Hybrid Ventilation Systems for Reduced Lifetime Emissions in Cold Climates

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Abstract. Heating, ventilation, and air conditioning systems are notable sources of emissions in buildings. In cold climates, mechanical ventilation systems are characterized by significant initial embodied emissions but benefit from reduced operational emissions related to heating energy. On the other hand, natural ventilation systems have the advantage of lower initial embodied emissions but will use more heating energy, in cold climates, for the same atmospheric quality, due to the general lack of efficient heat recovery solutions. Hybrid ventilation systems are hybrids of these, using a combination of driving forces. This study utilized a life cycle assessment (LCA) to compare lifetime emissions of hybrid and mechanical ventilation systems in a Nordic climate. Findings suggest that hybrid ventilation systems can yield lower lifetime emissions, provided upfront emissions are reduced without significantly increasing energy consumption. Reduction potential in upfront emissions is more substantial in open landscape offices than classrooms due to higher person density in classrooms necessitating more fresh air, limiting reductions that can be achieved without thermal discomfort during the winter season. Our study shows the feasibility of reducing the carbon footprint of ventilation systems by employing hybrid climatization strategies.

1 Introduction

The imperative to address the climate crisis necessitates a comprehensive reduction of greenhouse gas emissions across all sectors, with particular attention directed towards buildings. Among the contributors to emissions in buildings, Heating, Ventilation, and Air Conditioning (HVAC) systems emerge as a significant source, encompassing both embodied emissions, arising from the manufacturing and transportation of materials, and operational emissions, originating from energy consumption. While mechanical ventilation systems are characterized by high upfront embodied emissions, they exhibit relatively low operational emissions attributable to their energy-efficient nature. In contrast, natural ventilation systems display the inverse pattern with low upfront embodied emissions, but with the risk of higher

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operational emissions for the same indoor quality due to the lack of heat recovery from the exhaust air.

Hybrid ventilation systems represent a promising approach by amalgamating the principles of natural and mechanical ventilation to create an indoor environment that optimizes both comfort and efficiency. Theoretically, hybrid systems offer the potential for lower upfront emissions compared to purely mechanical systems, albeit with somewhat elevated operational emissions. The critical question, however, is whether hybrid ventilation systems yield lower lifetime emissions when considering the temporal dynamics of greenhouse gas emissions and their implications for global warming potential over time.

Addressing this question, this study employs a Life Cycle Assessment (LCA) methodology to scrutinize and contrast the lifetime emissions of hybrid and mechanical ventilation systems. The analysis aims to shed light on whether hybrid ventilation systems can indeed offer a substantial reduction in lifetime emissions compared to their mechanical counterparts, all while preserving an acceptable indoor thermal environment.

2 Related studies

Despite numerous investigations into the energy-saving potential and cost-effectiveness of hybrid ventilation systems in mixed-mode buildings, there is a paucity of studies addressing the environmental impacts associated with this type of system.

Flourentzou et. al [1] compared controlled natural ventilation (bidirectional ventilation) to mechanical ventilation with heat recovery in a school gymnasium. The study underscores the importance of reevaluating natural ventilation's efficiency, even in colder climates, as an energy-efficient cooling solution. Their findings affirm that demand-controlled natural ventilation provides superior air quality, comfort, and lower environmental impact compared to mechanical systems, especially for large spaces. This resulted in an approximate reduction of 15% in CO_2 emissions and 25% in yearly global pollutants.

Willkomm [2] compared the environmental impacts of a hybrid ventilation (HV) system and a mechanical ventilation system with heat recovery (MVHR) in an office building in Lystrup, Denmark. The HV system, consisting of automated natural ventilation (NV) and mechanical exhaust air ventilation (MEV), shows lower global warming potential (GWP) and abiotic depletion potential (ADP) fossil, indicating lower contributions to climate change. Both systems have similar impacts in other environmental categories. The HV system also requires less space, potentially resulting in lower material usage and environmental impact. Overall, the HV system appears more environmentally friendly, particularly in terms of GWP and ADP fossil. Furthermore, promising HV system results suggest the need for location-specific studies, given varying environmental impacts from energy sources and production locations, as well as transportation distances.

Xue et al. [3] used a simulation-based multi-objective optimization to minimize life cycle cost and CO_2 emissions in a passive residential building with hybrid ventilation in a severe cold climate. Employing parametric simulations and neural network models, they identified optimal designs, achieving potential reductions of 13.5%–22.4% in CO_2 emissions compared to the initial design. However, the study did not provide a detailed breakdown of CO_2 emissions specifically attributed to the hybrid ventilation system.

Elnabawi and Saber [4] investigated the integration of with photovoltaic (PV) panels in an educational building situated in an arid climate. Their results indicate that the adoption of hybrid ventilation significantly reduced carbon emissions, achieving a reduction of approximately 66% compared to a mechanical ventilation system. This reduction is primarily attributed to the notable energy savings facilitated by the hybrid ventilation approach. It is noteworthy that the research does not delve into the discourse on embodied emissions.

While there have been some literature studies addressing the environmental impacts linked to hybrid ventilation systems, these studies are limited in number, and the results lack comprehensive detail. There remains a notable gap, emphasizing the essential need for a more in-depth analysis of the environmental impacts arising from hybrid ventilation systems. Accordingly, this study seeks to address this gap by presenting a detailed methodology for assessing the environmental impacts across various stages of the LCA specific to hybrid ventilation systems.

3 Methodology

The current study engaged in a LCA of greenhouse gas (GHG) emissions, employing two distinct tools. Our in-house developed tool was utilized for analysing embodied emissions across construction, production, replacement, and end-of-life stages. Simultaneously, the IDA Indoor Climate and Energy (IDA-ICE) tool, version 5.0, was employed to assess operational energy use and the associated environmental impacts of the ventilation system, as depicted in Figure 1.

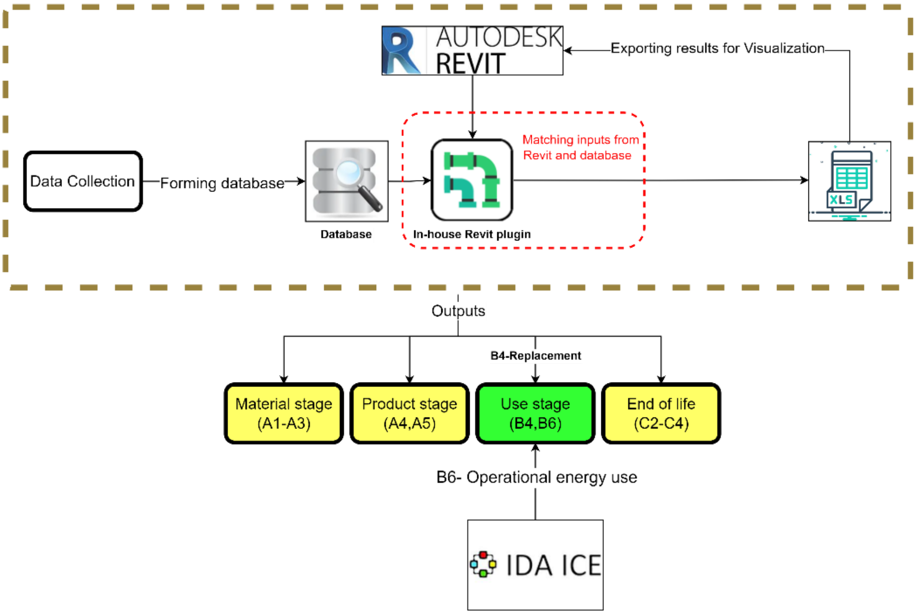


Fig. 1. Flowchart illustrating an in-house developed method for assessing LCA GHG emissions, encompassing embodied and operational energy use, Mechanical and Plumbing systems in buildings.

3.1 Embodied emissions

The evaluation of embodied emissions involves four key stages: construction (A1-A3), product (A4, A5), replacement (B4), and end-of-life (C2-C4). GHG emissions associated with these stages were analysed using the methodology outlined in Figure 1 (enclosed within a dashed lined box).

In the initial phase, all environmental performance declarations (EPDs) were systematically gathered using the OneClick LCA tool [5]. These EPDs encompassed the existing environmental profiles of the inventory, sourced from relevant EPDs within OneClick LCA, both imported from the Ecoinvent life cycle inventory [6] as well as additional EPDs collected from private manufacturers, all of which were imported into the OneClick tool.

Moving to the second step, the model for the present study (the ventilation system) was developed using Revit. Subsequently, components utilized in the model were exported to our in-house plugin within Revit. This plugin facilitated the matching of components with those present in the database, enabling the calculation of corresponding environmental impacts.

Once all embodied emissions were computed, the results were exported to an Excel file for categorization into distinct stages of embodied emissions. Thereafter, these outputs were exported to Revit for visualization purposes.

3.2 Emissions due to operational energy use

The quantification GHG emissions from operational energy consumption was conducted utilizing the IDA-ICE software. The analysis accounted for the energy supplied to the building and employed emission factors associated with the energy sources. This study examined two specific energy configurations, with specifications listed in Table 1.

Table 1. The two energy configurations used as references in this study.

	Heating SCOP (Seasonal Coefficient of Performance)					
	Base load			**Top load**		
	Type	%	SCOP	Type	%	SCOP
Alt 1	District heating	100 %	0,87	-	-	-
Alt 2	Heat pump	90 %	2,91	Electric boiler	10 %	0,86

	Cooling SEER (Seasonal Energy Efficiency Ratio)					
	Base load			**Top load**		
	Type	%	SEER	Type	%	SEER
Alt 1	Chiller with dry cooler	100 %	2,2	-	-	-
Alt 2	Free cooling	60 %	10	Chiller with dry cooler	40 %	2,4

The carbon dioxide equivalent (CO_2-eq) factor for electricity was computed following the Norwegian standard Method for greenhouse calculations for buildings [7], set at 0.096 kg CO_2-eq/kWh. The computational methodology adopted a production mix paradigm, taking into account the electricity supply in the EU28 + Norway. This involved projecting an anticipated average over a 50-year timeframe, with an initial reference point derived from the mean values observed during the 2018-2020 period. For district heating, the adjusted CO_2-eq factor was determined as 0.04 kg CO_2-eq/kWh [8].

3.3 Case studies

The study examined two distinct building typologies: an office building and a school building, each representing a standard floor plan prevalent in Norwegian constructions. Figures 2 and 3 display the floor plans, showcasing typical layouts. The office building and school building exhibit total floor areas of 763 m^2 and 794 m^2 respectively.

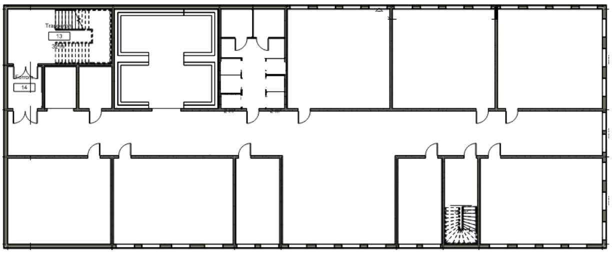


Fig. 2. Floor plan of the school building

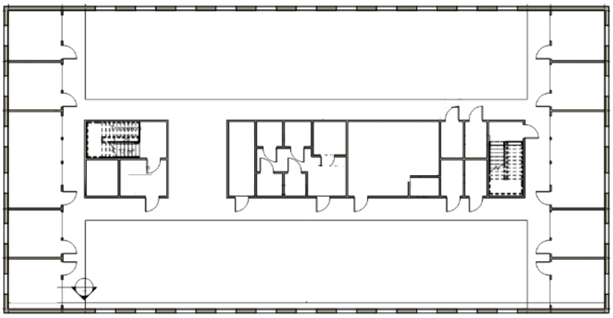


Fig. 3. Floor plan of the office building

The building envelope characteristics, lighting system, HVAC system, and setpoints were meticulously chosen in adherence to the stipulations outlined in the Norwegian building code [9] and the technical requirements for schools in Oslo Municipality [10]. Internal gains due to occupancy, equipment, and lighting along with their usage profiles chosen in accordance with the Norwegian standard specifications for building energy performance [11]. The windows are partitioned into two distinct sections. The larger lower portion, spanning 1.8 meters in height, features an automated external solar shading system and remains non-openable. In contrast, the smaller upper section, measuring 0.4 meters in height, is designed to be opened. The building properties, internal gains, and mechanical ventilation specifications are described in Table 2 [12].

Table 2. Details of the building envelope properties, internal gains, and mechanical ventilation specifications

Parameter, Units	**Value/properties**
External wall U-value, W/(m^2.K)	0.18
Glass U-values, W/(m^2.K)	0.70
Solar heat gain coefficient g-value (glass only / with solar shading)	0.50 / 0.05
Normalized thermal bridge ψ, W/(m^2(floor aera) .K)	0.03
Infiltration n_{50}, (1/h)	0.60
External solar shading strategy	Blinds on, if Q_{sol} > 175 W/m^2, outside window
Internal gains (persons/lighting/equipment)	Office landscape: 6m^2/person-8W/m^2-25W/m^2
	Cell office: 1 person - 6W/m^2-9W/m^2
	Meeting room: 2m^2/person-6W/m^2-22W/m^2
	School: 2m^2/person-6W/m^2-15W/m^2
Usage profile of internal gains	Based on [12] for office and school buildings
Nominal specific fan power (SFP)	1.5 kW/(m^3.s)
Average heat recovery efficiency	80%

3.4 Ventilation control and space heating strategies

The ongoing study contrasts three scenarios related to ventilation and space heating:

- Case 1: Implements full Variable Air Volume (VAV) *mechanical ventilation*, with CO_2 and temperature controllers, incorporating strategically positioned water radiators along external walls, especially under windows.
- Case 2: Adopts a *hybrid ventilation approach*, where mechanical ventilation is the primary system, supplemented by window openings when the mechanical system is insufficient to meet thermal comfort requirements or maintain the desired CO_2 levels in the room. This case utilizes the same space heating method as Case1.
- Case 3: Applies the same *hybrid ventilation approach* as in Case 2, incorporating *floor heating* and cooling into the space.

The heating, cooling, and air flow rate to climatize the space was chosen based on indoor climate simulations. It is worth noting that the air flow rate for the hybrid solutions was set so that the façade openings did not operate in the coldest periods of the year, thus ensuring that the indoor climate comfort is not adversely affected by cold air entering the space. This is a conservative assumption, but in line with practical experiences of the authors in real life system design.

Detailed information on airflow rates applied in different ventilation strategies for two distinct building typologies is presented in Table 3.

Table 3. Airflow rates in different ventilation control and space heating strategies

Ventilation strategies	**Classroom**		**Office**	
	Min. (m^3/h/m^2)	**Max. (m^3/h/m^2)**	**Min. (m^3/h/m^2)**	**Max. (m^3/h/m^2)**
Case1	2.5	20	Cell office	
			7	7
			Meeting room	
			2.5	20
			Office landscape	
			2.5	10
Case2	Constant air volume (CAV)		Cell office	
			3.5	3.5
	10	10	Meeting room	
			13	13
			Office landscape	
			5	5
Case3	CAV		Cell office	
			3.5	3.5
	12	12	Meeting room	
			10	10
			Office landscape	
			4	4

The airflow rates vary between the cases, but are calibrated so that the functional unit, i.e. a square meter of climatized space, is equivalent across the cases.

For each of the cases indoor climate simulations were made to ascertain the necessary combination of ventilation, cooling, and heating. These were then used as the basis for a full BIM modelling of all the scenarios. As an example, the model for Case 1, is shown in figure 4.

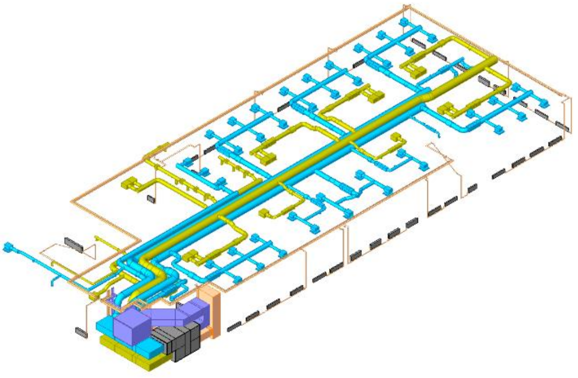


Fig 4. The BIM model for the case 1

3.5 Functional unit for this study

A prerequisite for comparing the LCA of various options is the establishment of a well-defined functional unit as the foundation of the comparison. For this comparison, the selected functional unit is one square meter of conditioned space, maintaining as equivalent an atmospheric and thermal quality as possible.

The climatized solutions differ substantially, requiring different in data for factors, e.g., airflow, to achieve comparable quality levels. Thus, a necessary step for comparison is to have a comprehensive understanding of the quality provided.

Figures 5 and 6 present a comparison of the operative temperature across three distinct scenarios on January 17th and June 15th, respectively, chosen as they represent a winter and a summer day, respectively, and evaluate their conformity with the indoor thermal climate categories as outlined in [13]. For all three scenarios, the operating temperature falls within the Category II comfort level recommended for commercial buildings. Although there is some internal variation between them, e.g., time of peak temperature.

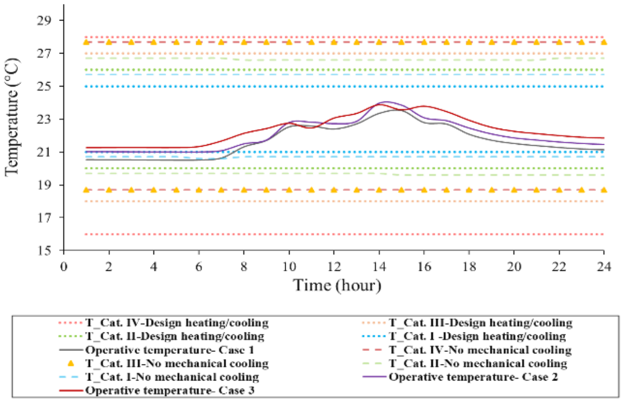


Fig. 5. Variation of office landscape operative temperature on January 17th

Likewise, Figures 7a and 7b show a comparison of CO_2 levels in the office landscape across three distinct scenarios on January 17th and June 15th, respectively. In all cases, the highest CO_2 concentration remains well below 1000 ppm throughout the year, adhering to the recommended guidelines for Norwegian commercial buildings as set by the Norwegian Labor Inspection Authority [14].

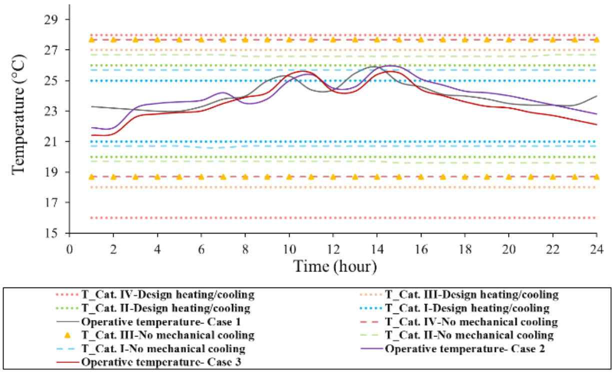
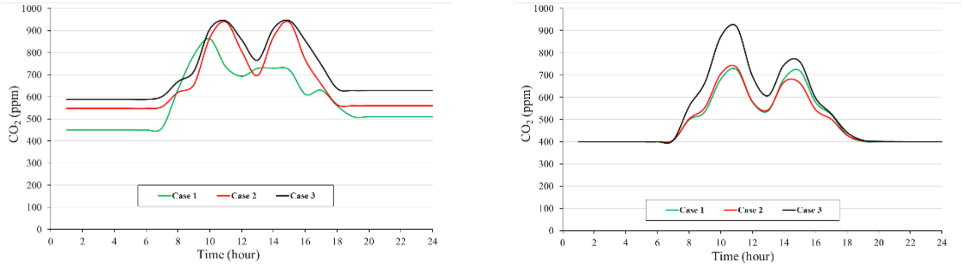


Fig. 6. Variation of office landscape operative temperature on June 15th

It's important to note that the distinction in CO_2 levels outside occupancy hours, 400 ppm during summer and higher in winter, is attributed to the practice of night-time ventilation through window opening, which is solely dependent on temperature. This mechanism, thoroughly explained in [12], leads to the windows being opened outside of operating hours in the summer, aligning the indoor CO_2 levels with that outdoors. Case 2 and 3, show higher CO_2 levels during nighttime in winter, as the minimum airflow is lower.



(a) (b)

Fig. 7. Variations in CO_2 levels in the office landscape on (a) Jan. 17th and (b) June 15th

4 Results

In this section, we present the outcomes derived from energy simulation and LCA calculations for office and school buildings across three ventilation control strategies.

Figure 8 visually represents the energy delivered to the buildings, accounting for two distinct office building types, three ventilation strategies, and two alternative energy supply systems simulated in IDA-ICE. Notably, Alt1 exhibits a higher delivered energy compared to Alt2. The utilization of a heat pump and free cooling is attributed to the lower energy consumption in Alt2.

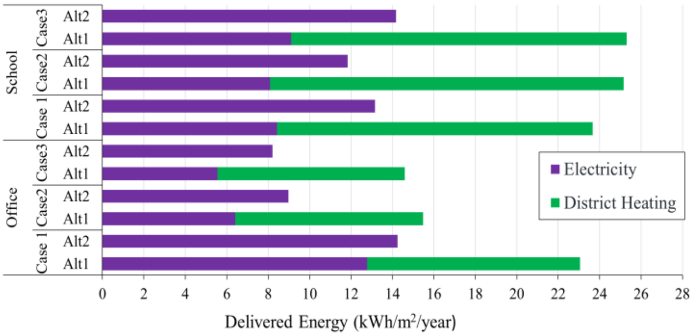


Fig. 8. Delivered energy to the building

Figures 9a, 9b and 10 depict the LCA of GHG emissions associated with both materials and operational energy, considering three ventilation control and heating strategies for office and school buildings. Emissions tied to operational energy use constitute the predominant portion of total emissions, particularly following the replacement and materials stages. The results further highlight that the implementation of hybrid ventilation can lead to a reduction of approximately 14% and 36% in total GHG emissions compared to the full mechanical ventilation for school and office buildings, respectively. This reduction is contingent on the specific energy supply alternative under consideration. By referencing figure 8 and comparing it with the findings in figures 9a and 9b, it becomes evident that the higher reduction in energy consumption, resulting in a corresponding 51% decrease in associated emissions, is a consequence of adopting hybrid ventilation. The disparity in GHG emission reduction between office and school buildings is connected to the higher energy reduction achieved through hybrid ventilation in the office setting. This is due to the limitations on the minimum air volume that could be used in the school case.

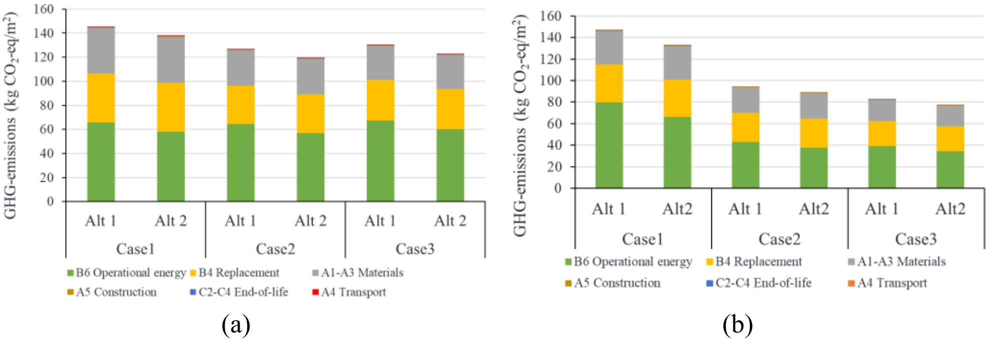


Fig. 9. GHG emissions linked to distinct phases of the LCA for all cases and energy configuration for (a) the school building and (b) the office building

To comprehensively assess the GHG emissions associated with various HVAC components in the LCA calculations, Figure 10 presents the embodied emissions for components within the ventilation, heating, and air conditioning systems. The adoption of floor heating/cooling in conjunction with a hybrid ventilation system (Case 3) results in the lowest embodied emissions among the three cases for the office building, achieving a reduction of approximately 30%. However, this combination reduces embodied emissions by around 24% in the school compared to full mechanical ventilation in Case 1.

A comparative analysis of Figures 8, 9a, 9b and 10 suggests that the choice of a hybrid ventilation system with floor heating/cooling (Case 3) offers dual advantages for office buildings, yielding reductions in both GHG emissions and building energy usage associated with HVAC systems in Norway. However, for schools, Case 2, featuring a conventional radiator heating system, proves slightly more beneficial than Case 3. Nevertheless, both Case 2 and Case 3 demonstrate superior performance in terms of GHG emission mitigation compared to Case 1 for both types of buildings.

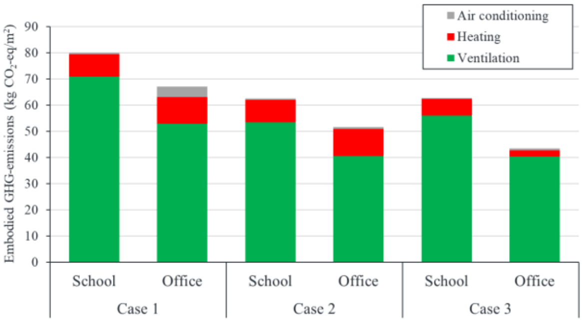


Fig. 10. GHG emissions embedded in the diverse components of ventilation and heating strategies connected to specific stages A1-A3, A4, A5, B4, C2-C4

Figure 11 shows an example of the visualization of the embodied emissions from the materials of the heating, ventilation, and air conditioning in different strategies. The colors are categorized to show which component emits higher or lower embodied emissions compared to other parts. In this example only material stage has been visualized. However, it is possible to visualizes other stages such as product and end of life. Figure 11 shows that air handling unit has, in this case, the highest embodied emissions in terms of materials.

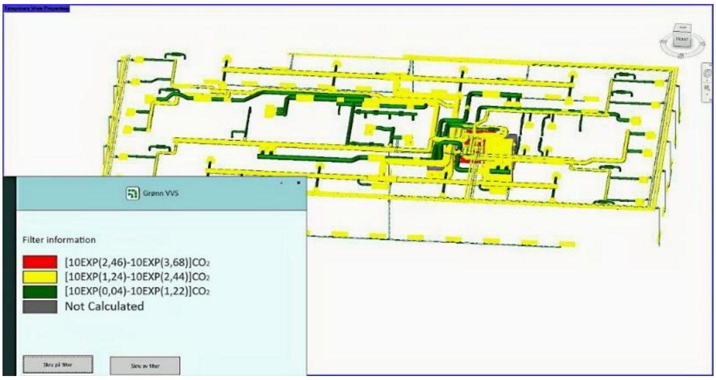


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Fig. 11. Visualizations of embodied GHG emissions originating from the materials (A1-A3), generated using the in-house Revit Plugin for Case 1. Note: The numerical values are presented in logarithmic format.

5 Discussion

The primary objective of this study is to focus on the lifetime emissions of ventilation systems in a cold climate, and how these can be reduced by implementing hybrid ventilation strategies. The GHG calculations include both up-front embodied emissions as well as energy need, leveraging established emission forecasts.

The results clearly show that hybrid ventilation strategies can yield lower lifetime emissions, and that these are primarily driven by lowering the up-front embodied emissions, while either reducing energy consumption or at least not increasing it severely.

Calculation of embodied emissions from HVAC systems is a young engineering field, and there is a paucity of EPD-data for HVAC systems. In this study we present both a state-of-the-art approach, leveraging BIM and available EPD-data to calculate the embodied emissions of six climatization solutions. Despite maintaining the highest degree of quality possible, it is likely that the calculation procedures and underlying data will evolve rapidly in the coming years, and these results should we viewed in this light.

A critical factor in predicting reductions in emissions from electricity usage is the percentage of renewable energy within the energy mix. In this investigation, the European mix (EU28+Norway) serves as the foundation for estimating GHG emissions from electricity. However, the utilization of another emission forecast, such as the one for purely Norwegian electricity mix, would likely change the conclusions that can be drawn from the study. A sensitivity analysis on this variable emerges as an important future work.

Acknowledgement

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References

1. F. Flourentzou, S. Pantet, K. Ritz. Design and performance of controlled natural ventilation in school gymnasiums. Int J Ventilation, **16(2)**,112-123 (2017). https://doi.org/10.1080/14733315.2016.1220202
2. J. Nilsson Willkomm. Comparison of a hybrid ventilation system and a mechanical exhaust air ventilation system with heat recovery through life cycle assessment perspective: A case study of a modern Danish office building (master's thesis). Karlstad University: Sweden (2020).
3. Q. Xue, Z. Wang, Q. Chen. Multi-objective optimization of building design for life cycle cost and CO_2 emissions: A case study of a low-energy residential building in a severe cold climate. Building Simulation, **15**, 83-98 (2022). http://dx.doi.org/10.1007/s12273-021-0796-5
4. M.H. Elnabawi, E. Saber. Reducing carbon footprint and cooling demand in arid climates using an integrated hybrid ventilation and photovoltaic approach. Environment, Development and Sustainability **24**, 3396–3418 (2022). https://doi.org/10.1007/s10668-021-01571-1
5. Bionova. (2020) Calculate your environmental impacts in minutes [Online] https://www.oneclicklca.com/
6. H. Althaus, M. Chudacoff, R. Hischier, N. Jungbluth, M. Osses, A. Primas, S. Hellweg. Life cycle inventories of chemicals. Ecoinvent data v3.9.1 Swiss Centre for Life Cycle Inventories, pp. 1-957 (2007).
7. NS 3720. Method for greenhouse gas calculations for buildings (in Norwegian), Norsk standard (2018).

8. Hafslund Oslo Celsio. The Norwegian EPD Foundation. Environmental Product Declaration. NEPD-3785-2721-EN. Valid to: 10.10.2027. Revision: rev3-160323 (2022).
9. TEK17. Technical Regulations for Planning and Execution of Construction Work. §13-4 Thermal indoor climate: Norwegian Ministry of Local Government and Modernisation (2017).
10. SKOK. Standard requirement specification for schools (in Norwegian). Oslo municipality (2022).
11. SN-NSPEK 3031 (2021). Energy performance of buildings Calculation of energy needs and energy supply. Standard Norge.
12. M. Rabani, A. J. Petersen. Detailed assessment of hybrid ventilation control system in a mixed-mode building in cold climate. IOP's JOURNAL OF PHYSICS Conference Series, 2600, 102006 (2023). https://doi.org/10.1088/1742-6596/2600/10/102006
13. EN 16798-1. Energy performance of buildings, Ventilation for buildings, Part 1: Indoor environmental input parametersfor design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics Module M1-6, European standard (2019).
14. Norwegian Labor Inspection Authority (2023), Indoor climate and air quality in the workplace [Online in Norwegian]. https://www.arbeidstilsynet.no/tema/inneklima/