuclear power, and 5.56% renewables (3.31% biomass, 1.65% solar, 0.61% water, etc.). A comparative analysis between different electricity mixes by country is presented in the Discussion Section.

During the life cycle impact assessment (LCIA) step, the LCI results were correlated with the environmental impact categories and indicators. First, the impacts were classified into impact categories and then they were characterized in standard units to allow for comparisons. The analysis of this study was based on the EN 15804 + A2:2019 standard [33], and the impact categories presented in Table 1 were used, as they are the most thoroughly investigated impact categories in the construction industry [22].

Table 1. Impact categories and their units of measurement.

Impact Categories	Acronym	Unit Measure
Acidification potential	AP	[kg—SO_2 eq.]
Ozone depletion potential	ODP	[kg—CFC-11 eq.]
Global warming potential	GWP	[kg—CO_2 eq.]
Eutrophication potential	EP	[kg—$(PO_4)^{3-}$ eq.]
Abiotic depletion potential elements	ADPf	[kg—Sb eq.]
Abiotic fossil fuel depletion	ADP	[MJ]

As a part of this stage, the ventilation systems and their environmental impacts were reviewed using the environmental footprint normalization and weighting method (EF 3.0) [23,38]. This method involves normalizing and weighting the results in order to group them into midpoint categories that can be summed up into a single score [39]. It is therefore admissible to use these single-score indicators resulting from the EF 3.0 method for a direct comparison of the performance of different ventilation systems in terms of a single numerical value. The indicators were then compared to identify the most environmentally friendly ventilation system in terms of the radon supply rate.

Lastly, as part of the life cycle interpretation step, the results from the LCI and LCIA were interpreted based on the stated goals and scope of the project. This step included checks for completeness, sensitivity, and consistency. As part of this step, the uncertainty and accuracy of the results were also discussed. Indeed, this step aimed to ensure that the results were meaningful and could be used to assist in making decisions. It also provided a greater understanding of the impacts and helped identify the potential areas for improvement.

2.3. Limitations of the Study

The house was considered as one air volume in which radon was evenly dispersed. The supply of radon was constant and was not affected by the ventilation system or the air flow rate. These assumptions allowed a simple determination of the total volume flow of outdoor air, at which the concentration dropped to the required levels of 100 or 200 Bq/m^3.

The layout of the house was not described because, for the purposes of our work, it was not necessary to know the air flows between individual rooms. To calculate the energy demand of individual ventilation systems, it was enough to know the total flow of air supplied to the house. From the total air flow, the power consumption of the fans and the energy needed to cover the heat losses from increased ventilation were calculated.

Moreover, using other open source LCA databases might have provided different EPDs and products for the embodied impacts (A1–A3 phases) of the ventilation systems. Nevertheless, the study provided a useful and reliable baseline for comparing the ventilation systems.

3. Results

3.1. Energy Needs for Ventilation Systems

All the important parameters of both ventilation systems, such as ventilation intensities and airflow rates required to reduce the indoor radon concentration to a value of C_{req} = 200 Bq/m^3, are presented in Table 2, and the parameters for C_{req} = 100 Bq/m^3 are presented in Table 3. As can be seen, higher radon supply rates require higher airflow rates and, as a result, higher fan power. However, note that as the airflow rate increases, the heat recovery efficiency decreases.

Table 2. Parameters of the considered ventilation systems for a reduction in the radon concentration to C_{req} = 200 Bq/m^3.

J_s (Bq/m^{3}h)	Q_v [m^3/h]	n_{req} [h^{-1}]	Fan Power Consumption		Efficiency of Heat Recovery η [%]	Example of a Ventilation Unit
			EV [1] [W]	CV [2] [W]		
50	100	0.25	25	30	88	R3 smart model (CV); exhaust fan (EV)
100	200	0.5	35	40	86	R3 smart model (CV); exhaust fan (EV)
150	300	0.75	60	80	84	R7V smart model (CV); exhaust fan (EV)
200	400	1.0	70	110	84	R7V smart model (CV); exhaust fan (EV)

[1] EV—exhaust ventilation, [2] CV—central ventilation.

Table 3. Parameters of the ventilation systems for a decrease in the radon concentration to C_{req} = 100 Bq/m^3.

J_s (Bq/m^{3}h)	Q_v [m^3/h]	n_{req} [h^{-1}]	Fan Power Consumption		Efficiency of Heat Recovery η [%]	Example of a Ventilation Unit
			EV [1] [W]	CV [2] [W]		
50	200	0.5	35	40	86	R3 smart model (CV); exhaust fan (EV)
100	400	1.0	70	110	84	R7V smart model (CV); exhaust fan (EV)
150	600	1.5	100	300	82	R7V smart model (CV); exhaust fan (EV)
200	800	2.0	120	500	80	R9 smart model (CV); exhaust fan (EV)

[1] EV—exhaust ventilation, [2] CV—central ventilation.

The parameters from Tables 2 and 3 were used to calculate the energy needs for the fan operation (E_f) and to cover heat losses (E_h) due to the increased ventilation. Two working modes were considered for each ventilation system—continuous operation (24 h), ensuring n_{req} throughout the year, and cyclic operation, where n_{req} was ensured for 15 h every day of the year, and for the remaining 9 h n = 0,1 h^{-1}. The calculated energy needs for a decrease in the radon concentration to a value of C_{req} = 200 Bq/m^3 are shown in Table 4, and for a decrease to C_{req} = 100 Bq/m^3 the energy needs are shown in Table 5.

Table 4. Energy needs of the ventilation systems for a decrease in the radon concentration to C_{req} = 200 Bq/m^3.

J_s (Bq/m^{3}h)	EV 24 h		EV 9/15 h		CV 24 h		CV 9/15 h	
	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)
50	3363	219	2607	203	404	263	287	230
100	6726	307	4709	257	942	350	624	285
150	10,089	526	6811	394	1614	701	1044	504
200	13,452	613	8913	449	2152	964	1380	668

Legend: EV—exhaust ventilation, CV—central ventilation, E_f—annual energy consumed by fans [kWh/y], E_h—annual energy needed for eliminating heat losses caused by ventilation [kWh/y].

Table 5. Energy needs of the ventilation systems for a decrease in the radon concentration to C_{req} = 100 Bq/m^3.

J_s (Bq/m^{3}h)	EV 24 h		EV 9/15 h		CV 24 h		CV 9/15 h	
	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)	E_h (kWh/y)	E_f (kWh/y)
50	6726	307	4709	257	942	350	624	285
100	13,452	613	8913	449	2152	964	1380	668
150	20,179	876	13,117	613	3632	2628	2305	1708
200	26,905	1051	19,321	723	5381	4380	3398	2803

Legend: EV—exhaust ventilation, CV—central ventilation, E_f—annual energy consumed by fans [kWh/y], E_h—annual energy needed for eliminating heat losses caused by ventilation [kWh/y].

For example, Table 4 shows that the total energy demand of the EV system working 24 h per day with a radon supply of 50 Bq/m^{3}h is over 3500 kWh/y, whereas, in identical conditions, operating the CV system requires just under 670 kWh/y. The cyclic operation of both ventilation systems is 20 to 35% less energy demanding. Since E_h had much higher values, it was essential to prioritize E_h over E_f when deciding which energy sources to use.

For example, Table 5 shows that the EV system working 15 h daily with a radon supply of 150 Bq/m^{3}h consumes over 13,500 kWh/y, whereas operating the CV system in the same conditions requires about 4013 kWh/y.

Tables 4 and 5 show that as the radon supply rate increases, the energy consumption levels of both ventilation systems increase. The EV is about 5.4- to 2.9-times more energy demanding than the CV. The most significant differences between the two systems were at low radon supply rates; in the case of the EV, the energy needed to cover the E_h caused by ventilation was more than 20-times greater than the energy needed to operate the fans E_f. In the case of the CV (which included heat recovery), the energy losses due to ventilation were only a maximum of 2.5-times greater than the energy required to operate the fans. This applied to the continuous and cyclic operations of both systems.

The data presented in Tables 4 and 5 were entered into SimaPro LCA software to calculate the environmental impacts of both ventilation systems used in the two operating modes.

3.2. Environmental Assessment

3.2.1. Embodied Impacts

The embodied impacts of the two ventilation systems were compared to understand those that affected the environment the most in the production stage (A1–A3). Based on the EF 3.0 single-score method, Figure 6a shows that the CV embodied impacts (orange) are significantly greater than the EV embodied impacts (blue). The reason for this result is that the emissions associated with the air handling unit and the steel air ducts significantly impact the overall results. Furthermore, Figure 6b,c illustrate the embodied impacts of each component of the CV (orange shades) and EV (blue shades).

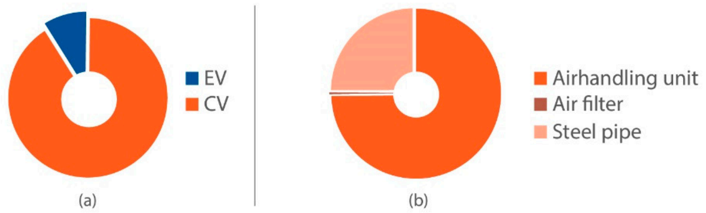

Figure 6. (**a**) Single score of the exhaust ventilation systems (EVs) and the central balanced ventilation system (CV); (**b**) embodied impact weights of CV divided by components; (**c**) embodied impact weights of EV divided by components.

3.2.2. Operational Impacts

As previously mentioned, the function of the ventilation systems for this comparative study was to provide ventilation air for reducing the indoor radon concentration of a single-family house in Prague. The energy required to perform this function was the energy E_f to run the supply and exhaust fans and the energy E_h to cover the heat losses induced by the increased ventilation. E_f was covered by electricity from the Czech electricity mix.

E_h was covered by the existing heating system. The calculation did not include the environmental impacts of the individual technical components of the heating system. However, the energy source used for heating was taken into account. The EF 3.0 method was used to calculate the single-score indicator.

Figure 7 illustrates the operational environmental impacts of the CV and EV in different operating modes considering the reduction in the indoor radon concentrations to 200 and 100 Bq/m^3. For this calculation, both E_f and E_h used the Czech electricity mix as the energy source.

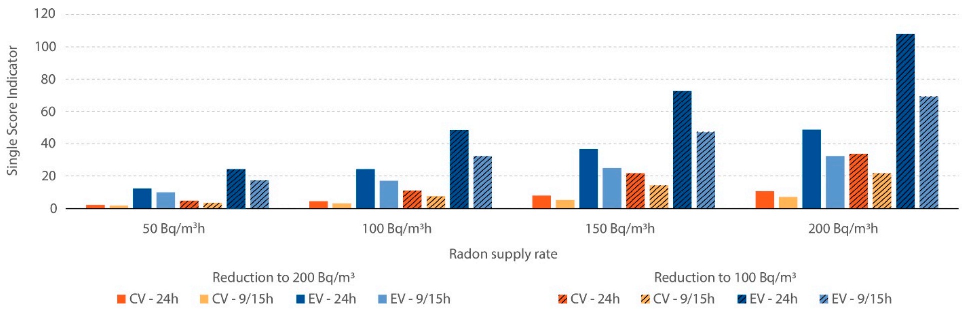

Figure 7. Performance of the ventilation systems in terms of single-score indicators for operational emissions sorted by radon supply rate values [Bq/m^{3}h].

For example, considering a reduction to 200 Bq/m^3, for EV 24 h, the EF3.0 single-score values changed from 12.30 for 50 Bq/m^{3}h to 24.24 for 100 Bq/m^{3}h, while for CV 24 h, the values changed, respectively, from 2.30 to 4.45. If considering a reduction to 100 Bq/m^3, and 9/15 h, the EV values changed from 9.69 for 50 Bq/m^{3}h to 17.12 for 100 Bq/m^{3}h, while the CV presented values of 1.78 and 3.13.

Regardless of the radon supply rate, the CV always had a lower environmental impact than the EV in both operating modes. This makes the CV the more environmentally friendly option, especially when operated in a cyclic mode. For all radon supply rates, it can be observed that the emissions resulting from E_h are much higher than those resulting from E_f (Figure 8). In fact, for a radon supply rate of 50 Bq/m^{3}h, the single score was composed of 94% of E_h and only 6% of E_f. This proportion was similar for all radon supply rates. The impacts of the elimination of heat losses were decisive.

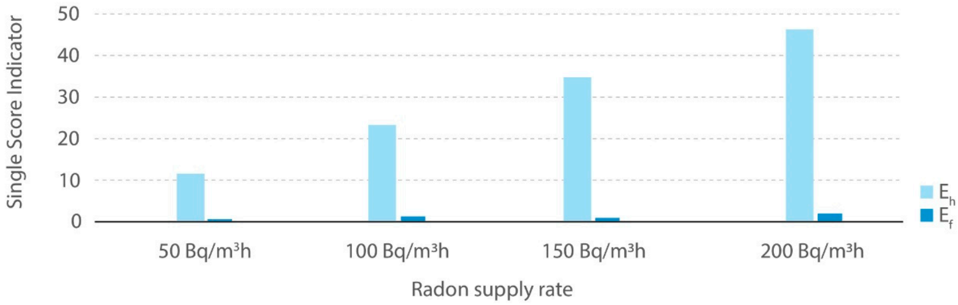

Figure 8. Exhaust ventilation system performance (continuous operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3) in terms of single-score indicators for operational emissions sorted by the energy needed for covering heat losses (light-blue columns), by the energy needed for the fans (blue columns), and by the radon supply rate values [Bq/m^{3}h].

It should also be taken into consideration that each energy source had a different environmental impact. Therefore, several energy sources were considered for covering the heat losses: electricity (CZ electricity mix), wood pellets, natural gas, and photovoltaics (Figure 9 (CV) and Figure 10 (EV)). The calculation was performed using SimaPro, which used Ecoinvent's LCI database. The calculation of E_f was always based on the electricity mix of Czechia. When comparing the energy sources, the electricity generated from the Czech energy mix had the greatest environmental impact. This was the result of the composition of the energy mix, which was dominated by lignite. Hence, the figures highlight the importance of choosing renewable energy sources to minimize the environmental impacts of electricity use.

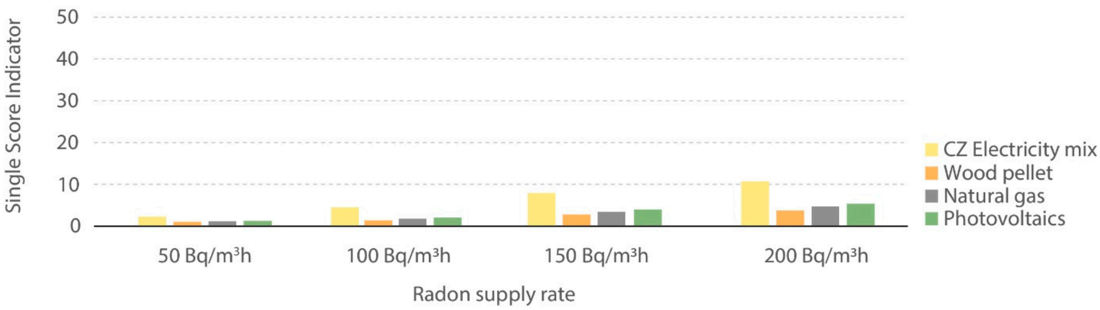

Figure 9. Comparison of energy sources for covering E_h in the CV (continuous operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3) by the radon supply rate [Bq/m^{3}h]. Column values are the sum of E_h + E_f; the energy source for E_f is always the CZ electricity mix.

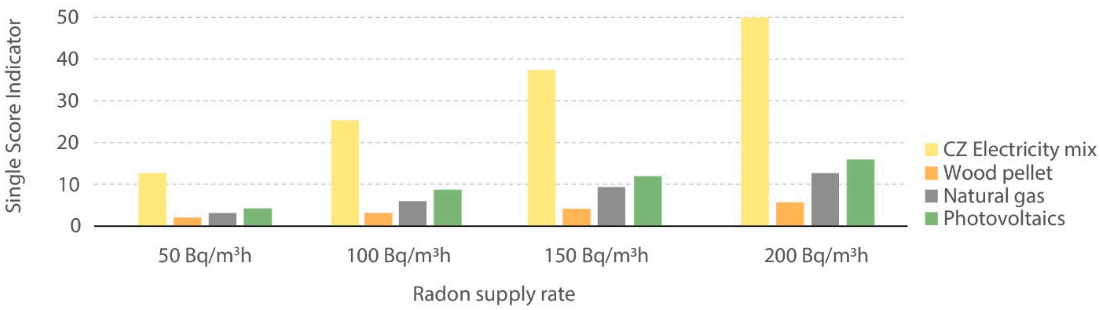

Figure 10. Comparison of energy sources for covering E_h in the EV (continuous operation for a decrease in radon concentration to C_{req} = 200 Bq/m^3) by the radon supply rate [Bq/m^{3}h]. Column values are the sum of E_h + E_f; the energy source for E_f is always the CZ electricity mix.

A significant difference can be noted between Figure 9, which considers the CV with a heat exchanger, and Figure 10, which considers the EV. This highlights the importance of the heat exchanger in terms of efficiency, as it significantly reduces the energy demand required to achieve the same performance, i.e., an indoor radon reduction to 200 Bq/m^3.

The single-score indicator was determined by taking into consideration multiple environmental impact categories, as shown in Figure 11. In particular, natural gas had a worse GWP value than wood pellets or photovoltaics. As for the impact associated with the use of electricity generated by photovoltaics, the result was influenced by the ADP impact category, which resulted from the production of photovoltaics.

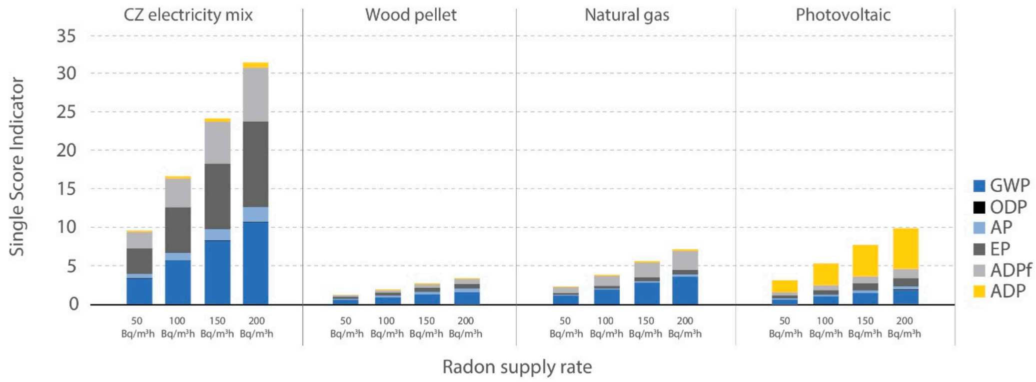

Figure 11. Single-score indicators by environmental impact category for each radon supply rate and energy source for the CV 9/15 h operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3.

3.2.3. Overall Impact

Tables 6 and 7 show that the operational impacts (I_o) are more harmful than the embodied impacts (I_e), mostly due to E_h. The operational impacts of the CV 24 h operation were less than those of EV, but they were still higher than the embodied impacts. Nevertheless, switching to a different energy source could result in significant reductions in operational emissions. Optimizing this system and energy source was therefore critical to ensure minimal operational impacts and cost savings.

Table 6. Embodied and operational impacts of the EV 24 h operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3.

J_s (Bq/m^{3}h)	EV 24 h							
	CZ Electricity Mix		**Wood Pellet**		**Natural Gas**		**Photovoltaics**	
	I_e (-)	I_o (-)	I_e (-)	I_o (-)	I_e (-)	I_o (-)	I_e (-)	I_o (-)
50	0.006	12.35	0.006	1.49	0.006	2.95	0.006	4.01
100	0.006	24.24	0.006	2.52	0.006	5.44	0.006	7.57
150	0.006	36.59	0.006	4.01	0.006	8.38	0.006	11.58
200	0.006	48.48	0.006	5.04	0.006	10.87	0.006	15.13

Legend: EV—exhaust ventilation, I_e—single-score indicator for embodied impacts [-], I_o—single-score indicator for operational impacts [-].

Table 7. Embodied and operational impacts of the CV 24 h operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3.

J_s (Bq/m^{3}h)	CV 24 h							
	CZ Electricity Mix		**Wood Pellet**		**Natural Gas**		**Photovoltaics**	
	I_e (-)	I_o (-)	I_e (-)	I_o (-)	I_e (-)	I_o (-)	I_e (-)	I_o (-)
50	0.07	2.30	0.07	0.99	0.07	1.17	0.07	1.30
100	0.07	4.45	0.07	1.41	0.07	1.82	0.07	2.12
150	0.08	7.98	0.08	2.77	0.08	3.47	0.08	3.98
200	0.08	10.74	0.08	3.79	0.08	4.72	0.08	5.41

Legend: CV—central ventilation, I_e—single-score indicator for embodied impacts [-], I_o—single-score indicator for operational impacts [-].

4. Discussion

In the course of examining the environmental impacts of two types of ventilation systems for the reductions in indoor radon concentration, we were able to determine whether these systems produced more or less evident effects from the 'cradle-to-gate' stage (LCA A1-A3—production phase) and from the operational stage (LCA B6—operational energy). An important finding of this study is that the CV presents higher embodied impacts than the EV (the EF3.0 single score of the CV was 0.07 versus 0.01 for the EV) due to the quantity of steel air ducts and the air handling unit; however, when taking into consideration the operational energy-related emissions under the same conditions (operating times and radon supply rate), the CV was less impacting than the EV—in the case of a reduction to 100 Bq/m^3, considering the radon supply at 150 Bq/m^3 in the 24 h cyclic mode, the CV's EF3.0 single score was 7.98, whereas the EV's was 36.59. The graphs clearly demonstrate that, as the radon supply rate increases, the environmental impact values increase, indicating that the impact worsens. In addition, quantifying the environmental impact of the ventilation system using a single-score indicator allowed decisions to be made on reducing resource consumption and increasing sustainability. This approach indicated that a cyclic CV system operating in a 9/15 h cycle was the most environmentally friendly solution—for 50 Bq/m^3, for example, the CV had a single score of 1.78 versus 9.69 for the EV.

Moreover, this study specifically focused on the energy sources used to compensate for heat losses. The Czech electricity mix was found to have particularly great environmental impacts, and a more extensive use of renewable sources would lead to better results. Figure 12 compares three energy mixes, Czech, German, and Swiss, and illustrates the very different impacts of using electricity when energy is not produced primarily through nuclear power or lignite, as in the case of Czechia.

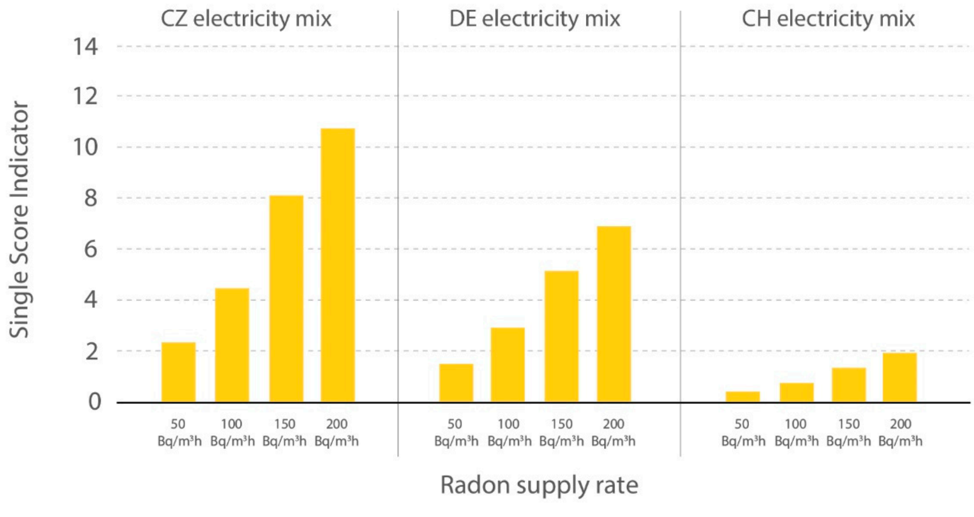

Figure 12. Comparison of the electricity mix by country for the CV continuous operation for a decrease in the radon concentration to C_{req} = 200 Bq/m^3—Czechia (CZ), Germany (DE), and Switzerland (CH).

However, the selection of ventilation systems and operational times could not be solely based on the environmental parameters and radon concentration reductions. Other pollutants may have also adversely affected the indoor air quality, resulting in higher ventilation rates and, therefore, higher energy consumption levels. To remove common pollutants and ensure good air quality, it is usually sufficient to operate ventilation systems in residential buildings with a ventilation intensity of up to 0.6 h^{-1}. Higher intensities do not seem to be efficient or environmentally friendly. When a higher intensity of ventilation is needed to reduce the radon concentration, it seems better to choose some other measure against this gas—for example, reducing the radon supply into the building by installing a continuous radon-proof membrane.

Furthermore, the results of this research were compared with Felicioni et al.'s findings [13], where radon-proof membranes (one of the easiest-to-install and cheapest passive solutions for this gas [40]) were analyzed to highlight the type of membrane (chemical composition and thickness) that was the most effective for radon control and environmental effects. Figure 13 shows that passive solutions, such as these radonproof membranes, particularly a polyvinyl chloride (PVC) membrane 2 mm in thickness and a low-density polyethylene (LDPE) membrane 2 mm in thickness, present lower embodied impacts than the ones related to the CV and have comparable values to those for the EV. The comparison took into consideration the results of the EF 3.0 single-score method. It should be added that membranes have no operational impacts.

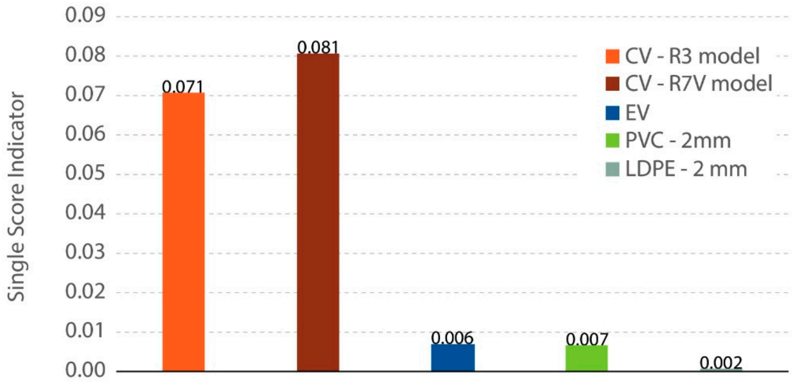

Figure 13. Comparison of embodied impacts (A1–A3 LCA stages) for ventilation systems and two kinds of membranes (PVC and LDPE) 2 mm in thickness.

5. Conclusions

This study examined the environmental impacts of ventilation systems intended to reduce the indoor radon concentration to 200 or 100 Bq/m^3 in accordance with the national legislative requirements. The purpose of the study was to assess two different ventilation systems utilizing two different operating modes (24 h or 15 h/day) in order to attain two levels of indoor radon concentrations that could be used to identify the most efficient and environmentally friendly ventilation system and operation mode. Using the methodology presented in this study, it was shown that mechanical ventilation systems could not be considered as a universal anti-radon measure suitable for any radon supply rate. They were suitable for radon supply rates up to 100 Bq/m^{3}h (e.g., when the source of radon was a building material). At higher radon supply rates, the energy consumption of these systems and their environmental impacts increased. Their applicability was determined by the source of energy used to reduce heat losses caused by increased ventilation. The methodology presented in this article made it possible to assess all the influences and evaluate whether, under the given conditions, it made sense to use a ventilation system to protect the house against radon.

The environmental impact was primarily influenced by operational impacts resulting from the energy consumption of ventilation systems. In this regard, they represented approximately 95% of the total impact, while the embodied impacts only represented 5%. This is to illustrate how energy consumption for operating ventilation systems can impact the environmental score. The balanced ventilation system (CV), which did not affect the pressure conditions or radon supply rate, may be considered to be a more efficient and more environmentally acceptable measure than the exhaust ventilation system (EV). For example, considering a reduction to 200 Bq/m^3, for the EV 24 h operation, the EF3.0 single-score values changed from 36.59 for 150 Bq/m^{3}h to 48.48 for 200 Bq/m^{3}h, while for the CV 24 h operation, the values changed, respectively, from 7.98 to 10.74. However, in both cases, an increase in the radon supply rates resulted in an increase in energy consumption levels, which increased the operational emissions. Indeed, the single scores for the operational energy of the EV system aimed for a reduction to 200 Bq/m^3 in a 9/15 cycle mode range from 9.69 (50 Bq/m^{3}h) to 32.27 (200 Bq/m^{3}h).

In this paper, it was pointed out that, when assessing the applicability of ventilation measures, it was not only necessary to consider the reduction in radon or other pollutants, but also the energy consumption and related emissions. The environmental impacts of ventilation systems can be significantly reduced by the following four approaches: (i) avoiding the use of ventilation systems with ventilation rates that are unnecessarily high and that lead to an increase in energy consumption and energy-related emissions; (ii) selecting the most environmentally friendly energy source to cover the energy for fans and heat losses; (iii) considering the use of passive radon control technologies to reduce the indoor radon concentration and thereby reduce the overall ventilation energy consumption; and (iv) choosing components of the ventilation system that have the lowest-possible environmental impacts. Finally, using this approach, anybody can potentially evaluate the environmental impacts of ventilation systems and their applicability to reduce indoor radon concentrations in any building since the used methodology does not focus on a particular type of building but is generic.

The impact on the environment of combined radon control technologies will be studied in future research. This paper formed a part of the EU RadoNorm project under the umbrella of the Horizon 2020 Framework Programme (H2020).

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Data Availability Statement: Data are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ADP	Abiotic fossil fuel depletion
ADPfs	Abiotic depletion potential elements
AP	Acidification potential
CH	Switzerland, Swiss
CO_2	Carbon dioxide
C_{req}	Required indoor radon concentration
CV	Central ventilation system
CZ	Czechia, Czech
DE	Germany, German
E_h	Heat loss
EPD	Environmental product declaration
EP	Eutrophication potential
EU	European Union
EV	Exhaust ventilation system
GWP	Global warming potential
I_e	Embodied impact
I_o	Operational impact
J_s	Radon supply rate
LC	Life cycle
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

LDPE	Low-density polyethylene
n	Ventilation intensity
n_{req}	Required ventilation intensity
ODP	Ozone-depletion potential
PVC	Polyvinyl chloride
Q_v	Volume flow of external air
WHO	World Health Organization

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