

Impact of window operation on indoor air quality and energy demand for residential buildings with Single-Flow and Balanced Ventilation systems

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Abstract. Acceptable indoor air quality in homes is largely governed by mechanical ventilation. Maintaining it with limited energy consumption requires balancing contaminant removal with space-heating demand. Brief window airing can refresh air yet increase air exchange and heat loss; impacts depend on climate, airtightness, wind exposure, and outdoor pollution. Although common, these behaviors are rarely evaluated with comparable metrics. This study fills this gap by comparing closed vs. scheduled window openings under different climates. The IAQ–energy trade-off is evaluated in a two-story multifamily building with (1) single-flow ventilation and (2) balanced ventilation with heat recovery and PM_{2.5} filtration. Each system is tested with (a) all windows closed and (b) a scheduled opening scenario for windows under eight boundary conditions combining airtightness (tight/permeable), wind intensity (weak/strong), and outdoor PM_{2.5} level (low/high). Heating operates from 1 October to 30 May, with a setpoint of 20°C and 16°C for day and night, respectively. Energy performance is based on fan electricity and air-renewal heat losses, while IAQ evaluation accounts for indoor concentration of CO₂, formaldehyde, PM_{2.5}, and relative humidity levels. Overall, scheduled window openings lead to a substantial increase in heat losses, while delivering only slight improvements in IAQ levels.

1 Introduction

Indoor air quality (IAQ) in residential buildings is critical to occupant health and comfort, considering that people spend roughly 90% of their time indoors. In addition, the Energy Performance of Buildings Directive (EPBD) has set objectives for decreasing energy consumption [1]. Achieving healthy IAQ while minimizing energy demand has therefore become a central challenge in modern building design and operation. Studies have shown

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that IAQ can influence sleep quality [2], [3]. Bedroom ventilation rates often do not meet standard requirements and can lead to elevated indoor concentrations of CO₂ and other pollutants during sleep, with potential effects on occupants' comfort and health [2, 3, 4]. Opening windows can improve bedroom ventilation [5, 6]. Field evidence from naturally ventilated Norwegian bedrooms shows that window and door positions strongly affect bedroom CO₂ levels and thermal conditions, with the highest CO₂ occurring when both window and door remain closed [7]. However, such airing comes at the cost of heat losses in winter (or heat gains in summer), potentially undermining energy efficiency efforts [8]. In mild or warm climates, residents tend to rely more on natural ventilation (open windows) for cooling and fresh air, whereas in colder climates, people keep windows closed longer to avoid heat loss [8]. In a survey from Denmark, 70% of 510 participants reported a preference for keeping their bedroom windows closed during sleep [6, 9]. A year-long field study across five climate zones in China found that bedroom windows were open on average 9.4 hours per day, but with substantially shorter durations in the cold northern regions than in warmer regions at similar outdoor temperatures [8]. Beyond individual pollutant studies, several works have emphasized the need for integrated and health-relevant IAQ assessment frameworks that account for multiple contaminants, occupant exposure, and building operation [10, 11]. There are notable gaps in existing literature. First, most studies are limited to a single climate or a narrow range of conditions, making it difficult to generalize findings or to understand how results translate to other climates. Cross-climate comparisons remain scarce; when available, they reveal significant differences in occupant behaviour and ventilation needs between regions [8]. Second, past studies often used single metrics to evaluate IAQ and energy performance. This lack of standardization in metrics and reference scenarios means that the reported IAQ improvements or energy penalties due to window opening are not directly comparable between different research works. Furthermore, relatively few studies have simultaneously quantified both the IAQ impacts and the energy impacts of occupant window operation, especially in the context of modern mechanical ventilation systems. Moreover, there are few studies comparing the effects of opening windows in the presence of two different ventilation systems. The present work, therefore, addresses this need by comparing scenarios with windows and interior doors closed versus scenarios with scheduled daily window opening, in the context of two different ventilation system types and multiple climates. We investigated a representative residential building equipped with either a Single-Flow (SF) or a Balanced Ventilation (BV) ventilation system with heat recovery. By modelling both systems, we aim to reveal how window operation interacts with each ventilation strategy's performance. The analysis is carried out for multiple climates (Helsinki, Strasbourg, and Athens) representative of cold, temperate, and warm regions of Europe, to examine climate sensitivity in a consistent framework. We employ IAQ metrics and energy metrics for all simulations – including contaminant concentrations (CO₂ as a proxy for human bioeffluents, formaldehyde for building emissions, and fine particulate matter PM_{2.5} for outdoor-sourced pollution) as well as relative humidity and the energy index accounting for both ventilation heat loss and fan electricity. We also consider variations in envelope airtightness (tight vs. permeable), outdoor PM_{2.5} level (high vs. low), and wind intensity (strong vs. weak), resulting in eight boundary condition configurations.

2 Methodology

2.1 Case study: building and climatic conditions

The study is conducted on a two-story multifamily residential building representative of European housing stock. Simulations are performed for three European climates to capture

climate sensitivity in the IAQ–energy trade-off: Helsinki, Strasbourg, and Athens. The building is assumed to be in an urban environment and is evaluated under two wind intensity levels, representing weak and strong wind exposure, to account for wind-driven infiltration and its interaction with ventilation and window opening. In addition, two levels of building envelope airtightness are considered: a tight envelope, representative of modern constructions, and a permeable envelope, representative of older or less airtight dwellings. Outdoor particulate pollution is introduced through two boundary conditions for PM_{2.5} concentration: a low pollution level (annual mean 10 µg/m³) and a high pollution level (annual mean > 20 µg/m³) (see Table 1).

Table 1. Boundary Conditions [12].

Case Number	Outdoor Environment		Building Tightness
	Wind Intensity	PM _{2.5} Levels	
1	Strong	<10	Tight
2	Strong	<10	Permeable
3	Strong	>20	Tight
4	Strong	>20	Permeable
5	Weak	<10	Tight
6	Weak	<10	Permeable
7	Weak	>20	Tight
8	Weak	>20	Permeable

2.2 Ventilation systems

Two mechanical ventilation system types commonly used in residential buildings are analyzed: 1) SF ventilation, based on mechanical air extraction, with outdoor air entering the dwelling through infiltration and/or air inlets; 2) BV, equipped with 78% heat recovery efficiency and 90% PM_{2.5} filtration efficiency on the air supply.

The design airflow rates of the mechanical ventilation systems were defined based on the default design extract airflow rates recommended for residential buildings in EN 16798-1 [13], as summarized in Table 2. In this study, Indoor environmental quality category II [13] is selected; therefore, the default airflow rates from Table 2 are applied without modification [13]. These values were used to size the extract terminals in wet rooms (kitchen, bathroom, and toilet) for all dwelling configurations considered in this study, ranging from one- to four-bedroom apartments. For each apartment size, the total design extract airflow rate was determined from the values in Table 2 (i.e., according to the number of main rooms and the type/number of wet rooms). These airflow rates are assumed to be constant over time, with no variation during the day or between weekdays and weekends. In the SF ventilation system, this airflow is provided by mechanical extraction, while outdoor air enters the dwelling through air inlets and infiltration; the air inlets were sized to ensure an overall airflow balance consistent with the design extract flow rate. In the BV system, the design supply airflow rate was set equal to the total design extract airflow rate, ensuring balanced operation. Supply air terminals were therefore selected to match the extracted airflow rates and to maintain air balance at the dwelling level. For each ventilation system, two operating scenarios are considered: a) closed scenario, in which all windows and interior doors remain closed; b) scheduled opening scenario, in which windows are open according to a predefined airing schedule representative of occupant behavior.

Table 2. Design extract air flow rates by room and building type [13].

Number of main rooms in the dwelling	Design extract air flow rates (l/s)				
	Kitchen	Bathroom or shower with or without toilets	Other wet room	Toilets	
				Single in dwelling	Multiple (2 or more in dwelling)
1	20	10	10	10	10
2	25	10	10	10	10
3	30	15	10	10	10
4	35	15	10	15	10
5 and more	40	15	10	15	10

2.3 Window opening schedule

Occupant-controlled airing is represented through a deterministic window opening schedule, designed to reflect common residential practices. On weekdays, bedrooms and living areas are ventilated through short morning window openings of 30 minutes, with an additional 30-minute midday opening in the kitchen and living–kitchen space. On weekends, the same opening durations are applied, but with a later start in the morning, reflecting delayed occupant routines. The same window opening schedule is applied consistently across all climates, ventilation systems, airtightness levels, wind intensities, and outdoor pollution scenarios.

2.4 Heating operation and indoor setpoints

The analysis for thermal energy loss focuses on the heating period, defined from 1 October to 30 May, to capture ventilation-related heat losses. Indoor temperature setpoints are fixed at 20 °C during daytime and 16 °C during nighttime for all simulation cases.

2.5 Simulation framework

Simulations are performed using HEAVENLY (Holistic Evaluation tool for Air VENTiLation sYstems), based on dynamic TRNSYS–CONTAM co-simulation, as described in (Kiani et al., 2024) [12]. The multizone airflow and pollutant transport are modelled using CONTAM [14], which simulates airflow between zones, infiltration, pollutant sources, interzonal transfer, and removal through ventilation and filtration. TRNSYS [15] is used to calculate indoor air temperature and relative humidity based on the building’s thermal properties, internal loads, and ventilation and infiltration rates (see Figure 1).

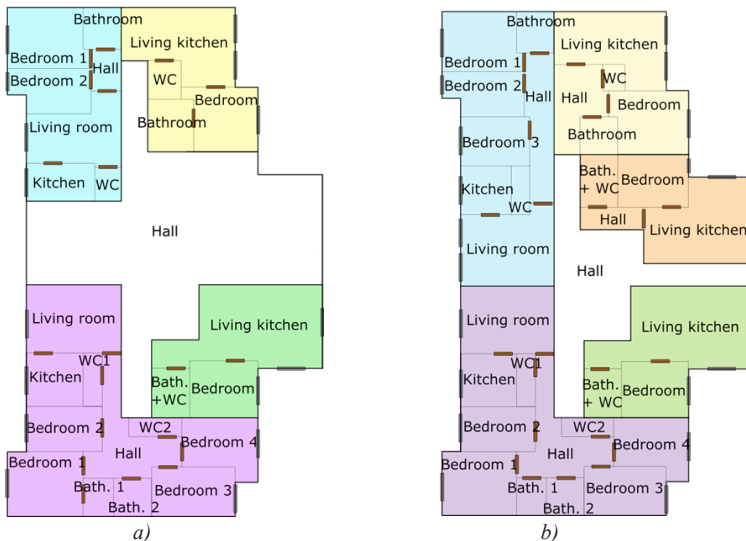


Fig. 1. Representation of the 1st floor (a) and 2nd floor (b) [12].

2.6 Performance indicators

2.6.1 Indoor air quality indicators

In this study, the detailed IAQ analysis is focused on bedrooms. IAQ assessment is based on indoor concentration levels of CO₂, used as a proxy for occupancy-related pollution and ventilation effectiveness; Formaldehyde, representative of indoor chemical emissions from building materials and furnishings; PM_{2.5}, representative of fine particulate matter influenced by outdoor pollution and filtration for BV system; and relative humidity levels, relevant for comfort, moisture balance, and potential health effects.

2.6.2 Energy performance indicators

Energy performance is evaluated using (i) fan electricity consumption over the full year and (ii) thermal energy losses associated with air renewal over the heating season, including mechanical ventilation, infiltration, and additional air exchange induced by window opening.

3 Results

3.1 SF vs BV: Windows are closed

3.1.1 IAQ Results

When all doors and windows are closed, the bedrooms show essentially the same indoor conditions under SF and BV across all eight boundary conditions (see Figure 2a and Figure 2b). Air temperature distributions are nearly identical with a consistent median around 20 °C, and relative humidity is likewise very similar, with medians around 30–31% and comparable spread. Any small shifts (BV being only marginally different) are negligible, so overall there is no meaningful performance difference between the two systems for either temperature or humidity in this fully closed scenario. As Figure 2.c shows, the bedroom CO₂ concentrations

under SF and BV are very similar across all eight boundary conditions. Median values are consistently around 570–580 ppm, with comparable interquartile ranges and nearly identical minimum concentrations close to outdoor background levels. Regarding formaldehyde, bedroom concentrations under SF and BV are broadly comparable across all eight boundary conditions, with very similar median values around 24–25 $\mu\text{g}/\text{m}^3$. SF ventilation tends to show slightly higher upper percentile concentrations, especially when building airtightness is weak (cases 2, 4, 6 and 8). BV, in contrast, consistently yields marginally lower central and upper-range concentrations and a slightly reduced spread. Overall, however, the differences between the two ventilation strategies remain small. For $\text{PM}_{2.5}$ under the fully closed condition, the ventilation strategy makes a clear difference, especially in the boundary conditions with high outdoor pollution (cases 3, 4, 7, and 8). In the low-outdoor-pollution cases (1, 2, 5, and 6), SF already leads to modest indoor $\text{PM}_{2.5}$ levels (median: 3.0 $\mu\text{g}/\text{m}^3$), whereas BV keeps concentrations very low (median: 0.3 $\mu\text{g}/\text{m}^3$). When outdoor $\text{PM}_{2.5}$ is high, indoor concentrations with SF increase substantially (median: 13.9 $\mu\text{g}/\text{m}^3$ with a much wider range), indicating strong penetration of outdoor particles, while BV remains far lower (median: 1.4–1.5 $\mu\text{g}/\text{m}^3$), showing a strong reduction of particle concentration.

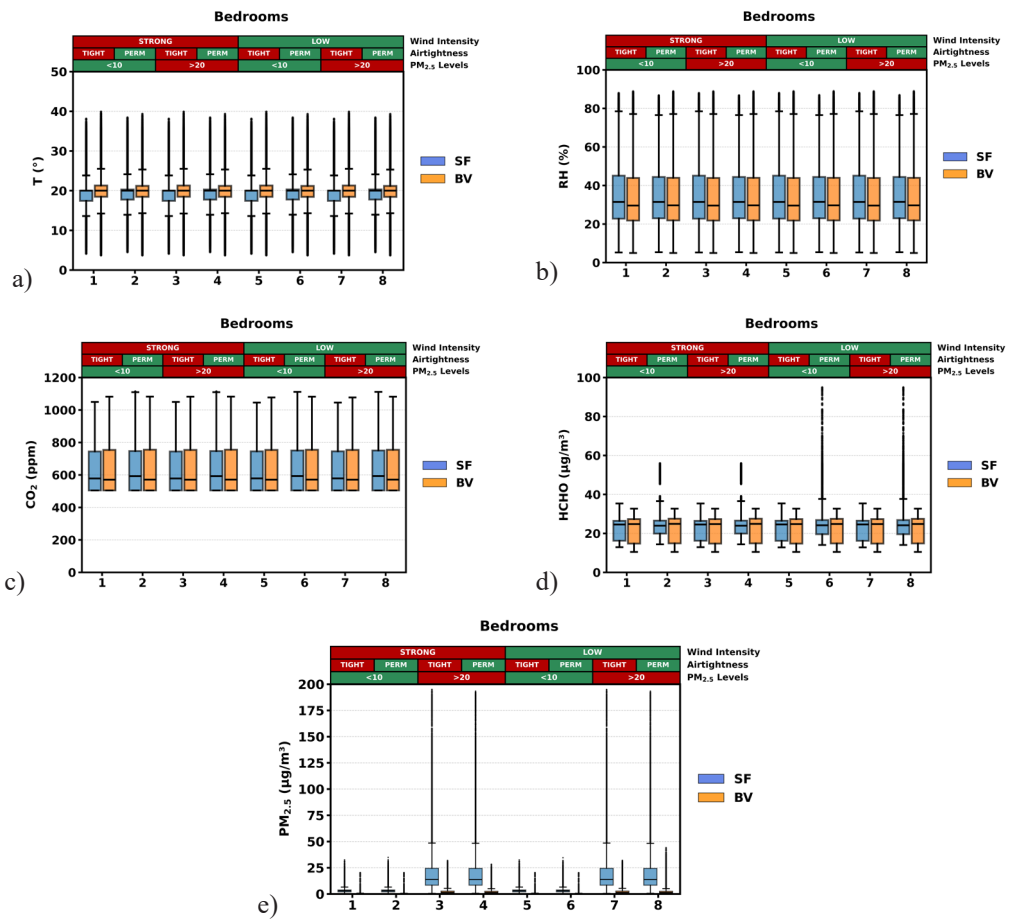


Fig. 2. Bedroom indoor air quality under SF and BV for the closed scenario across boundary conditions BC1–BC8: (a) temperature, (b) relative humidity, CO₂ (c) formaldehyde (d), and PM_{2.5} (e).

3.1.2 Energy Results

As shown in Figure 3 for the closed scenario, clear differences are observed between SF and BV in terms of ventilation-related energy use across all boundary conditions. SF exhibits low fan electricity consumption, ranging from 4 to 5 kWh.m⁻².year⁻¹, but this is accompanied by very high air-renewal heat losses, on the order of 140–142 kWh.m⁻².year⁻¹, with slightly higher losses in permeable buildings. In contrast, BV requires substantially higher fan electricity, approximately 27 kWh.m⁻².year⁻¹ in all cases, due to the use of both supply and exhaust fans; however, this is offset by a strong reduction in air-renewal heat losses, which decrease to 38 kWh.m⁻².year⁻¹ in tight buildings and 48–49 kWh.m⁻².year⁻¹ in permeable buildings. Overall, BV reduces ventilation heat losses by approximately 65–75% compared to SF under closed conditions.

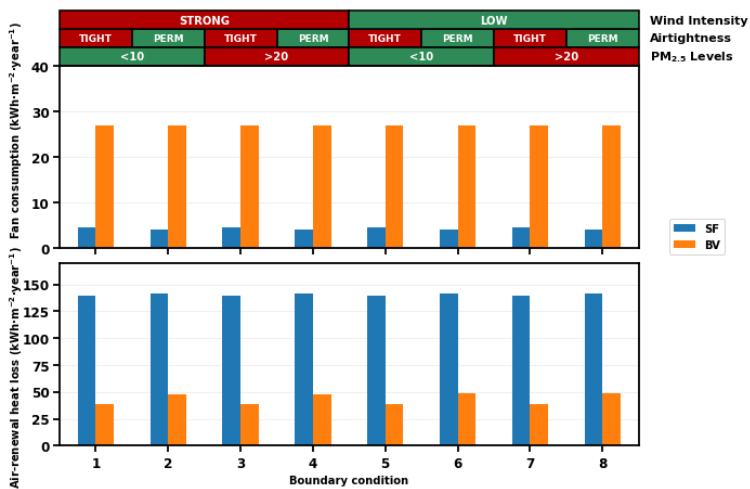


Fig. 3. Closed-scenario ventilation energy performance across boundary conditions BC1–BC8: fan electricity consumption (top) and air-renewal heat loss (bottom) for SF and BV.

3.2 SF vs BV: Windows are opened according to the schedules

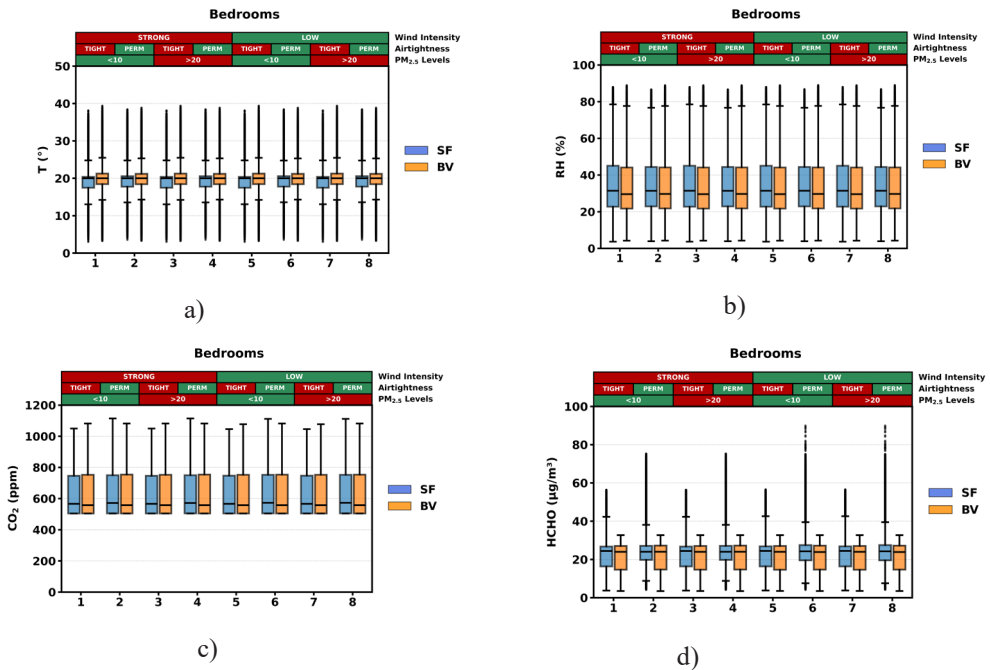
3.2.1 IAQ Results

Figure 4 a and b show the results for temperature and humidity for the scenario with scheduled window opening, in bedrooms. The bedrooms exhibit very similar indoor thermal-humidity conditions under SF and BV across all eight boundary conditions. Indoor air temperature remains tightly controlled in both systems, with a constant median of 20 °C and the interquartile ranges largely overlap. Relative humidity shows a similarly consistent pattern, with SF yielding median values around 31–32% and BV slightly lower values around 29–30%, but with comparable spreads and variability. For the window-opening scenario, bedroom CO₂ concentrations are very similar under SF and BV across all eight boundary conditions (see Figure 4.c). SF shows median values around 566–573 ppm, while BV is slightly lower at about 556–558 ppm, but the distributions largely overlap and differences in variability, and upper percentiles are small. As shown in Figure 4.d, formaldehyde concentrations in bedrooms remain broadly comparable between SF and BV across all eight boundary conditions. Median values stay close to 24.0–24.7 µg/m³ in all cases, with only small differences between systems. SF tends to show slightly higher concentrations in some boundary conditions and a somewhat wider upper tail (higher P75–P95 and maximum

values), whereas BV is generally marginally lower and more stable. For the window-opening scenario, PM_{2.5} concentrations show a clear and consistent contrast between SF and BV, particularly under high outdoor pollution conditions (cases 3, 4, 7, and 8). In low outdoor PM_{2.5} cases, SF results in moderate indoor levels with median values around 3.0 µg/m³, while BV maintains very low concentrations (0.3–0.4 µg/m³). When outdoor PM_{2.5} is high, indoor concentrations under SF increase substantially (median: 13.9 µg/m³ with a wide upper range), whereas BV strongly limits particle concentration, keeping median values below 2.0 µg/m³.

3.2.2 Energy Results

Figure 5 illustrates the results for the open-window scenario, under SF and BV systems. Under SF, fan electricity consumption remains unchanged by opening and stays low, at 4–5 kWh.m⁻².year⁻¹ across all boundary conditions, depending on building tightness. However, air-renewal heat losses increase substantially with opening, reaching 151 kWh.m⁻².year⁻¹ in tight buildings and 153–154 kWh.m⁻².year⁻¹ in permeable buildings, indicating a clear penalty associated with uncontrolled openings. In contrast, BV maintains a constant fan electricity consumption of 27 kWh.m⁻².year⁻¹ across all open cases, but air-renewal heat losses increase more markedly compared to the closed scenario, rising to 53 kWh.m⁻².year⁻¹ in tight buildings and 63–64 kWh.m⁻².year⁻¹ in permeable buildings. Despite this increase, BV continues to exhibit substantially lower absolute heat losses than SF under open conditions. Across all boundary conditions, BV air-renewal heat losses remain approximately 55–65% lower than those of SF, confirming that balanced ventilation retains an energy advantage even when windows are opened.



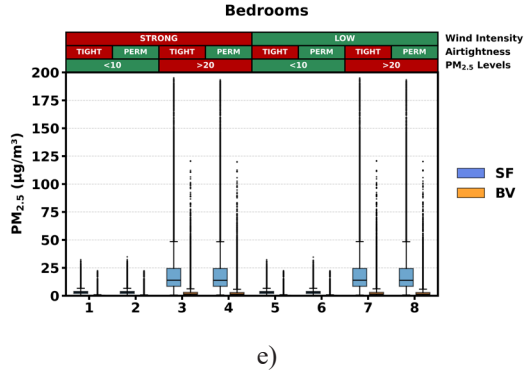


Fig. 4. Bedroom indoor air quality indicators under SF and BV for the open scenario across boundary conditions BC1–BC8: (a) temperature, (b) relative humidity, CO₂ (c), formaldehyde (d), and PM_{2.5} (e).

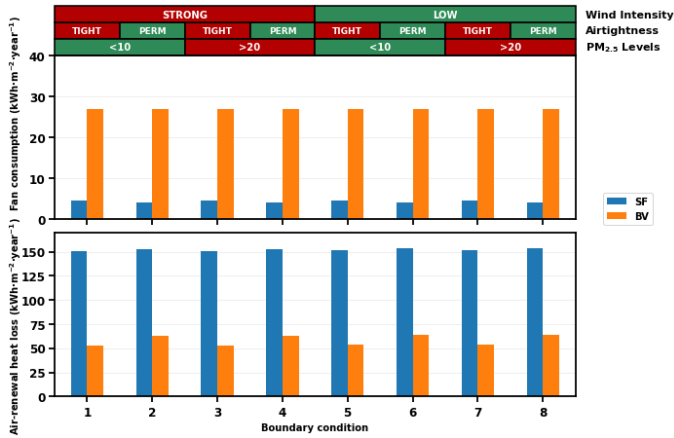


Fig. 5. Open-scenario ventilation energy performance across boundary conditions BC1–BC8: fan electricity consumption (top) and air-renewal heat loss (bottom) for SF and BV.

3.3 Cross-system comparison (SF vs BV)

For boundary condition 7, Figure 6 compares the energy impact of window opening across Helsinki, Strasbourg, and Athens for SF and BV. In all climates, fan electricity consumption is unaffected by opening, whereas air-renewal heat losses increase in both systems. In Helsinki, SF fan electricity remains 5 kWh.m⁻².year⁻¹ under both closed and open conditions, while air-renewal heat loss increases from 140 to 151 kWh.m⁻².year⁻¹ (+11 kWh.m⁻².year⁻¹; +7.9%). For BV, fan electricity remains 27 kWh.m⁻².year⁻¹, while heat loss rises from 38 to 53 kWh.m⁻².year⁻¹ (+15 kWh.m⁻².year⁻¹; +39.5%). In Strasbourg, SF fan electricity remains 6 kWh.m⁻².year⁻¹, and heat loss increases from 96 to 103 kWh.m⁻².year⁻¹ (+7 kWh.m⁻².year⁻¹; +7.3%), whereas BV fan electricity remains 29 kWh.m⁻².year⁻¹, and heat loss increases from 28 to 37 kWh.m⁻².year⁻¹ (+9 kWh.m⁻².year⁻¹; +32.1%). In Athens, SF fan electricity remains 6 kWh.m⁻².year⁻¹, with air-renewal heat loss increasing slightly from 54 to 56 kWh.m⁻².year⁻¹ (+2 kWh.m⁻².year⁻¹; +3.7%), while BV fan electricity remains 30 kWh.m⁻².year⁻¹, and heat loss increases from 18 to 23 kWh.m⁻².year⁻¹ (+5 kWh.m⁻².year⁻¹; +27.8%). Across all three climates, BV consistently maintains substantially lower air-renewal heat losses than SF under

both closed and open conditions, although window opening reduces this advantage. In Helsinki, BV heat losses are 73% lower than SF when closed (38 vs. 140 kWh.m⁻².year⁻¹) and 65% lower when open (53 vs. 151 kWh.m⁻².year⁻¹). Similar trends are observed in Strasbourg (71% lower when closed; 64% lower when open) and Athens (67% lower when closed; 59% lower when open). Overall, window opening leads to a modest relative increase in heat loss for SF (+3.7% to +7.9%) but a much larger relative increase for BV (+27.8% to +39.5%), demonstrating that occupant-driven openings systematically increase ventilation-related heat losses and affect the energy advantage of balanced ventilation, particularly in colder climates.

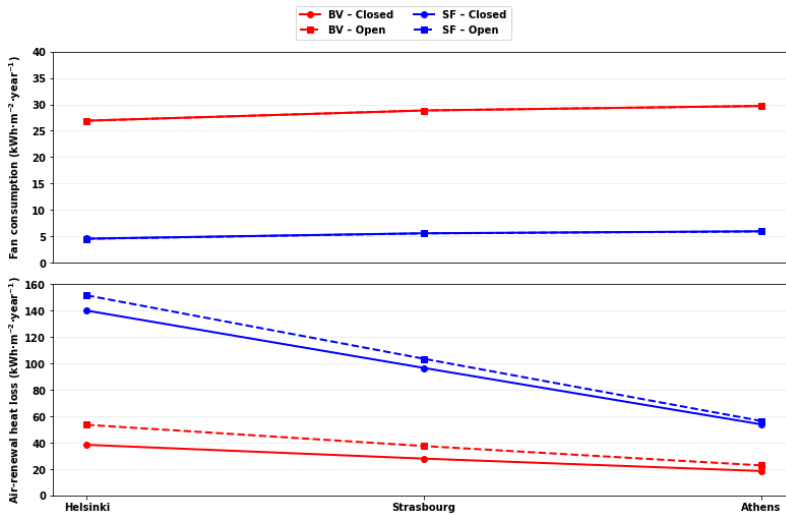


Fig. 6. BC7 cross-climate ventilation energy results (Helsinki, Strasbourg, Athens): fan electricity consumption and air-renewal heat loss for SF and BV under closed and window-opening conditions.

Table 3. BC7 (Helsinki) Bedroom IAQ indicators for SF and BV under closed vs scheduled opening.

Parameter	SF – Closed	SF – Open	BV – Closed	BV – Open
T (°C)	20.0	20.0	20.0	20.0
RH (%)	32.5	31.4	29.6	30
CO ₂ (ppm)	579	566	571	558
Formaldehyde (µg/m ³)	24.6	24.5	24.8	24.0
PM _{2.5} (µg/m ³)	13.9	13.9	1.5	1.6

Table 3 compares bedroom IAQ indicators for BC7 (Helsinki) under SF and BV, for closed and opening scenarios. Indoor thermal conditions remain largely unaffected by window opening. Temperature is unchanged, with a constant median of 20 °C for both SF and BV. Relative humidity is almost unchanged (SF: 32.5 to 31.4%, BV: 29.6 to 30%), indicating a negligible impact on thermal comfort. The most pronounced system difference is observed for PM_{2.5}. Under high outdoor pollution, SF maintains high indoor particle concentrations with a median of 13.9 µg/m³, which remains essentially unchanged with opening, whereas BV maintains very low PM_{2.5} levels, increasing only slightly from 1.5 to 1.6 µg/m³. This corresponds to an approximately 9-fold reduction in PM_{2.5} with BV compared to SF, confirming the strong effectiveness of filtered air supply even when windows are opened. CO₂ concentrations show only minor sensitivity to opening, with SF medians from 579 to 566 ppm and BV from 571 to 558. Formaldehyde concentrations remain similar across

systems and scenarios, with medians around 24.6 to 24.5 $\mu\text{g}/\text{m}^3$ for SF and 24.8 to 24.0 $\mu\text{g}/\text{m}^3$ for BV, suggesting that formaldehyde levels are dominated by indoor sources rather than ventilation strategy. Overall, these results confirm that the primary IAQ benefit of balanced ventilation lies in particle control, while temperature, humidity, CO_2 , and formaldehyde remain largely unaffected by the transition from closed to scheduled window-opening conditions.

4 Conclusion

This study evaluated the IAQ–energy implications of window opening in a two-story multifamily dwelling across three European climates (Helsinki, Strasbourg, Athens), comparing a constant airflow rate ventilation system i.e. single-flow extraction ventilation with balanced ventilation including heat recovery and supply-air filtration. Across the full parametric matrix (geographical location, airtightness, wind exposure, and outdoor $\text{PM}_{2.5}$ level), scheduled openings produced a clear and consistent energy penalty through increased air-renewal heat losses, while fan electricity remained largely unaffected by openings in both systems. Temperature, relative humidity, CO_2 concentration, and formaldehyde remain essentially unchanged, indicating no meaningful impact from the different scenarios. The clearest system-level difference is observed for $\text{PM}_{2.5}$ because of outdoor air filtration. Under high outdoor pollution, the single-flow system maintains elevated indoor particle concentrations (median of 13.9 $\mu\text{g}/\text{m}^3$) regardless of opening in both closed and open cases, whereas balanced ventilation with air filtration consistently maintains very low $\text{PM}_{2.5}$ levels (around 1.5 $\mu\text{g}/\text{m}^3$), with only a slight increase when windows are opened. This corresponds to an approximately 9-fold reduction in $\text{PM}_{2.5}$ between the two system typologies, demonstrating the robustness of filtered air supply even under window-opening conditions. From an energy perspective, window opening leads to increased air-renewal heat losses in both systems, while fan electricity consumption remains unchanged. This increase is moderate for single-flow ventilation but substantially larger for the balanced one, as openings bypass heat recovery and reduce its effectiveness.

Nomenclature

T	Indoor air temperature, $^{\circ}\text{C}$
RH	Relative humidity, %
CO_2	Indoor CO_2 concentration, ppm
$\text{PM}_{2.5}$	Indoor $\text{PM}_{2.5}$ concentration, $\mu\text{g}/\text{m}^3$

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