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Research on Battery Electric Vehicles' DC Fast Charging Noise Emissions: Proposals to Reduce Environmental Noise Caused by Fast Charging Stations

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Abstract: The potential of electric vehicles (EVs) to support the decarbonization of the transportation sector, crucial for meeting greenhouse gas reduction targets under the Paris Agreement, is obvious. Despite their advantages, the adoption of electric vehicles faces limitations, particularly those related to battery range and charging times, which significantly impact the time needed for a trip compared to their combustion engine counterparts. However, recent improvements in fast charging technology have enhanced these aspects, making EVs more suitable for both daily and long-distance trips. EVs can now deal with long trips, with travel times only slightly longer than those of internal combustion engine (ICE) vehicles. Fast charging capabilities and infrastructure, such as 350 kW chargers, are essential for making EV travel times comparable to ICE vehicles, with brief stops every 2–3 h. Additionally, EVs help reduce noise pollution in urban areas, especially in noise-saturated environments, contributing to an overall decrease in urban sound levels. However, this research highlights a downside of DC (Direct Current) fast charging stations: high-frequency noise emissions during fast charging, which can disturb nearby residents, especially in urban and residential areas. This noise, a result of the growing fast charging infrastructure, has led to complaints and even operational restrictions for some charging stations. Noise-related disturbances are a significant urban issue. The World Health Organization identifies noise as a key contributor to health burdens in Europe, even when noise annoyance is subjective, influenced by individual factors like sensitivity, genetics, and lifestyle, as well as by the specific environment. This paper analyzes the sound emission of a broad sample of DC fast charging stations from leading EU market brands. The goal is to provide tools that assist manufacturers, installers, and operators of rapid charging stations in mitigating the aforementioned sound emissions in order to align these infrastructures with Sustainable Development Goals 3 and 11 adopted by all United Nations Member States in 2015.

Keywords: battery electric vehicle; DC fast charging; noise pollution; sound emission

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1. Introduction

Electric vehicles (EVs) constitute a viable alternative for the transition towards decarbonizing the current energy model, particularly within the transportation sector. The need to achieve the greenhouse gas emission reduction targets set by the Paris Agreement compels member states to adopt urgent measures in key sectors such as automotive transportation. In fact, one of the strategic objectives is to promote sustainable mobility through the development and implementation of electric vehicles. However, the limitations of electric vehicles, in comparison to fossil fuel-powered vehicles, mean that their adoption still remains limited, despite the numerous advantages they offer over conventional vehicles.

Two of the main limitations of electric vehicles are their range and the time required to recharge the battery. However, both factors have improved significantly in recent years, enabling, in most of cases, not only routine trips but also long journeys without significant differences compared to combustion engine vehicles, currently being between 11% and 27% longer than the time needed for an ICE vehicle [1,2]. It is during these longer trips where the fast charging capability of the vehicle and the charging infrastructure play a crucial role in achieving travel times comparable to traditional vehicles, as both elements significantly affect charging sessions' times. In fact, long journey travel times for EVs are expected to be similar to ICE vehicles' journeys, with a short stop every 2–3 h of driving, thanks to 350 kW chargers [3].

On the other hand, the introduction of electric vehicles into the automotive fleet has individually contributed to a reduction in the acoustic disturbance caused by conventional internal combustion engines [4]. This attenuation of noise pollution is particularly significant in acoustically saturated areas of urban environments, thereby facilitating an overall decrease in urban noise levels, which contributes to a healthier living environment [5].

However, the gradual expansion of the DC conductive fast charging network for electric vehicles, which is the most common method nowadays [6], along with the convenience of their proximity to commercial areas or other services such as restaurants, has led to the emergence of fast charging stations near workplaces and even residential areas. However, during the battery fast charging process, these charging stations emit high-frequency noise within the upper range of the sound spectrum, which can be disturbing to people nearby. As a result, some operators of charging stations have been forced to either shut down or limit the charging power at various locations due to complaints from local residents.

In urban environments, noise-related annoyance is arguably one of the most prevalent concerns, as auditory stimuli are ubiquitous across various soundscapes where individuals engage in their daily activities [7]. The World Health Organization identified noise as the second most significant contributor to the "burden of disease" attributable to ambient noise in European Union (EU) countries [8].

The annoyance induced by noise is a subjective phenomenon that cannot be wholly quantified or measured, as it is contingent upon the individual perceiving it. In this context, evaluating noise annoyance necessitates consideration of not only the inherent characteristics of the sound itself but also the situational context and the environment in which it occurs [9].

The impact of continuous noise on an individual is influenced by both the physical (acoustic) properties of the sound and various factors related to the individual and the surrounding environment. In fact, in certain instances, the acoustic characteristics of the noise may not significantly contribute to the development of this perceptual construct [10]. Factors such as noise sensitivity, genetic predisposition, physiological responses, psychological state, and lifestyle choices can exacerbate an individual's reaction to noise [11], thereby playing a crucial role in the overall experience [12].

In order to reduce the annoyance caused by noise emissions during the rapid charging of electric vehicles' batteries, this research analyzes both the sound emission and propagation of a broad sample of DC fast charging stations from leading EU market brands. The goal is to provide tools that assist manufacturers, installers, and operators of rapid charging stations in mitigating the aforementioned sound emissions.

2. Materials and Methodology

2.1. Noise Measurement Procedure

This section explains the measurement procedure to obtain noise emissions of electric vehicle DC fast charging stations. The noise measurement procedure applied in this research is based on a standardized method, according to Annex 4 of the Royal Decree 1367/2007, of October 19, which implements Law 37/2003, of November 17, on Noise, regarding acoustic zoning, quality objectives, and acoustic emissions [13], and the ISO 1996:2016 Acoustics—Description, measurement and assessment of environmental noise [14]. This regulation establishes the criteria and limits applicable for assessing and controlling environmental noise in different areas, to protect human beings against noise pollution, setting the maximum permissible noise levels according to the type of area (residential, industrial, healthcare, etc.) and the period (day, evening, or night).

The measurement procedure is carried out according to the Regulation. First, the noise source has to be connected in the loudest possible operating mode. In the case of EV fast charging stations, this means charging at the highest power output available. Then, the location where the noise level is highest must be identified. In this case, as all the fast charging stations do not share a location where the noise level is higher, measurements were registered on all four sides. According to the Regulation, 5 measurements were made at a distance of 1.5 m from the charger's surfaces and 1.5 m above the ground. These measurements, of L_{Aeq} (dBA), were registered over 10 s.

On the other hand, with the charging station stopped, the background noise was measured at the same points. Once again, 5 measurements were made at a distance of 1.5 m from the charger's surfaces and 1.5 m above the ground. These measurements, of L_{Aeq} (dBA), were also registered over 10 s.

2.2. Noise Measurement Corrections

To ensure that the measurement results consider only the noise source and, therefore, exclude environmental factors such as background noise, several correction factors must be considered. Once the background noise has been registered, an in-depth analysis of the measured values needs to be carried out in order to determine which corrections have to be implemented, where applicable, according to the Regulation. This section analyses them and explains how to apply these corrections to the measurements at each point.

2.2.1. Corrections Due to Background Noise

According to the Regulation, when the evaluated level exceeded background noise by 10 dBA, no correction was applied. If the evaluated level exceeded the background noise level by between 3 and 10 dBA, a background noise correction was applied according to the following Equation (1):

$$L_{A_{eq},corr} = 10 \cdot log\left(10^{L_{Aeq}/10} - 10^{L_{Aeq,background}/10}\right) \quad (1)$$

On the other hand, when the evaluated level did not exceed the background noise level by 3 dBA, the measurement was discarded, and the measurement was registered again when the background noise had decreased.

2.2.2. Corrections Due to Emergent Tonal Components (K_t)

In this case, a third-octave analysis, both with the fast charger in operation and stopped, to measure background noise, must be performed.

Background noise correction was applied, when the evaluated level exceeded the background noise level by between 3 and 10 dB, according to the following Equation (2):

$$L_{f_{eq},corr} = 10 \cdot log\left(10^{L_{feq}/10} - 10^{L_{feq,background}/10}\right) \quad (2)$$

When the evaluated level exceeded background noise by 10 dBA, no correction was applied, while if it did not exceed the background noise level by 3 dBA, the measurement was discarded, and the measurement was registered again when the background noise had decreased.

Then, the tonal component K_t is obtained according to L_t and considering the following Table 1:

$L_t = L_f - L_s$, where L_f is the emergent band level and L_s is the arithmetic mean of the adjacent bands.

Table 1. Tonal component K_t.

Frequency Band	**L_t (dB)**	**Tonal Component K_t (dB)**
From 20 to 125 Hz	If $L_t < 8$	0
	If $8 \leq L_t \leq 12$	3
	If $L_t > 12$	6
From 160 to 400 Hz	If $L_t < 5$	0
	If $5 \leq L_t \leq 8$	3
	If $L_t > 8$	6
From 500 to 10,000 Hz	If $L_t < 3$	0
	If $3 \leq L_t \leq 5$	3
	If $L_t > 5$	6

2.2.3. Corrections Due to Low-Frequency Components

Once again, when the evaluated level exceeded the background noise level by 10 dBC, no correction was applied. In those measurements where the evaluated level exceeded the background noise level by 3 to 10 dBC, the correction due to low-frequency components L_{Ceq} was applied according to the following Equation (3):

$$L_{C_{eq},corr} = 10 \cdot log\left(10^{L_{Ceq}/10} - 10^{L_{Ceq,background}/10}\right) \quad (3)$$

On the other hand, when the evaluated level exceeded background noise by 10 dBA, no correction was applied, while if the evaluated level exceeded the background noise by 3 to 10 dBA, background noise correction L_{Aeq} was applied according to the following Equation (4):

$$L_{A_{eq},corr} = 10 \cdot log\left(10^{L_{Aeq}/10} - 10^{L_{Aeq,background}/10}\right) \quad (4)$$

Then, the low-frequency component K_f is obtained according to L_f and considering Table 2:

$$L_f = L_{Ceq,corr,Ti} - L_{Aeq,corr,Ti}$$

Table 2. Low-frequency component K_f.

L_f (dB)	Low-Frequency Component K_f (dB)
If $L_f \leq 10$	0
If $10 > L_f \leq 15$	3
If $L_t > 15$	6

2.2.4. Corrections Due to Impulsiveness

A sound with impulsive components is a high sound pressure level and short-duration sound. Corrections due to impulsiveness follow the same pattern. No correction was needed when the level exceeded background noise by 10 dBA, while if the level exceeded the background noise by between 3 and 10 dBA, correction was applied according to the following Equation (5):

$$L_{A_{eq},corr} = 10 \cdot log\left(10^{L_{A_{eq}}/10} - 10^{L_{A_{eq},background}/10}\right) \quad (5)$$

The impulsive component K_i is obtained according to L_i and considering the following Table 3:

$$L_i = L_{AIeq,corr,Ti} - L_{Aeq,corr,Ti}$$

Table 3. Impulsive component K_i.

L_i (dB)	Impulsive Component K_i (dB)
If $L_i \leq 10$	0
If $10 > L_i \leq 15$	3
If $L_i > 15$	6

2.2.5. Corrections $K_t + K_f + K_i$ Applied in Each Point

Once the correction factors $K_t + K_f + K_i$ had been calculated, they were applied in each point, according to the Regulation, as follows:

- $L_{keq,Ti} = L_{Aeq,Ti} + K_t + K_f + K_i$ (If $K_t + K_f + K_i > 9$, then the total correction will be capped at 9).
- The resulting value will be rounded up by 0.5 dBA, taking the integer part as the final result.
- Take as the result the highest $L_{keq,Ti}$ value from the three measurements.

2.3. Tested DC Fast Charging Stations

In order to ensure that the results are significant, and the conclusions are consistent, this research required conducting a large number of tests at numerous DC fast charging stations from leading EU market manufacturers. Therefore, a representative sample from different models of charging stations currently available in the EU market was tested. This research included fast charging stations (50 kW), as well as super-fast (100–150 kW) and ultra-fast (>150 kW) charging stations. A list of the different charging stations which were tested can be seen in the following Table 4.

All these charging stations are equipped with CCS Combo 2 connectors, which is the standard type of connector for fast charging in the EU. However, some of the older charging stations, such as Ingeteam Rapid 50 Trio, also offer Type 2 connectors for three-phase AC rapid charging (between 11 and 43 kW), and CHAdeMO, the standard DC fast charging connector for old Japanese electric vehicles (up to 63 kW) that has been gradually replaced for CCS Combo 2 in the latest Japanese models. This research was carried out only with CCS connectors, as AC rapid charging does not produce significant noise emissions and CHAdeMO is not included in new-generation fast charging stations. A first-generation 50 kW fast charging station, with all three types of connectors, can be seen on the left of the following Figure 1, while a last-generation 180 kW fast charging station, with only CCS Combo 2 connectors, can be seen on the right.

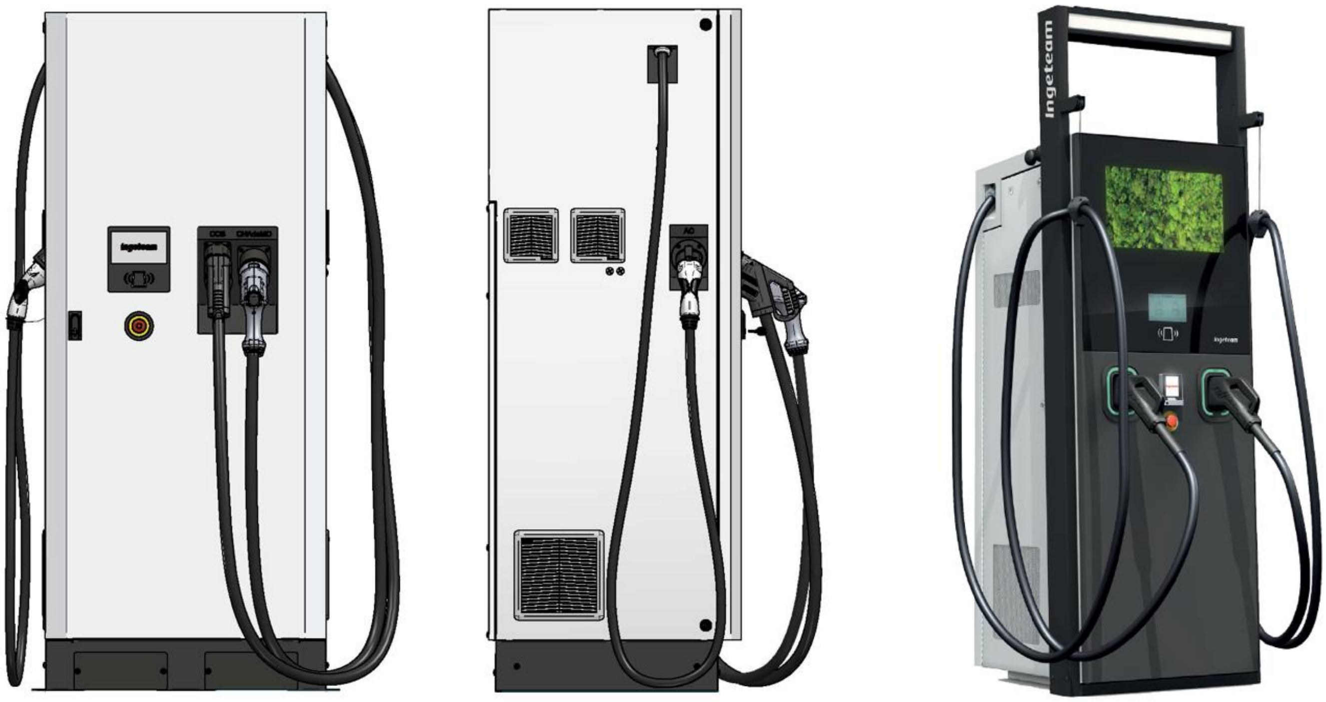

Figure 1. Ingeteam Rapid 50 Trio (**left**) and Ingeteam Rapid 180 (**right**) fast charging stations.

Table 4. Tested DC fast charging stations.

Manufacturer	Model	Máx. Power Output (kW)
Ingeteam (Spain)	Rapid 50 One/Duo/Trio	50
	Rapid 60 Duo	60
	Rapid 180 Duo	180
	Rapid ST 200	200
	Rapid ST 400	400
Circutor (Spain)	Raption 50 Trio	50
	Raption 100	100
Alpitronic (Italy)	HYC 50	50
Wall Box (Spain)	Supernova 60	60
	Supernova 150	150
ABB (Switzerland)	Terra 124HC CC	120
	HP CP500 CJ	175
Tesla (U.S.A.)	V2	150
	V3	250
GSS Power (Spain)	DP-ESC-193	160

2.4. Measurement Configuration and Microphone Set-Up

The noise measurement configuration and microphone set-up applied in this research is based on a standardized method, according to Annex 4 of the R.D. 1367/2007 and the ISO 1996:2016. Noise emission measurements were made on all four sides of each fast charging station. According to the standard, the microphones were placed at a distance of 1.5 m from each side, and 1.5 m high from the ground. The microphone set-up can be seen in the following Figure 2 (front view) and Figure 3 (side view).

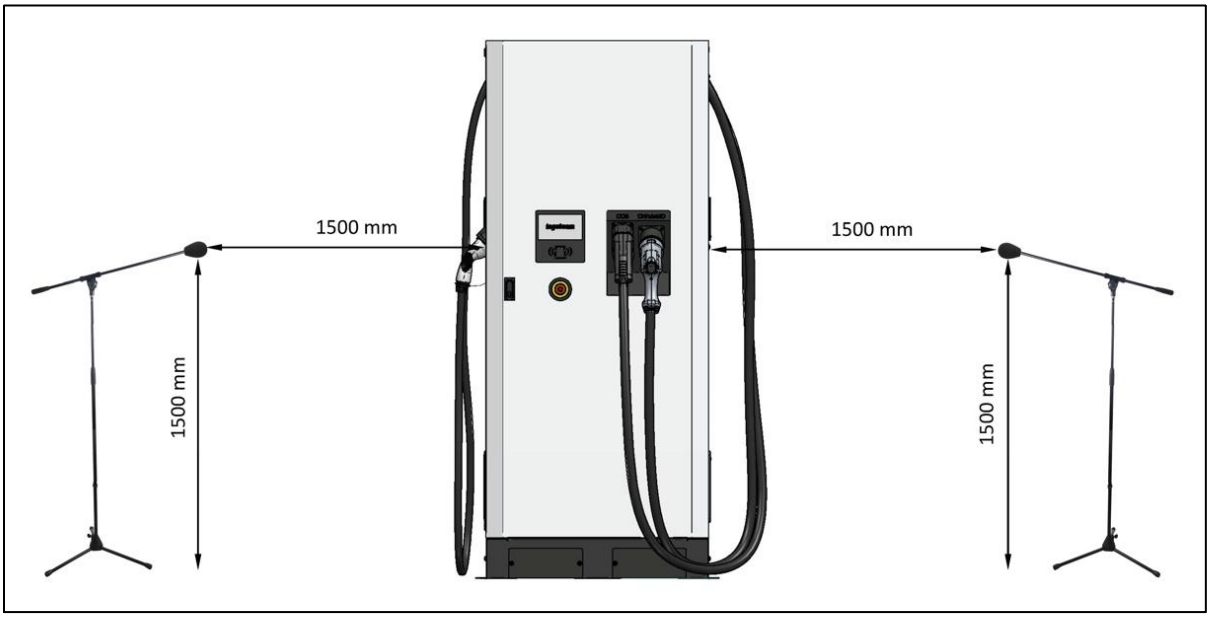

Figure 2. Microphone set-up. Front view.

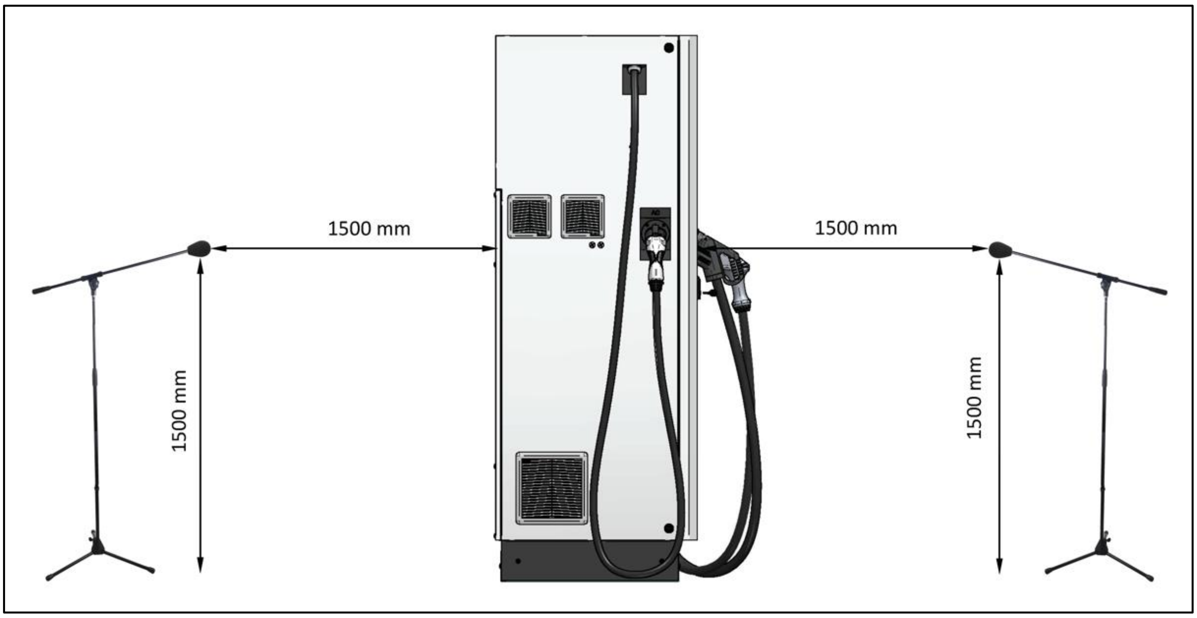

Figure 3. Microphone set-up. Side view.

The modular type 1 acoustic pressure analyzer recorded signals of 10 s between 80 Hz and 12.5 kHz at an integration time of 125 ms (fast). All these data were processed in 1/3 octave bands. Five measurements were registered for each measuring point, as well as for background noise.

2.5. Instrumentation and Acoustic Environment

The measurement instruments used for all noise evaluations, where the use of octave-band or 1/3 octave-band filters is required, must comply with the accuracy requirements for Type 1/Class 1 precision, as specified in standard IEC 61260 Octave-band and fractional-octave-band filters [15]. Table 5 shows a list of all the measurement instruments used in this research, which fulfilled this requirement.

Table 5. Measuring instruments used in the tests.

Test Instrumentation	Model
Modular type 1 acoustic pressure analyzer	Bruel&Kjaer 2250
Modular type 1 acoustic pressure analyzer	Bruel&Kjaer 2260
Microphone sound calibrator	Bruel&Kjaer 4231
Thermo-hydro-anemometer	PCE-THA 10

Tests were carried out in real-life test conditions. Therefore, noise was not only measured during the charging sessions but background noise was also registered for each measurement in order to calculate and apply the background noise correction. According to the Regulation, when the evaluated level did not exceed the background noise level by 3 dBA, the measurement was dismissed, and new measurements were registered when the background noise had decreased.

The ISO 9613-2 Standard, Acoustics. Attenuation of Sound during Propagation Outdoors [16] specifies that wind speed must not exceed 5 m/s under any circumstances during a time period deemed representative of prevailing meteorological conditions. This requirement was verified by measuring with the PCE-THA 10 calibrated thermo-hydro-anemometer.

On the other hand, as established in Regulation 1367/2007, ambient temperature must be between 0 and 40 °C, while relative humidity must be between 20 and 100%. All the measurements in this research were registered at a temperature range between 14 and 26 °C, and relative humidity was between 42 and 73%. Both temperature and humidity were also measured with the PCE-THA 10 calibrated thermo-hydro-anemometer.

An example of the real-life measurement tests can be seen in the following Figure 4.

Figure 4. Ingeteam 50 kW fast charging station (**left**) and Tesla V2 Supercharger 150 kW (**right**).

On the other hand, in collaboration with one of the leading charging networks, several fast charging stations could be measured under laboratory-controlled conditions, with very limited background noise, in Iberdrola's Smart Mobility Lab. This laboratory, located in

Bilbao (Spain), has a wide range of DC fast charging stations and permitted testing and measurement under a wide range of charging variables. These included testing DC fast charging stations with a sound-dampening device, specially designed in order to reduce noise emissions that produce first-generation chargers. Figure 5 shows Iberdrola's Smart Mobility Lab facilities.

Figure 5. Iberdrola's Smart Mobility LAB, Bilbao (Spain).

3. Results and Analysis

First of all, once the noise measurement procedure was carried out, the background noise was measured, and the corrections were applied according to the Regulation. Sound pressure levels (SPLs) for each DC fast charging station were calculated. The following Figure 6 shows a comparison of each fast charger's SPL values, both measured and corrected. According to the Regulation, sound pressure levels, once the corrections have been applied, must not exceed 65 dBA at any time during operation (this limit is represented as a black line in Figure 6). However, as can be seen in Figure 6, most of the DC fast chargers were noisier, with the Ingeteam Rapid 50 kW being the noisiest, while some of the ultra-fast chargers (>100 kW) were quieter.

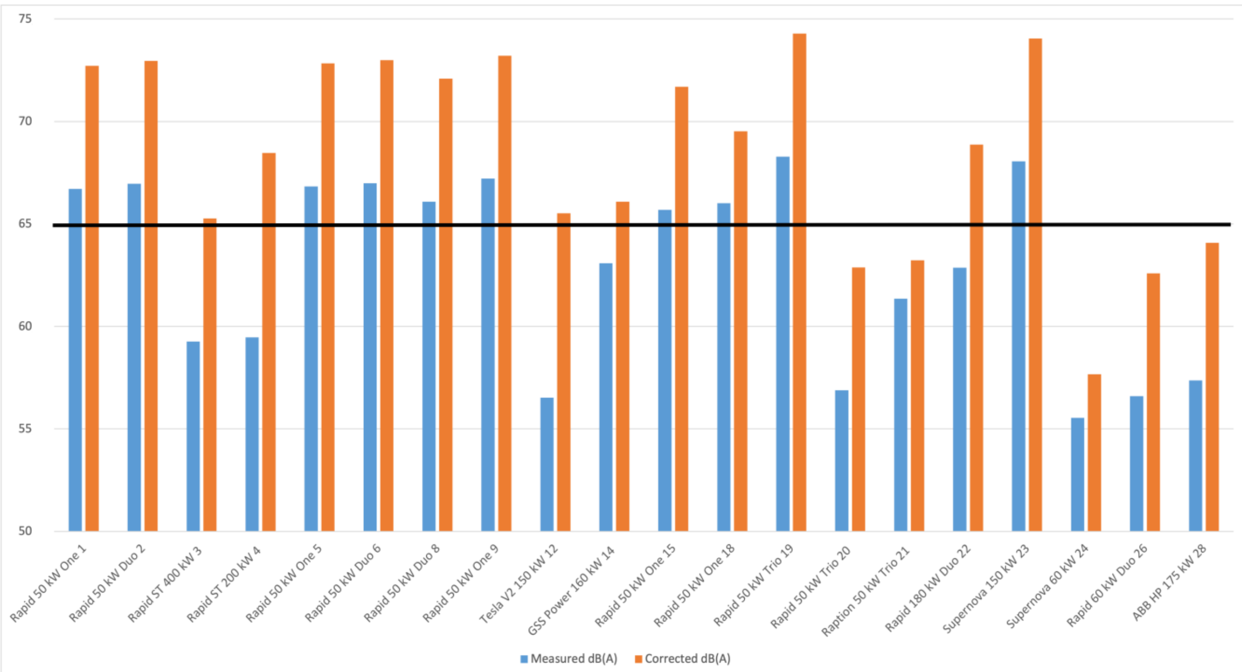

Figure 6. Measured and corrected sound pressure levels for all DC fast chargers tested.

Due to the high number of DC fast charging stations tested, and to be able to compare them in a more comprehensive way, an in-depth noise frequency was carried out. The results are preliminary shown all together, which means that all manufacturers and models are compared. This leads to a widespread graph showing every fast charging station noise emission spectra, as can be seen in the following Figure 7.

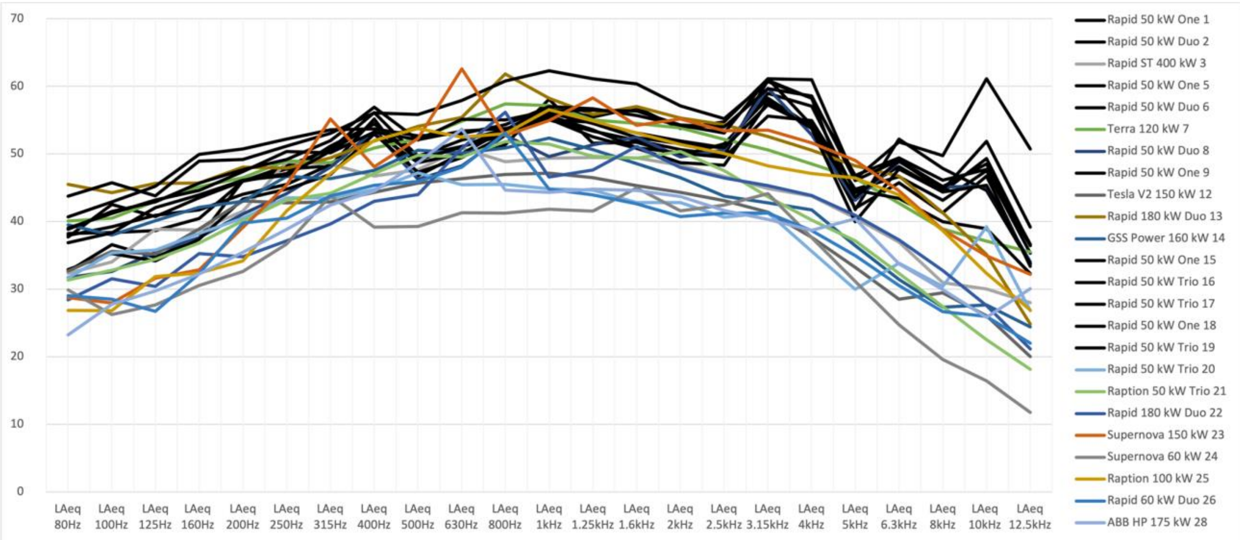

Figure 7. Noise emission spectra for all DC fast chargers tested.

Figure 7 shows the noise spectra for all DC fast charging stations tested in this research. Ingeteam Rapid 50 kW fast chargers stand out at the top of the graph as the noisiest chargers. Please note that all of them are in black color to help identify this feature. Conversely, high-power chargers, such as the Wall Box Supernova 150 kW, Tesla V2 150 kW, or Ingeteam Rapid ST 400, are quieter chargers.

Significant differences can be appreciated between first-generation (50 kW) and last-generation (>100 kW) fast charging station noise emissions, as the former are much noisier than the latter. In fact, only these first-generation (50 kW) fast chargers exceed the maximum permissible noise levels for residential areas established in the previously mentioned Regulations, while the last-generation (>100 kW) fast charging stations are significantly quieter, including some of them whose noise emissions are almost imperceptible for human beings. This feature can be better appreciated in Figure 8.

Figure 8 shows the average noise spectra for all the fast charging stations tested, which have been classified, according to their rated power, into four groups: first-generation Ingeteam Rapid 50 kW (black), chargers from 100 to 150 kW (blue), chargers from 150 to 200 kW (green), and chargers over 200 kW (red). The first group (50 kW) shows the highest noise spectrum of all groups, especially in the high-frequency ranges.

As the aim of this research is to mitigate DC fast charging noise emissions, an in-depth evaluation of the noisy fast chargers, which exceed the maximum permissible noise levels, was carried out. In this case, the assessment of noise emission was not limited to their spectra, but the propagation was also taken into consideration. To begin with, the noisiest first-generation Ingeteam Rapid (50 kW) fast chargers where compared, as can be seen in Figure 9.

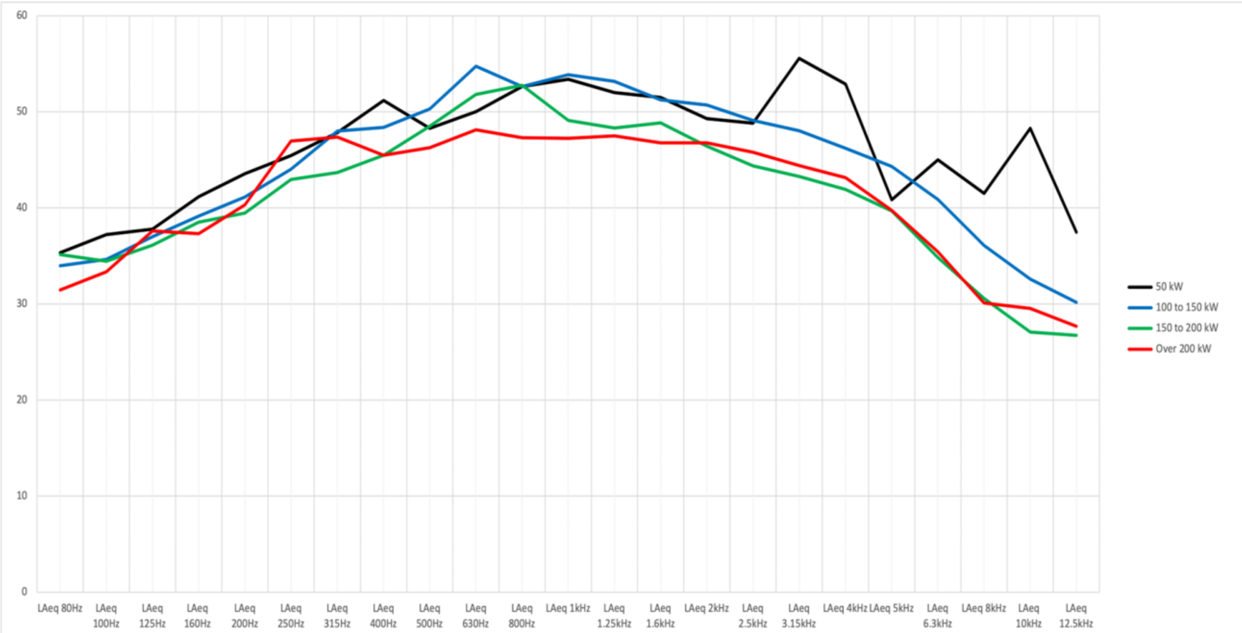

Figure 8. Average noise emission spectra for fast chargers tested according to their rated power.

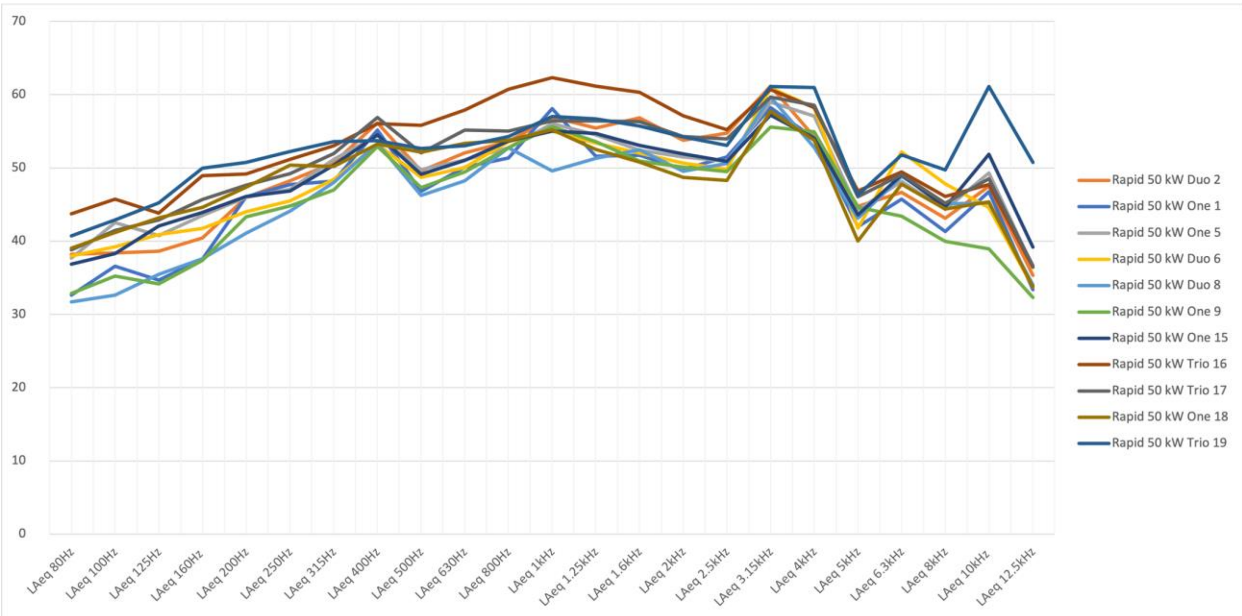

Figure 9. Comparison between different first-generation Ingeteam Rapid (50 kW) fast chargers noise emission spectra.

Figure 9 shows different first-generation Ingeteam Rapid (50 kW) fast chargers noise emission spectra. All of them have similar noise spectra, no matter whether it is the One, Duo, or Trio model. As can be seen, the noise spectra show two high-frequency peaks: the first one is around 3150–4000 Hz, and the other one is at 10,000 Hz. This high-frequency noise, which causes disturbance to people, exceeds the environmental noise limits established in the Regulation.

Once the chargers which go beyond noise Regulation limits had been identified, several ways to reduce their sound emissions were tested. A first attempt was performed by installing a sound-dampening device on the charger's surface. This device consists of three metallic covers, one on each side, and another one on the back of the charger's body, filled with high-density sound-absorbing foam panels. This sound-dampening device, installed in a Ingeteam Rapid 50 kW Trio fast charging station, can be seen in the following Figure 10.

Figure 10. Ingeteam Rapid 50 kW fast charging station with a sound-dampening device.

Noise was measured on this modified fast charger and compared with several standard units of the same manufacturer and model in different test conditions. The results showed that, even when the sound-dampening device achieved a noise reduction in almost all one-third octave bands, this reduction was very limited in most of them, and practically negligible in high-frequency bands, which are the ones that determine disturbance to people nearby. This can be seen in the following Figure 11.

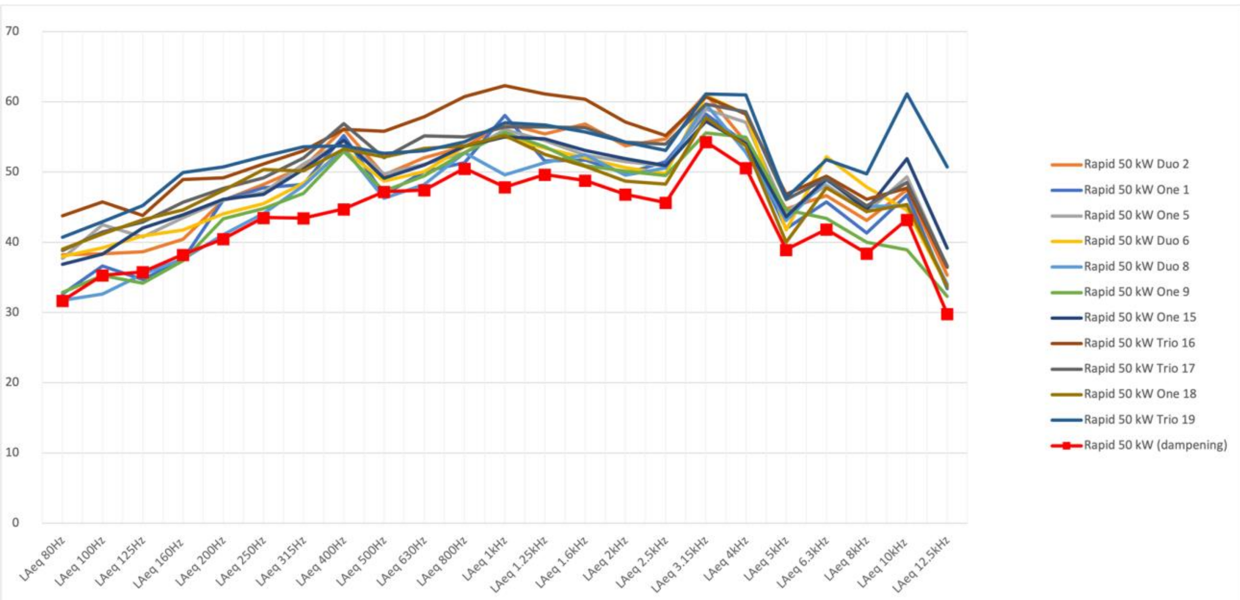

Figure 11. Noise emission spectra of different Ingeteam Rapid 50 kW fast charging stations.

Figure 11 shows the noise spectra for all Ingeteam Rapid 50 kW fast charging stations tested in this research. Ingeteam Rapid 50 kW, with the sound-dampening device installed (red line with square marker type), has a slightly lower spectrum than the chargers which have not been modified. However, this reduction is, in most cases, lower that 2 dB in high frequencies such as 4 and 10 kHz, which makes this measure very limited, as this noise reduction would not be enough to fulfill the noise Regulation limits in most of the tested fast chargers. As can be seen in Figure 6, only three fast charging stations (Rapid ST 400 kW, Tesla V2 150 kW, and GS Power 160 kW) could benefit from this noise reduction to avoid exceeding 65 dBA.

On the other hand, sound propagation was measured to evaluate the possibility of installing noisy fast chargers in a position that reduced disturbance, or even turning around the ones which are already installed. The following Figures 12 and 13 show the Ingeteam Rapid 50 kW fast charging station sound propagation. Note that the data are LA_{eq} (dBA).

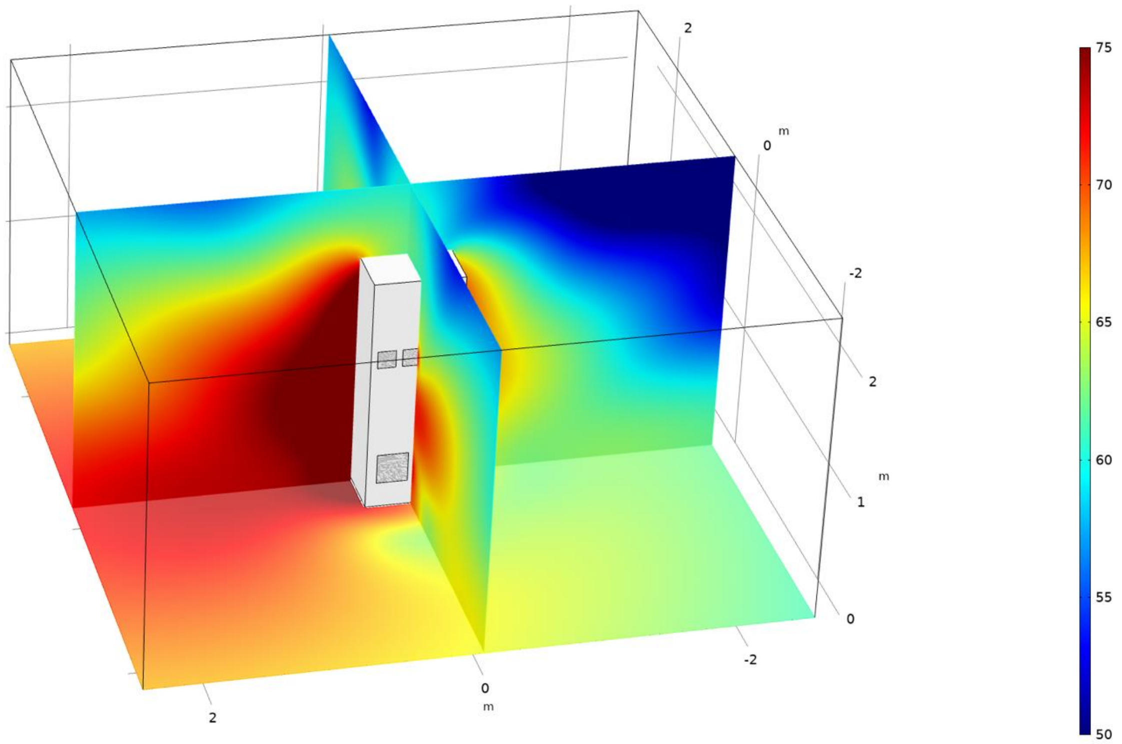

Figure 12. Sound propagation of the Ingeteam Rapid 50 kW fast charging station LA_{eq} (dBA).

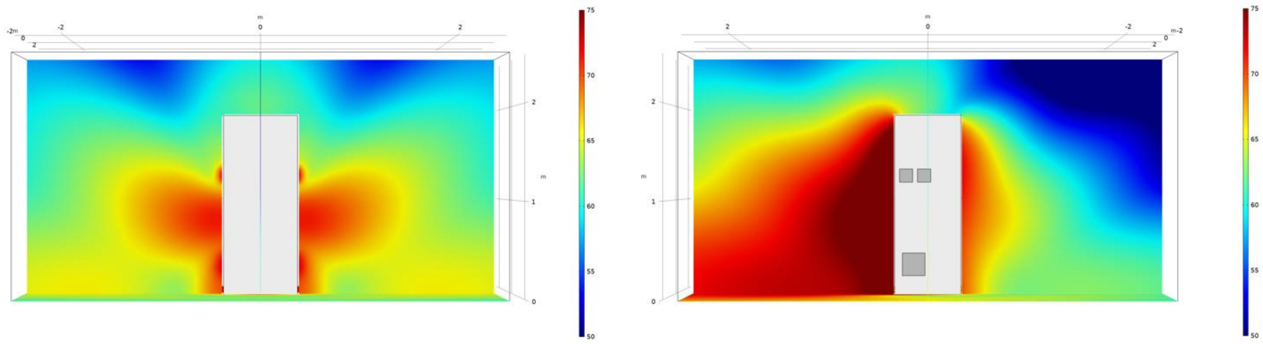

Figure 13. Sound propagation of the Ingeteam Rapid 50 kW fast charging station, front view (**left**) and side view (**right**).

Figures 12 and 13 show the Boundary Element Method sound propagation simulation of the Ingeteam Rapid 50 kW fast charging station, obtained from the measured values LA_{eq} (dBA). As can be seen, the front side is the quietest, with the rest of the sides being considerably noisier, with differences of up to 12 dBA. Having only one "quiet side" makes it pointless to install the charger in any position with the objective of reducing disturbance. In fact, the position of the charger should be determined by the cables' optimal position to let the vehicles reach the connectors, taking into account the charger's situation in relation to the parking spot.

Finally, the relationship between charging power and noise emissions was also assessed. Even when a DC fast charger has a nominal power output, which typically varies between 50 and 400 kW, actual charging power depends on several factors. Optimal fast charging speeds are only achieved when the battery's state of charge (SoC) is low [3] and at an ideal temperature [17,18]. For example, if the battery's SoC is high—generally over 60%—or if it is not within the ideal fast charging temperature, which is around 40 °C, charging power can be reduced considerably, especially when the battery is too cold. In unfavorable conditions, DC fast charging power can be as low as 20 kW, or even less. This research also evaluated how charging power can affect DC fast charging noise emissions, as high-frequency noise is emitted by the charger's power electronics, which transforms, converts, and rectifies an AC high-voltage current into a DC current between 400 and 800 V.

Ultra-fast chargers are more likely to work under their maximum rated power when compared with first-generation 50 kW fast chargers, which are functioning at 100% most of the time. However, DC fast charging power is determined by the Battery Management System (BMS), depending mainly on the battery's temperature and SoC, so the user cannot choose DCFC power. Moreover, only first-generation 50 kW DC fast chargers go beyond the noise limits set by the Regulation. For these reasons, a noise reduction due to the power limitation approach was only considered in 50 kW fast chargers. Sound pressure levels, for different charging powers, were measured, as can be seen in the following Table 6:

Table 6. Sound pressure level at different charging power for the Ingeteam Rapid 50 kW fast charging station.

Charging Power (kW)	**50**	**45**	**40**	**35**	**30**	**25**
Sound pressure level (dBA)	74.2	73.6	71.8	68.6	63.9	58.8

Table 6 shows the relationship between charging power and noise emission for the Ingeteam Rapid 50 kW fast charging station. Please note that the values shown are sound pressure levels, with the corresponding corrections as explained in Section 2.2, according to the Regulation. As can be seen, sound pressure levels decrease, in a non-proportional way, when charging power is reduced. If charging power is reduced to half the charging station's nominal power (i.e., from 50 to 25 kW), noise emissions decrease by 15 dBA. In order to reduce appreciably the charger's noise emissions and to be within the noise limits set by the Regulation, charging power should not be higher than 30 kW.

4. Discussion

As explained in the previous section, three strategies to reduce fast chargers' noise emissions have been tested. Firstly, a sound-dampening device was installed on the charger's surface. This device slightly improved noise emissions, reducing them in some frequencies. However, this reduction was very limited both in high-frequency bands (4 and 10 kHz), which are the frequencies that mostly cause disturbance to people, and in the overall equivalent sound pressure level, which is the value considered in the Regulation, which would exceed, in most cases, even when the sound-dampening device was installed. In fact, as can be seen considering the information provided in Figures 6 and 10, the Ingeteam Rapid 50 kW, which is the noisiest fast charger model, would not achieve enough noise reduction to fulfill the requirements of the Regulation. Moreover, this solution is quite expensive when taking into account the results, the cost/benefit ratio, and when comparing with other noise reduction measures.

On the other hand, the charger's sound propagation proved that the front side was the quietest, and the rest of the sides registered similar noise emissions. Even when this finding could help to orientate the charger in order to reduce disturbance, the effectiveness of this measure is very limited, as there is only one "quiet side", and there are aspects such as the device's screen orientation or the cables' optimal position that could be more restrictive when considering the charger's orientation.

Finally, this research has evidenced that there is a relationship between charging power and noise emissions. Reducing the charger's power output has not only been demonstrated to be the most effective way to reduce noise emissions but also the optimal cost-effectiveness manner between the three strategies which have been considered. However, this method only achieves a significant noise reduction if the power output is capped to 30 kW.

Most electric vehicle's AC charging is limited to 11 kW, while DC fast charging may vary between 50 and 400 kW [19,20]. This research has shown that last-generation fast charging stations, whose power output is over 100 kW, are not a problem in terms of noise emissions, and that first-generation 50 kW fast chargers exceed the noise limits set by the Regulation. For this reason, in order to mitigate the noise emissions of these chargers, and consequently reduce disturbances to people, it is suggested that a software-based limitation on charging power to 30 kW to the chargers that are already installed near residences be implemented. This is practically three times faster than AC charging which, if an interesting price strategy is established, can be an interesting option for EV users that can plan a charging session between 1 and 3 h when carrying out routine tasks such as weekly shopping or when going to the cinema or having lunch. Moreover, this type of mid-power charging causes less battery degradation than high-power charging [1,21]. However, it is important to take into account that the charger's efficiency is considerably reduced if it works under 85% load, so this measure should only be applied where there are no better alternatives in order to avoid near residents' complaints.

Finally, it is suggested that the noisy 50 kW first-generation equipment, which has already been bought by CPOs and still remains to be installed, should be placed at highway stops where they do not cause disturbances, alongside faster chargers (100–400 kW). This way, customers can choose between different charging speeds based on their needs. Similarly, it is recommended that installing noisy fast charging stations near urban areas is avoided, where their noise emissions cannot be mitigated unless their power output is significantly limited. However, this is often not economically viable, as there are many AC charging stations of 11 and even 22 kW that are virtually silent.

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