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# SIMULATION-BASED ANALYSIS OF THE SOUND EMISSIONS OF DECENTRAL AIR-TO-WATER HEAT PUMPS IN RENOVATED MULTI-FAMILY BUILDINGS

**William Monteleone**[1*] **Fabian Ochs**[1]
[1] Unit for Energy Efficient Building, University of Innsbruck, Austria

## ABSTRACT

To decarbonize Europe's building stock by 2050, renovation rates must rise, and fossil-based heating systems must be phased out. Heat pumps (HPs) are central to this effort, but their installation in multi-family buildings presents challenges like space limitations, noise, and invasive infrastructure work. As part of the "PhaseOut" research project, seven multi-family buildings in Vienna will undergo renovations. Each will use a centralized, speed-controlled monobloc air-to-water HP for space heating. The feasibility of decentralized, façade-integrated mini-split air-to-water HPs for domestic hot water will also be explored. To support this, 3D simulation models of a single façade-integrated HP will be created using COMSOL and CadnaA, a commercial acoustic modeling tool. Both platforms will then be used to assess the acoustic impact of multiple HP units installed on façades, highlighting differences in modeling approaches. Simulations in CadnaA will also evaluate the environmental sound pressure levels on the renovation site. Preliminary findings show that sound emissions from decentralized HP units remain within legal limits at the property boundary. However, while tools like CadnaA effectively estimate sound levels across broad areas, they struggle to model near-field acoustics and complex interactions from multiple noise sources with high precision.

**Keywords:** *Heat pumps; renovation; multi-family buildings; sound emissions; simulation*

**Corresponding author: william.monteleone@uibk.ac.at*


## 1. INTRODUCTION

In nearly-zero energy buildings (nZEBs) a combination of adequate insulation of the building and efficient heat pump (HP) based hydronic systems is required [1,2] to reach the goal of the European Union of a fully decarbonised building stock by 2050 [3]. For existing multi-family buildings, the energy performance of the building envelope can be improved fast and reliably by means of serial prefabricated retrofit solutions [4]. In prefabricated renovation solutions, most of the work can be performed off-site to reduce the installation time and disruption to the building tenants. Moreover, decentral air-source heat pumps can be efficiently integrated in prefabricated façade elements, thereby reducing the amount of disruptive and cost-intensive installation work within the flat, as shown in [5] and [6]. For prefabricated façades with integrated building services, an integral design and analysis approach which unites building physics, thermodynamics and architecture is required [7]. However, one of the main concerns for the extensive acceptance of HPs in residential buildings is noise [8] and the actual legislative framework in Europe does not accurately consider the relationship between HP placement and its operational state [9,10], as frequently the sound power level reported in technical datasheets is not measured at full capacity. Within the Austrian research project PhaseOut [11], seven identical social housing multi-family buildings in Vienna, with each six flats, will be renovated. In two of them, a silent façade-integrated mini-split HP for flatwise domestic hot water (DHW) preparation, installed in a prefabricated timber frame façade, will be installed, while space heating (SH) will be provided by two external monobloc air-to-water HPs. First, the analysis will focus on the comparison between a 3D COMSOL [12] simulation model of the sound propagation around a single façade-integrated mini-split HP and a 3D simulation model developed within the environment of the commercial software of CadnaA [13]. Then a 3D simulation will be performed in both simulation programs considering the sound emissions of three façade-integrated HPs to evaluate the modelling of interference patterns. Finally, simulations within the software environment will assess the sound propagation on the whole renovation site (i.e. for all seven buildings) and the resulting sound pressure level considering only the decentral DHW HPs will be compared with the limits imposed by the existing regulations. Based on the simulation results, recommendations are made for the creation of a reduced-order simulation model for the pre-design of HP systems.

## 2. RENOVATION CONCEPT

The mini-split HP concept developed within the research project "PhaseOut" is depicted schematically in Figure 1. The system combines a façade-integrated outdoor unit including the evaporator and four parallel axial fans with an indoor unit housing the compressor, the condenser and the expansion valve. The HP indoor unit is in turn connected hydraulically with a compact 120 Litres hot water storage for the delivery of the DHW demand. The nominal HP heating capacity corresponds to 1.5 kW (A2W55) at an airflow rate of 350 m$^3$/h. A 2.73 x 2.73 m timber frame test façade was built to measure the HP performance under real operating conditions and installed in a so-called PASSYS test cell [14] at the University of Innsbruck, as shown in Figure 2. The outdoor unit of the mini-split air-to-water HP is integrated in a 120 x 60 x 20 cm niche within the test façade (see lower casing in Figure 2). The back side of the outdoor unit is further insulated towards the inside with a 5 cm aerogel layer (see also Figure 1). A vapour barrier is inserted between the prefabricated façade and the existing wall. Seven three-storey multi-family houses will be renovated in Vienna, Austria. Each building consists of six flats (see also Figure 3), with an average flat size of 55 m$^2$. SH in the flats is provided currently mainly by decentral gas boilers or electric ovens, while DHW is either supplied by electric boilers or by the same gas-fired boiler used for SH, if existing.

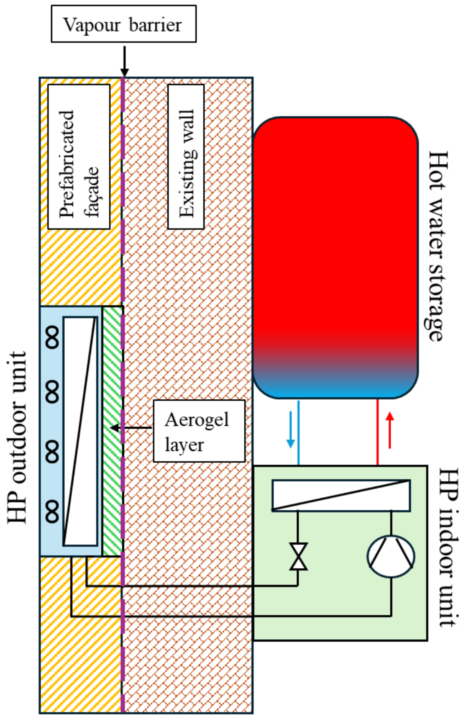


**Figure 1.** Schematic drawing of the developed façade-integrated air-source mini-split-type HP.

**Figure 2.** Outdoor unit of a façade-integrated mini split air-to-water heat pump for domestic hot water installed at the University of Innsbruck.

Figure 4 gives an aerial overview of the seven buildings subjected to renovation as well as an indication of the property limit (red dotted line), which is crucial for the evaluation of the sound emissions. Each of the seven buildings will undergo deep renovation to achieve a heating demand of 25 kWh/($m^2$ y). Buildings 1 and 4 will be equipped with two centralised speed-controlled air-to-water HPs with a nominal thermal capacity of 5.3 kW each (A2W35) supplying low-temperature water to a water-to-water speed-controlled 7.2 kW (W15W55) booster HP in each flat for SH and DHW preparation. For buildings 2 and 7 the SH demand will be covered by two centralised air-to-water HPs, identical to those in buildings 1 and 4, while DHW preparation will be provided through the developed façade-integrated mini-split air-to-water HP on the south-east façade (see Figure 1, Figure 2 and Figure 3). Buildings 3, 5 and 6 will feature instead a fully centralised system with two monobloc 5.3 kW speed-controlled air-to-water HPs identical to those in the other buildings, one for SH and one for DHW.

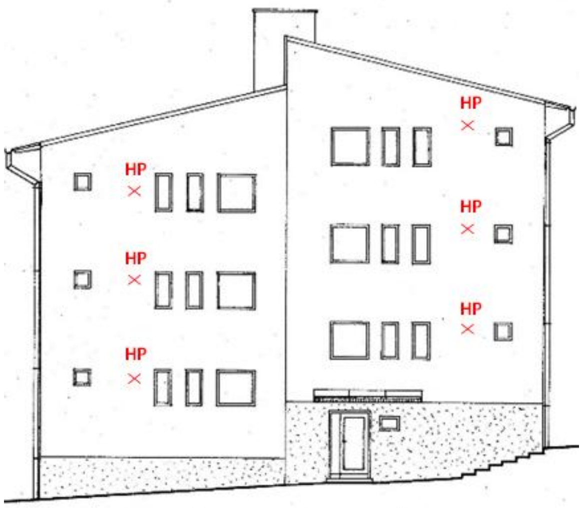


**Figure 3.** Drawing of the east façade of one of the three-storey buildings subjected to renovation in Vienna within the research project "PhaseOut" with indication of the possible position of the façade-integrated DHW HP.


**Figure 4.** Aerial view of all seven buildings on the renovation site located in Vienna with indication of the property limit (dotted red line).

## 3. REGULATORY FRAMEWORK

In Austria, environmental noise propagation is assessed based on ÖNORM S 5021, ÖAL Guideline No. 6 (Austrian Noise Abatement Association), and relevant Federal Province regulations. ÖNORM S 5021:2017 establishes planning values for noise emissions, considering both location (zone) and time of day.

For urban residential areas, the reference sound pressure levels are:

- 55 dB(A) from 6 a.m. to 7 p.m.
- 50 dB(A) from 7 p.m. to 10 p.m.
- 45 dB(A) from 10 p.m. to 6 a.m.

According to ÖNORM S 5021 and ÖAL Guideline No. 6, a continuously operating system (e.g., heat pumps) is deemed non-intrusive if the sound pressure level at the property boundary remains below the base level. This base level is generally approximated as 10 dB lower than the permitted assessment level [15]. Therefore, in the absence of more detailed in-situ measurements, the critical conditions are expected to occur at night and a maximum sound pressure level of 35 dB(A) must not be exceeded at the site boundary.

## 4. METHODOLOGY

For the simulations model in COMSOL, the measured sound power level of the outdoor unit of the mini-split HP shown in Figure 5 (described also in [16]) was used as a base for the definition of the properties of the sound source.

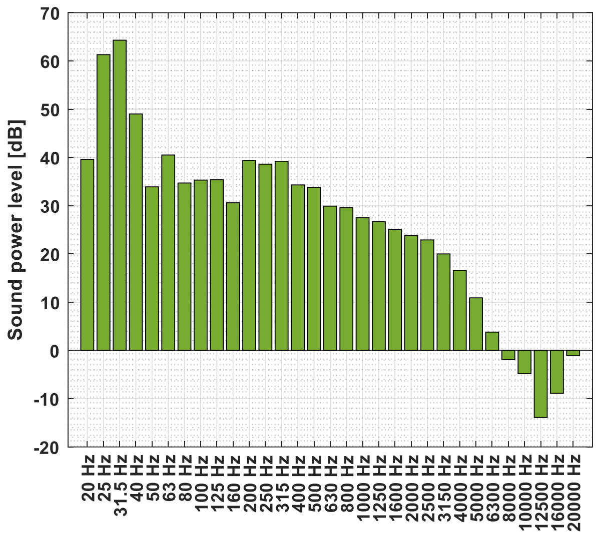


**Figure 5.** Measured sound power level spectrum of the outdoor unit of the façade-integrated mini-split HP.

The analysis is performed at 125 Hz for sake of manuscript length, but the same methodology can be applied to the remaining frequencies in the spectrum.

A first simulation is performed with a single homogeneous sound source, while a second one is performed for three identical sound sources, with a distance of 3 m between one source and the next one. The sound source is placed at a height of 5 m above ground level and the sound pressure level is evaluated on a horizontal plane orthogonal to the sound source(s).

In the CadnaA simulation model the sound source is modelled as a two-dimensional object with the frontal dimensions of the mini-split HP together with the building façade on which it is installed. The sound pressure level $L_r$ in every point of the domain and for each frequency is calculated according to Eqn. (1):

$$L_r = L_w + L_z + K_0 - 20\,\log r - C \;\; / \; [dB] \qquad (1)$$

Where $L_w$ is the sound power level of the sound source, $L_z$ the eventual correction for low-frequency tonalities, $K_0$ the adjustment value for the position of the HP, r the distance from the sound source and C a constant correlating sound power level and sound pressure level, depending on the sound propagation pattern (e.g. hemispherical or spherical). In Table 1 a summary of the applied boundary conditions (BC) for the CadnaA simulations can be found. For the sake of simplicity, it was decided to discard the influence of low-frequency tonalities for the current analysis. The absorption coefficient of the building façade at 125 Hz $\alpha_{f,125}$ is assumed to be equal to 0.05 and the ground absorption coefficient $\alpha_{g,125}$ corresponds to 0.25.

**Table 1.** Summary of selected boundary conditions for the CadnaA simulations.

| BC | Value |
|---|---|
| $L_z$ | 0 dB |
| $K_0$ | + 3 dB (façade installation) |
| C | 8 dB (hemispherical propagation) |
| $\alpha_{f,125}$ | 0.05 |
| $\alpha_{g,125}$ | 0.25 [17] |

In the COMSOL simulations, an air volume of 10 m x 10 m x 10 m is defined for the calculation of the sound pressure level (see Figure 6), which includes a fictitious building façade (highlighted in Figure 6) and the ground. The HP is modelled as a cavity in the air volume and a sound pressure is applied to its front surface. The assigned sound pressure is derived by the measurement of the sound power level shown in Figure 5. An impedance boundary condition is assigned to the building façade and to the ground, with absorption coefficients equal to those presented in Table 1. The remaining surfaces are assumed to be open boundaries. The pressure field within the air domain is solved by the software by means of the Helmholtz equation, shown in Eqn. (2), which applies if no monopole or dipole domain sources are assumed. It is also assumed that the background pressure is zero, so the total sound pressure is equal to the scattered pressure.

$$\nabla \cdot \left( -\frac{\nabla p_t}{\rho_a} \right) - \frac{k^2\, p_t}{\rho_a} = 0 \qquad (2)$$

Where $p_t$ is the total sound pressure in [Pa], $\rho_a$ the density of air in [kg/m$^3$] and k the wave number in [1/m]. To minimize the computational effort of the model, a hybrid FEM-BEM (Finite Element Method – Boundary Element Method) approach was used, with all the surfaces except the façade and the ground acting as a BEM-FEM boundary.

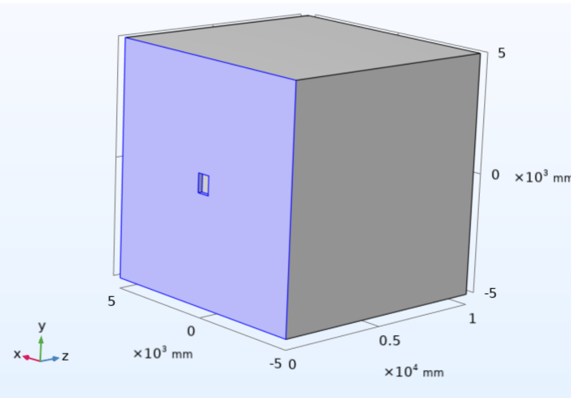


**Figure 6.** Depiction of the control volume of air assumed in COMSOL. The façade of the building is highlighted, and it is possible to see the HP cavity.

Finally, to calculate the sound emissions due to the DHW HPs around the renovation site, a model in CadnaA was built replicating the location and assuming a total of six façade- integrated heat pumps (e.g. one for each flat) on the east-southeast façade of building 2 and six heat pumps on the east-northeast façade of building 7 (see also Figure 3). To check the compliance with the regulations at night, fictitious receivers have been placed at the property boundary at a height of 2 m. The HPs have been modelled in this a case as one-dimensional sound sources.

## 5. RESULTS

The sound pressure level on a 2D plane perpendicular to the sound source is depicted in Figure 7 and Figure 8 for the CadnaA and COMSOL simulations respectively. In Figure 7, ideal receivers on the same plane of the sound source can be scene at distances between 0.5 m and 5 m from the sound source. Compared to CadnaA, the COMSOL simulation in Figure 8 is able to represent in a more detailed the sound propagation pattern caused by a two-dimensional sound source, as the sound propagation deviates from a purely hemispherical pattern for distances higher than about 2.5 m. Evaluating the sound pressure level at 125 Hz on a line perpendicular to the sound source yields the diagram in Figure 9. Below 1 m distance from the sound source a similar decay in the sound pressure level can be observed in both CadnaA and COMSOL simulations. Between 1 m and 2.5 m the COMSOL simulations slightly overestimate the sound pressure level compared to CadnaA and for distances higher than 3 m from the sound source, the profiles deviate.

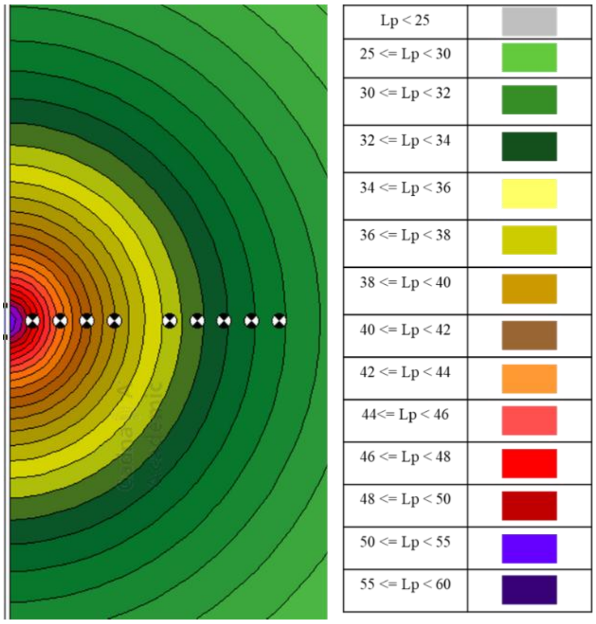


**Figure 7.** 2D plane of the overall sound pressure level in dB generated by a single HP in CadnaA.

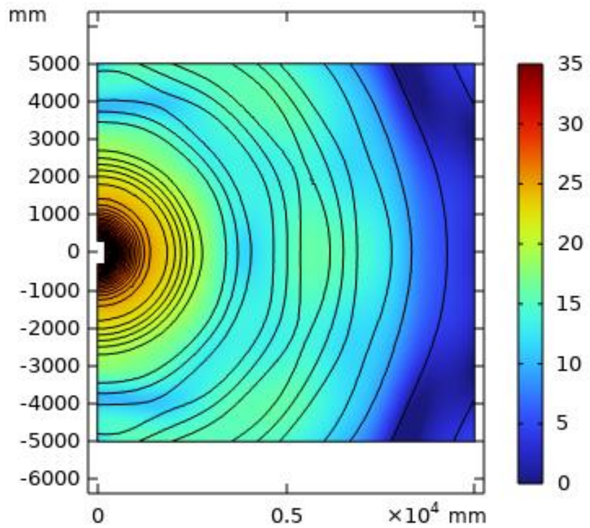


**Figure 8.** 2D plane of the sound pressure level in dB at 125 Hz generated by a single HP in COMSOL.

The differences between the two simulation tools are more clearly visible if three operating HPs are considered, as shown in Figure 10 and Figure 11. While near (within 1 m of) the sound source the sound pressure levels exhibit similar behaviour, as the distance from the HPs grows, the COMSOL simulation is able to reproduce the constructive and destructive interference patterns caused by the simultaneous sound emission of the three HPs and the reflections from ground a façade, while the sound pressure level in CadnaA assumes a more homogenous behaviour.

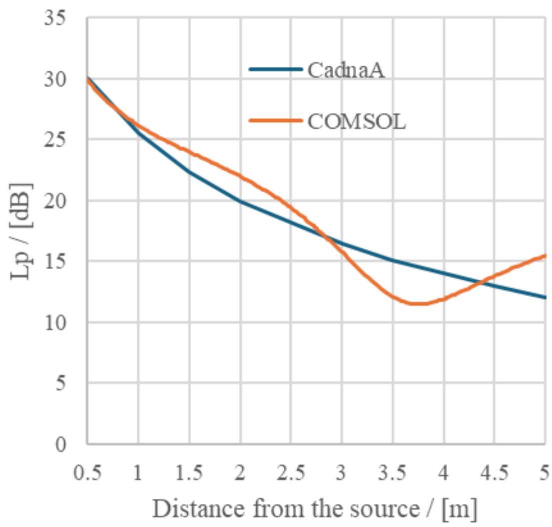


**Figure 9.** Comparison between CadnaA and COMSOL of the sound pressure level at 125 Hz with a single HP on a line perpendicular to the sound source.

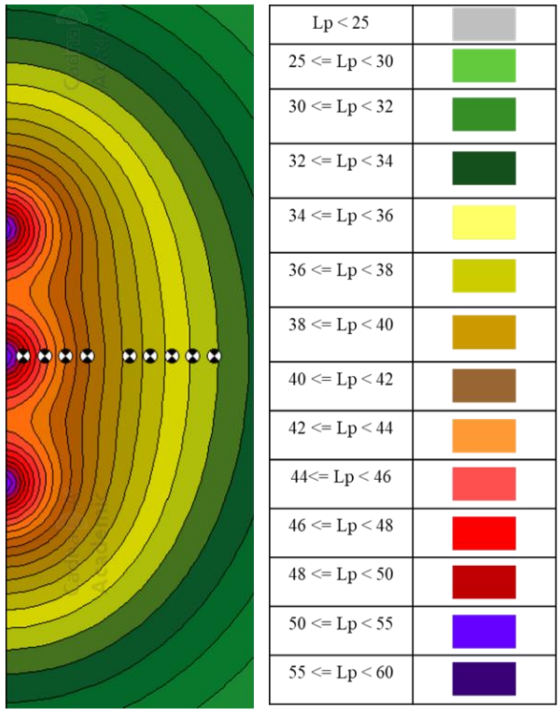


**Figure 10.** 2D plane of the overall sound pressure level in dB generated by three HPs in CadnaA.

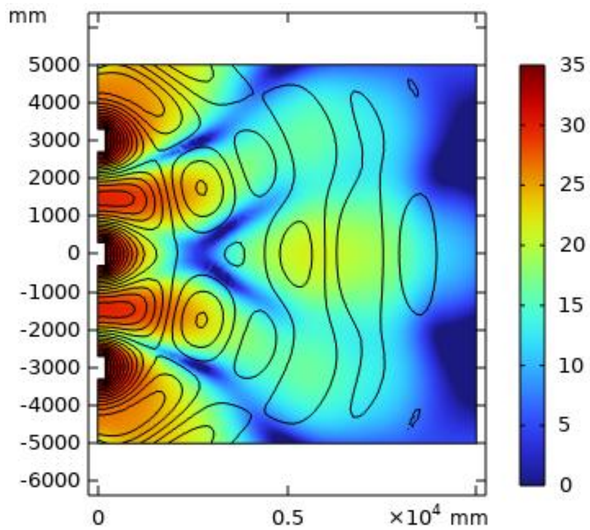


**Figure 11.** 2D plane of the sound pressure

level in dB at 125 Hz generated by three HPs in COMSOL.

As a result, the sound pressure level on a line perpendicular to the central HP in Figure 12 shows large deviations between the CadnaA and the COMSOL model for normal distances from the sound sources higher than 1 m.
Reflections in the COMSOL model contribute therefore first to a reduction in the sound pressure level from 1 m to 2.5 m, with a minimum around 5 dB and then to an increase from 2.5 m to 5 m.

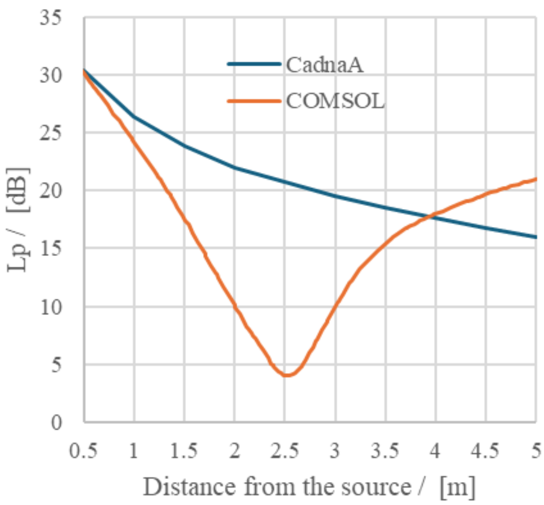


**Figure 12.** Comparison between CadnaA and COMSOL of the sound pressure level at 125 Hz with three HPs on a line perpendicular to the central HP.

In Figure 13 the simulated sound pressure level at 2 m height on the renovation site described in section 2 is observed considering the simultaneous operation of the twelve DHW HPs, six for building 2 and six for building 7. During night, the most critical property boundaries are therefore for building 2 the points exactly in front of the façade where the HPs are installed and for building 7 also the points southeast of the building. The maximum overall sound pressure level (considering only the DHW HPs) at the property boundaries near building 2 corresponds to 20.4 dB(A), while a maximum value of 29.3 dB(A) is observed near building 7 where the distance between sound sources and property boundary is at its minimum. In both cases, therefore, the regulatory limit is met.

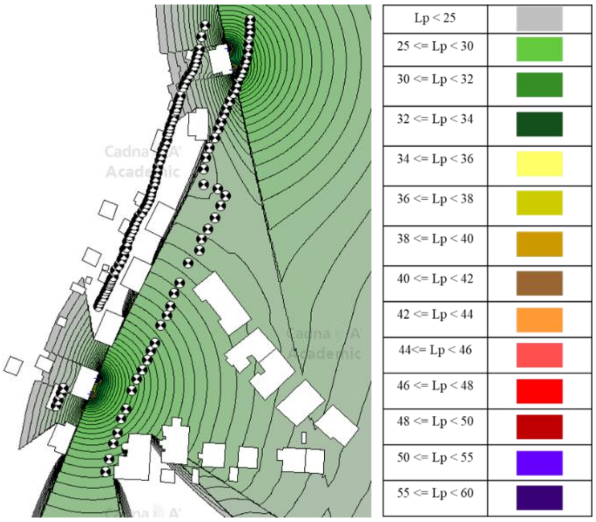


**Figure 13.** CadnaA simulation of the sound pressure level at the renovation site considering only the decentral DHW HPs. Ideal receivers are placed on the property boundary.

## 6. CONCLUSIONS

As part of the PhaseOut research project, seven multi-family buildings will undergo deep renovation. In two of these buildings, domestic hot water (DHW) will be supplied using compact, façade-integrated mini-split air-to-water heat pumps (HPs). This study evaluated the sound pressure levels around the renovation sites using the software CadnaA, specifically considering the nighttime operation of the DHW heat pumps alone.
Simulation results show that the sound pressure level at the property boundary remains below regulatory limits (e.g., 35 dB(A)) even at the shortest distance between the HPs and the boundary, where a value of 29.3 dB(A) was observed.
Additionally, the sound propagation characteristics of a single HP and of three HPs were analysed using two simulation models developed in CadnaA and COMSOL. Both models exhibited similar sound pressure level decay within 1 meter of the sound source. However, when simulating three simultaneous sound sources, significant deviations—up to approximately 15 dB—were observed at greater distances. This discrepancy is attributed to COMSOL's more accurate representation of wave phenomena, in contrast to the more uniform sound propagation observed in CadnaA.
These findings suggest that geometric acoustic simulation tools like CadnaA are more suitable for evaluating HP

installations over larger domains. However, for detailed assessment of sound propagation at short distances—especially in scenarios where HPs are installed close to property boundaries—FEM-based physical models like those in COMSOL offer greater precision.
To validate these results, future measurements will be conducted using a mock-up of a prefabricated timber façade integrated with an integrated mini-split HP. Furthermore, the effect of directional sound sources will be incorporated into the simulation models, and the results will be compared with in-situ measurements.

## 7. ACKNOWLEDGMENTS

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