

Impact on indoor and outdoor acoustic comfort in the decarbonization process of residential areas

Fabio Serpilli¹, Valter Lori¹

¹ Dipartimento di Ingegneria Industriale e scienze matematiche, Università Politecnica delle Marche, AN

Abstract. The decarbonization of residential buildings, driven by the new EPBD4 directive, involves replacing fossil fuel generators with heat pump solutions. While these measures significantly reduce emissions and improve energy efficiency, they also lead to increased outdoor noise impact and potential issues of sound intrusion in indoor environments. This paper examines the acoustic implications of the energy transition, highlighting the challenges posed by heat pump noise and proposing mitigation strategies to ensure both indoor and outdoor comfort. Current regulations and future perspectives for integrating energy efficiency with acoustic quality are also discussed.

1 Introduction

Over the last decades, European and international policy frameworks have progressively tightened energy requirements for buildings to reduce fossil-fuel dependency and mitigate greenhouse-gas emissions, placing the building sector at the core of decarbonisation strategies [1,2]. In Europe, this policy evolution has recently converged into an updated regulatory push that strengthens renovation trajectories and the uptake of low-carbon technologies, embedding energy performance targets within broader implementation and monitoring frameworks [3,4]. Alongside this policy shift, the technical discourse has evolved from the Nearly Zero-Energy Building (NZEB) paradigm towards Zero-Emission Building (ZEB) concepts, with ongoing refinement of definitions and calculation approaches [5,6]. The resulting acceleration of retrofit activity is expected to drive a substantial diffusion of electrified heating technologies, especially heat pumps, supported by evidence of their role in low-carbon pathways. However, the large-scale deployment of heat pumps in dense urban fabrics introduces an acoustical dimension that is often secondary in energy-driven planning yet central to environmental quality and acceptance. Air-source and hybrid heat pump systems can become relevant contributors to the urban sound environment because their outdoor units are frequently installed close to receivers (façades, balconies, rooftops, courtyards) and operate for extended periods, including night-time. In such conditions, sound immission may be shaped by short source–receiver distances, multiple reflections, partial shielding, and façade-to-façade propagation, potentially increasing the probability of nuisance in residential contexts [7]. Recent reviews highlight that measured noise outcomes depend not only on nominal sound power levels but also on installation practices, operating

regimes and local boundary conditions, calling for assessment approaches that explicitly link source behaviour, transmission paths and receiver exposure [8]. From an acoustics standpoint, heat pump noise is typically associated with compressors and fans, with additional contributions arising from structural vibration and aeroacoustic interactions. Component-level mechanisms and operational modes can alter spectra, temporal variability and perceptual attributes; for instance, defrosting cycles and fan–heat exchanger interactions may modify sound signatures and increase the likelihood of detectability and annoyance [9]. Laboratory vs field comparisons further indicate that in-situ performance can deviate from controlled measurements due to mounting conditions, reflections and coupling with the built environment, reinforcing the need for context-sensitive evaluation. Crucially, the acoustic impact of heat pump installations is twofold. First, it concerns outdoor environmental noise, where cumulative immission in neighbourhoods may emerge as installations increase in number and density. Second, it concerns indoor acoustic comfort, where airborne transmission through façades/openings and structure-borne paths via brackets, slabs and connected services can lead to audible noise within dwellings. The indoor dimension is particularly sensitive because the perceived impact is influenced not only by level-based descriptors but also by the intrusiveness of the sound. Its ability to attract attention, interfere with activities, and disrupt rest and sleep in private environments. In the Italian context, the concept of intrusive noise has specific relevance in technical and legal practice, and its operationalisation through national guidance has been discussed in relation to disputes and the applicability limits of assessment standards [10]. Accordingly, the UNI/TS 11844 technical specification provides an explicit reference framework for evaluating intrusive noise conditions, which is especially pertinent when heat pump operation results in indoor audibility that occupants may perceive as intrusive, even when conventional outdoor indicators suggest compliance [11]. Beyond purely acoustic metrics, recent literature on renovation and urban regeneration stresses that non-energy impacts, including environmental and social acceptance should be considered to avoid unintended consequences of decarbonisation measures [12]. This is consistent with decision-support and modelling research calling for integrated, multi-criteria approaches that can anticipate trade-offs between energy performance, environmental exposure and quality-of-life outcomes at urban scale [13,14]. Against this background, the present study focuses on the acoustic implications of EPBD-driven heat pump deployment in urban residential settings, explicitly addressing outdoor sound immission at neighbourhood scale and indoor acoustic comfort with emphasis on the intrusive character of noise and its assessment within the UNI/TS 11844 perspective [10].

2 Materials and Methods

This study is conceived as a direct continuation and methodological refinement of the authors' previous work on the acoustic implications of the EPBD-driven decarbonisation pathway in dense urban settings [11]. In that earlier contribution, the potential noise consequences of a progressive diffusion of heat pumps were investigated using the historic central area of Ancona (Italy) as an emblematic case study, representative of many European compact cities where retrofit actions are spatially constrained and receiver proximity is high. The focus was on how an increasing number of outdoor units installed on existing buildings in response to EPBD renovation and electrification trends, may alter the urban acoustic climate as installations scale up over time. The workflow adopted in the previous study consisted of two main steps. First, the authors established a baseline characterisation of the current acoustic environment through an urban-scale noise mapping of the study area, providing a spatially resolved reference scenario against which further changes could be

compared. The results of the urbane-scale noise mapping are summarized in Figure 1. The noise mapping was developed with the software Softnoise Predictor.

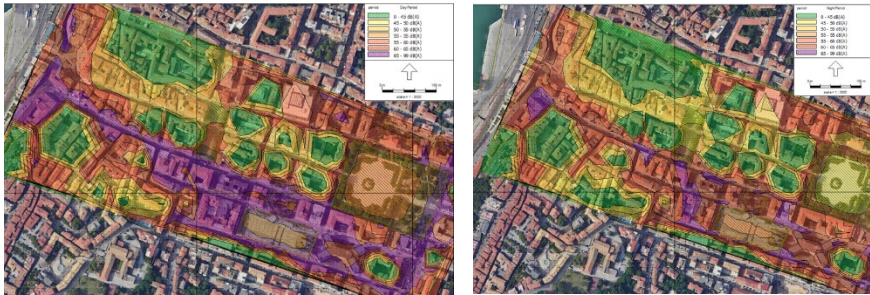


Fig. 1. Noise Mapping-Present. (a) Day Period, (b) Night Period.

Second, starting from this baseline, they evaluated a set of incremental installation scenarios representing a progressive increase in heat pump adoption across the building stock, with the aim of quantifying how the additional sound emissions might translate into changes in sound immersion at the urban scale. In this work is presented an intermediate scenario of installation. This scenario-based approach enabled the assessment of potential trends (rather than single-site effects) and supported an interpretation aligned with policy-driven trajectories, where retrofit measures are expected to be deployed gradually but extensively. The assessment of future noise scenarios required the definition of a set of transparent and reproducible assumptions on how heat-pump installations may diffuse across the existing building stock. In the investigated district, a complete set of technical information (heating system type, HVAC layout, available mounting locations, rooftop accessibility, etc.) was not consistently available for every single property. To avoid introducing arbitrary variability, the scenario model was therefore built on a combination of targeted field observations and sample surveys, used to infer typical system configurations for representative buildings, and rule-based assignments applied consistently across the full dataset. This approach is commonly adopted in urban-scale environmental acoustics when detailed building-by-building inventories are incomplete, provided that assumptions remain explicitly stated and sensitivity is discussed. For the purpose of scenario generation, buildings were grouped into four functional categories reflecting different usage patterns, system needs and retrofit likelihoods:

1. Public buildings. In the baseline condition, these were assumed to predominantly rely on fossil-fuel-based heating. A large share was observed to use cooling devices for summer operation; however, cooling-only equipment was not modelled within the present work, as the analysis focuses on heat-pump deployment for space heating.
2. Private buildings open to the public (e.g., retail and services). Large floor-area units were assumed to more frequently adopt centralised heat-pump solutions (often with outdoor units located on less exposed façades or rooftops). Smaller commercial premises were assumed to exhibit mixed configurations: a partial penetration of heat pumps, with the remaining fraction served by electric systems or fossil-fuel boilers.
3. Private residential apartments (primary use). In the baseline scenario, heat pumps were considered still limited for winter heating, with a penetration below one quarter of units, in line with typical retrofit dynamics observed in similar contexts.
4. Private apartments used for other purposes (e.g., offices, professional studios). A higher adoption rate of heat pumps for winter heating was assumed compared to

standard residential use, reflecting different occupancy patterns and investment behaviours.

For each category, future scenarios were constructed by progressively replacing boiler-based heating with heat pumps. From an acoustical perspective, this transition is relevant because properties relying on traditional boilers typically present no comparable outdoor point sources attributable to the heating system. Conversely, heat pump retrofits introduce new outdoor sound sources (compressor and fan-related emissions), potentially affecting both façade receivers and the urban sound field.

To represent this change in a tractable way at district scale, each retrofitted unit (or building subsystem, depending on the category) was assigned one equivalent outdoor source. The use of a single representative source per unit is a modelling compromise that preserves scenario comparability while avoiding an unmanageable proliferation of sources in the urban model. This choice was aligned with local prescriptions and common installation practices, as captured in municipal guidance and technical recommendations.

Because source location strongly affects immission, a hierarchical set of siting rules was applied to define plausible installation positions while prioritising less exposed façades. The rules were designed to mimic typical “best-practice” choices under space constraints and were applied consistently across the building stock:

- For buildings with multiple façades, outdoor units were preferentially located on façades not facing the main road, in order to reduce direct exposure at the most noise-sensitive street front.
- Where present, façades overlooking internal courtyards were prioritised, reflecting common retrofitting solutions in compact urban blocks.
- For top-floor units and buildings with flat roofs, outdoor units were located on the rooftop, consistent with frequent practice when façade space is limited.
- For buildings with only street-facing façades, a pragmatic placement was assumed above the entrance area, representing a recurring solution in constrained layouts.

The type of HVAC/heat-pump system assigned to each property depended on building size and use. Small-scale properties were represented using split or hybrid configurations, whereas larger buildings were modelled using multi-split/VRV–VRF-type architectures. These selections were informed by studies addressing HVAC typologies and retrofit choices for buildings and blocks in comparable climatic and construction contexts.

To prevent under- or over-estimation in the absence of accessible floor plans or indoor inspections, a normalised sizing rule was adopted. When internal data were unavailable, a nominal capacity of 8 kW per 100 m² was assigned. This scaling provides a consistent basis for associating each retrofit with a representative heat-pump class, while acknowledging that actual installed capacities may differ depending on envelope performance, occupancy schedules, and design set-points [15-17].

Table 1. Heat pumps - Noise input data (*L_w*, dBA).

Pn (Heating)	Frequency [Hz]							
	63	125	250	500	1000	2000	4000	8000
5-10 kW	75	74	67	62	56	50	45	42
11-20 kW	79	80	75	66	70	62	58	50
21-30 kW	83	85	80	79	75	70	68	63
31-50 kW	84	86	83	80	77	73	65	60
51-100 kW	88	90	82	85	82	70	72	66
>101 kW	91	92	93	84	83	81	67	71

Sound emission input data for the heat pump sources were derived from manufacturer technical documentation for current-generation products. For each nominal power class, the corresponding sound power level was extracted and used as the emission descriptor in the propagation model. The resulting sound power values, grouped by nominal capacity, are summarised in Table 1.

In addition to the district-scale environmental simulations, a set of local assessments was carried out on selected sample buildings to capture effects that may be diluted in large-area noise mapping yet are critical for exposure at the receiver level. The rationale for this coupled strategy is twofold:

- (i) at urban scale, the modelling is primarily aimed at describing the spatial redistribution of sound immission across the neighbourhood under progressive installation scenarios;
- (ii) at building scale, the objective shifts towards quantifying façade sound pressure levels at specific receivers and evaluating the resulting indoor exposure, which directly relates to residential comfort and potential complaints/disputes.

For each selected building, the outdoor units were positioned according to the siting rules described in the scenario section, and the sound pressure level at façade was simulated at receiver points representative of noise-sensitive rooms and/or typical dwelling façades. Receiver locations were defined to reflect realistic exposure conditions (e.g., near windows or along the most exposed façade portions) and to allow comparison between alternative installation configurations (façade vs courtyard vs rooftop) under comparable propagation assumptions. Indoor levels were estimated using the calculation framework provided by ISO 12354 for deriving the acoustic performance of buildings from element properties, specifically adopting the outdoor-to-indoor transmission approach (from external sound field / façade incident level to indoor sound pressure level). In practice, the method was applied by combining: the simulated external level at the façade (as input), the assumed or available façade acoustic descriptors (e.g., glazing type, façade element performance, or representative values when detailed data were unavailable), and room-related parameters required by the ISO 12354 approach (e.g., receiving room characteristics and absorption assumptions), to obtain an estimate of the indoor sound pressure level attributable to the heat pump source. Where direct access to building information was not possible, façade and room parameters were assigned using conservative, literature-informed or code-consistent values to ensure repeatability and avoid optimistic underestimation.

Indoor results were reported using two complementary perspectives:

1. Energetic descriptor – Indoor sound levels were expressed as A-weighted equivalent continuous sound pressure level (LAeq) over the relevant evaluation period. This indicator supports comparability with conventional building and environmental acoustics assessments and provides a direct measure of average exposure attributable to the heat pump contribution.
2. Perceptual/forensic descriptor (intrusiveness) – In parallel, indoor conditions were also interpreted through the intrusive noise framework by applying the method proposed in UNI/TS 11844, which is specifically intended to evaluate situations where a sound component is perceived as intrusive within indoor environments (e.g., due to its prominence, detectability, or disturbance potential), even when absolute levels are moderate. This second representation is particularly relevant for heat pump noise, given its potential tonal or narrowly banded features and its ability to emerge above quiet indoor backgrounds, especially during evening/night-time operation. The UNI/TS 11844 -based outcome was therefore used to complement

L_{Aeq} by providing an assessment lens more closely aligned with the perceived intrusiveness that often triggers complaints and disputes.

The evaluation procedure outlined in UNI/TS 11844 involves the measurement of both environmental and background noise levels, followed by the estimation of the intrusive component attributable to the specific source under investigation. This approach facilitates a systematic and reproducible assessment of acoustic intrusiveness in complex auditory environments. The analytical procedure for assessing intrusive noise involves determining the contribution of the specific source under investigation, denoted as *L_s*, using the following expression the analysis procedure includes determining the noise from the specific source under examination, denoted as *L_s*, using the following relationship in Equation (1):

$$L_{Aeqs} = 10 \log (10^{L_{Aeqa}/10} - 10^{L_{Aeqr}/10}) \quad [\text{dB(A)}] \quad (1)$$

where:

- *L_{Aeqa}* is the equivalent continuous sound level of environmental noise [dB(A)];
- *L_{Aeqr}* is the equivalent continuous sound level of background noise [dB(A)];

Equation (1) yields reliable estimates of the source-specific noise level *L_s*, provided that the algebraic difference between environmental and background noise satisfies the following condition (Equation (2)):

$$\Delta L = L_{Aeqa} - L_{Aeqr} \geq 3 \quad [\text{dB(A)}] \quad (2)$$

However, acoustic disturbance is not solely determined by the overall A-weighted sound pressure level. The intrusiveness of a noise source is influenced by several psychoacoustic and contextual factors, including:

- The spectral distribution of sound energy relative to the background noise;
- The presence of tonal components;
- The impulsive nature of the sound;
- The duration and temporal characteristics of the emission;
- The time of occurrence (e.g., daytime vs. nighttime).

To address these complexities, the technical specification UNI/TS 11844 introduces the Detectability Level *D' L*, originally defined by Fidell [10], as a metric for quantifying the perceptual intrusiveness of a sound source relative to background noise. This approach is grounded in Signal Detection Theory (SDT), a psychophysical framework that models an observer's ability to detect a signal in the presence of masking noise.

The detectability index for a given frequency band *ii*, denoted *d'_i*, is computed:

$$d'_i = \eta \sqrt{BW_i} \times \frac{10^{(L_{si}/10)}}{10^{(L_{ri}/10)}} \quad (3)$$

where:

- *η* is the assumed efficiency of the human observer, typically set to 0.4 based on empirical studies;
- *BW_i* is the bandwidth of the *ii*-th third-octave frequency band;
- *L_{si}* is the sound pressure level of the source in the *i*-th band [dB];
- *L_{ri}* is the sound pressure level of the background noise in the same band [dB].

To obtain the cumulative detectability index d_c' across N frequency bands, the following expression is used:

$$d_c' = \sqrt{d_1^2 + d_2^2 + d_3^2 + \dots + d_n^2} \tag{4}$$

The final Detectability Level $D' L$ is then calculated as:

$$D' L = 10 \log(d_c') [dB] \tag{5}$$

The value of $D' L$ is directly proportional to the perceptual intrusiveness of the noise source. Higher values of $D' L$ indicate greater detectability and, consequently, a higher degree of intrusiveness. This parameter offers a more nuanced assessment than global A-weighted levels, as it incorporates spectral characteristics and psychoacoustic sensitivity across frequency bands. To evaluate the variability of $D' L$, all possible combinations of third-octave band spectra for the source and background noise were analysed. The methodology is detailed in Annex A of the UNI/TS 11844 standard. The resulting optimal numerical scale for $D' L$ is presented in Table 1, providing a standardized reference for assessing acoustic intrusiveness.

Table 2. *Intrusiveness Magnitude.*

D'L	Magnitudo of Intrusiveness
<13	Negligible
13<D'L<18	Very low
18<D'L<23	Low
23<D'L<33	Medium
33<D'L<43	High
D'L>43	Very high

The calculation of $D' L$, which is based on the signal-to-noise ratio between the spectra of the specific source and the background noise, considers the possible presence of tonal components as well as impulsive events both known to distribute their energy across all frequency bands. Furthermore, comparing these spectra enables the identification of frequency bands with the highest $D' L$ values, thereby supporting targeted interventions aimed at reducing noise intrusiveness.

3 Results and discussion

A The results are presented according to the multi-scale framework described in Materials and Methods. First, we report the neighbourhood-scale outcomes of the environmental simulations, providing spatially resolved indicators for the entire district. These outputs are summarised through noise maps for both daytime and night-time reference periods, enabling a direct comparison between baseline conditions and future deployment scenarios. Second, we complement the district-wide view with building-scale analyses performed on a set of representative sample buildings, where the modelling focuses on sound pressure levels at façade receivers and indoor sound pressure levels obtained through the outdoor-to-indoor transmission procedure. This combined presentation is intended to connect urban-scale immission patterns with the outcomes most directly related to dwelling-level acoustic comfort. Although the EPBD driven trajectory points towards a progressive phase-out of fossil-fuel-based heating, a fully comprehensive and immediate conversion of the existing

stock is not considered realistic in the short-to-medium term for the investigated urban area. The studied district includes buildings with heterogeneous construction periods and technical constraints, and the feasibility of retrofits is moderated by economic capacity, space availability for installations, administrative/heritage restrictions, and local acceptance factors. In particular, portions of the historic centre are subject to constraints consistent with cultural heritage preservation, which may limit the speed and extent of system replacement and the range of viable outdoor-unit placements. For these reasons, we adopted a conservative scenario in which less than half of the buildings undergo conversion to ZEB compatible solutions or are equipped with renewable-based heating systems within the considered time horizon. Following the assumptions introduced in the scenario definition, the simulation workflow generated two future scenarios for each reference period (daytime and night-time). The corresponding future noise maps are reported in Figure 2, where spatial changes relative to the baseline are visualised across the study area. Separating daytime and night-time results is essential because heat pump operating regimes, background sound levels and the potential for disturbance may differ substantially between these periods, and identical absolute immission values can have different implications in terms of detectability and perceived impact.

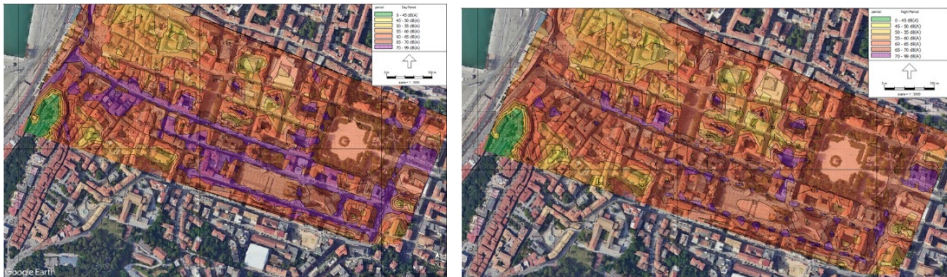


Fig. 2. Noise Mapping-Future. (a) Day Period, (b) Night Period

To maintain continuity with previous assessments, scenario outcomes were also extracted at a set of control points corresponding to those used in earlier evaluations. At these locations, computed values were grouped by daytime and night-time periods and are reported in Table 3.

Table 3. Comparison Actual vs Future scenarios (*H* receivers = 1,5m)

Reference Point	Laeq Day [dBA]			Laeq Night [dBA]		
	Actual	Future	Δ dB	Actual	Future	Δ dB
1	57,4	63,5	6,1	53,3	62,8	9,5
2	70,0	71,5	1,5	66,0	68,4	2,4
3	74,0	76,6	2,6	70,2	72,7	2,5
4	61,6	62,8	1,2	57,6	60,1	2,5
5	62,5	64,6	2,1	58,6	61,1	2,5
6	70,9	71,3	0,4	66,9	67,9	1,0
7	54,8	55,5	0,7	50,8	52,5	1,7
8	68,0	68,0	0	64,0	64,1	0,1
9	54,8	62,9	8,1	50,7	62,3	11,5
10	69,0	69,1	0,1	65,0	65,2	0,2

The reference points are shown in Figure 3.



Fig. 3. Reference points positions, used for measurements and calibrations.

Local-scale results are presented for the selected sample buildings, providing estimated façade sound pressure levels at representative receiver points and the corresponding indoor sound levels derived from the outdoor-to-indoor calculation method. Importantly, the sample buildings were intentionally chosen in the vicinity of the control/reference points used for the neighbourhood evaluation. This spatial coupling strengthens the cross-scale interpretation in two ways: it links the building-scale façade and indoor estimates to the same spatial anchors used to summarise the environmental maps, and it enables comparison against the baseline environmental sound levels previously characterised at those reference locations. As a result, local results can be interpreted not only in terms of incremental contributions from future heat pump deployment, but also relative to the existing acoustic context, supporting a more robust discussion of detectability, potential intrusiveness and plausibility of local impacts. Indoor outcomes are reported using two complementary perspectives: A-weighted equivalent continuous sound pressure level (L_{Aeq}), as an energetic descriptor of exposure, and an intrusive-noise interpretation to reflect conditions in which heat pump noise may become perceptually prominent within dwellings even at moderate absolute levels. The combination of neighbourhood maps, control-point metrics and building-scale indicators is intended to provide a coherent picture of how distributed heat pump adoption may translate into both urban soundscape changes and dwelling-level acoustic consequences [18,19]. Table 4 reports the indoor sound pressure levels calculated for the dwellings selected as reference buildings in the local-scale analysis. Indoor levels were derived from the simulated façade sound pressure levels by applying the outdoor-to-indoor transmission method described in the ISO 12354 framework, under a set of conservative yet realistic building-acoustics assumptions. In particular, the building envelope was assumed to provide a minimum façade sound insulation consistent with the requirements of the Italian regulation DPCM 5 December 1997, which establishes threshold values for acoustic performance in residential buildings. This assumption reflects a lower-bound performance level for existing dwellings and allows the results to be interpreted as representative of ordinary housing conditions rather than optimised or newly refurbished façades.

Moreover, the receiving rooms were modelled as furnished residential interiors, assuming the presence of typical furniture and finishes and, consequently, indoor absorption conditions compatible with normal dwelling use. This choice avoids the unrealistic representation of empty rooms and ensures that calculated indoor levels correspond to plausible occupancy scenarios. Indoor results (Table 4) are presented using two complementary indicators: the

A-weighted equivalent continuous sound pressure level (LAeq), which provides an energetic measure of exposure, and the outcome of the intrusive-noise evaluation, aimed at identifying situations in which heat pump noise may emerge perceptually within the indoor environment despite moderate absolute levels. This dual representation supports a more comprehensive interpretation of potential acoustic impacts on occupants, linking quantitative level estimates with qualitative aspects of indoor acoustic comfort.

Table 4. *Indoor results at control points.*

CP	Laeq Day [dBA]			Laeq Night [dBA]		
	Facade	Indoor	D'L	Future	Indoor	D'L
1	63,5	25,1	16	62,8	24,4	17
2	71,5	33,1	21	68,4	30	20
3	76,6	38,2	26	72,7	34,3	23
4	62,8	24,4	16	60,1	21,7	14
5	64,6	26,2	17	61,1	22,7	14
6	71,3	32,9	21	67,9	29,5	21
7	55,5	17,1	13	52,5	14,1	12
8	68	29,6	20	64,1	25,7	18
9	62,9	24,5	16	62,3	23,9	17
10	69,1	30,7	20	65,2	26,8	19

4 Conclusions

The building-scale analysis indicates that the predicted indoor sound pressure levels associated with the simulated heat pump installations are, in general, relatively low. When expressed as A-weighted equivalent levels (LAeq), indoor values are found to be mostly acceptable in both the daytime and night-time reference periods for the sampled dwellings. Exceptions are limited to specific locations where the indoor level is not driven by the heat pump contribution alone, but rather by the combined effect of the added source and the pre-existing urban noise climate. In these cases, the current outdoor environment, already characterised by non-negligible sound immission, acts as a background component that increases the overall indoor energetic indicator, making some receivers more critical than others even under the same heat-pump emission assumptions. A consistent picture also emerges when indoor outcomes are interpreted through the intrusive-noise framework. The UNI/TS 11844-based assessment predominantly yields low to medium intrusiveness classes, suggesting that, for the majority of cases considered, the heat pump contribution is not expected to generate highly intrusive indoor conditions. Importantly, this aligns with the LAeq-based findings: situations that remain energetically moderate tend to also fall within non-critical intrusiveness ranges, supporting the overall coherence of the multi-indicator approach. However, the indoor results must be read in light of a key modelling assumption regarding façade performance. The outdoor-to-indoor calculation was conducted by adopting a façade sound insulation descriptor $D_{2,m,nT,w} = 40$ dB, chosen to represent a minimum compliance level consistent with the national regulatory baseline for residential buildings. This assumption is intentionally conservative in the sense of representing a lower bound for compliant buildings; nevertheless, it is also a critical sensitivity driver for indoor exposure. Because the indoor level is strongly dependent on façade insulation, deviations from this

assumed value can lead to appreciable differences in predicted indoor conditions. In this respect, the presence of buildings constructed before 1997 introduces a relevant uncertainty: for parts of the existing stock predating the introduction of the referenced minimum requirements, it is plausible that in some cases the actual façade insulation may be lower than 40 dB. Under such circumstances, the same outdoor immission would translate into higher indoor sound levels, increasing both the energetic exposure (LAeq) and the probability that the noise becomes more perceptually prominent. Consequently, the intrusiveness classification could shift from low/medium towards high intrusiveness, which would be particularly penalising for occupants, especially in quiet indoor contexts or during night-time, where intrusive noise can interfere with rest and domestic activities. This highlights that compliance-oriented façade assumptions, while necessary for standardised modelling at district scale, may underestimate impacts for portions of the older building stock, and reinforces the value of combining urban-scale predictions with targeted building diagnostics when prioritising mitigation. Overall, the indoor findings confirm that, under minimum-law insulation assumptions, heat pump deployment is unlikely to cause widespread critical indoor exposure in the investigated scenario; nevertheless, they also show that local vulnerabilities exist where baseline urban noise is already significant and where façade insulation may be substandard. These cases should be considered as priority targets for preventive measures, including improved installation choices (location and mounting), vibration control, and, where feasible, façade performance upgrades, to avoid disproportionate burdens on residents in the most sensitive dwellings.

References

1. H. Zhang, K. Hewage, H. Karunathilake, H. Feng, R. Sadiq, Research on policy strategies for implementing energy retrofits in the residential buildings. *Journal of Building Engineering* 43, 103161 (2021). <https://doi.org/10.1016/j.jobe.2021.103161>.
2. United Nations Environment Programme (UNEP), 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. UNEP, Nairobi (2021). <https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction>.
3. European Commission, Energy performance of buildings (recast). European Parliament legislative resolution of 12 March 2024 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast). European Union, Brussels (2024).
4. A. Stechemesser, et al., Climate policies that achieved major emission reductions: Global evidence from two decades. *Science* 385(6711), 884–892 (2024). <https://doi.org/10.1126/science.adl6547>.
5. A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings* 43(4), 971–979 (2011). <https://doi.org/10.1016/j.enbuild.2010.12.022>.
6. D. D’Agostino, F. Minelli, F. Minichiello, N. Russo, The impact of the new EPBD “Green Houses” in the Italian building context: Technical-economic analysis on improving the energy class of existing buildings. *E3S Web of Conferences* 523, 04005 (2024). <https://doi.org/10.1051/e3sconf/202452304005>.
7. S. Sangsinsorn, B. Nienborg, Noise Immissions by Air Source Heat Pumps: A Case Study in Germany. *Building and Environment* (2025), 113037.

8. T. Gindre, T. Oltersdorf, C. Vering, J. Emhofer, C.R. AIT, K.A. DTI, Report on Task 4: Analysis of the Effect of Operating Conditions of Heat Pumps on Acoustic Behaviour. (2020).
9. S. Wagner, X. Carniel, J. Rohlfing, K. Bay, H. Hellgren, Acoustic signatures of heat pumps: Part 9-3 Overview on heat pump component noise and noise control techniques. IEA HPT Annex 51 Final Report (2020). <https://etkhpcorderapi.extweb.sp.se/api/file/2167>.
10. F. Serpilli, S. Di Loreto, V. Lori, S. Montelpare, Noise and Legal Dispute: Applications and Limits of the Italian Standard UNI/TS 11844. Standards 3, 373–384 (2023). <https://doi.org/10.3390/standards3040026>.
11. F. Serpilli, V. Lori, The acoustic impact of the new EPBD4 in urban context. Building Acoustics (2025). <https://doi.org/10.1177/1351010X251389688>.
12. I. Delponte, V. Bianco, V. Costa, The role of non-energy impact assessment in boosting energy efficiency and urban regeneration projects: the RenOnBill project and experiences from Liguria Region. Energies 15(11), 4093 (2022).
13. C. Xue, M. Shahbaz, Z. Ahmed, M. Ahmad, A. Sinha, Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? Renewable Energy 184, 899–907 (2022). <https://doi.org/10.1016/j.renene.2021.12.006>.
14. A.R. Suppa, I. Ballarini, Supporting climate-neutral cities with urban energy modeling: a review of building retrofit scenarios. Sustainable Cities and Society 98, 104832 (2023).
15. L. Gibbons, S. Javed, A review of HVAC solution-sets and energy performance of nearly zero-energy multi-story apartment buildings in Nordic climates. Energy 238, 121709 (2022). <https://doi.org/10.1016/j.energy.2021.121709>.
16. A.S. Gaur, D.Z. Fitiwi, J. Curtis, Heat pumps and our low-carbon future: A comprehensive review. Energy Research & Social Science 71, 101764 (2021).
17. S. Hinterseer, T. Bednar, Noise Emissions of Air Source Heat Pumps – Defrosting Cycle. (2018).
18. S. Di Loreto, F. Serpilli, V. Lori, Soundscape Approach in the Seaport of Ancona: A Case Study. Acoustics 4(2), 492 (2022).
19. S. Di Loreto, A. Ricciutelli, V. Lori, F. Serpilli, S. Montelpare, Pattern recognition and neural networks for acoustic monitoring and conservation of the historic port of Ancona. CEUR Workshop Proceedings (2024), p. 38.