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Review on Ventilation Systems for Building Applications in Terms of Energy Efficiency and Environmental Impact Assessment

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Abstract: Buildings are responsible for approximately 30–40% of energy consumption in Europe, and this is a fact. Along with this fact is also evident the existence of a defined and strict legislation framework regarding energy efficiency, decarbonization, sustainability, and renewable energy systems in building applications. Moreover, information and communication technologies, along with smart metering for efficient monitoring, has come to cooperate with a building's systems (smart buildings) to aim for more advanced and efficient energy management. Furthermore, the well-being in buildings still remains a crucial issue, especially nowadays that health and air quality are top priority goals for occupants. Taking all the above into consideration, this paper aims to analyze ventilation technologies in relation to energy consumption and environmental impact assessment using the life cycle approach. Based on the review analysis of the existing ventilation technologies, the emphasis is given to parameters related to the efficient technical design of ventilation systems and their adequate maintenance under the defined guidelines and standards of mechanical ventilation operation. These criteria can be the answer to the complicated issue of energy efficiency along with indoor air quality targets. The ventilation systems are presented in cooperation with heating and cooling system operations and renewable energy system applications ensuring an energy upgrade and reduced greenhouse gas emissions. Finally, the mechanical ventilation is examined in a non-residential building in Greece. The system is compared with the conventional construction typology of the building and in cooperation with PVs installation in terms of the environmental impact assessment and energy efficiency. The methodology implemented for the environmental evaluation is the Life Cycle Analysis supported by OpenLca software.

Keywords: ventilation systems; energy efficiency; life cycle analysis; environmental impact assessment

Citation: Giama, E. Review on Ventilation Systems for Building Applications in Terms of Energy Efficiency and Environmental Impact Assessment. *Energies* **2022**, *15*, 98. https://doi.org/10.3390/en15010098

Academic Editor: Christian Veje

Received: 31 October 2021
Accepted: 16 December 2021
Published: 23 December 2021

1. Introduction

The defined objectives for clean energy, reduced greenhouse gas emissions, and sustainable and resilient infrastructure in terms of circularity and social sensitivity set the base for future accomplishments in the building sector. The targets for reducing carbon emissions have been rescheduled based on the European Green Deal. The target of 20-20-20 has almost been attained in the majority of EU countries.

Within this framework, on 14 July, the EU has reformed and updated the future goals for energy and environment in order to reduce CO_2 emissions by at least 55% by 2030, compared to 1990 levels. Achieving these ambitious emission reductions in the next decade sets the base for a carbon neutral EU by 2050, and makes the European Green Deal a realistic target for EU members.

Focusing on Renewable Energy Sources (RESs), the European Union aims to achieve a 20% share (of its final energy consumption) from RES by 2020, and at least a 32% share (not broken down into nationally binding targets) by 2030. The key instruments at the EU level to promote RESs include directives, such as the 2009 Renewable Energy Directive [1]. The EU supports the legislative framework with schemes and financial programmes. For instance, the EU Emission Trading Scheme (ETS) is one of the EU's efforts to support RES implementation. On one hand, there is the demand of EU regulations, and on the other hand, there is the need for developing health buildings ensuring users quality of living. Indoor air quality is an important consideration for health and well-being, since people worldwide spend most of their time indoors, either at home or at their workplace. Undoubtedly, monitoring and improving the indoor air quality in homes, workplaces, and public facilities can lead to an increased understanding of indoor air pollution and its effects on health, and the formation of a global regulatory framework for indoor air quality, which is currently lacking. Indoor air pollution is a complicated mixture of particulate and various gaseous components, and the compositions differ significantly depending on sources, emission rates, and ventilation conditions.

The main indoor air pollutants are PM, VOCs, CO, CO_2, ozone, radon, heavy metals, aerosols, pesticides, biological allergens, and microorganisms. In general, indoor air pollution originates either from outdoor-to-indoor infiltration or through various occupants' activities (e.g., heating, cooling, cooking) and emissions from construction materials and indoor equipment [2]. In this direction, implementing smart air disinfection and purification devices (e.g., HVAC, robots) and materials to improve air quality, powered by automatic decision support and personalized guidance, is a key issue in building management in terms of air quality, energy efficiency, and environmental impact.

The design, control, and identification of the technical characteristics of the central heating and air conditioning systems for buildings is feasible in terms of energy efficiency, thermal comfort, and indoor air quality. Operational conditions, indoor environmental parameters (air flow, air infiltration, thermal comfort) as well as occupants' behavioral characteristics can be used in order to ensure the minimization of pollutants in indoor environments.

The main objective of this paper is to underline the significance of ventilation and present the different types and technologies. The effects of ventilation technology implementation are related to:

- health and well-being, which are, especially nowadays, key issues for building management and the protection of users;
- cooperation with other energy systems in the building ensuring thermal comfort and energy efficiency;
- environmental impact analysis, which proved to be the scientific gap as there were no significant applications based on the literature review on this scientific area.

More specifically, the paper presents, based on the literature review, the basic benefits of ventilation technologies, mainly focused on energy efficiency, as well as the health and well-being of users, and it identifies the gap in the environmental impact analysis. The attempt to close this gap and give an answer to the environmental impact of ventilation technologies was given with the LCA implementation in an office building in Greece.

2. State-of-the-Art Overview of Ventilation System Technologies

The main target of ventilation systems is to supply the indoor environment with fresh air, aiming to improve the air quality and ensuring the energy efficiency improvement in cooperation with the heating and cooling systems. The air exchange rate depends on several parameters, such as the type of activities, the number of users, the hours of occupancy in the building, the type of building, the behavioral characteristics of occupants, or the climatic conditions [3]. Therefore, it is important to understand that ventilation is a technical issue with societal parameters that should definitely count towards the system's operational conditions. The basic ventilation systems are mainly categorized into three types:

- natural ventilation (NV);

- mechanical ventilation (MV);
- and hybrid ventilation systems (HVs).

Natural ventilation is the air input with natural forces and depends significantly upon the architecture of the building. NV does not use mechanical components to achieve ventilation. It is evident that in order to improve and, in a way, boost the NV, it is possible to add mechanical parts to the ventilation system, such as exhaust air units. In this way, the HV is created, which is actually the combination of NV with mechanical assistance in order to ensure the air exchange and indoor air quality. Most of the time, the HVs combine smart sensoring applications to control the air exchange and take advantage of the weather conditions to permit the fresh air flow in the building.

The accurate design of automations are of major importance in reducing energy use and attaining the appropriate indoor air quality levels in indoor environments. These systems are often designed with the help of computational fluid dynamics (CFD) simulations. Keeping in mind that it is an EU as well as national legislative demand to improve energy efficiency in buildings, the ventilation systems should also contribute to this direction. Concerning the MV systems, the heat recovery ventilation (HRV) systems as well as the energy recovery ventilation (ERV) systems provide the indoor environments with fresh air. This kind of ventilators insert clean air in the building and expel stale air, while keeping 70% to 90% of the heat from the discharged air and returning it to the incoming air. Moreover, HRVs and ERVs assist to moisture control in the air. Both systems have the same technical operation, but there are some differences in the material used in the heat exchanger. Without a doubt, MV systems overcome the restrictions of NV systems and do not depend on weather conditions providing a constant environment in terms of air quality, but there are definitely some issues to discuss. The MV systems should be well-designed, properly installed, and maintained in order to have positive results. Otherwise, not only do these systems not arrive to the expected results, but they also cause extra health problems to the vulnerable population. For instance, an improperly maintained filter or a filter with non-certified materials can cause infectious diseases. On the other hand, NV is definitely more cost-effective compared to MV systems, but it depends on weather conditions and behavioral parameters. The main applications of ventilation technologies (Table 1) are focused on energy efficiency but mainly to the improvement of indoor air quality and the health and well being of users [3,4].

Table 1. State-of-the-art on ventilation system applications in buildings in terms of energy efficiency, indoor air quality, and environmental impact assessment.

Reference	Ventilation System	Type of Ventilation System	Type of Building	Target of the System Installed
[5]	Natural ventilation	Openings, air pressure	Residential and office buildings	Energy efficiency, energy consumption
[6]	Mechanical ventilation, decentralized units, chilled ceilings	Decentralized units, chilled ceilings	Office	Energy efficiency, energy consumption
[7]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Energy efficiency, energy consumption
[8]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Energy efficiency, energy consumption, 22–33% reduced environmental impact
[9]	Hybrid ventilation systems	Natural ventilation in combination with variable air volume systems	Office	Energy efficiency, energy consumption, in combination with PV system
[10]	Natural ventilation	Openings, air pressure	School	Energy efficiency
[11]	Hybrid ventilation	Recovery (VAV) active supply diffuser and natural ventilation	Office	Energy efficiency, energy consumption, in combination

				with Photovoltaic (PV) system
[12]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Energy efficiency and cost effectiveness
[13]	Mechanical ventilation and Hybrid ventilation systems	NA	Office	Indoor air quality
[14]	Natural ventilation	Openings, air pressure	Residential	Indoor air quality
[15]	Natural ventilation	Openings, air pressure	Residential	Indoor air quality
[16]	Mechanical ventilation	Model development for pollutants concetration	All type of buildings	Indoor air quality and thermal comfort
[17]	Natural Ventilation	Air pressure, passive cooling	Residential	Energy efficiency, reduction of the energy consumption and thermal comfort
[18]	Ventilation	Natural, Hybrid	NA	Indoor air quality focused on PMs
[19]	Ventilation	NA	All type of buildings	Indoor air quality and reduction of energy consumption
[20]	Natural ventilation	The significance of the building design, openings, air pressure and volume	All type of buildings	Indoor air quality
[21]	Mechanical ventilation	The role of filtration to the system	Office	Indoor air quality
[22]	Natural ventilation	Openings, air pressure	School	Indoor air quality
[23]	Mechanical ventilation	Variable air volume (VAV) systems, air filtration	School	Indoor air quality, emphasis to PMs and operational cost reduction
[24]	Hybrid ventilation	Natural ventilation in combination with mechanical components	NA	Indoor air quality
[25]	Natural ventilation	Openings and architecture design	Office	Indoor air quality
[26]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Environmental impacts material use for the air supply unit
[27]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Environmental impacts material use for the air exhaust units
[28]	Mechanical ventilation	Variable air volume (VAV) systems	Residential	Environmental impacts
[29]	Hybrid ventilation	Emphasis to night ventilation benefits in summer	Residential	Energy efficiency, reducing cooling loads
[30]	Mechanical ventilation	Variable air volume (VAV) systems	Office	Environmental impacts material use for the silencer
[31]	Natural ventilation	Heat recovery	All type of buildings	Energy efficiency in buildings
[32]	Mechanical ventilation	Duct/heat exchanger unit experimental application	All type of buildings	Indoor air quality and energy efficiency in buildings
[33]	Mechanical ventilation	decentralized ventilation systems.	All type of buildings	Indoor air quality and energy efficiency in buildings
[34]	Mechanical ventilation	Mechanical ventilation systems in collaboration with natural ventilation	All type of buildings	Indoor air quality
[35]	Ventilation technologies, mechanical as well as natural ventilation	Hybrid ventilation technologies for residential and non-residential buildings	Non residential	Indoor air quality
[36]	Mechanical ventilation	Non-residential applications	Non residential	Indoor air quality airborne infection transmission
[37]	Mechanical ventilation	Sensor Technology for demand-controlled ventilation	All type of buildings	Energy efficiency and indoor air quality
[38]	Hybrid ventilation system	Low energy and ventilation technologies	All type of buildings	Energy efficiency and environmental impact

[39]	Mechanical Ventilation	Heat recovery system residential buildings	Residential	Energy efficiency
[40]	Mechanical ventilation	Heat recovery system residential buildings	Residential	Energy efficiency
[41]	Mechanical ventilation	Demand-controlled ventilation technology (DCV) for controlling air flow rates Application in office and school buildings	Office and school building	Indoor air quality and thermal comfort
[42]	Mechanical ventilation	The role of mechanical ventilation in indoor environments and the effect on certain pollutants	All type of buildings	Indoor air quality focused on airborne pathogen transmission
[43]	Mechanical ventilation	Mechanical ventilation in commercial buildings	Commercial	Energy efficiency
[44]	Mechanical	The impact of demand-controlled and economizer ventilation in buildings	All type of buildings	Energy efficiency

Aflaki et al. [5] focused mainly on the examination of ventilation systems in tropical climates and on natural ventilation measures and systems applied in the building facade. The majority of the case studies have given technical details about the fan power, air tightness, and heat recovery. The natural ventilation applications are mainly related to openings, air circulation, and infiltration rate. The ventilation systems are strongly connected with the energy efficiency and the energy consumed in the buildings because they also affect the heating and cooling process.

Based on the European Ventilation Industry Association (EVIA) [45], the energy consumption with mechanical ventilation systems is 20–25 kWh/m^2/yr while with hybrid ventilation systems the energy consumed is lower, at about 7–8.5 kWh/m^2/yr. Along with the energy benefits, the health and economic benefits from the reduction of operational costs because of the ventilation interventions is another point to be discussed based on the analysis by Yuan [46], who proved the positive impact of ventilation systems by reducing PM2.5 in indoor and outdoor origins in urban Beijing. According to Niemelä, the simulation of heat pumps could also improve the energy efficiency of buildings [47].

An issue that is essential to be discussed and analyzed is the cost effectiveness of the ventilation systems, because it is evident that a new system has an initial cost that should be balanced with the profit of the operational cost reduction and have a low payback period. In this term, the investment is definitely cost-effective. Therefore, in the design stage, apart from the technical specification and the appropriate conjunction with the other mechanical systems, the cost effectiveness should also be determined. For example, mechanical ventilation with heat recovery, which is a very common application in buildings, is a more complex system that needs more components and more materials because it includes ventilation ducts (steel use), the insulation of the ducts (in most cases rock-wool), an air supply exhaust unit (electro-galvanized steel and plastic), air exhaust fans (galvanized steel and iron), an air handling unit (galvanized steel and aluminum), and a silencer mechanism (galvanized steel and mineral wool). All these extra components need to be examined in terms of cost, but also in terms of environmental impact assessment. The production and use of these materials are responsible for environmental impacts, and this is also a point of analysis in the life cycle of buildings. In that sense, a life cycle approach of the systems is a useful tool to quantify the environmental impact. To conclude, HV systems or MV systems with a proper technical design, adequate maintenance, and the synergy with the heating and cooling systems of the building under the defined guidelines and standards of mechanical ventilation operation can be the answer to the complicated issue of energy efficiency, along with the indoor air quality targets [48,49].

Ventilation is an important parameter for energy efficiency in buildings, which is why airtightness levels are included in the legislation framework, as well as in the technical guidelines and standards. Efficient airtightness levels positively affect the design and installation of heating and cooling systems, and therefore, the energy consumption.

Moreover, ventilation, as mentioned above, contributes to indoor air quality, which significantly affects the occupants' well-being and quality of living. An important role in energy efficiency is the optimization of ventilation in a way that ensures the indoor air quality standards and does not exceed the energy consumption levels because of the continual operation of the ventilation systems. Taking this under consideration, emerging technologies such as advanced ventilation systems, smart sensoring and monitoring, internet of things, and automations provide solutions towards the optimization of the ventilation systems. In order to increase the effectiveness of pollutant removal and reduce heating and cooling energy demands in buildings, a time-controlled air supply is proposed by using CFD simulations [35]. Emerging technologies and innovative materials are also implemented in mechanical ventilation, as is the case of Phase-Change Material (PCM) in mechanical ventilation systems and the effect on thermal performance [50] as well as the dynamic simulations for the optimization of energy systems [51].

3. Results on Ventilation Systems Application in Non-Residential Buildings: The Environmental Impact Assessment Analysis

In order to evaluate the ventilation system in cooperation with the other mechanical systems of the building, the life cycle approach is used. The goal is to connect the use of ventilation systems with the energy consumption and the use stage of the building. The Life Cycle Assessment (LCA) methodology ensures the evaluation of the environmental impacts of a product's life cycle based on ISO 14040 and 14044 standards, which provide the framework for LCA implementation.

LCA methodology aims at assessing the potential environmental impacts of a product or a service during its whole life cycle. According to ISO 14040, an LCA study shall be divided into the following main steps [52]:

1. Goal and scope definition: in this stage, the functional unit and the system boundaries are determined;
2. LCI (life cycle inventory): the initial system is separated into different subsystems and the energy as well as the materials input are quantified and registered;
3. LCIA (life cycle impact assessment): all the environmental impacts are estimated for all the processes set in the LCI; a specific characterization factor determines its impact in the studied impact category. Normalization can also be used in this stage of analysis.

4. Interpretation of the Results: Discussion of the Results, Conclusions, Sensitivity Analysis, Improvement Suggestions, Uncertainty

For the system environmental impact assessment, the Ecoinvent database and the OpenLCA (GreenDelta Company, Berlin, Germany) software are used. The basic environmental impacts evaluated are climate change, acidification, eutrophication, photochemical oxidation, and abiotic sources depletion. The system analyzed in terms of energy and environmental impact is an office building in Greece constructed in 1990. The building has a typical concrete block masonry. More specifically, and as far as the insulation, the building is insulated with stone wool. The height of the floor is 3.6 m, while, as can be seen from the picture, the length of the masonry is 2.8 m. Three scenarios are studied related to the energy efficiency and environmental impact assessment in the construction and use phase:

- Scenario 1 (SC1) is the conventional one, without extra ventilation systems or renewable energy systems. Therefore, in SC1, the building has a NV system according to the architectural design and the openings in the envelope. The typical construction typology of the building envelope is based on the requirements of the Energy Performance of Buildings and forms the construction input for SC1. The external wall is formed by a typical medium-weight brick wall, insulated with extruded polystyrene (XPS) of 10 cm thickness, while also including a single-layer gypsum board with 12.5 mm thickness on the interior side and a layer of gypsum plaster on the exterior. All the internal walls consist of two double-layer gypsum boards at about 25 mm thickness. The floor and ceiling consist of a 150 mm concrete slab with no additional coating;

- In Scenario 2 (SC2), a renewable energy system and more specific PVs are added. Some technical details related to PVs are defined (Table 2). Moreover, it is worth mentioning that the PV system is implemented in the building facade;
- Scenario 3 (SC3) is a combination of renewable energy systems, PVs, as well as mechanical ventilation in order to reduce the heat exported from the PVs operation and therefore contribute to the building's cooling in summer. The technical details related to the MV system are presented (Table 3). In SC1, the conventional case study, the total annual consumption is at about 150 kWh/m^2.

Table 2. Technical characteristics of PVs.

Characteristics	Dimensions
External dimensions of the system	1.58 × 664 mm^2
Thickness	38 mm
Weight	117 kg
Front cover	3.2 mm of tempered glass
Dimension of the junction boxes	60 × 60 × 11.5 mm^2
Cable lengths	200/300 mm

Table 3. Technical characteristics of ventilation system.

Basic Components	Type and Number of Items
Air fan	Cross flow, 3 items
Arduino board	3 items
Arduino data logger	Shield with RTCV1, 3 items
Dimmer module	50–60 Hz for Arduino, 3 items
Power supply	12VDC, 3 items
Sensors	DS18820

Inevitably, the high temperatures resulting from the absorption of heat by the solar radiation reduce the efficiency of the solar cells of the PV at SC2. This will probably have an effect on the life cycle of the system, leading to the maintenance and replacement of the technical components and the significant reduction of the life cycle, and even the system's end of life. Based on Giama and Papadopoulos, the maintenance or collapse of a system means extra raw materials, new production of products, and thus extra energy and sources in terms of circularity, and this will definitely mean greater environmental impacts [53]. Furthermore, a lack of ventilation tends to cause condensation within the building structure (much more so if ventilation is completely absent). Moreover, overheating in indoor environments can negatively affect the occupants and cause thermal discomfort.

To achieve this, one can configure a naturally ventilated open channel at the back of the photovoltaic panel. This measure not only provides effective means of releasing heat, but also helps to reduce the thermal gain of the building shell. The air in the channel behind the photovoltaic units can be circulated either with the help of electromechanical equipment (blowers, pumps, compressors), which operates from the generated current, or passively, with natural ventilation that utilizes the power of buoyancy.

The fluid flow and heat transfer to the photovoltaic facade cavities are extremely important for improving the energy efficiency and thermal behavior of the building. The relevant research has been thoroughly engaged in the theoretical and numerical modeling of air flow and heat transfer in the air duct behind the photovoltaic units. Sandberg and Moshfegh [54] investigated the flow of fluid behind photovoltaic modules implemented in the building shell using CFD analysis. In addition, photovoltaics installed on the facades of buildings increase the overall heat compared to PVs installation on the roof; in this way, the energy efficiency is reduced. [55]. Finally, taking the building as a parameter for evaluating the energy efficiency, the combination of mechanical ventilation with PVs increases energy efficiency, reduces the final energy consumed, reduces thermal load in summer, and also prevents the accumulation of snow on PV cells in winter, a parameter that reduces PVs technical efficiency. The equipment used for the mechanical ventilation of the photovoltaic cells consists of three fans, a tangential power of about 50 W and an air supply of 350 m^3/h each. The profile dimensions of the fans are 10 × 10cm with a length of 60 cm and there is no air heating system (coil).

The PV system in SC2 does not fully cover the building's demand for electricity but reduces the energy consumption at about 10–15%. For the environmental impact analysis, it was considered that 127 kWh m^2 per year will be covered by the conventional energy source of the country and the rest from the PV system. In correspondence to SC2, the SC3 installs the mechanical ventilation in order to improve indoor air quality and also reduce the final energy consumption by controlling the heat produced form the PVs installation. Specifically, as for the MV system, a total of three tangential flow fans with a power of about 50 W each and an air supply of around 350 m^3/h are used. The electricity saved by the use of mechanical ventilation was considered to be around 7% compared to the previous scenario, so the total requirement of the building is reduced to 118 kWh/m^2. According to Nilsson's [56] impact assessment results, validation has been implemented (Table 4) according to the environmental impact findings presented in Table 5. The environmental impact assessment results are in detail, presented per scenario and stage of life cycle analysis in Table 5. More specifically, the environmental impacts analyzed are climate change, ozone depletion, acidification, eutrophication, and photochemical oxidation.

Table 4. Environmental impact assessment results validation for ventilation system applications in buildings.

Impact Categories	Giama (2021) SC3 Impact Results (Table 5)	Nilsson (2020) Impact Results [56]
Climate Change (kg CO_2-Eq/m^2)	248.4	164,375
Ozone Depletion (kg CFC-11-Eq/m^2)	0.001	0.000001
Acidification (kg SO_2-Eq/m^2)	118.66	155
Eutrophication (kg NOx-Eq/m^2)	9.69	8.3
Photochemical Oxidation (kg ethylene-Eq/m^2)	0.88	0.1

Table 5. Environmental impact assessment results for different construction scenarios and systems in non-residential buildings.

Stage	SC1 Conventional Operation (no MV, no RES)										
	Acidification (kg SO2-Eq/m^2)	**Climate Change (kg CO$_2$-Eq/m^2)**	**Depletion of Abiotic Sources (kg Antimony-Eq/m^2)**	**Eutrophication (kg NOx-Eq/m^2)**	**FAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Human Toxicity (kg 1,4-DCB-Eq/m^2)**	**Radiation (DALYs/m^2)**	**MAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Photochemical Oxidation (kg Ethylene-Eq/m^2)**	**Ozone Depletion (kg CFC-11-Eq/m^2)**	**TAETP-100a (kg 1,4-DCB-Eq/m^2)**
Construction	0.12	77	9.9×10^{-5}	0.3	0.01	0.6	0	0.68	0.0008	6×10^{-7}	0.07
Use	150	90.4	7.96	11.5	18.95	2729	2.3×10^{-5}	1565.5	1.1	1.3×10^{-3}	3.97
Transportation	0.011	2	0.014	0.018	0.051	0.37	4×10^{-9}	0.38	0.0005	2.7×10^{-7}	0.0003
Total	150.1	169.5	7.98	11.82	19.02	2730.5	2.3×10^{-5}	1566.6	1.11	1.3×10^{-3}	4.04

Stage	SC2 PV Installation (no MV)										
	Acidification (kg SO2-Eq/m^2)	**Climate Change (kg CO$_2$-Eq/m^2)**	**Depletion of Abiotic Sources (kg Antimony-Eq/m^2)**	**Eutrophication (kg NOx-Eq/m^2)**	**FAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Human Toxicity (kg 1,4-DCB-Eq/m^2)**	**Radiation (DALYs/m^2)**	**MAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Photochemical Oxidation (kg Ethylene-Eq/m^2)**	**Ozone Depletion (kg CFC-11-Eq/m^2)**	**TAETP-100a (kg 1,4-DCB-Eq/m^2)**
Construction	0.65	175.2	54.74	0.62	22.56	129.7	10^{-6}	94.54	0.008	9.92×10^{-6}	0.11
Use	127	76.56	6.74	9.74	16.1	2311	2×10^{-5}	1325.4	0.93	1.1×10^{-3}	3.4
Transportation	0.011	2.1	0.015	0.019	0.053	0.38	4.5×10^{-9}	0.39	0.0005	2.8×10^{-7}	0.0003
Total	127.7	253.9	61.5	10.4	38.7	2441	2.1×10^{-5}	1420.4	0.94	1.1×10^{-3}	3.51

Stage	SC3 PV Installation and MV										
	Acidification (kg SO2-Eq/m^2)	**Climate Change (kg CO$_2$-Eq/m^2)**	**Depletion of Abiotic Sources (kg Antimony-Eq/m^2)**	**Eutrophication (kg NOx-Eq/m^2)**	**FAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Human Toxicity (kg 1,4-DCB-Eq/m^2)**	**Radiation (DALYs/m^2)**	**MAETP-100a (kg 1,4-DCB-Eq/m^2)**	**Photochemical Oxidation (kg ethylene-Eq/m^2)**	**Ozone Depletion (kg CFC-11-Eq/m^2)**	**TAETP-100a (kg 1,4-DCB-Eq/m^2)**
Construction	0.65	175.2	54.74	0.62	22.56	129.7	10^{-6}	94.54	0.008	9.92×10^{-6}	0.11
Use	118.0	71.1	6.26	9.05	14.92	2147.1	1.8×10^{-5}	1231.55	0.87	10^{-3}	3.15
Transportation	0.01	2.1	0.01	0.02	0.05	0.4	4.5×10^{-9}	0.39	0.001	2.78×10^{-7}	0
Total	118.66	248.4	61	9.69	37.53	2277.2	1.9×10^{-5}	1326.48	0.88	10^{-3}	3.26

Both systems were related with office building operations. The indicator was normalized to the surface dimension in order to be comparable. The climate change impact is higher in the case of the Greek office building because apart from the mechanical ventilation system operation, there is also PV implementation. The environmental impact assessment is calculated with CML indicators under the LCA methodology implementation. According to the LCA results and for SC3, in which the ventilation system is implemented, the most significant contribution to the environmental impacts of acidification, eutrophication, radiation, and ozone depletion is the use phase because of the energy consumption. It is worth mentioning that for climate change, the construction phase is most responsible for the environmental impact at about 90%, while the use phase contributes only 10% (Table 6).

Table 6. Percentage contribution of life cycle stages to environmental impact of SC3 (ventilation systems are included).

Stage	Acidification (kg SO_2-Eq/m^2)	Climate Change (kg CO_2-Eq/m^2)	Depletion of Abiotic Sources (kg Antimony-Eq/m^2)	Eutrophication (kg NOx-Eq/m^2)	FAETP-100a (kg 1,4-DCB-Eq/m^2)	Human Toxicity (kg 1,4-DCB-Eq/m^2)	Radiation (DALYs/m^2)	MAETP-100a (kg 1,4-DCB-Eq/m^2)	Photochemical Oxidation (kg ethylene-Eq/m^2)	Ozone Depletion (kg CFC-11-Eq/m^2)	TAETP-100a (kg 1,4-DCB-Eq/m^2)
Construction	0.5%	70.53%	89.72%	6.4%	60.1%	5.7%	5.26%	7.13%	0.9%	0.99%	3%
Use	99.4%	28.62%	10.26%	93.4%	39.8%	94.29%	94.71%	92.84%	99.0%	98.98%	97%
Transportation	0.01%	0.85%	0.02%	0.2%	0.1%	0.018%	0.02%	0.03%	0.1%	0.03%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

5. Discussion—Further Research

Without a doubt, the main objective for advanced ventilation systems is the air disinfection and purification of devices in a smart and digitalized manner. The complicated issue of energy efficiency along with indoor air quality and the well-being of users is the future challenge of ventilation systems. In addition to all these, cost effectiveness is always one of the parameters that one should not forget when designing and implementing a system. Supporting smart systems and keeping in mind the Green Deal objectives for net emissions of greenhouse gases by 2050, economic growth, and saving resource use, having circular economy as a guide and the social aspect high in the agenda. In this direction, new technologies, innovative materials, and dynamic simulations support the entrance and the synergy of advanced energy systems in buildings.

Another significant parameter is the integrated design, control and identification of technical characteristics considering the central heating and air conditioning systems for buildings in terms of energy efficiency, thermal comfort, and indoor air quality with the use of specialized simulation tools in order to optimize the parameters examined. The outputs from the dynamic simulation focusing on HVAC systems operation, indoor environmental parameters (air flow, air infiltration, thermal comfort), as well as occupants' behavioral characteristics can be used in order to ensure the minimization of pollutants in indoor environments. All methods and multiscale simulations can be used to capture spatiotemporal patterns and correlate the impact of varying indoor conditions on the efficiency and the energy consumption of HVAC systems, recommending suitable energy systems and operational scenarios based on optimum indoor environmental conditions. Another significant parameter in smart designing and the efficient control of buildings is sensoring. Cost-effective sensor technologies for monitoring air pollutants have undergone rapid progress in recent years, providing easier-to-use portable tools for gathering highly temporally resolved data in real time. Future analyses will focus on the evaluation of ventilation systems in collaboration with other energy systems and innovative technologies providing the health and well-being of occupants along with resilience in the building's management.

6. Conclusions

The depletion of natural resources, the high, intensive energy consumption from manufacturing processes, and the increased GHG emissions from industry and other sectors have led to an increased awareness towards environmental issues. Moreover, there is a defined EU strategy towards energy-saving measures, clean energy use, RES introduction, and reduced CO_2 emissions. National legislation framework and EU funding programmes are in total compliance with EU energy and environmental policy and Green Deal objectives for energy and environment. Within this framework, in this manuscript, the environmental impact related to ventilation systems based on the life cycle thinking approach has been examined.

The ventilation technologies have been presented in detail based on the review analysis. The basic ventilation technologies implemented in residential as well as non-residential buildings are natural ventilation (NV), mechanical ventilation (MV), and hybrid ventilation systems (HV). Based on the need for compliance with the defined legislation framework presented, considering energy efficiency and carbon emissions as well as environmental impact connected with well-being of users, MV is examined in a non-residential building in Greece. MV is compared with the conventional construction typology of the building and also in cooperation with PVs installation. The methodology implemented for the environmental impact assessment is the Life Cycle Analysis supported by OpenLca software (GreenDelta Company, Berlin, Germany).

Specifically, as for the MV system, a total of three tangential flow fans with a power of about 50 W each and an air supply around 350 m^3/h are implemented. The electricity saved by the use of mechanical ventilation was considered about 7% compared to the previous scenario with the conventional typology and no MV addition, so the total requirement of the building is reduced to 118 kWh/m^2. The environmental impact assessment results are presented in detail per scenario and stage of life cycle analysis. More specifically, the environmental impacts analyzed are climate change, ozone depletion, acidification, eutrophication, and photochemical oxidation. According to the LCA results, for SC3, in which the ventilation system is implemented, the most significant contribution to the environmental impacts of acidification, eutrophication, radiation, and ozone depletion is the use phase because of the energy consumption. It is worth mentioning that for climate change, the construction phase is most responsible for the environmental impact at about 90% while the use phase contributes only 10%.

Based on the LCA results (Tables 5 and 6), the construction phase contributes at about 70% to the environmental impact of climate change compared to the use phase (28%) and transportation, which counts less than 1%. The significant contribution of the material use, therefore the construction phase, counts for other environmental impacts, such as the depletion of abiotic sources (almost 90% comparing to 10% of use phase and only 0.02% due to transportation). To conclude, climate change and the depletion of abiotic sources are more affected by the construction phase, while other environmental impacts, such as acidification, eutrophication, human toxicity, ozone depletion, and photochemical oxidation are affected by the use phase and energy consumption. More specifically, the use phase contributes at about 99% for acidification, 93% for eutrophication, 94% for human toxicity, 99% for ozone depletion, and 99% photochemical oxidation, while the correspondence percentage for the construction phase is less than 8%.

Ventilation is not only suggested as an intervention related only to energy efficiency, but also for the significant contribution to indoor air quality. The requirements, which are specified by the legislation framework, standards and technical regulations are basically the air speed, the maximum operating temperature in summer, the minimum operating temperature in winter, the maximum carbon indicators, the occupants, the operating hours, and in some cases, the daylight factor, as well.

In this direction, implementing smart air disinfection and purification devices (e.g., HVAC, robots) and materials to improve air quality, powered by an automatic decision support and personalized guidance is a key issue in building management in terms of air quality, energy efficiency, and environmental impact. The implementation of different types of ventilation contributes to the improvement of energy efficiency. This can be resulted from the three scenarios presented and the quantification of the energy used in the scenario where the mechanical ventilation is implemented. Nevertheless, the strongest benefit of ventilation is not the energy efficiency but the improvement of indoor quality and the well-being of occupants, and this is the key issue of the analysis presented. Finally, parameters such as the synergy of different systems, innovative materials and filtration in HVAC systems, and controlled air supply are also proposed by using CFD simulations contributing to great extent to the efficiency of the systems implemented in buildings, also positively affecting the environment in terms of climate change.

Funding: The research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Project to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Project Number: 4104).

Data Availability Statement: Not applicable.

Acknowledgment: The author would like to express their gratitude to the Hellenic Foundation for Research and Innovation.

Conflicts of Interest: The author declares no conflict of interests.

Nomenclature

NV	Natural Ventilation
MV	Mechanical Ventilation
HV	Hybrid Ventilation
CFD	Computational Fluid Dynamics
ERV	Energy Recovery Ventilation
HRV	Heat Recovery Ventilation
VAV	Variable Air Volume

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