DOI: 10.61782/fa.2025.0363

FORUM ACUSTICUM EURONOISE 2025

EVALUATION OF ACOUSTIC PERFORMANCE IN SMART VENTILATED WINDOWS WITH INTEGRATED HEAT STORAGE

Andrea Gerbotto[1*] **Louena Shtrepi**[1] **Fabio Favoino**[1] **Arianna Astolfi**[1]
[1] Department of Energy, Politecnico di Torino, Italy

ABSTRACT

Windows are essential façade components that balance multiple functions, including daylighting, natural ventilation, and thermal regulation. However, conventional windows often suffer from significant energy losses and inadequate air exchange, even with regular ventilation. To address these challenges, the iclimabuilt project has developed a smart, ventilated window that integrates advanced technologies, including PCM (phase-change material) heat storage, triple glazing with air-filled chambers for enhanced thermal insulation, and 3D-printed components for noise reduction and air purification. These innovations minimise energy losses, improve thermal management, and promote occupant health and well-being.

This study focuses on evaluating the acoustic performance of the three operational modes of the fans integrated into the window of a Living Lab environment. Noise measurements were conducted in accordance with EN ISO 16032:24, both with and without an acoustic filter installed in the PCM box and air filtration unit. Data were collected from three microphone positions: a corner and two reverberant field points. The analysis reveals that the noise levels generated by the fans are in the 35–45 dB range, exceeding standard limits. Moreover, the findings highlight the need to further optimise noise control strategies in smart window design while maintaining their energy efficiency and indoor air quality benefits.

Keywords: *ventilation noise, ventilated window, smart window*

*__Corresponding author__: *andrea.gerbotto@polito.it.*

1. INTRODUCTION

The integrated assessment of acoustic conditions, ventilation, and overheating prevention is essential to ensure that residential developments provide a balanced indoor environmental quality (IEQ) [1]. Neglecting any of these aspects may lead to housing that fails to meet occupants' overall comfort and well-being.

Windows and other ventilation openings constitute the primary interfaces between the indoor and outdoor environments and have been the subject of increasing research and development [2]. However, this connection poses a significant challenge for natural ventilation, as it creates a trade-off between fresh air intake and external noise intrusion. This conflict often prevents naturally ventilated buildings from complying with background noise limits established by acoustic standards, building regulations, and rating protocols. In response, extensive research has focused on developing solutions that enable ventilation without compromising façade sound insulation [3, 4].

Over recent decades, double-glazed windows have been enhanced to provide excellent sound insulation when closed. However, they restrict natural ventilation, increasing reliance on mechanical ventilation and leading to higher energy consumption. To address this issue, windows with integrated mechanical ventilation have been introduced. These systems allow for a reduced opening area without diminishing the air exchange rate, significantly improving acoustic comfort and energy efficiency [5]. Despite their advantages, integrated mechanical ventilation systems introduce a continuous noise source within the room. This internal noise must be accurately measured and, if necessary, mitigated to ensure overall acoustic comfort.

2. METHODOLOGY

2.1 Test case

The Test Case is a smart, ventilated heat-harvesting window that consists of a ventilated window with additional functions supporting ventilation, thermal management, and improved air quality in indoor spaces, which sound reduction index has been measured in [6].

Figure 1. The Test Case; PCM-Air exchanger (blue); outer bottom vent (green); Air Filtration Unit (red)

The smart window is composed of the following main sub-components (figure 1):

- Triple-glazed window unit with a ventilated exterior chamber, Air-filled interior chamber, NIR absorbing layer, and omniphobic coating;
- Upper box – PCM-Air exchanger unit which hosts:
  - One axial fans per unit;
  - A stack of five plates filled with Phase Change Material;
  - One 3D printed acoustic absorbers, each consisted of one casing (H130 mm x W130 mm x T100 mm) with nine panels (approx. H120 mm x W120 mm x T3 mm);
- Lower box – Indoor Air Filtration Unit which includes:
  - One 3D printed CO_2 absorber consisted of one casing (H130 mm x W130 mm x T425 mm) with twenty five electro-spun membranes;
  - One 3D printed acoustic absorbers, each consisted of one casing (H130 mm x W130 mm x T100 mm) with nine panels (approx. H120 mm x W120 mm x T3 mm);
  - Ventilator for air circulation.

2.2 Operational modes

The outer cavity of the TGU can be activated using electrical fans, with an airflow path from the outside (with an outer bottom vent integrated into the framing system) to the inside (with an inner top vent integrated into the framing system) to provide the indoor environment with primary ventilation air at a temperature level closer to the indoor required temperature, in heating dominated conditions (Supply Air, SA, operation mode).

In cooling dominated conditions instead the TGU outer cavity ventilation is used with an airflow path from the outside to the outside (with an outer top vent integrated into the framing system), to reduce the g-value (total solar energy transmittance) of the TGU by removing unwanted solar gains absorbed within the glass layers (Outdoor Air Curtain, OAC, operation mode), while a fan-assisted vents provide primary ventilation bypass within the top part of the framing system.

In order to reduce the differences between the air temperature entering the room through the glazing ventilation and the thermal comfort conditions inside the building, the air from the glazing ventilation is conveyed to a PCM to

Air heat exchanger before being delivered to the indoor environment.

Finally, the TGU can also be used as a conventional TGU, in conditions in which solar radiation is not very high and in which ventilation is not needed, by switching off the fans and closing all the vents included in the system (Thermal Buffer, TB, operation mode).

2.2.1 *Supply Air throught the window*

To assess the noise generated by the fan in the bottom box, the system was operated in Supply Air window mode. In this configuration, external forced air enters through the bottom outdoor inlet, flows through the window cavity, and is directed to the PCM-Air heat exchanger by the fan located in the bottom box.

2.2.2 *Supply Air direct*

To evaluate the noise produced by the fan in the PCM box, the system was set to Supply Air direct mode. In this setup, external forced air is drawn in through the top outdoor inlet and directly supplied to the PCM-Air heat exchanger by the fan installed in the PCM box.

In both configurations (figure 2), the fan speed, which can be continuously adjusted with a potentiometer from 0 to 100, was set to either 30% or 100%.

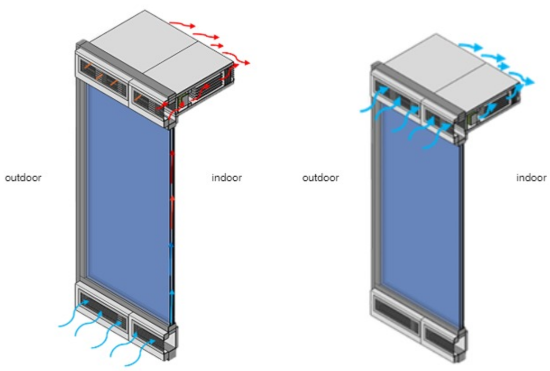

Figure 2. The two considered operational modes

2.2.3 *Air filtration*

For improving indoor air quality and wellbeing, the Test Case features CO_2 capturing filters. The 3D printed component design consists of a Light-Weight PLA-based casing with a customisable number of incisions to integrate

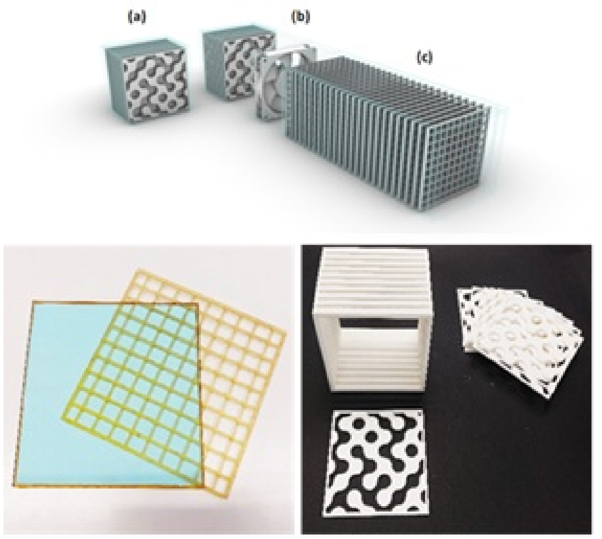

Figure 3. Design of 3D printed air-filtration unit and collateral acoustic components (top); functional panel with CO_2 absorptive properties made of (a) a High HDT photocurable resin-based frame and (b) an electro-spun MOFs/PAN polymer membrane (bottom-left); functional component with acoustic properties based on thermoplastic with foaming agents (bottom-right)

resin-based frames with MOFs/PAN layers of electro-spun CO2 Capturing Membranes and a fan for air circulation. Additionally, an acoustic absorber was integrated in the assembly to reduce the noise of the fan (figure 3).

For all the configurations considered, the air flow rates generated by the fans were measured (table 1).

Table 1. Volumetric flow measurements

Mode	Velocity [%]	Q_{max} $[m^3/h]$
SA_{window}	30	12.68
SA_{window}	100	29.23
SA_{direct}	30	30.53
SA_{direct}	100	35.70
$Airfiltration$	100	4.45

Figure 4. Fixed microphone positions

2.3 Test equipment and method

The sound pressure level, L_i, from the service equipment is measured in a fixed position i as the linear (Z weighted) spectrum in one-third-octave-bands during the operation time of the service equipment under test.

For each measurement it is determined the equivalent continuous sound pressure level, $L_{Zeq,i}$, over a period of $t = 30$ seconds. The sound pressure levels taken in the three positions are then used to calculate the average sound pressure levels L_{Aeq} in one-third-octave bands. These average sound pressure levels are then corrected for background noise, measured over $t = 30$ seconds in the same positions before and after the operation time.

The background noise-corrected average sound pressure levels $L_{Aeq,corr}$ in one-third-octave bands are then used to calculate the standardized average sound pressure levels $L_{Aeq,corr,nT}$ to a reference reverberation time as:

$$L_{corr,nT} = L_{corr} - 10 \log \left(\frac{T}{T_0} \right) \tag{1}$$

where:

- T is the measured reverberation time in seconds;
- T_0 is the reference reverberation time 0.5 seconds.

2.3.1 *Filter*

The acoustic performance is evaluated by measuring the insertion loss (IL), calculated by the difference between the sound pressure level (SPL) in the room with and without the filter applied. Therefore, the IL of the filter is calculated as

$$IL_{filter} = SPL_{wout} - SPL_w \tag{2}$$

where:

- SPL_{wout} is the A-weighted SPL measured without the filter, in dB;
- SPL_w is the A-weighted SPL measured with the filter, in dB.

2.4 Measurements

The Test Case was installed on the south-oriented vertical façade in the Living Lab at Politecnico di Torino (Torino, Italy), a single office room of approximately 10 m^2 floor area.

Three different conditions of the test room have been defined, and, for each condition, three measurement positions, one in a selected corner of the room and two positions in the reverberant sound field (figure 4), have been used to characterize the room acoustically, according to EN ISO 16032:2024. For each measurement position, three repetitions were performed. Figure 5 and figure 6 present the equivalent sound pressure levels (L_{Aeq}) of the background noise and the L_{Aeq} for fan speeds of 100% and 30% for the two operational SA modes (through the window and direct), while figure 7 presents that of air filtration box. These curves have been adjusted for background noise and the room's reverberation time (figure 8), measured using the impulse response method in the 100 Hz to 5 kHz one-third-octave bands.

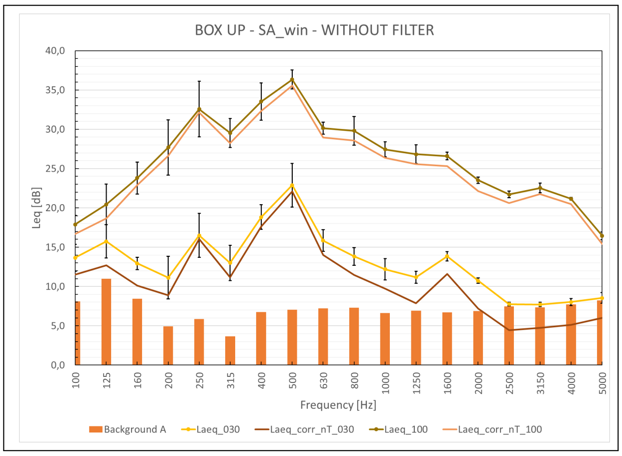

Figure 5. Supply Air window

3. RESULTS AND DISCUSSION

It can be observed that the background noise remains relatively low (< 15 dB for each third octave band) and has a

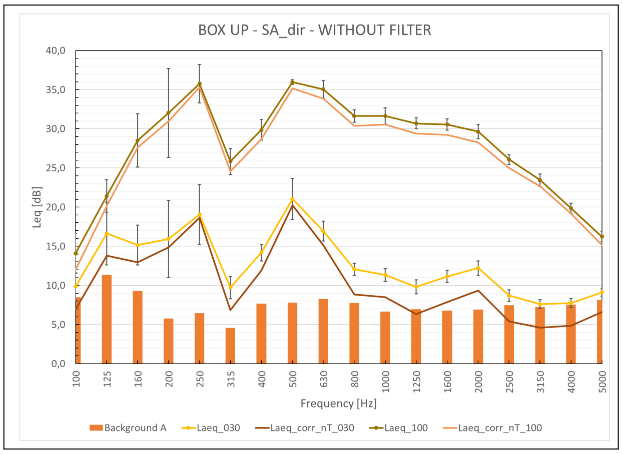

Figure 6. Supply Air direct

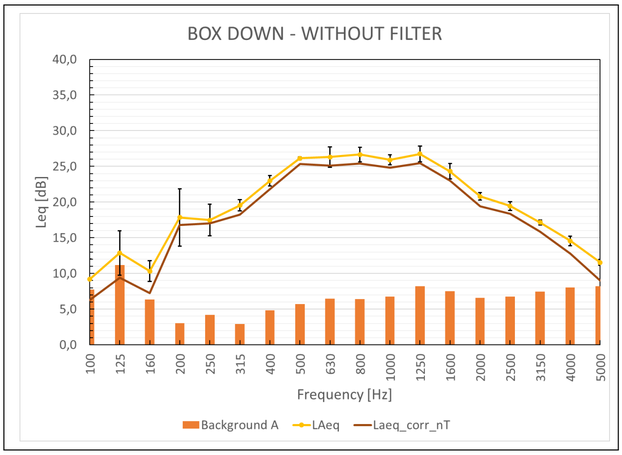

Figure 7. Air filtration

lot of influence in the low-speed condition. The correction for the background noise and the reverberation time standardisation minimally impacts the results for the condition with the fan speed at 100%, this leads to a limited difference between the two curves, L_{Aeq} and $L_{Aeq,corr,nT}$. Thus the test room could be considered appropriate for evaluating the noise produced only by the fans and the effects of the acoustic filters.

Both the fan in the lower box and the one in the PCM box have two peaks at 250 Hz and 500 Hz, which amplify as the speed increases and which are responsible for exceeding the 30 dB(A) threshold indicated in literature as critical for living spaces, particularly bedrooms [7]. The path through the window in the SA_{win} mode filtered the

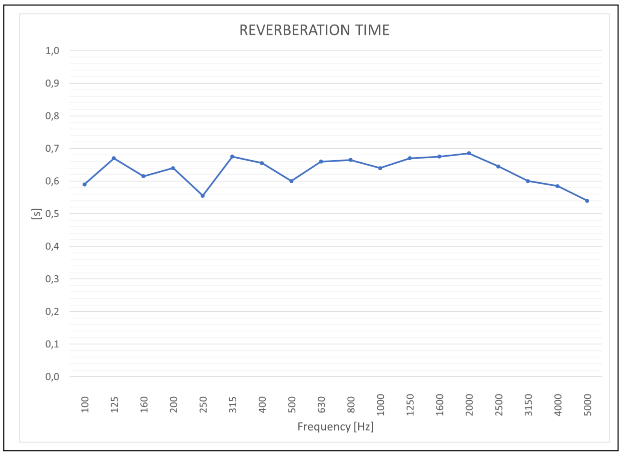

Figure 8. Reverberation Time

Table 2. Measurements results

Mode	$L_{A,back}$	L_{Aeq}	$L_{Aeq,nT}$
SA_{win} 100 %	20.8 dB	41.6 dB	40.7 dB
SA_{win} 30 %	20.8 dB	27.9 dB	26.3 dB
SA_{dir} 100 %	21.1 dB	43.4 dB	42.4 dB
SA_{dir} 30 %	21.1 dB	27.3 dB	25.7 dB
$Airfil$ 100 %	20.6 dB	35.1 dB	33.9 dB

frequencies above 630 Hz and below the 250 Hz and amplify the range between 315 Hz and 500 Hz, probably due to a resonance in the PCM box, also found in the measurement of the sound reduction index of the test case in [6].

The tested filter, designed as a series of panels with staggered incisions to hinder the transmission of sound with labyrinthine channels to increase the distance sound must travel, enhancing phase cancellation, reveals a frequency-dependent behavior, indicative of a filter optimised for mid-to-high frequency performance. At mid and low frequencies (100–1250 Hz), the insertion loss fluctuates between -1.6 dB and +1.4 dB, with a minimum observed at 1000 Hz. These results suggest limited attenuation capacity in the lower frequency range, likely due to the relatively long wavelengths and reduced interaction with the filter geometry. Above 1250 Hz, the filter demonstrates more attenuation, reaching up to +2.0 dB at 5000 Hz. This indicates enhanced interaction with shorter wavelengths.

Overall, the filter exhibits modest insertion loss across the full spectrum and needs some improvements, as trying to implement helmholtz resonators or using layered impedance transitions to improve energy dissipation.

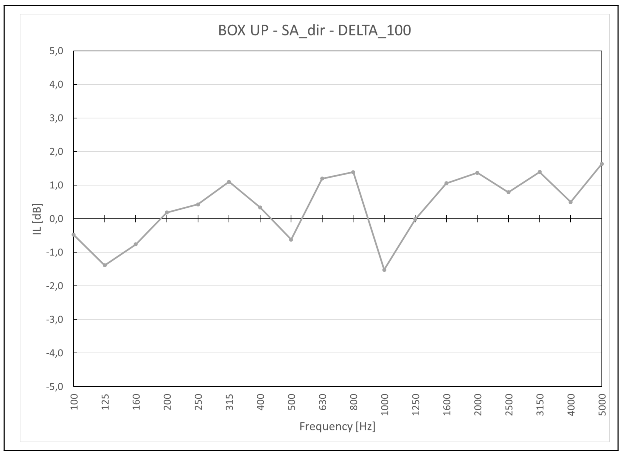

Figure 9. Insertion Loss

4. CONCLUSION

This study presented an experimental evaluation of the acoustic performance of a smart, ventilated window system with integrated phase-change material (PCM) and air purification modules. The results demonstrated that the noise levels generated by the fans in all operational modes exceed recommended indoor background noise limits for residential or office environments, particularly at full-speed operation. While the integrated acoustic treatments provided measurable insertion losses, their effectiveness was not sufficient to reduce fan noise to acceptable levels.

The findings highlight a key challenge in balancing acoustic comfort with advanced functionalities such as heat recovery and indoor air quality control. Future developments should focus on optimising fan design and speed control, improving the acoustic performance of integrated absorptive materials. A holistic design approach is essential to ensure that smart façade components can meet the increasingly stringent performance criteria for indoor environmental quality in low-energy buildings.

5. ACKNOWLEDGMENTS

The experimental activities presented in this paper were carried out as part of the H2020 project “iclimabuilt—Functional and advanced insulating and energy harvesting/storage materials across climate adaptive building envelopes” (Grant Agreement no. 952886). We gratefully acknowledge the support Anna Karatza and Vaia Tsiokou (BIOG3D, Greece) provided for generously sharing detailed design information, which was instrumental in developing this study, Asmaa Ali (Rubitherm GmbH, Germany) and Gianni Cassera (BGTec Sp. z o.o., Poland) for the preparation of the mock-ups.

6. REFERENCES

[1] J. Harvie-Clark, A. Chilton, N. Conlan, and D. Trew, “Assessing noise with provisions for ventilation and overheating in dwellings,” *Building Services Engineering Research and Technology*, vol. 40, pp. 263–273, May 2019.

[2] F. Favoino, R. C. Loonen, M. Michael, G. De Michele, and S. Avesani, *Advanced fenestration—technologies, performance and building integration*. 2021.

[3] S. Torresin, R. Albatici, F. Aletta, F. Babich, T. Oberman, and J. Kang, “Acoustic Design Criteria in Naturally Ventilated Residential Buildings: New Research Perspectives by Applying the Indoor Soundscape Approach,” *Applied Sciences*, vol. 9, p. 5401, Dec. 2019. MAG ID: 2994653179.

[4] C. Rubino, S. Liuzzi, G. Fusaro, F. Martellotta, C. Scrosati, and M. Garai, “Balancing ventilation and sound insulation in windows by means of metamaterials: A review of the state of the art,” *Building and Environment*, vol. 275, p. 112780, May 2025.

[5] L. Du, S.-K. Lau, S. E. Lee, and M. K. Danzer, “Experimental study on noise reduction and ventilation performances of sound-proofed ventilation window,” *Building and Environment*, vol. 181, p. 107105, Aug. 2020.

[6] L. Shtrepi, A. Gerbotto, F. Favoino, and A. Astolfi, “Sound insulation characterisation of innovative natural ventilated façade in the context of living lab installations,” *inter noise*, vol. 270, pp. 10094–10102, Oct. 2024.

[7] J. Harvie-Clark, N. Conlan, W. Wei, and M. Siddall, “How loud is too loud? noise from domestic mechanical ventilation systems,” *International Journal of Ventilation*, vol. 18, pp. 303–312, Oct. 2019.