Thermal and Acoustic Simulation of a Technical Enclosure for High Voltage Control Equipment

Edoardo A. Piana – University of Brescia, Italy – edoardo.piana@unibs.it
Somayan Basu – University of Brescia, Italy – s.basu@unibs.it
Francesco Palone – TERNA Rete Italia SpA, Italy – francesco.palone@terna.it
Simone Sacco – TERNA Rete Italia SpA, Italy – simone.sacco@terna.it
Roberto Spezie – TERNA Rete Italia SpA, Italy – roberto.spezie@terna.it

Abstract

The development of the electric power grid addresses the needs deriving from the growing use of renewable sources and from the dispatching flexibility required by mobility electrification. New infrastructures to control the grid parameters and configuration are also being installed in the urban environment, and the relative equipment must generally be enclosed in technical rooms to prevent unauthorised access. Such enclosures must fulfil two conflicting requirements: on the one hand, they must be closed enough to reduce the potentially disturbing noise emitted by the inner equipment, and, on the other hand, they must feature openings for natural ventilation, as high-voltage elements may get damaged due to overheating. Therefore, cooling and sound insulation aspects must be properly integrated during the design phase, keeping an eye on other potential issues, such as condensation. This paper presents a possible strategy of dual acoustic and thermal simulation applied to the design of a new high-voltage control system that allows the expensive technical equipment to be safeguarded while reducing the risk of noise annoyance.

1. Introduction

As detailed in the Electricity Ten Year Statement (Leslie, 2021), with the growing requirement of having smart electric distribution grids capable of adapting to the different needs of the users, transmission system operators (TSO) are developing new solutions with the aim of achieving a remotely operated fast re-configuration of the power grid (Chen et al., 2016). The expansion of green power and the refurbishment of old plants able to withstand the shortage of natural gas have shown the importance of voltage regulation and reactive power compensation (Leborgne & Stypulkowski, 2017). This situation overlaps with the increasing demand for electricity due to the development of electric vehicles and the ever-growing expansion of air conditioning systems. The need for having a flexible distribution network is even more important in the light of the recent developments related to the international situation.

In many cases, the devices used to re-configure or control the power grid are better integrated into the distribution system if they are placed close to the users, and then in the proximity of residential areas (Cohen et al., 2014). Since these devices are based on mechanisms that, under certain circumstances, can produce noise (Piana et al., 2018), it is important to control the sound emitted by the installations. For TSO it is not possible to decrease the noise emissions through a better design of the source itself. The next step is to work on the structures through the implementation of sound insulating shelters containing the noise sources and the related control systems. One drawback of this type of solution is that, in order to avoid damage due to overheating, the thermal power generated by the current flowing through the conductors must be properly dissipated. A sensible solution to avoid adding further noise sources is the use of natural ventilation (Izadyar et al., 2020). If the shelter is properly designed, the ventilation openings will be responsible for the main noise contributions in the surroundings.

These must be large enough to allow a certain air mass flow and, at the same time, small enough to

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prevent noise spreading in the neighborhood. For this reason, an accurate thermal and acoustic design of the shelter is necessary. The goal of the present article is to give the reader an idea of the procedure that can be adopted to design the openings necessary to guarantee a sufficient degree of cooling to the high-voltage-control equipment contained in the enclosure, assuring, at the same time, that the noise produced by the devices is compatible with the limits applied to very quiet areas. The amount of heat dissipated by the openings can be improved by using conductive materials (Neri & Pilotelli, 2019; Neri et al., 2020).

The study will be carried out through two different types of simulation software: the first one to predict the indoor thermal conditions and the second one to assess the acoustic impact of the installation. The structure of the article is as follows. Section 2 briefly gives the geometric, thermal, and acoustic parameters needed for the simulations. Section 3 describes the thermal model implemented in EnergyPlus. In Section, 4 the outcomes of the thermal simulations in terms of opening dimensions will be used to assess the sound pressure level distribution around the shelter using Ramsete. Finally, Section 5 will draw the conclusions.

2. Materials and Methods

The shelter considered in the present study consists of a single volume having dimensions 7 x 7 x 6 m^3. The size has been specifically chosen by the TSO research and development team so that it can contain all the devices needed to implement the remotely controlled system and all the related auxiliary components, maintaining at the same time a suitable occupation of public land. Due to safety reasons, the main volume must be kept apart from undesired accesses of people and animals. For this reason, the walls and the roof must be made of solid materials. Moreover, the structures must be strong enough to withstand natural events (wind, rain, and snow). For aesthetic reasons, the main volume will be enclosed in a buffer of panels acting as a second skin with camouflage purposes. If properly selected, such panels can also behave as a sound barrier. The distance of the second skin from the main volume is about 500 mm. After a discussion with the technical team responsible for the structural design, it was decided that the panels selected for the main structure can be standard sound-insulating sandwich panels made of two external 1 mm thick steel laminates and a 300 mm gap filled with 70 kg/m^3 stone wool. The aesthetic panels can be selected from a wide range of solutions. For the purposes of the present study, their mass per unit area is of importance since they must behave as sound barriers. For this reason, it was decided that the mass per unit area of such panels must be higher than 30 kg/m^2.

The sound source placed inside the shelter is represented by a set of mechanical switches generating impulsive noise (Fig. 1).

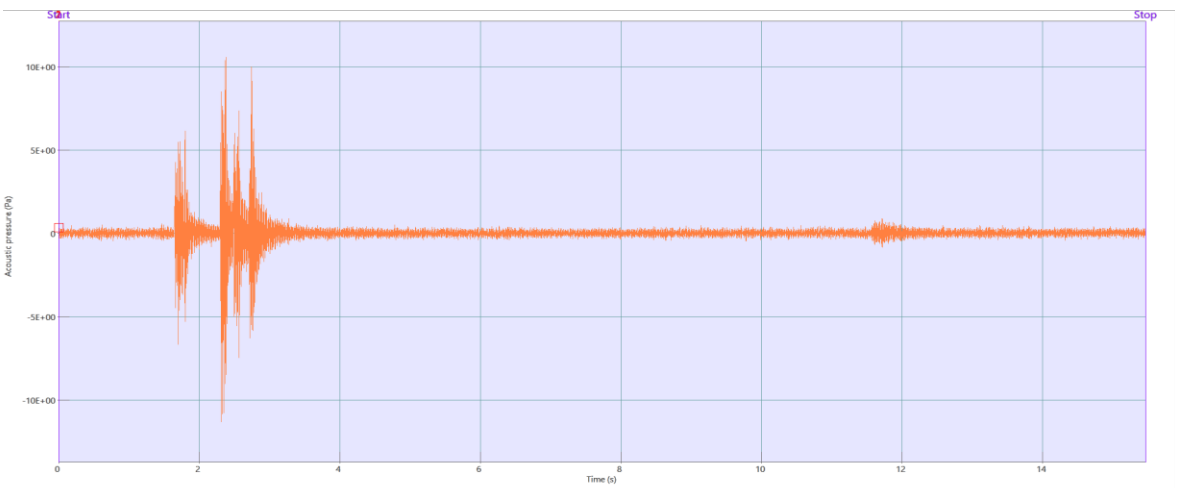

Fig. 1 – Recording of the pressure signal measured at 2 m distance from the switch

The average sound pressure level measured at 2 m distance from one of these switches is reported in Fig. 2. The overall sound energy level due to the single event, according to the international standard ISO 3744 (ISO, 2010), is equal to 114 dB(A) *re* 1pW. It is interesting to note that most of the sound pressure level encompasses between 250 Hz and 20 kHz. This means that, since the sound insulation in the low frequency range is usually dominated by the mass-per-unit area, the required value of this parameter for the panels surrounding the noise sources does not need to be extremely high.

Concerning the thermal simulations, the main parameter to be considered is the thermal power, which needs to be dissipated inside the volume. The current generates heat due to the joule effect. This contribution can be computed once the electric current running through the switching apparatus, the length of the conductors and their resistance known. From a first evaluation of the current (900 A) and of the resistance and length of the conductors, a total thermal power of 4 kW caused by the joule effect can be estimated. In addition, the control and anti-dew systems placed inside the shelter add a further 2 kW to the thermal load, bringing the total amount of thermal power to be dissipated at 6 kW. To prevent damage to the electrical systems, the average temperature inside the volume must be kept below 40 °C.

Fig. 2 – Average sound pressure level measured at 2 m distance from the switch

Since the decision was made to use a natural ventilation system, the amount of heat dissipated depends on the dimensions of the openings and on the external air temperature.

It is known that a fluid possesses a density which decreases with its temperature. If a fluid is less dense than the surrounding one, it tends to shift upwards, generating a convective motion. The two openings of the shelter must be located in such a way that the cold air flowing through the inlet is heated when passing through the volume. The density reduction due to heating generates a convective motion towards the higher part of the shelter, where the air can exit the volume through the outlet. Hence, it is necessary to place the outlet in a position which simplifies the discharge of the warm air. In the simulations, the inlet and the outlet does not have initial mean flow assigned and the pressure is assumed to be atmospheric. Concerning the walls, they are assumed to be rigid but not adiabatic. From this point of view, it is important to find suitable materials possessing both thermal and acoustic properties, as stated by (D'Amore et al., 2020) and (Caniato et al., 2017). The region where the shelter is located is very important. For the purposes of the present study, the thermal simulations were made considering the shelter located in Brescia, northern Italy. The meteorological data of this location, such as the wind speed, the wind direction and the solar gain were given as an input to EnergyPlus.

3. Thermal Simulations

The thermal simulations were carried out using EnergyPlus. A first drawing of the shelter was made in Sketchup. After the work of Correia et al. (2020), and a section of the openings equal to 3 x 1 m^2 to guarantee at least 20 air volume changes each hour was chosen. To exploit the chimney effect due to the different density of the air inside the shelter volume, the two openings (inlet and outlet) have a height difference of 4 m. For the purpose of properly considering the thermal transmittance of the walls, these were virtually assembled in EnergyPlus according to the description given in Section 2 and using the characteristics of the materials shown in Table 1.

The total transmittance for the entire envelope of the main volume is 0.377 W/(m^2 K).

Table 1 – Materials used for the walls of the shelter

Material	Thickness [mm]	Density [kg/m³]	Thermal conductivity [W/(m K)]
Steel plate	1	8000	52
Mineral wool	98	70	0.04
Steel plate	1	7800	52

The thermal load acting on the shelter can be divided into two contributions: the internal thermal load (6 kW distributed on the floor of the main volume) and the solar gain. A reasonably accurate way of simulating the heat source within the volume is to let the heat enter the volume through its floor. This can be considered a reasonable assumption because the components which dissipate heat are located close to the bottom of the shelter. The heat source can be assumed to be a uniformly distributed 122.5 W/m² heat flux, for a total amount to 6 kW.
The solar gain is automatically taken into account by EnergyPlus once the location of the construction is selected as an input.
In the case at hand, the shelter is considered as being situated in Brescia. In this way, EnergyPlus can also consider the average external air temperature, the solar gain and wind speed/direction. These parameters represent the boundary conditions of the simulation. The dataset used encompasses a one-year span, so that the outputs can cover both winter and summer times.
EnergyPlus can give a large number of parameters as outputs. For the present work, the most interesting ones are the average temperature inside the volume, the temperature of the walls and the mass flow rate of the air through the openings. Fig. 3 shows a plot of the mean radiant temperature (black line), the mean air temperature inside the volume (blue line) and the outdoor air temperature (cyan line). In Fig. 4, the mass flow rate of the air running through the openings is given. Fig. 3 and Fig. 4 are yearly-based plots. They can give a reasonable projection of what happens during one "average" year as a function of the meteorological conditions and of the solar gain. It is interesting to note that such simulations give temperatures that are always between -8 °C and 40 °C. This last value represents the limit fixed for the overheating protection of the devices. The natural ventilation of the volume is then able to assure that the temperature is kept below the limit with a certain safety margin, which can be assumed as 4 °C.

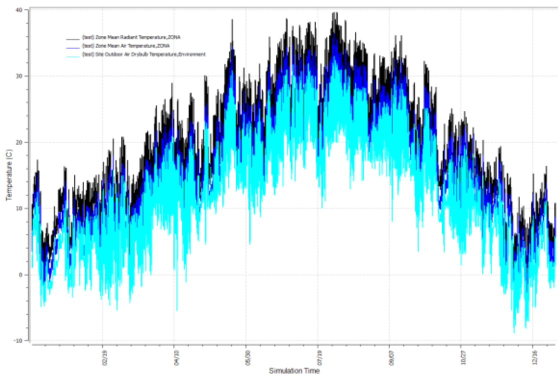

Fig. 3 – Average temperature of the air inside the technical volume of the shelter

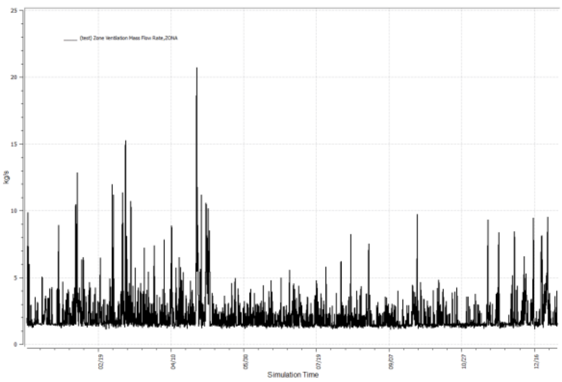

Fig. 4 – Mass flow rate of the air through the openings

Of course, the simulation run assuming a certain location, thus the results cannot be extended to any other possible construction site. The situation can be very different in other contexts like, for example, southern Italy. In this case, a new thermal simulation can be easily made using the specific meteorological dataset of the location chosen as final installation site. In case the proposed dimension of the opening is not sufficient, it can be easily increased, or, in extreme cases, a ventilation system can be added to ensure proper cooling. In the latter case, the noise contribution of the fan must be considered as an additional contribution to the acoustic simulations.

4. Acoustic Simulations

Once the thermal simulation gives feasible results, suggesting a reasonable dimension for the openings, it is possible to run the acoustic simulation to check the sound pressure level distribution around the shelter. The use of acoustic simulation on thin structures was already proved to be effective (Caniato et al., 2020). The simulations were carried out using Ramsete, a software specifically developed for the simulation of the acoustic quality of rooms (Tronchin, 2013), which is also capable of performing the calculation of the noise spreading outdoors (Farina, 2000). One of the characteristics of this software is that it can take sound absorption, sound insulation and the diffraction of the structures into account. This means that the second skin represented by the lightweight panels can be properly represented both in terms of its sound reduction index and diffraction effect. In this sense, the position of the openings is extremely important since the effectiveness of a sound barrier depends on the additional path of the sound wave compared to the direct path. The inlet is placed close to the ground and has an area of 3 x 1 m². The outlet placed on the opposite vertical face of the shelter has the same area, and its lower side is at 4 m from the ground. The walls of the shelter have the sound absorption coefficient and the sound reduction index reported in Fig. 5.

	31 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
α	0.092	0.137	0.277	0.608	0.855	0.840	0.794	0.741	0.679	0.639
R	11.0	17.0	23.4	25.6	30.4	26.6	38.2	44.0	50.0	56.0

Fig. 5 – Sound absorption coefficient α and sound reduction index R – shelter walls

The choice of the material for the aesthetic lightweight panels surrounding the shelter was made by architects. The material chosen for these panels is Perspex. The sound-absorption coefficient and the sound-reduction index of the Perspex panels is shown in Fig. 6.

	31 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
α	0.040	0.070	0.050	0.030	0.020	0.020	0.030	0.020	0.010	0.010
R	16.0	14.0	18.0	24.0	30.0	36.0	42.0	40.0	48.0	56.0

Fig. 6 – Sound absorption coefficient α and sound reduction index R – aesthetic walls (Perspex glass)

Fig. 7 shows a 3D sketch of the acoustic model imported in Ramsete. The model can give the sound pressure level distribution of the sound emitted by the installation as an output. This means that the sound pressure level computed by Ramsete represents only the contribution of the source placed in the shelter, without the contribution of the background noise. According to Italian legislation (Italian Parliament, 1995), the allowed "Emission Level" in built-up areas depends on the destination of the area itself and on the time of day. Considering the daytime (6-22) and the nighttime (22-6), the emission level limits are summarized in Table 2.
Looking at Table 2 and given the intention of installing the shelter in residential areas, it is sensible to design the shelter so that the limits for Class II during the nighttime (40 dB(A)) are fulfilled. Since the final installation site is not known in advance, satisfying the limits for Class I (35 dB(A)) is still a goal that, if possible, represents an optimal achievement for the project.

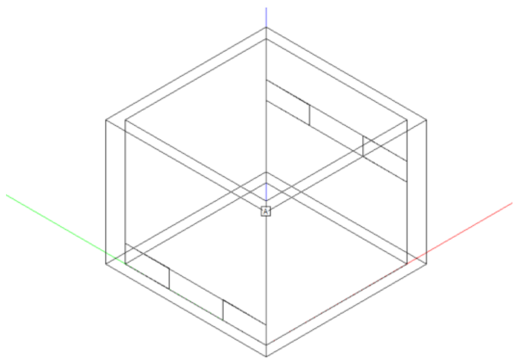

Fig. 7 – Sketch of the acoustic model

Fig. 8 and Fig. 9 show the sound pressure level computed by Ramsete on a horizontal grid of receivers placed at 2 m one from the other, at a height of 1.5 m from the ground and on the vertical mid-section of the shelter, up to a height of 16 m. The sound pressure level inside the shelter is very high and reaches values close to 97 dB(A).

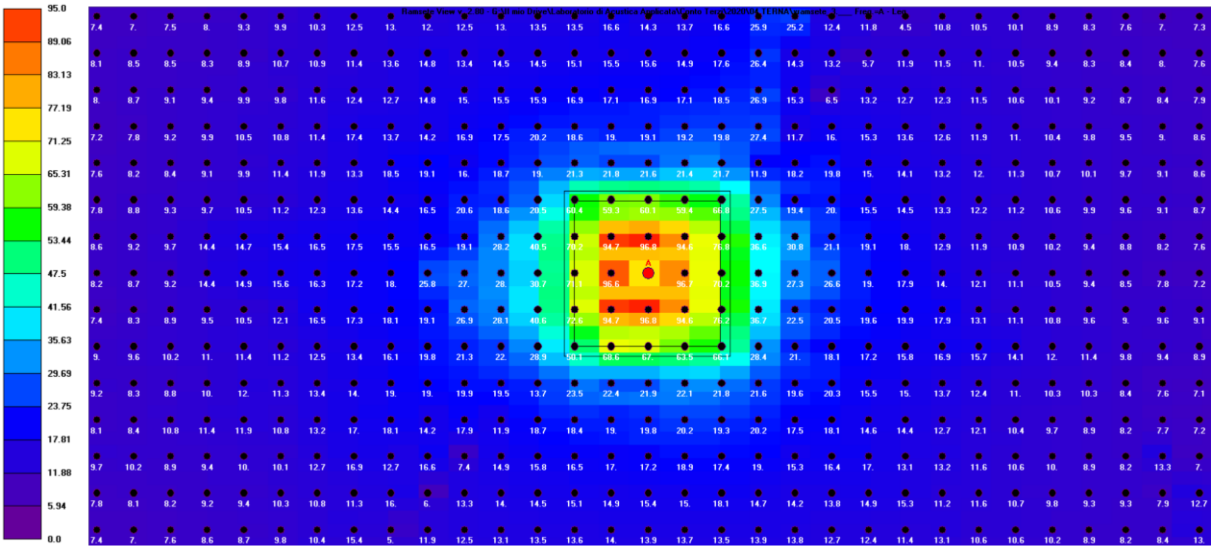

Fig. 8 – Sound pressure level distribution around the shelter – site map

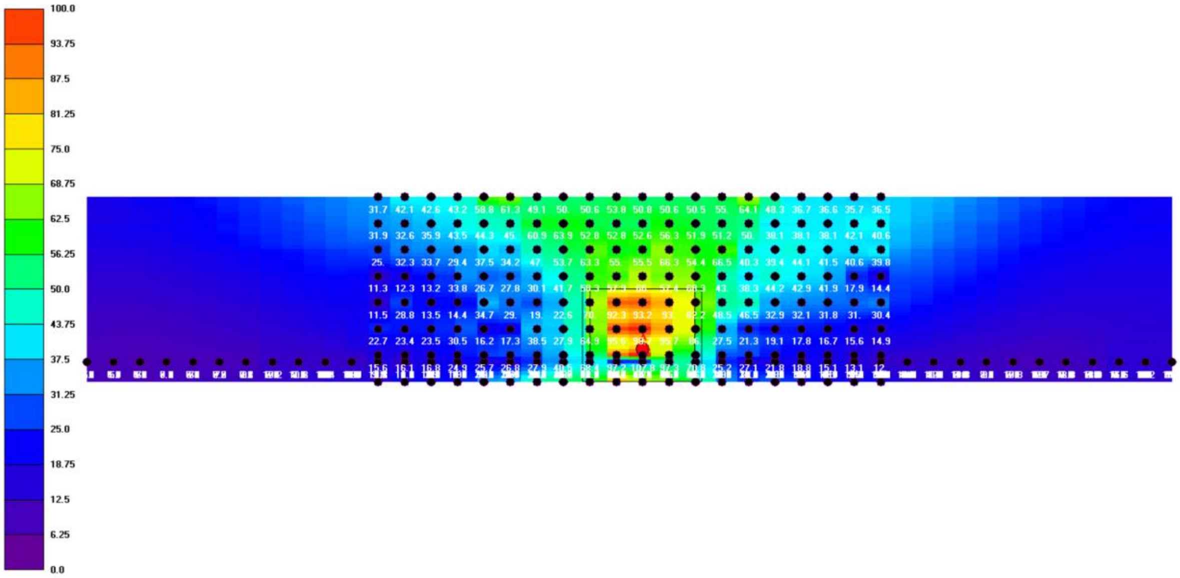

Fig. 9 – Sound pressure level distribution around the shelter – vertical section

Table 2 – Emission level limits

Area destination	Daytime [dB(A)]	Nighttime [dB(A)]
I - Sensitive	45	35
II - Residential	50	40
III - Mixed	55	45
IV - Intense activity	60	50
V - Industrial	65	55
VI – Excl. industrial	65	65

It is important to note that, for keeping sound pressure level as low as possible, the inner side of the shelter walls must feature a certain sound absorption. From Fig. 9 it can be noted also that the sound pressure level in the gap between the shelter and the aesthetic panels depends on the position considered. If a point in front of the opening placed closer to the ground is selected, then the sound pressure level is near 76 dB(A), while on the side where the opening is at 4 m from the ground the sound pressure level is around 72 dB(A). The other two sides of the shelter are characterized by sound pressure levels around 60 dB(A). The result is that,

beyond the aesthetic panel, the sound pressure level is more than acceptable.
Looking at the zones characterized by the higher sound pressure levels, the values at different distances are reported in Table 3.
The sound pressure level values reported in Table 3 show that the sound emission of the shelter is compatible with the limits of Class I starting from 10 m from the wall featuring the air outlet, which is the one giving the highest sound pressure level values. Since it can be expected that no buildings can be erected at a distance lower than 30 m from the shelter, the result achieved allows full compatibility of the installation with the built environment also in the case of the class featuring the lowest emission limits.

Table 3 – Sound pressure levels at different distances from the walls [dB(A)]

Distance [m]	Inlet side	Outlet side
5	30	37
10	19	26
20	10	15

5. Conclusions

A flexible distribution grid, capable of being configured in real time depending on the needs of the customers, is becoming an important point for transmission system operators. This capability has strong advantages when discontinuous green power technologies or loads are integrated in the transmission line. TERNA Rete Italia is working to develop a set of remotely operated systems allowing a fast reconfiguration of the distribution grid.
Since the devices used for the reconfiguration can emit noise and the system is more effective if placed in close vicinity of the users, the acoustic compatibility of this solution with the residential areas is crucial. Nonetheless, assuring acoustic compatibility requires the noisy devices to be enclosed in a shelter having sufficient sound insulation and, at the same time, the capability of allowing a certain cooling of the high voltage systems contained in it.

The present paper presented the thermal and acoustic simulations used to verify the compatibility of the system with the noise limits proposed by Italian legislation for a residential area. The study started with the dimensioning of the openings required for cooling the shelter volume. To avoid additional sound sources, reliance on only natural ventilation was chosen. The simulations were carried out using EnergyPlus and considering the solar gain as well as the temperature distribution outdoors across the entire year. As a result, the dimensions and the position of the openings required for a proper cooling were set. The next step was to check the noise emission of the entire installation. The sound power level of the devices to be placed in the shelter was derived from experimental measurements. Using Ramsete software and properly selecting the materials for the walls and the roof of the shelter, it was possible to run the simulations necessary to predict the noise emissions. A big advantage derived from the choice of the architects to improve the visual impact of the installation by placing four “aesthetic walls” around the shelter. Such structures, from an acoustic point of view, act as noise barriers, shielding the sound spreading from the ventilation openings.
Merging the results of the thermal simulations with the results of the acoustic simulations, it was possible to predict the full compatibility of the installation with the limits of Italian legislation for residential areas. Moreover, the sound emissions are so low that compatibility is assured also for sensitive areas featuring the lowest emission limits allowed by Italian legislation.

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