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Ph.D Thesis of
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Analytical assessment of wind turbine noise impact at receiver by means of residual noise determination without the farm shutdown

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Appendix
1. Introduction

Wind energy is one of the most “green” energy solutions in the non-fossil policy of the modern society. Extremely low CO2 emissions during its entire lifespan make a wind farm a very reliable and efficient choice in windy sites. Besides the visual aspects, the noise impact may represent a major hindrance to new wind farms. Especially in hilly areas, the most common situation where Italian wind turbines are planted, amenity and quietness are the main attractiveness and characteristics.

The presence of isolated receivers, often holidays-farms, even very far from a wind turbine (WTG), requires a careful assessment procedure that includes the measurement of low noise levels and a correct determination of the relationships between wind profiles and noise propagation in the prevailing atmospheric conditions.

In those scenarios the influence of wind profiles on noise generation and propagation is very complex due to the sites topography, making it tricky and weighty the evaluation of landscape and environmental impact of a wind farm. The proper determination of sound propagation path and wind induced residual noise is a complex issue in very irregular terrains (hills, valleys, thick tree coverage) and for far receivers, normally included between 400 and 1500m from the farm. The relationships between wind speed and direction at hub height and wind speed at receivers height have a paramount interest. Then, considering the differences of wind speed and direction between each turbine of the wind farm caused by the complexity of the terrain profile is also an important aspect. Because of these, only few countries have a proper method to evaluate the noise impact of a wind farm.

The present thesis, after an examination of the actual wind energy situation around the world, will summarize what is known in the scientific literature about wind turbine noise (WTN) generation, propagation, wind-noise interaction and the well-known phenomenon of the amplitude modulation.

Extensive studies have been dedicated to the collection of international regulations (Licitra and Fredianelli, 2013), to the effects that WTN and annoyance have on human health, with a special attention to low frequencies for the WTN, considered strongly annoying by some authors and not by others.
Particular attention will be given to the direct and the indirect health effects of noise, underlying that WTN is significant for the indirect ones, particularly for the annoyance. Since WTN results much more disturbing than the other most common noise sources, the reasons to consider annoyance as a health effect and its effects on people will be discussed.

One of the aims of this work is to propose a specific limit for WTN and it will be reached by considering the annoyance dose-response relationships for different sources and deriving a limit value according with ones already issued for the other sources (Fredianelli and Licitra, 2014).

Then, all the issues relating to the background noise measurement in a wind field will be analysed in details (Fredianelli, et al., 2012). By means of 9 long-term measurement campaigns performed in Tuscany and Puglia (Cicciotti, et al., 2014), the purpose of providing suitable parameters to assess noise impact of a wind farm in a complex terrain is achieved.

Moreover, the lack of a proper and complete regulation to consider the masking sound contribute to the noise level at the receiver, suggested the main objective of this thesis: a standard procedure to measure and to analyse noise and wind data, with the aim of characterizing wind turbine and background noise in all kinds of terrain (Gallo, et al., 2016). The procedure will be able to compare the results with national law limits, but it can be adapted to other international requests. Through iterative steps, the method provides the evaluation of noise impact produced by operational wind farms, without stopping the energy production for measurement purpose. The outputs of the procedure are the noise immission levels at receiver as a function of $N_{eq}$, a new parameter that simultaneously considers the blades rotational speed of the whole wind farm, the residual noise at receiver as a function of $v_{gr}$ and the total immission and residual noise at receiver. The levels are evaluated on the measurement period distinguishing between night-time and daytime.

In a specific Chapter a confidence level for the outputs of the procedure and an estimate of their uncertainty is acquired through a Monte Carlo procedure (Fredianelli, et al., 2015). Due to the complexity of the subject, where both the immission and the residual are not reliably predictable, the validation of the procedure outputs results a complex task. Nevertheless, it is performed in three alternative ways (Carpita, et al., 2016). The first is a comparison of the immission levels of the procedure with the noise prediction models, the second is a check of the difference between the measured 10 min environmental noise level and the environment levels on 10 min from the procedure. The third is a method based on the
implementation of a computational model for simulated scenarios, where hypothetical set of measured noise levels are simulated summing a theoretical residual noise function to a theoretical immission noise and to a random noise. When applied to this set of data, the procedure should return the two inputs theoretical functions.

At the end, a sensitivity analysis on the $N_{eq}$ parameter and a deeper explanation of some numerical parameters involved are presented, aiming to reduce the procedure uncertainty (Licitra, et al., 2015). This analysis will allow a better understanding of which procedure parameters requires better accuracy in order to reduce the procedure’s uncertainties.

In summary, the aims of the thesis are:

- A summary of WTN generation, propagation, wind shear-noise interaction and AM.

- A review of the international regulations and the effects that WTN and annoyance have on human health, with focus on low frequencies and annoyance.

- To propose a WTN limit considering the annoyance dose-response relationships.

- An analysis of all the issues relating to the background noise measurement in order to provide suitable parameters to assess noise impact of a wind farm in a complex terrain.

- A standard procedure to measure and analyse noise and wind data, with the aim of characterizing wind turbine and background noise in all kinds of terrain. The procedure should be able to compare the results with Italian law limits, but it should be also adaptable to other international requests.

- Estimate of the confidence level for the procedure’s outputs and their uncertainty through a Monte Carlo method.

- Validation of the procedure outputs.

- A sensitivity analysis on the parameters involved are presented, aiming to reduce the procedure uncertainty.
2. Wind energy

2.1 Wind energy market in 2015

According to the Global Wind Energy Council (GWEC), the 2015 was a record year for the wind industry and for the green energy revolution thanks to a series of positive events culminating with the landmark Paris Agreement in December, a rare triumph of multilateralism where 186 governments have finally agreed on where we need to get to in order to protect the climate for future generations (GWEC, 2016). Among the positive signals, there were: decadal low fossil fuel prices have had no appreciable effect on the growth of wind and solar; the Financial Stability Board’s pronouncements on the climate related risks to the global financial system; China’s State Grid calling for first a regional and then a global grid to transport clean energy around the world – a new Silk Road; the growing divestment from fossil fuels by institutional investors. All of this led to an even better growing installation levels respect to the previous years and record low prices of both wind power and solar photovoltaic.

As reported in Figure 2.1, in 2015 the energy production reached another milestone as annual installations topped 63 GW, a 22% increase respect to 2014. A total of 433 GW of wind power were worldwide presents at the end of the previous year, a cumulative 17% increase. It is also remarkable that wind power supplied more new power generation than any other technology in 2015.
Looking at the country's production, China led the way, as usual, with a record 30.8 GW of new installed capacity and a total of 145 GW of wind power installed as reported in Figure 2.2, more than in all of the European Union. Last year it was the first country ever to invest more than USD 100 billion in renewable in a single year. India is the second main producer in Asia and has now surpassed Spain to move into 4th place in the global cumulative installations ranking.

Europe’s 2015 was a surprisingly good year, led by Germany’s record setting 6 GW of installations, bolstered by more than 2 GW of offshore wind; and the US market had a remarkable end of the year with an 8.6 GW market, much higher than most had expected.

The continued proliferation of new markets across Africa, Asia and Latin America, spurred by the need for competitive, clean, and indigenous energy sources to fuel development led
countries like Brazil, Mexico and South Africa to had strong years, whilst the first commercial wind farms in Jordan, Guatemala and Serbia Perhaps were registered.

Looking ahead, the GWEC foresees a period of steady growth in Asia while Europe will move steadily towards its 2020 targets, although there may be some bumps in the road. In North America, both Canada and the US seem poised for another round of growth while in Latin America, Brazil will continue to lead, although Chile, Peru, Uruguay and now Argentina will make a contribution. In Africa and the Middle East, besides market leader South Africa, both Morocco and Egypt seem poised for solid growth in the next five years, and smaller markets in Kenya, Ethiopia and elsewhere are moving. All told, wind capacity should nearly double in the next five years.

Figure 2.2. Top 10 Countries for new installed and cumulative wind capacity in 2015 (GWEC, 2016).
In Italy, the first wind farms were installed in 1995 in the Apulia and Campania regions, the windiest areas of the country. As reported in Figure 2.3, the wind industry and market grew steadily until 2013, but after five years of solid growth at a 1 GW per year rate, the Italian wind installations fell dramatically to 437 MW in 2013 and even further to 107.5 MW in 2014 (GWEA, 2015).

The fundamental decline is a result of the substantial changes introduced to the support schemes for wind and other renewable energy sources. A new and complex legislation also came into force in 2012, with a lack of clear and stable rules, and annual quotas for each type of generation, which has stifled the market. In 2014, 107.5 MW of wind power was installed across wind farms mainly in the Apulia and Basilicata regions, bringing the total capacity to 8,663 MW. In 2014 wind generated 15 TWh, which was approximately 5% of national electricity consumption.

![Figure 2.3. Italian total installed capacity from 2001 to 2014 (GWEA, 2015).](image)

2.2 Wind energy generation

This worldwide clear growth in wind energy production in recent years has been made possible by the modern wind turbines, both those with horizontal (HAWT) or vertical (VAWT) axis of rotation, but the second type is not much widespread because of the difficulty in creating large models. The VAWT and the small scale HAWT will not be in the objectives of this thesis, but further works may include them.
As sketched in Figure 2.4, the HAWTs have the main rotor shaft and electrical generator in a nacelle on the top of a tower, rotating in order to face the wind coming to the blades. Small turbines, whose definition varies from country to country, are pointed by a simple wind vane, while large turbines (>0.5 MW) generally use a wind sensor coupled with a servo motor. Most of them have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Turbines used in wind farms for commercial production of electric power are usually three-bladed and can rotate from nearly 6 to 22 revolutions per minute (rpm), depending on the incoming wind.

The energy power generation is described by the Betz’s law (Betz, 1966):

\[ P_g = \eta_g \cdot \eta_m \cdot C_p \cdot \frac{1}{2} \rho A v^3 \]

Where \( \eta_g \) and \( \eta_m \) are the generator and mechanical yields, \( C_p \) is the performance coefficient (i.e. ratio between output and maximum attainable power), \( \rho \) and \( v \) the density and speed of the air and \( A \) is considered area.

Thus, the energy produced is proportional to the rotor diameter, which is linked to the tower height for structural reasons. Typical turbine heights are between 60 and 100 m for power between 1 and 3 MW, but the tallest offshore turbine at present can even reach 125 meters for 10 MW of power. The evolution of wind turbines by height and power is reported in Figure 2.5.
Each turbine has its specific power curve, a graph relating the wind speed to the electric power delivered by the generator. A minimum wind speed is required for starting the turbine (cut-in wind speed), ranging between 3-5 m/s depending on the wind turbine model. After the cut-in there are wind speeds during which the machine reaches the rated power (rated wind speed) up to the maximum wind speed threshold (cut-out wind speed), nearly 20 m/s. Past the cut-out speed, the wind turbine is put into safety and stops the production of electricity in order to avoid damage.

According to the Betz's law, the energy produced is proportional to the cube of speed, thus an accurate analysis of the wind conditions of the site is required in the process of a wind farm design in order to estimate the wind energy capability. At the same time, this analysis is very useful for the simulation and prediction of noise, which is also strongly dependent on the wind, as it will be described in the next Chapter.
3. Wind Turbine noise

Over the last years, an increase of complaints by citizens against the noise produced by wind farms has taken place. This is an evident sign that wind turbine noise can be a serious problem as well as the noise produced by other anthropic sound sources (Bowdler, et al. 2011), with similar health effects on people that will be described in the following of this work. The lack of a proper management of the noise by manufacturers of the plant and by the control bodies, with the consequent inability to resolve the complaints when they arise, has resulted in the birth of an opposition faction to wind energy. The reason for this lack of legislature is also attributable to the complexity of the topic itself, in which many physical parameters are involved in the noise generation, propagation and the receiver's' perception. For these reasons, the noise issue results the most important impact, together with the visual one, slowing the diffusion of wind farms.

3.1 Generation of wind turbine noise

Noise is produced by a wind turbine in two main ways:

1. by the engine, the gearbox or the transmission (mechanical);
2. by the interaction of wind-blade (aerodynamic).

For a typical 2 MW wind turbine, the overall A-weighted noise power level is in the order of 104 (A), given by the sum of many contributions as sketched in Figure 3.1.
The mechanical noise, generated by the friction between the mechanical components, is negligible for the modern wind turbines if properly operating. However, the principal component of noise produced by a wind turbine is the aerodynamic one.

The principal mechanism of sound generation of an incoming air flow is the interaction of a turbulence with the blade edge in the flow direction (leading edge noise). The noise produced is mainly around 200 Hz, thus becoming less important when perceived by humans with their A-weighting. On the contrary, when a stationary or laminar flow interacts with a blade, a multitude of sound generation occurs due to the airfoil self-noise (Brooks, et al., 1989) and its predominance depends on the laminar or turbulent state of the flow. Generally, the responsible of sound production is the turbulence, a fast variation in space of the wind speed and direction, which originates from the interaction between the air flow and the blade. The most important interaction of airflow with a blade and the relative sound production mechanisms (Zhu, et al., 2005) are reported in Figure 3.2 and then described (Lowson, 1993).
Figure 3.2. Interaction of an incoming air flow on a blade and the most important sound production mechanisms. Elaborated from (Rogers, et al., 2006; Lowson, 1993).

Turbulent boundary layer trailing edge noise (TBL-TE)

The turbulent layer of air surrounding the blade profile interacts with the thin trailing edge generating an acoustic wave described by the formulation of Lighthill (Lighthill, 1952). It relies on an analogy between the full nonlinear flow and the linear theory of acoustics. The conservation equations are rewritten to form the following inhomogeneous wave equation:

\[
\left( \frac{\delta}{\delta t} - c_0^2 \nabla^2 \right) (\rho - \rho_0) = \frac{\delta T_{ij}}{\delta x_i \delta x_j} (x, t)
\]

Where \( \rho \) is the density, \( c_0 \) is the ambient sound speed, the Lighthill stress tensor \( T_{ij} = \rho u_i u_j + \left( p - c_0^2 \rho \right) \sigma_{ij} - \tau_{ij} \) with \( u_{ij}, \sigma_{ij}, \tau_{ij} \) the velocity components, the pressure and the viscous stresses respectively.
The TBL-TE is a broadband noise demonstrated to be the predominant one for a wind turbine (Oerlemans, et al., 2009), especially for the high frequency range. A direct consequence of this aspect is that the trailing edge plays a fundamental role in sound production, such that the material and shape of it are subject of study to reduce the noise impact of a wind turbine.

*Laminar boundary layer vortex shedding noise (LBL-VS)*

Instability in the laminar flow separated by the airfoil produces vortex shedding and a consequent sound production, resulting to be a tonal noise with a peak at 3 kHz. A good blade design, i.e. serrated edge, can reduce this component.

*Flow separation noise (SEP)*

The sound produced will be low when the airflow is laminar. However, for high speed of the incoming air or for long blade the turbulence appears over the blade. Turbulence at the end of the blade produces the TBL-TE. However, the boundary layer in the low pressure side of the blade increases when the pitch angle increases, thus reducing the energy production and increasing the sound generation by flow separation.

*Trailing edge bluntness vortex shedding noise (TEB-VS)*

The TEB-VS is produced by instabilities in the wake caused by the thickness of the blunt trailing edge. The resulting noise has a peak at 2 kHz and is reducible through a thinner edge.

*Tip vortex noise (TIP)*

The tip vortex noise derives from vortex around the blade’s tip due to the rotation, which interacts with edge itself. The sound produced is broadband with peaks at 2 and 3 kHz (Drobietz, Borchers, 2006). The TIP can be mitigated by a correct design of the blade’s tip.

The combination of all the previously described components led to a broadband signal (Petitjean, et al., 2011), similar to that produced by the heating, ventilation, and air conditioning in buildings. In Figure 3.3 the reported spectrum does not consider LBL-TS, because a laminar condition is not permanent on a blade, nor the TEB-VB that is negligible for large turbines.
All the mechanisms described are related to a blade with inflow. A further sound generation derives from the movement of blades in a medium. During the rotation, the air at the front edge is pushed sideways to come back again on the back edge. If the rotational movement is periodic, the air is periodically forced causing the so called “thickness sound”. However, the movement is relatively laminar and the acceleration produced is small, thus not causing a significant sound emission. When a blade passes close to the tower, it runs into a step change in pressure causing a slow down in the wind that is forced to move laterally along the edge. Then, a variation in the blades’ attack occurs, resulting in a sudden change of forces friction and lifting agents on the blades that increase the thickness sound at the repetition rate of the blade passing in front of the tower. This is true for a downwind rotor, which creates a wake causing a significant change in the load of the blade. Fortunately, in modern rotors a device rotates the tower in order to always have the windward condition, resulting in less load variation of the blade than the downwind turbines.

The overall noise produced by a wind turbine, usually called “blade swish” (Van den Berg, 2006a), can be seen through a noise camera or by simulation programme as in Figure 3.4.
3.2 Wind shear and noise propagation

Wind power without the wind is obviously impossible. The wind, as already described, affects the noise generation by means of complex mechanisms proportionally to its speed, but also affects the noise propagation at distances where normally the receivers are sited. Also the noise perception is influenced by the wind, which can create a masking effect by interacting with vegetation and the obstacles nearby. The knowledge of the vertical wind profile in a site is of extremely importance, allowing the prediction of both energy and noise production of a wind farm. Most of the studies on wind shear were mainly performed for energetic purposes, whilst much less attention has been given to its influence on the noise emitted.

The atmospheric stability has a deep effect on the vertical wind profile and intensity of the atmospheric turbulence. Indeed, it is determined by the net heat flux to the ground resulting from the solar radiation balance of the incoming and outgoing heat radiation, with the addition of the latent and sensible heat exchange with the air and with the subsoil. When the incident radiation dominates, the air is heated from below and begins to rise causing the atmospheric instability. The thermal turbulence implies vertical air movements that prevent
large variations in the vertical gradient of wind speed, i.e. the average change in time of the
wind speed with height (Petersen, 2007). When the outgoing radiation dominates, the air
starts on cooling from below, with consequent development of a density gradient from the
bottom to the top leading to a stable configuration with damped vertical movements. The
decoupling of horizontal layers of air in the daily cycle allows, then, a higher vertical wind
velocity gradient. The neutral atmosphere occurs when the thermal effects are less significant,
usually corresponding to high cloudiness or strong advection (Van den Berg, 2006a).
Several analytical descriptions have been given to wind shear, among which the Garrat one
(Garrat, 1991):

\[ \frac{v_{h1}}{v_{h2}} = \frac{\ln(h_2)}{\ln(h_1)} \]

The equation allows to calculate the wind speeds at a height h1 given the wind speed at the
h2 height, with z0 the roughness length.
Carrying out a measurement of the wind speed at 10 m height and deriving the vertical speed
profile by means of the above equation is currently a standard procedure at international
level, such as the standard IEC 61400-11 (IEC 61400-11:2012) for the assessment of a wind
turbine noise power.
Another analytical representation of wind shear, widely used in the engineering field (Kwon,
2010), is the following:

\[ \frac{v_{h2}}{v_{h1}} = \left( \frac{h_2}{h_1} \right)^m \]

The relationship between wind speed at different heights is a function of the shear exponent
m in this formulation. This relation has empirical validity when h is bigger than the roughness
length, but not at very high altitudes where the wind speed is more or less constant. Based on
Pasquill stability classes (Pasquill, 1961), m has a value of 0.1 or more in the plains, from
0.14 for a neutral atmosphere to 0.1 in an unstable atmosphere with the dominant diurnal
thermal effects. In a stable atmosphere, the vertical movements are damped due to the cooling
of the soil, thus m is about 0.7 (Smedman, et al. 1996). The Pasquill classes will be used to
derive a parameter in the procedure developed in the thesis.
Both the relations can efficiently work in flat terrain. However, as it will be shown through
measurements in a following paragraph of this thesis, in complex orography many physical
phenomena occur making these equations unreliable.
Near a mountainous relief the wind is deflected at the summit, thus locally increasing the speed and creating a vertical component in the wind speed that alters the wind shear. In addition, based on the morphology of the terrain or the wind speed, the downstream flow will also be turbulent (Stull, 2000). Then, the wind shear description of very different grounds compared to the ideal flat ground is extremely complicated and is normally not suitable to analytical representations.

The general case in complex non-wooded soil is a wind shear smaller than in the flat ground because the prevailing force on small scale is no longer the friction of the ground but the compression of the flow rising from the slopes. However, an inverse wind shear on the hills due to hill effect can occur, meaning that the wind speed may actually decrease with increasing height instead of growing (Wagner and Marthur, 2009). In addition to issues related to hilly terrain profile, the presence of thick vegetation on the ridges interacts with the wind field. The procedure commonly used to reconstruct the vertical wind profile from a simple measurement of the wind at a height close to the surface becomes thus even more unlikely (Van den Berg, 2007; Hui, Crockford, 2007).

### 3.3 Wind shear influence on noise

The wind shear not only complicates the reconstruction of the wind profile given a measure on the ground, but also affects the noise both in its generation and in its propagation. Indeed, changes in wind between day and night occur: from an atmosphere with thermal turbulence in daytime to a neutral atmosphere at night, with the typical adiabatic gradient of temperature. The variation from night to day results in a higher wind speed at hub height, hence a higher turbine sound power level compared to that of the daytime period. At the same time, there will be less wind speed at ground height, where receivers are sited, resulting in less vegetation noise and a minor masking effect, described in a following Chapter.

The influence of wind shear on the source is of the double type: the first related to the temporal variability of the wind that generates the rotation of the blades and consequently the energy and sound production (Wharton, Lundquist, 2012), the second is a variability in the intensity of the wind due to the size of the blades. Indeed, in modern large turbines, the distance between the tips of the upper and the lower blade is of tens of meters. At such a
distance a speed difference is created and results in turbulent motions, with consequent
difference of angle of attack of the wind on the blades. An increased angle of attack
consequently produces an increment in noise level, which is dependent on the wind shear
(Van den Berg, 2006a). Thus, when the wind shear raises due to atmospheric stability, also
the sound emission increases, being higher than the predicted from a ground wind speed in
neutral atmosphere. This results in a higher noise impact on neighbouring residences than the
one predicted by models (Van den Berg, 2008a).

3.4 WTN propagation

As any other source of noise in the external environment, the propagation of the WTN is
determined by the directivity of the source, the geometrical divergence, the atmospheric
absorption, the reflection and absorption on the ground or surfaces and the meteorological
effects.
The noise produced by a wind turbine does not have the same intensity in all directions, but
presents a cardioid emission with the primary radiation from the outer blade portion toward
the bottom (Oerlemans, et al., 2007). At a considerable distance, the receiver is usually in line
with the acoustic rays coming from the lower emission part of the blades, thus most of the
noise is usually heard under the turbine but not much farther. Unfortunately, in the external
environment the sound can propagate over long distances and be perceived over 1 km away,
even 2 km in exceptional cases (Shepherd D. et al., 2011). Normally, directional sound fades
for geometrical spreading as it moves away from the turbine (distribution of an energy of a
growing area) and for atmospheric absorption. The latter, in particular, is most efficient at
high frequencies than at low. Consequently, the low frequencies propagate at greater
distances, so that with increasing distance the noise is perceived deeper.
In the propagation of the WTN meteorology plays an important role (Öhlund and Larsson,
2015), whose main effect is led by changes in wind shear and temperature profile (Wagner, et
al., 1996). When the source is immersed in a wind field, a "shadow region" is created upwind
to the source and consequently more noise will be in the downwind direction. In extreme
conditions of thermal inversion, the sound rays of the raised sources with respect to the
receiver can be bent to the ground in the downwind area and create focusing effects at
considerable distances from the source, resulting in slightly higher noise immission compared to the case of absence of wind and no inversion.

Given the complex combination of dependencies between the source characteristics, the source-receiver geometry, the type of terrain and meteorology, empirical and semi-empirical models to predict the external noise are quite popular (Attenborough, et al., 2007). These models are usually designed for road, rail or industry sound sources, but they can also be functional to predict WTN.

The source directivity, of cardioid type for wind turbines, the geometric spreading and the atmosphere absorption are well described phenomena in all models, whilst the reflections due to the terrain and the weather effects are hard to model and also the best softwares can have high uncertainties on them.

The predictive models most commonly used and applicable to the WTN propagation are here briefly described.

**Method ISO 9613-2**

The method estimates the equivalent continuous A-weighted sound pressure LfT (DW), also in octave bands, at a receiver in the meteorological conditions favourable to sound propagation. LfT (DW) with central frequencies ranging from 63 Hz to 8 kHz is calculated as the sum of the sound power level of each point source, including their images, with their directivity and an attenuation term. The attenuation is includes all the factors involved in the propagation of sound from the source to the receiver: geometrical divergence, atmospheric absorption, soil effect, presence of obstacles and other heterogeneous effects (ISO 9613-2:1996, 1996). The method has always proved to be functional for a multitude of source, however it does not consider the wind shear, the size of the turbine and its impact on the lateral attenuation, the propagation of sound downwind. An accurate representation of the noise produced by wind farms levels is possible with the ISO 9613-2 method, even though the constraint on the ground attenuation of source height less than 30 meters remains a problem (Kalapinski, 2009).

**CONCAWE**
The method (Manning, 1981) allows to consider a sound diffusion of spherical type with corrections for atmospheric absorption, ground effect (including the influence of the height of propagation), the effect of the barriers and the meteorological effects (refraction).

The weather conditions are grouped into six categories, defined by the Pasquill classification, based on the incoming solar radiation, time of day and the wind speed. The acoustically neutral conditions are assumed corresponding to the fourth meteorological class, while the case of strong downwind condition corresponds to category 6. The weather corrections are described by a polynomial equation of the third order of the logarithm of the horizontal separation between source and receiver. As in the ISO method, the model allows the simultaneous presence of acoustically hard and soft ground along the propagation path. However, it uses only the distance travelled on the soft ground in the calculation of the ground correction, rather than defining the proportions of the source, the medium and the receiver.

Compared to ISO 9613-2 method, CONCAWE does not provide the attenuation of the vertical edges and the attenuation for propagation between buildings, but it provides a wider range of weather condition rather than just the case of “moderate downwind” as the ISO 9613-2. Furthermore, it can calculate the ground effect reduction in octave bands also in the presence of a horizontal barrier and not simply assume the loss of it if a barrier is present. CONCAWE represents an interesting model for sound propagation outdoors, given its better provisions for different weather conditions and interactions with barriers, ground and weather effects. However, an improvement may consider several classes of ground, instead of just the one hard or soft.

**NORD2000**

The model predicts the noise long distance from all the types of source taking into account the terrain profile and any combination of surface types. Attenuations for the atmospheric absorption are included, calculated on the basis of ISO 9613-1 (ISO 9613-1:1993, 1993) and for the ground effect, assessed by the theory of geometric rays and the reflection coefficient of the spherical waves. The shielding also produced by obstacles is considered by the diffraction theory in combination with the geometric theory, and the reflections are processed through the image sources and a treatment of the Fresnel zone. The effect of atmospheric
refraction is calculated using a heuristic algorithm or by the geometric theory. The model takes into account the simple topography and six categories of ground from hard to very soft. Nord2000 has proven to be very reliable to describe point sources and sufficiently reliable for wind turbines, although it has some limitations (Plovsing, Sondergaard, 2009): the sound pressure level is only simulated for frequencies below 10 kHz, the model need to simulate a complex source by splitting it into many point sources, the terrain profile from the source to the receiver must be approximated in a series of contiguous linear segments. Furthermore, to simulate the weather effect on the propagation the vertical profile of the wind speed is considered as the logarithmic equation (Garrat, 1991), with all the problems related to it that will be described in Chapter 7.

3.5 Amplitude modulation

None of the previously described noise models can deal with the most particular aspect of WTN and the real cause of disturbance to people: the amplitude modulation (AM), sometimes called “blade swish”. Being a very complex issue, many studies have been dealing with it and in the recent years an increased knowledge on the subject has been developed. Unfortunately, there is still no generally accepted metric for describing and quantifying AM noise in general, even though some recently appeared (NT ACOU 112, 2002; Lee, et al., 2009; Lenchine, 2009; NZS 6808:2010, 2010; Di Napoli, 2011; Lundmark, 2011; McCabe, 2011; McLaughlin, 2011; Atzler, et al., 2011; NSW, 2011; Gabriel, et al., 2013; Cooper and Evans, 2013; RUK, 2013; Levet and Craven, 2014; Fukushima, et al., 2013; BS4142, 2014). Mostly, all of these methods can be grouped into two groups: one deriving a value of the AM to penalize the noise level value, the other evaluates a threshold of acceptability, beyond which the AM is not tolerable and noise mitigation actions should be taken. Unfortunately, a method which is perfectly reliable and that has no defects of any kind has not yet been found, thus a continuous study on them is even necessary (INWG, 2015).

More in details, the noise generated by the interaction of turbulence and the blades is amplitude modulated when its level shows periodic fluctuations, which is at the blade-passing frequency for a fixed observer. This AM is always present in the proximity of an operational
wind turbine and is commonly described as “swish”. An observer would experience periodically varying levels of noise related to the passage of each blade because of the principal source, the trailing-edge noise. Since it has a particular directional radiation characteristics, the AM resulting from the trailing edge noise directivity effect has been named “Normal AM” (NAM), being a normal feature of WTN.

The theory of Oerlemans (Oerlemans and Schepers, 2009), with the further development accounting for non-uniform flow into the rotor disc (Oerlemans, 2011), suggests that NAM would not be expected to be apparent, or with less than 3 dB(A) variation. Some studies show the existence of periodic variations in overall level as well as higher AM levels in the far-field (5-10 dB), down-wind from wind turbines (van den Berg, 2004; Di Napoli, 2011).

The noise was generally described as being more impulsive in character, better described as a “whoosh” or “thump” rather than a “swish” (Bowdler, 2008), with increased dominance of frequencies in the 200-400 Hz region (Stigwood, et al. 2013). AM phenomena with different characteristics from the expected NAM have been termed “Other AM” (OAM).

In 2011 (Bullmore et al., 2011), the causal mechanisms of OAM were not understood. At present, the causes are clear and are described in the following, but they are all dependent on turbine-specific blade design and operational characteristics. It is therefore not possible to predict with any certainty whether or not a given turbine on a particular site would generate OAM. Only in 2015 the first remedies for AM mitigation came out (Cand and Bullmore, 2015).

The variation of wind speed on blades due to the wind shear cannot, in itself, lead to increased modulation or account for the observed characteristics of OAM. Partial stall is triggered for part of the rotation by wind shear; an increasing inflow wind speed increases the effective angle of attack of the flow onto the blade, or other flow non-uniformities, such as turbulence, the wake of another turbine etc., could trigger similar effects. The localised blade stall led the turbulent air to create an increase in noise generation with lower frequency content and different directivity characteristics if compared to the ordinaries. Thus, the momentary and periodic increase in noise level is created when such flow separation occurs over a small area of each turbine blade in one part of the blade’s rotation only.

Less frequently OAM in the upwind direction are experienced, but generally is the downwind direction the one where the highest overall noise levels are reported in the far-field of the turbines due to favourable propagation conditions.
The different acoustical features with their downwind impact of OAM, compared to the more limited and predominantly crosswind impacts of NAM, can then be due to the combination of a transient stall source generation mechanism, its associated directivity effects and the propagation effects (Oerlemans, 2013). The characteristics of the stall region (SEP) determine the increased AM and eventual additional lower frequency content (Makarewicz and Golebiewski, 2015), whilst turbulence ingestion can be excluded from the direct source mechanism (Smith, 2012).

For a receiver, even if the intensity of WTN is low, the perceived noise is a sound twice modulated: once in its amplitude and once in time due to the variability of the wind field in time and space. The directivity of the OAM in the far-field is highest downwind and more limited cross-wind, the opposite of what happens in the near-field for NAM. The WTN during a typical amplitude modulated period is shown in Figure 3.5. Relatively impulsive modulation observed in the far-field downwind location does not show the same modulation in the cross-wind direction. At the same time, in the immediate near-field, the opposite and standard pattern of modulation appears (Cand, et al., 2012).

Figure 3.5. Measurements of OAM in two far-field (downwind and crosswind) and two near-field locations (cross- and downwind) (Cand and Bullmore, 2015).

3.6 Background noise and the masking effect
The disturbance perceived by citizens is determined by the ratio of WTN and the background (or residual) noise, responsible for the so-called masking effect. The masking is the process by which the threshold of audibility of a sound is increased by the presence of another sound that covers it. As part of the human perception of noise generated by wind farms, masking due to environmental noise plays an important role, making it seems the noise produced by an aerogenerator less disturbing or even not audible to a particular receiver. The background noise is then of crucial importance, so much that some researcher studied the possibility of masking the WTN with road traffic noise due to their different impact on annoyance (Pedersen, et al., 2010)

Particularly in rural areas, the main component to the noise is generally of natural origin, generated by the wind passing in the vegetation. The sound produced by this mechanism grows as a function of wind speed, just like the WTN. Consequently it is of great interest to know how the sound produced by the vegetation varies and what its sound masking potential is. The detection thresholds for WTN in the presence of natural sounds from trees and sea waves can arrive to around −8 to −12 dB on the signal to noise ratio (Bolin, et al., 2010).

The temporal variations to which the vegetation noise is subjected have a big effect on masking potential, but the background noise generation is a time, weather and site dependent phenomenon. Under these conditions, the inference and prediction of masking in generalized environmental and weather conditions are impossible.

Not by chance, few field studies are present in literature besides that of Fégeant (Fégeant, 1999a; 1999b). Its semi-analytical empirical prediction model of noise differentiates vegetation by species and geometries. To overcome the complexity of the wind turbulence phenomenon, the author uses a combined discrete model of vegetation noise with a stochastic prediction model of turbulence in order to evaluate the fluctuations in the sound produced by the vegetation caused by wind variation.

However, the number of tests carried out by the author was limited and the subsequent studies of Bolin (Bolin, 2007; 2009a) verified the actual validity of the theory, especially at different range of wind speeds than those used by Fégeant. The different atmospheric conditions can strongly influence the predicted noise and therefore had to be taken into account in the model. Furthermore, the number of computations performed for the
Simulations is very high and only short time sequences can be predicted, leading to a reduced turbulence statistics describable and thus a low use of the model (Bolin, 2005). Such a great casualness in the residual noise always makes necessary to carry out background measurements during the evaluation of acoustic impact of a wind farm.

Several measurement methods are present in literature, but the best known is the one proposed by Bowdler in 2007 (Bowdler, 2007). The acquisition of wind measurements and noise occurs every 10 minutes, with the wind measured at 10 meters above the ground under the wind turbines. The noise is measured at the receiver and the acquired data are reported in function of the wind on the ground.

Experimentally, it appears very clear that the noise produced by the vegetation is always composed of a constant trend at low speed, i.e. independent from the wind, plus an increasing trend after a certain threshold speed. This threshold separates the non-wind induced noise from the wind induced one and the slope of the trend depends on multiple factors, including proximity to the vegetation of the measurement point, the type of vegetation, etc. The best fit of the residual noise is the sum of two functions, a constant plus a logarithmic, or a 2nd degree polynomial: \(L = A \log v + B\).

\(L\) is the level of residual noise, \(A\) and \(B\) are two constants and \(v\) is the wind speed at 10 meters above the ground measured in the vicinity of the wind turbines. As will be shown in the following, this method of measurement has some shortcomings, mainly related to the height of wind measurement and the conversion of the wind speed through the wind shear equation.

When the noise measurement is long term, a subdivision of the data in the day and night period allows reducing the dispersion of the 10 minutes values around the fit, in addition to being necessary for legislative reasons. The points distant from the fit are related to complex parameters that during outdoors measurements can come into play and can lead to unexpected and incorrect data, making impossible to obtain reproducible results in two identical measures taken in the same place.

Indeed, not all the data out of the fit would to be discarded or to be held erroneous. In Chapter 7 of this thesis a possible solution will be proposed for some of these issues arose, among them: a correct positioning of the equipment and the choice of parameters to be used, the measurement length, a proper elimination of the spurious events.
4. Noise perception

With the increasing installation of wind farms, the attention of citizens to the WTN issue has grown. The scientific community has responded promptly increasing the studies and the social surveys in order to better understand what is the cause of their disturbance and which indicator better describes and is related with it. The present Chapter deals with these studies, which may also be divergent, paying attention to the low frequencies / infrasounds and how they affect people. Particularly attention will be given to the direct and the indirect health effects of noise, underlying that WTN is significant for the indirect ones, particularly for the annoyance. Since wind turbine noise results much more disturbing than the other most common noise sources, the reasons to consider annoyance as a health effect and how it can affects people life are discussed. All the analysed researches are based on long term noise indicators, but the choice of the noise metric to which relate the health effects and people reactions is still an open problem deserving further studies.

4.1 Introduction

Around the world wind turbines are being installed over recent years as a common practice to boost the production of non-fossil energy. Unfortunately, this quest for green energy is not always sufficiently followed by a careful analysis of the damage or disturbance suffered by people. In the particular case of noise pollution, complaints by citizens living at a distance up to 1500 m from the farm are growing continuously (NHMRC, 2015).

The issue of noise effects on health is much more complicated and the scientific community is discordant about the harmful effects of the noise levels at the receivers produced by wind turbines, which usually vary between 35 and 50 dB(A). While some authors argue that these levels are not a problem for citizens (Kaldellis, et al., 2012; Knopper and Ollson, 2011; Schmidt and Klokker, 2014), the WHO and other authors have an opposite opinion, supported by the actual complaints of the citizens. It is not coincidental that the proposed dose-effect curve for highly annoyed to WTN (Janssen, et al., 2011a) shows a more pronounced slope compared to conventional noise sources (Miedema, Vos, 1998).
The clear understanding of a minimum WTN value to be avoided at receivers can be very important in the design phase of new wind farm, because the weight of evidence suggests that when sited properly, wind turbines are not related to adverse health effects (Knopper, et al., 2014).

This Chapter tries to justify the strong disturbance caused by the wind turbines even at low noise levels. This is performed by looking at the studies in literature concerning the harmful effects caused by generic or specific low noise levels, with particular attention to the ambiguous problem of low frequency noise (LFN), on which some literature reviews lack of completeness and contain omissions (Horner, et al., 2013) while other in the very last years did not (SHC, 2013).

Finally, it is crucial not to underestimate the effects that annoyance has on health because noise is not just a physical process, but is an emotionally charged term with etymological links to nauseous and noxious stimuli. The response to noise is a complex process connected to the reticular system, the brain portion that helps regulate the level of body activation, motivation and consciousness (Klæboe, 2011).

4.2 Low frequency noise and wind turbines

Wind turbines have always been considered a source of LFN because of their particular sound emission. However, this changed with the introduction of modern machinery, built with more attention to noise emissions. Both infrasound and the low end of the audible noise spectrum are normally included in the definition of low frequency. This Chapter try to clarify the issues related to these misunderstanding, including the interactions that low frequency has with humans. The main results of the studies analysed are that (McCunney, et al., 2014):

- infrasound are not a problem, being not usually noticeable to human ear;
- LFN disturbs the population, especially during sleep and work activities;
- LFN are less attenuated and can be heard at great distances, mainly in rural areas with low background noise.
4.2.1 Effects of low frequency noise on health

The exposure to low frequency noise during night can cause short periods of sleep and can reduce the waking period (Fecci, et al., 1971; Landstrom, et al., 1982; 1983; 1985; 1991; Landstrom, Bystrom, 1984). Studies (Persson Waye, et al., 1997; 2001) have shown that low frequency can also lead to performance degradation of workers in the assigned tasks. Kyriakides and Leventhall (Kyriakides and Leventhall, 1977) showed that a worker affected by such noise have the same loss of performance of an employee under the influence of alcohol. Moreover, the exposure to infrasound increases the time needed to perform tasks. A constant exposure to LFN has also been classified as a "background stress" factor, defined as persistent events that can become routine elements of our lives and then eventually become more severe stress (Benton and Leventhall, 1994; Benton, 1997). In studies (Leventhall, 2003; 2004), LFN has been recognized as a particular environmental problem in acoustics, especially for sensitive people inside their homes or in the workplace. A rough estimate is that about 2.5% of the population, about 1,000,000 people in the age group 50-59 years in the EU-15, may have a hearing threshold at least 12 dB more sensitive than the average at low frequency. Specific criteria for the recognition of LFN have been introduced in some countries, but they do not adequately consider the fluctuations of the individual sensitivity, or their validation was made only for a limited range of sounds and subjects.

4.2.2 Infrasound and low frequency noise

The first models of wind turbines generated pulses at levels such that the vibrations produced effects on buildings. For turbines with two blades this occurred twice for each revolution. K. P. Shepherd showed in (Shepherd and Hubbard, 1991) that a slow series of pulses occurring once per second is analysed and recognized as an infrasound with a harmonic series in steps of 1 Hz. The peak pressure of the pulses is actually the cause of the transient effects in buildings and not the emission of a continuous infrasonic wave, like often misunderstood. Even the modern wind turbines produce infrasonic impulses, but they have such lower levels (50-70 dB) that they are below the hearing threshold. This allows to neglect the infrasound in the evaluation of the noise from modern wind turbines (Jung, et al., 2008), even though some studies still are investigating on them.
Several studies, e.g. (Turnbul, et al., 2012), performed measurements of infrasound from wind turbines, showing mostly the same results. The one-third octave level at 10 Hz is around 60 dB at residential distances, with a negative spectrum slope of 3 to 6 dB per octave. The levels decrease with distance and may be masked by background noise. A sounds below the hearing threshold do not produce a response in the auditory cortex, thus no evidence that the low levels of infrasound from wind turbines are harmful to humans are emerged, as well as they can impact the vestibular system (Ellenbogen, et al., 2012). Anyway, some people remains convinced that they are harmed by infrasound from wind turbines, because some studies (Pierpont, 2009; Alves-Pereira and Castelo Branco, 2007; Salt and Kaltenbach, 2011) stated that LFN can be harmful and many wind farm opponents took this very seriously for opposite publicity. A complete understanding of this phenomenon will surely require a multidisciplinary approach (Leventhall, 2013).

The boundary between infrasound and LFN is so thin that sometimes the terms are confused. However, in conventional measures of environmental noise, such as when using the A weighting, the audible noise at low frequency has some undetectable annoying features. The difference between responses to LFN / infrasound and other frequencies is in Figure 4.1. Although the low-frequency sounds require a higher intensity to be perceived, annoyance increases more rapidly at higher levels. At 4 Hz higher annoyance levels are reached in an increase of only 10 dB, compared with about 50 dB at 1000 Hz.

![Annoyance to low frequency noise](image)

*Figure 4.1. Growth of annoyance at low frequency. Annoyance is evaluated through a Visual Analogue Scale. Modified from data reported in (Leventhall, 2005).*
The famous "swish noise" is the AM of the natural frequencies of the system perceived as a nearly LFN. The low frequencies properly produced from wind turbines were mechanical in origin and are significantly reduced in modern models. However, the generation of the low frequency occurs when the inflow air interacts with the blade in a very turbulent state. A study from Leventhall (Leventhall, 2005) shows that the LFN produced by wind turbines, if any, is perceived as a component not naturally present in the environment and therefore as a negative stimulus that will disappear when the turbine is stopped or if the wind changes. The no habit of listening low levels of broadband noise and low frequency is probably the most important aspect causing annoyance in WTN.

In the recent Canadian study (Health Canada, 2014), long-term measurements over a period of 1 year were conducted in relation to infrasound levels and the main results were:

- Infrasound from wind turbines could sometimes be measured at distances up to 10km from the wind turbines, but was in many cases below background infrasound levels.
- The levels decrease with increasing distance from the wind turbine at a rate of 3dB per doubling of distance beyond 1km, downwind from a wind turbine.
- The levels of infrasound measured near the base of the turbine were around the threshold of audibility that has been reported for about 1% of people that have the most sensitive hearing.

4.3 Wind turbine noise and health effects

4.3.1 Health effects from direct exposure to noise

Until the recent study performed by Health Canada (Health Canada, 2014), the assessment of the health effects related to exposure to WTN has been limited to few studies. Most of the repeatable studies are based on measurements of well-being or quality of life and on the extent to which noise alters various human activities (such as sleep). Self-reported health problems include, among others, nausea, dizziness, heart palpitations, stress, peak blood pressure, sleep disorders and discomfort (Harry, 2007; Pierpont, 2009; Krogh, et al., 2011). To date, no studies have included objective health measures in study design that could lend support to some of the statements derived from the questionnaires.
Generally, noise disturbance in urban or residential environments is more affected by highways, railways and airports than wind farms. However, wind power plants are usually placed in rural environments, where anthropogenic noise sources are minimized. Noise has the potential to affect health through stress and hearing loss (Merlin, et al., 2013). Regardless of the type of community, prolonged exposure to noise can directly or indirectly affect the health of individuals. Direct effects occur when the sound pressure levels are above 75 dB(A), potentially causing permanent hearing loss based on the duration of exposure and the sensitivity of the individual. The recent Health Canada study (Health Canada, 2014) published a summary of results of the objective measures for stress and sleep quality that were not found to be associated with calculated outdoor WTN levels. WTN was not observed to be related to hair cortisol concentrations, blood pressure, resting heart rate or measured sleep (e.g., sleep latency, awakenings, sleep efficiency). Nevertheless, the indirect effects resulted very important. The most common of them is, among others, the sleep disturbance with its long term complications. Sleep disorder in populations living near wind farms has been found in some studies (Knopper and Ollson, 2011). Timmerman (Timmerman, 2013) reports that WTN can be a source of real discomfort and adverse health effects. However, there is insufficient evidence that it is directly causing health problems or disease, while a relation to annoyance is found, as it will be deeper analysed in the following. Moreover, a study (Salt and Kaltenbach, 2011) of the Commonwealth of Massachusetts Department of Environmental Protection sentenced that none of the limited epidemiological evidence reviewed suggests an association between WTN and pain or stiffness, diabetes, high blood pressure, tinnitus, hear impairments, cardiovascular disease and headache. On the contrary, other authors (e.g. (Kirschbaum and Hellhammer, 1999)) state that wind turbines could affect those living nearby, basing of the interaction between infrasound and ear, but this was an important public debate related to old downwind wind turbines.

4.3.2 Annoyance and sleep disorder: indirect health effect

Indirect effects on health cannot fail to include annoyance, recognized as a psychological state that represents a degree of mental discomfort to noise (WHO, 1999). A high degree of community annoyance from noise constitutes an adverse health effect, as reported by Michaud (Michaud, et al., 2008a).
The author underlined the role of the percentage of highly annoyed (%HA), the parameter used to measure people's reaction to a specific source, as one of most important health end-points for an environmental assessment. The author also used it to justify the limit fixed in Ontario. On the other hand, the definition of health goals made by the World Health Organization (WHO, 2009) is "a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity" and it is "the extent to which an individual or group is able, on the one hand, to realize aspirations and satisfy needs, and on the other, to change or cope with the environment ". Already in 1999 Guidelines For Community Noise (WHO, 1999) is argued that:

- In homes the effects of noise are typically sleep disturbance (especially for bedrooms), annoyance and speech interference. Measurable effects on sleep disorder by indoor noise disturbance start from 30 dB(A) of $L_{Aeq}$.
- The interference in speech and the difficulty in reading, especially in children, occurs with an ambient noise levels of 15 dB lower than the typical 50 dB(A) of communication, thus is around 35 dB(A).

The annoyance has been identified by WHO as one of the effects of noise on health for which the guideline values were fixed (Fields, et al., 1997):

- 42 dB (A) sound level at night outdoors to have interference on the quality of sleep and to have a self-reported disorder.
- 40 dB (A) sound level at night outdoors to have sufficient evidence of use of sedatives and sleeping drugs.

For the primary prevention of adverse effects on health related to noise, although subclinical, the WHO recommends that the population should not be exposed to levels of external noise at night above 40 dB(A).

The Good practice guide on noise exposure and potential health effects of the European Environmental Agency (EEA, 2010) listed the negative effects of noise on health and the corresponding thresholds, as shown in the Table 4.1.
Table 4.1. Negative effects of noise on health for the EEA (EEA, 2010).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Dimension</th>
<th>Acoustic indicator</th>
<th>Threshold</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annoyance</td>
<td>Psychosocial, quality of life</td>
<td>$L_{den}$</td>
<td>42</td>
<td>Chronic</td>
</tr>
<tr>
<td>Self-reported sleep</td>
<td>Health, quality of life</td>
<td>$L_{night}$</td>
<td>42</td>
<td>Chronic</td>
</tr>
<tr>
<td>disturbances</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The WHO (WHO, 2011) confirmed once again that annoyance may be taken as a basis for noise impact assessment on the population exposed and can be considered a negative effect on health. Moreover, people disturbed by noise can experience a variety of negative responses, such as anger, disappointment, dissatisfaction, helplessness, depression, anxiety, distraction, agitation or exhaustion (Fields, et al., 1997; 2001). In addition it was seen that the stress-related psychological symptoms, such as fatigue, stomach upset and stress itself, are associated with exposure to noise and annoyance (Öhrström, 2004; Öhrström, et al., 2006).

Moreover, considering the "high annoyance" (%HA) as a harmful effect is consistent with the definition of health provided by WHO and can explain why:

1. the %HA is related to chronic stress and other health effects (Klæboe, 2011);
2. the %HA has a strong dose-response relationship with the day-night and day-evening-night noise level and with the main descriptors for evaluating the impact of community noise in the United States and in European Union (END, 2002);
3. there are well-established standards based on the variation in %HA which is used as a criterion for evaluation of environmental noise.

The previous points are only valid for highly disturbed (%HA) and not just simply disturbed (%A). In many ways the chronic disorder can reflect the inability to cope with noise. A high chronic disorder to noise has the potential to increase its allostatic load, constantly requiring that the person adapts to noise (allostasis). This could potentially lead to a reduction in physical and mental health, including cardiovascular disease, sleep disorders, depression and anxiety (Anisman and Merali, 1997; 1999; Anisman, et al., 2001; Matheson and Anisman, 2003; Mantler, et al., 2005; Bierhaus, et al., 2003; Player, et al., 2007). Some of the quantifiable indices of allostatic load include systolic and diastolic blood pressure, adrenaline, noradrenaline, cortisol levels, waist-hip ratio, ratio of total cholesterol to high density lipoprotein levels (McEwen, 1998; 2000; McEwen and Lasley, 2003). It has been
shown that lower allostatic load correlates with better physical and mental health (Seeman, et al., 1997). The effects of interaction between annoyance and psychological suffering (Stansfeld and Matheson, 2003; Stansfeld and Clark, 2011) and between annoyance and sleep are well described as expectable and possible. 

It is known that the %HA has a certain dispersion both with the level of noise exposure and with the incidence of adverse health effects (Schultz, 1978; Babisch, et al., 1993; 2005; van Kempen, et al., 2002; Fidell, 2003; Fidell and Schomer, 2007), therefore a strong correlation between annoyance and health issues is difficult to demonstrate. Despite this, some elements in literature indicate that a high level of noise annoyance can increase the risk of disease. Firstly, there is evidence that exposure to everyday stress factors (family topics or work deadlines) can worsen the health and the subjective well-being (Almeida, 2005). Jacobs (Jacobs, et al. 2007) has recently shown that having a negative state of mind in front of everyday stressors is associated with lower cortisol production. In addition, long-term psychological stress has been shown to increase the risk of developing cardiovascular disease among men and women in the "Atherosclerosis Risk in Communities study" (Andren, et al., 1982). The Israeli study "Cardiovascular Occupational Risk Factors Detection" (CORDIS) has shown that for %HA there is a statistically significant impact on increasing cholesterol levels associated with noise (Melamed, et al., 1997). Further support to the relationship between %HA and physiological health effects is provided by the results of a recent study on living environments and health carried out by the WHO and the LARES (Large Analysis and Review of European Housing and Health Status) (Niemann, et al., 2006; Maschke and Niemann, 2007). This study has shown that a high level of self-reported annoyance among adults towards the traffic noise is statistically associated with high risks related to the prevalence of a variety of diseases, including hypertension and migraine. It also showed that the model for the prevalence of disease was also similar to the general noise annoyance to sources as the neighbourhood activity and the roads. Exposure to such stimuli involving an intense annoyance can be a serious risk factor for allergy, symptoms of arthritis, bronchitis, cardiovascular symptoms, depression, hypertension, migraine, respiratory symptoms.

The U.S. Department of Housing and Urban Development has recognized the %HA as a parameter that reflects a long-term response to exposure to noise levels and their ability to interfere with daily activities. Scores of annoyance are correlated with answers to questionnaires that investigate specifically the activity of interference and harassment caused,
which in turn are correlated with the noise levels (Fields and Hall, 1987). The %HA has been accepted by two federal agencies of the United States to assess the impact of noise (U.S.FTA, 1995; U.S.FRA, 2005; ANSI, 1996) and ISO 1996-1 (ISO 1996-1:2003, 2003). The noise disturbance is also pointed out as an harmful effect in the European Union, providing a basis for the indicator $L_{den}$.

Michaud (Michaud, et al., 2008b) showed that %HA by road traffic noise is statistically related to:

1. increase of the intensity of the voice during a conversation outdoors;
2. interference with the ability to sleep;
3. interference with the listening ability;
4. interference with the reading and the writing.

Furthermore, the canadian study findings support a potential link between long term high annoyance and health and reported a statistical relation between WTN annoyance and several self-reported health effects (blood pressure, migraines, tinnitus, dizziness, scores on the PSQI, and perceived stress) and a relation with measured hair cortisol, systolic and diastolic blood pressure.

As reported also by Michaud (Michaud, et al., 2008b), the sleep disturbance and annoyance are closely linked. A relation between WTN, annoyance and self reported disturbed sleep has been calculated by Janssen, (Janssen, et al., 2008), and is reported in Figure 4.2. Economical benefits has been shown to have a clear reducing effect on sleep disturbance and on noise annoyance.

![Figure 4.2. Average score for annoyance from WTN vs self reported frequency of sleep disturbed by (any) sound (Janssen, et al., 2008).](image-url)
When WTN is modulated and audible in the bedroom it can be above the sleep disturbance threshold, such that the high number of beats leads to a relatively high probability of sleep disturbance. The epidemiological study of Janssen (Janssen, et al., 2008) reported the sleep disturbance relation for exposure to WTN at night, Figure 4.3.

On the contrary, Michaud (Michaud, et al., 2016) evaluating sleep quality by means of the Pittsburgh Sleep Quality Index over a sample of almost 700 participants, suggested that sleep was not influenced by exposure to WTN. Specifically, the responses to the sleep questions on the questionnaire and the data collected with the sleep watch were not found to be dependent on the level of WTN at the participant's household. This still leaves open the scientific debate on the subject.

![Figure 4.3. Exposure-response relationships for sleep disturbance annoyance from exposure to WTN (Janssen, et al., 2008).](image)

### 4.4 Dose–response relationships for highly annoyed to WTN

Depending on the type of the source, a noise can be more or less disturbing than others while having the same energy. What has been described so far about wind turbines is reflected in the perception of people and in their evaluation of a particular type of noise. The percentage
of highly annoyed (%HA) is a parameter used to measure this reaction to the specific source. It represents the degree of acceptability of a source, rather than the sound energy detected. Annoyance is estimated through specific socio-acoustical surveys that comply with well defined international standards.

To the best of my knowledge, the following studies are those that have provided various degrees of relationship between WTN and annoyance, expressed in dose response relationship for %HA:

1. a Danish study (Pedersen and Nielsen, 1994);
2. the first Swedish study (Pedersen and Persson Waye, 2004);
3. a more recent Swedish study (Pedersen and Persson Waye, 2007);
4. a European study carried out in Denmark, Netherlands and Germany (Pedersen, et al., 2009);
5. an analysis of previous studies which provides a cumulative curve of the results so far (Janssen, et al., 2011a);
6. a Canadian study (Michaud, 2013);
7. a Polish study (Pawlaczyk-Luszczyńska, et al., 2014);
8. a Japanese study (Kageyama, et al., 2016).

The studies 2, 3 and 5 use the $L_{Aeq}$ as noise indicator, successively converted in $L_{den}$ using Van den Berg correction factor (Van den Berg, 2008b). The outdoor noise levels are simulated at receivers on a hypothetical period of time using the sound emission of all turbines in favourable propagation conditions, with 8 m/s of wind measured at 10 m height. In the Japanese study, noise was measured outdoor, although only for five days, and social surveys were conducted between the 2010 and 2012. The exposure-annoyance relationship obtained has a trend consistent to the former international studies.

A comparison between the dose-effect relations for the most common noise sources, shown in Figure 4.3, points out that the WTN becomes highly disturbing at much lower levels of noise from road and rail traffic, probably due to the AM. Compared to the old Miedema’s curves, WTN resulted even more disturbing than the airport one, known to be a very disturbing noise and actually widely studied for its high impact on population (Licitra, et al., 2014). Aircraft noise has then been shown to be more annoying since these curves were constructed (Janssen, et al., 2011b). In Figure 4.4 are also reported limits for the preferred
and maximum allowable noise levels according to the Dutch Noise Act, where the single limit for WTN leads to a somewhat higher percentage compared to the preferred limit for road traffic, trains and industry, but lower when compared to the maximum limit (Van den Berg, 2013).

Finally, also a recent study (Van Renterghem, et al., 2013) confirmed that people can easily recognise WTN and be subject of high annoyance by it, by means of a two-stage listening experiment on participants with normal hearing abilities. The WTN did not result more annoying than highway noise for low indoor noise levels.

![Figure 4.4. Dose-effect relationship of %HA to different noise sources (Van den Berg, 2013).](image)

4.5 Discussion

The promotion of the growth of wind energy has a strong impetus and is supported by many organizations around the world. However, citizens and installers require accurate information on the environmental impact that this fairly new technology causes, as well as any other possible source of pollutants, in order to allow a greater integration of wind farms in the territory and a better control during of environmental impact assessment for either existing or planned wind farms.

In this Chapter attempts have been done to find a path in the jungle of articles, even conflicting with each other, in order to quantify the minimum level of noise that may already be an inconvenience to citizens. From the review performed it results clear how there is a lack of specific studies for WTN and its health effects especially at low noise levels. Direct
effects have not been described yet in peer reviewed articles (Kurpas, et al., 2013), and health problems referred to as "indirect" are often disregarded, but they represents the main negative effects of exposure to low noise levels. This analysis has shown that a WTN level that can cause a fair percentage of annoyance among citizens is already 40 dB(A), as inferred from dose-effect curves based on the %HA. To support this theory, the relations that annoyance has on human health have been listed, to the best of my knowledge. This noise level is also a source of health problems as highlighted by the World Health Organization and by other scientists that recognise the key role of annoyance in health assessment. Among these diseases, the low levels of WTN can in fact disturb sleep, but also affect outdoors social activities, especially during summer.

It is not by chance that the WHO has identified an annual average night-time noise level outdoor of 40 dB(A) as recommended limit to protect public health noise, given the scientific evidence on the lowest observed adverse effect level for the sleep disorder. WHO limit is based on night-time road/rail/air traffic noise sources, but this value can be valid especially for the more disturbing wind turbines.

The low frequency and infrasound noise state of the art is not uniform and still deserving further and recent studies. The low frequencies, together with the AM (Lee, et al., 2011), are the cause of profound discomfort caused by WTN to the population even at low noise levels. It is possible to suggest that already 40 dB(A) of outdoor WTN is a noise level to be avoided at the receivers. Unfortunately, the WTN is a noise nearly constant on daily basis and 40-45 dB(A) can be often achieved during the night for the typical distances at which the receivers are actually located in the quiet country areas, for which also UK, e.g., basing on tranquillity surveys suggested a noise limit between 37-44 dB(A) (Watts and Pheasant, 2015).

All the studies concerning dose-effect relationship are based on the indicator of long term noise (L_{den}), which has an intrinsic limit related to people's perception of noise. As will be discussed in Chapter 6, the population is generally not disturbed by long-term average exposure, especially for fluctuating sources, but more likely by some shorter periods when noise exceeds a particular level. For this reason, noise limits based on that indicator may be unsatisfactory for citizens exposed to a source that they feel strongly annoying only a few times in particular conditions and remembers those situations in time (Licitra and Fredianelli, 2013; Fredianelli and Licitra, 2014; Larsson and Ohlund, 2014).
5. International legislative and regulatory framework

5.1 Introduction

The installations of wind farms are continuously increasing, as well as the complaints from receivers. These are caused by a variety of factors, including that in some countries wind turbines are also planned in amazing and quiet areas (i.e. Mediterranean countries), where dwellings are restored for touristic reasons and are chosen for their amenity and quietness as principal attractiveness. The disputes that follow the complaints often become legal actions, because the existing limit values have not been thought for WTN and there are still no well defined limits at international level, but they are fixed following different approaches.

The evaluation of noise at receivers is performed using outdoor measurements, obviously it depends on the measurement of background noise, which varies with wind speed. The solution adopted by some standards is here analysed, with a particular focus on the assessment of background noise. In common between all normative approaches there is often a lack of a scientific reason for the choice of the limit value.

The international legislative and regulatory framework is not very uniform, although some general remarks are now widespread (Weed, 2006). Among these:

- WTN has the unique characteristic that the noise level from each WTG increases as the wind speed at the site increases.
- The background noise also generally increases with wind speed and can mask the WTN.

As the impact of all the other noise sources, WTN is closely linked to the amount it exceeds the background noise, but the same noise in a quiet rural area will generally have a greater adverse impact than in a busy urban area, because of the masking effect of high ambient noise environments.

The assessment of WTN can be done comparing the noise impact of the source with a base noise level, but this is not sufficient: a wind farm could comply with this base level at lower wind speeds and exceed it at higher wind speeds. Most international jurisdictions, but not all, set a base noise level for low wind speeds and also ensure that WTN does not exceed the background noise by more than 5 dB(A) when the wind speed increases. Some of the most
important national regulations are summarized in the following.

5.2 International regulations

U.K.

The ETSU-R-97 noise limit (ETSU, 2005) is a combination of a fixed limit (in the range of 35 dB to 40 dB L_{A90}) and a derived relative limit (prevailing background curve + 5 dB). For the protection of the sleep during night, an external free field level of 43 dB L_{A90} is appropriate when background noise levels are low. When background noise levels are sufficiently high, then the noise limits are set to the prevailing background +5 dB. A single lower fixed limit of 35–40 dB(A) can be imposed when the background noise levels do not vary significantly, analyzed during the amenity periods and the night.

France

A wind turbine specific standard (NF S31-114–Acoustics– Measurement of Environmental Noise Before and After Wind Turbine Installation) has been drafted. At the present time, however, the applicable guidance is the Decret 2006-1099 (Decret n° 2006-1099, 2006) that specifies how the combined effect of any new noise with the existing noise should not exceed the existing noise level by more than 5 dB during the day and 3 dB at night. Noise levels are required to be measured in octave bands.

Germany

Noise limits are defined in a generic document from 1998, the TA Lärm (GMBI Nr. 26/1998, 1998), and reported in Table 5.1.
Table 5.1. Summary of limits for WTN in Germany.

<table>
<thead>
<tr>
<th>Area</th>
<th>Day [dB(A)]</th>
<th>Night [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial area</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Commercial area</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>Residential areas mixed with high commercial activities</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Residential areas and small villages</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Purely residential areas</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Areas with hospitals, health resorts, etc.</td>
<td>45</td>
<td>35</td>
</tr>
</tbody>
</table>

Netherlands

Regulations on noise from wind turbines were introduced in the Netherlands in 2001 (Koninkrijk der Nederlanden 487, 2001). The limits follow a wind speed dependent curve. For the night-time the limit starts at 40 dB(A) at 1 m/s and increases with the wind speed to 50 dB(A) at 12 m/s. For daytime the limit starts at 50 dB(A) and for evenings at 45 dB(A).

New Zealand

WTN should not exceed the background sound level by more than 5 dB(A), or a level of 40 dB(A) $L_{A90}$ (10 min), whichever is the greater. For some locations that are particularly quiet this limit of 40 dB(A) would be considered to be unreasonable. For this purpose, the 2010 Standard introduces a lower limit of 35 dB(A) $L_{A90}$ (10 min) for high amenity areas. A sketch is reported in Figure 5.1.
South Australia and New South Wales

The predicted equivalent noise level $L_{\text{Aeq,10min}}$, adjusted for tonality in accordance with the guidelines, must be evaluated at all relevant receivers for each integer wind speed from cut-in to rated power of the wind turbines. WTN should not exceed 35 dB(A) or the background noise (evaluated as the $L_{\text{A90,10min}}$) by more than 5 dB(A), whichever is the greater (EPA, 2009).

Denmark

WTN should not exceed the following limit values:

1) At the most noise-exposed point in outdoor living area, no more than 15 meters from dwellings in open countryside:
   (a) 44 dB(A) at a wind speed of 8 m/s.
   (b) 42 dB(A) at a wind speed of 6 m/s.

2) At the most noise-exposed point in areas with noise-sensitive land use:
   (a) 39 dB(A) at a wind speed of 8 m/s.
   (b) 37 dB(A) at a wind speed of 6 m/s.

Where “noise-sensitive land use” are the areas designated for residential, institutional, holiday home, camping, allotment purposes or recreational activities (DEPA, 2011).
Canada

Ontario, Alberta and British Columbia are the only Canadian provinces with guidance specific to wind turbines.

In Ontario the current Guide (MOE, 2008) sets the noise limits at a receiver in rural areas (class 3) ranging from 40 dB(A) to 51 dB(A), depending on wind speeds in the range of 6 to 10 m/s at 10 m of height. For class 1 and 2 (urban) the limits range from 45 dB(A) to 51 dB(A), as shown in Table 5.2 and Figure 5.2.

Table 5.2. Summary of limits for WTN in Ontario (MOE, 2008).

<table>
<thead>
<tr>
<th>Wind speed (m/s) at 10 m height</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTN level limits class 3 area, dB(A)</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
<td>43.0</td>
<td>45.0</td>
<td>49.0</td>
<td>51.0</td>
</tr>
<tr>
<td>WTN level limits class 1&amp;2 area, dB(A)</td>
<td>45.0</td>
<td>45.0</td>
<td>45.0</td>
<td>45.0</td>
<td>45.0</td>
<td>49.0</td>
<td>51.0</td>
</tr>
</tbody>
</table>

Figure 5.2. Summary of limits for WTN in Ontario and reference wind induced background noise (MOE, 2008).
Due to the particular acoustic emission as a function of wind speed, the critical condition for compliance with the noise limits in most cases occurs at the 6 m/s wind speed. Therefore, the noise limit at the receiver is generally considered to be the same for all wind speeds and wind turbine operating conditions at 40 dB(A) (MOE, 2009).

In a quiet rural area, application of Alberta's Energy Utilities Board Directive 038 (AER, 2007) would yield a criterion with a night-time $L_{eq}$ of 40 dB(A) for rural area. This is because the average rural ambient noise level in Alberta is about 35 dB(A) during night and the limit is fixed 5 dB(A) above it. The only wind speeds for which the Directive prescribes predictions are between 6 and 9 m/s. The limit increases depending on the number of dwellings in the area and on the category of the area, as shown in Table 5.3.

<table>
<thead>
<tr>
<th>Proximity to transportation</th>
<th>1-8 dwellings; Night-time [dB(A)]</th>
<th>9-160 dwellings; Night-time [dB(A)]</th>
<th>&gt;160 dwellings; Night-time [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>40</td>
<td>43</td>
<td>46</td>
</tr>
<tr>
<td>Category 2</td>
<td>45</td>
<td>48</td>
<td>51</td>
</tr>
<tr>
<td>Category 3</td>
<td>50</td>
<td>53</td>
<td>56</td>
</tr>
</tbody>
</table>

In British Columbia the “Land use operational policy, wind power projects on Crown land” (MAL, 2007) fixes the maximum WTN level at 40 dB(A), determined at constant wind speeds between 8 and 10 m/s.

**Italy**

Italy has no specific regulation for WTN, therefore its assessment falls in the “industrial facilities” category, following the general norms on noise impact (Italian Law 447, 1995).
particularly important decree is the D.P.C.M. 14/11/97, which sets noise level limits according to six different classes of use of the territory. A further decree (D.M. 16/3/98, 1998) defines the procedures for the assessment of environmental noise and the correction factors applicable for the presence of tonal, low frequency or impulsive components. The noise descriptor to be used is the equivalent A-weighted sound level ($L_{Aeq}$) calculated on daytime (6:00-22:00) and night-time (22:00-6:00). The outdoor measurements must be performed at 4 meters height in free field or with a congruent microphone height and at least one meter distance from the building façade in presence of receivers. During measurements rain must be absent and wind speeds must not exceed 5 m/s.

The legislation provides two types of noise limits that differ in the period of evaluation: “absolute” during reference time (day and night) and “differential” during the measurement time. The absolute limits are the emission limits, related to specific sources, and the immission limits, related to all the sources together. In this work we will not consider the immission one because the measurement sites are only affected by WTN. The emission level is given by energetic subtraction of the residual noise from the overall measured noise and to connect with the international name, is then called “immission level”. The differential level is the algebraic subtraction of the two and is thought in order to consider the masking effect of the background noise.

The Italian law allows the use of data sampling technique also for the verification of absolute limits. In this way a technician could determine if a wind farm is impacting or not at a receiver simply performing short term measurements in different periods, although contiguous with similar conditions. This data sampling leads to a characterization that can vary by some dB(A) depending on the measurement time and on weather or measuring conditions. Furthermore, the typical Italian wind farms are located in not easily accessible areas, generally far away from major population centres. Therefore, a measurement campaign in situ requires a considerable amount of time and money, which results in a difficulty to return several times on the site in case of lack of adequate measurement conditions.

5.3 Discussion

The evaluation of noise to the receiver is performed using outdoor measurements, obviously
dependent on the measurements of background noise, which varies with wind speed. The solution adopted by some standards (i.e. Netherlands, Ontario) is to use limits variable with wind speed at a standard height. The assessment of background noise remains a problem: in Ontario a possible definition of it was given as a function of wind speed (Lightstone et al., 2010), which, however, is strongly dependent on the measurement site, on the eventual complex terrain and on the boundary conditions, which can be very different and variable.

In Italy, the assessment is even more critical, because the regulations require to calculate the difference between environmental noise and background noise in the same weather conditions. In Chapter 7 of this thesis it will be shown that for these reasons, long-term measurements and subsequent statistical analysis of obtained results are necessary to provide a proper and consistent WTN assessment.

Noise limits are based on specific noise metrics to ensure the quality of life of the population, but the metrics used to regulate WTN is not uniform between countries. Disparities arise in the noise measurement duration, wind speed and statistical data collection. A study (Fowler et al., 2013) involving 39 countries shown that the $L_{\text{Aeq}}$ indicator is the most common used for regulating wind farm noise: 16 on the 39 regulations examined. Five countries use a metrics that is derived from it, like $L_{\text{den}}$, but includes a penalty for parts of day with increased sensitivity. $L_{\text{den}}$ is defined in the EU Directive Environmental Noise 2002/49/EC (END, 2002) and is the yearly averaged noise level. $L_{\text{Aeq}}$ is defined as the “equivalent sound level” and is based on a time-integrated measurement period which varies between countries and regulations. The time period ranges from a 1 hour to a 24 hour measurement (evaluation period). The noise threshold established for the $L_{\text{Aeq}}$ shows to be an approximate 20 dB variation depending on the regulation. Most European countries, South Australia, New Zealand and a number of states in the USA, have a noise limit which depends on the type of area or the existing background noise levels. Exceptions are The Netherlands, Norway, the Belgian Region Wallonia, the Canadian province of Alberta and a number of states and counties in the USA, which all have fixed limit values. Countries like France, Sweden, South Australia and New Zealand have more stringent noise limits for rural areas with relatively low background noise levels than for residential areas. On the contrary, the Belgian Region Flanders, Denmark and Germany allow higher noise levels at dwellings in a rural area than at residential areas. A few countries use statistical noise metrics ($L_{\text{90}}, L_{\text{50}},$ and $L_{\text{10}}$), but more do not have any published noise regulations.
The limit of the methodology based on long term noise indicators (L_{den}) is that the population is generally not disturbed from long-term average exposure, especially for WTN. WTN is indeed a highly fluctuating source in the short period, for amplitude modulation, and in the long period, for the atmospheric phenomena. For this reason, the population is not satisfied by long term limits for a source that feels strongly annoying only few times in particular conditions and remembers those situations in time. The second methodology is very selective, and case, time and weather conditions dependent.
6 A wind turbine noise legislation considering annoyance

As described in Chapter 4, WTN is perceived much more disturbing than a conventional noise source with equivalent intensity. In this Chapter, a specific limit for WTN that considers the real annoyance perceived by population in relation with the type of the source is suggested. Furthermore, looking at the metrics used in the international framework on WTN it is found that they can be basically divided into two main categories: one based on long term noise measurements or simulations and one on short term measurements performed in the worst conditions. The pro & cons of these approaches are analysed aiming to propose solutions for a future legislation that must protect people's needs and have a scientific basis.

6.1 Introduction

Wind turbine noise is more annoying than a conventional noise source with equivalent intensity. This aspect and the continuous installation of wind farms, closer and closer to houses, led to an increase in complaints from receivers that often become legal action because of a lack of proper limits. In this Chapter a specific limit for WTN is suggested by considering the annoyance dose-response relationships for different sources and deriving a limit value according with ones already issued for those other sources. To do this, from Miedema’s curves the number of highly annoyed (HA) that corresponds to the Italian limits for road traffic noise (RTN) are extracted. The sound level for WTN corresponding to that %HA has been determined from recent dose-response relationships. Particular attention is given to the conversion factor used to convert a short term noise indicator (L_Aeq) to a long term one (L_den). The results have been compared with the limits issued in various national regulations, in order to evaluate their accordance with this approach. The method can be a useful tool to update limits when further studies will be performed to improve the reliability of dose-response relationship for WTN in relation to different contexts. The limit proposed, however, can be immediately used to guide national legislation and to provide a scientific criterion to address the disputes between
citizens and the wind farms operators.

6.2 Estimate of a tolerance threshold for WTN

Depending on the type of the source, a noise can be more or less disturbing than others while having the same energy. A parameter used to measure this reaction is the percentage of highly annoyed (%HA) to the specific source. Therefore, the present assessment is based on the perceived noise and its degree of acceptability compared to other type of sources, rather than on detected sound energy. Annoyance is estimated through specific socio-acoustic surveys that comply with well defined international standards.

As already reported in the previous Chapter and as underlined by Michaud (Michaud et al., 2008), %HA is an important health end point for an environmental assessment and it is used to justify the limit fixed in Ontario. The authors (Keith et al., 2008) used the Schultz relation (Schultz, 1978) for %HA that is generic for all noise sources. Following that approach, the recent psychoacoustic studies have been used as a starting point for calculating the tolerance threshold for WTN. The logical process followed is summarized in Figure 6.1. A limit value for WTN has been determined starting from the Italian one for road traffic noise (RTN) during daytime and night-time, equal or similar to those of many European countries. The percentage of highly annoyed corresponding to the limit for RTN, converted in L_{den}, have been extracted from Miedema’s dose-response relationship for %HA (Miedema and Vos 1998; Miedema and Oudshoorn, 2001). Then, the tolerance threshold for outdoor WTN levels has been taken from the WTN dose-response relationship (Janssen et al., 2011a), derived from data coming from three studies (Pedersen & Persson Waye, 2004; Pedersen & Persson Waye, 2007; Pedersen et al., 2009), at the %HA identified for RTN. The result has been converted from L_{den} to L_{Aeq} using Italian period: day from 6:00 to 20:00, evening from 20:00 to 22:00, night from 22:00 to 6:00.
Figure 6.1. Graphical summary of the process for the determination of the limit. Blue is Miedema’s dose-response relationship for RTN, green is Janssen’s for WTN.

The limit value obtained, calculated with negligible background noise, is 42.9 dB(A) of $L_{Aeq}$ and is particularly comparable with the recent Danish standards (DEPA, 2011).

The following steps are necessary to correctly use the data in Figure 6.1 and are further explained:

1. Conversion from $L_{Aeq}$ to $L_{den}$ of the Italian law limits for road traffic noise.
2. Determination of %HA corresponding to the law limits for road traffic noise through their dose-response relationship for highly annoyed.
3. Calculation of the tolerance threshold for outdoor wind turbine noise levels corresponding to the %HA identified.

6.2.1 Conversion from $L_{Aeq}$ to $L_{den}$ of the Italian law limits for road traffic noise

The maximum noise level admitted in Italy (Italian Law 447, 1995) for outdoor RTN is 70 dB(A) during the daytime (day and evening) and 60 dB(A) during night-time in a 100 m area around every type of road, except the very local ones. These limits are also almost the same or similar as those in most European countries, including the Czech Republic, France, Germany, Netherlands, Spain, Sweden (Milieu Ltd., 2010).

The transformation of $L_{Aeq}$ in $L_{den}$ can be done through the formula in (Makarewicz and Galuszka, 2010), adapted according to the definition of $L_{den}$ in Italy that considers only 2...
hours for evening period and 14 for the day period:

\[
L_{DEN} = 10 \log_{10} \left\{ \frac{14}{24} \times 10^{0.1L_{day}} + \frac{2 \sqrt{10}}{24} \times 10^{0.1L_{evening}} + \frac{8 \times 10}{24} \times 10^{0.1L_{night}} \right\}
\]

Assuming a road where the noise is exactly equal to the limit, the value corresponding to the limits in Italy for roads obtained is 70.7 dB (A) of \(L_{den}\).

### 6.2.2 Determination of \(\%HA\) corresponding to the law limits for road traffic noise through their dose-response relationship for highly annoyed.

In order to calculate the \(\%HA\) corresponding to the law limits for RTN it is possible to use the formula given in the EEA Technical report of 2010, “Good practice guide on noise exposure and potential health effects” (EEA, 2010), referring to Miedema’s studies, that is:

\[
\%HA = 9.868 \times 10^{-4} (L_{den} - 42)^3 - 1.436 \times 10^{-2} (L_{den} - 42)^2 + 0.5118 \times (L_{den} - 42)
\]

With 70.7 dB (A) of \(L_{den}\), the \(\%HA\) corresponding to the law limits for road traffic noise is the 26.2%.

### 6.2.3 Calculation of the tolerance threshold for outdoor wind turbine noise levels corresponding to the \(\%HA\) identified

This calculation is based on the assumption that the \(\%HA\) obtained is considered tolerable according to generic Italian noise limits. This percentage should be the same for each type of source for a uniformity in the treatment of people exposed to noise, given that the specificity of the source is already considered in the diversity of the dose-response relationship.

A tolerance threshold of 49.1 dB(A) of \(L_{den}\) is calculated inverting the Janssen’s equation of the dose-response relationship for \(\%HA\) in outdoor environment (\(\%HA_{outdoors}\)), obtaining:

\[
\%HA_{outdoors} = -97.94 + 9.627 L_{den} - 0.3175 L_{den}^2 + 0.003522 L_{den}^3
\]

The corresponding \(L_{Aeq}\) limit for WTN is then calculated with the equation in paragraph 6.2.1 and it is equal to 42.9 dB(A).

The starting point of the derivation of this limit was the study of Janssen (Janssen et al., 2011a), which refer to those of Pedersen and Van den Berg (Pedersen & Persson Waye, 2004; Pedersen & Persson Waye, 2007; Pedersen et al., 2009), in which the WTN has been
calculated for a wind speed of 8 m/s at 10 meter of height from the ground, in flat terrain and without background noise.

6.3 The difference in dose-response relationship for WTN and RTN

What makes so high the annoyance to WTN perceived by population is the sound character of wind turbine noise. As already shown, noise comes from a height above the receiver, leading to an amplitude modulated sound with a constant change in AM character that increases attention and cognitive appraisal and reappraisal, inhibiting acclimatization of citizens to sound (Stigwood, 2013). WTN may particularly be heard in otherwise quiet areas, where people do not expect to hear industrial noise and the mostly rural position of wind turbines may contribute to heighten the annoyance response. In addition to the ambient noise level, the expectations of a living environment supposedly influence an individual’s appraisal of an uncontrolled sound. The special characteristics of omnipresence, periodic nature, random occurrence and low frequency content make WTN a very annoying sound (von Hunerbein, 2013).

The overall difference results in a different slope of the dose-response curves. Therefore, the transition from a curve to another one is not linear. At the same disturbance, it is not possible to provide a simple conversion value between WTN and RTN. We have seen that this is very different as a function of noise exposure. For standard values of WTN exposure the difference between WTN and RTN varies from a minimum of 10 dB to a maximum of 25 dB. Figure 6.2 reports the difference of $L_{den}$ between RTN and WTN with equal percentages of highly disturbed as a function of $L_{den}$ of WTN that has been calculated. This means that for a given $L_{den}$ of WTN is necessary to add the corresponding value given by the curve in order to obtain the value of $L_{den}$ for RTN that causes the same disturbance to the exposed population. The curve was obtained by subtracting for each %HA the inverse of the equation of Janssen’s dose effect relation by the inverse of the Miedema’s and reporting this difference as a function of $L_{den}$ of WTN.
Figure 6.2. Difference of $L_{den}$ between RTN and WTN with equal %HA as a function of $L_{den}$ of WTN.

6.4 Conversion factor from $L_{den}$ to $L_{Aeq}$

The equation used to convert $L_{den}$ in $L_{Aeq}$ and vice-versa does not take into account the variability of wind turbine operations and presumes the wind turbine is operating at its maximum sound level 100% of the time. Moreover, converting from $L_{den}$ to the maximum hourly $L_{Aeq}$ for wind turbines requires the evaluation of day/evening/night wind statistics. Our approach was correctly defined as conservative, but a +3 to +5 dB(A) adjustment to the hourly $L_{Aeq}$ was expected.

The deeper analysis started from the noise levels used in Janssen’s dose-response relationship. In this study annual $L_{den}$ was calculated from the immission levels determined in the original studies. The outdoor A-weighted sound pressure levels from the nearest wind turbine were determined with a neutral atmosphere at a constant wind velocity of 8 m/s at a height of 10 m in the direction towards the respondent. A correction of +4.7 dB(A) was applied to these data following the mean difference between $L_{den}$ and the A-weighted sound pressure level calculated by Van den Berg (Van den Berg, 2008b). The understanding of the origin of this conversion factor of 4.7 dB(A) is of paramount importance. For this reason here are summarized the steps that led to it. The author started from the sound power level as a function of wind speed at hub height for two different Dutch wind farm, obtained by a 4th
power polynomial fit of the noise data in the range of 4-12 m/s of wind. The distribution of wind speed per diurnal period over 11 and 7 years were available at various heights from meteorological towers. The distributions of wind speed at hub height directly yields the distribution of sound power levels and $L_{\text{day}}$, $L_{\text{evening}}$ and $L_{\text{night}}$ were so calculated on annual basis through a wind class calculation. The $L_{\text{den}}$ on annual basis has been obtained using the formula reported in END. This was calculated for various wind turbine height using the wind distribution at different height.

A generic constant sound power over time, if subtracted to these values of $L_{\text{den}}$, results in a difference of 6.4 dB, whereas the difference is 5.2 dB for a sound power mainly active during the night. Van den Berg found that the difference is variable with sound power (i.e. wind speed) when subtracting to the $L_{\text{den}}$ the value of the sound power as a function of wind speed. In particular, he considered the cases of wind speed of 7 and 8 m/s at 10 meters of height, which are the most likely for the sites studied by him. The results were 5.2±2 dB of difference between $L_{\text{den}}$ and noise power at 7 m/s of speed and 4.7±1.5 at 8 m/s, with uncertainties due to the height, location and type of turbine.

Returning to the epidemiological studies of Pedersen, Persson Waye, van den Berg et al. and Janssen, they all assign a noise level to the investigated receivers by simulations with a wind speed of 8 m/s at 10 m in flat terrain. The number 4.7 previously shown was added to the $L_{\text{Aeq}}$ at the receptors to transform them into $L_{\text{den}}$ in order to construct the dose-effect curve related to $L_{\text{den}}$.

The conversion factor of 4.7±1.5 (Van den Berg, 2008b) was obtained using the sound power levels, so it would be absolutely plausible for short distances around the turbines. However, this has been hired as true in those epidemiological studies for the sound pressure levels at the receivers, although there is the possibility that during sound propagation this value does not remain constant. Nevertheless, without other information, this translation is assumed as true also for the present work.

In paragraph 6.2 a tolerance threshold for outdoor WTN levels of 49.1 dB of $L_{\text{den}}$ has been found. The corresponding $L_{\text{Aeq}}$ was calculated by subtracting 6.2 dB, simply inverting the formula for $L_{\text{den}}$ and considering a constant noise throughout the day. The time periods used are the Italians day evening night (14 hours a day, 2 night, night 8). This is different than in the epidemiological studies, where WTN is not considered constant on the day but having a distribution over time using the coefficient of van den Berg.
The aim of the present work was to provide a limit for wind turbine noise. To do this, in fact, choosing 4.7 dB as the conversion factor from $L_{den}$ to $L_{Aeq}$ is not always the best choice, since this number was obtained only on two sites and is not always correct, but can vary with many parameters. So, considering a standard deviation for the value of $4.7 \pm 1.5$, it is precisely obtained the chosen value of 6.2 dB, at the edge of the uncertainty found in the work of van den Berg. With this new assumption having turned $L_{den}$ in $L_{Aeq}$ subtracting 6.2 is not just having considered the source as uniform during the day, but it respects the studies in the field of meteorological variability without neglecting the fact that the emission can vary during the year.

6.5 A possible approach based on monthly measurements at the receptor

A criticism of the dose effect curves concerns the use of the indicator $L_{den}$ on the annual period, not being sure that people suffer disturbance based on an annual average level but it is more likely that they express their annoyance basing on the periods in which they are most disturbed. Probably $L_{den}$ is not the right metric, but epidemiological studies are based on it and the same path has been followed to get a limit for WTN. This paragraph propose an approach that considers short-term noise exposure on the basis of an equivalent level $L_{Aeq}$ which is however linked to long-term noise exposure. The method considers noise levels obtained with a measurement campaign at the receiver, which lasts about a month in order to have a sufficient data. From the distribution of $L_{Aeq}$ acquired every 10 min a percentage of data could be discarded, which is assumed to be the 10%. This is the percentage of eliminable transits by exceptional events accepted by the Italian D.M.16/3/98 (D.M. 16/3/98, 1998) for the assessment of railway noise. In this way, all the possible random events that may occur during measurements are not considered. The idea is to consider the noise level exceeded in the 90% of the time ($L_{10}$), which is not a simulated value but it is effectively obtained at the receiver through measurements, and to find a correlation with $L_{den}$. In this way it is possible to understand what level of annoyance the citizen has according to the dose-effect curves previously shown. To do this, however, there is the need of a new link to $L_{den}$ and $L_{10}$. This relation should be calculated according to the way in which van den Berg did for $L_{den}$-$L_{Aeq}$, but it will require long-term noise and

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60
meteorological data. The process would be possible whether the relationship between annual \( L_{\text{den}} \) and \( L_{10} \) on limited time would exist. This aspect should be investigated and the hope is that it will be a starting point for researchers having enough data.

The method has been applied to the available measurements that are later described in Chapter 7, even if they have not an annual statistic. Particularly, the method has been applied to measurements campaigns performed from 2010 to 2013 of noise and wind near a receiver at 6 wind farms in various regions of Italy. The measurements always lasted between 3 and 4 weeks. The topography of the sites varies from flat to hilly with rough vegetation or forest. In the analysis of noise data periods with rain or with wind speed at the receiver greater than 5 m/s were removed, as well as noise events not directly related to the source or the sound of wind. The measurements are those further reported in Table 7.1 and in Appendix, with the exception of “San Giovanni in Lamis” whose data belong to a different study (Cicciotti, et al., 2014).

For each measurement site, the \( L_{10} \) has been calculated from the distributions of \( L_{\text{Aeq}} \) every 10 min (as in Figure 6.3). This number has been compared to a value of \( L_{\text{den}} \) calculated taking the value exceeding in 90% of cases the distribution of the \( L_{\text{den}} \)s calculated on daily basis.

Basically the \( L_{10} \) of the daily \( L_{\text{den}} \)s is taken as a measure of the entire \( L_{\text{den}} \). Results are reported in Table 6.1. The mean difference from \( L_{\text{den}} \) and \( L_{10} \) among the sites is 5.5 ± 1.4, a value
similar to van den Berg’s result for the difference between $L_{\text{den}}$ and $L_{\text{Aeq}}$.

Table 6.1. $L_{\text{den}}$ and $L_{10}$ with their occurrences and difference between $L_{\text{den}}$ - $L_{10}$ for each measurement sites.

<table>
<thead>
<tr>
<th>Location</th>
<th>$L_{\text{DEN}}$</th>
<th>$# L_{DEN}$</th>
<th>$L_{\text{Aeq}}$</th>
<th>$# L_{Aeq}$</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Giovanni in Lamis (FG)</td>
<td>51,1</td>
<td>26</td>
<td>48,1</td>
<td>2882</td>
<td>3,0</td>
</tr>
<tr>
<td>Montecatini Scapiccioli (PI)</td>
<td>51,7</td>
<td>22</td>
<td>45,4</td>
<td>2661</td>
<td>6,3</td>
</tr>
<tr>
<td>Montecatini Palareta (PI)</td>
<td>54,2</td>
<td>18</td>
<td>48,6</td>
<td>1776</td>
<td>5,6</td>
</tr>
<tr>
<td>Montecatini Provinca (PI)</td>
<td>46,8</td>
<td>18</td>
<td>41,9</td>
<td>1913</td>
<td>4,9</td>
</tr>
<tr>
<td>Scansano (GR)</td>
<td>57,6</td>
<td>18</td>
<td>51</td>
<td>2003</td>
<td>6,6</td>
</tr>
<tr>
<td>Lucera (FG)</td>
<td>53</td>
<td>30</td>
<td>46,2</td>
<td>2076</td>
<td>6,8</td>
</tr>
</tbody>
</table>

Following that first analysis, it appears that use the level $L_{10}$ plus a correction or the method of $L_{\text{Aeq}}$ plus a correction are not so different and obtain approximately the same uncertainty, thus further analysis are necessary.

6.6 Discussion

A limit value for WTN has been determined starting from the Italian one for road traffic noise during daytime and night-time, which are equal or similar to those of many European countries. The %HA corresponding to the limit for road traffic noise, converted in $L_{\text{den}}$, have been extracted from its dose-response relationship for highly annoyed. Then, the tolerance threshold for outdoor WTN levels has been taken from the WTN dose-response relationship at the %HA identified for road traffic noise. Due to their nature, the dose-response curves of WTN and RTN have different slope. The curve of the difference as a function of the $L_{\text{den}}$ of WTN has been calculated.

This limit value is derived from the curve of Janssen, which is calculated using also the data from Pedersen and van den Berg. Thus, this curve is determined by calculating the noise at receiver and through propagation models in generic conditions of wind (8 m/s wind speed at 10 m height). Such operational conditions not necessarily determine those noise levels in any environmental conditions, because they also depend on other factors, including the atmospheric stability and the topography of the site.
The limit value obtained, calculated with negligible background noise, is 42.9 dB(A) and is comparable with the standards analyzed in Chapter 5, particularly the British and the Danish ones. The regulations also establish limit values increasing with residual noise, and therefore with the speed of the wind. The derivation of these values with general validity, however, is complex, because residual noise levels depend exclusively on the environmental and weather conditions of the measurement site. The measuring mode then becomes determinant to the results, which are dependent on the wind, on the direction of sound propagation, on the presence of any other source, on the distance from obstacles, etc. Also the presence of vegetation, which varies seasonally, could influence the outcome of a measurement campaign which may result in exceeding the limit or not if carried out in winter rather than summer. Thus, in any legislation, the period in which to perform the measurement campaign of the residual noise and the duration of it has to be chosen very carefully.

The method can be a useful tool to update limits when further studies will be performed to improve the reliability of dose-response relationship for WTN in relation to different contexts. The limit here proposed, however, can be used immediately to guide national legislation and to provide a scientific criterion to address the disputes between citizens and the wind farms operators.

A deep analysis of the studies on which the calculation of the limit is based shown that the conversion from $L_{Aeq}$ to $L_{den}$ and vice-versa takes into account the variability of wind turbine operations by means of the conversion factor of van den Berg and that the conversion factor used in the present calculation is similar but more precautionary. The result has then scientific bases and is in a precautionary manner respect to the variability of the difference between $L_{den}$ and $L_{Aeq}$ of WTN experienced by van den Berg.

In order to take into account the variability of the source and its influence on people's reactions, a method for converting measurements on a limited period to an annual $L_{den}$ is proposed. It resulted that using the $L_{10}$ plus a correction factor or the van den Berg’s method of $L_{Aeq}$ plus a correction is not so different and methods have approximately the same uncertainty.
7. WTN noise measurements

The noise level from a wind farm may be quite low but differs from noise emitted by other sources in terms of generation, propagation and perception by neighbors. Everything about it is particular, therefore specialized techniques for measurements and data analysis are necessary to rationally assess impacts from existing and new operational projects. From the overview of the international standards in Chapter 5, it is evident that all the assessments of noise impact are carried out by means of field measurements and then subtracting the residual noise from the environmental one. In this Chapter the issues relating to the application of these methodologies to multi-turbine wind farms located in complex terrain are highlighted. This reports a preliminary study (Fredianelli, et al., 2012) aiming to propose suitable parameters for the elaboration of a procedure to monitor noise impact of operating wind farms, with the specific intention to compare the results with Italian noise limit values. The results obtained are based on the analysis and processing of noise data, wind speed at hub height, wind speed at receiver height and operational settings of the wind turbines acquired during a series of long term measurements performed near the wind farm "La Miniera" in the municipality of Montecatini Val di Cecina (PI), in Tuscany. A list of all the other measurement campaigns performed during the following years is here reported.

7.1 Measurement description

7.1.1 Setup and procedure

The generation of WTN and residual noise are both closely related to the presence of wind, thus they are poorly correlated each other. Furthermore, they are highly variable in time due to the wind variability, especially in complex terrain. Therefore, assessing the noise impact with a single short duration measurement is impossible. In order to overcome this issue, each \( L_{Aeq} \) measurement must be linked, in consecutive and suitable time intervals, with continuous measurements of wind speed performed at the receivers and simultaneously at the hub height. For the purpose of this work, the measurements were performed placing the weather station...
at 3 meters of height above ground, therefore inside the range suggested by the ISO 9613-2, as close as possible to the microphone. The microphone was placed at 4 meters above ground and 30 m far from the receiver, not screened by obstacles in wind farm direction and with distance >5 m from reflective surfaces. In order to acquire a complete set of weather conditions, continuous and long-term measurements were performed to detect and separate the contributions of the immission and residual noise, in order to cover all the combinations of wind speed and direction at ground and at hub height. For each receiver, the temporal profile of $L_{Aeq}$ on 1sec time-basis was acquired. Periods with rainfall or spurious events, almost always anthropogenic or animal ones, were discarded as they may distort the results. According to literature (Appelquist and Almgren, 201; ETSU, 2005), sampling the acquired data in intervals of 10 min was considered appropriate, because it is a sufficient amount of time with no significant changes in the WTN emission and in atmospheric conditions. A minimum set of at least 2000 measurement intervals, i.e. 2 continuous weeks, with at least 400 corresponding to the most severe conditions of noise emission, i.e. high blades speed with downwind propagation and low wind speed at ground, are considered necessary in order to have a sufficient data statistic. In the long term this can lead to an elongation of the measurement period and drawing the graphs of the wind directions for each wind turbine could be useful to check the most severe conditions data requirement. The noise measurements were related to averages over 10min of wind speed at ground and to wind direction at ground. The wind data and operative conditions relative to each WTG were requested to the infrastructure manager, thus wind speed and direction and blades rotational speed at the hub height of each turbine have been available without further measurements.

7.1.2 Wind farm and the measurement sites

"La miniera" wind farm is located at 570 m a.s.l. in a hilly area with irregular terrain, stretches of forest and few crops, where no other major noise sources except a small local road with very low traffic are present. The farm is composed of 6 “Leitwind 77 1.5 IEC IIIa" three blades HAWT with a rated power of 1.5MW and a declared sound power level of 102 dB(A) at a wind speed at hub of 8 m/s. Hub height is 61.5 m and blades length is 38.5 m. The measurements used in this analysis were performed at the following receivers: in the period from 19/10/2010 to 19/11/2010 at "Palareta" (485 m from the nearest WTG), from
24/11/2010 to 12/12/2010 at "Provinca" (1040 m from the nearest WTG) and from 22/12/2010 to 12/01/2011 at "Scapiccioli" (630 m from the nearest WTG). The satellite map of the area with wind turbines and receivers is in Figure 7.1.

![Wind farm "La miniera" satellite map](image)

**Figure 7.1.** Map and acoustic classes of the area with the wind turbines and the receivers highlighted.

With the collaboration of the Environmental Protection Agency of the Tuscany Region (ARPAT), and of the Apulia Region for the wind farm “Lucera”, at present a total of 9 measurements campaigns have been performed. A summary of the measurements is reported in Table 7.1, a deeper explanation is reported in Annex A.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>No. of WTG</th>
<th>Receiver alias</th>
<th>WGS 84 coordinates</th>
<th>Period of measurement</th>
<th>Receiver -nearest WTG distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poggi alti</td>
<td>10</td>
<td>Poggi alti Scansano</td>
<td>11°23′27,92&quot; E 42°44′17,63&quot; N</td>
<td>5/7/11-22/7/11</td>
<td>280</td>
</tr>
<tr>
<td>La Miniera</td>
<td>6</td>
<td>Scapiccioli</td>
<td>10°44′03,65&quot; E 43°23′19,62&quot; N</td>
<td>22/12/10-12/1/11</td>
<td>630</td>
</tr>
<tr>
<td>La Miniera</td>
<td>6</td>
<td>Provinca</td>
<td>10°43′04,18&quot; E 43°24′14,62&quot; N</td>
<td>24/11/10-22/12/10</td>
<td>1040</td>
</tr>
<tr>
<td>La Miniera</td>
<td>6</td>
<td>Palarreta</td>
<td>10°43′21,90&quot; E 43°23′38,62&quot; N</td>
<td>19/10/2010-19/11/1</td>
<td>485</td>
</tr>
</tbody>
</table>
### 7.1.3 Elimination of spurious data and verification of the conditions examined

In the data post-processing the spurious sound events of anthropic or animal origins were discarded, as well as the periods where rainfall was > 0.2 mm or wind speed at ground was > 5 m/s. If the duration of a single 10 min cleaned data resulted <5 min (50% of the original span) after the previous filtering, the data has been discarded. The influence of weather conditions related to wind speed at ground can be seen from the graph in Figure 7.2, which shows the result of measurements at the site of "Provinca".

![Figure 7.2. \( L_{Aeq} \) values as a function of wind speed at WTG-2 hub height in the site “Provinca”.

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Ph.D Thesis of Dr. Luca Fredianelli - Analytical assessment of wind turbine noise impact at receiver by means of residual noise determination without the farm shutdown.
Despite the strong scattering of data, a doubling of the trend is well evident at high speeds, leading to noise levels unrealistically high for the wind farm. The higher branch disappears if data with wind speed at ground > 5 m/s are selected. This confirmed the need to delete data with wind speed at ground exceeding 5 m/s, which are too influenced by the residual noise generated by the wind and by the interaction of the microphone windscreen foam with the microphone itself due to wind turbulence (Hessler, 2009).

Before the beginning of the study, in literature were many doubts concerning the possibility of performing measurements of WTN precisely because of the impossibility of measuring noise in a wind field. The solution is to consider the deletion of periods with wind speed > 5 m/s but only for wind speed at ground, properly measured near the microphone.

The Weibull distributions of the wind speed at hub height have been drawn for each direction and for each wind turbine (Figure 7.3 for WTG-2), together with the corresponding wind rose plot. The two graphs can help to check if during the measurement the receiver has been downwind respect of the turbines for at least 25% of the measurement period. The results of both elaborations were compared with directions receiver-WTG, as shown in Figure 7.4 for WTG 1 and 2 at "Scapiccioli". The condition has been verified within an angle of ±45° around the directions receiver-WTG.
Figure 7.3. Weibull distributions of the wind at WTG-2 hub height for each direction.

Figure 7.4. Wind rose plots compared with the directions receiver-WTG for WTG 1 and 2 at "Scapiccioli".
7.2 Results analysis

7.2.1 Wind speed

The calculation of a wind speed at a particular height from a measurement at a different height is usually performed using the logarithmic equation of vertical profile already described in this thesis. However, the equation is not often able to describe the wind shear in presence of complex terrain (hilly area and heavily vegetated), the most common situation in which Italian wind farms are installed. In those configurations, the wind shear description is extremely complicated and is not suitable to direct analytical representations. This can be verified by observing the dispersion of measured wind speed data at hub height as a function of those measured at the receiver height, as shown in Figure 7.5 for "Scapiccioli" and WTG 2 (54 m of relative height and 61.5 m of rotor height).

![Figure 7.5. Wind speed measured at WTG-2 hub height as a function of wind speed measured at "Scapiccioli".](image)

Both the fit obtained with linear regression and minimum chi-square methods are reported in Figure 7.5. The difference between them underlines the strong scattering of data. High wind speeds at ground usually correspond to high wind speeds at hub height, thus the opposite condition almost never occur, causing the very wide dispersion of the data (up to 12m/s). A simple division of the data into daytime and night-time did not result in further improvements, thus filtering data for wind direction at hub height (±45° respect to the
direction source-receiver) leads to a reduction of the dispersion. In the last case of Figure 7.6 the two different fits tend to converge, however a significant dispersion still remains especially at low wind speeds due to the site orography.

An analytical correlation of the wind speeds at various heights in complex terrains with acceptable accuracy appears then to be impossible. Therefore, deriving the wind speed at great heights only with one measurement of wind speed at ground or vice-versa is a procedure to be avoided. A sufficient description of wind shear can therefore be obtained by performing two different measurements of wind, one at ground height near the microphone and one at hub height by means of the weather station on the nacelle, obtainable in accordance with the farm manager.

An analytical correlation of the wind speeds at various heights in complex terrains with acceptable accuracy appears then to be impossible. Therefore, deriving the wind speed at great heights only with one measurement of wind speed at ground or vice-versa is a procedure to be avoided. A sufficient description of wind shear can therefore be obtained by performing two different measurements of wind, one at ground height near the microphone and one at hub height by means of the weather station on the nacelle, obtainable in accordance with the farm manager.

The dispersion of the wind data already discussed also complicates the extraction of useful information from the graph of noise levels as a function of the wind at ground. Indeed, the increasing trend is accompanied by a very large dispersion up to 20 dB(A). In addition, the high variability of noise levels at low wind speeds at ground also corresponds to the conditions for which the WTN component is very impactful, being low residual noise and significant emissions. The graph of noise levels as a function of wind speed at hub has a more pronounced trend, with a dispersion of no more than 10 dB(A). A descriptor most suitable for

![Wind speed measured at WTG-2 hub height as a function of wind speed measured at "Scapiccioli" height for day period in favorable direction.](image)

**Figure 7.6.** Wind speed measured at WTG-2 hub height as a function of wind speed measured at "Scapiccioli" height for day period in favorable direction.

### 7.2.2 Noise levels

The dispersion of the wind data already discussed also complicates the extraction of useful information from the graph of noise levels as a function of the wind at ground. Indeed, the increasing trend is accompanied by a very large dispersion up to 20 dB(A). In addition, the high variability of noise levels at low wind speeds at ground also corresponds to the conditions for which the WTN component is very impactful, being low residual noise and significant emissions. The graph of noise levels as a function of wind speed at hub has a more pronounced trend, with a dispersion of no more than 10 dB(A). A descriptor most suitable for
analysis, however, is the blades rotational speed, being WTN properly generated by the rotation and not by the wind speed itself (Van den Berg, 2006a). Rotor speed is often, but not always, uniquely related to wind speed at hub by a relation extractable from the acquired data. Even if the wind is the cause of blades rotation, the blades are electronically controlled by the operator and there may be times in which a turbine is mechanically stopped even if the wind is blowing. Thus, wind speed at hub height is almost never a good descriptor of noise levels produced at receivers.

![Figure 7.7. Dispersion of $L_{\text{Aeq}}$ as a function of blades rotational speed for WTG-2 at “Scapiccioli”.](image)

The trend of noise levels as a function of the blades rotational speed in Figure 7.7 starts growing from the cut-in value (in this case about 6 rpm) and has a smaller dispersion for higher speeds. The noise levels in figure are not the immission level produced by a single wind turbine, but they are the overall measured noise, then including contributions from the other nearby wind turbines and the residual noise from wind at ground. The relation between noise and rotor speed would have a reduced spread in case of wind farm with single turbine or considering only the contribution of the immission level without the residual one. In the common situation of multi-turbine wind farms, the average 10 min blades rotational speed of the closer WTG should be theoretically the same, but in the real scenarios there are conditions for which the rotation is not the same for all the turbines. The search for a suitable parameter linking together the rotational speed of all the wind turbines in a farm in order to have better trends of the WTN levels at receiver in complex terrain is very important and will
be analyzed in the following Chapter. The aim of not requiring the farm manager to stop the turbines production, as usually necessary for the instrumental verification of the noise impact for industrial sources, is achieved performing a long term measurement campaign. In this way, is possible to catch the periods in which the blade rotational speed is too low to produce noise levels perceivable to the receiver, generally present during the normal operating cycle of a wind farm.

Therefore, the corresponding measurements data can be used for a prior evaluation of residual noise levels instead of stopping the farm to measure the residual noise. The energetic average of these 10 min data $L_{Aeq}$ is equivalent to calculate the value of $L_{Aeq}$ on a single period given by the sum of all the intervals of 10 min considered. This value should correspond to a sufficiently wide range of wind speeds on the ground if the number of useful intervals is high enough, but it depends on the duration of the measurements.

### 7.3 Discussion

In this Chapter the critical issues related to data analysis and evaluation of WTN in a complex terrain were analyzed and discussed, particularly taking into account the Italian legislation. This work proposed a specific data acquisition methodology useful for the noise monitoring of WTN in complex territory, where no analytical relation between wind speeds at hub and ground heights works. Furthermore, it was observed that relating noise immission to the blades rotational speed instead of the wind speed at hub is more useful, as well as it is better to relate the residual noise to the wind at ground while avoiding the data with wind speed greater than 5 m/s. The determination of the best parameter that simultaneously considers the blades rotational speeds of multiple WT impacting on a receiver still remains an open issue. It has also been verified that it is possible avoiding to require the wind farm shutdown in order to measure the residual noise by performing a sufficiently long measurement campaign. This happens because the periods in which wind turbines are ordinarily still can be use to roughly estimate it. The contributions of the residual noise as a function of wind speed at ground and of the emission as a function of the blades rotational speed can be determined by appropriate statistical analysis starting by grouping the results of weather and noise measurements in sequences of useful data, each relating to a single minimum interval of 10 min.
8. The new procedure for WTN assessment

The noise assessment at the receivers due to wind turbines in operation is usually performed through outdoor measurements. Background noise and wind turbines noise (WTN) are related to wind speed and both contribute to the overall measured noise levels (environmental noise). Nevertheless, the relation between noise and wind speed is not easily predictable, especially when the wind farms are installed in hilly terrains, where the wind shear is truly remarkable. In Italy and in other countries, this kind of assessment is even more difficult to perform due to the national regulations that require to compute the difference between environmental and background noise levels with the same weather conditions. Thus, to get a reliable and approved measurement of the residual noise it would be necessary to turn off the wind farm. This work suggests a new procedure to simultaneously estimate the immission and the residual noise components measured nearby a wind farm when the residual noise is mainly generated by wind. This allows the evaluation of the noise impact produced by operational wind farms, without requiring the farm shutdown. The aim of this study was also to develop an engineering method with a solid scientific basis to be used as an assessment procedure by consultants and public bodies.

8.1 Introduction

The most important feature distinguishing WTN from other noise is the increase in the overall noise level due to wind blowing during measurements at the receivers. The wind turbulence on the microphone surface (Hessler, et al., 2008), the residual noise from the other nearby sources, the vegetation and wind induced noise, are all effects hard to separate from the WTN. Both the immission (WTN at the receiver) and the residual components of the measured noise levels are dependent on wind speed, therefore their identification using the results of any measurements performed when the plant is operational is difficult. As already shown, in some countries (e.g. Italy, France, U.K., New Zealand) such a separation of the contributions is required for the assessment of compliance with regulatory limits. All the actual procedures require the plant to be temporarily shutdown in order to measure the
residual noise at several wind speed, with the consequent impact on the production of energy and hence on the wind farm economic return. An additional problem is that the wind speed and its direction at ground level are affected by time and space variations not always related with the variations of wind at hub height, particularly in complex terrain, as shown in Chapter 7. A measurement of residual noise can lead to an incorrect noise evaluation if it is performed: a) in a different time period from the environmental measurement one; b) simultaneously to the environmental noise measurement but in a site far from the receiver.

Indeed, the outdoor sound propagation at large distance is affected by the vertical wind speed profile (wind shear), by the wind intensity and direction and by the atmospheric stability conditions (vertical temperature gradient) (Holtslag, 1984; EPA-454/R-99-005, 2000). These aspects significantly affect the propagation conditions of sound waves, bending the ones coming from the sources (Peters, 2011). These phenomena have to be considered in the characterization of the residual and the emissive noise components. Problems arise because the receivers are often located far from the source and the measurements must be performed in a representative period of the typical weather and background conditions. Moreover, as already described, in complex orography the wind speed varies discontinuously with the height due to the ground irregularities and the possible presence of dense vegetation and the logarithmic description for wind shear loses its validity. Therefore, to extrapolate the wind speed at a certain height if the measurement is performed at a different one it is almost impossible.

This Chapter describes a specific procedure to simultaneously estimate the immission and the residual noise components measured outdoor at the receivers in the area surrounding a wind farm. It is shown that the identification of the different components in the measured noise is possible on the basis of at least two weeks measurement campaign of weather data and environmental noise, a phase of data cleaning from spurious events (anthropic and animals noise) and an iterative data analysis.

This allows the adequate evaluation of noise impact produced by an operational wind farm without shutting down the plant. The proposed method has the necessary scientific foundation to perform a correct noise evaluation, being at the same time simple enough to be used as an assessment procedure by the consultants and public bodies.

The procedure was conceived working on the reorganization of the Italian WTN legislation,
therefore its output was determined in order to comply with the Italian legislative and regulatory framework. Modifications for the use in other countries are expected to be simple.

8.2 Data acquisition and analysis

In order to define and assess the new procedure, two different Italian wind farms were chosen in rural areas with complex orography:
- wind farm "La Miniera" in “Località Scapiccioli", Municipality of Montecatini Val di Cecina (PI) (WGS 84 10°44'03,65" E 43°23’19,62” N);
- wind farm “Poggi Alti”, in the Municipality of Scansano (GR) (WGS 84 11°23’27,92” E42°44’17,63” N).

The measurement campaigns lasted for 22 and 19 days respectively. The infrastructure managers, WPP UNO AG spa and E.ON Italy Srl, provided blade's rotational speeds and data from weather stations at the hub of each wind turbine. The receivers and the wind turbines positions are shown in Figure 8.1.

Figure 8.1. Google satellite image of the sites, with receivers (red) and closer turbines (blue) highlighted."Poggi alti” is on top, “La Miniera” is on the bottom.
The 1 sec time-history of noise was recorded with the microphone equipped with a 90 mm windscreen foam, placed in free field at an height of 4 m and near the receiver. The microphone pointed in the direction of the wind farm without obstacles and at a distance > 5 m from any reflective surfaces. The weather probe was placed 3 m above the ground (hereafter “ground height”), as close as possible to the microphone.

The instrumentation for measuring sound pressure levels meets the requirements for a class 1 instrument according to IEC 61672-1 (IEC 61672-1, 2003).

Figure 8.2 shows the relation between the wind speed measured at ground height at the receiver and the one measured at hub height of the nearest wind turbine. The site is “La Miniera - Scapiccioli” and the hub height for WTG-2 is 67 m, with relative altitude of 50 m and 700 m of distance from receiver. In the graphs are considered: a) all the data collected (averaged on 10 minutes), b) only the data for daytime and with favourable conditions of receiver downwind with respect to the source.

![Figure 8.2. Relation between wind speed at receiver (3 m above the ground) and wind speed at hub height (67+50 m) of the nearest wind turbine to the site of “La Miniera - Scapiccioli”. a) all data included, b) data of only daytime period with receiver downwind with respect to the source.](image)

The high dispersion of data within the graphs, confirms that the analytical model of wind shear is not reliable in hilly areas. It is not possible to apply a simple formula to extrapolate a significant value of wind speed at rotor height from the measurements at ground height or vice versa. For this reason, it was decided to maintain both the information for each time interval of 10 min.

Figure 8.3 shows the time history of $L_{Aeq,15}$ during a 10 min period when noise from the
turbines was dominant. Superimposed are the levels $L_{\text{Aeq,10 \ min}}$ (red) and $L_{90,10 \ min}$ (green) computed over the same period. It is evident that $L_{90,10 \ min}$ is not suitable to assess noise impact at receivers since it would exclude a large amount of sound energy from the source, after spurious event removal. $L_{\text{Aeq,10 \ min}}$ appears to be more relevant for the evaluation of health effects, while $L_{90}$ (used in some regulation (Larsson and Öhlund, 2014)) does not include the variability of noise level, related to swish-noise. Hence $L_{\text{Aeq,10 \ min}}$ for consecutive intervals of 10 minutes was selected as the noise indicator, computed after elimination of spurious sound events of anthropic or animal origin.

The 10 min data segments affected by rainfall or wind speed at ground higher than 5 m/s were also discarded according to the Italian legislation, as well as those with a duration shorter than 5’ after elimination of spurious data, such as human activities or animals noises. The decision of discarding the data with wind speed at ground exceeding 5 m/s is a practice supported by the scientific literature (Hessler, et al., 2008), them being significantly influenced by the residual noise generated by the wind and by the interaction of the microphone windscreen foam with the microphone itself due to wind turbulence. Data in Figure 8.4 show that in spite of a strong scattering of data, it is evident a splitting of the trend at high speeds. When those data characterised by a wind speed at ground $>5$ m/s are excluded, the higher branch disappears, indicating that the noise levels are overestimated in conditions of wind induced microphone noise (Van den Berg, 2006b).
8.3 Definition of the parameter involved

As already described, the inflow wind is the cause of the blades’ motion, which rotation in a wind field generates noise in multiple ways (Doolan, et al., 2012). The two phenomena are physically related, however two important aspects can make the relation between the wind at the hub and the blade rotation speed (N) not univocal on long term basis (Figure 8.5), leading to periods in which noise is not generated even if the wind is blowing: 1) The wind turbines stop when the wind speed is below the cut-in, usually $v_{\text{cut-in}} = 3 \text{ to } 5 \text{ m/s}$, or is over the cut-off, usually $v_{\text{cut-off}} \approx 25 \text{ m/s}$. 2). Sometimes the wind turbines are forced to stop or rotate at reduced speed for maintenance, production or others operational needs. Moreover, due to the wind fluctuations in a large and complex area or due to the plant manager intervention, it is unlikely that in a wind farm all the turbines have simultaneously the same N, especially if these are many.
A procedure for noise assessment needs to take into account the relation between the noise emission and a measurable variable, which has to represent the operativeness of the wind farm. Therefore, it appears inaccurate to relate the noise emission either to the inflow wind speed at hub or to a single N. This is the reason that led to propose a single parameter that considers the different simultaneous N of all the disturbing turbines of the farm. Consequently, the emission and the immission of WTN are associated to an equivalent blades rotational speed ($N_{eq}$) of the wind farm, which is directly related to the different N values, rather than considering the wind speed at the hub height.

8.3.1 $N_{eq}$ definition

The $N_{eq}$ parameter can be defined according to the formulation suggested by the ISO-9613 standard for calculating the outdoor sound pressure level $L_p$ at a distance $d$ from a directional source with sound power level $L_W$. The total attenuation $A$ is due to the geometric divergence, the atmospheric absorption, the ground effect and other effects that are not relevant in the present model. The directivity of the source is considered to be related to the wind direction at the hub height ($D_{0,wind}$, where $\theta$ represents the wind direction). The sound power level $L_W$ of a single wind turbine is set in the form $10\log\beta$, with $\beta$ fixed, allowing therefore to
estimate the sound pressure level due to the presence of the ith wind turbine at a distance \( d_i \) using Equation (8.1), where \( k \) is a constant that takes into account the other attenuation effects that can be considered common to all the turbines.

\[
L_{p,i} = 10 \log N_i^\beta - 10 \log d_i^2 + D^i_{\theta,\text{wind}} + A^i_{\text{atm,ground}}(d_i) + k
\]  

(8.1)

The overall WTN level from the whole wind farm at receiver is given by the sum of each single WTN of the farm:

\[
L_p = 10 \log \left( \sum \left( N_i^\beta \cdot 10 \frac{D^i_{\theta,\text{wind}} + A^i_{\text{atm,ground}}}{d_i^2} \right) \right) + k \equiv 10 \log \left( \frac{N_{eq}^\beta}{d_1^2} \cdot 10 \frac{A_{\text{atm,ground}}}{10} \right) + k
\]  

(8.2)

In Equation (8.2) the overall WTN level at receiver depends on a single parameter of the farm, the \( N_{eq} \), which represents the rotational speed of a single “virtual” turbine generating the overall noise pressure level of the whole wind farm. The virtual turbine is placed in the position \( d_1 \) corresponding to the turbine closest to the receiver. Following Equation (8.2), the \( N_{eq} \) can be defined as:

\[
N_{eq} = \beta \sqrt{\sum_i \left( N_i^\beta \cdot \left( \frac{d_i}{d_1} \right)^2 \cdot C_i \cdot K_i^\beta \right)}
\]  

(8.3)

\( C_i \) can be seen as a directivity correction depending on the difference in wind direction between the ith turbine and the nearest one. It also includes the meteorological effects on sound propagation, as it will be discussed in the following section. \( K_i \) takes into account the combined effects of ground attenuation and air absorption. These parameters can be expressed as in (8.4).

\[
C_i = 10 \frac{D^i_{\theta,\text{wind}}}{\beta^{10}}, K_i = 10 \frac{A^i_{\text{atm,ground}} - A_{\text{atm,ground}}}{\beta^{10}}
\]  

(8.4)

In this way, the problem of multiple turbines is transformed in a simpler single virtual wind turbine that generates at receiver the equivalent noise level of all the impacting turbines. The virtual turbine is placed in the position of the closest turbine \( (d_i) \) and its blade rotational speed is \( N_{eq} \).
8.3.2 Parameters and attenuation terms

The full definition of the $N_{eq}$ is completed by defining the source parameter $\beta$, the attenuation term $A_{atm,ground}$ and the correction $D_{0,wind}$.

The broadband trailing edge noise is the dominant WTN source (Oerlemans, et al., 2007). It is generated in the outer part of the blades and its power scales with the fifth power of the local flow speed. Also the inflow turbulent noise and the tip noise are other important mechanisms of noise generation that scales with the fifth power of the wind speed (Fleig, et al., 2004; Oerlemans, et al., 2009; Tangler, 2000).

The blades rotational speed ($N$) is the most important parameter affecting the noise emission (Leloudas, et al., 2007) and the wind speed incoming on the blades is generally linearly related to $N$. The total noise emission is proportional to the fifth power of wind speed and consequently of $N$ (Oerlemans, et al., 2007; Lee, et al., 2009; Jianu, et al., 2012), even looking at the immission noise at receiver far from the sources (Van den Berg, 2004). Thus, for the purpose of the procedure, $\beta$ was set equal to 5.

According to the ISO 9613, the air absorption is a function of frequency, temperature and humidity. The ground effect attenuation depends on the orography, on the ground typology and on the distance. It is possible to combine them in a single attenuation term linearly dependent on distance (8.5).

\[
A_{atm,ground} = -\alpha \cdot d \quad (8.5)
\]

Different $\alpha$ were estimated for both flat and complex terrain. For flat terrain the Monte Carlo Method (MCM) was applied using the ISO 9613 as noise propagation model to the WTN power spectrum of the “2MW Vestas v100”, with the uncertainty reported in Table 1. The noise power spectra do not significantly vary among different turbine models (Van den Berg, et al., 2008). In details, the analysis followed these steps:
- from a distance of 50 m from the turbine up to a distance of 1500, a set of 30 calculation points was taken, one every 50 meters;
- in each of these points, a noise levels distribution was computed through an MCM approach using the ISO 9613 propagation model and a number $m$ of runs, with a random sampling of the parameters reported in Table 8.1 within their distribution ranges. The temperature and humidity were chosen according to the typical Italian climatic values;
- $m$ sound level trends over the distances were obtained by a random sampling of a single level value from each levels distribution over distance;
- the alpha distribution was obtained calculating an OLS linear regression over the distance for each $m$ sound level trend and it is reported in Figure 8.6;
- the number of runs $m$ was adjusted to assure the convergence of the alpha distribution, about $m=10^4$ runs were sufficient.
Therefore $\alpha = 3$ dB/km was obtained from the average value of the alpha distribution for flat terrain, rounded to the first integer.

Table 8.1. Distribution, mean and range for the parameter used in MCM calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>distribution</th>
<th>mean</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum uncertainty</td>
<td>Gaussian</td>
<td>0</td>
<td>$\sigma=3$</td>
</tr>
<tr>
<td>[dB]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T temperature [°C]</td>
<td>Gaussian</td>
<td>12.5</td>
<td>$\sigma=5$</td>
</tr>
<tr>
<td>RH humidity [%]</td>
<td>uniform</td>
<td>70</td>
<td>40 - 100</td>
</tr>
<tr>
<td>Hub height [m]</td>
<td>uniform</td>
<td>80</td>
<td>60 - 100</td>
</tr>
<tr>
<td>Receiver height [m]</td>
<td>uniform</td>
<td>4</td>
<td>3.5 – 4.5</td>
</tr>
<tr>
<td>G ground factor</td>
<td>uniform</td>
<td>0.5</td>
<td>0 - 1</td>
</tr>
</tbody>
</table>

Figure 8.6. $\alpha$ distribution resulting from the MCM calculation. The continuous line is the average, the dotted lines are the 95% quantiles coverage interval.
The same approach applied to hilly terrain and considering the average over various random altitude profiles for single turbine pathways resulted in a range of different values depending to the pathway itself. An average value of $\alpha = 5 \text{ dB/km}$ was chosen corresponding to a higher ground absorption that may happen in complex terrain compared to a flat one.

The $D_{\theta,\text{wind}}$ considers the influence of wind direction and meteorological effects as wind and temperature gradients in the propagation of noise.

$$D_{\theta,\text{wind,Day}}^i = 10\beta \log \left( 1 + \gamma_{\text{day}} \cdot \cos(\theta_i - \phi_i) \right)$$

$$D_{\theta,\text{wind,Night}}^i = -10\beta \log \left( 1 + \gamma_{\text{night}} \cdot \cos(\theta_i - \phi_i) \right) \quad (8.6)$$

$\theta$ represents the angle between the North and the prevailing wind direction during the 10 min interval at the hub of the $i^{\text{th}}$ wind turbine while $\phi$ is the angle between the North and the line joining the receiver with the $i^{\text{th}}$ wind turbine. Both angles are referred with positive direction in a clockwise direction. The cosine expression was chosen to have a continuous variation from downwind to upwind conditions. The downwind condition correspond to a $\theta_i - \phi_i = 180^\circ$, while the upwind to $\theta_i - \phi_i = 0^\circ$. The different sign in Equation 8.6 for daytime or night-time conditions was chosen in accordance with the $\gamma$ values calculated in the following, in order to have the appropriate attenuation values.

The coefficient $\gamma$ depends on the meteorological conditions, such as wind speed and atmospheric stability. Its value was estimated with (8.6) calculating the broadband sound attenuation due to the meteorological effects in the CONCAWE propagation model (Manning, 1981). A distance source-receiver of 500 m was considered, sufficient for having significant meteorological effects. The sound power spectrum used is an average spectrum (Van den Berg, et al., 2008). A reference noise level spectrum at the receiver has then been calculated subtracting the geometrical divergence, air absorption and ground effect attenuations. The attenuations extrapolated from the CONCAWE meteorological curve for each frequency band were subtracted from the reference spectrum obtaining a spectrum at the receiver for each meteorological category of CONCAWE. The broadband meteorological attenuation for each category was obtained subtracting the broadband meteorological levels from the broadband reference level. The resulting attenuations are reported in Table 8.2.
Table 8.2. CONCAWE categories and relative attenuation calculated.

<table>
<thead>
<tr>
<th>CONCAWE categories</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.7</td>
</tr>
<tr>
<td>2</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>3.8</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-4.0</td>
</tr>
<tr>
<td>6</td>
<td>-4.8</td>
</tr>
</tbody>
</table>

The broadband attenuations were calculated for daytime/night-time and downwind/upwind condition weighting the attenuations in Table 8.2 with the percentages in Table 8.3. The percentages represent the estimated probability for each CONCAWE category corresponding to the average meteorological condition supposed. The results are in the “CONCAWE attenuations” row of Table 8.3.

Table 8.3. Probability of the CONCAWE categories supposed, with the meteorological attenuation calculated.

<table>
<thead>
<tr>
<th>CONCAWE categories</th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downwind</td>
<td>Upwind</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>20%</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>70%</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>10%</td>
</tr>
<tr>
<td>4</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>80%</td>
<td>-</td>
</tr>
<tr>
<td>CONCAWE attenuations</td>
<td>-4.6 dB</td>
<td>6.0 dB</td>
</tr>
<tr>
<td>Estimated attenuations</td>
<td>-5.0 dB</td>
<td>6.0 dB</td>
</tr>
</tbody>
</table>

The estimated attenuations in the last row of Table 8.3 are calculated using Equation 8.7 in accordance with Equation 8.6 taking the opposite of $D_\phi$, rounded to 0.5, with:
\[ \gamma_{\text{day}} = +0.25 \Rightarrow \begin{cases} D_{\theta, \text{down wind}, \text{day}} = 50 \log (1 + \gamma_{\text{day}}) = 4.8 \\ D_{\theta, \text{up wind}, \text{day}} = 50 \log (1 + \gamma_{\text{day}}) = -6.2 \end{cases} \\
\gamma_{\text{night}} = -0.15 \Rightarrow \begin{cases} D_{\theta, \text{down wind}, \text{night}} = -50 \log (1 + \gamma_{\text{night}}) = 3.5 \\ D_{\theta, \text{up wind}, \text{night}} = -50 \log (1 - \gamma_{\text{night}}) = -3.0 \end{cases} \]  

(8.7)

The attenuations corresponding to the \( \gamma_{\text{day}} \) and \( \gamma_{\text{night}} \) resulted comparable to the CONCAWE ones reported in Table 8.3, in a ±0.5 dB(A) range.

A quick view of the benefits brought introducing the \( N_{eq} \) parameter comes from the comparison of Figure 8.7 and Figure 8.8. In Figure 8.7 the noise levels (\( L_{Aeq,10 \text{ min}} \)) measured in “Scansano” and in “La Miniera” are related to the \( N \) of the nearest wind turbine, while in Figure 8.8 the same noise levels are related to the \( N_{eq} \). The noise levels are separated into day and night periods. The dispersions in Figure 8.8 have smaller spreads of data than those in Figure 8.7, showing that noise has a better relation with \( N_{eq} \) than with the \( N \) of a single turbine.

Figure 8.7. Dispersion of \( L_{Aeq,10 \text{ min}} \) as a function of \( N \) of the nearest turbine in “Poggi alti - Scansano” (upper) and “La Miniera - Scapiccioli” (lower) during daytime (blue) and night-time (red).
8.4 The procedure for WTN assessment

The Figures 8.7 and 8.8 in the previous section show the overall measured noise levels, i.e. the sum of the contributions from WTN and from residual noise. For a proper WTN assessment the residual noise levels as a function of wind speed at ground \(v_{gr}\) need to be separated from the environmental ones.

For rotational speeds below the cut-in threshold, the data spread in Figure 8.7 appears higher than expected, since for \(N\) less than the cut-in threshold no contribution to the overall noise level from wind turbines should be measured. Therefore, the dispersion in the noise levels is attributable to the effects of wind at ground (at the speed \(v_{gr}\)) and/or to other close turbines with an \(N\) value higher than the plotted one in Figure 8.7. By using the \(N_{eq}\) (Figure 8.8), the parameter that considers the rotational speed of all the turbines, it is possible to identify the time periods where all the turbines have a low enough rotational speed not to affect the noise levels at the receiver. Consequently, as in these periods the noise levels mainly depend on \(v_{gr}\), their identification can be the starting point for the estimation of the residual noise in the

Figure 8.8. Dispersion of \(L_{\text{Aeq,10 min}}\) as a function of \(N_{eq}\) in “Poggi alti - Scansano” (upper) and “La Miniera – Scapiccioli” (lower) during daytime (blue) and night-time (red).
measurement site without requiring the farm shutdown. The reconstruction of both the residual noise level as a function of $v_{gr}$ and the immission noise levels as a function of $N_{eq}$ can be performed with an iterative application of the following steps to the data of the outdoor measurement campaign.

The procedure is based on the following assumptions:

1. The wind speed at hub height is not directly related to the ground wind speed, especially in hilly areas. The sound production at high altitude is related to $N$ and then it can be separated from the residual sound production at low altitude.
2. The wind farm immission level depends on the $N_{eq}$ parameter, not on $v_{gr}$.
3. The residual level after the elimination of the spurious noise events depends on $v_{gr}$, not on $N_{eq}$.
4. The procedure is only valid in absence of relevant anthropic noise. Therefore, if the spurious events cannot be removed during the preliminary data cleaning, the measurement campaign must be repeated.

Based on these assumptions, the procedure is able to identify in the measured noise levels the contribution of the wind farm immission as a function of $N_{eq}$ and the one of the residual as a function of $v_{gr}$. Considering the difference in outdoor propagation between day and night and in order to comply with regulatory prescriptions, the whole procedure, sketched in Figure 8.9, is performed independently for daytime and night-time. It consists of the following steps:

- Elimination of the spurious noise events from the acquired data;
- Preparation of the database and $N_{eq}$ calculation;
- Estimation of the residual noise level at receiver for low $v_{gr}$;
- Construction of a look-up table for the energetic average and the occurrence number of 10 min segments as a function of $N_{eq}$ and $v_{gr}$;
- Iterative phase:
  - Immission and residual noise tables filling;
  - Final estimation of the residual and immission noise level at the receiver.

After the iterative phase, the best estimate of the wind farm immission level at receiver $L_{I,x}$ is an energetic average over all the wind speeds (k), where at each iterative step the residual level at $v_{gr}=k$ was subtracted from all the measured sound levels at $v_{gr}=k$. The best estimate of the residual level is obtained in the meanwhile as the energetic average of all the sound productions corresponding to all $N_{eq}$ from the activation one, where the best immission level
at $N_{eq-x}$ has been subtracted from all the measured sound levels at $N_{eq}$.

8.4.1 Preparation of the data sets and $N_{eq}$ calculation

The first step is the creation of a database with noise, site and weather data ($L_{Aeq,10 \text{ min}}, v_{gr}, d_i, \varphi_i$) and the information provided by the plant manager ($\theta_i, N_i$). The noise data were preliminarily cleaned by the anthropic and animal spurious events. Each row of the table corresponds to a time interval of 10 min and a column is added with value of $N_{eq}$ calculated according to Equation (8.3).

$L_{Aeq,10 \text{ min}}, v_{gr}$, and $N_{eq}$ are the only data considered in the subsequent steps of the procedure. As reported in the example of Table 8.4, each row then becomes a triplet (from now on "useful datum") of $L_{Aeq,10 \text{ min}}, v_{gr}, N_{eq}$ for a specific interval of 10 min. The values of $v_{gr}$ and $N_{eq}$ are approximated to the nearest integer, whereas the $L_{Aeq,10 \text{ min}}$ value to 0.5 dB(A).

Two separate data sets are created in order to consider separately the day and the night.
periods.

Table 8.4. Example from the database in “Poggi alti - Scansano” during daytime.

<table>
<thead>
<tr>
<th>Date &amp; Time</th>
<th>$L_{Aeq,10}$</th>
<th>$V_{gr}$</th>
<th>$N_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/07/2011 17.20</td>
<td>41.5</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>05/07/2011 17.30</td>
<td>40.5</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>05/07/2011 17.40</td>
<td>40.5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>05/07/2011 17.50</td>
<td>40.0</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>05/07/2011 18.00</td>
<td>39.5</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>05/07/2011 18.10</td>
<td>38.5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>05/07/2011 18.20</td>
<td>37.5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>05/07/2011 18.30</td>
<td>36.5</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>05/07/2011 18.40</td>
<td>34.5</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>05/07/2011 18.50</td>
<td>37.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>05/07/2011 19.30</td>
<td>40.5</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>05/07/2011 19.40</td>
<td>33.5</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

8.4.2 Residual noise level at the receiver for low wind speeds at ground

The reconstruction of the residual noise as a function of $v_{gr}$ starts from the measurement periods during which the contribution of the WTN at the receiver is negligible if compared to the residual noise. For this purpose, the useful data are grouped according to the different values of $N_{eq} = x$, where $x$ is an integer number varying from 0 to the maximum value of $N_{eq}$. Then it has to be computed the energetic average ($L_x$) of the $n_x$ measured $L_{Aeq,10 \text{ min}}$ included in the $x^{th}$ group for all $x$ values. Similarly, the cumulative energetic average $L_{cum,x}$ of the $L_x$ for all the $N_{eq}$ values from 0 to $x$ is calculated, following Equation 8.8. All the results are rounded to 0.5 dB(A).

\[
L_x = 10 \log \left( \frac{1}{n_x} \sum_{i=1}^{n_x} 10^{0.1 L_{Aeq,10 i'}} \right), \quad L_{cum,x} = 10 \log \left( \frac{1}{1+x} \sum_{j=0}^{x} 10^{0.1 L_{xj}} \right) \quad (8.8)
\]

$L_x$ and $L_{cum,x}$ are nearly equal when increasing $N_{eq}$ until the WTN contribution begins to be significantly above the residual noise. The first index $x$ for which $L_x - L_{cum,x} > 2$ dB(A) for at least two consecutive $x$ is what is called the “activation threshold” $\bar{x}$, with a minimum value of $\bar{x} = 3$ rpm. The WTN contribution begins to be significant when $N_{eq} \geq \bar{x}$.

Figure 8.10 shows a graphical example of the activation threshold. If no activation threshold
is found, the procedure suggests to check the data cleaning process or to perform a new measurement campaign.

No significant noise immission at receiver occurs when $N_{eq} < \overline{\nu}$, so these noise levels can be used for a first rough estimate of the residual noise. The latter depends on the background noise of the area, but especially on $v_{gr}$. This first estimate of the residual noise is not complete, because for low $N_{eq}$ only low $v_{gr}$ are usually measured. Nevertheless, it represents the starting point for the following phases, in which the description of the residual noise will be obtained up to a $v_{gr}$ of 5 m/s.

![Activation Threshold](image)

*Figure 8.10. Identification of the activation threshold. Data measured in “Poggi alti - Scansano” during daytime.*

### 8.4.3 Calculation matrices

The subsequent iterative calculations require a pair of data look-up tables called the energetic average matrix and the occurrences matrix. The rows are the integer values of $N_{eq}$ from 1 to the maximum $N_{eq}$ ($x_{\text{max}}$), and the first row corresponds to $N_{eq} < \overline{N}$. The columns are the integer values of $k = v_{gr}$ from 0 to 5 m/s. The matrix size is then $[(2 + x_{\text{max}} - \overline{N}) \times (k + 1)]$. The occurrences matrix cells contain the number $n_{x,k}$ of $L_{Aeq,10 \text{ min}}$ used in the energetic average.
calculation of the corresponding cell. The cells of the energetic average matrix contain instead the energetic average \((L_{x,k})\) of the \(n_{x,k}\) values of \(L_{Aeq,10\ min}\) having \(N_{eq} = x\) and \(v_{gr} = k\), approximated to the nearest integer. The cells with \(n_{x,k} \leq 1\) should be left empty for statistical reason. An example of both matrices is reported in Table 8.5.

\[
\text{Table 8.5. Example of energetic average and occurrences matrices of data measured in “Poggi alti - Scansano” during daytime.}
\]

<table>
<thead>
<tr>
<th>Energetic average matrix</th>
<th>Occurrences matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{gr})</td>
<td>(N_{eq})</td>
</tr>
<tr>
<td>(&lt;4)</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>39</td>
</tr>
<tr>
<td>7</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>9</td>
<td>44</td>
</tr>
<tr>
<td>10</td>
<td>43</td>
</tr>
<tr>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>14</td>
<td>44</td>
</tr>
<tr>
<td>15</td>
<td>43</td>
</tr>
<tr>
<td>16</td>
<td>44</td>
</tr>
<tr>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td>18</td>
<td>51</td>
</tr>
<tr>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>52</td>
</tr>
<tr>
<td>21</td>
<td>51</td>
</tr>
</tbody>
</table>

8.4.4 Iterative phase

8.4.4.1 Immission and residual matrices

The previous matrices contain environmental noise and occurrences values that do not vary during the procedure, but they are used for two other matrices (immission and residual matrices) that change instead during the iterative phase.

To start the process of separating from the environmental noise the contribution of WTN and the residual noise, it is assumed that the first approximation of the residual noise levels at receiver is the first row of the energetic average matrix \((L_{0,k})\), that is the row with \(N_{eq} < \bar{x}\).
Since it is assumed that no other noise sources are present, by energetically subtracting \( L_{0,k} \) from the individual value of \( L_{x,k} \) of the corresponding \( k \) of the energetic average matrix, a first estimate of the noise immission levels produced by a WTG at receiver is obtained for each \( x \) value. Therefore, the first step of the immission matrix contains the \( L_{1,x,k} \) calculated according to equation 8.9, for each \( x \geq \bar{x} \) and for each \( k \), rounded to the first decimal place. The lines with \( x < \bar{x} \) are omitted.

\[
L_{L_{1,x,k}} = 10\log \left( 10^{0.1L_{x,k}} - 10^{0.1L_{0,k}} \right) \quad (8.9)
\]

When the residual level is not lower than the measurement value (\( L_{x,k} \leq L_{0,k} \)), it was decided to replace the result of (8.9) with the value \( L_{1,x,k} = L_{x,k} - 10 \) in order not to lose statistics without inserting numbers that could alter the procedure’s outcome. This particular substitution is still under review process.

The noise immission levels \( L_{1,x} \) for each \( x \geq \bar{x} \), rounded to the nearest integer, is then calculated with the energetic weighted average reported in equation 8.10:

\[
L_{L_{1,x}} = 10\log \left( \frac{1}{n_x} \sum_{k=0}^{\bar{k}} n_{x,k} 10^{0.1L_{L_{1,x},k}} \right) \quad (8.10)
\]

\( n_x = \sum_{k=0}^{\bar{k}} n_{x,k} \) and \( \bar{k} \) is the maximum \( v_{gr} \) for which \( L_{0,k} \neq 0 \).

It is likely that the first estimate of the noise immission does not yield a level for all the \( x \) values, because the \( L_{0,k} \) at the first step may not be complete for all \( v_{gr} \) but only for the lowest ones. For a complete estimate of the residual noise levels at receiver, the residual matrix is built following the same approach used for the immission matrix with the replacements:

\( L_{1,x,k} \rightarrow L_{R,x,k} \), \( L_{0,k} \rightarrow L_{1,x} \).

This means that the \( L_{1,x} \) is energetically subtracted from all the values of the energetic average matrix with the same \( N_{eq} (x) \) and variable \( v_{gr} (k) \). The residual noise \( L_{R,k} \) might be obtained grouping the element \( (L_{R,x,k}) \) of the residual matrix for each \( k \) and taking the energetic weighted average reported in equation 8.11:

\[
L_{R,k} = 10\log \left( \frac{1}{n_k} \sum_{x=0}^{x_{max}} n_{x,k} 10^{0.1L_{R,x,k}} \right) \quad (8.11)
\]

\( n_k = \sum_{x=0}^{x_{max}} n_{x,k} \) and \( x = 0 \) corresponds to the matrix elements with \( x < \bar{x} \). Only the values of \( x \) for which \( L_{1,x} \neq 0 \) are considered and \( L_{R,k} \) is rounded to the nearest integer. According to the
procedure, the first line of the residual matrix is identical to the first line of the energetic average matrix (L_{R,0,k} = L_{0,k}).

8.4.4.2 Final estimation of the residual and immission levels at receiver

At the end of the previous phase, the L_{R,k} may well not yield a value for all the v_{gr} and N_{eq} and the same might happen for L_{I,x}. In addition, the number of filled cells of the residual and the immission matrices may not be the same as those of the energetic average one. However, the L_{R,k} contains more information than the L_{0,k} considered as the former residual noise. Therefore, the energetic subtraction of L_{R,k} from the energetic average matrix can lead to a better estimate of the L_{I,x}. Following the previous section, with a better L_{I,x} is possible to have a new L_{R,k} better than the initial one. An example of the immission and residual matrices for the first two runs of the procedure is reported in Table 8.6.

Table 8.6. Example of immission and residual matrices after the 1st and the 2nd run of data measured in “Poggi alti - Scansano” during daytime.

<table>
<thead>
<tr>
<th>Immission matrix after 1st run</th>
<th>Immission matrix after 2nd run</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{gr})</td>
<td>0</td>
</tr>
<tr>
<td>(N_{eq})</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
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<td>7</td>
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<td></td>
<td>20</td>
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<tr>
<td></td>
<td>21</td>
</tr>
</tbody>
</table>
After the 2nd iteration, more cells are filled and new values of $N_{eq}$ appeared since the $L_{R,k}$ covered more $v_{gr}$ than previously, therefore the $L_{I,x}$ are calculated on a wider set of data, but still with not all the available data. The residual noise for each $v_{gr}$ ($L_{R,k}$) is used to repeat the calculation of $L_{I,x}$, and vice-versa, in an iterative way in order to refine the estimates of $L_{I,x}$ and $L_{R,k}$ until their values do not stabilize. The iteration ends when the matrices are no longer different between the (i-1)th run and the ith run.

The final immission and residual matrices, obtained after 3 iterations, are reported in Table 8.7 as an example, together with the final estimates for residual noise as a function of $v_{gr}$ ($L_{R,k}$) and the immission level at receiver as a function of $N_{eq}$ ($L_{I,x}$).
Table 8.7. Examples of the final immission and residual matrices, together with the $L_{R,k}$ and $L_{I,x}$ for the data measured in “Poggi alti - Scansano” during daytime.

The trend of the noise immission as a function of $N_{eq}$ can present strong oscillations in correspondence of some $N_{eq}$ values. This may happen especially if the farm is multi-turbine or the site is in complex terrain, where the wind direction and the thermal inversion could be not uniform enough among all the wind turbines.

Over a long period of measurements, the atmospheric conditions could be very different, from stable to unstable. This led to period with low residual noise and high immission, or high residual noise and low immission to be considered in the same matrix. Also the background noise levels can be variable with non-wind sources over a long period. Thus, the procedure provides as outputs average values over the measurement period, obtaining in this way results that can be eligible for all conditions, within the uncertainties given by the variability of data occurred during the measurement campaign. The longer the measurements period is, the more conditions are covered. Significant differences in the residual noise come with different seasons, due to different vegetation, suggesting a proper seasonal characterization for a complete noise assessment.

A compensation for the fluctuations to generalize the association between the immission
levels at receiver and the $N_{eq}$ can be obtained considering an ordinary least squares fit of the final immission data $L_{I,x}$ as a function of $x$. Data that are negligible compared to the minimum residual noise and those with insufficient statistic are not considered: $n_x > 10$ and $L_{I,x} \geq \min(L_{R,I}) - 10$ are required. The function to be used at first is the logarithmic expression $L_{I,theor}(x) = A \log x + B$. A value of $R^2 \leq 0.7$ has been chosen as the reference value for the fit acceptability. In this way, the 70% of the variance in the response variable can be explained by the independent variables, a sufficient value for the purpose of the procedure. Further studies will be performed in order to optimize this assumption. If this condition is not satisfied, a polynomial curves not exceeding the 3$^{rd}$ degree can be used. If the fit continues to be unreliable, the procedure suggests to check the data cleaning process or to perform a new measurement campaign. An example of the fit is in Figure 8.11. The procedure does not consider a fit on the residual noise because it is site-dependent and has few points to be based on.

$$L_{I,theor}$$

$$y = 0.0054x^3 - 0.1539x^2 + 1.6887x + 36.0341$$

$$R^2 = 0.9064$$

![Figure 8.11. Example of the fit obtained using the ordinary least squares applied to the final immission values for “Poggi alti - Scansano” during daytime.](image)

In order to evaluate the noise compliance with the Italian noise limits for the immission level, an overall immission level can be calculated with 8.12.

$$L_{I,tot} = 10\log\frac{1}{n_{tot}} \sum_{x}^{x_{max}} n_x \frac{L_{I,x}}{10}$$ (8.12)

Ph.D Thesis of Dr. Luca Fredianelli - Analytical assessment of wind turbine noise impact at receiver by means of residual noise determination without the farm shutdown - 97
8.5 Discussion

The aim of a noise impact assessment is the estimation of both the immission and residual components of the noise levels measured in proximity of the receivers. Several difficulties in the noise impact evaluation arise when the receiver is placed in a complex orography, with many wind turbines, where the wind produces high residual noise and has high and unpredictable shear. The noise levels are described by the parameter $L_{Aeq,10min}$ acquired for at least 2 weeks, the wind speed at receivers’ height ($v_{gr}$) and the blades rotational speed (N) are considered as two separate variables.

The method proposed in this work does not consider the immission levels of a wind farm as a function of the wind speed at hubs height, but instead as a function of a new parameter that considers the rotation of all the turbines: the equivalent blades rotational speed $N_{eq}$. The residual noise level is evaluated as a function of the $v_{gr}$.

The proposed procedure reconstructs these trends starting from a noise and weather measurement campaign of at least two weeks without requiring the plant shutdown. The periods when the wind turbines had rotational speed low enough not to increase the noise at receiver are used as a first estimate of the residual noise level. The final residual noise as a function of the $v_{gr}$ and the immission levels as a function of $N_{eq}$ are computed through appropriate iterative phases of energetic subtraction between the measured noise levels grouped by classes of $v_{gr}$ and $N_{eq}$. On this basis, the Federal Council of the National and Regional Environmental Protection Agencies of Italy suggests this procedure to verify the WTN compliance with the present Italian legislation (ISPRA, 2013), nonetheless nothing prevents its use in other countries. This procedure is based on the data of two different sites, but it was tested in all the Italian wind farms described in the Appendix.

Nevertheless, a proper scientific validation is needed in order to verify the residual output, as will be discussed in Chapter 10. The implementation of the method in an automatic software procedure results in a faster analysis of the acquired data.

In order to enable an appropriate analysis of the uncertainties associated with the procedure, new measurements in different conditions, Monte Carlo simulations and a sensitivity analysis on the parameters involved are shown in the following.
9. Uncertainty analysis through Monte Carlo method

In 2013 the previously described procedure for the assessment of noise impact of operational wind farms has been published by the Italian Institute for Environmental Protection and Research (ISPRA) and the Environmental Protection Agency of Tuscany Region (ARPAT). From now on, the 2013 procedure will be named “Italian procedure”.

By means of measurement campaigns of specific noise and weather parameters at the receivers lasting at least 2 weeks, the procedure simultaneously provides an estimate of noise immission and prevailing background noise, also if the main component of the latter is due to wind.

Through iterative steps, the method provides the evaluation of noise impact produced by operational wind farms, without stopping the energy production for measurement purpose. Moreover, the implemented algorithm involves the use of several specific numerical values to be assigned to the parameters for the calculation of noise propagation.

The method has been successfully tested through specific measurement campaigns in nine Italian sites with different orography conditions, as shown in a following Chapter, but a proper uncertainty analysis has not been performed yet.

This Chapter provides a confidence level for the outputs and defines an empirical approach to estimate their uncertainty. The estimation of the coverage interval associated with the output noise levels of the Italian procedure is performed through a Monte Carlo procedure.

9.1 The Italian procedure

In the Italian procedure, the residual noise levels are considered as a function of wind speed at ground and the immission levels at receivers as a function of the equivalent blades rotational speed $N_{eq}$. Both are computed through appropriate iterative phases and energetic subtraction between measured noise levels grouped in classes of wind speed at ground and blades rotational speed. The procedure is sketched in Figure 9.1. Mainly, a phase of data acquisition is followed by an iterative computational phase.
9.1.1 Data acquisition

The procedure is based on data from outdoor measurements and allows different calculation for day and night-time, flat terrain and complex terrain. For each receiver, the following set of data are acquired over 10 min:

- $L_{Aeq, 10 \text{ min}}$;
- Average wind speed at ground (at a height of 3 m above ground);
- Precipitation (rain, snow, hail);
- Most frequent wind direction at each turbine rotor;
- “N”: the average blades rotational speed for each turbine with a distance receivers-blade less than or equal to 1 km;

A database is built with the data acquired, where the rows are the 10 min intervals and at each row corresponds a column with all requested parameter for that interval. For each ten minutes data, the $N_{eq}$ is calculated from the single $N_{eq,i}$ with suitable parameters according to the ISO 9613-2 (ISO 9613-2:1996, 1996) propagation, including: distance and direction between wind turbines, wind direction, ground type, period of the day and atmospheric attenuation. In its final form, each row of the data array should display the values of $L_{Aeq, 10 \text{ min}}$, wind speed at ground ($v_{gr}$) and $N_{eq}$ correspondingly to each consecutive time interval of 10 min. The values of $v_{gr}$ and $N_{eq}$ are approximated to the nearest integer, whereas the $L_{Aeq, 10 \text{ min}}$ values to 0,5 dB(A).
9.1.2 Iterations and outputs

The iterative phase consists in 3 steps:

1. A first calculation of the residual noise, not dependent on $v_{gr}$;
2. An estimate of the noise immission at receiver of the whole wind farm as a function of $N_{eq}$;
3. An estimate of the residual noise as a function of $v_{gr}$.

At Point 1 an initial residual noise level is obtained with a $N_{eq}$ threshold, for which $N_{eq}$ value below that threshold can be considered as not relevant for noise impact on the receiver. The residual noise level has a wind speed dependence. At Point 2 and 3, noise levels are respectively classified for finite interval of $N_{eq}$ and $v_{gr}$. To calculate the noise immission as a function of $N_{eq}$, the residual level as a function of $v_{gr}$ is energetically subtracted to the measured noise, then a best fit is produced. This fitted relation is energetically subtracted to measured noise to obtain a residual noise as a function of wind speed at ground. Again, a best fit of this relation is produced. Point 2 and Point 3 are strictly connected and based one another. Indeed, once a first estimation of the noise immission is obtained, it is used to calculate a better estimate of the residual noise and vice-versa. This iteration of energetic subtraction of the fitted relations continues until no new information are added between an iteration and the following.

The outputs of the procedure are noise immission levels at receiver as a function of $N_{eq}$, residual noise at receiver as a function of $v_{gr}$ and the total immission and residual noise at receiver (i.e. the equivalent mean levels evaluated on the measurement period distinguishing between night-time and daytime) that is computed weighting the noise levels in each classes with the corresponding occurrences.

9.2 Monte Carlo uncertainty analysis

The uncertainty analysis with a Monte Carlo method (MCM) was performed using the adaptive procedure presented in the GUM, “Guide to the expression of Uncertainty in Measurement” (JCGM 101:2008, 2008). The MCM basically consists in propagating the distributions of the inputs through the model to obtain a consequent distribution of the outputs. MCM can be summed up in the following steps:
1. set up of a probability distribution function (PDF) for every input;
2. pseudo-random numbers sampling from the PDFs;
3. computation of the model for every sampled value;
4. assemblage of the distribution function for the outputs (G);
5. calculation of uncertainty on the outputs from the standard deviations of the Gs.

The convergence of MCM is assured increasing the number of iterations until the stabilisation of the statistical parameters as defined by GUM.

The $N_{eq}$ parameter has a key role in the Italian procedure, an estimation of its uncertainty is preliminary to the uncertainty analysis of the iterative phase of the procedure.

The procedure and the Monte Carlo Method were implemented in R Free Software programming language (R Development Core Team, 2008).

### 9.2.1 Testing Sites

In this analysis, the Monte Carlo method has been applied to the Italian procedure with data coming from the six wind farms reported in Table 9.1. Figure 9.2 shows the distribution of the turbines around each receiver.

<table>
<thead>
<tr>
<th>Wind farm</th>
<th>Turbines considered</th>
<th>Number of 10’ data</th>
</tr>
</thead>
<tbody>
<tr>
<td>La miniera-Scapiccioli</td>
<td>4</td>
<td>1725</td>
</tr>
<tr>
<td>La miniera-Provinca</td>
<td>4</td>
<td>1287</td>
</tr>
<tr>
<td>Poggi alti-Scansano</td>
<td>7</td>
<td>1297</td>
</tr>
<tr>
<td>Lucera</td>
<td>3</td>
<td>997</td>
</tr>
<tr>
<td>Riparbella</td>
<td>6</td>
<td>1384</td>
</tr>
<tr>
<td>Santa luce</td>
<td>5</td>
<td>2209</td>
</tr>
</tbody>
</table>
9.2.2 Uncertainty of $N_{eq}$ parameter

$N_{eq}$ is a parameter calculated for each 10 min interval considering the $N$, weather and plant measured data and two fixed parameters. These parameters concern the environment surrounding the receivers and in this paper they are assumed without uncertainties. The measured input data, along with their PDF and available measurement uncertainties, are reported in Table 9.2.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>PDF</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$ [r.p.m.], blades rotational speed</td>
<td>rectangular</td>
<td>Half width=0.5</td>
</tr>
<tr>
<td>$\theta_w$ [deg], wind direction from North</td>
<td>Gaussian</td>
<td>$\sigma=3$</td>
</tr>
<tr>
<td>$\theta_r$ [deg], directions turbine-receiver from North</td>
<td>rectangular</td>
<td>Half width=1</td>
</tr>
<tr>
<td>$r_r$ [m], distances turbine-receiver</td>
<td>rectangular</td>
<td>Half width= $r_r*0.03$</td>
</tr>
</tbody>
</table>

The $N_{eq}$ uncertainty has been estimated for each 10 min data using the sigma of the Gaussian PDF that fits the obtained MCM numerical distribution. In Figure 9.3 two examples are reported for a single $N_{eq}$. The uncertainties for each $N_{eq}$ in each test site have been reported on a graph in Figure 9.4.
The uncertainties on the singles $N_{eq}$ result less than 0.4 rpm for every test site and every $N_{eq}$ value. This value is assumed as the $N_{eq}$ uncertainty ($u_{Neq}$) and it results comparable with the uncertainty on the input measured rotational speed $N$.

$$u_{Neq} = 0.4 \text{ [rpm]}$$
9.2.3 Coverage interval of the procedure

In this section the uncertainties of the outputs in the procedure are analysed by using the MCM over the iterative phase. As already reported, the input variables are the following 10 min parameters: \( L_{Aeq, 10\text{ min}} \), \( v_{gr} \) and \( N_{eq} \). The inputs of the model are 3 times the number of 10 min data. As an example, Scapiccioli test site has 1725 data, so 1725\( \times 3 \) inputs. Each input varies according to the distributions in Table 9.3.

Table 9.3. Input data with probability density function for the calculation of the uncertainties of the procedure.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PDF</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{Aeq,10\text{ min}} )[dB(A)]</td>
<td>Gaussian</td>
<td>( \sigma = 1.3 )</td>
</tr>
<tr>
<td>( v_{gr} )[m/s]</td>
<td>rectangular</td>
<td>Half width=0.4</td>
</tr>
<tr>
<td>( N_{eq,1hr} )[rpm]</td>
<td>Gaussian</td>
<td>( \sigma = 0.4 )</td>
</tr>
</tbody>
</table>

\( L_{Aeq, 10\text{ min}} \) uncertainty has been evaluated as the root mean square of the type B uncertainties:

- \( u_{str} = 0.5 \text{ dB(A)}, \) instrumental uncertainty;
- \( u_{cond} = 0.2 \text{ dB(A)}, \) measurement conditions uncertainty;
- \( u_{meteo} = 1.2 \text{ dB(A)}, \) meteorological conditions uncertainty.

These values have been evaluated following prescriptions of GUM (ISO ENV 13005:1999, 1999), ISO 1996-2:2007 (ISO 1996-2:2007, 2007), UNI/TR 11326 (UNI/TR 11326:2009, 2009). Uncertainty associated to \( v_{gr} \) is the measurement one, while the \( N_{eq} \) uncertainty was previously calculated. Table 9.4 reports the day average noise immission and residual calculated with Monte Carlo procedure and their respective coverage interval (CI).

Table 9.4. Immission and Residual over the whole measurement period and their coverage interval (CI).

<table>
<thead>
<tr>
<th>Test site</th>
<th>Emission [dB(A)]</th>
<th>CI (95%) [dB(A)]</th>
<th>Residual [dB(A)]</th>
<th>CI (95%) [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapiccioli</td>
<td>40.3</td>
<td>2.2</td>
<td>38.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Scansano</td>
<td>45.7</td>
<td>2.4</td>
<td>43.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Lucera</td>
<td>43.4</td>
<td>2.6</td>
<td>40.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Riparbella</td>
<td>41.6</td>
<td>2.0</td>
<td>40.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Santa Luce</td>
<td>38.4</td>
<td>1.2</td>
<td>33.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Provincia</td>
<td>36.5</td>
<td>2.0</td>
<td>35.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>
In Figure 9.5 the output G distributions obtained by MCM are plotted. All the G distributions failed most popular normality tests (Chi Squared, Lilliefors, Anderson-Darling, Cramér-Von Mises...). For symmetric Gs coverage intervals have been evaluated by using quantile values from resulting distributions. A 95% coverage interval has been chosen selecting endpoints at $q_{2.5\%}$, $q_{97.5\%}$ quantiles.

$$CI (95\%) = (q_{97.5\%} - q_{2.5\%})$$

For asymmetric distributions, e.g. Scapiccioli and Scansano, coverage interval endpoints have been evaluated by taking the 95% CI with minimum width according to paragraph 5.3.4 of GUM (JCGM 101:2008, 2008).

The evaluated CIs show some differences from site to site (except the very sharp one at Santa Luce), of about 1.2 dB(A), suggesting a not very strong dependence on measurement conditions and on testing sites.
9.2.4 Uncertainties on immission vs $N_{eq}$ and on residual vs $v_{gr}$

An intermediate step of the Italian procedure allows the evaluation of the immission noise levels as a function of $N_{eq}$, and the residual noise as a function of wind speed at ground. The uncertainties of this part have been evaluated as in the previous section for every $N_{eq}$ value. Figure 9.6 represents the immission vs $N_{eq}$ and the residual vs $v_{gr}$ of all the test sites. Figure 9.7 shows how uncertainties depend on $N_{eq}$ with minimum values for central $N_{eq}$ range, and higher values at extreme $N_{eq}$ values, for nearly all the testing sites. Figure 9.8 represents the uncertainties of noise vs $v_{gr}$.
Figure 9.6. Immission vs $N_{eq}$ and the residual vs $v_{gr}$ of all the test sites.

Figure 9.7. Uncertainty on immission vs $N_{eq}$ for all the test sites.
9.3 Discussion

The new procedure for evaluating the noise immission from operational wind turbines provides a useful approach to technicians and competent bodies in order to monitor the noise impact on receivers without stopping the farm.

The 95% coverage interval obtained with the Monte Carlo simulations varies from 1.2 to 2.6 dB(A) for noise immission levels and from 1.2 to 1.8 dB(A) for residual levels evaluated over the whole measurement period. These results are suitable for the assessing compliance to normative prescriptions at least in Italy. Higher values have been demonstrated at low wind speeds, where noise data have a bigger spread due to meteorological effects on measurements.

The uncertainties obtained in this Chapter have been evaluated applying the MCM to data from six measurements, thus they have not to be considered as valid in all the scenarios. However, the uncertainties obtained in each measurement are very similar one another. A
better estimate of the procedure’s uncertainties can be acquired by repeating the MCM for every new measurement in order to obtain specific uncertainties for each measurement. The results of this analysis do not include possible difference between obtained value from the expected value (bias) due to the procedure itself, but it only correspond to the propagation of the type A and B input uncertainties. In Chapter 10 the bias will be evaluated during the validation phase, thus the present results will be composed with the bias.
10. Validation of the procedure

10.1 Introduction

The new data analysis procedure presented in this thesis extrapolates the immission and residual components of noise from the environmental levels measured at the receiver during a measurement campaign lasting at least 2 weeks, even if 3 are preferred. The aim of not requiring the farm shutdown for the estimation of the residual level is reached through the following basic ideas:

- the residual noise is correlated to the wind speed measured at ground near the receiver \(v_{gr}\);
- the immission levels are correlated to a new parameter, the equivalent blades rotational speed \(N_{eq}\) representing the rotational speed of a virtual turbine producing the overall wind farm immission. The \(N_{eq}\) is calculated as an average of the single turbines rotor speeds weighted according to the different propagation paths and conditions.
- the use of a long term measurement campaign allows to select the 10 min intervals when the immission levels are negligible respect to the background noise. By calculating the activation threshold, an initial rough estimate of the residual noise can be evaluated.

A numerical evaluation of the uncertainty of the outputs has been presented in the previous Chapter, however the validation on virtual and real scenarios and a sensitivity analysis of the input parameters are mandatory steps in order to evaluate the effectiveness of the procedure for wind turbine noise assessment. The sensitivity analysis is presented in Chapter 11, whilst the present Chapter deals with the validation.

The validation is even more a complex task, because of the need of comparing the outputs with other values assumed as true. The immission levels can be simulated with noise software, with their due uncertainties, but the residual noise evaluation is the major problem, it being related to the exact time and place of evaluation. The best way to validate the procedure would be to check the residual noise from the procedure with a specific measurement campaign with the wind farm shutdown. However, this conflicts with the
economic and technical problem of stopping the farm for long period in order to allow the characterization of all meteorological and vegetation conditions. In a similar way, a valid alternative would be obtained using a wind farm under construction, where the residual can be measured before the installation. Also in this case, there would be the problem of finding two periods with exact meteorological and vegetation condition to be compared, especially among different seasons or years. Moreover, new farms are becoming very rare in Italy and to date no plant managers allowed the required shutdown.

Indeed, the most common methods in literature for residual measurement in the WTN assessment have spatial or temporal flaws, related to measurements in different sites or periods, that lead to not sufficiently reliable results (Duncan et al., 2015).

1. In the “proxy method” the spatial coherence between the residual estimated at the proxy position and the actual residual at the receiver is not guaranteed.
2. In the “ante-operam residual assessment” temporal flaws are the primary disadvantages.
3. In the “shielding method”, the total exclusion of the noise source is not guaranteed, especially for low frequencies. Also spatial flaws could occur.
4. The “turbines shutdown method” has a big economic impact and may also present temporal flaws.

The Proxy Method involves the use of a “proxy” background sound level monitoring location, located far enough away from the receiver site that turbine noise is negligible. The sound environment should be similar to monitoring location(s) near the turbines (without turbines operational). This requires matching locations for flora, fauna, meteorological conditions, nearby roadways with similar traffic, residential noise sources, and commercial/industrial noise sources (Hessler, 2011).

Limitations of the proxy method are mostly due to difficulties in finding suitable proxy locations, especially in a mountainous region, where meteorological conditions, land use, vegetation and roads change rapidly. To determine appropriate proxy locations, measurements need to be performed in advance of project operations, thus becoming the ante-operam residual assessment. Unfortunately, the ante-operam method is very difficult to be available for already existing wind farm. When available, it is an expensive and time consuming process since, to get a fair sample size, each test monitoring session lasts for two weeks. In any case, being performed in a different period, problem related to different
vegetation or meteorological conditions can occur.

The shielding method involves the use of two microphones, one is exposed to the wind power facility (open monitor), the other is placed behind a shielding mechanism to block sound from the source (shielded monitor). The basic principle of the shielding method is that the open monitor is collecting sound level data that is representative of the wind farm with background sound while the shielded monitor is only collecting sound level data that is representative of background sound. The method presents several clear theoretical flaws: the difficulty of founding an efficient shielding structure and a spatial disadvantage. Indeed, assuming that the background sound levels measured this way are representative of the background sound levels at the open monitor results to be a strong assumption because the shield may also block sound from other sources of background noise that the open monitor may be exposed to. This would result in an overestimation of sound levels attributable to a wind farm. In addition, depending on the location of the source of background sound, it may be possible for the background levels to be amplified by reflections off the shielding mechanism, which would not be an accurate representation of the background sound levels at the open monitor and results in an underestimation of sound levels attributable to a wind farm. Also the shielding mechanism itself may create noise with either wind blowing over the surface or breakout noise from sources located indoors if the shield is a building.

The shutdown method is one of the most common methods used to assess background sound levels at an operating wind farm. Wind turbines are shut down to measure background sound levels for a period of time. Depending on the location of the compliance monitor and the wind turbines, some or all of the turbines need to be shut down.

Thus, the most important negative factors with this method are the operational and financial burden it poses on the wind power operator and the potential problems of fluctuating the power supply to the grid at peak power output. Thus, the shutdown method does not allow for continuous compliance monitoring, allowing the background measurement only for discrete time evaluation. This led to another downside of this method related to the possibility that background sound levels change between the operational periods and the shutdown periods.
For these reasons, the validation will be performed in three alternative ways:

1. A comparison of the immission levels of the procedure with the noise prediction models.

2. A method based on the implementation of a computational model for simulated scenarios. An hypothetical set of measured noise level, corresponding to the procedure’s measurement period, is simulated summing a theoretical residual noise function of \( v_{gr} \) to a theoretical immission noise as a function of \( N_{eq} \) and to a random noise. When applied to this set of data, the procedure should return the two inputs theoretical function.

3. A check of the difference between the measured 10 min environmental noise level and the environment levels on 10 min from the procedure.

A better understanding of the influence of different background noise base level and wind turbine immission on the procedure results is earned.

### 10.2 Immission levels validation

The procedure has been applied to the measurement campaigns reported in Appendix and in Table 7.1. For all the farms, the maximum immission noise level for both daytime and night-time (\( L_{I,max,procedure} \)), corresponding to the maximum \( N_{eq} \), was compared to the immission noise level predicted by the NORD2000 noise model (\( L_{I,max,predicted} \)) for the maximum sound production conditions (wind speed 10 m/s). The results are reported in Table 10.1, together with the uncertainties. The uncertainties on the procedure’s immission are those reported in Chapter 9, rounded to the first integer, whilst for the noise model they are estimated with a coverage factor 1 (68% L.C.).
Table 10.1. Comparison between the procedure’s maximum immission noise level for daytime and night-time and the immission noise levels predicted by the NORD2000 noise model in the seven measurement sites.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Receiver alias</th>
<th>$L_{I,max,procedure,day}$ [dB(A)]</th>
<th>$L_{I,max,procedure,night}$ [dB(A)]</th>
<th>$L_{I,max,predicted}$ [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poggi alti</td>
<td>Poggi alti Scansano</td>
<td>51±3</td>
<td>53±3</td>
<td>53±3</td>
</tr>
<tr>
<td>La Miniera</td>
<td>Scapiccioli</td>
<td>43±3</td>
<td>44±3</td>
<td>41±3</td>
</tr>
<tr>
<td>La Miniera</td>
<td>Provinca</td>
<td>40±3</td>
<td>36±3</td>
<td>37±3</td>
</tr>
<tr>
<td>La Miniera</td>
<td>Palareta</td>
<td>47±3</td>
<td>45±3</td>
<td>42±3</td>
</tr>
<tr>
<td>La Miniera</td>
<td>Palareta 2</td>
<td>47±3</td>
<td>47±3</td>
<td>46±3</td>
</tr>
<tr>
<td>Poggio Palmorelle</td>
<td>Santa Luce 1</td>
<td>44±3</td>
<td>43±3</td>
<td>44±3</td>
</tr>
<tr>
<td>Poggio Palmorelle</td>
<td>Santa Luce 2</td>
<td>The measurements are recent and the analysis are still in progress.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poggio Malconsiglio</td>
<td>Riparbella</td>
<td>45±3</td>
<td>45±3</td>
<td>45±3</td>
</tr>
<tr>
<td>Lucera</td>
<td>Borgo San Giusto</td>
<td>50±3</td>
<td>48±3</td>
<td>47±3</td>
</tr>
</tbody>
</table>

For all the wind farms, the immission noise levels were comparable with the predicted ones within the uncertainties.

10.3 Numerical validation

The overall procedure can be divided in a data acquisition and a data analysis phase.

1. Data acquisition: data are acquired for at least 2000 measurement 10 min time intervals, considering only valid data:
   - $L_{A_{eq,10min}}$ (in this Chapter named $L_{E,10min}$): measured outdoor broadband equivalent noise levels;
   - $v_{gr}$: average wind speed measured at the receiver, 3 m above ground;
   - $N$: the average blades rotational speed for each turbine;
   - $w_{dir}$: average wind direction measured at each turbine hub;
   - precipitation periods (rain, snow, hail).
2. DAP (Data Analysis Procedure): data are cleaned by removing spurious events, anthropic or animal noises, precipitation periods, and windy periods \( (v_{gr} > 5\text{m/s}) \) in order to reduce the wind induced noise on the microphone. The data are successively analysed separately for daytime and night-time, because of the different atmospheric conditions and for compliance purposes. The DAP can be separated in:

a. \( N_{eq} \) calculation: for each 10 min data, the wind farm immission is described by the \( N_{eq} \);

b. STAF (Single Turbine Analysis Filtering): the \( L_{E,10\text{min}} \) are filtered to estimate the immission and residual curves as functions of \( N_{eq} \) and \( v_{gr} \).

The preliminary uncertainty analysis of the DAP through a Monte Carlo Method is the one presented in Chapter 9. The resulting 95% coverage intervals range from 1.2 to 2.6 dB(A) for the immission levels and from 1.2 to 1.8 dB(A) for the residual levels. These uncertainties correspond to the propagation of the type A and B input uncertainties. In order to estimate the systematic errors of the DAP a complete validation analysis is necessary. An experimental way consists in comparing the immission and residual curves calculated by the DAP with the curves obtained by an alternative measurement method. The immission or residual curves are measurable with the methods previously described, but the related issues do not always allow reliable results.

In order to overcome the described experimental difficulties, a validation based on numerical simulations is feasible. In this approach the DAP is applied to simulated input data sets, obtained from known theoretical immission and residual curves. In this way a comparison between the experimental curves calculated by the DAP and the \( a\ priori \) theoretical curves is possible. The application of a numerical validation method to the STAF of the Italian procedure for WTN assessment, in order to verify the filtering method and estimate the systematic errors, is here presented. The STAF can also be used as a standalone data analysis procedure in the case of single turbine measurements, using the rotor speed \( N \) instead of the \( N_{eq} \) parameter, or in the case of receiver-turbine distances compatibles with a single turbine approximation. The numerical validation method will be successively extended to the overall DAP phase, simulating the interaction between various turbines.
10.3.1 Numerical validation methodology

The numerical validation method is summarized in the flowchart reported in Figure 10.1. The first part of the numerical validation consists in simulating the immission \((L_{I,10min})\) and residual noise time histories \((L_{R,10min})\), which energetically summed up yield the simulated environmental time histories \(L_{E,10min}\). The noise simulation is based on a semi-empirical approach, in which the noise levels are simulated by using the models in Equations 10.1 applied to real measured time histories of \(N, w_{dir}, v_{gr}\). The experimental curves are then calculated by applying the STAF to the simulated noise levels. The comparing of the experimental curves to the theoretical curves allows to calculate the uncertainty indicators, RMSE and bias, as described in the following.

\[ \text{Figure 10.1. Flow chart of the numerical validation methodology.} \]

The noise models in Equations 10.1, not used for prediction purposes, attempts to simulate in a simple but realistic way the possible distribution of levels measured in an hypothetical measurement campaign. This aim is achieved, besides the models equations, by:

- using as input data for the models the single turbine measured data \(N, v_{gr}, w_{dir}\) coming from a WTN database collected in the 7 measurement campaigns performed between 2011-2015 along Italy;
- including in the models random dispersions \(\varepsilon\), which are normally distributed with zero mean and standard deviation \(\sigma\), calculated by a pseudo-random number generator.

The use of real data, especially the measured correlation between \(N\) and \(v_{gr}\), also allows to not simulate the wind shear, whose analytic equations are not reliable especially in hilly areas. Figure 10.2 shows the real data of a single turbine used as test-case in the numerical validation. The upwind, downwind and crosswind conditions have been determined dividing the wind directions in quadrants.
Figure 10.2. Daytime 10 min data of a single turbine from a measurement campaign.

\[ L_1(N, w_{dir}, \text{par}_E) = L_0 + 10\log(N^{\text{pow}}) - 10\log(4\pi r^2) - \alpha r + A_{\text{wind}}(r) \cos w_{dir} + \epsilon_1(\text{par}_E) \]

\[ L_{R, \text{lin}}(v_{\text{ground}}, \text{par}_R) = R_0 + R_{\text{lin}}v_{\text{ground}} + \epsilon_1(\text{par}_R) \]

\[ L_{R, \log}(v_{\text{ground}}, \text{par}_R) = R_0 + R_{\log} \log(1 + v_{\text{ground}}) + \epsilon_1(\text{par}_R) \]

(10.1)

The immission model in Equation 10.1 is based on the ISO 9613-2 propagation model, with the attenuation terms accounting for geometrical spreading, combined atmospheric/ground absorption and a wind direction correction. The turbine sound power level is modelled as \( L_w(N) = L_0 + 10\log(N^{\text{pow}}) \), as in (Van den Berg, 2004) and determines the immission dependence on \( N \). The parameter \( \text{pow} \) can be determined by fitting the experimental results as in (Van den Berg, 2004), in which \( \text{pow} \) resulted equal to 6.7, or by theoretical assumptions. In the second approach, the trailing edge noise can be considered the dominant noise production mechanism obtaining \( \text{pow} = 5 \) (Oerlemans et al., 2009). \( L_0 \) is calculated with the condition \( L_w(N_{\text{max}}) = L_0 + 10\log(N_{\text{max}}^{\text{pow}}) = 105\text{dB}(A) \). The combined atmospheric/ground absorption term is modelled with a linear dependence on distance as in the simplified model in (NZS 6808:1998, 1998). The wind correction depends on the wind direction \( w_{dir} \) and has an amplitude depending on distance: the \( A_{\text{wind}}(r) \) is calculated by using the CONCAWE meteorological curve for category 6 at 1 Khz (Manning, 1981).

The residual models in Equation 10.1 have been chosen according to the vegetation noise wind speed dependence analysis in (Bolin, 2009b). The standard deviations used for the dispersions terms are typical values observed in measured data. Furthermore, subsequently to the noise simulation, another normal distributed dispersion with \( \sigma_N \) has been added to the \( N \) values. \( \text{par}_E \) and \( \text{par}_R \) indicate the model's parameters, which can be changed to obtain different simulated data sets. The simulated noise levels represented in Figure 10.3 have been calculated by applying the noise models with the parameters reported in Table 10.2 on the
real data shown in Figure 10.2. These simulated noise levels are successively used as test case to illustrate the STAF procedure.

![Figure 10.3. Simulated noise levels for the test-case.](image)

**Table 10.2. Simulation parameters used in the test-case.**

<table>
<thead>
<tr>
<th>r [m]</th>
<th>pow</th>
<th>α [dB(A)/km]</th>
<th>σE [dB(A)]</th>
<th>σN [rpm]</th>
<th>R0 [dB(A)]</th>
<th>Rlin [dB(A)/(m/s)]</th>
<th>σR [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>623</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>25</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

### 10.3.2 The Single Turbine Analysis Filtering

In this section the Single Turbine Analysis Filtering (STAF) is summarized and applied to the test-case, using as inputs the real data N, vgr, and the simulated environmental levels L_E,10min, represented in Figures 10.2 and 10.3. In this way the experimental immission and residual curves L_{STAF,I}(N) and L_{STAF,R}(v_{gr}) are extrapolated.

#### 1. Activation threshold

The environmental levels L_{E,10min} are grouped by the N values rounded to the nearest integer. For each group of n_N levels the energetic average L_{N}, and successively the cumulative energetic average L_{cum,N}, are computed using Equation 10.4. The turbine emission increases with N, increasing the difference Δ_N = L_{N} - L_{cum,N}. The activation threshold N_{th} is taken as the first value of N for which Δ_N > 2 dB(A) for at least two consecutive N, with a minimum value of 3rpm. N_{th} indicates the rotor speed at which the immission levels become significantly
above the residual. In Figure 10.4 the activation calculation is applied to the test-case.

\[
L_N = 10 \log \left( \frac{1}{N} \sum_{i=1}^{n_N} 10^ {L_{E,10min}^{(i)}} \right) \\
L_{\text{cum},N} = 10 \log \left( \frac{1}{N+1} \sum_{N_i=0}^{n} 10^{0.1L_{N_i}} \right)
\]

(10.4)

Figure 10.4. Activation threshold calculation for the test-case.

2. Data binning

The environmental levels \(L_{E,10\text{min}}\) are grouped in classes according to the variables \(N\), \(v_{gr}\) rounded to the nearest integer. The classes with \(N < N_{Th}\) are gathered together. The energetic average levels \(L_{N,v_{gr}}\) and the number of occurrences \(occ_{N,v_{gr}}\) are computed for each class and reported in the environmental matrix \(M_{E}\) and occurrences matrix \(M_{\text{occ}}\), represented in Table 10.3. The classes for which \(occ(N,v_{gr}) < 2\) are left empty by the STAF.

Table 10.3. Environmental matrix \(M_{E}[\text{dB(A)}]\) and occurrence matrix \(M_{\text{occ}}\) for the test-case.

<table>
<thead>
<tr>
<th>(v_{gr}) = 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>(\text{occ}(N))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N &lt; 11)</td>
<td>28.0</td>
<td>33.0</td>
<td>36.0</td>
<td>39.0</td>
<td>49.0</td>
<td>52.0</td>
</tr>
<tr>
<td>(N = 11)</td>
<td>33.0</td>
<td>34.0</td>
<td>39.0</td>
<td>41.0</td>
<td>42.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>31.0</td>
<td>36.0</td>
<td>40.0</td>
<td>40.0</td>
<td>-</td>
<td>37.2</td>
</tr>
<tr>
<td>13</td>
<td>32.0</td>
<td>35.0</td>
<td>40.0</td>
<td>42.0</td>
<td>-</td>
<td>39.5</td>
</tr>
<tr>
<td>14</td>
<td>32.0</td>
<td>36.0</td>
<td>42.0</td>
<td>42.0</td>
<td>47.0</td>
<td>40.6</td>
</tr>
<tr>
<td>([\text{rpm}]) 15</td>
<td>32.0</td>
<td>35.0</td>
<td>38.0</td>
<td>45.0</td>
<td>45.0</td>
<td>39.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(L(v_{gr}))</th>
<th>28.7</th>
<th>33.9</th>
<th>39.2</th>
<th>42.8</th>
<th>46.4</th>
<th>52.0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(v_{gr}) = 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>(\text{occ}(N))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N &lt; 11)</td>
<td>803</td>
<td>195</td>
<td>39</td>
<td>2</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>(N = 11)</td>
<td>22</td>
<td>13</td>
<td>14</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>17</td>
<td>35</td>
<td>8</td>
<td>-</td>
<td>85</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td>9</td>
<td>30</td>
<td>18</td>
<td>-</td>
<td>72</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>17</td>
<td>20</td>
<td>23</td>
<td>2</td>
<td>75</td>
</tr>
<tr>
<td>([\text{rpm}]) 15</td>
<td>26</td>
<td>53</td>
<td>47</td>
<td>21</td>
<td>6</td>
<td>153</td>
</tr>
</tbody>
</table>

\(occ(v_{gr})\) = 904 304 185 77 15 15 1300
3. Initial residual estimate
The former residual curve $L_{R}(v_{gr})$ is estimated considering the environmental levels below $N_{th}$, and, coherently with the definition of $N_{th}$, it is the first row of $M_{E}$.

4. Immission matrix calculation
The immission matrix $M_{I}$ is obtained by energetically subtracting the estimated residual curve $L_{R}(v_{gr})$ from each row of $M_{E}$, for corresponding $v_{gr}$ values.

5. Immission curve estimate
Assuming that the turbine emission only depends on $N$ and not on $v_{gr}$, the immission curve $L_{I}(N)$ is obtained from $M_{I}$ by calculating the energetic average for each row, at a fixed $N$, weighted with the corresponding occurrences in the occurrences matrix.

6. Residual matrix calculation
The residual matrix $M_{R}$ is obtained by energetically subtracting the estimated emission curve $L_{E}(N)$ from each column of $M_{E}$, for corresponding $N$ values. The first row of $M_{R}$ is the initial residual estimate, which is the first row of $M_{E}$.

7. Residual curve estimate
The residual curve $L_{R}(v_{gr})$ is obtained from the $M_{R}$ calculating the energetic average for each column, at fixed $v_{gr}$, weighted with the occurrences in $M_{occ}$.

8. Negative differences criterion.
The energetic differences calculated to obtain the $M_{I}$ or $M_{R}$ may assume negative values. For example, the estimated residual, which is an average value, could be greater than the corresponding environmental level. In these cases the STAF substitutes the value reported in the immission or residual matrix with $L_{E}(N,v_{gr})-10$ dB(A).

9. Levels rounding
The initial time histories are rounded to the nearest integer for $N$ and $v_{gr}$, while to 0.5 dB(A) for $L_{E_{10min}}$. The environmental matrix levels are rounded to the nearest integer, such as the immission and residual curves. The $M_{I}$ and $M_{R}$ levels are rounded to 0.1 dB(A).

10. Iterative phase
Steps 4 to 8 are repeated until the convergence of immission and residual curves. The convergence happens when the curves of two successive iterations are equals. The final $M_{I}$ and $M_{R}$ calculated for the test-case are reported in Table 10.5, whilst the first iteration is in Table 10.4. In the last rows the final immission curve $L_{I}(N)$, and the final residual curve $L_{R}(v_{gr})$ are reported.
### Table 10.4. 1st iteration for immission $M_{i}$ and residual matrix $M_{r}$ for the test-case [dB(A)].

<table>
<thead>
<tr>
<th>$v_{ge}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>$L_i(N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N &lt; 11$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$N = 11$</td>
<td>31.3</td>
<td>27.1</td>
<td>36.0</td>
<td>36.7</td>
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<td>33.0</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>28.0</td>
<td>33.0</td>
<td>37.8</td>
<td>33.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>29.8</td>
<td>30.7</td>
<td>37.8</td>
<td>39.0</td>
<td>-</td>
<td>-</td>
<td>37.0</td>
</tr>
<tr>
<td>14</td>
<td>29.8</td>
<td>33.0</td>
<td>40.7</td>
<td>39.0</td>
<td>37.0</td>
<td>-</td>
<td>38.0</td>
</tr>
<tr>
<td>$[rpm] 15$</td>
<td>29.8</td>
<td>30.7</td>
<td>33.7</td>
<td>43.7</td>
<td>35.0</td>
<td>-</td>
<td>37.0</td>
</tr>
</tbody>
</table>

### Table 10.5. Final iteration for immission $M_{i}$ and residual matrix $M_{r}$ for the test-case [dB(A)].

<table>
<thead>
<tr>
<th>$v_{ge}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>$L_i(N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N &lt; 11$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$N = 11$</td>
<td>31.3</td>
<td>27.1</td>
<td>32.1</td>
<td>31.0</td>
<td>32.0</td>
<td>31.0</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>28.0</td>
<td>33.0</td>
<td>35.7</td>
<td>30.0</td>
<td>-</td>
<td>-</td>
<td>33.0</td>
</tr>
<tr>
<td>13</td>
<td>29.8</td>
<td>30.7</td>
<td>35.7</td>
<td>32.0</td>
<td>-</td>
<td>-</td>
<td>34.0</td>
</tr>
<tr>
<td>14</td>
<td>29.8</td>
<td>33.0</td>
<td>39.8</td>
<td>32.0</td>
<td>40.1</td>
<td>-</td>
<td>36.0</td>
</tr>
<tr>
<td>$[rpm] 15$</td>
<td>29.8</td>
<td>30.7</td>
<td>28.0</td>
<td>42.0</td>
<td>35.0</td>
<td>-</td>
<td>35.0</td>
</tr>
</tbody>
</table>

**Table 10.4. 1st iteration for immission $M_{i}$ and residual matrix $M_{r}$ for the test-case [dB(A)].**

<table>
<thead>
<tr>
<th>$v_{ge}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>$L_i(N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N &lt; 11$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$N = 11$</td>
<td>31.3</td>
<td>27.1</td>
<td>36.0</td>
<td>36.7</td>
<td>32.0</td>
<td>33.0</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>28.0</td>
<td>33.0</td>
<td>37.8</td>
<td>33.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>29.8</td>
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<td>-</td>
<td>-</td>
<td>37.0</td>
</tr>
<tr>
<td>14</td>
<td>29.8</td>
<td>33.0</td>
<td>40.7</td>
<td>39.0</td>
<td>37.0</td>
<td>-</td>
<td>38.0</td>
</tr>
<tr>
<td>$[rpm] 15$</td>
<td>29.8</td>
<td>30.7</td>
<td>33.7</td>
<td>43.7</td>
<td>35.0</td>
<td>-</td>
<td>37.0</td>
</tr>
</tbody>
</table>

**Table 10.5. Final iteration for immission $M_{i}$ and residual matrix $M_{r}$ for the test-case [dB(A)].**

### 11. Immission OLS regression

In order to compensate the immission fluctuations, an ordinary least square regression is performed using a logarithmic model $L_{STAF,I}(N) = A + B \log(N)$. The criterion for the fit acceptability is $R^2 > 0.7$, otherwise a maximum third degree polynomial fit is performed. If in all cases $R^2 < 0.7$ the fluctuations are considered too large, and new measurements are necessary.

### 12. Overall weighted levels

The overall immission and residual noise levels, which are used especially for compliance purposes, are calculated with Equations 10.5, considering energetic weighted average of the STAF curves with the corresponding observed marginal occurrences reported in the $M_{occ}$ in Table 10.3:

$$
L_{STAF,I} = \frac{1}{occ_{tot}} \sum_N occ_N 10^{0.1L_{STAF,I}(N)} \\
L_{STAF,R} = \frac{1}{occ_{tot}} \sum_{v_{ground}} occ_{v_{ground}} 10^{0.1L_{STAF,I}(v_{ground})}
$$

### 10.3.3 Validation analysis

The experimental immission and residual curves from the STAF phase are compared with the
Theoretical ones through the uncertainty indicators RMSE and bias, described in Equation 10.6 for the immission curve. The residual one can be obtained substituting IeR and Navg.

The RMSE represents the average uncertainty on the curves levels. The bias applied to the levels in Equations 10.5 is used to examine the overestimation or underestimation of the immission and residual levels obtained from the STAF.

\[
\text{rmse} = \sqrt{\frac{1}{n} \sum_{N} (L_{\text{STAF},I}(N) - L_{\text{theo},I}(N))^2} \quad \text{bias} = L_{\text{STAF},I} - L_{\text{theo},I} \tag{10.6}
\]

The theoretical curves \(L_{\text{theo},i}(N), L_{\text{theo},r}(v_{gr})\) are calculated by grouping the simulated immission and residual levels \(L_{1,10\text{min}}, L_{R,10\text{min}}\) by rounding to the nearest integer \(N\) and \(v_{gr}\) and calculating the energetic average for each group. The overall weighted theoretical levels are calculated equivalently with Equations 10.5. The theoretical and experimental curves, for the test-case presented in Figures 10.2 and 10.3, are reported in Figure 10.5 together with the resulting uncertainty indicators. The overall validation has been repeated for about \(R = 4000\) runs varying the residual according to Equations 10.2 and 10.3 and changing the parameters \(p_{R} = R_{0}\) in a range \([20, 40]\) dB(A), \(R_{\text{lin}}\) in \([0, 6]\) dB(A), \(\frac{\delta}{m}\), \(R_{\log}\) in \([0, 50]\) dB(A). The real data and the immission parameters have been fixed. The resulting indicators obtained for each simulated data set are reported in Figure 10.6 and are plotted as a function of the signal to noise ratio (SNR). The SNR is calculated as the difference between the overall theoretical immission level and the overall theoretical residual level over the activation threshold as reported in Figure 10.7. In a range of \(\pm 3\) dB(A) of SNR, the obtained immission bias values range between \(\pm 2\) dB(A). The negative sign indicates that the STAF underestimates the actual theoretical immission. The immission RMSE results are included in a range interval between 0 - 2 dB(A). Looking at a wider range of SNR, \(\pm 6\) dB(A), the immission bias and RMSE can reach peaks of 6 dB(A). The STAF residual resulted to be an overestimation of the real residual, being the bias always positive. Anyway, for SNR in a range of \(\pm 3\) dB(A) no significant difference appears, whilst in a \(\pm 6\) dB(A) a \(\pm 2\) dB(A) in bias resulted for residual. Nearly the same is for the residual RMSE. For a wider range of SNR both the bias and RMSE increase in a linear way, but those value of SNR are not important for practical use.
Figure 10.5. Theoretical and experimental curves plotted over the simulated immission and residual levels.

Figure 10.6. Uncertainty indicators calculated for 3 test wind farm for the validation. Each point is a run of the STAF.
10.3.4 Multi-turbine analysis

In the previous paragraph the validation has been applied to STAF, thus limited to a single turbine case. The validation of the whole procedure has to consider the general case of a wind farm including more than one turbine. The same approach used for the validation of the STAF can also be used in this case, adding that the immission will be now generated by more than one turbine. On the contrary, the residual noise remains generated by the same relation with the wind speed at ground reported in Equations 10.1. In case of a generic number n of turbines, the immission level is given by:

\[ L_I = \sum_i^n 10^{L_{IJ}/10} \]

Considering a case with n=6 and applying Equations 10.1 to a set of real data, the obtained single immissions and the total immission are reported in Figure 10.8. The results of the validation are reported in Figure 10.9. Limiting to a SNR range of [-3; 3] dB(A), the immission Bias in included in (1; -2) dB(A) and the residual in (2; -1). For a wider SNR range [-6; 6], the immission Bias in included in (2; -3) dB(A) and the residual in (-1; 3). As expected, not much is the difference with the STAF case and a slight underestimation of the immission levels and overestimation of the residual levels are confirmed. Further analysis including a wider range of data will be performed.
Figure 10.8. Blades rotational speed and $N_{eq}$ trend and the simulated immission levels.

Figure 10.9. Uncertainty indicators calculated for 3 test wind farm for the validation. Each point is a run of the multi-turbine procedure.
10.4 Environmental noise levels validation

An indirect validation method consists in comparing the measured environmental noise levels ($L_{Aeq,10min}$) with those calculated by the procedure, which is the energetical sum of the immission and residual noise resulting from the procedure. For each interval of 10 min it is then sufficient to apply the output curves function of $N_{eq}$ and $v_{gr}$ to each interval of 10 min in order to have the constructed $L_{Aeq,10min}$.

The time histories of measured and calculated environmental noise levels are compared for each of the measurement campaigns, an example is reported in Figure 10.10. The largest deviations occur when noise levels are very low or when the residual, which is subject to the greater fluctuations, is predominant.

![Environmental noise levels time histories for Scapiccioli](image)

*Figure 10.10. Time histories of measured and calculated (processed) environmental noise levels for "La miniera - Scapiccioli".*

In order to deepen the validation, the correlation coefficient and the mean square error RMSE were calculated.
The correlation coefficients resulted quite high for all of measurement campaigns in Table 10.6. The largest RMSE are for measurement campaigns where the greatest problems in the application of the procedure have been highlighted, in particular the recent Palareta 2. Figure 10.11 shows the differences calculated every 10 min between the measured environmental levels and those calculated for all measurements of campaigns.

To restrict the analysis to the truly useful information for the procedure, the differences were only calculated for the periods in which the activation threshold is exceeded. The resulting distribution is almost symmetrical with average around 1dB, however close to zero. The 90% of the differences lies in a range between -5 and +6 dB(A).

It should be noted that the purpose of the procedure is not to estimate the immission and residual values every 10 min but their average over the measurement period. Therefore, the wide differences shall in part attributable to the strong fluctuations that may occur in the short time intervals of 10 min, which are exactly what the procedure intends to flatten.

Table 10.6. Correlation and RMSE between the difference of measured and calculated environmental noise levels for all the farm.

<table>
<thead>
<tr>
<th></th>
<th>corr</th>
<th>rmse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scapiccioli</td>
<td>0.88</td>
<td>3.71</td>
</tr>
<tr>
<td>Scansano</td>
<td>0.75</td>
<td>3.45</td>
</tr>
<tr>
<td>Lucera</td>
<td>0.85</td>
<td>3.94</td>
</tr>
<tr>
<td>Riparbella</td>
<td>0.78</td>
<td>4.30</td>
</tr>
<tr>
<td>SantaLuce</td>
<td>0.89</td>
<td>3.35</td>
</tr>
<tr>
<td>Provinca</td>
<td>0.83</td>
<td>3.04</td>
</tr>
<tr>
<td>Palareta1</td>
<td>0.89</td>
<td>3.75</td>
</tr>
<tr>
<td>Palareta2</td>
<td>0.85</td>
<td>5.41</td>
</tr>
</tbody>
</table>
10.5 Discussion

The Italian procedure can assess the WTN by means of a Data Analysis Procedure (DAP) applied to data from a single measurement campaign, not requiring the wind farm shutdown and avoiding a big economic impact for the farm manager. The DAP extracts the immission and the residual noise from the overall measured environmental levels using a specific filtering analysis, the Single Turbine Analysis Filtering (STAF).

The immission noise levels validation by comparison with NORD 2000 simulations showed that, for all the wind farms analysed, the immission noise levels were comparable with the predicted ones within the uncertainties.

The environmental noise levels validation confirmed the good results, being all the signal well correlated. Furthermore, the histogram of the difference between measured and calculated environmental noise levels over all the test sites showed an almost symmetrical distribution with average around 1dB, with the 90% of the differences ranging between -5 and +6 dB(A).

In order to verify and validate the procedure, a numerical validation method based on a semi-empirical simulation of immission and residual noise has also been presented. At first,
the uncertainty indicators bias and RMSE relative to the immission and residual curves resulting from the STAF are calculated by comparison with the simulated curves. Then, the same methodology has been used to extend the analysis to a multi-turbine case.

The validation results for the presented test-cases are quite good for the immission estimate, being the bias values included in a range between [-2; 2] dB(A) for a SNR range of [-3; 3] dB(A), and [-3; 2] dB(A) for a SNR range of [-6; 6] dB(A). For the residual estimate the results were also good, being the bias values included in a range between [-1; 2] dB(A) for a SNR range of [-3; 3] dB(A), and [-1; 3] dB(A) for a SNR range of [-6; 6] dB(A).

Generally, a slight underestimation of the immission levels and an overestimation of the residual levels that linearly increases with the SNR, i.e. the difference between the immission and residual levels, are experienced.

Unfortunately, some unexpected case with variation of nearly 6 dB(A) occurred, particularly in the residual noise. These special cases will need further developments of the procedure, as described in Chapter 12. For this reason, some of the parameters/steps of the Italian procedure are currently under investigation.
11. Sensitivity analysis of modelling parameters in the procedure

11.1 Introduction

In the Chapter 9, using Monte Carlo simulations on the procedure, it resulted that the 95% coverage interval of the output of the Italian procedure varies from 1.2 to 2.6 dB(A) for the noise immission levels and from 1.2 to 1.8 dB(A) for the residual levels evaluated over the whole measurement period. These results are acceptable for the assessing compliance to normative prescriptions. The higher values of the coverage interval were at low wind speeds, where noise data have a bigger spread due to meteorological effects on measurements. A key parameter used in the Italian procedure is $N_{eq}$, which is involved in many procedure steps. In this Chapter a sensitivity analysis on $N_{eq}$ and a deeper explanation of some numerical parameters involved are presented, aiming to reduce the procedure uncertainty. This analysis will allow a better understanding of which procedure parameters requires better accuracy and will help reducing the uncertainties of the noise impact prediction.

11.2 The $N_{eq}$ calculation in the Italian procedure

For a better understanding of the sensitivity analysis, the procedure is concisely summarized in the following steps:

1. Data acquisition: acquisition of outdoor noise level and meteorological data;
2. Data cleaning: spurious events and meteorological unwanted events are removed;
3. $N_{eq}$ calculation: for each 10 min data, based on propagation model, as explained in the following;
4. Activation calculation: a $N_{eq}$ threshold, for which values below can be considered as not relevant for noise impact on the receiver;
5. Iterative phase: measured levels are binned by $N_{eq}$ and $v_{gr}$ and an iterative energetic subtraction of measured immission and residual levels is performed, until convergence is obtained;
6. Procedure’s output: an estimation of the noise immission at the receiver as a function
of $N_{eq}$ and the residual noise as a function of $v_{eq}$ is provided. The sensitivity analysis is applied to the calculation of $N_{eq}$, which is computed according the following equations:

$$N_{eq} = \sum_i N_i^5 \left( \frac{d_0}{d_i} \right)^2 K_i^5 C_i$$

$$K_i = 10^{\frac{A_{atm,ground}^{(i)} - A_{atm,ground}^{(0)}}{50} - \alpha(d_i - d_0)}, \quad C_i = 1 + \gamma \cos(W_{dir}^{(i)} - Dir^{(i)}) = 10^{\frac{A_{wind}^{(i)}}{50}}$$

Where $A_{atm,ground}$ is the broadband combined atmospheric/ground attenuation, $A_{wind}$ is the wind direction correction. Zero index refers to the receiver nearest turbine, while the $i$ index considers each turbine of the farm. Alpha and gamma parameters figure in the attenuation terms, as show in the description of the procedure.

### 11.3 Sensitivity Analysis

#### 11.3.1 Introduction to Global Sensitivity Analysis

The sensitivity analysis on $N_{eq}$ has been performed using the variance based methods (Saltelli, et al., 2008; Saltelli, et al., 2010), which are mainly founded on the previous work of the Russian mathematician I.M. Sobol. These methods are defined as Global sensitivity analysis because the whole input space is explored using averages, differently respect to OAT (once at a time) or differential approaches (Saltelli, Annoni, 2010). Given a generic multivariable model $Y = f(x_1, x_2, ..., x_k)$ with $k$ uncertain input factors, the variance $V$ of $Y$ can be fully decomposed into terms depending on the factors and their interactions. As an example, for a 3 factors function $Y = f(x_1, x_2, x_3)$ the output variance is decomposed as:

$$V(Y) = V_1 + V_2 + V_3 + V_{1,2} + V_{1,3} + V_{2,3} + V_{1,2,3}$$

where terms $V_1, V_2, V_3$ are the variance fractions explained by only single inputs, and the other terms are interaction effects. The decomposition is unique only for independent input factors. The Sobol variance decomposition (or ANOVA-HDMR) allows the straightforward definition of the global sensitivity indexes:

- Main Index, or first-order effect $S_i = V_i/V(Y)$, depending only on a single factor;
- Total Index, accounting for all the decomposition terms, interactions included,
containing a single factor. For the above example: \( S_T(1)=S_1+S_{1,2}+S_{1,3}+S_{1,2,3} \)

Various estimators are available for the sensitivity indexes, calculated in a MCM framework (Saltelli, et al., 2010), where “Jansen 1999” estimators are used for both indexes.

The Global sensitivity analysis is performed using specific settings as explained in (Saltelli, et al., 2008):

- **Factor Prioritization (FP)**, is used to identify a factor which, when fixed to its true value, leads to the greatest reduction in the variance of the output. This setting allows the detection and ranking of those factors which need to be better measured or defined, in order to reduce the output variance;
- **Factor Fixing (FF)**, is used to identify factors which, left free to vary over their range of uncertainty, make no significant contribution to the output variance. The identified factors can then be fixed at any given value within their range of variation without affecting the output variance.

The two settings correspond with the sensitivity indexes:

- **FP** - Main indexes: \( S_i \) indicates by how much one could reduced the output variance fixing the factor \( X_i; \)
- **FF** - Total indexes: \( S_{Ti} \approx 0 \) implies that a factor \( X_i \) is non influential and can be fixed at a value in its distribution without affecting the output variance.

The difference between Total and Main indexes accounts for the strength of the interactions in the model. An useful characteristic of these methods is that sensitivity indexes can be calculated for groups of factors. The Main index of a group contains also the interactions between group factors. The sensitivity analysis on the Italian procedure has been performed in R Free Software programming language.

### 11.3.2 Neq Sensitivity

The parameter \( N_{eq} \) is calculated for every 10 min data and it depends on \( 4T_n+2 \) factors, where \( T_n \) is the turbines number of the measurement site. Considering 3 turbines, the input factors are then:

\[
N_0, N_1, N_2, W_{dir,0}, W_{dir,1}, W_{dir,2}, D_0, D_1, D_2, Dir_0, Dir_1, Dir_2, \alpha, \gamma
\]

That can be grouped in the 6 variables:

\[
N, W_{dir}, D, Dir, \alpha, \gamma
\]
classified in 3 main categories:

- measured data: N, \( W_{\text{dir}} \), blades rotational speed and wind directions for each 10 min measurement period, and each turbine
- measurement configuration: D, Dir, turbines-receiver distances and directions
- theoretical parameters: \( \alpha, \gamma \)

\( N_{eq} \) has been calculated for all possible factors combinations of measured data and configurations within the ranges reported in Table 11.1. In order to efficiently explore all the ranges a Sobol sequence of low-discrepancy numbers has been generated (Chalabi, et al., 2015).

Table 11.1. \( N_{eq} \) factors, uncertainties are reported as the half widths of uniform distributions.

<table>
<thead>
<tr>
<th>factor</th>
<th>category</th>
<th>range</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N ) (rpm)</td>
<td>data</td>
<td>0-30</td>
<td>0.5</td>
</tr>
<tr>
<td>( W_{\text{dir}} ) (°)</td>
<td>data</td>
<td>0-360</td>
<td>3</td>
</tr>
<tr>
<td>D (m)</td>
<td>configuration</td>
<td>50-1500</td>
<td>3%</td>
</tr>
<tr>
<td>Dir (°)</td>
<td>configuration</td>
<td>0-360</td>
<td>1</td>
</tr>
<tr>
<td>( \alpha(dB(A)/m) )</td>
<td>theoretical</td>
<td>fixed</td>
<td>0.002</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>theoretical</td>
<td>fixed</td>
<td>0.05</td>
</tr>
</tbody>
</table>

For each combination of the factors the main and the total sensitivity indexes have been estimated, varying the factors uncertainties within the experimental/theoretical uncertainties, reported in the last column of Table 11.1. The analysis has been repeated for various number of turbines. The differences between the main and the total indexes are negligible, within their uncertainties. The total indexes values (equal to main index values) are reported in Table 11.2 and represented in Figure 11.1 and 11.2. The estimated \( N_{eq} \) uncertainties are reported in the last column of Table 11.2.

Table 11.2 Total indexes.

<table>
<thead>
<tr>
<th>Turbines Number</th>
<th>N</th>
<th>Wdir</th>
<th>D</th>
<th>Dir</th>
<th>( \alpha )</th>
<th>( \gamma )</th>
<th>( N_{eq}(rpm) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.29</td>
<td>0.03</td>
<td>0.05</td>
<td>0.003</td>
<td>0.28</td>
<td>0.35</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
<td>0.03</td>
<td>0.05</td>
<td>0.003</td>
<td>0.35</td>
<td>0.36</td>
<td>0.64</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.03</td>
<td>0.06</td>
<td>0.003</td>
<td>0.40</td>
<td>0.32</td>
<td>0.58</td>
</tr>
<tr>
<td>10</td>
<td>0.19</td>
<td>0.03</td>
<td>0.07</td>
<td>0.003</td>
<td>0.40</td>
<td>0.32</td>
<td>0.58</td>
</tr>
<tr>
<td>15</td>
<td>0.18</td>
<td>0.03</td>
<td>0.08</td>
<td>0.003</td>
<td>0.41</td>
<td>0.32</td>
<td>0.56</td>
</tr>
<tr>
<td>means</td>
<td>0.21</td>
<td>0.03</td>
<td>0.06</td>
<td>0.003</td>
<td>0.37</td>
<td>0.33</td>
<td>0.6</td>
</tr>
</tbody>
</table>
11.4 Discussion

The global sensitivity analysis provided an useful method to deeply understand some aspects of the Italian procedure for WTN assessment. At this stage only a preliminary assessment of
the key parameter $N_{eq}$ has been performed, a complete analysis will be necessary. As $N_{eq}$ value is involved in many steps of the procedure, sensitivity analysis is expected to have significance on the procedure outputs. The Factor Prioritization setting has allowed to order the $N_{eq}$ input factors by their influence on the $N_{eq}$ output uncertainty, as in Figure 11.1 and 11.2. The estimated Main and Total sensitivity indexes coincide, revealing no variance interaction effects between the input factors. It has been found that the theoretical parameters $\alpha$, $\gamma$, accounts for about 70% of the $N_{eq}$ variance, suggesting that their variance reduction could improve the overall uncertainty of the procedure output. A deeper analysis of these parameters will be the aim of further research. On the contrary the uncertainties on the measurement configuration factors are not very important for $N_{eq}$ uncertainty, accounting for less than 10% of the $N_{eq}$ variance. It is expected that their contribution to the total uncertainties of the procedure can be neglected too. Furthermore, for small number of turbines $T_n$, the influence of $\alpha$ uncertainty increases with $T_n$ itself, as clearly shown in Figure 11.1. This is coherent with the fact that the sum of all turbine-receiver distances increases with turbines number and $\alpha$ is related to distance parameters. Moreover, blades speed uncertainties are less influential increasing turbines number.
12. Future developments

The uncertainties analysis by Monte Carlo method, the validation and the sensitivity analysis shown in the previous Chapters have been useful to understand the pro and cons of the procedure for the WTN assessment presented in this thesis. In this Chapter some of the issues that can limit the field of applicability of the procedure will be underlined, together with the solutions that are already under study for the procedure improvement. Nearly almost of them have been conceived as a consequence of the data from “Palareta 2” measurement site, in which the immission did not resulted to have a verosimile trend.

All the foreseen future developments aim to reduce the uncertainties and the bias of the procedure. Nevertheless, the purpose of the procedure should not be forgotten, which is to find a simple method usable by technicians in the WTN assessment.

Attention will be given to the parameters involved in the calculation of $N_{eq}$. In particular, the estimate of $\alpha$, $\beta$ and $\gamma$ parameters can be improved using the procedure with a feedback type method. In this approach, the output of the process will be used for new estimates of the input parameters to be used to refine in a progressive way the results of the procedure. This will probably lead to an estimation of the parameters that is site dependent.

In the proposed procedure, when the residual level is not lower than the measurement value ($L_{r,k} \leq L_{o,k}$), it was decided to replace the result of Equations 8.9 with $L_{r,x,k} = L_{r,k} - 10$. With the due changes, the same happens when the immission level is not lower than the measured value. This substitution was conceived in order not to lose useful data for a statistic purpose, without inserting numbers that could alter the procedure’s outcome. Unfortunately, it has been recognized that the inclusion of such an arbitrary value can result in errors in immission and residual noise estimates. This could be one of the causes that could lead to over-estimate the residual values, as resulted by the validation. The values that would be currently replaced in this process may instead be excluded from the procedure. In this way the amount of data would be reduced, but the quality of the output would gain value.

Another possible bias generator may lie in the calculation of the difference between the environmental values and residual, or between the environment and the immission, when their values are very close. In the procedure, the differences are calculated even when there is a minimum difference (1 dB) that can be due to statistical fluctuations. This can lead to
overestimate / underestimate the immission and residual noise. A possible solution, currently under test, is to introduce in the calculation of the difference a criterion based on the levels of uncertainty and on a statistical test.

The same type of uncertainty, then the same type of solution, could be in the calculation of the “activation threshold” \( \bar{x} \), where the energetic average \( L_{x} \) of the \( n_{x} \) measured \( L_{\text{eq,10 min}} \) included in the \( x^{th} \) group for all \( x \) values is subtracted from the cumulative energetic average \( L_{\text{cum,x}} \) of the \( L_{x} \) for all the \( N_{\text{eq}} \) values from 0 to \( x \).

In the phase of the procedure in which the reliability and goodness of the fit for the immission levels curve is evaluated, a level of acceptability of \( R^2 = 0.7 \) is currently been fixed as an indicative value. This choice can then be investigated, as well as the eventual use of other indicators to assess the goodness of fit.

The implementation of the above issues/solutions will lead to a new updated version of the procedure that will be tested and compared following the already presented validation methods.

In the context of the Italian WTN regulatory system, the future procedure will need to respect the current regulation, allowing then the calculation of the differential limit, but also to predict what the actual disturbance to population the studied wind farm produces.

Since it has been shown that the amplitude modulation is the cause of the higher annoyance for WTN than other types of noise, in order to complement the assessment procedure it will be necessary to establish a procedure for the AM recognition and quantification. This will be performed applying the already existing methods in literature to the measurement campaigns presented in this thesis. In case of detection of AM, a penalization for the immission noise level will be applied in the same way as the already existent for the tonal or low frequency presence.
13. Conclusions

With 63 new GW, the worldwide wind energy production reached a total of 433 GW in 2015, with China leading the way in the last years. This increasing installation of wind farms raises the attention of citizens to the wind turbine noise (WTN) issue, which results to be a very disturbing type of noise.

From a review performed in this thesis, it results a lack of specific studies for the health effects of WTN, especially at low noise levels, which is probably the cause of the very different normative and legislative framework among the various countries of the world.

The low frequencies components, together with the amplitude modulation, are the cause of profound discomfort caused by WTN to the population even at low noise levels.

The relations that annoyance has on human health have been listed, showing that a WTN level that can cause a fair percentage of annoyance among citizens is around 40 dB(A), as inferred from dose-effect curves based on the %HA. This noise level is also a source of health problems as highlighted by the World Health Organization and by other scientists that recognise the key role of annoyance in health assessment. Among these diseases, the low levels of WTN can disturb sleep, but also affect outdoors social activities, especially during summer.

A limit value for WTN has been determined in this thesis starting from the Italian one for road traffic noise during daytime and night-time, which are equal or similar to those of many European countries. The %HA corresponding to the limit for road traffic noise, converted in $L_{den}$, has been extracted from its dose-response relationship for highly annoyed. Then, the tolerance threshold for outdoor WTN levels has been taken from the WTN dose-response relationship at the %HA identified for road traffic noise. The limit value obtained, is 42.9 dB(A) and is comparable with the standards analysed in the article, particularly the British and the Danish ones.

The regulations also establish limit values increasing with residual noise, and therefore with the speed of the wind. The derivation of these values with general validity, however, is complex, because residual noise levels depend exclusively on the environmental and weather conditions of the measurement site. The measuring mode then becomes determinant to the results, which are dependent on the wind, on the direction of sound propagation, on the
The residual noise level is evaluated as a function of the wind speed at receivers’ height ($v$) that varies seasonally, could influences the outcome of a measurement campaign that may result in exceeding the limit or not if carried out in winter rather than summer. Thus, in any legislation, the period in which to perform the measurement campaign of the residual noise and the duration of it has to be chosen very carefully.

The noise assessment at the receivers due to wind turbines in operation is usually performed through outdoor measurements. Being such a particular and complex type of noise in term of its generation, propagation and perception, the critical issues related to WTN assessment for compliance with noise limits have been analysed and discussed, particularly for wind farm in complex terrain. A specific data acquisition methodology useful for the noise monitoring of WTN in complex territory, where no analytical relation between wind speeds at hub and ground heights works, has been proposed. Furthermore, it was observed that relating noise immission to the blades rotational speed instead of the wind speed at hub is more useful, as well as it is better to relate the residual noise to the wind at ground while avoiding the data with wind speed greater than 5 m/s. It has also been verified that by performing a sufficiently long measurement campaign it is possible avoiding to require the wind farm shutdown in order to measure the residual noise, because the periods in which wind turbines are ordinarily still can be use to roughly estimate it.

Generally, to get a reliable and approved measurement of the residual noise it would be necessary to turn off the wind farm, with consequent lost of money by the farm owner.

On the basis of 9 measurements campaigns of sound and meteorological data performed in Italy, this thesis suggested a new procedure to simultaneously estimate the immission and the residual noise components measured nearby a wind farm when the residual noise is mainly generated by wind. This allows the evaluation of the noise impact produced by operational wind farms, without requiring the farm shutdown.

The method considers the immission levels of a wind farm as a function of a new parameter that considers the rotation of all the turbines: the equivalent blades rotational speed $N_{eq}$. The residual noise level is evaluated as a function of the wind speed at receivers’ height ($v_{gr}$).

The proposed procedure reconstructs these trends starting from a noise and weather measurement campaign of at least two weeks without requiring the plant shutdown. The periods when the wind turbines had rotational speed low enough not to increase the noise at receiver are used as a first estimate of the residual noise level. The final residual noise as a
function of the $v_{gr}$ and the immission levels as a function of $N_{eq}$ are computed through appropriate iterative phases of energetic subtraction between the measured noise levels grouped by classes of $v_{gr}$ and $N_{eq}$.

The implementation of the method in an automatic software procedure results in a faster analysis of the acquired data.

A sensitivity analysis has been applied to the key parameter $N_{eq}$. As $N_{eq}$ value is involved in many steps of the procedure, sensitivity analysis is expected to have significance on the procedure outputs. The Factor Prioritization setting has allowed to order the $N_{eq}$ input factors by their influence on the $N_{eq}$ output uncertainty. No variance interaction effects between the input factors have been pointed out, whilst it has been found that the theoretical parameters $\alpha$ and $\gamma$ accounts for about 70% of the $N_{eq}$ variance, suggesting that their variance reduction could improve the overall uncertainty of the procedure’s outputs. On the contrary, the uncertainties on the measurement configuration factors are not very important for $N_{eq}$ uncertainty, accounting for less than 10% of the $N_{eq}$ variance. It is expected that their contribution to the total uncertainties of the procedure can be neglected too. Furthermore, for small number of turbines $T_{nr}$, the influence of $\alpha$ uncertainty increases with $T_{nr}$ coherently with the fact that the sum of all turbine-receiver distances increases with turbines number and $\alpha$ is related to distance parameters. Moreover, blades speed uncertainties are less influential increasing turbines number.

The global uncertainties analysis has been performed through a Monte Carlo method. The 95% coverage interval obtained varies from 1.2 to 2.6 dB(A) for noise immission levels and from 1.2 to 1.8 dB(A) for residual levels evaluated over the whole measurement period, suitable results for the assessing compliance to normative prescriptions. These values only correspond to the propagation of the type A and B input uncertainties, thus they do not include possible difference between obtained value from the expected value (bias) due to the procedure itself.

The bias has been evaluated during the validation phase. Due to the described issues in providing a reliable prediction of the residual noise levels, the validation of the procedure outputs resulted a complex task. Nevertheless, it has been performed in three alternative way. A comparison of the immission levels of the procedure with the noise prediction models, in which the immission noise levels resulted comparable with the predicted ones within the uncertainties. A method based on a hypothetical set of measured noise level, corresponding to
the procedure’s measurement period, which is simulated summing a theoretical residual noise function of \( v_{gr} \) to a theoretical immission noise as a function of \( N_{eq} \) and to a random noise. The validation for the test-cases resulted quite good for the immission estimate, being the bias values included in a range between \([-2; 2]\) dB(A) for a SNR range of \([-3; 3]\) dB(A), and \([-3; 2]\) dB(A) for a SNR range of \([-6; 6]\) dB(A). The results were also good for the residual estimate, being the bias values included in a range between \([-1; 2]\) dB(A) for a SNR range of \([-3; 3]\) dB(A), and \([-1; 3]\) dB(A) for a SNR range of \([-6; 6]\) dB(A). Generally, a slight underestimation of the immission levels and overestimation of the residual levels that linearly increases with the SNR, i.e. the difference between the immission and residual levels, are experienced. Some unexpected case with variation of nearly 6 dB(A) occurred, which will need further developments of the procedure. For this reason, some of the parameters/steps of the Italian procedure are currently under investigation.

The third validation approach was based on a check of the difference between the measured 10 min environmental noise level and the environment levels on 10 min from the procedure. The environmental noise levels validation confirmed the good results, being all the signals well correlated. Furthermore, the histogram of the differences between measured and calculated environmental noise levels over all the test sites showed an almost symmetrical distribution with average around 1 dB(A), with the 90% of the differences ranging between -5 and +6 dB(A).

In summary, the results of this work are:

- A review showed a lack of specific studies for the health effects of WTN, especially at low noise levels. The low frequencies components, together with the amplitude modulation, are the cause of profound discomfort caused by WTN to the population. As a consequence, the normative and legislative framework resulted very different among the various countries of the world.

- A limit value of 42.9 dB(A) for WTN has been determined starting from the Italian one for road traffic noise during daytime and night-time. The limit value obtained is particularly comparable with the British and Danish standards, as well as being a noise level recognised by the WHO to be a source of health problems.

- It being such a particular and complex type of noise in term of its generation, propagation and perception, the critical issues related to WTN assessment for compliance with noise limits have been analysed and discussed, particularly for wind farm in complex terrain.
A specific data acquisition methodology useful for the noise monitoring of WTN in complex territory has been proposed. It was observed that relating noise immission to the blades rotational speed instead of the wind speed at hub is more useful, as well as it is better to relate the residual noise to the wind at ground while avoiding the data with wind speed greater than 5 m/s. It has also been verified that by performing a sufficiently long measurement campaign it is possible avoiding to require the wind farm shutdown in order to measure the residual noise.

On the basis of 9 measurements campaigns of sound and meteorological data performed in Italy, this thesis suggested a new procedure to simultaneously estimate the immission and the residual noise components measured nearby a wind farm. This allows the evaluation of the noise impact produced by operational wind farms, without requiring the farm shutdown. The method considers the immission levels of a wind farm as a function of a new parameter that considers the rotation of all the turbines: the equivalent blades rotational speed $N_{eq}$. The residual noise level is evaluated as a function of the wind speed at receivers’ height ($v_{gr}$).

The sensitivity analysis showed no variance interaction effects between the input, whilst the theoretical parameters $\alpha$ and $\gamma$ accounts for about 70% of the $N_{eq}$ variance. On the contrary, the uncertainties on the measurement configuration factors are not very important for $N_{eq}$ uncertainty, accounting for less than 10% of the $N_{eq}$ variance. Moreover, blades speed uncertainties are less influential increasing turbines number.

The global uncertainties analysis has been performed through a Monte Carlo method. The 95% coverage interval obtained varies from 1.2 to 2.6 dB(A) for noise immission levels and from 1.2 to 1.8 dB(A) for residual levels evaluated over the whole measurement period, suitable results for the assessing compliance to normative prescriptions. These values only correspond to the propagation of the type A and B input uncertainties, thus they do not include possible difference between obtained value from the expected value (bias) due to the procedure itself.

The validation phase evaluated the bias in three different phase, due to the complex task of providing a reliable prediction of the residual noise levels. A first comparison of the immission levels of the procedure with the noise prediction models showed comparable values among the two different set of data. The second method was based on a hypothetical set of measured noise level, simulated summing a theoretical residual noise function of $v_{gr}$ to a theoretical immission noise as a function of $N_{eq}$ and to a random noise. The validation for the test-cases resulted quite good both for the immission and residual estimates. The third validation approach checked the difference between the measured 10 min environmental noise level and the
environment levels on 10 min from the procedure. The environmental noise levels validation confirmed the good results, being all the signals well correlated.

- A slight underestimation of the immission levels and overestimation of the residual levels that linearly increases with the difference between the immission and residual levels are experienced. Some unexpected case with variation of nearly 6 dB(A) occurred, which will need further developments of the procedure.
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